IV. PROGRESS IN THE ANALYSIS OF THE FINE STRUCTURE AND GEOLOGY OF THE LUNAR SURFACE FROM THE RANGER VIII AND IX PHOTOGRAPHS*

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A. Introduction

The pictures acquired from the Ranger VIII and IX missions contain a wealth of new data about the lunar surface and supplement our knowledge of the Moon in several ways.

First, the Ranger VIII and IX pictures greatly augment the information about the fine structure of the lunar surface obtained from the Ranger VII mission. Other parts of the Moon were shown to be similar to the part first photographed with high resolution by Ranger VII in Mare Cognitum, and, in a general way, predictions based on the data obtained in this mission were confirmed. In addition, certain features, such as the small lineaments, that were only faintly discernible in the Ranger VII pictures, were found to be more prominent and much more widespread than had been anticipated. The improved portrayal of small features of low relief is due mainly to the fact that the Ranger VIII and IX target areas were closer to the terminator at the time of impact than was the target area of Ranger VII.

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**All Sections not identified by author were written by Mr. Shoemaker.
Both the Ranger VIII and IX pictures contain much new information as to the detailed topography of the lunar plains. In the Ranger VIII mission, the decision was made to terminate the cruise-mode operation of the spacecraft during the final approach to the Moon's surface, specifically for the purpose of obtaining good stereoscopic coverage along the surface trace of the trajectory. The pictures thus acquired provide the best material for photogrammetric measurement of the shape of small features on the Moon among all of the photographs obtained from the entire Ranger series.

Inasmuch as the Ranger VIII and IX pictures cover major samples of the lunar highland areas as well as of the plains, they contain a great deal of new information on areas of complex geology. It is possible to map the geology of selected areas from these photographs at many different scales, ranging from 1:1,000,000 (the scale employed in the Earth-based telescopic mapping program) up to approximately 1:10,000 (a scale typically employed for highly detailed geologic mapping on Earth).

Finally, the Ranger VIII and IX data, combined with those from Ranger VII, provide the basis for preliminary planning and evaluation of the scientific tasks that may be successfully executed by astronauts in the early landings on the Moon of Project Apollo. On the basis of the high-resolution Ranger pictures, it is now possible to identify many of the types of geologic features that will be of specific interest to the scientific community, and to estimate the time and evaluate the activities that will be required for the astronauts to conduct meaningful investigations.

The reduction and synthesis of the data obtained from the Ranger VIII and IX missions is still in a preliminary stage. This report presents an analysis of the data, as it occurs upon the above categories, based largely upon qualitative considerations. The quantitative analysis, for the most part, must await completion of the detailed photometric and photogrammetric reduction of the pictures that has just begun. However, many general conclusions can be drawn at this time which are expected to be modified or refined only slightly by the final program of analysis.

**d. New Data on the Fine Structure of the Lunar Surface**

The most significant new information about the fine structure of the lunar surface obtained from the Ranger VIII and IX missions includes: (1) the frequency distribution and morphology of small craters on several different classes of lunar terrain; (2) the morphologic details of very small craters that are related to the mineralogical properties of the lunar surface material; (3) the distribution and orientation of small lineaments and their spatial relation to certain types of craters, especially on the floor of Alphonsus; and (4) the small topographic details of broad, sloping surfaces, such as the walls of Alphonsus.

On the basis of the size distribution and the shapes of craters observed in the high-resolution Ranger VII pictures of Mare Cognitum, a model of ballistic erosion and deposition on the mare surface was formulated (Ref. 1, pp. 130-132), leading to several explicit predictions about the surface features to be seen in the target areas of Rangers VIII and IX. Most craters observed in Mare Cognitum were interpreted in this model to be of impact origin, and the population of small craters was considered to be in a steady state. The possible presence of other types of craters was recognized, but, in my opinion, no conclusive evidence for their presence could be found in the Ranger VII pictures.

In the model developed from the Ranger VII data, the ratio of craters of secondary-impact origin expected to have been formed on Mare Cognitum to craters of primary-impact origin is about 50:1 for craters of 1-m diameter. The predicted cumulative distribution functions of primary- and of secondary-impact craters converge at a crater diameter between 2 and 3 km. About 500 times as many craters greater than 1 m in diameter were predicted as were actually seen. This predicted number of craters is far too large to be observed because their cumulative area exceeds the area of the mare surface by more than an order of magnitude. Thus there should have been frequent superposition of craters and destruction of old craters by newer ones during the long history of the mare surface.

The predicted cumulative distribution function of primary-impact craters and the observed distribution function of enigmatic, craters shown in the Ranger VII.

*In the Ranger VII experimenters' report (Technical Report No. 32-700, Part II, Jet Propulsion Laboratory, December 15, 1964), the term *primary crater* was used to describe a class of craters with a certain well defined shape (Ref. 1, p. 76). Inasmuch as this class of craters was interpreted to be of primary-impact origin later in the Report, the designation *primary crater* has acquired strong genetic implications for others with whom I have discussed the Ranger data. To avoid confusion, the term *enigmatic crater* will be used here as a descriptive name for a sharp-rimmed, steep-walled crater and is synonymous with *primary crater* as defined and illustrated by Shoemaker (Ref. 1, pp. 76-85).*
pictures of the mare surface converge at a crater diameter of about 300 m, the predicted and the observed cumulative distribution functions of all craters converge at about 300-m crater diameter. The crater size at the points of convergence was interpreted as the upper limit of the steady part of the observed distribution functions. In other words, the size-frequency distribution of craters in the size range of 1 to 300 m was considered to be in a steady condition. If the flux of primary and secondary objects is of constant size distribution, the size-distribution of impact craters 1 to 300 m in diameter does not change with time. Old craters of any given size smaller than 300 m are destroyed as rapidly as new craters of that size are formed.

When applied to other lunar plains, the model derived from the Ranger VII data requires that similar parts of the crater size-distribution functions be in a steady condition. The upper limit size of the steady part of the distribution on any one plain would depend on the age of the plain, which is reflected by the number of large craters it contains. The steady parts of the distribution functions should be nearly identical for all plains. Thus it was expected that the distribution of small craters in Mare Tranquillitatis, which has approximately twice as many large craters as Mare Cognitum, would be nearly the same as that in Mare Cognitum. Similarly, the floor of Alphonsus, which has about 10 times as many craters larger than 1 km in diameter as Mare Cognitum, would also have nearly the same distribution of small craters as Mare Cognitum. When account has been taken of the photometric effects on recognition of shallow craters, for pictures taken at different distances from the terminator, these predictions have been borne out, as shown by N. J. Trask in Section 1 below.

I believe that the model developed from the Ranger VII data, which led to the identification of steady-state populations of small craters on the lunar plains, has been essentially confirmed by the Ranger VIII and IX data. The final test of the model must await the detailed photometric reduction of the Ranger pictures. Crater populations can then be compared by shape, and account taken of the varying recognizability of extremely shallow craters at different angles of solar illumination.

Several types of craters of other than impact origin are believed to be identifiable in the Ranger VIII and IX picture, i.e., half or more of the craters observed on the floor of Alphonsus may prove to be of these other types. The presence of other crater types in no way invalidates the model of ballistic erosion and deposition. It simply means that a complete theory of the lunar surface must take into account all of the operating processes and recognize that many processes besides impact have contributed to the topography and to the fine structure of the surface.

One of the most important new conclusions to be drawn from the Ranger VIII and IX data has to do with the mechanical properties of the material at or near the lunar surface. Several of the Ranger VIII and IX pictures reveal the very small surface details of craters comparable in size to terrestrial craters produced experimentally by impact and by explosion. By comparing small lunar craters with experimental craters, H. Moore has shown, in Section B2, that a few of the small lunar craters revealed in greatest detail occur in material of low cohesion. Such material probably extends locally at least to a depth of 1 to 2 m in the areas photographed with high resolution near the impact points of Rangers VIII and IX. This means that the Moon’s surface at these places is underlain by fragmental material with a grain size less than the line-pair separation resolution of the Ranger photographs. A fragmental layer of this kind is precisely what is predicted by the ballistic model of erosion and deposition developed from the Ranger VII crater shape and size-frequency distribution data and is essentially confirmed by the Ranger VIII and IX data; I believe that this fragmental layer is indeed observed. The ballistically generated fragmental layer may overlie either solid rock or fragmental deposits of volcanic or other origin.

On the basis of the ballistic model, it is expected that most of the surface layer of fragmental debris is very fine-grained, at least close to the surface. Because the layer has low cohesion, the porosity is probably not abnormally high at depths exceeding a few tens of centimeters. Only highly cohesive material will sustain, under pressure, an abnormal amount of void space between the grains. Material beneath the ballistically generated fragmental layer could have abnormally high porosity, however, if it is cohesive and highly vesicular.

The bearing strength of the surface must still be considered indeterminate, but the chances are good that it is moderate to fairly high. On the basis of Moore’s results for the cohesion of material near the surface, I believe there is reason for optimism about the problem of the foot pads of the Apollo spacecraft sinking after touchdown on the lunar surface.

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Among the most striking features observed in the Ranger VIII and IX pictures are the systems of small lineaments and the parallel alignment, with the lineaments, of many small elongate craters and chains of small craters. These features are especially prominent on the floor of Alphonsus, as shown by M. H. Car. in Section B3, but are also observed on the maria.

The small lineaments, elongate craters, and crater chains are also aligned with major, telescopically resolvable lineaments that have a well-defined orientation and regional pattern on the Moon. This parallelism indicates that the small lineaments and aligned craters are secondary, or younger, structures that are superimposed on the terrain on which they occur, rather than primary structures, such as flow ridges or collapsed lava tubes of typical basaltic lava flows. The small lineaments are probably formed over joints and fissures, as suggested in Section B4. Many of the very small, aligned craters probably have been formed by local drainage of the weakly cohesive or cohesionless ballistically generated fragmental layers into underlying fissures.

Finally, the density of craters on broad, sloping surfaces observed in the Ranger IX photographs, particularly on the walls of Alphonsus, provides important clues about the fine structure of the lunar surface and the processes by which it is formed. Care must be taken in evaluating the difference in appearance between these sloping surfaces and the relatively level areas, such as the floor of Alphonsus, because part of this difference is due solely to photometric effects arising from variations of the component of slope in the phase plane. Surfaces sloping toward the Sun are brighter, and shallow craters are more difficult to detect on them than on level surfaces of the same albedo. After allowance has been made for the photometric effects, however, there is clearly a deficiency of small craters on the walls of Alphonsus as compared with the floor.

I believe that the small crater population is in a steady state on the walls, just as on the floor of Alphonsus, but that the rate of destruction of small craters on the walls is greater than on the floor. The increased rate of crater destruction may be due primarily to downslope mass movement of material with low cohesion. There is no need to postulate that the walls are younger than the floor or that they are covered with some unusual deposit of material.

1. Size and Spatial Distribution of Craters Estimated From the Ranger Photographs, Nevel J. Task

The Ranger VIII and IX photographs, together with the earlier Ranger VII photographs, have made possible the measurement of size and spatial distribution of small craters on the Moon in three contrasting terrains: (1) ray areas on the maria, (2) ray-free parts of the maria, and (3) relatively flat highland-basin terrain exemplified by the floor of Alphonsus. Size-frequency distributions of craters in the two widely separated mare areas photographed, one in Mare Cognitum and the other in Mare Tranquillitatis, are closely similar. Crater densities on the floor of Alphonsus are higher than on the maria for craters of large diameters but, significantly, are very close to the densities on the maria for craters of small diameters. In addition, data from Ranger IX point to important differences in crater densities in different parts of the lunar terrace.

Detailed comparison of the maria with the floor of Alphonsus is difficult because of the probability that several types of craters are present, possibly in different proportions, in each area. In this Section, the main emphasis is placed on the size-frequency distributions of total craters regardless of form or origin. Recently acquired high-resolution telescopic distributions of craters photographed with the Ranger photos are used here to make comparisons of areas studied in the Ranger photographs with other similar areas for the range of crater sizes resolvable at the telescope.

a. Distribution of Craters in the Maria

Data on the size-frequency distribution of craters in Mare Tranquilitatis were compiled from the Ranger VII A- and F-camera photographs for diameters less than 3 km and from Lick Observatory plate L-24 for the larger craters. The cumulative crater size-frequency distribution obtained for Mare Tranquilitatis is compared with the crater distribution in Mare Cognitum, based on the Ranger VII photographs, in Fig. 1. The data for Mare Cognitum are typical of areas between the rays down to diameters of 10 m and of the ray areas for smaller diameters (Ref. 1, p. 110). The crater size-frequency distributions in both maria show an abrupt change of slope (on the log-log graph) in the vicinity of 3-km crater diameters; the steepest slopes are observed in the 0.5- to 3-km size range. Below 0.5 km, the average slope in both maria is slightly greater than −2 down to the smallest craters measurable. The measured spatial densities are slightly greater in Mare Tranquilitatis than in Mare Cognitum in each size class. This difference is
Fig. 1. Cumulative size-frequency distribution of all craters in Mare Cognitum (Ranger VII, B and P cameras) and Mare Tranquillitatis (Ranger VIII, A and P cameras, and Lick plate L-24).
real for crater diameters over 1 km and has been documented by earlier studies (Ref. 2). In the smaller size classes, the differences could be entirely apparent because the lower Sun angle in the Ranger VIII photographs of Mare Tranquillitatis permits discrimination of more very shallow craters than in the Ranger VII photographs of Mare Cognitum. The differences in the size classes greater than 1 km may not be statistically significant because of the low total number of craters in these classes.

The crater size-frequency distribution for Mare Tranquillitatis and Mare Cognitum can be compared with distributions for other mare surfaces by using photographs taken recently by G. Herbig with the 120-in. reflecting telescope at Lick Observatory. These photographs permit study of the distribution of craters down to diameters of 1.5-2 km. Three additional mare areas were studied for comparison with the areas covered by Rangers VII and VIII: Mare Serenitatis, part of Mare Imbrium, and part of Oceanus Procellarum (Fig. 2). In all of these mare areas, there is an abrupt change of slope of the crater size-frequency distribution between crater diameters of 2 and 6 km (Fig. 3). The larger numbers of craters in the smaller size classes, giving rise to slopes of the size-distribution curve between 3 and 4, could not be measured on earlier Earth-based photographs (Refs. 2, 3, and 4). When allowance is made for the fact that the numbers of the smallest craters observable on the three Lick plates are slightly low (because of loss of contrast as the resolution limits of the plates are approached), it is clear that the crater size distributions obtained from telescopic photographs in other mare areas correspond closely to the distribution in Mare Cognitum. Mare Tranquillitatis has a distinctly higher crater density than the other maria studied.

Of the many craters portrayed in the Ranger photographs, the class of circular craters with sharp raised rims (here referred to as eumorphic craters) can be most easily discriminated from the rest. My counts of craters in this class for Ranger VII (Fig. 4) agree closely with Shoemaker’s (Ref. 1, p. 118). The size-frequency distribution of craters in this class for Mare Tranquillitatis is identical with that for Mare Cognitum, within the limits of probable random variation of the counts for the small numbers of craters actually observable on the photographs (Fig. 4).

The eumorphic craters were interpreted by Shoemaker (Ref. 1) as being of primary-impact origin. Some of the
Fig. 3. Size-frequency distribution of craters in mare areas, based on Ranger photographs and on Lick Observatory telescopic photographs. (Locations of areas are shown in Fig. 2. A—eastern Mare Serenitatis, light central portion, Lick plate L-32; B—Mare Imbrium, N and W of Archimedes, Lick plate L-35; C—Mare Cognitum, Ranger VII A-camera frames 155 and 179; D—Oceanus Procellarum, N of Letronne, Lick plate ECD-70; E—western Mare Tranquillitatis, Lick plate L-24 and Ranger VIII A-camera frame 43.)
Fig. 4. Cumulative size–frequency distribution of eumorphic craters on Mare Cognitum (Ranger VII) and Mare Tranquillitatis (Ranger VIII). (Distribution of total craters from Lick plate L-24 and Ranger VIII shown for comparison.)
fresh circular craters on Mare Tranquillitatis may be isolated secondary-impact craters associated with the large crater Theophilus, and similar to the circular secondary craters of Tycho shown in the Ranger VII A-camera series. Classification according to form of the remaining craters shown in the Ranger photographs is still in a preliminary stage.

b. Distribution of Craters in the Terrae

The Ranger IX mission provided very high-resolution photographs over parts of the flat floor and east rim of the crater Alphonsus. Geologic mapping in the equatorial region of the Moon by the U. S. Geological Survey indicates that material similar to that on the floor of Alphonsus is widespread in other parts of the terrae. These relatively smooth, flat areas within and between the walls of large craters in the terrae superficially resemble the maria but have a higher albedo and a higher density of telescope-resolvable craters (Refs. 5 and 6).

