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THE LUNAR SURFACE

Preface

Within the past few years, the literature on lunar studies has become extensive without comparable reduction in controversy and conflicting concepts. Periodically, surveys for various Boeing proposal efforts such as APOLLO and Lunar Landing studies have been necessary.

~~This report is an attempt to describe briefly~~ The lunar observational techniques and their limitations and ~~to summarize~~ some current concepts relating to the surface of the moon are described in order to provide some insight to the current state of knowledge. Recent books, papers, charts and publications in the open technical literature through August 1962 ~~have been~~ were the principal sources of information.

~~For those who wish to~~ For a review ~~prior Boeing lunar~~ of studies related to this subject, a selection of applicable document references is included.

1.0 INTRODUCTION

1.1 Purpose of Studies

Speculation on the origin of the moon and its nature is as old as history and controversies today are more rampant than ever. We will continue to be dependent upon speculation regarding anything but rather gross features until man has traveled the lunar surface and returned with his observations. The quest for an understanding of the lunar surface has, until recently, proceeded at a rather slow pace. Since the development of rocket propulsion has made manned exploration of the lunar surface not only a possibility but a probability within the forseeable future, studies of the moon have received greater impetus. Where lunar observations and studies previously were given little attention by astronomers whose main efforts were directed toward galactic and extra-galactic investigations, now a major effort is being made toward a more thorough understanding of lunar problems.

Although the moon is the closest celestial object, our knowledge of surface details is limited. The limitations are those imposed by distance, the capabilities of the instruments, and by the presence of the earth's atmosphere. Telescopic observation is, first, limited by the theoretical resolution of the instrument; in the case of the 200 inch telescope it is 0.07 sec. of arc.

The second limitation of telescopic observation is imposed by the degradation of resolution caused by atmospheric turbulence. This is of particular importance in photography since the image is distorted during the time of exposure. As a result, photographic resolution is limited to about 0.4 sec of arc.

The two limitations, instrument resolution and the effects of the atmosphere whether due to refraction or absorption, apply to all lunar observations from earth. The present state of knowledge of lunar surface conditions is inadequate in the detail necessary for successful manned vehicle landings. Areas which appear virtually smooth and featureless with the best possible optical observations may, in fact, be quite rough at the scale important to successful vehicle landing. Further, the true physical properties of the overlying surface material are still a matter of considerable controversy. Estimates range from a dust layer of millimeter to kilometer depths covering a basalt like rock or sand and gravel, to thick layers of dust, sand, rubble and rock froth. Observations supporting widely divergent views must lead to the conclusion that one concept is about as valid as another. This accents the need for unmanned surface observing vehicles to precede manned landings. It is only in this way that facts can supplant speculation and costly if not catastrophic errors can be avoided.

2.0 LUNAR INVESTIGATIONS

2.1 Methods and Limitations

2.1.1 Telescopic Observations

2.1.1.1 Visual

Visual observation of the lunar surface features is confined primarily to description and to providing some additional detail to photographs in which atmospheric turbulence has degraded the resolution by image motion. An observer can take advantage of very brief moments of "quiet" to see detail closer to the theoretical resolution limit of the instrument, but he cannot record these with the accuracy of a camera.

2.1.1.2 Photographic

Nearly all of the basic information of the lunar topography is obtained by photography since it provides a permanent detailed record which can be measured and scaled. The photograph also can be studied in detail to examine features which may be overlooked by visual observation. The advantages of the photograph generally are much greater than the disadvantages of loss of resolution.

Both refracting and reflecting telescopes are used in lunar observations. Some of the instruments which have been used for most of the recent detailed studies are listed in Table I with some of their characteristics.

TABLE I

Refractors	diam	f	focal length	Theor. Resolution
Pic du Midi	24 in.	f.30	60 ft.	0.23" of arc
Yerkes	40 in.	f.18.6	63 ft.	0.12"
Lick Obs.	36 in.	f.19.3	58	0.14"
Reflectors				
Palomar	200 in.	Prime f. 3.3 Cass f 16 Coude f 30	54 263 492	0.025"
Lick	120 in.	f 5	50	0.04"
Mt Wilson	100 in.	f 5	42	0.05"

2.1.1.2.1 Topographic Measurements

Until about 1961, all existing maps of the moon had been based essentially on drawings rather than measurements, whether from visual observation or photographs. Although several excellent photographic atlases have appeared, there have been no maps having the precision of terrestrial surface charts with respect to location of lunar landmarks. The situation has been even worse with respect to elevations.

Kopal (1960) states that this situation was stressed in 1928 by Blagg who showed that early statements of lunar heights determined with inadequate instruments were uncritically taken over from one author to the next. Mean values of two or three very discordant measures were seriously given to within a few feet and in some cases, through errors in identification, the measurements were of different points.

The urgency in the requirement for more adequate charts arising from the imminent lunar exploration resulted in the initiation in 1958 of a large-scale effort on the part of Kopal and others, working with the U.S.A.F. Chart and Information Center to prepare a series of Lunar Atlas Charts to a scale of 1:1,000,000. To date, only a few of these charts have been published.

Because of the stringent photographic requirements, the best work of many observatories has been used. Some of the most outstanding work has been done at the Pic du Midi observatory which is noted for having the least atmospheric degradation of any observatory. Photographs from this observatory exhibit close to theoretical resolution on about 10% of the photographs. The principal instrument is a 60 cm refractor of 18 meter focal length. The linear scale in the focal plane is 11.4 sec of arc per mm., corresponding to 21.3 Km on the moon per mm. The theoretical optical limit of resolution, determined by the diameter of the first Airy disk, is equal to 0.23 sec of arc, 20 microns at the film plane, or 430 meters on the surface of the moon.

Since the measured rate of shortening or lengthening of shadows cast by lunar mountains can be reduced to indicate the altitude of a peak above the surrounding terrain and the unevenness of the ground upon which the shadow is cast, photographs were taken at a rate of 1 to 3 per minute. Because of the finite angular size of the solar disk all shadows have a penumbral band. To overcome this, shadows are measured by scanning a high contrast negative with a photometer having a slit width the diameter of the Airy disk and a length 3 or 4 times that amount. The output of the photometer is recorded, and the data necessary for the height evaluations is read from the smooth curve and processed by a computer. The accuracy, as stated by Kopal, enables them to triangulate relative heights of lunar mountains with an uncertainty of less than ±10 meters. The measurements have shown that slopes are generally less than 10° which agrees with measurements made of mountains on the limb of the moon.

2.1.1.3 Photometric measurements

Measurements of the character and intensity of light reflected from the moon have been made by many investigators in attempts to define both the physical characteristics of the surface and the nature of the material. The measurements have been made by a number of techniques. The intensity of the telescopic image may be measured directly by the use of photo tubes, radiometers, thermocouples or other photosensitive devices. Photographs are taken either with white light or through filters to confine the light to specific spectral bands. Spectrographs have also been used for more precise spectral studies particularly in the determination of luminescense. The selective absorption of the earth's atmosphere, as well as instrument resolution, are significant problems in these areas of study. Variations in polarization of the reflected light with location on the lunar surface and angle of illumination have been noted and inferences drawn concerning the type of material and particle size.

2.1.1.4 Infrared Thermal Measurements

Measurements of infrared radiation have been made to determine the temperature of the lunar surface. These measurements are from a rather thin surface layer as contrasted to thermal measurements obtained from radio wave studies. Resolution of temperature measurements over the surface is limited by the size of the sensor. Shorthill and Saari have measured local temperature variations to a resolution of 10 miles. The rate of change of surface temperature has provided information on the physical properties of the surface materials. Measurements have been made both across the disk to obtain the variations during a lunation and during an eclipse to observe changes occuring as a result of much more rapid changes in the intensity of illumination.

2.1.2 Microwave radio measurements

In recent years, microwave radio has been used to gain additional information on surface properties. Some information on roughness and the thermal regime have been obtained, but the results obtained by the various investigators do not provide a consistent picture. "Resolution" is, again, a limiting factor in obtaining data from localized areas. Results are values averaged over appreciable areas of the surface.

In addition, the wavelength of the radar used introduces another variable due to the dependence of reflectance on the physical characteristics of the material. A loose, unconsolidated material may be rather transparent to wavelengths of a few centimeters and the returning signal may be related to subsurface strata at some depth. We have then, a problem with three variables; the wavelength used, the reflectance of the surface material, and the scale of the surface irregularities. Daniels (1961) obtained a crude pictorial representation of the small scale structure by analysis of radar fading data using CW and pulsed radar at 68 mc. An exponential autocorrelation function was used for the analysis, assuming the surface to be a perfect reflector.

Until reliable information is obtained on the nature of the surface material it is difficult to interpret radar data. Although the radar data indicates a roughness at a scale of 10 cm or so, other studies indicate larger scale roughness. Part of the inconsistency may be the result of the undefined depth of "transparency" of the surface to the radar. Thus radar measurements do not end speculation but instead may add to it.

2.1.3 Model Studies

Many attempts have been made to derive theories of the mechanisms by which the lunar features were formed by producing "scale model" craters and comparing the experimentally produced craters with the lunar "prototypes." Generally, these experiments were made in efforts to evaluate the impact theory of crater formation.

Pellets have been impacted into almost the entire gamut of imaginable materials, and under a variety of conditions, such as velocity, air pressure and pellet compositions. The results of these experiments have been as varied as experimental results can vary - from complete failure, to what appears to be rather credible success. A recent, and what appears to be one of the more successful model studies was carried out by V.P. Head (1962). In his experiments he was able to produce small craters which scaled dimensionally and in appearance with prototype craters such as Kepler. In addition a population of secondary craters resulted which also agreed remarkably with the prototype population in the Kepler region. Thirdly, he obtained "ray" patterns which were realistic. From these experiments, and by comparison with lunar data obtained from photographs, he extrapolated populations of craters having diameters below the present limit of resolution.

Model experiments are always questionable until they can be substantiated, preferably by direct observation or measurement of the prototype, and extrapolations are particularly suspect. However, as Head points out, "It is only reasonably to assume that (his) inferences are not more certain than many contradictory and widely held views." The results of these experiments will be discussed later.