The size-frequency distribution of craters on the flat part of the floor of Alphonsus is illustrated in Fig. 5. For crater diameters above 1 km, the count applies to the entire floor, exclusive of the central peak and elongate central ridge; for small crater diameters, it applies only to the crater floor east of the central ridge. Because of the relatively small area of the floor of Alphonsus, no meaningful statistics can be obtained for craters with diameters greater than 5 km. The size-distribution curve maintains a slope of −2 from about 1-m crater diameter, the smallest observed, to about 500-m diameter. For diameters above 500 m, the curve has an average slope of −2.7.

The size distribution of craters on the floor of Alphonsus can be compared with the distributions in similar flat areas in the terrae, for which good Lick Observatory plates are available. Crater distributions for two areas near Mare Tranquillitatis (Fig. 2) were obtained from Lick plate L-24 (Fig. 6). Again, meaningful statistics for craters with diameters greater than 5 km cannot be obtained because of the small areas involved. The distributions agree closely for crater diameters near the limit of resolution of the Lick plate, and the distribution of small craters on other flat areas of the lunar terrae is probably similar to that on the floor of Alphonsus.

A significant observation made in the Ranger IX photographs is the apparent low density of craters on the exterior rim of Alphonsus, as compared to the density of craters on the floor. Photographs of the rim show craters down to 250-m diameter. At this diameter, the density of recognizable craters is approximately 2½ times less than on the floor (Fig. 7). The crater density on the highlands east of Alphonsus varies from place to place. Some low, flat areas in this upland region (Fig. 8) are similar to the floor of Alphonsus and have similar crater density. Other parts of the highlands are gently rolling to rugged; some are covered with craters, whereas others appear to be only sparsely cratered. Since no single crater distribution can adequately describe such an area, a separate distribution has been obtained from each of three selected B-camera photographs (Fig. 7). The areas studied are outlined in Fig. 8. Low, flat areas similar to the floor of Alphonsus, areas in shadow, and areas inclined toward the Sun so that they appear bright and featureless (such as the west-facing east wall of Alphonsus) have been omitted from the crater counts. A restricted highland area with a relatively high average slope has a low density of craters smaller than 2 km in diameter compared with the floor of Alphonsus, but the density of craters larger than 2 km in a broader highland area matches the density on the floor of Alphonsus.

c. Interpretation

A striking aspect of the crater distributions noted in photographs from all three Ranger missions is the tendency for the total crater densities to converge at small crater diameters, despite differences in the densities of large craters. This observation is consistent with the models of the cratering process on the maria proposed by Moore (Ref. 7) and Shoemaker (Ref. 1), in which the size-frequency distribution of small craters is in a steady state. In these models, craters with diameters below a certain limiting size are destroyed as rapidly as they are formed, with the destruction proceeding not only by the superposition of larger crater on smaller but also by the erosion of rims and the infilling of crater floors by the impact of small fragments and the deposition of ejecta from such impacts. The steady-state crater density is the limiting high density toward which any part of the lunar surface evolves with time; below a certain limiting size, small crater densities tend to be the same on all parts of the Moon's surface that have reached the steady-state density. For a surface of a given age, the limiting crater diameter for the steady-state size-frequency distribution of craters slowly increases with time.

A possible steady-state size-frequency distribution function for craters of all sizes on the level parts of the Moon may be estimated by combining the distributions of small craters observed in the Ranger photographs...
Fig. 5. Cumulative size–frequency distribution of craters on floor of Alphonsus.
Fig. 6. Cumulative size–frequency distributions of craters in lunar terrae. Locations of areas are shown in Fig. 2. A—terra area I, Lick plate L-24; II—floor of Alphonsus, exclusive of central peak and ridge (Ranger IX); C—terra area II, Lick plate L-24."

Fig. 7. Cumulative size–frequency distribution of craters on rim of Alphonsus and adjacent highlands compared with size–frequency distribution of craters on floor of Alphonsus. (Locations of areas are shown in Fig. 8.)"
Fig. 8. Ranger IX B-camera frame 15, showing areas studied for crater size–frequency distribution given in Fig. 7. (Different types of terrain in lunar highlands indicated by symbols: l—low, flat areas with crater densities the same as on floor of Alphonsus; hs—high, smooth areas with few craters; hr—high, rough areas with many craters.)
with the distribution of large craters observed in certain ancient parts of the terrae. In some parts of the terrae, craters 18 km in diameter and larger overlap one another and are packed together so closely that the superposition of another crater of the same size would result in complete or partial destruction of one or more of the preexisting craters (Refs. 8 and 3). This may represent a condition of steady-state crater density for large craters. A crater size-frequency distribution fitted to the data of Young (Ref. 9) and those of Palm and Strom (discussed by Baldwin in Ref. 10) for ancient craters in the terrae, and to the data for the smallest craters observed in the Ranger photographs (Fig. 9), is represented by the power function:

\[ N = 10^{10} d^{-2} \]  

where \( N \) is the cumulative number of craters per 10 km² with diameters greater than \( d \) (in meters). For a simple power function distribution with an exponent of -2, the area occupied by craters in each decade of diameters is constant.

If the power function given by Eq. (1) is taken as representative of the steady-state crater distribution for the level parts of the Moon, it may be used to determine what part of an observed distribution in level terrain may be in a steady state. The rates of crater formation and destruction on a surface having such a distribution would balance each other so that there is no net change in distribution with time, but these rates are not known. Moore (Ref. 7) suggested two possible rates and combined them in a way to give a power function representing a steady-state distribution very close to that given by Eq. (1) and illustrated in Fig. 9. If more shallow craters are present on Mare Cognitum than can be counted under the conditions of illumination encountered by Ranger VII, the distribution there may be in a steady state at diameters below a few hundred meters, in agreement with the interpretation of Shoemaker (Ref. 1), while the distribution on the floor of Alphonsus may be in a steady state at all diameters below about 1 km.

The occurrence of secondary-impact craters in significant numbers is interpreted here as the principal cause for the rapid increase in the density of craters with diameters between 2 and 6 km on the maria. The high-resolution Lick Observatory photographs show that many of the craters in this size range occur in clusters at the ends of diffuse ray elements. It is also the size range in which craters that are clearly secondary to such large primary craters as Copernicus, Langrenus, Aristoteles, and Theophilus become abundant. Craters of other origins probably also contribute to the rapid increase in crater density at these diameters. A few irregularly shaped craters with diameters of about 1 km discernible on the Ranger VIII photographs, appear to be localized along mare ridges and may have been formed by internal processes of the Moon.

At least two interpretations seem possible for the local differences in crater density in the highlands east of Alphonsus. Low densities may occur where there has been relatively recent mantling of older craters by volcanic materials, possibly related to suspected volcanism within Alphonsus itself. A second suggestion is that small craters are obliterated by various surface processes more rapidly in the highlands than on the relatively smooth, flat floor of Alphonsus. The density of craters 3 km in diameter and larger is essentially the same in the two areas. Small craters may be destroyed more rapidly in the highlands because of slumping or mass movement of weakly consolidated materials on the slopes of the rolling highland terrain.

### 2. Cohesion of Material on the Lunar Surface

Henry J. Moore

The highest-resolution Ranger photographs show craters within the size range of experimental craters produced by chemical and nuclear explosives and missile impacts in natural materials. Craters and other features down to 25 cm across may be seen in the last partial B frame and the last P frames of the Ranger IX photographs. The smallest craters observed are comparable in size to those produced experimentally by impact and to similar craters produced by shallow, subsurface bursts of explosives. Some inferences about the lunar-surface materials can be made on the basis of data from these experiments if one assumes that the craters examined resulted from projectile impacts. These inferences suggest that a layer of fragmental material that is probably weakly cohesive to noncohesive underlies the lunar surface.

Calculations on the distribution of craters produced by the influx of meteoroids and of other solid objects from space that may be expected on the Moon show that the lunar surface should be completely covered with impact craters of various sizes. Moore's calculations (Ref. 7) suggest that on a billion-year-old lunar surface, 10% of the area should be covered by recognizable craters with diameters between 0.1 and 1.0 m, 10% by craters, 1.0–10 m across, and possibly 10% by craters 10–100 m across. In each of these size intervals,
the shape of the craters would range from fresh, unmodified forms to forms produced by erosion and infilling. The erosion is caused by the ejection of debris during crater formation by impact, the infilling results from the deposition of the debris, which preferentially collects in depressions because of gravitational forces. The form and size-frequency distribution of craters seen in the Ranger photographs closely resemble those predicted for impact craters. Similar results might also be produced by the impact of fragments ejected from very large craters along rays (Ref. 1, pp. 75-134, and Ref. 7). It is not to be construed that all the craters seen on the Ranger photographs have resulted from impact, for clearly they have not. Only those which have sharply defined raised rims and which appear to be the least modified will be compared with experimental craters.

a. Comparison of Crater Morphologies

The two lunar craters considered here appear on the last partial B-camera and the last two P-camera photographs of Ranger IX (Figs. 10 and 11). These craters were selected because their sizes are consistent with the sizes of experimental craters produced by explosives and missile impacts and because they appear to be relatively unmodified in form. In addition, they have asymmetrical rims (higher on one side than the other) and are morphologically similar to craters of nearly the same size which were produced by inert missiles with oblique trajectories at White Sands Missile Range, New Mexico (Ref. 11). Although the craters photographed by Ranger IX are used as examples, the following reasoning is applicable to other craters observed in the highest-resolution Ranger VII and VIII photographs.

The important features associated with the two craters under consideration are: (1) little evidence of blocks on the rims and around the craters; (2) low, lumpy structures on the walls, the rims, and around the craters; (3) asymmetrical rims which are higher and wider on one side than the other; (4) slopes that are less than 45 deg and probably near 35 deg or less; and (5) a scalloped rim on one crater.

A conspicuous absence of large, sharply defined blocks around these craters implies the existence of one of the following situations: (1) large blocks were not ejected from the craters because the surface materials were composed of fragments or rock units with linear dimensions too small to be resolved in the photographs (~25 cm); (2) large blocks were ejected and subsequently reduced to finer material; or (3) the entire surface was covered by some material after the craters were formed which obscured the blocks. The conclusion to be drawn in either of the first two cases is that the surface around the craters is underlain by fragments generally below the resolution of the photographs.

In order to illustrate the paucity of blocks in the Ranger photographs, two craters formed by chemical explosives in basalt are shown in Fig. 12. The craters were produced by 40,000 and 1000 lb of TNT detonated about 7.9 and 3 m, respectively, below the surface (Ref. 12). The basalt in which the craters were formed has densities between 2.2-2.75 g/cm$^3$ and an unconfined shear strength near 10$^6$-10$^7$ dynes/cm$^2$.

Blocks in and around these two explosive craters are conspicuous, whereas no such blocks are apparent in the Ranger photographs. Blocks up to 2.4 m in length are found in and around the large crater and up to 1.5 m in and around the small one. Many of the blocks around the craters exceed 25 cm. Some blocks are found beyond one crater diameter from the rims, although they are concentrated near the rims. If the illumination conditions were the same as those under which the Ranger photographs were taken, the blocks around the craters in basalt would produce shadows about 5 times the length of the blocks.

The Ranger photographs show a few low mounds, some on crater rims, walls, and flanks, and others peculiarly isolated in relatively uncratered areas. These mounds

Fig. 9. Comparison of cumulative size-frequency distributions of craters photographed by Rangers VII, VIII, and IX. (Equation of curve for steady-state crater size-frequency distribution determined by combining data of Young, and Palm and Strom with data for small craters observed in the Ranger photographs.)
are rare and cast weak, short shadows. The author has observed craters produced by explosives and by missile impacts (Ref. 11), with similar associated low mounds. These mounds are composed of lumps of fragmental debris ejected from the craters rather than discrete blocks. The lumps are found on the crater rims and flanks, and also, isolated, at considerable distance from the crater. For missile-impact craters up to 5.5 m across,
Fig. 11. Last Ranger IX P-camera photographs. (Largest crater in upper frame is about 25 m across.)
isolated lumps up to several feet in length and 15-30 cm high have been observed. Similar lumps around craters produced by chemical explosives are well illustrated in Ref. 13.

A crater produced by 40,000 pounds of TNT detonated at 13 m (Ref. 12), partly in basaltic cinders and partly in basalt flow rocks (Fig. 13), has greater similarity to the lunar craters. The crater is about 41 m across and 13 m deep. Ejecta are predominantly blocks of flow basalt on the left flank and noncohesive basaltic cinders and clinkers on the right flank. Low ridges and small rocks may be seen on the right flank, but large blocks are rare. The upper right section of the crater is scalloped (partly as a result of slumping and sliding of noncohesive cinders) much like part of the rim of the large crater shown in both frames of Fig. 11.

Craters produced by missile impacts at White Sands Missile Range (Figs. 14 and 15) are similar to many craters of comparable dimensions shown in the Ranger photographs. In both cases, raised rims completely surround the craters, but the rims are higher and wider on one side than on the other. The impact crater shown in Fig. 14 is 9 m across and 2.7 m deep. The target was weakly cohesive gypsum (cohesion = 6 × 10^3 dynes/cm^2) saturated with water. The inclined projectile trajectory resulted in a thicker and wider deposit of ejecta on one side of the crater than on the other. After the initial formation of the crater, slumping of the walls produced the lumps on the floor. Hummocks of debris, along with small blocks, occur around the crater, and a few blocks up to 30 cm across are found in and around the crater. Another crater (about 3.2 m across) with an asymmetric rim (Fig. 15), was produced by oblique projectile impact into moist gypsum (cohesion = 6 × 10^3 dynes/cm^2); it is similar in form to a number of small lunar craters shown in Figs. 10 and 11.

In craters produced by missile impact in weakly cohesive alluvium (cohesion = 1 × 10^3 dynes/cm^2), local slopes of crater walls exceed 60 deg in places, and in
Fig. 13. Crater formed partly in basalt and partly in basaltic cinders. (Crater is about 41 m across. Left side is in basalt, right side in basaltic cinders. Cinder block on upper left rim is 5.5 m long. Crater produced by 40,000 lb of TNT at 13 m by Sandia Corporation. Note difference in form and texture between right and left sides of crater.)

Fig. 14. Crater produced by missile impact in water-saturated gypsum. (Crater is about 9 m across. Projectile kinetic energy was $1.6 \times 10^{11}$ erg and angle of impact near 45 deg. Note asymmetry of ejecta blanket. U.S. Army photograph.)
some cases are vertical. For craters 5.5 m across in alluvium with a cohesion near $5 \times 10^5$ dynes/cm$^2$, the slopes are composed predominantly of fragmental debris at the angle of repose, namely, 25–38 deg. No evidence has been found for slopes as high as 60 deg in the walls of small lunar craters, and very few appear to exceed about 38 deg. The steepest walls of the small lunar craters are probably underlain by fragmental material at the angle of repose; this angle should be essentially the same for lunar as for terrestrial noncohesive fragmental material (Ref. 14).

**b. Interpretation**

The combined evidence resulting from comparison of the morphology of lunar and experimental craters suggests that the lunar surface materials are weakly cohesive to noncohesive. The paucity of blocks indicates that the near-surface materials do not have high cohesive like flow basalts and rocks of comparable strength. The low mounds shown in the Ranger photographs may be piles of fragmental material ejected from craters, similar to the mounds observed around missile-impact craters.

The fragmental material piled around the terrestrial craters has a grain size generally less than 25 cm. The moderate slopes of the walls of the small, sharp-rimmed lunar craters also suggest that the lunar materials are noncohesive and fragmental.

In the comparison of the small lunar craters with the experimental craters, it should be kept in mind that stresses in the materials due to relief are one-sixth those that would be developed at the surface of the Earth. For example, materials on the Moon with a cohesion of 1 bar will behave somewhat like materials with a cohesion of 6 bars on the Earth (Ref. 14).

It is also important to note that cohesion and bearing strength are not synonymous. Flow basalts and granite have both high cohesion and bearing strength, whereas the sand in a sand pile has no cohesion but high bearing strength. In addition, low-density and noncohesive fragmental layers may have high bearing strength, as is the case at Mono Craters, California, where some surfaces which are underlain by pumice fragments (estimated density = 0.4 g/cm$^3$) will permit the passage of jeeps and pedestrians.

3. **The Structure and Texture of the Floor of Alphonsus**

Michael H. Carr

The principal characteristics that distinguish the floor of Alphonsus from other areas photographed with high resolution in the Ranger missions are the extent to which the floor is cratered and the large number of observable linear features. Although craters are the most obvious topographic features, many linear structures are also present, such as ridges, depressions, and breaks in slope. Many craters are aligned along, and evidently related to, the linear structures. The size-frequency distribution of craters on the floor of Alphonsus varies from place to place. Areas with significantly different crater distributions and densities can be distinguished, so that the floor can be divided into several geologic units, each of which is characterized by a different size-frequency distribution of craters.

**a. Textural Units**

The relatively flat part of the floor of Alphonsus has been divided into six units on the basis of albedo, relief, structural patterns, and distribution of small craters (Fig. 16). The size-frequency distributions of craters on four of the floor units are shown in Fig. 17. All observable depressions were classed as craters in determining the size-frequency distributions. Most of the units differ
significantly in the distribution of craters larger than 0.3 km, but the density of craters less than 0.3 km in diameter is essentially the same. Some differences are also observable, however, among the smaller craters. The paucity of large craters in unit 2, for example, allows small, very indistinct craters to be distinguished, bringing the total crater count up to that of unit 3, for which many of the very small craters counted had sharp outlines. Although there are no significant differences in their crater counts, units 3 and 4 have a different appearance because many of the craters larger than 0.5 km in diameter in unit 4 have more subdued outlines than craters of equivalent sizes in unit 3. A unit labeled **dh** on the map is distinguished from the others by its low albedo; units 2 and 5 are distinguished mainly on the basis of linear texture and relief, rather than crater size-frequency distribution. A more detailed description of some of these textural units as geologic units is given by McCauley in Section D2.

### b. Lineaments and Structurally Controlled Craters

Lineaments observed in the *Ranger* photographs of Alphonsus are plotted in Figs. 18, 19, and 20 at the approximate scales of 1:400,000, 1:77,000, and 1:13,000, respectively. The linear features are ridges and linear depressions, breaks in slope, and straight crater walls. At the smallest scale, 1:400,000, four distinct sets of lineaments can be distinguished on the basis of azimuthal frequency (Fig. 21). Three of these, the northwest-southeast, the northeast-southwest, and the north-northeast-south-southwest sets, belong to the lunar grid system of lineaments (Ref. 15); the fourth is radial to the center of Mare Imbrium. On the rim and central ridge of Alphonsus, the north-northeast-south-southwest set and the Imbrium radials are more prevalent than on the floor, but at the map scale of 1:400,000, all four sets are distinguishable on the floor. In contrast, at the larger scales, which reveal the finer details of the floor of Alphonsus, the northwest-southeast and northeast-southwest sets dominate the structural pattern, and the Imbrium radials and the north-northeast-south-southwest set are almost entirely absent.

In nearly all cases, the observable lineaments are undetected as they cross topographic features, except at the largest scales of observation. If the lineaments are caused by planar structures intersecting the surface, then the dips of these structures are close to vertical. In a few cases, the directions of dip have been determined from the deflections of surface trends of the lineaments across topographic relief; in the observed cases, structures controlling the northwest-southeast set dip steeply to the southwest, and structures controlling the northeast-southwest set dip steeply to the northwest. The lack of observable shallow dips does not mean that there are none present, as shallow dipping structures are very difficult to discern on aerial photographs. The only recognized exceptions to the generally steep dips are seen in the last complete *B* photograph (Fig. 20), where many of the lineaments are deflected as they cross shallow craters. The apparent shallow dips observed here may reflect true dips of the underlying structures, or the deflections of the lineaments may result from down-slope creep in the top few meters of the lunar surface.

Lineaments control the location and shape of many craters on the floor of Alphonsus in all of the textural units, and on the central ridge and rim. Craters that are unambiguously controlled by the lineaments are plotted in Fig. 18. To avoid including possible lines of secondary craters that might be unrelated to local structure, a conservative approach was used in identifying the structurally controlled craters. Only groups of craters aligned along depressions, ridges, or breaks in slope were plotted; other lines of craters are not considered to be controlled by the lineaments. Many of the craters along a lineament are elongate in a direction parallel to the lineament; some of these have straight walls, whereas others are circular in outline except for a linear depression breaching one side of the crater. Most, but not all of the structurally controlled craters are rimless. None of the circular craters with sharp, raised rims and outer flanks that are concave upward (eumorphic craters) appear to be structurally controlled, but every other morphological type of crater is observed among the structurally controlled group of craters. Comparison of the craters having demonstrable structural control with the rest of the craters on the floor of Alphonsus suggests that a majority of such craters may be structurally controlled.

### c. Interpretation

The alignment of craters along lineaments that are part of a Moon-wide structural system is very strong evidence that many craters on the floor of Alphonsus were formed by mechanisms originating within the Moon. These craters may have been formed in a variety of ways, among which subsidence may have predominated. Although the majority of the aligned craters have no observable rims, many do, a fact which indicates that subsidence alone cannot explain all of the aligned craters.
EXPLANATION

**dh** Material surrounding dark halo craters exhibits low albedo and relatively few craters. Craters especially low in frequency in the size range 0.1 to 0.3 km in diameter. Associated with rille and elliptical craters 0.8 to 3 km in diameter which have broad, low rims that are convex upward.

**UNIT 1** Resembles dh but has a larger number of craters and a higher albedo. Has relatively few craters in the size range 0.3 to 10 km, and craters less than 0.5 km in diameter commonly have a more subdued form than in units 2, 3, and 4.

**UNIT 2** Material with intermediate albedo and marked linear texture. Crater density intermediate between units 1 and 3 for craters larger than 0.5 km in diameter. Size-frequency distribution resembles that of unit 3 for craters with diameters less than 0.5 km.

**UNIT 3** Material with intermediate albedo and relatively high density of craters.

**UNIT 4** Resembles unit 2 but lacks its marked linear texture. Appears to overlie subdued older features and is part of a rille.

**UNIT 5** Material with prominent ridges and depressions approximately 1 km apart. Crater density probably same as for unit 3 but cannot be determined because of the rough terrain.

**P** Circular craters with sharp raised rims having outer flanks that are concave upward (eumorphic craters).

Fig. 16. Distribution of textural units in northern part of Alphonsus floor. (Base mosaic prepared from Ranger IX A-camera photograph 57 and B-camera photograph 87.)
Fig. 17. Size–frequency distribution of craters in different textural units on floor of Alphonsus.
d rims of dark-halo craters appear to be the best examples of constructional features around structurally controlled craters. The dark rims, pitted with many small craters up to 50 m across, are broad and gently sloping, and partly cover or fill adjacent rilles and craters. The dark material extends up to 4 km from the central crater. No linear features, lobate structures, or scarps resembling flow fronts have been observed on the dark rims, which resemble, in form, a broad deposit of pyroclastic material with little or no associated lava extrusions. Craters with such pyroclastic rims are common on Earth, particularly where the eruptions are andesitic or basaltic.

Minakami (Ref. 16) measured the ejection angles and velocities of material thrown out of the andesitic volcano Asama. The measured velocities ranged from 176 to 183 m/sec, with ejection angles of 37–43 deg. On the Moon, similar ejection velocities and angles would throw material on ballistic trajectories as far as 17 km. Volcanic eruptive activity could therefore account for dark halos extending 4 km from the main crater, if the ejection velocities of fragments were comparable to those on Earth.

Textural units 1, 2, and 3 are here interpreted as being similar in origin to, but older than, the dark-halo material, with unit 1 the youngest and unit 3 the oldest on the basis of crater density. Unit 4 surrounds a large crater on a rille. Although the rim material of the crater is not dark, the unit appears to blanket the surrounding terrain and is therefore interpreted as ejecta from the crater. In form, the crater resembles the dark-halo craters and is assumed to have a volcanic origin. Unit 5 appears to be an area where the presumed volcanic material filling the floor of Alphonsus (represented by units 1-4) is thin or absent and underlying, older materials of the floor are exposed.

The lineaments observed in Alphonsus are believed to reflect underlying fractures and faults. Strom (Ref. 15) has suggested several mechanisms for the origin of the lineaments on the Moon. The relationship between the lineaments on the floor of Alphonsus and the lunar grid system suggests that the process of formation of small, close-spaced fractures on the lunar surface is related to the processes that cause the major structures on the Moon. Separate deformational processes could be invoked to explain the minor fractures by assuming that their orientation is controlled by the orientation of the major fractures. This hypothesis, however, does not explain the absence of the Imbrian and the north-northeast–south-southwest sets at large scales. If it were entirely true, the two sets of lineaments should be absent at all scales. A more likely explanation is that northeast-southwest and northwest-southeast fractures are still being formed and that the same processes causing the broad features, kilometers across, also cause fractures that are spaced centimeters apart. According to this hypothesis, small, close-spaced Imbrian and north-northeast-southsouthwest fractures are absent because the processes that formed these lineaments are no longer operative, although movement may have occurred along them since their main period of formation.

4. Lunar Patterned Ground

In the last A-camera and the last few P-camera frames from Ranger VII, a distinctive pattern of gentle ridges or mounds and intervening troughs was discovered whose appearance was likened to the bark of the ponderosa pine. The high-resolution pictures acquired from Rangers VIII and IX have shown that this pattern of small ridges and troughs is very widespread on the Moon. As it was seen in the highest-resolution frames of all the Ranger target areas, there is reason to suspect that it may occur over most of the lunar surface.

A general descriptive term is needed for this pattern of low ridges and troughs, and I will here refer to it as lunar patterned ground. It has some resemblance to certain types of patterned ground formed in the permafrost areas of the arctic and subarctic regions on Earth, but no implication that lunar patterned ground is necessarily related to permafrost is intended.

Good examples of lunar patterned ground are shown in the last Ranger VII P-camera photograph (Ref. 1, p. 112), the last Ranger VIII B-camera photograph (Fig. 36 in Section E), and the next-to-last Ranger IX B-camera photograph (Fig. 20). In these examples, the lunar patterned ground occurs on different types of geologic terrain but is similar in all of the areas. Individual ridges or mounds range from 5 to about 30 m in width and from 15 to about 200 m in length. Relief on the mounds, normal to the general slope of the lunar surface, has not yet been accurately measured but is estimated at from 10 to a few tens of centimeters. The slopes on the sides of the mounds are extremely low, and the patterned ground is, therefore, difficult to detect, except under conditions of low-angle illumination. For this reason, in the pictures from all three Ranger missions, it is most easily seen on low scarps and crater walls that are inclined almost parallel with, or at very small angles to, the Sun’s rays; the patterned ground is generally
Fig. 18. Ranger IX A-camera photograph 57, showing lineaments and structurally controlled craters in Alphonsus.
Fig. 19. Ranger IX A-camera photograph 68, showing lineaments on floor of Alphonsus.
Fig. 20. Ranger IX B-camera photograph 87, showing lineaments on floor of Alphonsus.
shown best in the \textit{Ranger IX} pictures, which were taken with the lowest angle of solar illumination.

The troughs between the mounds have been mapped as small lineaments by Carr (Fig. 20) and by Schmitt (Fig. 37 in Section E). In each of the areas in which it has been observed, the predominant orientations of the linear elements of the lunar patterned ground tend to be parallel with the larger lineaments seen in the \textit{Ranger} pictures and with dominant regional lineaments observed with the telescope. This parallelism suggests that the patterned ground is controlled by underlying structures, which, in turn, are controlled by the regional structural pattern. Two dominant orientations are generally found in the patterned ground at each locality, typically separated in azimuth by 60 to 90 deg. Thus, viewed over a broad area, the lunar patterned ground exhibits a grid pattern. Local departures from the principal grid orientation are common, however. The grid is most easily seen in pictures in which the coherent noise and video scan lines have been suppressed or removed.

The \textit{Ranger VII} pictures that show the patterned ground are all high-resolution photographs of part of a ray of Tycho on Mare Cognitum. The observed patterned ground occurs on the floor, walls, and rim of two secondary craters of Tycho and also on nearly level parts of the ray that are relatively free of resolved craters. Elements of the grid are oriented northwest and north-northeast, intersecting at an angle of about 70 deg. A series of en echelon scars on the wall at one secondary crater and a sinuous set of subdued scars cutting across the floor of the other are parallel or subparallel with the dominant north-northeast element of the grid. These scars were interpreted by Shoemaker (Ref. 1) as having been formed by slumping within the craters. Both elements of the grid are approximately parallel with major lineament systems in the Mare Cognitum region plotted by Strom (Ref. 1).

The most prominent lunar patterned ground seen in the \textit{Ranger VIII} pictures of Mare Tranquillitatis occurs on the rim and floor of the large crater shown in the southeast corner of the last B-camera photograph. Orientation of the troughs (Fig. 38 in Section E) is not as uniform at this locality as in other examples of lunar patterned ground, but the most prevalent orientations are again northwest and north-northeast. Systematic minor differences in orientation of the grid elements from
one part of the crater rim to another suggest that the patterned ground is controlled at least in part by the local structure of the rim. The north-northeast element of the grid is roughly parallel with a long, shallow linear depression that transects the wall of the crater, whereas the northwest element is approximately parallel with the long axes of numerous very shallow, elongate, oriented craters that occur in nearby parts of the mare.

Lunar patterned ground occurs over most parts of the floor of Alphonsus shown in the highest-resolution Ranger IX photographs. The elements of the grid intersect nearly at right angles here and are oriented northwest and northeast. As Carr has shown, these elements are approximately parallel to much larger linear features in the floor of Alphonsus and to major lineaments in this region of the Moon. Deviations from the prevailing grid orientation generally occur where the patterned ground crosses crater walls. These deviations or deflections are of the type that would be expected for the surface trace of a plane, in some cases dipping away from the center of the crater and in others toward it. Where the grid is deflected toward the center of the crater, it is also possible that the deflection is due to downslope creep. In Fig. 20, a row of dimple craters, each about 40 m in diameter, is oriented subparallel with the northwest grid element.

It seems highly probable that the lunar patterned ground is related to joints (fractures) and fissures in material that underlies the lunar surface at shallow depths. Each trough in the patterned ground may be localized over an individual joint or fissure. The depth to the jointed material probably does not much exceed a few meters where patterned ground is observed; if the depth were much greater, it would be difficult to account for spacing of the troughs as close as 5 to 10 m. In most places, the jointed material probably directly underlies the ballistically generated fragmental surface layer.

The jointed material almost certainly differs in origin, and probably in physical characteristics, from place to place. Where the patterned ground was observed in Mare Cognitum and Mare Tranquillitatis, the jointed material probably consists of thrown-out blocks of rock, which form a layer of rocky debris on the crater rims and breccia under the crater floors. On the floor of Alphonsus, the jointed material may be consolidated volcanic ash. The strength of the jointed material need not be very great, as only weakly consolidated sediments are known to be capable of sustaining joints on Earth.

It is, perhaps, significant that the most prominent patterned ground seen in the Ranger VIII pictures of Mare Tranquilinitatis occurs on the rim and floor units of a relatively large crater. These are the places where material derived from depths on the order of tens of meters below the original mare surface should lie close to the present surface, and, hence, where rocky material is most likely to occur at shallow depth, whereas relatively cohesive volcanic material might underlie the ballistically generated surface layer in adjacent parts of the mare. In addition, the ballistically generated surface layer itself should be thinner on the rim and floor of the crater than on the adjacent older parts of the mare.

The troughs and ridges of the patterned ground may have been formed by jostling of the underlying joint blocks. In the jostling process envisioned, the relatively cohesionless fragmental surface layer tends to be heaved up slightly toward the centers of the joint blocks and thrown away from the edges of the blocks. Troughs would thus be formed over the joints. Some loss of fine-grained surface material probably also takes place by drainage down open joints or fissures between the blocks, thereby deepening the troughs.

A very crude analog of the lunar patterned ground may be represented by a pattern of fissures developed along the Atacama fault zone in northern Chile (Fig. 22), which was brought to my attention by G. E. Ericksen of the Geological Survey. Here a grid of fissures has developed as a result of horizontal strain adjacent to a recent trace of displacement in the fault zone. Open fractures or fissures occur in Jurassic volcanic rocks that are covered with about 1 m of colluvium. The surface pattern is formed by drainage of the colluvium into the fissures. In this case, the pattern of linear depressions has developed as a result of simple distension of the surface rather than by jostling of the joint blocks, as postulated for lunar patterned ground.

Jostling of joint blocks on the Moon may take place primarily as a consequence of the passage of seismic waves propagated from relatively high-energy impacts. It is also possible that surface waves of significant amplitude are generated by seismic events originating in the lunar interior. The jostling must occur with sufficient frequency to maintain the lunar patterned ground against ballistic erosion and deposition, which tends to erase or destroy it. Intermittent jostling is probably an active process at the present time. In addition, there may be active tectonic processes leading to
further development of joints or opening of pre-existing joints in preferred directions, as Carr has suggested for the floor of Alphonsus in Section 3.

C. Preliminary Photogrammetric Analysis of the Topography of Small Areas on the Moon

The Geological Survey is investigating the photogrammetric reduction of selected stereoscopic pairs of Ranger photographs for the purpose of obtaining control for the compilation of detailed topographic maps by photometric methods. This control is required in order to determine the local photometric function of small areas on the lunar surface and to connect photometrically derived profiles in the direction normal to the phase-angle plane (Ref. 1, pp. 129–130). A general study of the photogrammetric reduction of Ranger pictures has been carried out by J. D. Alderman, W. T. Borgeson, and S. S. C. Wu.

As a part of the photogrammetric investigations, H. J. Moore and R. V. Lugn set up an experimental stereo model with an ER-55 plotter and, using two A-camera photographs from the Ranger VIII mission, studied the problems of design and use of an anaglyphic projection instrument suitable for analysis of Ranger photographs. Such stereo models aid greatly in the analysis and plotting of the geology and in the general stereoscopic study of the lunar surface. A topographic map compiled from their model is presented in this Section in order to illustrate
the type of result that may be obtained by analglyphic projection techniques and to provide a preliminary base map for the geological analysis by N. J. Trask of the area represented by the model (described in Section D3). The preliminary photogrammetric results reported here are entirely experimental in nature but represent an approximate solution of the topography of the area studied.