2.1.4 Satellite observations

To date, observations made from unmanned orbiting or impacting lunar exploratory vehicles have not added to our information of the lunar surface detail. The most significant information on the general features was obtained by the Russian lunar vehicle which obtained photographs of the far side in 1959. One of the more outstanding disclosures was the apparent absence of large mare areas. The quality of the photographs limited recording to only rather gross features.

PHYSICAL CHARACTERISTICS

Formation of the Moon

The formation of the moon has been a subject of speculation for a great many years and many theories have been put forth. Darwin, in 1898 proposed that the moon separated from the earth during the early formative period as a result of tidal action. A more recent theory is that at one time the material which has formed the planets existed in large condensing bodies called "protoplanets." Within most of these bodies there existed smaller centers of condensation, the proto-satellites. Studies of the moments of inertia tend to indicate that the moon has been quite rigid during the whole history of the Earth-Moon system. There is some data supporting the hypothesis of entirely independent origins for the Earth-Moon system and that the earth captured a small independent planet already in a rigid condition.

Kopal (1962) discards the model of a rigid moon as well as a fluid moon as incompatible with the details of observational evidence and known behavior of materials under the conditions prevailing in the lunar interior. He proposes a gravitational collapse of an agglomeration of pre-existing solid particles into the moon over a period of $10^6 - 10^7$ years at low temperature. Radioactivity generated heat sufficient to result in slow convective flow. This may be the main reason why the distribution of mass inside the moon deviates from hydrostatic equilibrium as evidenced by the motion of the moon. It is not necessary for actual melting to take place since convection can arise in a viscoelastic medium. As further evidence, Kopal cites the unequal distribution of maria and believes that the floors of small circular maria might represent the tops of sub-surface convective cells. Urey (1960) approached the problem from the standpoint of density of the lunar material, and the composition and processes which are compatible. He suggested that this line of evidence tends to support the nucleogenesis theory of formation. Recently, however, he has adopted the "hot moon" hypothesis.

Head (1962), as a result of laboratory model studies and lunar observational data, presents a somewhat different theory. The apparent lack of enough heavy radioactive elements to produce melting, coupled with apparent indication that a molten surface did exist, led him to postulate the occurance of surface melting in the last stages of growth. An increased rate of energy influx, with both the "collision diameter" and parabolic velocity of a growing moon, can be shown to lead to a likelihood of surface melting as the growth rate reached a maximum when the moon was some 97% of its final diameter. A very few impacts at high seismic Mach number by particles from outside the solar system can then account for all the explosive disruptions of the lunar surface. He postulates that the "uplands" may be likened to slag on the molten material which, in the region of Mare Crisium, may have had a depth approaching 20 miles. The various lunar features from maria to small craters and rays resulted from impacts on the molten surface and later as the cooling resulted in increased viscosity and final solidification. This sequence has resulted in a mare surface in which the strength of the material increases with depth.

It is seen that a number of conflicting hypotheses exist for the formation of the moon, each with its set of supporting evidence. Acceptance of any one as the "correct" theory now must be made on the basis of incomplete knowledge and would be a matter of personal convictions.

3.2 Topography

The description, measurement, and representation of lunar topography must be based upon telescopic observation and photography. The limitations of these methods place a limitation on the accuracy and the detail of representation of the surface features.

The size of observable detail is limited by resolution to a lower limit of about 500 to 1000 meters with the best telescopes.

The accuracy of position or location suffers from the lack of precise horizontal control and knowledge of absolute altitudes. Degradation of accuracy increases toward the limbs. The determination of elevations on the lunar surface has presented imposing difficulties due to a lack of suitable reference or datum and to the measurement techniques available. The use of photographic stereo pairs, as in terrestrial aerial mapping, is unsuitable because of the impossibility of obtaining an adequate base line, even with the assistance of the lunar librations. The method that has provided the most reliable indication of elevations is based upon the measurement of angular shadow lengths. This method suffers from several difficulties: (1) the precision of measurement of the shadow length is limited by the resolution of the photograph, (2) it is affected by the slope of the surface, (3) even if on a "level" surface, it indicates elevation of the point above the adjacent surface rather than the absolute elevation above a standard datum, (4) measurements in a N-S direction are far less reliable than E-W, (5) low slope angles do not provide adequate shadows or clear cut boundaries, (6) horizontal control of position lacks precision.

The shadow measurement method has had its greatest application in the determination of relative heights of mountains, but it tends to fail in extensive areas devoid of mountains. A refinement of the method has been used in such cases, as in the maria.

A photographic negative of a lunar area is scanned with a photometer across a gently undulating sunlit area in a direction parallel to the "brightness equator." By making auxiliary scans in closely adjacent regions where there are no very obviou mounds or ridges, a mean, smoothed curve of transparency can be plotted against distance across the surface. By superimposing the smooth curve on an individual trace, a point may be found on the mean curve which has the same intensity as any chosen point on the individual curve. The distance which separates the two points subtends a lunar radial angle equal to the slope of the ground at the point in question. A profile can be constructed from a series of such measurements. The method assumes a uniform albedo. While this method is sensitive it is not as accurate as the mountain-shadow method.

The method of measuring absolute heights of points (the distances of surface points above the center of the mean sphere of the moon) reduces essentially to the accurate measurement of the position of these points. All measurements must be referred to some fixed reference system. This has been established such that the origin is the center of the mean sphere. The z axis extends to the observer and the x and y axis then lie in the plane of the limb.

When the moon is in the position of mean libration, the axes define the standard coordinates for a point on the surface. The quantity z cannot be measured directly but can be derived from x and y by the equation of the mean sphere, after corrections for the projection of the moon, optical distortions, atmosphere effects, etc.

Measurements made by J. Franz in 1901-1903 and S.A. Saunder (1900-1911) established 150 "standard points" which provided the basis for selenographic measurements. The original catalog was revised by Schratka-Rechtenstamm in 1958 and is the basis of present topographic measurements.

3.2.1 Topographic features

The surface of the moon presents a variety of features which have been given designations relating them to terrestrial features. Many of them date back to the very early observations and, although misinterpreted, have been retained in current nomenclature.

3.2.1.1 Maria

The maria or "seas" are the large, apparently smooth areas covering about half of the visible lunar surface and are of low albedo (0.6-0.8). They appear mostly on the eastern and western sides of the visible disk with the largest, Oceanus Procellarium on the western* side. The recent observations by the Russian Lunik have shown

* Orientation of cardinal directions is in accordance with the resolution adopted by IAU General Assembly, 1961, which reversed the original astronomical convention to agree with terrestrial orientation with respect to rotation of the moon on its axis, i.e., east is preceding and west following.

that they occur to only limited extent on the far side with none comparable in size to those on the visible disk.

The maria occur as irregular to nearly circular plains ranging in size from 300 to 500 km, generally bounded by mountainous areas.

The maria are everywhere lower than the adjacent uplands (or continents). They contain a variety of features of low relief including braided systems of low ridges, low rounded scarps and domes. Although there are various theories regarding their origin, it is generally accepted that the maria were formed from molten rock or lava, during the early history of the moon. Whether the source of lava was the lunar interior or produced as a result of impact of asteroid-like bodies is a subject of controversy. There is evidence indicating the Mare Imbrium was formed by a great collision. Large grooves, radiating from the collision area, appear to have been plowed by high density objects, some of which were of kilometer dimensions and may have been fragments of the colliding body. Fielder (1961) and others have pointed out a pattern of faults apparently related to an Imbrium collision.

Mare Tranquilitatis appears more as a lava flow than any of the other maria. It is i regular in shape, dark in color, and appears to have some features distorted in a manner which would be expected by flow of a dense liquid. The flow seems to have come from Mare Serenitatis.

The other maria are smooth as might be expected from solidification of fluid lava, but their appearance is not inconsistent with that which would be produced by a fall of great quantities of finely divided material from the great collisions.

Baldwin maintains that the lavas in the lowlands were not formed by meteorites and planetesimals impacting and cratering the moon. He concludes that the maria and craters were formed in a dry condition and that the lava flow was a much later and separate phenomena. He also supports the "hot moon", with melting caused by radioactivity, solar radiation and impact energy. In his model, the moon for a long time absorbed meteoric impact by isostatic adjustment of the mantle. Later, as surface cooling reached greater depths, new craters were less deformed. Finally, the surface became sufficiently strong to register the great impacts forming the maria. As isostatic adjustments of the cooling moon continued, with the interior molten from the heating of the concentrated long-lived nucleides, great cracks formed through which lava flowed out to depths of thousands of feet to form the maria. Flows occurred at different locations and times and of different compositions. Several advancements and retreats of lava occurred to form the present character of the maria.

Firsoff (1961) has discarded the impact theories completely as being unable to account for all lunar features, and instead supports the concepts of volcanic mechanisms. His concept of the mare surface, or areas in which molten lava escaped to the surface is that of "foam-stone" or exaggerated pumice having a density far less than 1. This concept is based upon the known behavior of molten glass or lava at 1200°C which, when exposed to high vacuum, will increase from 20 to 50 times its original volume by foaming or frothing. In the maria the rock froth, together with layers of volcanic debris has been compacted, degassed, and hardened by some agency such as heat from the interior of the moon or permiation of liquids or gasses. This concept provides a stratified structure which accounts for theterraced appearance of the inside slopes of the larger marial craters.

The mare areas have undergone changes since their formation which has affected their surface character. The most apparent has been the formation of craters of various sizes ranging from Copernicus, 56 miles in diameter down to the limit of telescopic resolution. In addition, there is evidence of techtonic changes producing ridges and faults or crevices, domes, etc. There is also some evidence of volcanism, even during the past few years, although the latter has been questioned. However, there have been no confirmed instances of appreciable change since the beginning of lunar observation.