In addition to high-resolution monoscopic pictures of the lunar surface, Ranger flights have provided a limited amount of usable stereoscopic coverage. This coverage will permit more detailed and accurate measurement of local slopes than can be accomplished with Earth-based methods, yielding information of importance to basic geological and engineering investigations.

Recovery of slope data from Ranger images involves a number of factors that are alien to conventional photogrammetry. The major problems are: (1) the narrow-angle lens systems of the Ranger cameras, (2) camera tilt, (3) camera calibration, (4) small base-to-height ratios, (5) image motion and image blur, and (6) video scan lines, image size, scale differences, low Sun angle, and lunar photometric effects. Initial studies have been concerned with the feasibility of systematic data reduction, rather than with actual attempts to produce quantitative base materials. The latter objective will be accomplished during a subsequent data-reduction program.

a. System Limitations

Narrow-angle lens systems. All Ranger cameras were narrow-angle lens systems, five of the six cameras on each spacecraft having extremely narrow-angle lenses. The use of such systems was required for compatibility with a 1-in. vidicon. The most severe limitation imposed, however, was the small format size selected for the P cameras because of the need for very rapid scanning and readout between frames. The terminal velocity of the Ranger spacecraft (8600 ft/sec) made rapid scanning necessary, particularly for the recovery and transmission of the last high-resolution frames. For that reason, an 0.11-in.-square format size that could be exposed, scanned, and transmitted in 0.21 sec was chosen for all the P cameras.

Good narrow-angle lens systems, like the central part of a wide-angle lens, have high resolution but are inherently ill-suited for stereoscopy, particularly if the optic axes of individual frames are parallel or divergent. In such systems, the space rays from corresponding photographic points intersect at angles so acute that the vertical (z) determination is highly imprecise. The situation can be compared to a surveying problem, in which a base line 200 ft long is used to determine the distance to a point 5 miles away; an error of 1 sec of arc leads to an error of 17 ft in the computed distance.

Available photogrammetric plotters (with the exception of the AP/2 and some first-order plotters) are designed for wide-angle camera systems with 70- to 120-deg fields of view. Other characteristics of first-order plotters limit their use in the recovery of the geometry of the Ranger pictures. When used in stereo plotters, the Ranger images occupy only the part of the angular field equal to that of the taking camera. The six components of orientation for each frame are difficult to control under these conditions, and only a precise presetting of the components will permit recovery of the geometry. Conventionally, the components are determined by ground control. A universal photogrammetric instrument such as the AP/2 plotter, designed to accommodate pictures taken with a narrow-angle system, should permit more precise geometric reconstitution because the x- and y-tilts can be more closely controlled on this plotter than on any other.

The P, and P, cameras have an angular field of view of 2.1 deg and a focal length of 3 in.; they are virtually useless for photogrammetric purposes, although, in theory, these cameras provide the maximum possible ground resolution. The P, and P, cameras have an angular field of view of 6.3 deg, a focal length of 1 in., and an 0.11 × 0.11-in. format. The angular fields of the P, and P, cameras are larger than those of the P, and P, but provide images of smaller scale. Although still weak, these increased angular fields present greater photogrammetric potential. The B camera, with an angular field of 9.3 deg, a focal length of 3 in., and a format of 0.44 × 0.44 in., offers only slightly more in terms of reconstituting the geometry than the P, and P, cameras. The A cameras have an angular field of 25 deg, a focal length of 1 in., and a format of 0.44 × 0.44 in.; the pictures taken with these cameras provide the strongest possible stereo models available in the Ranger series.

Unfortunately, only a few high-resolution A-picture combinations are available for stereo models (see Table 1).

Camera tilt. Camera tilt is objectionable even under optimum photogrammetric conditions where the z (alti-
Table 1. Stereoscopic pairs of Ranger photographs from which useful photogrammetric measurements can be made

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<th>Altitude, km</th>
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<td>45.216</td>
<td>39.949</td>
<td>27</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>A51</td>
<td>1/3,673,000</td>
<td>95.838</td>
<td>85.612</td>
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<td></td>
<td>A54</td>
<td>1/2,123,000</td>
<td>55.395</td>
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<td>8</td>
<td>A57</td>
<td>1/1,104,000</td>
<td>35.009</td>
<td>30.859</td>
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<tr>
<td></td>
<td>A58</td>
<td>1/234,000</td>
<td>24.772</td>
<td>21.785</td>
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<td>45.216</td>
<td>39.949</td>
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*Principal distance A camera = 26.09 mm, B camera = 74.8 mm.
†Ranger 7A photographs, all others are Ranger VIII frames.

titude) difference of image points is to be determined either analytically or with stereoscopic plotting instruments. If both tilt and relief of unknown magnitudes are present, the direction of image-point displacements is indeterminate. Relief displacement is radial from the nadir point and is a function of the first power of the radial distance from the nadir point to the image point, and of the height of the object. Tilt displacement is radial from the isocenter and varies both with the square of the radial distance and with the cosine of the angle that a line through the image point and isocenter makes with the direction of tilt.

The absolute components of tilt cannot be calculated without ground control. An analytical solution is dependent upon the validity of the tracking and spacecraft-orientation data, and upon the ability of an operator to reference discrete image points in each photo of a stereo pair. Unfortunately, very few well defined common image points exist in the high-resolution Ranger stereo pairs. This virtually eliminates the use of a comparator in analytical profile determination. Hence, a stereo model recovery is superior to any other mode of photogrammetry for these pictures.

The advantages of using a stereoscopic plotting instrument rather than analytic methods are:

1. Datum orientation is more reliable.
2. Slope components can be determined in any direction.
3. Detailed profiles can be compiled across ill-defined areas in the images.
4. Small formats are more easily handled.
5. Photomechanical processing of the pictures is less detrimental.
6. The measurements do not require complete acceptance of trajectory and spacecraft orientation data.
7. The stereo model can be used to aid geological investigations.
The main disadvantages are:

1. The number of usable stereo models is strictly limited.
2. Nearly all available plotters are limited in their ability to accommodate tilt.
3. Most plotters cannot accommodate large $z$-differences.
4. The range of focal length that most plotters can accommodate is restricted (normally 3'-8' in).

**Camera calibrations.** At the time of exposure of a picture, the rays from the various object points have a unique angular relationship with one another and with the camera axis. The purpose of all camera calibrations and plotter compensations is to allow these relationships to be regenerated with accuracy. Recovery of the image geometry at the instant of exposure requires knowledge of three essential elements: (1) location of the principal point, (2) camera-lens focal length, and (3) distortion of the total system, including distortion introduced by the electronic parts of the camera and the picture reconstruction system.

**Location of the principal point.** The principal point is defined as the intersection with the image plane of the line perpendicular to the image plane passing through the camera-lens nodal points. When the image plane is perpendicular to the lens axis, the principal point is coincident with the intersection of the optic axis and the image plane. At the principal point, the images, some kind of fiducial system must be used to define it. It is also necessary that the lens be so aligned that the fiducial system actually defines the principal point, or, at least, a point whose distance and direction from the true principal point are fixed and known. Wide-angle (90-deg) cartographic cameras are required to have a fiducial system that defines the true principal point within 15 $\mu$. In narrow-angle systems, principal-point location is not so critical, and a positional uncertainty of about 75 $\mu$ can be tolerated without detriment. Interior orientation of a stereo model is dependent upon reproduction in the plotter of the image plane and the optic-axis relationship of the taking camera. Mislocation of the principal point or points will distort the model in different ways, depending upon the direction of shift. In the case of the Ranger pictures, only principal-point displacements in opposite $x$-directions contribute to significant vertical scale errors.

The principal point is represented by the central reticle of the Ranger cameras, normally within ±1 min of arc, and is not a source of error. It is difficult to align the small cross of the central reticle with the principal point of a projector, however, and a small interior orientation error is introduced when optic centering is performed.

**Camera-lens focal length.** The second item of interest to the photogrammetrist is the principal distance of the negative. In the original image, the principal distance is the distance from the image plane to the interior nodal point. When the lens is focused for infinity, this distance is equal to the lens focal length, sometimes called the effective focal length. The effective focal length is gaged to give the best average focus over the entire image plane, and is not necessarily the same as the focal length determined on-axis.

In vidicon systems, the focal plane is shifted away from the lens by the interposition of the glass faceplate into the optical path. This introduces a curvature of field, convex toward the lens, which results in negative distortion. The shift in the focal plane can be allowed for, but the curvature of field changes the effective focal length (Ref. 17). For narrow-angle (10-deg) systems, these faceplate effects—especially field curvature—are small.

**Radial distortion of the total system.** The methods and instruments of photogrammetry treat a picture as a central point perspective of the object imaged. Most of the geometric imperfections of optical systems are displacements directed either radially away from (+) or toward (-) the principal point and have a magnitude that is a function only of the radial distance from the principal point. When the camera axes of a stereo pair of photographs are parallel and vertical, the chief effects of radial distortion are errors in $z$. As the angle of convergence increases, radial distortion begins to affect the accuracy of $x$ and $y$ (planimetry).

A rough estimate of maximum distortion allowed for in so-called “distortion-free” images can be derived from experience with cartographic photogrammetry. In pictures considered distortion-free, the distortion is equal to or less than one-fifth the line-pair resolution. Larger distortions can be dealt with by corrector plates in a printer or emus in plotters, or by analytic treatment, provided the distortion has previously been measured. It is necessary to know the distortion of the camera system as a whole, and not just that of the lens.

The vidicon faceplate used in the Ranger has an effect on distortion, even when it is optically flat. In essence, it
is part of the lens system. The glass plate lying between the lens and the focal plane displaces the focal plane away from the lens; the displacement along the optic axis is about one-third the glass thickness. This distortion can be removed by insertion of an equivalent glass plate in a ratio printer when diapositives are made.

The electronic link between the vidicon faceplate and the reconstituted picture with which the photogrammetricist works generates distortions of both systematic and random character.

**Base-to-height ratio.** The base-to-height ratio for the Ranger stereo images is defined as the ratio of the perpendicular distance from the center of the camera at the lower altitude to the optic-axis extension of the second, higher camera, divided by the range (optical center to lunar surface along the optic axis) of the lower camera. This definition is similar to that used in terrestrial stereometric photography, where one of the two cameras is not normal to the base line.

The high-angle trajectory of the Ranger spacecraft resulted in stereo images with extremely small base-to-height ratios. The ratio of the base separation of two frames to the range to a common image point is approximately the sine of the angle of convergence. The three-dimensional geometry of the system is strongest when the angle of convergence is 90 deg. A measure of reliability of z-measurements (normalized for \(d = 90\) deg) may be expressed as

\[
\text{weight factor} = 2 \sin \frac{d}{2}
\]

where \(d\) is the angle of convergence. It is evident that as \(d\) approaches zero, the reliability of determining \(z\) on a stereo plotter is drastically reduced. Normally, 12 deg is considered the limiting angle of convergence from which reliable z-measurements may be made in an anaglyptic plotting system; the limiting angle is approximately 8–9 deg in a first-order instrument. A convergence angle as small as 1 deg 55 min can be accommodated on a C-6, with a repeatability of \(z\) reading within 0.1 mm (Ref. 18). X parallax measurements with an AP/2 plotter are reputed to be reliable (90% confidence), with a base-to-height ratio of 0.025 (1 deg 25 min convergence). These accuracies can be obtained only with good images; decrease in the quality of the images will increase the limiting angle of convergence required for reliable measurements.

The base-to-height ratios of Ranger images may be derived from coordinates in the following manner:

1. **Higher position of spacecraft**

\[ R_1 = R + H, \quad \text{where } R = \text{lunar radius and } H = \text{vertical distance of spacecraft to lunar surface} \]

\[ \lambda_1 = \text{colatitude of spacecraft} \]

\[ \beta_1 = \text{longitude of spacecraft} \]

The coordinates are

\[ x_1 = R_1 \sin \lambda_1 \cos \beta_1 \]

\[ y_1 = R_1 \sin \lambda_1 \sin \beta_1 \]

\[ z_1 = R_1 \cos \lambda_1 \]

2. **Lower position of spacecraft**

\[ R_2 = R + H \]

\[ \lambda_2 = \text{colatitude} \]

\[ \beta_2 = \text{longitude} \]

The coordinates are

\[ x_2 = R_2 \sin \lambda_2 \cos \beta_2 \]

\[ y_2 = R_2 \sin \lambda_2 \sin \beta_2 \]

\[ z_2 = R_2 \cos \lambda_2 \]

3. **Optical-axis intersection on lunar surface of higher spacecraft**

\[ \lambda_3 = \text{colatitude} \]

\[ \beta_3 = \text{longitude} \]

\[ R = \text{lunar radius} \]

The coordinates are

\[ x_3 = R \sin \lambda_3 \cos \beta_3 \]

\[ y_3 = R \sin \lambda_3 \sin \beta_3 \]

\[ z_3 = R \cos \lambda_3 \]

Equation for vector from (3) to (1):

\[ (x_1 - x_3)i + (y_1 - y_3)j + (z_1 - z_3)k \]

Unit vector e:

\[ e = \frac{(x_1 - x_3)i + (y_1 - y_3)j + (z_1 - z_3)k}{\sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2 + (z_1 - z_3)^2}} \]
Equation for vector from (2) to (3):

\[ \mathbf{v} = (x_2 - x_1)\mathbf{i} + (y_2 - y_1)\mathbf{j} + (z_2 - z_1)\mathbf{k} \]

Perpendicular distance from (2) to vector (1) to (3):

\[
\text{Distance} = |\mathbf{v} \cdot \mathbf{e}| = |\mathbf{v} \cdot \mathbf{e}| = \frac{1}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}} \cdot \begin{vmatrix} i & j & k \\ x_1 - x_2 & y_1 - y_2 & z_1 - z_2 \end{vmatrix}
\]

\[
= \frac{[(y_1 - y_2)(z_2 - z_1) - (z_1 - z_2)(y_2 - y_1)]i + [(z_1 - z_2)(x_2 - x_1) - (x_1 - x_2)(z_2 - z_1)]j + [(x_1 - x_2)(y_2 - y_1) - (y_1 - y_2)(x_2 - x_1)]k}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}}
\]

or

\[
|\mathbf{v} \cdot \mathbf{e}| = \frac{(y_1 - y_2)(z_2 - z_1) - (z_1 - z_2)(y_2 - y_1) + (z_1 - z_2)(x_2 - x_1) - (x_1 - x_2)(z_2 - z_1) + (x_1 - x_2)(y_2 - y_1) - (y_1 - y_2)(x_2 - x_1)}{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}
\]

The base-to-height ratio = distance/range of lower position. (See Table 1 for numerical base-to-height ratio.)
Image motion and image blur. During the finite time that the shutter is open, any movement of the camera results in a blurring and distortion of the images. The magnitude and direction of image blur and distortion depend on the magnitude and direction of the camera velocity vector relative to the object being imaged, the camera orientation, and the relief of the area being imaged.

When a "between-the-lens" shutter is used, all parts of the picture are exposed simultaneously, and the centers of blurred image points are not displaced from the relative positions they would have had if the camera had been stationary; thus, there is no image distortion, and the picture may be treated as a central point perspective. Image blurring in this case only degrades resolution, as image points are elongated in a direction and by an amount determined by relative camera velocity and camera orientation.

When a focal-plane shutter is used, different parts of the picture are exposed at different times while the camera is at different points in space. In the resulting picture, the image points are displaced from the relative positions they would have had if all parts of the picture had been exposed simultaneously. The resulting displacements may be considered as distortions from a true-perspective center picture, or the picture may be considered as having been produced by a camera in which the perspective center has been replaced by a perspective line. The magnitude and direction of the distortion depend upon the direction and speed of the shutter motion, the direction and magnitude of the camera velocity relative to the object that was imaged, and the camera orientation. Image blurring occurs as an additional effect. Except for the AP/2, existing plotters are not designed to cope with the effect of a focal-plane shutter.

The resolution of the Ranger images that are suited for photogrammetry is such that image motion and blur have little effect upon photogrammetric reduction. (For an analysis of image motion and blur see the Appendix to this Section.)

Video scanning, image size, scale differences, low Sun angle

Video scanning. The television scanning systems used in Ranger limited the resolution of the cameras. Whereas the lenses had a resolution of 50 line pairs/mm, resolution of the camera systems was approximately 36 line pairs/mm. Linearity is probably the limiting factor in resolution, and nonlinearity of the scanning is a major contributor to the unknown scan model distortions. Video "jitter" (random electron beam displacements) tends to produce a model much softer than normal photographs. The full effects of nonlinearity of scanning and jitter are, at present, unknown.

One unavoidable aspect of television pictures that is detrimental to photogrammetry is the scan line. At latent image size, the effect is not particularly harmful, but when the images are enlarged, the blanking spaces become very noticeable. The effect is similar to looking at an object through a one-directional, thick wire screen. When the latent image is enlarged six times and set up in a first-order plotter, this effect creates a pseudo-datum that the operator must penetrate in order to place the floating mark upon the surface. Under these conditions contouring is accomplished with more confidence than is the reading of elevations—a reversal of the normal photogrammetric condition.

Image size. One aspect of image format that has created operator difficulties is the very small size of the images. It is difficult for a photogrammetrist to adjust his long-developed techniques in dealing with formats of 7 x 7 in. or 9 x 9 in. to formats occupying an area of 0.7 x 0.7 in. Interior orientation by alignment of reticles defining center lines of the format is restricted by reticle width (0.005-0.002 in.) and linear separation (0.5 in.)

Image scale differences. Camera stations along the Ranger spacecraft trajectory are at greatly different altitudes, and the pictures from cameras of equal focal length are, therefore, at greatly different scales.

When there is a large difference in scale between two photographs of a stereo pair, a plotter operator will not be able to achieve image fusion if he is employing an orthographic viewing system. Scale difference in first-order plotters would be acceptable if zoom oculars were available, but only the AP series of first-order plotters can accommodate a scale discrepancy without a major redesign of the optical system. It may be noted that the photogrammetric system that most closely meets the demand of equal image scale by recovery of all spatial relationships is the double-projection system first designed by Zeiss in 1928.

One problem created by disparate image scale concerns the operator link in the stereo plotter system. It
is separate from, but related to, the problem of accommodating disparate camera altitudes within the mechanical and optical limitations of the plotter. Although the human eye and brain can accommodate some imagescale disparity and still achieve stereo fusion, scale differences exceeding 4-5% will cause eyestrain when long viewing times are involved.

The most harmful effect of altitude difference is the resulting ground-resolution change for each photograph. When small relief features are subdued or eliminated from one photo, the ability to form a stereo model is curtailed.

Low Sun angle. The minimum solar altitude normally used for terrestrial photography is 30 deg. Below this angle, shadows cast by features with slopes greater than 30 deg obscure parts of the detail. In addition, the brightness of a horizontal surface decreases rapidly (approximately 1%/deg) when the Sun angle is below 60 deg. On the other hand, when small features are involved and albedo differences are also small, small shadows enhance detail and generally improve the quality of the image. Thus, a low Sun angle, resulting in small shadows, would have some photogrammetric value in areas of minor relief.

A crude attempt was made to evaluate lighting effects on a model of varying relief and with no albedo differences. The setup consisted of two multiplex projectors tilted 25 deg, separated along the z-axis by about 100 mm. Exposures were made on glass plates in the projectors for convenience in resetting. A spotlight was used as an illuminating source and set at 60 and at approximately 20 deg. Each model was then reset and a comparison made: the model obtained from the images that were illuminated at 20 deg was the poorest.

The low Sun angle, in combination with narrow-angle systems, is felt to be the factor that prohibits the reversing of stereo effects. No matter how the high-resolution Ranger photographs are oriented, pseudostereo (reversal of relief) cannot be achieved. This fact has prompted statements to the effect that true stereo does not exist in the Ranger images. It can be demonstrated that equivalent central parts of vertical terrestrial photographs of monotone areas (sand, snow, grain fields) at Sun altitudes of 45 deg tend to produce the same effect.

b. First-Order Plotters

The inherent qualities of first-order plotters, some of which have already been described, led to their selection for use in our first attempts to reconstitute the Ranger images.

Four additional factors prompted the choice of these instruments: (1) their heighting accuracy (root-mean-square error of spot elevations) is at least three times better than that of a second-order instrument such as a multiplex; (2) the images are separated by a viewing system for each eye, and there is no ghost picture caused by incomplete image extinction by color or Polaroid filters; (3) data pertaining to relative and absolute orientation can be set in and read out; and (4) theoretically, the base-to-height ratio can be set almost to zero.

The instrument that appeared most suitable for recapturing the unorthodox geometry of the Ranger imaging system was the AP/2. Numerous contacts were made with the agencies having a plotter of this type in an attempt to arrange a cooperative research effort. The Geodesy, Intelligence and Mapping Research and Development Agency of the U.S. Army of Engineers agreed to incorporate two Ranger VIII models (P-18, P-17 and A58-A59) into their AP/2 evaluation program. The Geological Survey furnished trajectory data and copy negatives, and a cursory examination of the Ranger pictures was made. The major factor preventing a more complete evaluation was the fact that the lowest viewing magnification (approximately 39 times) severely degraded image quality. (This situation could not be corrected without modification of the AP/2, which was committed to many other programs requiring the existing optical system.) Large magnification in any optical viewing system tends to degrade the images to a point where stereo perception becomes difficult, and—to compound the problem—video scan lines, upon magnification, form a strong pseudo-datum that is almost impenetrable. An attempt to alleviate the scan-line interference by optical-diffraction methods and by photomechanical subduing resulted in image degradation of such a magnitude that stereo viewing was not significantly improved.

Removal of the coherent noise by optical-diffraction methods theoretically offers the ideal way to improve the photogrammetric quality of spacecraft television images, but the presently developed instruments have serious deficiencies which prevent their routine use. A development program to correct the shortcomings of optical diffraction is underway and should be completed in about one year. Its results will be applicable not only to video
systems, but also to others, such as electromechanical scanning systems, for removal of coherent noise. In addition, techniques of image enhancement by selective filtering will improve detection of lineation patterns that are useful for geologic interpretation.

A total of five attempts were made to use other first-order plotters for the reduction of Ranger pictures, but their limitations did not allow the exact reconstruction of the original orientation. The instruments used were the Wild A-5, AP/C, and Zeiss C-8. One form line map was compiled in the Wild A-5, using rectified prints of Ranger VIII A frames 58 and 59.

Time and cost limitations prohibit the modification of first-order plotters for Ranger data reduction by the Geological Survey. The most practical alternative was to modify anaglyphic plotters used in base map construction and stereo photogeological interpretation. Use will be made of first-order plotting systems for specific measurement of crater depth-to-diameter ratios from stereo pairs of extreme base-to-height ratios where vertical and horizontal scale differences can be evaluated.

c. Anaglyphic Plotters

A review of the Ranger data indicated that the available anaglyphic-type projectors would not accommodate the Ranger stereo image combinations without modification of one or more projector components. With the full realization of the effects of not adhering to a general recovery of the geometric taking conditions, two selected Ranger VII stereo pairs, P,106-P,107 and A,198-A,199, were set up in BL 30-mm multiplexer projectors for stereoscopic evaluation. The following were the major limiting factors in this effort: (1) projector heights above datum were greatly different, (2) base-to-height ratios were very small, and (3) the condensing-lens housings tended to fall off when the projectors were tilted.

Of the two stereo pairs studied, only the base-to-height ratio of the F-frame pair could be met without considerable modification of the projectors. Despite the fact that the proper conditions for an oriented stereo model could not be fulfilled, the models were cleared of parallax in an approximate orientation to determine whether any stereo potential was available. It was found that the floating dot could be fused repeatedly at the same apparent surface. The stereoscopic viewing of the unoriented models was sufficiently encouraging to suggest that the Ranger geometry could be recovered with some degree of reliability through further refinements and by the use of other types of plotters. To initiate additional investigation of multiplex compatibility, several BL 30-mm projectors, four Zeiss 46-mm projectors, and approximately half a dozen lens assemblies were procured from the Topographic Division of the Geological Survey.

The major problems in the application of double-projection plotters to photogrammetric reduction images are:

1. Projector supporting frames allow for only a small Z-separation. In this case, Z is defined as the distance along the optic axis from the perspective center of one camera to a point formed by the intersection of a line perpendicular to this optic axis from the perspective center of the other camera. The perpendicular line is the base line. Compatible stereo frames from the Ranger series of pictures exceed the Z-limitations of available projectors and require a supporting-frame modification. The complexities arising from a large Z-difference prohibited the redesign of present supporting frames to accommodate the Ranger stereo models (designated in Table 1), except for the A58-A59 combination. The detrimental effects are: magnification of the low-resolution pictures, projector instability; extreme depth of focus requiring very small apertures; insufficient model illumination; and lower projector interference with image projection from the upper projector. Projector modifications are planned which take these effects into consideration.

2. The light source is one of the most critical factors in the recovery of stereo models by double projection. The entire field should be illuminated at nearly equal intensity, as errors introduced by varying light intensity and low light level may be large when picture resolution is low. It has been demonstrated that where light intensity varies, warping of the model, similar to the effects of tilting one projector about the y-axis, may occur over different parts of the model. A large Z-separation of the projectors makes it difficult to obtain sufficient and balanced illumination with the systems available at the present. The redesigned projectors will probably incorporate a light source similar to the spotlight type employed on the Kelsh projectors; as the angular field will not exceed 25 deg, full field illumination can be obtained.

3. The depth of focus of any projection system depends upon the lens aperture and focal length. Depth of focus may be defined as the range of image distance, with a fixed object distance within which image points have a circle of confusion smaller than a given
limit. For good viewing, the diameter of the circle of confusion should normally not exceed 0.2 mm.

Because of the large range difference in the usable Ranger stereo pairs, the image from only one projector would be well defined if the principal distance and aperture of the two projectors were kept equal. Reduction of the aperture size of the higher projector would increase the depth of focus, but, unfortunately, would also reduce the amount of illumination if present lighting systems were used.

4. The physical size of the projectors is the limiting factor in recovery of the base-to-height ratio. The maximum settings are one to three for the Balplex, one to four for the BL30-mm, and one to five for the Zeiss 46-mm projectors. If smaller ratios are obtained for any particular projector pair, either part of the field will be blocked out or the projectors will be brought into physical contact before the desired base-to-height ratio has been established.

Miniaturation of the projectors will not prevent interference of light rays by the lower projector in the models listed in Table 1. It will be necessary to shift the geometry from the projector by use of a parallelogram mirror system or a beam splitter.

To test the validity of using an anaglyphic projection system further, a series of rough models were set up using Ranger VIII A-, P-, and P-camera images. The following conclusions were reached:

1. The conditions are environmentally extrinsic to a photogrammetricist. It will require a training period of nominal duration to allow even the superior operator to adjust to the adverse circumstances of the unusual and very weak geometry.

2. The quality of the Ranger images permits considerably more latitude in the model setup than is possible with conventional photographs.

The introduction of principal-point error by deliberate displacement of one Ranger VIII P frame (the central reticle was not used as the principal point) showed that no visible effects on parallax scale, or datum occurred until the displacement was approximately 0.5 mm. However, when the displacement was 0.5 mm in the y-direction, the parallax could not be completely cleared from the model, and in the x-direction, appreciable tilting of the datum was noted. The expected effect was a change in vertical scale. When projectors are constructed to accommodate the camera taking conditions, this experiment will be repeated.

The principal distance in one projector was varied by placing shims under the diapositive. The datum did not tilt visually until the principal distance had been increased by some 7.0 mm, at which point the image from one projector was almost lost.

A double-projection system is desirable for geologic analysis and mapping base-map compilation, and the establishment of photometric control. Such a system will be constructed to accommodate the unusual geometry of the Ranger images and will be used extensively in subsequent investigations.

Appendix

Image-Blur Analysis

It is easier to visualize the blurring process if, instead of considering a camera with a vector velocity V and a fixed lunar surface, the conditions are reversed and a fixed camera and a lunar surface with a vector velocity -V are used.

For convenience, the ground point is represented by X, Y, Z coordinates in a right-hand orthogonal system whose origin is at the ground position of the projected central reticle (principal point), with +X toward the ground nadir and +Z vertically upward. The corresponding picture coordinates are x and y: +x is measured from the principal point along the principal line toward the nadir, and y is perpendicular to x and parallel to Y. With this set of coordinates, the camera tilt t is contained in the XZ-plane, and its value is determined by the following formula:

$$\cos t = \frac{\text{camera altitude}}{\text{slant range}} = \frac{H}{S}$$

$$f = \text{lens focal length}$$

$$z = \text{slant range to ground position of central reticle}$$

$$x = \frac{f}{S} (X \cos t + Z \sin t)$$

$$y = \frac{fy}{S - (X \sin t + Z \cos t)}$$
Differentiation of these expressions with respect to the
time would give velocity components, but the results
would be unnecessarily complicated. To avoid this, a
datum plane perpendicular to the camera axis and pass-
ing through the ground principal point is used instead of
the Moon's surface. This new plane intersects the lunar
surface along the Y-axis, and the dihedral angle between
the plane and the lunar surface is the tilt angle $t$.

The coordinates of a ground point in the new system
are given by the equations

$$X' = X \cos t - Z \sin t$$

$$Y' = Y$$

$$Z' = X \sin t + Z \cos t$$

Picture coordinates in the new system are given by
the following equations. These equations are identical
to those used for terrestrial vertical photography when
$S$ represents the flight height.

$$x = \frac{fx'}{S - Z'}$$

$$y = \frac{fy'}{S - Z'}$$

$$\frac{dx}{dt} = v_x + \frac{f}{S - Z'} \left( \frac{dx'}{dt} + \frac{fx'}{(S - Z')} \right)$$

$$\frac{dz}{dt} = \frac{f}{S - Z'} V_x' + \frac{x'}{S - Z'} V_z$$

$$\frac{dy}{dt} = v_y + \frac{f}{S - Z'} V_y' + \frac{y}{S - Z'} V_z$$

where $V_x'$ and $V_y'$ are components of motion perpen-
dicular to the optical axis. If $V_z'$ were zero and $Z'$ fixed,
then the above equations would describe the usual
terrestrial case of vertical photographs and level flight,
with ground points imaged as lines. The length of every
line smear would be the same, and each would be par-
allel to the flight path. Variations in $Z'$, small compared
to $S$, will produce only second-order effects in the length
of smear lines. In the case of the Ranger P images, al-
though $Z'$ will vary with ground $X$, the narrow taking
angle ensures that $X$, and therefore $Z'$, will always be
small compared to $S$. Hence, the above argument for the
terrestrial case holds also for the Ranger photographs.

The effect of $V_z'$, which is parallel to the camera axis,
is to displace all image points radially from the principal
point by an amount proportional to the radial distance:
that is, the image scale is changed. The scale change during
the exposure is that due to the change in the slant range
during the time the shutter is open.

For example, substituting JPL data for two late frames
of the Ranger VII P camera,

$$t = 32.1 \text{ deg from vertical}$$

$$V = 2.62 \text{ km/sec} \cdot 25.8 \text{ deg from vertical} \text{ (In this case, \ V was within 1 deg or so of being within the vertical plane containing the nadir.)}$$

$$V_z = 2.62 \sin (32.1 - 25.8 \text{ deg}) = 2.62 \sin 6.3 \text{ deg} \text{ m/msec} = 0.287 \text{ m/msec}$$

$$V_z = 0 \text{ (not quite true, but close enough for blur analysis)}$$

$$V_z = 2.62 \cos 6.3 \text{ deg} = 2.60 \text{ m/msec}$$

Exposure time = 2 msec

Blur due to $V_z = 2 \times 0.287 = 0.574$ m

Blur due to $V_z$ is due to change in $S$ of 5.2 m

From JPL data,

$S = 20.35$ km for P, frame 181

$S = 1.74$ km for P, frame 189

$S = 0.519$ km for P, frame 190

(A change of $S$ of 5 m will have a negligible effect on
image quality, although there is a small amount of radial
distortion.)

Lunar curvature is not considered a factor in the last
Ranger frames. Relief is a contributing element but has
relatively minor significance.
2. Experimental Topographic Map of a Small Area of the Lunar Surface From the Ranger VIII Photographs

Henry L. Moore and Richard V. Luga

During the Ranger VIII mission, the decision was made to maintain the cruise-mode orientation of the spacecraft rather than to perform a terminal maneuver, in order to obtain extensive stereoscopic coverage of the lunar surface along the flight path. The trajectory and orientation of the spacecraft were such that some of the stereo photographic coverage obtained had a base-to-height ratio that could be accommodated by modification of an available anaglyphic-projection stereo plotter. This Section presents the preliminary topographic results obtained from experiments undertaken to study the problems of design of an appropriate anaglyphic projection instrument. An ER-55 plotter was used.

a. Procedure

Two consecutive A-camera photographs, 58 and 59, were selected for the preliminary experiment (Figs. 23 and 24), mainly because they have a base-to-height ratio that could be used in the ER-55 projector system. They are the second and third photographs from the end of the A-camera series and show details not seen before in this area of the Moon. The photographs include a relatively large crater, and it was thought that the orientation of the shadow within the crater could be used to provide control which would supplement the information provided by the spacecraft telemetry and tracking. As there is considerable vertical separation in camera stations, it was necessary to adapt the supporting bar of the ER-55 so that this separation could be reconstructed to give the proper relative orientation of the projectors (Fig. 25).