3.2.1.2 Uplands

The upland or "continental" areas are markedly different from the maria. They are heavily cratered and rough and appear as bright irregular areas. It is generally believed that the uplands are older than the maria, being those regions which were not flooded by the lava which produced the maria. It is believed by many observers, that great, bright mountainous areas of the southern and southeastern parts of the near side approximate somewhat to the original surface of the moon. Examples of such features are "Hellplain" a very large and very shallow depression within which Clavius is found, Janssen, and the long scarps of the southeastern quadrant. If this concept is correct, the highlands would consist of the original material, collected by the moon during its last stage of formation, but modified by the effect of the final barrage of meteoric material which produced most of the observable craters. The distribution of post-mare craters on the uplands should resemble the distribution on the maria.

Head (1962) is of the opinion that the uplands can be likened to "slag" which floated over the molten surface material. This concept requires that the uplands should have markedly different physical properties than the maria and perhaps even the underlying strata. One would also infer that the uplands would not, then, be indicative of the primeval lunar material because of the metamorphism occuring during the period that the surface was molten.

The volcanic theory of formation, as suggested by Firsoff, considers the uplands to be composed of superimposed layers of coarse and fine volcanic matter, erosion and meteoric debris, and strata of porous or frothy lava. At greater depths the material has been compacted by pressure of the overburden to form a tuff. He does not make an estimate of depth but infers that it may be very large.

3.2.1.3 Craters

3.2.1.3.1 Formation

Craters are the dominant topographic form of the lunar surface. As such, they have received a great deal of attention and study. The mechanism of formation is the subject of speculation, and theories, although contradictory, are widely held. Of the two which are most prominent, one ascribes their formation to the impact of meteroids, while the other attributes them to volcanic processes. It is possible that both may be correct in part; it is doubtful if a single mechanism could account for all of the observed crater features. The impact theory seems to be most widely held, and evidence that at least some craters are of impact origin seems virtually irrefutable.

The sequence of formation can, in many areas be inferred by the occurance of over-lapping, physical characteristics, and alteration by "geologic" processes. Age is often indicated as "pre-mare" and "post-mare" although such a classification may be difficult in the upland areas. Apparent modification of the crater appearance by erosive processes such as micrometeoric impacts, solar particulate radiation, thermal changes etc., have been used as indicators of age, although the effectiveness of such processes and their ability to produce the observed range of apparent change is questionable. In the first place, the physical properties of lunar surface material are not known with sufficient certainty to be able to define the effect of the environmental factors. Second, the magnitude of the effecting processes cannot be assessed in all cases. Some workers discount erosive processes such as radiation and thermal changes as the principal factor in alteration of topographic features, and suggest that a cover of dust from meteoric infall and explosion debris would produce a smoothing effect. Others propose that drowning by the lava flow or partial remelting would explain the appearance of some crater rims and isolated peaks, as well as the flat bottoms of large craters.

The existence of central peaks in a very large number of craters has been taken as evidence supporting both the impact and the volcanic theory for crater formation. In the first case, they are believed to be the result of rebound following the impact or the material from the impacting body. In the second, they are volcanic cones built up within the main crater. To be sure, small craters have been observed at the peak of a number of such mountains, giving them the appearance of terrestrial volcanos, but not in the majority of cases. Adherents to the volcanic theory point out the resemblance of terrestrial maars and calderas to explains the variation in crater characteristics as being due to the combination of conditions, occuring over a time period, resulting from the initial condition of a fluid surface. The flat bottoms are attributed to the effect of the gradient in surface strength, rather than due to melting from the impact energy. The variation in rim structure is explained by the changing viscosity of the surface layer as it cooled. Thus impacts during the period of greater fluidity would be less prominent. As cooling progressed and a "skin" was formed, rims would be more prominent but some remelting or subsidance could occur. Finally impacts following final solidification, with the strength gradient extending to the surface, would result in craters such as Copernicus, Kepler, and others having the associated ray structures and large numbers of smaller secondary craters produced by impact of debris.

In propounding the volcanic origin of lunar features, Firsoff objects to the tendency of some authors to base concepts on "non-geologic" processes. He prefers to rely upon known terrestrial mechanisms which have produced features having a counterpart on the moon. He points out that the moon exhibits familiar techtonic features such as uplands, mountains, calderas, maars, volcanoes, lava flows, as well as faults, horsts and graben.

3.2.1.3.2 Spatial distribution

Large, well-formed craters occur more frequently in the lunarite or bright continental regions. This has been attributed to the formation of the maria subsequent to the time of maximum rate of infall of the material forming the moon. Pre-existing craters in these regions would have been covered. The existence of "ghost" craters in the maria have long been known and appear to be the result of inundation by the lava. Because of the time period over which the formation of the craters occured and the changing conditions which existed, the distribution of existing craters does not show a random nature over the surface as a whole. This has resulted in the maria, presumably younger than the continental areas, having more widely scattered craters of appreciable size, while the continents are almost completely covered with craters, many of which overlap.

In any case, considering the full range of sizes, a completely random distribution does not exist since the larger craters have smaller secondary craters associated with them which occur in a pattern produced by the impact explosion. Fielder has made a study of the distribution of secondary craters associated with Copernicus and Tycho. Crater-chains occur which have been correlated with tectonic changes, and thus meteoric origin is improbable. However it is considered that an impact such as formed Copernicus may have resulted in surface disturbances which promoted the formation of chain craters.

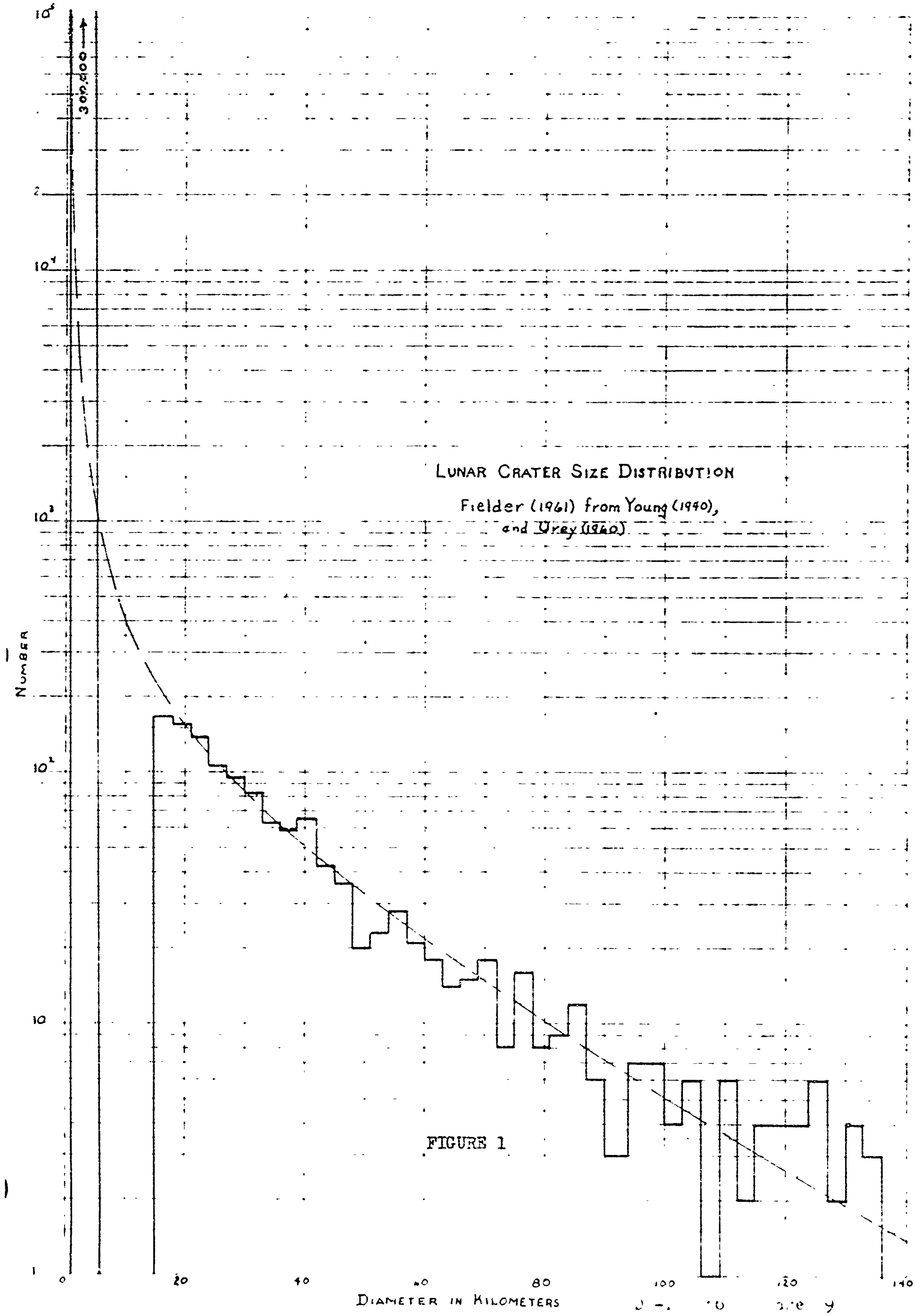
Detail of the distribution of maria and craters on the far side is lacking, but the photographs obtained 14 September 1959 by the Russian Lunik III indicate that there are few maria in comparison with the near side, and much of the surface is probably mountainous and rich in craters.

3.2.3.3 Size Distribution of Craters

In general, the number of craters in a given diameter grouping increases as the mean diameter of the grouping decreases. Fielder points out that a number of studies of the size distribution have been made but they are incomplete when extended to small diameter. This results from limitations of resolution of the photographs, the difficulties of identification in highly cratered areas, and the sheet difficulty of counting. Craters under about 1 km cannot be charted accurately and knowledge of craters smaller than a few miles in diameter is incomplete.

McDonald (1931) plotted the number of craters against the mean value of a diameter range and found the curve to be clearly hyperbolic. Young, in 1940, using more adequate data found that there was a change in the distribution curve at a diameter of about 40 km. A histogram, based upon Young's data of 1940, is shown in Figure 1. It will be noted that the minimum diameter listed by Young is 14-18 km; the estimate of 300,000 between 1 and 5 km is from Urey.

In his model studies, Heat attempted to derive crater populations attributed to secondary impacts, below resolvable diameters. By comparing size distributions, obtained from measuring and counting craters shown on the lunar atlas photographs with photographs of his models, he was able to make extrapolation to a diameter equivalent to 41 feet on the lunar surface. A comparison of populations derived from Allen, the lunar atlas in the region of Kepler, and the model studies is shown in Table 2.