No ground control is available on the Moon for mapping at the scale of the high-resolution Ranger photographs; it is therefore necessary to depend for control on the position and orientation of the cameras as obtained from spacecraft tracking and from the spacecraft orientation-system telemetry. To solve this problem using an anaglyphic projection system, the geometry of the flight camera positions and the camera orientation are reconstructed with the stereo-plotting instrument. In order to maintain the correct geometry, the ratio of the scale of the diapositives used in the projectors to the scale of the latent image on the vidicon target of the television camera must be the same as the ratio of the projector principal distance to the camera principal distance. As the principal distance of the projector is 55 mm (Ref. 19) and that of the camera is nominally 26.06 mm, this ratio is 2.11. The Omega D-2 Enlarger was used to make the diapositive plates. Although the use of this enlarger leads to unknown errors, it was considered suitable for a preliminary study. The lack of precise calibration of the camera principal distance, and the alignment and position of the vidicon are additional sources of error in the present photogrammetric use of the Ranger photographs. Among other effects, this error leads to a small unknown vertical distortion and tilting of the stereo model. Other sources of error, such as electronic distortions of the image and image blur, were ignored for this experimental study.

To achieve orientation of the projectors, the images were projected onto a level surface separately, and the ratios of the image format boundaries for each frame were set equal to the ratios obtained from the camera-orientation data provided by the Jet Propulsion Laboratory.* As a check on the projector orientations, measurements were then made of the emission angles at the format extremes and at the central reticles. The two planes defined by the optic axes and verticals from the projectors were parallel, and it was established that the optic axes were essentially parallel. The projectors were adjusted until the base-to-height ratio was the same as the computed base-to-height ratio of the two exposure stations. Finally, the ratios of the optic-axis ranges of the two Ranger exposure stations were compared with the ratios of the optic-axis ranges of the projectors and found to be in good agreement. The appropriate data are listed in Table 2.

When the projectors were properly oriented, the stereo model appeared clear of y-parallax, and no further adjustments of the projector motions were attempted. It was then assumed that the stereo model represented a model of the actual lunar surface and that it was correctly oriented.

The projector representing the upper exposure station projected the image 87.8 cm, which is well beyond the optimum projection distance of 52.5 cm. Although such a great projection distance results in a poorly defined image, no effort was made to correct this by lowering the projectors because the appropriate corrections would have resulted in interference from the lower projector. No attempt was made to change the position or orientation of the projectors in order to provide a convenient scale for compilation.

The scale of 1:27,400 was determined by comparing the dimensions in the stereo model that could be equated

*Data tabulation for Ranger VIII camera A, as amended (1965).
Fig. 23. Ranger VIII A-camera photograph 58.
Fig. 24. Ranger VIII A-camera photograph 59.
Fig. 25. Photograph of ER-55 plotter, showing setup used for experimental compilation of topographic map from Ranger photographs.
Table 2. Comparison between Ranger VIII camera orientations and ER-55 projector orientations

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Item</th>
<th>JPL data</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Field of view</td>
<td>25 deg*</td>
<td>24.63 and 24.77 deg</td>
</tr>
<tr>
<td>2</td>
<td>Optic-axis range (assumed principal point) (ASB)</td>
<td>24.77 km</td>
<td>87.8 km</td>
</tr>
<tr>
<td>3</td>
<td>Optic-axis range (AS9)</td>
<td>14.51 km</td>
<td>52.7 km</td>
</tr>
<tr>
<td>4</td>
<td>Horizontal distance between principal points on surface</td>
<td>5.16 km</td>
<td>18.6 km</td>
</tr>
<tr>
<td>5</td>
<td>Separation of optic axes</td>
<td>4.53 km</td>
<td>16.3 km</td>
</tr>
<tr>
<td>6</td>
<td>Ratio of items 4 and 3</td>
<td>1/2.82</td>
<td>1/2.83</td>
</tr>
<tr>
<td>7</td>
<td>Ratio of items 5 and 3</td>
<td>1/3.20</td>
<td>1/3.23</td>
</tr>
<tr>
<td>8</td>
<td>Ratio of items 2 and 3</td>
<td>1.70</td>
<td>1.66</td>
</tr>
<tr>
<td>9</td>
<td>Emission angles (ASB)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NW corner</td>
<td>23.49 deg</td>
<td>22.9 deg</td>
</tr>
<tr>
<td></td>
<td>NE corner</td>
<td>43.86 deg</td>
<td>43.2 deg</td>
</tr>
<tr>
<td></td>
<td>SE corner</td>
<td>39.67 deg</td>
<td>39.9 deg</td>
</tr>
<tr>
<td></td>
<td>SW corner</td>
<td>15.52 deg</td>
<td>15.7 deg</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>28.62 deg</td>
<td>28.3 deg</td>
</tr>
<tr>
<td>10</td>
<td>Emission angles (AS9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NW corner</td>
<td>23.64 deg</td>
<td>23.0 deg</td>
</tr>
<tr>
<td></td>
<td>NE corner</td>
<td>43.91 deg</td>
<td>43.6 deg</td>
</tr>
<tr>
<td></td>
<td>SE corner</td>
<td>39.72 deg</td>
<td>40.2 deg</td>
</tr>
<tr>
<td></td>
<td>SW corner</td>
<td>15.72 deg</td>
<td>16.0 deg</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>28.79 deg</td>
<td>28.5 deg</td>
</tr>
<tr>
<td>11</td>
<td>Theoretical scales</td>
<td>1/2.76 × 10⁴</td>
<td>1/2.76 × 10⁴ and 1/2.81 × 10⁴</td>
</tr>
<tr>
<td>12</td>
<td>Measured scale</td>
<td>1/2.76 × 10⁴</td>
<td></td>
</tr>
</tbody>
</table>

\*Because of a mask on the vidicon faceplate, this angle may be near 24.3 deg.

\*Obtained using length of north edge of model and corresponding JPL data.

with data received from JPL, ranges and projection distances used in the computation of the scale are listed in Table 2. The altitude of the spacecraft was 21,800 m for the higher camera position. It was arbitrarily decided to compile with a contour interval of 55 m, which represents 2 mm at the map scale.

b. Results

Stereo models obtained from Ranger photographs are appreciably degraded compared to models obtained from conventional aerial photographs taken for photogrammetric mapping. Stereoscopic interpretations by two operators were found to be generally the same, although they differed significantly in topographic detail; for example, both operators found that the mare surface was nearly level on the average, although local gentle slopes near 7 deg were present. For the east–west slope of the wall of the largest crater, one operator obtained 31 deg and the other, 26 deg. This result is consistent with measurements of slopes of craters of slightly larger sizes using shadow techniques (Ref. 20).

The inclination (or slope) of the shadow in the large crater was measured as 14 ± 2.0 deg, a result consistent with the local elevation of the Sun at the time of Ranger VIII impact. This indicates that the stereo model may have been approximately level, with a possible maximum tilt of 2 deg in the east–west direction.

In detail, the two operators differed significantly. The error of reading the position at a point on the model was found to be about equal to the contour interval used (55 m). Because of the low photogrammetric quality of the photographs, the lack of photogrammetric calibration of the Ranger camera, and the errors introduced by the procedures used for this experimental study, the results must be viewed cautiously. One of the experimental maps is shown in Fig. 26, however, to illustrate the product of this technique.
EXPLANATION

CONTOUR, APPROXIMATELY LOCATED

SUPPLEMENTARY CONTOUR

DEPRESSION CONTOUR

CRATER RIM

SHADOW OUTLINE

CONTOUR INTERVAL 55 m
ARBITRARY DATUM
SCALE 1:27,500

Fig. 26. Topographic map of small area of lunar surface.
c. Conclusions

Although the Ranger VIII photographs and the experimental topographic maps do not conform to terrestrial mapping standards, important topographic data are obtainable from selected Ranger photographs with the use of applicable photogrammetric techniques. Such data, when combined with photometric measurements from the photographs, can be used to derive the local photometric functions and to provide control over large distances for the preparation of more detailed topographic maps by photometric methods (Ref. 1 pp. 129–130). This investigation is in a preliminary stage and the techniques used may be significantly improved upon by means of better diapositive printing procedures, corrections for electronic distortions and noises, and modifications of the projectors for accommodation of differences in camera heights, base-to-height ratio, depth of field, and illumination.

D. Use of the Ranger Photographs in Geologic Mapping of the Moon

Two major objectives of lunar exploration are to determine the present structure of the Moon and to interpret its history. The geologist attempts to achieve these objectives by the method of geologic mapping, in which the structures exposed at the surface and the distribution of recognizable stratigraphic units are plotted on suitable topographic or planimetric map bases. The decipherable history of the Moon is recorded in its structure and stratigraphy.

Both the structural and stratigraphic features of a given part of a solid planetary surface are recognized or discriminated primarily by their elements of topographic form and by their array or pattern of physical characteristics, such as albedo, color, and surface texture. Much of these data ordinarily employed in geologic mapping can be recorded in photographs, and, where well exposed, the structure and stratigraphy of a given area can be worked out largely from the data contained in appropriate photographs. Such is the case for the Moon, where the broad features of the geology are being mapped at a scale of 1:1,000,000, chiefly by means of data obtained from telescopic photographs and from direct visual telescopic examination of the lunar surface.

The photographs obtained in the Ranger missions provide an opportunity to examine the geology of the Moon locally at much larger scales than has been possible heretofore. The following Sections describe the preliminary results of geologic mapping at successively larger scales, of selected parts of the Moon on the basis of the data contained in some of the Ranger VIII and IX photographs. The most detailed study, made by N. J. Trask, has been carried out at a scale comparable to that employed in detailed geologic mapping on the Earth. Many of the new problems encountered in the large-scale mapping, however, have been shown that the general geologic techniques developed in the earlier telescopic mapping are applicable to the geologic analysis and reduction of high-resolution photographs acquired from spacecraft and that the stratigraphic units thus recognized can be placed within the gross stratigraphic classifications worked out at the telescope.

1. Geology From a Relatively Distant Ranger VIII Photographs, G. S. Milton and D. E. Wiedemier

The most striking achievement of the Ranger missions was the acquisition—in the last seconds before impact—of photographs revealing fine features of the lunar surface whose nature could previously only be inferred by indirect means. The more distant photographs in the sequence from each mission may be less spectacular, but they also contain much new information of interest. They are similar to photographs obtained by Earth-based telescopes but have better resolution (except for the earliest in the sequence). Thus they can be used directly in the small-scale geologic mapping of the Moon carried out by the U.S. Geological Survey.

B-camera photograph 34 of the Ranger VIII series (Fig. 27) serves as a good illustration of the methods, product, and, particularly, the problems of lunar geologic mapping. The area shown, which is approximately 100 km on a side, had been covered by preliminary geological maps previously prepared by E. C. Morris and the writers at a scale of 1:1,000,000, or approximately one-third the scale of the photographs. These maps are now being revised, mostly on the basis of the Ranger photographs. As yet only qualitative methods have been used, but eventually the descriptions of such features as hummocky terrain and highly cratered surfaces should and will be supplemented by quantitative methods of slope and crater-distribution analysis. Although for this study as much of the mapping as possible was done from B-camera photograph 34, Earth-based photography was used to examine the area at different Sun angles, particularly to determine albedo at full Moon, and other photographs in the Ranger VIII series were used to clarify details.
Fig. 27. Ranger VIII B-camera photograph 34. (Reticle marks are about 20–25 km apart.)
a. **Objectives and Method of Geologic Mapping**

Every geologic process produces deposits or structures that partially or completely erase or conceal the evidence of earlier processes. The task of the geologist is to isolate the layers of the earthpast by the relations of superposition and intersection of the features. From these relations, the chronologic sequence of the events recorded in the layers and structures is deciphered.

In Figs. 28 and 29, some of the salient features shown on B-camera photographs are indicated. The compilation is not complete but serves as a guide to be supplemented by further inspection of the photographs. Figure 28 shows linear features (lineaments); those along which there is a displacement or offset of the surface are denoted by a solid line with a bar on the down-dropped side. Scairs bounding ridges on the mare surface are marked by a special symbol, and other lineaments are shown by dashed lines. In Fig. 29, more or less round depressions (craters) are outlined. There is a continuous gradation from craters that are sharply defined to ones so subdued as to be near the limit of detection. Those with raised rims, which are generally deeper and have sharp, even crests, are drawn in solid lines; more subdued craters, which are generally shallower, are outlined by dashed lines. A hachured symbol is used to denote the edges of irregular depressions that appear to be transitional between round craters and the depressed areas between parallel lineaments.

Figure 30 is based upon a slightly more interpretive analysis of the photographic data. The lines delineate areas which appear to have different surface texture and albedo. Areas enclosed within a given boundary exhibit similar texture and albedo, suggesting a common origin. A still more interpretive step—to which most of this Section is devoted—is the analysis of these areas as geologic units, which implies a genetic variety and specific age for each. The product of this analysis is the geologic map (Fig. 31).

Classification of mappable geologic units according to relative age is one of the chief goals of geologic mapping. Relative age is determined from the stratigraphic relationship of superposition of the geologic units. On the Moon, the superposition, or overlap, of one unit upon another is in general determined from the areal pattern of the units; the rim material and rays of a ray crater, for example, are recognized as superposed on older geologic units where the rays extend across the older units. In many cases, the stratigraphic relationship of two geologic units cannot be determined solely from their local patterns, and in order to determine relative age, it is necessary to correlate the local units with other geologic units in regions where the stratigraphic relations can be solved.

A basic stratigraphic classification scheme, modeled after the scheme used internationally for geologic mapping on Earth (Ref. 21), has been adopted for the lunar geologic maps prepared by the U.S. Geological Survey. The lunar scheme consists of three parts: (1) a classification of surface materials into formations and groups on the basis of physiographic and optical characteristics, (2) a classification of these units according to stratigraphic sequence, and (3) a corresponding classification or subdivision of lunar geologic time (Ref. 22). The recognized sequence of overlapping geologic units is subdivided into major groups called systems; in ascending stratigraphic order there are the Imbrian, Eratosthenian, and Copernican Systems. Geologic units in the Copernican System overlie the ones in the Eratosthenian and Imbrian Systems, and units in the Eratosthenian System overlie those in the Imbrian System. Geologic units in the Imbrian System overlie still lower, mappable units which have not yet been formally divided into systems but are collectively referred to as pre-Imbrian units. The Imbrian System is further subdivided into two series, the Apenninian (at the base) and the Archimedean (at the top).

The geologic time scale adopted for the Moon comprises (from the beginning of lunar history to the present) pre-Imbrian time and the Imbrian, Eratosthenian, and Copernican Periods, representing the intervals of time during which the materials of the corresponding systems were deposited or formed. The Imbrian Period is divided into the earlier Apenninian Epoch and the later Archimedean Epoch. A task for future lunar exploration will be the determination of approximate dates, in terms of years, for the boundaries of the periods and epochs by isotopic analysis of appropriate samples recovered from the recognized geologic units.

b. **Age and Origin of Structures and Geologic Units**

**Pre-Imbrian structural features.** The earliest events recorded in the structure and distribution of geologic units in the area studied are recognizable to a large extent only from structures that have influenced the deposition of later materials. The most prominent of these structures is the arcuate series of broad high ridges, the middle one of which extends from Hypatia E to Delambre B. These ridges constitute the western part of a multiwalled circular feature at least 150 km in diameter. It is apparently a smaller member of a group of very large circular
Fig. 28. Lineaments shown in Ranger VIII B-camera photograph 34. (Faults are shown by solid line with bar and ball on downdropped side, mare scarps by solid line with barb pointing downhill, other lineaments by dashed lines. NW–SE trending lineaments on terra belong to the Imbrian sculpture system.)
Fig. 29. Craters and other depressions shown in Ranger VII B-camera photograph 34. (Craters with sharp rim crests and raised rims are marked by solid lines, subdued craters by dashed lines.)
Fig. 30. Geologic units exposed in the area of Ranger VII B-camera photograph 34.
(Explanation of symbols is given in Fig. 32.)
Structures and deposits of Imbrian age

Imbrian sculpture and the Apenninian Series. A second major lineament system on the terra, less prominent but more widespread than the ancient avenate structures, trends northwest-southeast (Fig. 28). In the western part of the map area, this lineament system is represented by close-set ridges and valleys, forming a superposed on the older, broad avenate ridges. These are a part of an extensive system of similar ridges and valleys, called Imbrian sculpture by Gilbert (Ref. 24), trending radially away from the Mare Imbrium basin. They are interpreted here as a series of tilted fault blocks. Their pattern is compatible with the hypothesis that the Mare Imbrium basin was formed by impact, which generated a radial fault pattern.