LUNAR CRATER SIZE DISTRIBUTION
Fielder (1961) from Young (1940), and Urey (1960)
300,000
NUMBER
DIAMETER IN KILOMETERS

FIGURE 1

TABLE 2

Three Extrapolations of Crater Distribution

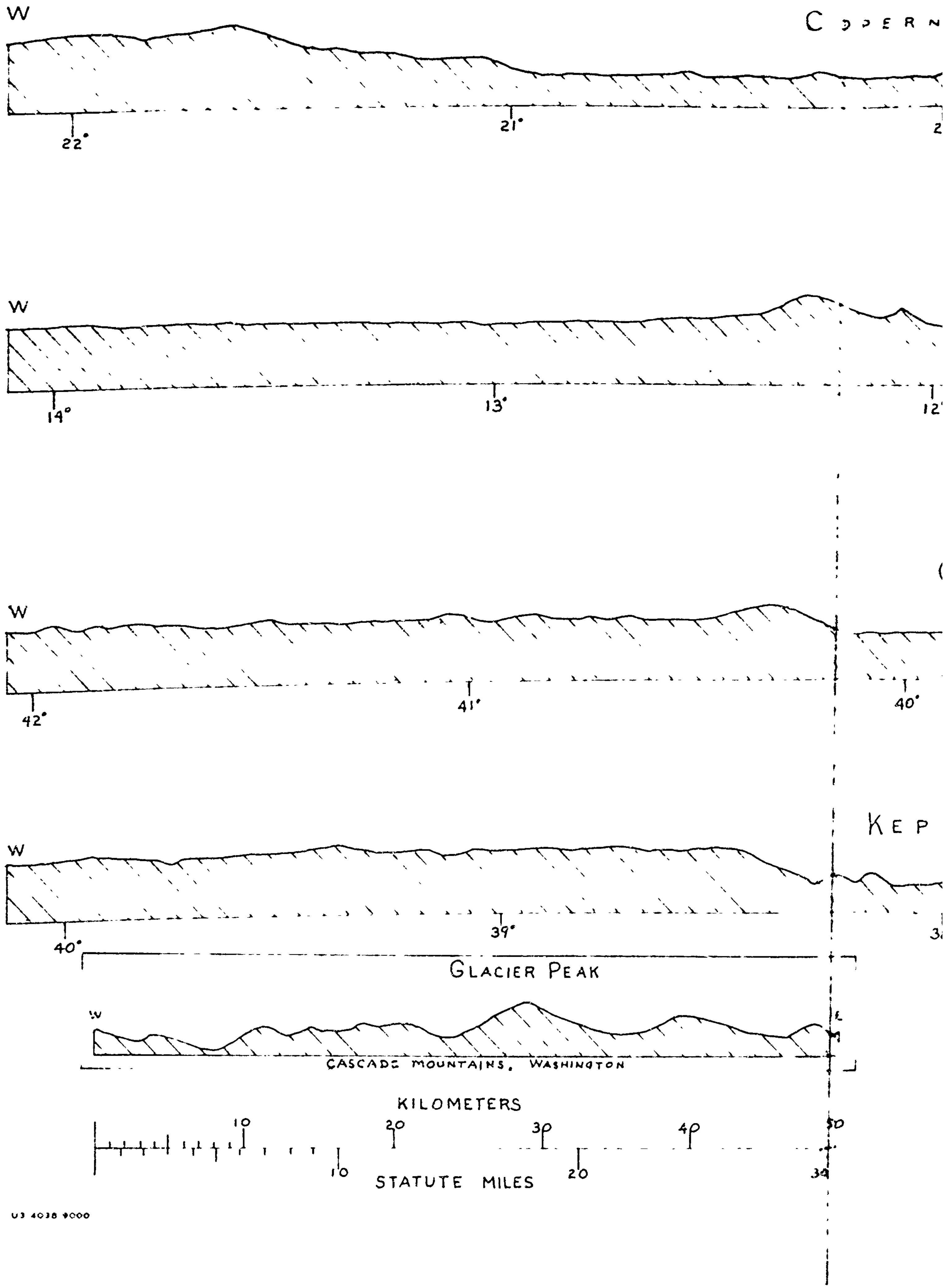
	No. of craters on an area of 21,000 mi^2		
	All types of terrain	Kepler region	Model
Diameter range	(Allen)	(Head)	(Head)
8 mi. and larger	5	2	4
2 to 8 mi.	77	42	141
0.5 to 2 mi.	1,230*	860*	5,080
0.125 to 0.5 mi.	19,000*	15,000*	42,000
165 to 660 feet	310,000*	115,000*	90,000
41 to 165 feet	5×10^6*	320,000*	50,000*[1]
less than 41 feet	infinite*	680,000*	10,000*[1]

* Extrapolated values

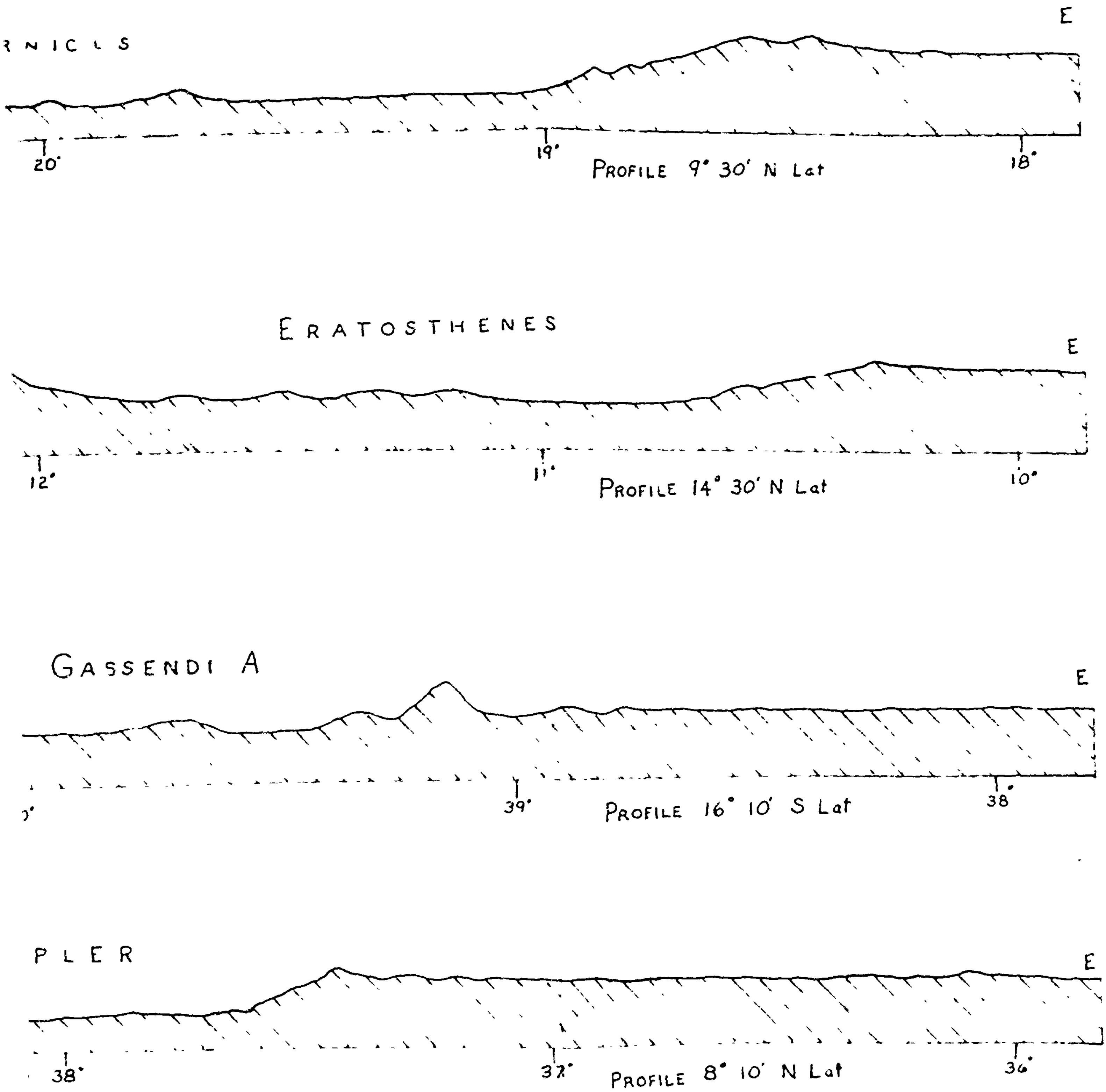
1 Values considered too low because of counting difficulty

It would appear that the areas, seemingly flat between themarial craters, may vanish as observational resolution increases. Thousands of craterlets a few hundred feet in diameter and less should become apparent for each crater now known. The roughness of such a terrain of overlapping craterlets would possibly present a serious problem to successful landing of a lunar vehicle and present a rather imposing problem of surface travel for exploration.

The slopes of the lunar features appear to be quite low, particularly in the marial areas where even the wrinkled areas rarely exceed 2°. The average slopes of the outer rims of craters have been given as 3° - 8° with some measurements ranging to 18°. The inner crater slopes are much greater, most measurements ranging between 30° and 40°, for craters 10-20 km in diameter. Generally, the large craters have smaller slopes while smaller craters are steeper. Inner slopes exceeding 50° have been estimated for many smaller craters. Daniels (1961) has estimated the slopes of surface features from the fading of radar signals. He found that the frequency distribution of slopes larger than radar wavelengths and smaller than visible were between 8° and 12° and that the slopes of small features appeared to be similar to large features. Hackman & Mason indicate slopes of 10° to 20° and occasionally higher may occur. Some examples of crater profiles, drawn from the Lunar Atlas Charts, are shown in Figures 2 and 3. The profiles are drawn with the same vertical and horizontal scale of 3 mm/km. The base curve follows the 1735 km lunar radius datum used for the Lunar Atlas Charts. A 50 kilometer east-west profile of a part of the Cascade mountains of Washington, which passes across Glacier Peak (elev. 10,400 ft.), is included for comparison. This profile was prepared by plotting elevations, at 1 km intervals, obtained from U.S.G.S. Topographic Charts, Glacier Peak and Stehekin, Washington, Quadrangles.


W
22°
21°
W
14°
13°
W
42°
41°
40°
KEP
W
40°
39°
GLACIER PEAK
W
CASCADE MOUNTAINS, WASHINGTON
KILOMETERS
10
20
30
40
50
10
20
30
STATUTE MILES

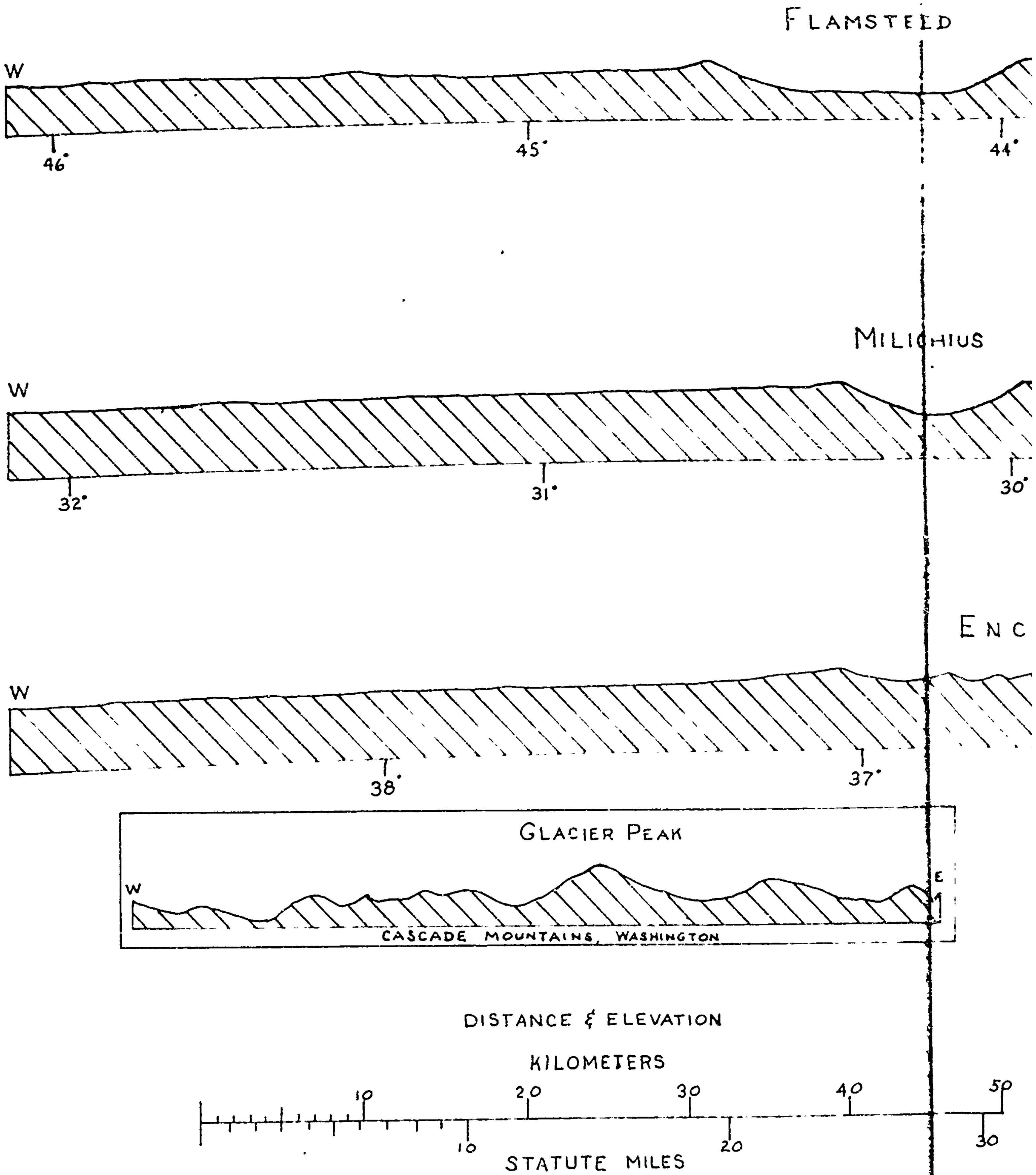
U3 4038 9000



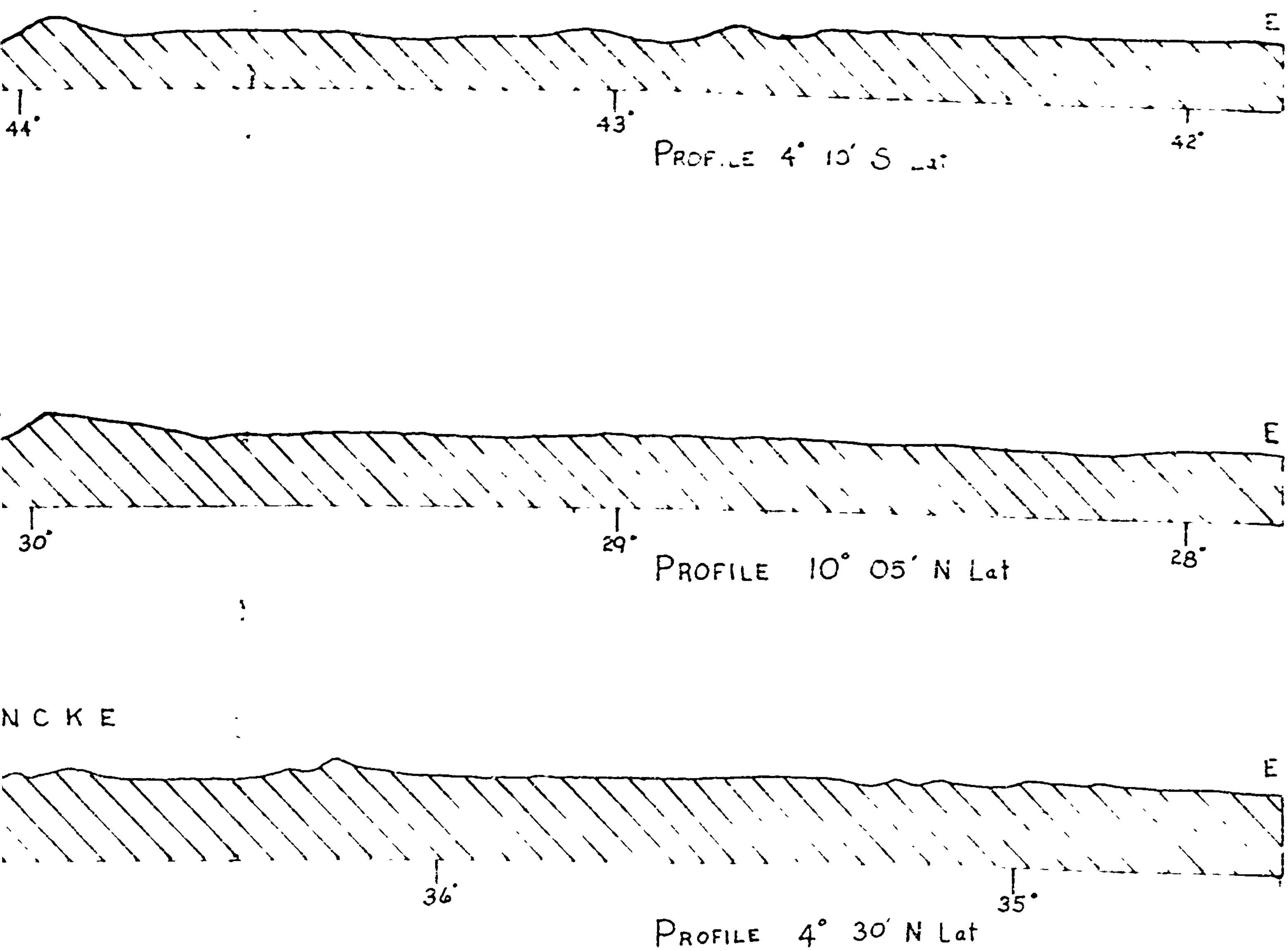
Longitude: Degrees West

Elevation Datum: Lunar Radius = 1735.4 KM

CALC		REVISED	DATE	Lu[illegible] Crater Profiles	Figure 2
CHECK					
APR				THE BOEING COMPANY	PAGE
APR					


FLAMSTEED
W
46°
45°
44°
MILICHIUS
W
32°
31°
30°
ENC
W
38°
37°
GLACIER PEAK
W
E
CASCADE MOUNTAINS, WASHINGTON
DISTANCE & ELEVATION
KILOMETERS
10
20
30
40
50
10
20
30
STATUTE MILES

US 4038 9000



LONGITUDE DEGREES WEST

ELEVATION DATUM LUNAR RADIUS = 1735.4 KM

5p
0

		REVISED	DATE		
CALC				LUNAR CRATER PROFILES	Figure 3
CHECK					D2-[illegible]36
APR				THE BOEING COMPANY	PAGE 3[illegible]
APR					

The lunar craters are relatively shallow in comparison to their diameter. Fielder shows the ratio of depth to diameter of 0.02 or 0.03 for craters 100 km in diameter and of the order of 0.1 for craters 10 km in diameter. The interior curves of well formed small craters tend to be paraboloidal.

Clues to the sub-resolution lunar terrain in the smoothest portion of any mare must be obtained by other than visual means. Attempts have been made on the basis of radar, IR studies, photometry, etc. Radar is hampered by the problem of surface transparency and there is no assurance that the measurements are of the true surface or of an underlying bed rock. Van Diggelen's work in photometry indicates a pitted surface with flats occupying about one-third of the area. The pits must be large with respect to the wavelength of light but there is no way of assigning diameters of a few centimeters or a few hundred meters to them. Other investigators would eliminate the flat areas and propose closely packed holes of all sizes, superposed and distributed, dug in a dark material. This latter concept agrees with Head's conclusions from the model studies. The photometric studies also infer that the pits must be deep in comparison to width.