Surrounding the Mare Imbrium basin is a regional geologic unit characterized by a distinctive hummocky topography in which the local relief generally decreases radially away from the basin. This unit is known as the Fra Mauro Formation, after a type locality in the western part of the Moon (Ref. 25), and is interpreted as being a deposit of ejecta from the Mare Imbrium basin. Much of the material around any large impact crater has been ejected with low velocity, forming a rim deposit thinning outward. Fewer but more energetic fragments follow longer trajectories and fall with greater kinetic energy, so that, instead of a continuous deposit of ejecta, they form discrete secondary-impact craters surrounded by local ejecta deposits. The area covered by the Ranger VIII photographs lies at a distance from the Mare Imbrium basin at which the continuous deposit of the Fra Mauro Formation is transitional outward into a thin discontinuous deposit, where poorly developed, Imbrian secondary craters are more prominent topographically than the ejecta hummocks. This transition zone, mapped as the pitted facies of the Fra Mauro Formation, covers most of the terra west of the central ridge of the map area and appears north of Hypatia C. The Fra Mauro Formation is probably also present on the steeper ridges, but recognition of it is difficult there because the dominant relief is controlled by pre-Imbrian structure. Areas in which the Fra Mauro Formation is probably very thin and pre-Imbrian rock is near the surface or locally exposed are indicated by dotted boundaries. The depositional hummocks and the secondary-impact craters have a crude orientation radial to Mare Imbrium. It is, therefore, difficult to make a clear distinction between the Imbrian sculpture, produced by faulting, and the Fra Mauro surface texture, produced by deposition and secondary cration.

The Fra Mauro Formation is the oldest well-established and widespread geologic unit in the lunar stratigraphic column; for this reason, it is taken as the basal unit of the Imbrian System, which is the earliest formally defined lunar system, and of the Apenninian Series. In this map area, only the Fra Mauro Formation can be unequivocally assigned to the Apenninian Series.

Archimedean Series. Geologic units assigned to the Archimedean Series in the area studied include three plains-forming units and dome materials on the terra, materials of the craters Sabine and Delambre, and mare material.

Most of the eastern part of the terra in the map area has an appearance fundamentally different from that of the Fra Mauro Formation. Here the terra is characterized by relatively level plains with subordinate craters and irregular elongate depressions. Three plains-forming geologic units have been mapped on the basis of the number and size of craters present.

Where the plains-forming materials are thin, they subdue but do not completely conceal the topographic features of the underlying geologic unit. Thus, the contact of the plains-forming units with the Fra Mauro Formation, which they overlap, is in many places indistinct. A few characteristic hummocks and craters of the latter can be distinguished within the areas mapped as the plains-forming unit. Where the plains-forming materials are thicker, the surface is a level plain with craters and irregular depressions but no intrinsic positive-relief features. The occurrence and thickness of the plains-forming units is apparently controlled by pre-existing structure. The contacts of the units tend to parallel the directions of Imbrian sculpture, perhaps following faults bounding the deeper basins in which the units were deposited.

The distinction between the three plains-forming units is primarily one of crater density, the unit Ip being the most densely cratered and Ip, the least (Fig. 28). In
Fig. 31. Geologic map based on Ranger VII B-camera photograph 34.
general, Ip, is the thinnest unit, and Ip, appears to be the thickest, with Ip, intermediate between them in crater density and apparent thickness. The shapes of the crater-form depressions superposed on the plains units are diverse. Many of the depressions on unit Ip, are elongate and rimless and may be volcanic collapse features aligned along deep-seated structures.

The plains-forming materials are believed to be volcanic, probably composed of ash from eruptive centers that cannot definitely be identified. The units may have been deposited slowly over a long period of time. All the resolvable craters formed during or since the start of deposition (as well as some older craters) are probably visible at the surface of unit Ip,, whereas most of the craters formed in areas of unit Ip, during the deposition period may be buried by the youngest volcanic strata.

The precise age assignment of the plains-forming units within the Imbrian Period is uncertain. The Archimedian Epoch of the Imbrian Period includes a series of events that follow a break in the depositional history after the Apeninian Epoch. Near Mare Imbrium, this break is easily recognized, but at the distance from the mare of the area mapped, a distinct break in the depositional sequence is difficult to recognize. The variation in crater density on the plains-forming units suggests that the units have been deposited over a long period of time and that at least the younger ones are Archimedian in age. The latter may, in fact, be contemporaneous with the Procellarum Group, whose material composes most of the maria.

A dome with a single crater on the summit occurs on the peninsula of terra south of the crater Sabine (in the area mapped as unit 1d). A narrow depression north of the summit pit is aligned with the pit and may continue onto the dome; however, the moire pattern of the photograph produced by electronic noise makes it difficult to trace the depression with certainty. Taken together, these features resemble a volcano with a summit crater localized on a small rift. The area around the dome is the smoothest part of the terra in the area studied, indicating that a blanket of volcanic material may be spread over about 100 km² of the surrounding rolling terrain. Both the photograph used for the base of the map and other Ranger VIII photographs that show the dome lack sufficient resolution to permit determination of the stratigraphic relation of the dome material to the adjacent mare material. The lack of superimposed craters suggests that the dome is young, but the area is too small for a valid crater count. Another possible volcanic feature in the map area is the crater on the west rim crest of Hypatia C, which seems to have a broader raised rim than most other craters, and in which is incised a narrow depression.

The deposits associated with several major craters in or close to the area—particularly Delambre, whose rim material lies in the southwestern corner of the map, and Sabine on the north edge—are tentatively assigned to the Archimedian Series. These craters have sharp rim crests, and the rim deposits have relatively few superimposed small craters. However, the secondary craters, which normally accompany young craters the size of Sabine, appear to be absent. This suggests that the outermost rim deposits of Sabine may be buried by the upper layers of Procellarum Group mare material. Delambre presents a similar problem. The lack of surrounding secondary craters, which should be abundantly represented on the older terrain surface, suggests that the secondaries may have been so modified as to be unrecognizable. It is possible, on the other hand, that craters such as Sabine and Delambre are basically different from large ray craters such as Theophilus and never had associated secondary craters large enough to be resolved in the Ranger photographs. If so, the normal criteria for recognizing the superposition of crater-rim deposits are not applicable.

The material at the surface of the maria is younger than any present in the widespread units of the terra, with the possible exception of unit Ip, as indicated by crater density and overlap relation at the margins of Mare Tranquilitatis. Correlation, on the basis of crater density, of the mare material in Mare Tranquilitatis with that of Oceanus Procellarum has led to the assignment of the mare material to the Procellarum Group. The Imbrian Period is defined as ending with the completion of deposition of the Procellarum Group.

Structures and deposits of Eratosthenian age. The most prominent structures superimposed on the mare material are the two Hypatia rilles, which appear to be complex graben. An instructive comparison may be made between these rilles and a graben east of Searles Lake, California (Fig. 32), which shows a similar, slightly en echelon pattern. According to C. I. Smith of the U. S. Geological Survey, who furnished the photograph, a fault crops out near the contact of the bedrock of the mountain front with the alluvium of the valley, and dips westward into the basement rocks beneath the alluvial valley fill. In the most recent movement on this fault, the upper plate
Fig. 32. Vertical aerial photograph of graben on E side of Searles Lake, San Bernardino County, California. (Small buildings near white dump W of graben give scale.)
slipped toward the valley, carrying the overlying alu-
vium with it. This resulted in tensional stresses in the
thin wedge of the alluvial deposits, which, in turn, led to
the collapse of the graben. In the case of the Hypatia
rilles, tensional stresses may have been caused by com-
paction of the mare material itself, rather than by tectonic
forces in the underlying material. Secondary craters of
Theophilus, a large crater of early Copernican age, appear
to be superimposed on the rilles. The rilles are therefore
probably of Eratosthenian age.

In addition to the rilles, a number of small craters with
relatively dark rim deposits are scattered over the surface
of Mare Tranquillitatis. These deposits are assigned to
the Eratosthenian System.

Craters and deposits of Copernican age. Several small
and large craters of Copernican age lie in or near the
map area, as well as some of the rays and secondaries
of the crater Theophilus, which is located over 300 km
to the southeast. Many of the smaller craters, with
elliptical outlines and sharp lips—particularly those in
the eastern part of the area—are probably Theophilus
secondaries. The higher areas just visible on the mare
in the eastern part of the photograph are rays of
Theophilus.

Erosion and mass wasting affect all exposed surfaces
on the Moon. The process primarily responsible for
these effects is probably micrometeorite bombardment,
which continually redistributes near-surface material.
On steeper slopes, gravity will cause a net downhill
migration of the bouldered material, which is aug-
mented by occasional landslides or rock falls on over-
steepened slopes. The high albedo of many steep slopes
suggests that fresh material has been exposed recently
or is continually being exposed. Such areas are mapped
as Copernican slope material. Older or gentler slopes are
darker, indicating that the material at the surface is
sufficiently stable to permit darkening, presumably by
solar irradiation.

c. Summary of Geologic History

The inferred geologic history may be summarized in
tabular form:

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imbrian Period</td>
<td>Deposition of the Fra Mauro Formation and secondary-impact craters of old surface by material ejected from the Mare Imbrium basin. Faulting of the Imbrian sculpture system.</td>
</tr>
<tr>
<td>Apeninnian Epoch</td>
<td>Intermittent volcanism on terra forming plains and dome units. Faulting and local subsidence along rejuvenated faults. Delambre, Sabine, Schmidt, and smaller craters formed. Filling of Tranquillitatis basin by Procellarum Group mare material (probably volcanic).</td>
</tr>
<tr>
<td>Eratosthenian Period</td>
<td>Small craters formed. Deformation of the mare material by faulting to form the Hypatia rilles and, probably by faulting or folding, to form the mare ridges.</td>
</tr>
<tr>
<td>Copernican Period</td>
<td>Hypatia E and smaller craters formed. Rays and secondary-impact craters formed by material ejected from crater Theophilus. Sliding on steep slopes, exposing fresh talus or slope material.</td>
</tr>
</tbody>
</table>

2. Intermediate-Scale Geologic Map of a Part of the Floor of Alphonsus, John F. McCauley

With the success of the Ranger VII, VIII, and IX
missions, it has become possible to carry out regional
geologic mapping at scales much larger than those used
in previous telescopic studies. By delineating the local
stratigraphic units revealed in the high-resolution Ranger
photographs, the new mapping can portray the detailed
physical history of the lunar surface more effectively.
The results of a preliminary study of the problems of
geologic mapping at the larger scales are presented in
this Section.

Inspection of the Ranger IX photographic sequence
revealed that A-camera photograph 66 and B-camera
photograph 74 provided contiguous coverage of approxi-
mately 640 km² of the northeastern part of Alphonsus
at nearly the same scale (Fig. 33). The area is
geologically complex and of a size appropriate for regional geologic mapping at a scale of approximately 1:1,000,000. As this scale is an order of magnitude larger than that used for telescopic geologic mapping, the increase in visible detail requires the definition of a variety of new stratigraphic and structural units.

The map prepared for this study shows the distribution of a complex stratigraphic sequence of crater materials and smoother basin-floor materials, all of which have contributed to the filling of the floor of Alphonsus. Nine geologic units, many of which are new subdivisions of units previously recognized in 1:1,000,000 mapping (Ref. 26), are described and classified according to relative age. The work is preliminary, however, and subject to considerable refinement, and the map is intended primarily to demonstrate the technique of geologic mapping at an intermediate scale. When quantitative topographic data have been derived by photogrammetric and photometric techniques, the geologic mapping can be carried out more rigorously. This type of geologic investigation will be applicable not only to other Ranger photographs but also to those acquired by unmanned and manned lunar orbiting spacecraft.

**a. Stratigraphy of the Floor of Alphonsus**

The part of the crater Alphonsus shown on the map exhibits a variety of crater materials, and relatively smooth and more widespread geologic units. Distinctions between the individual geologic units are made on the basis of morphology, slope angles as determined by shadows, surface texture, crater density and relative albedo. The age relations between the units are established by observed stratigraphic superposition, intersection of structures, and regional correlation. The total crater density on the floor of Alphonsus is higher than on the maria, and a greater variety of crater types can be recognized. A more complex geologic history can, therefore, be deciphered in Alphonsus than on the maria.

**Imbrian (?) System.** Crater-wall material along the walls of Alphonsus (Fw) is the oldest geologic unit in the map area (Fig. 34). This wall unit, which appears only along the extreme eastern edge of the map, has not been studied as closely as the floor units of Alphonsus, which are the major subject of this Section. The Alphonsus wall material is characterized primarily by moderate local relief and an albedo slightly higher than that of the brightest floor unit. It occurs on closely spaced large hills and terraces which form the walls of the main crater. Typical slopes of the hillsides range from about 5 to more than 10 deg. Numerous small craters appear on the crests of individual hills, but fewer are recognizable on the banks. The variety of crater types and the overall crater density on the Alphonsus wall material are less here than on the oldest of the floor units (Lcm in Fig. 34). The contact with the adjacent floor units is well defined locally by subtle linear depressions, which are too indistinct for accurate mapping at this scale. In other places, the contact is indefinite or gradational, suggesting that particular wall materials have moved downslope and buried the original contact between units. Instability of materials on the hillsides may account, in great part, for the lower observed crater density.

The Alphonsus wall material is considered the oldest geologic unit in the area because of its position in the crater wall and because it is overlapped at the edge of the crater floor by a series of smoother floor units which partially fill the original crater. The exposed wall material may consist either of a regional deposit derived from Mare Imbrium or of deformed and altered material derived entirely from the pre-Imbrian crater Alphonsus. It is tentatively assigned an Imbrian age, pending further detailed regional studies.

**Imbrian System.** Cratered floor material (Lcm) occurs along the western edge and in the central part of the map area. It is a regional unit which occurs widely over the floor of Alphonsus and is typified by a crater density significantly greater than that of the average mare (see Sections B1 and B3). A wide variety of types of small craters is present, the most common of which have subdued rims. Irregularly shaped depressions and circular indistinct craters abound. Because of its high crater density, this geologic unit has a rougher surface texture than the other floor units. It has an intermediate albedo which is approximately the same as that of the younger, superposed, smooth floor materials.

Within the map area, the cratered floor material is the oldest floor unit; it is overlapped by several other floor-filling units, and its surface is characterized by more numerous craters. A long history of bombardment by interplanetary and secondary objects is inferred from the numerous partially destroyed or subdued and indistinct craters present on its surface. The unit represents a blanket of material masking the original relief on the floor of Alphonsus. It may consist of regional material derived from Mare Imbrium, intercalated with ejecta from local impact events and with volcanic material that may have partially filled Alphonsus early in its history. The detailed lithology of this unit is likely to be variable.
PHOTOGRAPHIC BASE FROM
FA 601, F3 582; R IX

GEOLOGY BY JOHN F. McCALLEY

IP IMPACT POINT
LAT 12.9°S, LONG 2.4°W
EXPLANATION

Fig. 34. Preliminary geologic map of part of Alphonsus.
and its history complex. It is assigned an Imbrian age because of its basal position in relation to the other floor units and its high crater density, which is characteristic of Imbrian units.

**Materials of Imbrian or Eratosthenian age.** Crater-rim material of subdued form (Eicr) occurs next in the stratigraphic sequence. The outer boundaries of the rim units are difficult to estimate because of the lack of sharp topographic expression; in addition, the contacts may be obscured by a thin blanket of surficial material that is not shown on the map. The slopes on the inner walls of the craters are generally greater than 10 deg, but their average lower reflectance suggests that they are less steep than the slopes on the walls of younger craters. In some places, the craters in this class are aligned and appear to be structurally controlled (as in the northwest corner of the map area), although the majority seem to be randomly distributed over the cratered floor material (Icfm). The units may include primary- and secondary-impact craters and volcanic vents. The abundance of these craters on the Imbrian (?) cratered floor material and their scarcity on younger units suggest that they are Imbrian or Eratosthenian in age.

**Eratosthenian System.** Smooth floor material of intermediate albedo (Esfm) occurs in the central part of the map area. It is closely related spatially to a series of linear depressions, which it partially mantles; it is smoother than the cratered floor material and has a lower crater density. The smooth floor material appears to mask a rougher topography of underlying cratered floor material of Imbrian (?) age and is therefore believed to be superimposed on the older floor unit. On the basis of crater density, the smooth floor material is placed in the Eratosthenian System. The unit is inferred to be primarily of volcanic origin on the basis of its areal pattern and apparent relation to possible linear vents.

The eastern part of the map shows a smooth floor unit (Edfm) that is similar in texture to, but darker than, the smooth floor material just described and that is also characterized by a relatively lower crater density. This unit overlies the Imbrian (?) cratered floor material but within the map area, does not lie in contact with the brighter smooth floor material. The similarity in crater density suggests that the two units are of about the same age (Eratosthenian), with the darker material possibly being slightly younger. Because the dark floor unit is also spatially related to linear features, it is believed to be of volcanic origin.

**Materials of Eratosthenian or Copernican age.** Crater-rim deposits with exterior profiles that are convex upward (CEcvt/d) occur adjacent to or on the Eratosthenian smooth floor materials. Two mappable facies are distinguished on the basis of albedo, one characterized by intermediate and the other by low albedo (the dark halos of craters). No sharp break in slope is present near the lip of the associated craters, and the craters are clearly related to structural depressions that are partially filled by the rim deposits. Both the dark- and intermediate-albedo rim units have numbers of distinct, superimposed, small rimless craters. Although the latter are difficult to distinguish in form from other small craters, they have been classified as "satellitic" craters (sc). They may have been formed by the impact of large blocks of cohesive material ejected from the central vent. Craters having convex rim deposits are interpreted as vents surrounded by blankets of volcanic ash which have been superimposed on older flat-lying blankets composed of the same general volcanic material (Esfm, Edfm). Because they clearly overlap the Eratosthenian smooth floor materials, these units are assigned to the Eratosthenian or Copernican System.