Most lunar craters which appear to be relatively young are circular in form. Many, however, appear to have undergone modifications other than by subsequent impact. In such cases, the craters appear in roughly polygonal outline. This also holds true to some extent with respect to some maria, and is almost entirely restricted to craters having a diameter greater than 20 km. In general such distortion is attributed to crustal movement subsequent to the crater formation, although this concept is not unanimously held.

3.2.1.4 Rays

Prominent, bright streaks referred to as "rays" are seen to spread across the lunar surface. The most prominent appear to be associated with three craters: Copernicus, Tycho, and Kepler. The most widely held opinion relates them to "splash" from the impacts causing the above major craters, but the volcanists attribute them to ash or volcanic glass from eruptions. Fielder (1962) has identified fifty-nine lunar craters, mostly between 1 and 5 km in diameter, with certain ray elements of the craters of Copernicus and Tycho. These small craters are demonstrated as being secondary impact craters produced by rock blocks ejected from Copernicus and Tycho. Numerous small craters exhibit small ray systems of their own. The rays show no preference to any particular type of country and do not appear to be deviated by mountains or other features, but rather cross over all other features. Some appear to originate in or near the walls of thecrater as well as near the center. Fielder shows that the orientation is due largely to the behavior of rock strata as a result of the impact energy. The shape of the ray structures vary, but may be grouped into three general types:

A. Thin, straight, and roughly radial, of the type associated with Aristillus

B. Broadly curved as those of Copernicus

C. Apparently structureless and having many craterpits.

Detailed studies of the ballistic trajectories of ejected material have been carried out in an effort to explain the length, orientation, and shape or curve of the ray structures, considering the energies, angle of ejection, and rotation of the moon (Shoemaker 1960, Fielder 1962).

The exact nature of the rays is a subject of considerable conjecture. For the most part, they exhibit a rather high reflectance although some dark patches, a few miles across are known within the crater Alphonsus and each spot contains a small crater.

All observations indicate that the ray structures have no appreciable thickness; they evidence no shadow with very low angle illumination.

There are many speculations regarding the "composition" of the rays, ranging from a thin layer of "ash" or dust and fine material to a roughening of the surface by the falling material which produced many small pits or left a thin layer of pellets, gravel, boulders and other debris. Fielder appears to favor the concept of a combination of cup-shaped hollows and pellets as being the most plausible explanation of the optical properties of the rays.

The rays appear to be one of the more recently formed features, based upon the fact they they overlie all other features and are associated with the least eroded craters.

3.2.1.5 Mountains

The lunar mountains or mountain ranges appear to be related to the maria, craters, and perhaps volcanism. Topographically high areas encircling the maria have been named mountains but they may be more appropriately considered as crater rims. They do not resemble terrestrial mountain chains, and there is no evidence of the formation of mountain ranges by folding. Isolated peaks are found centrally located in many of the larger craters and a few prominent peaks are isolated near theedges of maria as are Piton and Pico in the northeast of Mare Imbrium.

In a sense, the lunar highlands or continents might be considered as mountainous in nature although the topography is that of heavy cratering. It is perhaps a question of nomenclature, but except for the generally circular formation, the crater rims would result in a rough mountainous-type terrain. The heights of the "mountains" which vary with the crater diameter, range from 20,000 feet to probably a few feet in elevation.

The features generally referred to as mountains or mountain ranges border the maria and are considered to be ejected from them. Some of the more prominent ranges will be mentioned. Two large ring mountain systems nearly encircle Mare Imbrium and Mare Serenitatis. The Carpathian mountains are those making up the southwestern part of the rim in the vicinity of Copernicus which presents the most rugged feature.

The Apennines extend 640 miles along the southeast rim of Mare Imbrium and 100 miles along the west side of Serenitatis. They are extremely rugged, faulted mountains with SE trending ridges. Peaks of 12,000 to 18,000 feet occur which are the tallest in the Imbrium-Serenitatis system. The Haemus mountains which lie to the south of Serenitatis and west of Tranquilitatis are also rugged, with a maximum elevation of about 8000 feet above the mare surface. Slopes range from 10° to 20° with the steepest toward Serenitatis and the Apennines. The Pyrenees, southeast of Tranquilitatis are more plateau-like uplands about 6000 feet above the mare surface. The Alps make up the northern section of the Mare Imbrium ring. The Alpine Valley believed to be a structural rift is a prominent feature in these mountains. The valley extends ENE 83 miles, varies from 3 1/2 to 6 miles in width and as much as 10,000 feet deep.

The central and southern highlands cover almost a third of the visible surface of the moon. They are covered with densely packed, contiguous, overlapping, and superimposed craters. Elevations generally range from rim heights of 10,500 feet to depths of 20,000 feet. Also included in this area, near the southern limb, are the Lebnitz mountains, some of the highest being 29,000 feet.

Mountains of distinctly volcanic origin are not common but some features are interpreted as being of volcanic origin. The Aristachus Hills and Riimkes Hills seem to be accumulations of lava extruded through vents. Some central peaks may be volcanoes, as some are topped by craters. However most of these craters are of such small size that they are identifiable only visually through a telescope.

3.2.1.6 Minor Surface Features

There are a variety of small, characteristic features, which occur on the lunar surface, attributed to tectonic processes, impacts and other causes. These features include ridges, rilles, clefts, domes and valleys. The linear structures, in many cases, appear to be associated in a more or less well defined grid system which may be of a radial pattern or parallel. The significance of the grid system has been studied in detail by Fielder (1961). He points out that there is a clearly marked radiating pattern around a center located in Mare Imbrium and that while a large scale collision probably contributed to the formation of the pattern it does not account for all of the elements. Visual observations have established that some components were formed after craters of the size of Tycho, and that tectonic mountain-forming actively occured subsequent to the formation of these craters.

3.2.1.6.1 Rilles

A rille is a relatively deep, narrow depression or crack which may extend as much as a few hundred kilometers across the surface. Fielder maintains that the wider rilles, at least, are quite shallow and all such features large enough for detailed examination appeared to have depths less than their respective widths. When several rilles occur in one region they frequently are approximately parallel.

One of the most prominent rilles is the Areadaeus Rille associated with the craters Areadaeus and Silberschlag, near the center of the disk. It is 5 km wide along the central portion and is of the order of 270 km in length with a depth ranging between 600 and 1200 meters.

Another large rille a short distance to the west is the Hyginus Rille or cleft.

A large number of smaller rilles have been observed associated with maria and with large craters. Often they tend to curve within the wall. The cross section of rilles is a subject of controversy. Baldwin (1958) stated that they are often deep in comparison to width whereas Fielder takes the opposite view. The slopes of the sides are therefore, also in doubt. In any event, it would seem that rilles may present a problem to surface travel if they are of such a size and shape that crossing would be difficult, since their length would preclude bypassing.

Faults resulting from vertical crustal movements would be related to rilles except that rather than being open cracks or clefts, there would be a difference in elevation on either side. Further, if faults occured similar to those on earth, slopes conceivably could be extremely steep. An example of such a lunar feature is the Straight Wall, located in the eastern part of Mare Nubium. The face of this feature is believed to be far from vertical, however.

3.2.1.6.2 Ridges

In contrast to the linear rills are the "wrinkle" ridges. In general, they are longer than the linear rills and sharp ridges and are found on the marebase, particularly around the borders of maria. Often they are approximately parallel. These formations are of low profile, having elevations of 100 to 200 meters and widths of from 2 to 20 km. Slopes are ordinarily in the order of 1° and rarely if ever exceed 5°.

The occurance of ridges of this type are attributed to a number of causes: buckling of the surface during readjustment, waves of solidifed lava or merely buried remnants of ringed plains. Kuiper believes that they are compression features. It has also been suggested that they may be the result of intrusion of magma in a dike structure but which did not reach the surface.

Kopal (1962) has pointed out an interesting concept regarding the wrinkle ridges. It has been suggested that these formations may be indicative of the presence of sub-surface moisture. The ridges may have been caused by the hydration of subsurface beds of anhydride minerals such as olivine which is accompanied by an increase in specific volume adequate to produce the observed bulging.

3.2.1.6.3 Domes

The lunar domes are low, rounded formations, circular, elliptical, or in some cases of irregular outline. Because their slopes do not seem to exceed 2° or 3° they are difficult to detect and may be more numerous than those observed. They occur in the maria but their presence would be masked in areas of irregular terrain if they occur there. Many of the domes possess small craters on or near their top.

Dome structures are found on earth but the mechanisms of formation are not all applicable to the moon. A few of the methods suggested for the formation of domes are listed below.

1. The intrusion of plastic igneous magma into or between surface rocks causing them to arc or rupture.
2. The intrusion or rise of lower density material into higher density material.
3. Large debris ejected in plastic or molten state during impact.
4. Angular blocks covered with smaller debris and dust.
5. Expansion of a mineral phase such as the serpentinization of olivine as a result of subsurface heating.

The last mechanism has been suggested by Salisbury (1960).

3.3 Characteristics of the Surface Material

Until direct observations have been made by first unmanned and later manned missions, the physical characteristics and composition of the lunar surface material must be inferred by indirect methods. In all cases the observations must be based upon measurements of incident, reflected, or emitted radiation extending from UV to RF frequencies. It also follows that the inferences are valid insofar as they can only compare or relate lunar m terial to terrestrial material exposed to a lunar environment. Because of these problems, the speculations and models of the surface are widely varying and often contradictory. The questions cannot be resolved until man travels the moon.

3.3.1 Physical Properties

3.3.1.1 Structure

The structural properties of the lunar surface is of major concern from the standpoint of landing vehicles, whether manned or unmanned, and for surface exploration. The design and engineering of landing structures and of vehicles for surface travel is dependent upon the load bearing properties of the surface and the texture of the materials. The determination of these parameters is beyond the capability of direct observation since telescopic resolution is of the order of 1/5 mile. Current information is thus based upon other observational methods and the data is subject to interpretation.

The maria are considered to be the result of lava flows to produce a relatively smooth surface. It is the concensus of most observers that the lava is covered by a porous material The nature of the overlying marial materials has been described variously as dust, sand, gravel, blocks and debris, rock froth, pumice-like, and hardened sand dunes.

Each concept has been based upon either speculation on the effect of meteoric impact and accumulation and other environmental conditons or upon optical, IR or radar measurements. Both methods suffer from limitations imposed by the remoteness of the moon, detailed knowledge of the true lunar environment, and effects of the earth's atmosphere on the observations.

Some of the more recent concepts are described below.

a. Pettit and Nicholson (1940)

   From observations of the rate of fall of temperature during a 1939 eclipse, they determined that a 3 cm depth of rock was involved. Later (1949) Wasselink using Pettit and Nicholson's data and his own radio measurements determined that the rock was covered with a 1 mm layer of grains of 0.1 to 0.3 mm diameter.

b. Jaeger and Harper (1950) concluded that thermal changes could best be explained if a thin dust layer overlies a substrata of pumice or gravel, with less than 5% base rock exposed.

c. Lettan (1951) believed Pettit's measurements were best explained by a dust cover having an average thickness of 0.5 meters.

d. Sharonoff (1954) on the basis of photometric and infrared measurements concluded that the surface material resembled a spongy, vesicular clinker produced by subsurface explosion and meteorite impact.

e. Shoemaker (1962) proposes a surface layer of unknown depth composed of irregular rocks and debris from impact. His concept was based upon optical, IR and radar data.

f. Hackman and Mason (1961) describe the maria surface as consisting "chiefly of fragmental and comminuted material thrown by explosions following meteoric impacts occuring after the extensive Maria lava flows." This produced layers of unsorted ejecta. However, they consider the lava to be "thinly covered." The surface of the lava is probably mostly smooth but in part rough and clinkery.

g. Head (1962) As a result of model studies and consideration of optical, IR, and radar data concludes that the surface is best described as an area of age-hardened sand dunes, and that the marial rock varies in strength in direct proportion to depth. His work indicates that the marial area near Kepler may be assumed to have a weak rock layer close to a mile in depth. Head presents a crude "rule of thumb" that the tensile strength may be obtained by multiplying the depth in feet by 4 to obtain pounds per square inch, and compressive strength about an order of magnitude greater. His estimate of the properties of the maria are shown in Table 3.

TABLE 3

Soil Strength Estimate for Lunar Maria

Depth in feet	Strength of Material (psi) Tensile	Compressive	Description
2	8	60	Settled but easily shoveled or bull-dozed
12	50	400	Hardpan - can be loosened with handpick or back-hoe
175	700	5,000	Year-old concrete
300	1,400	10,000	Sandstone
500	2,000	15,000	Porcelain
Several thousand	10^4 +	10^5 +	Glassy bedrock

Some examples of lunar surface models which have been proposed are illustrated in Figure 4.

h. Firsoff (1961)

Uplands: Strata of course and fine volcanic material, erosion and meteoric debris, and very porous or frothy lava. Light and porous in the upper layers with graded compaction to tuff at depth by pressure of the overlying material.

Maria: Similar in composition to uplands but compacted, hardened and metamorphosed by some agency such as heat from lunar interior or infusion of liquids and gasses from volcanism..

Accumulation of meteoric dust hidden by very porous nature of surface.

PROPOSED LUNAR SURFACE MODELS

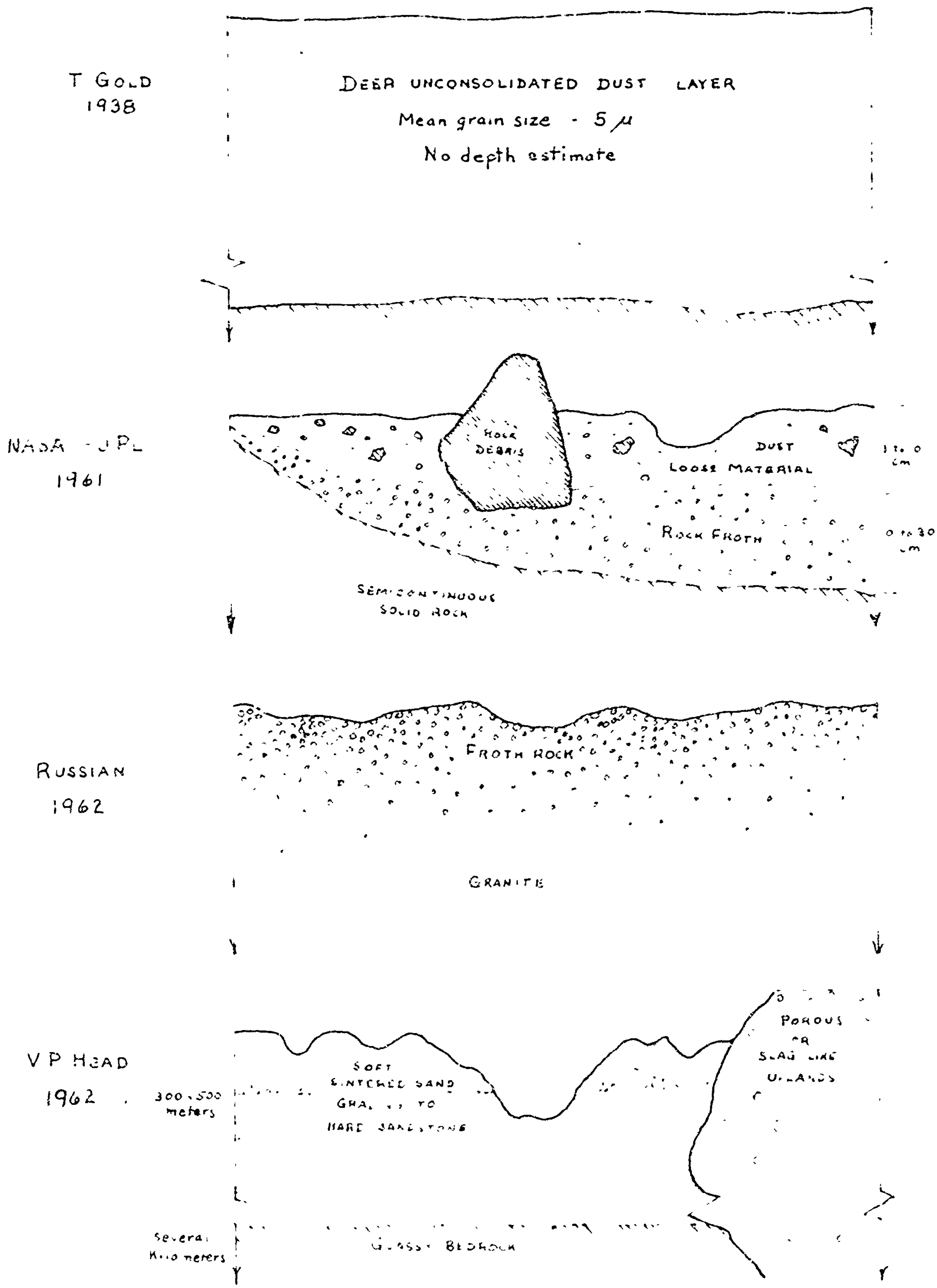


Figure 4

3.3.1.2 Thermal Properties

The determination of the thermal regime of the moon has provided significant information regarding the nature of the surface material. Both infrared and radio wave techniques have been used, providing data not only of the immediate surface but also, presumably, to some depth as a result of the transparency of unconsolidated material to the radio frequencies used.

Pettit and Nicholson (1930) at the Mt. Wilson Observatory did the most significant work on the temperature of the moon using very sensitive thermocouples as sensors with the 100-inch telescope. They observed a maximum surface temperature of 407°K at the center of the full moon and a minimum of 120°K at the center of the dark hemisphere. They observed that the temperature of the subsolar point varied with phase, being only 358°K at quarter phase. They attribute this difference to roughness of the surface.

Additional significant information regarding the lunar surface has been from measurements made during the course of total eclipses. All of the measurements are characterized by an extremely rapid change in temperature during the penumbral phase of the eclipse. In the hour required for a point on the moon to move through the penumbra, the temperature drops to about 200°K or lower. The temperature then continues to lower slowly until sunlight again falls on the area at the end of totality and then rises rapidly until by the end of the eclipse it is back to its starting point. The rapid change indicates a very low thermal "inertia". The thermal inertia is defined parametrically as $(k \rho c)^{\frac{1}{2}}$

where k is the thermal conductivity

ρ density

c specific heat.

Sinton found that a value of 0.002 agreed reasonably well with the observational data for the moon. A comparison of thermal inertial values for common materials is given below in Table 4.

TABLE 4

Thermal Inertias

Lunar Surface	0.002
Granite, basalt	0.05
Dry soil, sand	0.01 - 0.02
Pumice	0.004
Powders $<$ 0.1 mm, in high vacuum	0.001

The above measurements would refer to a homogeneous surface, and other investigators have proposed that combinations of materials or layered structure could be defined which could account for the behavior.

Microwave measurements do not show the rapid and extreme thermal variations exhibited by the IR data. This has been attributed to the transparency of the surface material which gives measurements representing changes below the surface. No significant temperature variation is observed on wavelengths greater than 3.2 cm. A mean depth of origin for the 1.25 cm radiation has been estimated at some 40 cm. It should be borne in mind that the microwave measurements must be considered as very much averaged values both across the disk and in depth because of resolution problems. Some of the results of thermal measurements are listed in Table 5.

TABLE 5

Lunar Thermal Measurements

Author	Wavelength	Temperature (°K)	
		Maximum	Minimum
Pettit & Nicholson 1930	8-14 μ	342 (near S. limb)	120 (near E.limb)
Pettit - 1940	8-14 μ	371 (center of disk)	∠ 156 (center of disk)
Gibson - 1958	8.6 mm	225 (central portion)	145 (central portion)
Dicke & Beringer 1949 Piddington & Minnett	1.25 cm	301 (central portion)	197 (cent. ptn) 145 (whole disk)
Zelinskaya, Troitsky & Fedoseyev 1959	1.63 cm	260 ±10 (central pos.)	190 ±10
Grebenkemper 1958	2.2 cm	210 (whole disk)	185
Troitsky & Zelinskaya 1955	3.2 cm	170 ±15 (whole disk)	170 ±15
Akabane 1955	10 cm	390 ±50 " "	240 ±50
Mezger & Strassl 1959	21 cm	250 ±30 " "	250 ±30
Westerhout	21.6 cm	245 " "	245
Denisse & LeRoux	33.3 cm	208 " "	208
Seeger, Westerhout & Conway 1957	75 cm	185 ±20 " "	185 ±20

3.3.1.3 Albedo and Color

It has been long known that the moon exhibits rather anomolous photometric properties and even 200 years ago it was realized that they were related to the structure of the surface. It is evident that the lunar surface has nothing in common with ordinary diffusing surfaces. It obeys, to some degree Lambert's law and consequently cannot be covered by a uniform layer of dust as some authors have suggested. There is little variation in the amount of light reflected as the angle of incidence changes, although a small difference has been noted in the variation with phase, the amount of light following full moon being slightly less than before full moon at corresponding phase angles. This may be attributed in part to a difference in distribution of features.

At full moon the maria are only about 3/4 as bright as the continents and the rays are brighter than the continents. Individual features also show wide variations in albedo as shown in the following Table 6. The albedos of some common materials are given in Table 7 for comparison.

Attempts have been made to relate the lunar albedos to the character of the surface material but no models which are completely satisfactory have yet been proposed. Both variations in material composition and surface texture below the limit of observational resolution have been considered.

TABLE 6

Albedo of Lunar Features

Area or feature	Albedo	
Floor of Grimaldi and Riccioli	0.061	Marial range
Floor of crater Boscovich	0.067	
Floor of Julius Caesar and Endymion	0.074	
Floor of Pitatus and Marius	0.081	
Floor of Taruntius, Plinius, Flamsteed, Theophilus and Mercator	0.088	
Floor of Hansen, Archimedes and Mersenius	0.095	
Floor of Ptolemaeus, Manilius, Guericke	0.102	
Environs of Aristillus	0.109	
Wall of Argo, Landsberg, Bullialdus and Environs of Kepler	0.115	
Wall of Picard, Timocharis, the Rays of Copernicus	0.122	
Wall of Macrobius, Kant, Bessel, Mosting and Flamsteed	0.129	
Wall of Lagrange, LaHire, Theatetus	0.135	
Wall of Ariadaeus, Behaim and Bode B	0.142	
Wall of Euclides, Ukert, Hortensius	0.149	Upland range
Wall of Godin, Copernicus, Bode	0.156	
Wall of Proclus, Bode A, Hipparchus C	0.163	
Wall of Mersenius, Mosting A	0.169	
Interior of Aristarchus	0.176	
Central mountains of Aristarchus	0.183	

TABLE 7

Albedos of some common materials

Lampblack	0.010
Slate	0.067
Moist Soil	0.08
Asphalt pavement	0.15
Concrete pavement	0.17
Bluestone (sandstone) SiO_2	0.18

Because of the low albedo of the maria, and the manner in which the reflected light varies with phase angle, the surface in addition to being very mountainous, must have a fine structure which is far from smooth. A highly porous, slag-like lava has been proposed for the maria by some, while others favor a large number of unresolvable indentations or pits, or a surface covered with loose, unsorted debris from the explosions which produced the craters, and spongy, vesicular clinker formed by subsurface explosion and meteorites.

The rays likewise have had several explanations for their high albedo. These include streaks of finely divided light rock, or a highly pitted surface produced by the fall of ejecta. It is believed that the rays are comparatively young features and their "freshness" has not yet been dimmed by micrometeorite infall or alteration of the rock minerals by solar energy.

Many workers have indicated that much may be learned about the composition of the lunar surface by photographing it in light of different wavelengths and comparing the relative intensities of the photographs with those of laboratory specimens treated in the same way. Dubois in 1960 compared the reflectivities of general types of lunar terrain with samples of crushed rocks in 17 wavelengths from 382-628 mµ. A gneiss, after being heated to red heat to lower the albedo, fitted the lunar curve best.

Spectrometric measurements have indicated that color variations occur over the surface, and are most marked in the maria. The continents reflect more red light than the maria, while the rays appear to reflect light of all wavelengths.

Very little color can be seen on the moon with the naked eye, but color differences can be detected, mostly in the maria. The continents reflect more red light than the maria, but the absolute reflectivity of lunar rocks is greatest in green light.

Some suggestions for the composition of the surface based on the color work are listed below. (Fielder 1961)

Wilseng and Schaner (1909)	Maria similar to lava
Barbascheff (1924)	Basalts, obsidians, lavas, volcanic ash
Wright (1927-1930)	Light colored rocks, such as pumice, quartz porphries, powders of transparent substances, trachytes, granites.
Stair and Johnson (1953)	Powdered silica glasses, small iron content
Dubois (1960)	Darkened gneiss, diorite, trachyte.

3.3.1.4 Polarization of Light

Light reflected from the moon exhibits some polarization, more so from the maria than the continents. The effect is greatest during first and last quarters and disappears at full moon. The plane of polarization lies in plane defined by the Sun, Moon, and Earth. The amount of polarization varies with albedo, ranging from about 5% for bright areas and about 20% for the darkest.

Inferences on the surface composition by comparison with the behavior terrestrial material include the following (Fielder 1961)

Barabasheff (1927)	Continents: brownish-yellow sand
	Maria: porous lava
Wright (1927-1929)	Pumice: powders of transparent material such as glasses, salts, marble, sulfur; powdered granite or sandstone
Dolfos 1952	Pulverized, light-absorbent materials, with a structure like that of black, opaque granules.

3.3.2 Presence of Water

The moon is ordinarily considered to be completely arid since there has been no positive indication of the presence of water. Recently thought has been given to the possibility that water may, in fact, be present either in the form of ice or in combination with minerals as hydrates or water of crystalization. As water would be one of the most valuable of all materials on the lunar surface, the possibility of its presence and feasible techniques of location and recovery is of major importance to lunar operations.

Volatiles involved in volcanism on earth are usually water, carbon dioxide, sulfur dioxide, hydrogen sulfide, hydrogen chloride and ammonia. Water is by far the most abundant constituent, with CO_2 second. The question is, then, if water was released as a volatile, would it have been lost? Watson et al (1961) have concluded that water would be by far the most stable volatile of the possible constituents of the lunar atmosphere. They postulate that migrating water molecules would collect in "cold traps" occuring in locations which continuously are in shadow. Suitable areas may be expected to exist from the lunar poles to a latitude of about 50°. Within this area it was estimated that about 39% would be permanently shadowed, or about 0.5% of the lunar surface. They have concluded that local concentrations of ice on the moon is well within the realm of possibility.

4.0 SUMMARY

From the foregoing account, it may be seen that the investigation of a body at the distance of the moon presents a great many difficulties. The limitations of our techniques and capabilities leave many questions unanswered and many subject to uncertainty. Much is speculation, based upon incomplete data, interpretation of often conflicting observations, and attempts to correlate measurements with laboratory experiments on terrestrial materials. Out of this mixture of observational data, speculation and theory, a generalized concept of the lunar surface begins to emerge.

The uplands or continental areas which are heavily cratered, resemble, to a degree, mountainous terrain. Bare rock is exposed in places. The surface is generally covered by unsorted broken rock ranging in size from blocks tens or hundreds of meters across, to fine sand. Slopes very likely do not exceed 30° with about 10° to 15° being average.

The maria are, at large scale, far smoother than the uplands with slopes generally ranging 1° to 2°, rarely exceeding 5°. The surface is composed of a lava-like material which varies from a fairly smooth surface to rough and clinkery. Overlying this base is a material resembling sintered sand, or pumice with the strength increasing with depth.

In the areas near craters, such as Copernicus and Kepler, the mare surface is heavily pitted with the secondary craters produced by the ejecta from the primary impact explosion. Many of the smaller craters, less than about 100 meters, have steep slopes, perhaps reaching 50° to 55°. Between the small craters there are closely spaced crater pits and unsorted debris which might resemble a glacial moraine on earth.

Rilles, ranging in size from the great Hyginus and Ariadaeus rilles which are as much as 5 km in width, nearly a kilometer in depth and several hundred kilometers in length, to the limit of telescopic resolution and below, stretch across the maria and bottoms of some larger craters. In many cases they occur in more or less parallel groups.

Extreme temperature ranges occur at the surface during the lunation and between lighted and shadow areas. Temperatures rise from near 120°K (-153°C) during the lunar night to near 400°K (130°C) at the subsolar point.

Similar, but possibly not as extreme a variation, can be expected between sunlit and shadowed areas during the day. A short distance beneath the mare surface (a meter or less) the temperature remains essentially constant near 210°K (-60°C).

It seems rather certain that the lunar surface must have been defined precisely, at least in part, by some investigator. The probability is high, however, that any one author is about as wrong as another. The correct answers to all the unresolved questions and unsolved problems await the return of the lunar explorer with his bag of moondust.

APPENDIX

Lunar Parameters

Distance from the earth		Maximum	Minimum	Mean
	Kilometers	406,700	356,400	384,400
	Stat. Miles	252,700	221,500	238,900
	Naut. Miles	219,500	192,500	215,000
Angular diameter from earth		29' 19.8"	33' 24"	31' 7.2"
1 second of arc subtends:	Kilometers	1.97	1.73	1.85
	Stat.Mi.	1.22	1.07	1.15
	Naut.Mi.	1.06	0.93	1.00
Mean diameter	Kilometers	3476		
	Stat. Mi.	2160		
	Naut. Mi.	1878		
Mean density		3.342 gm/cc		
Mean surface gravity		162.0 cm/sec^2		
		5.31 ft/sec^2		
		0.163 g		
Mass		7.34 x 10^{25} gm		
Maximum libration		7° 54' in longitude		
		6° 50' in latitude		
Axial rotation		27.32 days		

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D7-2517	Lunar Temperatures	Unclassified
D7-3037	Lunar and Cis-Lunar Environment	Secret