Craters with rim deposits that are sharply concave upward near the crater lip (CEcfr) appear to be randomly but sparsely distributed over the entire floor of Alphonsus, and are superimposed on all the other units previously described. Some of the smaller craters of this class are surrounded by a bright rim deposit, or halo; other concave crater-rim materials show little or no difference in albedo from the surrounding geologic units. The two largest examples are in the northeastern and northwestern corners of the map area. The rim topography is smooth, and no satellite or secondary craters have been noted. These craters are interpreted as being of impact origin and, on the basis of morphology, albedo, and stratigraphic position, are assigned an age ranging from Eratosthenian to Copernican. The brightest deposits are believed to be the youngest.

Small, rimless depressions of funnel shape, generally less than 200 m in diameter, are common throughout the map area. The material within these depressions is labeled CEcf on the map (Fig. 34). In some cases, the interior walls of the funnels appear to be slightly convex upward; these are the so-called "dimple craters." They become increasingly more numerous with decreasing size. The structural fabric of the floor of Alphonsus controls their distribution (see Section 33). The funnel craters are present on all the recognizable stratigraphic units and, therefore, are among the youngest features observed.
in the area. They may result from the drainage of loosely compacted surficial material into subjacent fissures and cavities. If so, they might be termed "negative vents," in contrast to convex-rimmed craters that are formed by the surface deposition of material ejected from below.

**Copernican System.** Copernican slope material (Ces) has been mapped on the inner walls of all those craters having interior slopes that significantly exceed 10 deg, as determined by the presence of sharp umbral shadows within the crater. This unit is generally of high albedo, as determined under full-Moon conditions, and is inferred to consist of fragmental material in an unstable condition that intermittently moves downslope.

**b. Structural Features**

No detailed analysis of the structural features seen in the area will be presented here, since, in Section B3, Carr gives a structural analysis of the entire floor of Alphonsus at a variety of map scales. Descriptions of the structural features observed are given in the explanation of the map (Fig. 34). Worthy of special note are the indistinct craters, which are shallow, generally circular depressions having no recognizable rim deposits. These craters are particularly common on the cratered floor unit (lfm); they may be degraded older craters, or they may have been formed as the result of the gentle subsidence of surface materials.

**c. Geologic History**

From the preliminary geologic map of part of the floor of Alphonsus, it is possible to reconstruct the sequence of events that led to the present configuration of the crater floor. The original crater is pre-Imbrian, and its walls (Pcw) and floor may have been covered with material derived by ejection from the Mare Imbrium region (Fra Mauro Formation). Additional study is required to determine the nature of the wall material more precisely. Subsequently, the crater was partially filled by a sequence of younger deposits (1fm), which may be in part volcanic in origin and in part derived from local and distant meteorite-impact events. This material was thoroughly cratered during a substantial interval of time after its initial deposition, and faulting and volcanism occurred during and after the early episode of basin filling and cratering. A number of large and small vents formed along major fissures, and a smooth blanket of material (Esfm) was deposited locally on the crater floor. The blanket is thickest near the vents and fissures and thins to a feather edge at the contacts with the older cratered surface. Another blanket, composed of darker materials (Esfm), formed along the eastern wall of Alphonsus, possibly somewhat later in lunar history. During the entire interval of time from the original blanketing of the crater floor to the time of late volcanic activity along the eastern wall, faulting, subsidence, and drainage of material into subjacent cavities was occurring along with continued cratering by impact.

**3. Preliminary Geologic Map of a Small Area in Mare Tranquillitatis, N. W. Trask**

The data received from future unmanned lunar spacecraft, and eventually from manned spacecraft landings, will permit the construction of topographic and geologic maps of the Moon at scales comparable to those used in detailed geologic investigations of the Earth. As a first step in the development of the techniques for large-scale lunar geologic mapping, a preliminary geologic map has been prepared for the small area in Mare Tranquillitatis covered by the overlap of Ranger VIII A-camera photographs 55 and 59 (Fig. 35). The map (Fig. 36) was made in conjunction with the topographic map of the same area compiled by Moore and Lugg, described in Section C2.

As the present lunar geologic mapping program of the U. S. Geological Survey is being carried out at a scale of 1:1,000,000, most of the geologic units studied are necessarily of regional extent. The map shown here has a scale approximately 30 times larger and gives a more complete indication of the density of contacts and diversity of materials that will be encountered within small areas on the lunar surface. Lunar terrain of the type covered by the geologic map (a ray-free mare terrain) will probably be encountered in early manned exploration. The scale of approximately 1:27,400 in Fig. 36 is large enough to allow the plotting of geologic contacts and structures that would be encountered in short manned traverses. By comparison, systematic geologic mapping of the United States is currently proceeding at scales of 1:62,500 and 1:24,000. Additional, improved geologic and topographic maps of selected areas on the Moon, at approximately the same scale, will be needed to plan missions for maximum return of significant scientific information.

**a. Method of Geologic Mapping**

The geology shown in Fig. 36 was worked out by stereoscopic examination of Ranger VIII A-camera photo-
Fig. 35. Ranger VIII A-camera photograph 59, showing area of geologic map of Fig. 36.
Fig. 36. Preliminary geologic map of a small area in Mare Tranquillitatis. (Base map is topographic map prepared by photogrammetric methods from Ranger VIII A frames 58 and 59 by Moore and Lugin, Section C2.)
graphs 58 and 59 with a conventional stereoscope and the ER-55 plotter used for the topographic map. Study of the rectified model projected by the plotting device permitted a close-up stereoscopic view of the surface and added important details to the study. The projected model was particularly helpful in the delineation and study of crater rims.

At present, the discrimination of geologic units in the Ranger photographs depends on observation of the same physical characteristics used to distinguish map units on the small-scale geologic maps prepared from Earth-based photography and visual telescopic observation (Refs. 27 and 28). Albedo and topographic form are the principal characteristics of the lunar surface materials on which the discrimination of mappable units is based. In the case of the large-scale Ranger photographs, data on normal albedo are lacking at sufficient resolution for mapping. Relative albedo can be estimated from the Ranger photographs by using the topographic map of Moore and Lugm to distinguish the differences in brightness that are due solely to differences in slope. Three relative units of albedo—dark, medium, and bright—have been visually estimated for the photographs. A program of quantitative determination of albedo from the Ranger photographs is under development by the Geological Survey.

b. Stratigraphy

The geologic units on the mapped part of Mare Tranquilitatis consist of crater materials and the regional materials on which the craters have formed. The crater materials can be classified on the basis of crater morphology and the relative albedos of the crater rims. The wall materials show differing degrees of brightness but are steeper than the crater-rim materials, their albedo can only be estimated by means of detailed photometric investigation of the photographs. The general outline of the classification scheme adopted is shown in the explanation to the map of Fig. 36.

In addition to grouping similar materials and separating those that are different, the classification scheme used on the map provides the dimension of time by indicating the order in which the materials have formed. Where two types of material are in contact, the principles of superposition and intersection should indicate their relative age. Most of the materials have essentially the same albedo, however, so that the overlap relations between many of the units are not well defined. Overlap relations between some of the materials are indicated on the map by the termination of the older unit against the younger. In order to place all of the map units in a stratigraphic column, it is necessary to adopt a model of the structure of the mare at the map scale. The model used is essentially that of Shoemaker (Ref. 1, pp. 75–134), which postulates that most of the craters on the mare are due to impact, but also recognizes that some of the craters may be collapse features of infertal origin, as suggested by Kuiper (Ref. 1, pp. 9–73). At the scale of this model, the mare surface has been covered with craters several times over, so that the original surface material is no longer present. As successive cratering wears down crater rims and fills crater bottoms, the degree to which a crater is subdued is an index of its age. The model also suggests that the material beneath the surface of the mare has, on the average, a higher albedo than the material at the surface because of the effects of ultraviolet radiation and solar-proton bombardment. Thus, the brightness of the ejecta around an impact crater is also an index of age, with the brightest materials being the youngest. The geologic relations found in the map area are all consistent with the model as outlined above. Additional mapping at small scales should eventually produce a self-consistent geology that will indicate the most likely model of the lunar surface.

In the following paragraphs, the geologic units on the map (Fig. 36) are discussed in order of ascending stratigraphic sequence, referred to the standard systems of the lunar stratigraphic column as defined by Shoemaker and Hackman (Ref. 22), and Shoemaker (Ref. 29).

Imbrian System. The geologic unit occupying the relatively featureless parts of the area between the mapped crater materials is referred to as mare material. The whole series of Ranger photographs indicates, of course, that this material is not featureless but is covered by small craters with diameters down to 1 m. The small craters cannot be mapped at the scale of Fig. 36, however. In previous geologic reports, which were based on telescopic photography and observation (Refs. 22 and 29), the material of the mare itself, as contrasted with its surface layer, has been assigned to the Procellarum Group of the Imbrian system. The smoothness of this material when viewed telescopically and its occurrence in depressions have led to its interpretation as a series of volcanic materials (Ref. 29). The depth to unaltered volcanic material probably varies widely over the map area.

Eratosthenian System

Material of indistinct craters. Some of the most abundant materials in the quadrangle occur in and around
very gentle depressions which have low rims and gently sloping interior walls. The walls of the depressions cast no shadow on the floors. The raised rims are distinguishable on the stereo model of the EB-53 plotter, but the gentle slopes of the rims could not be shown on the topographic map, as their relief is less than the contour interval. The albedo of the materials of indistinct craters is the same as that of the intercrater material mapped as mare material.

Because of the high degree of modification and the low albedo of their materials, the indistinct craters have been assigned to the Eratosthenian System. This system includes those materials formed after the maria but before the rayed craters (Ref. 22). The indistinct craters are interpreted as worn-down impact and volcanic craters. The original form of any given crater cannot be determined.

Chain-craterr material. The material occupying rows of craters having similar morphology is mapped as chain-craterr material. All gradations may be found between chains of craters with well-defined, raised rims and lines of very shallow, irregular, rimless depressions that are mapped as lineaments. Most of the chain craters are aligned parallel to a system of lineaments occurring in the same area.

All of the chain-craterr material has been placed in the Eratosthenian System because of the subdued nature of most of the crater rims and the fact that many of the chains are overlapped by materials that are also assigned to the Eratosthenian System, although a few may be younger. The strict parallelism of many of the chains with the regional system of lineaments leaves little doubt that they are of internal origin. The raised rims are probably caused by the venting of ejected material around the margins of the craters.

Dark-craterr materials. Materials of craters which have rims with the same albedo as the mare material and walls sufficiently steep to cast shadows are common in the map area and are shown as dark-craterr materials. Most of the dark craters have subdued rims, but three of them have relatively sharp rims. One of the latter is the large crater that dominates the western side of the map area. Its outer rim is markedly concave upward and contains distinct radial ridges that resemble in pattern the radial ridges in the rim deposits of small experimental impact and explosion craters (Figs. 13 and 15). The topographic map shows that the rim of this crater is higher on the east side than it is on the north and south. Unfortunately, the west rim is not covered by the stereo model, but in the photographs it appears to be lower than the rim on the east side.

The dark-craterr materials are placed in the Eratosthenian System because of their low albedo and the fact that they are overlapped in places by brighter materials of younger age. The subdued dark craters are taken to be modified sharp craters, but their original form cannot now be determined. The large crater with a sharp rim in the western half of the area may be post-Eratosthenian in age. The asymmetry of its rim may indicate that it is a secondary-impact feature (Ref. 30).

Materials of Eratosthenian or Copernican age

Material of rimless pits and cratered cones. Rimless pits are circular depressions with steep walls and bowl-shaped floors; cratered cones are low, nearly conical mounds with summit craters. Both types of features are rare. Their albedo is the same as that of the mare material and the dark-craterr materials.

These pits and cones are relatively sharp features, whose age is uncertain and whose original form and albedo are not known. Both features are unlike any known impact structures. The rimless pits apparently were formed by the drainage of material through a vent, while the cratered cones look like small terrestrial volcanoes with summit calderas.

Intermediate-craterr materials. Craters with rims exhibiting an albedo intermediate between the albedo of the dark-rimmed craters and that of the bright-rimmed craters are moderately abundant. All the examples of such craters are small. They have rims that appear to be sharp and concave upward, with the exception of one crater in the northeast corner of the map, which has a moderately subdued rim. The materials of medium albedo extend beyond the areas occupied by the topographically raised rims and have a somewhat irregular outline.

Copernican System. Craters with bright rims are scattered over the map area, but are slightly less abundant than craters with rims of intermediate albedo. They are similar in all respects to the latter, except that none of the bright-rimmed craters have subdued relief. The materials of high albedo extend well beyond the observable raised rims and overlap the materials of some of the darker craters in places.
Both the overlap relations and the brightness of the crater rims indicate that the materials of the bright-rimmed craters are the youngest in the map area. They are accordingly assigned to the Copernican System. They are probably of impact origin.

Materials of craters with rims of medium and high albedo overlap darker materials at several places in the map area, indicating that the lighter materials are younger. This relation is consistent in all the Ranger VIII photographs. No examples of darker material overlapping brighter have been noted. There is also no evidence in any of the Ranger photographs that the bright-rimmed craters have been modified by the formation of later, relatively young collapse craters; most of the indistinct craters and subdued craters are probably old, eroded features. The young, bright craters have sharp rims and exterior profiles that are concave upward. The stratigraphic succession in the map area indicates that lunar-surface materials darken with time and that a concurrent process of erosion wears down sharp features such as crater rims.

c. Structure

Mare ridges and scarps. A few low ridges and broad, rounded scarps, mostly with a north-south orientation, are present in the map area. This orientation coincides with the dominant trend of more prominent nearby ridges and scarps on Mare Tranquillitatis. Relief of the prominent north-south scarp in the northwestern quarter of the area is shown on the topographic map. The gentle ridges have much less relief and are not revealed by the map. Their age cannot be determined by mapping in this one small area.

Lineaments. The remarkably widespread system of lineaments on the lunar surface is well represented in the map area, with the greatest concentration appearing in the southern half. The lineaments are subdued scarps, very shallow linear depressions, and lines of shallow linear depressions. The straight sides of some crater walls lie along lineaments or their extensions. An azimuth-frequency plot (Fig. 37) of the lineaments shown on the map reveals a marked preferential alignment in the northwest-southeast and northeast-southwest directions. As the stereo model on which the surface trends of the lineaments were measured is rectified, the azimuths are believed to be accurate to 1 deg.

The regularity of the lineaments indicates that they are of internal origin (Ref. 29) and are probably the reflection of a system of fractures or joints in the lunar subsurface. It is worth noting that, on the Earth, fractures can propagate upward to the surface from bedrock through essentially unconsolidated material. In western Canada, lineaments are present in nearly unconsolidated glacial deposits ranging from a few feet to several hundred feet above bedrock (Ref. 31), and their orientations are generally similar to those of the fractures and joints in the nearby exposed bedrock. The presence of closely spaced lineaments on the lunar surface thus does not rule out the possibility that the lunar surface material is only weakly consolidated.

Irregular depressions. Very gentle, rimless depressions with irregular outlines have been mapped as irregular depressions. They are shown by a structural symbol and most likely were formed by collapse of the surface materials.

E. Utilization of High-Resolution Photographs in Manned Lunar Geologic Investigations

Harrison H. Schmitt

The primary goals of geologic investigation of the lunar surface are to determine the stratigraphy and structure of the outermost parts of the Moon and, from these data, decipher the Moon's history. The ultimate purpose of such an investigation is to make an interpretive comparison of the Moon with the Earth and, eventually, with the other terrestrial planets. Both unmanned and manned exploration will be required to achieve these geologic goals. Man's active role on the lunar surface will be to obtain the observations, the samples, and the measurements of physical properties that cannot be obtained by remote sensing from the Earth or from space near the Moon. On the other hand, the geologic and engineering data that can be obtained from photographs similar to those taken during the flights of Rangers VIII
and IX will form the basis of plans for future manned exploration. The following discussion illustrates how the geology of areas portrayed by the Ranger photographs (or by similar photographs to be acquired from lunar orbit) can be of importance to the planning of geologic field work in early manned missions and indicates the nature of some of the scientific data that can be expected to accrue from geologic studies carried out on the lunar surface.

1. Geology of Mare Tranquillitatis as Shown in the High-Resolution Ranger VIII Photographs

The last few Ranger VIII frames confirmed that many small features on Mare Tranquillitatis are similar to those photographed on Mare Cognitum by Ranger VII. Features associated with ray material predominate in the largest-scale photographs of Mare Cognitum. Similar features are present locally on Mare Tranquillitatis; however, some of the features shown in Ranger VIII photographs, such as B-camera frame 90 (Fig. 38), may be more characteristic of mare material itself and may have been formed by processes connected with the deposition of the mare material or by tectonic processes that are currently active within the mare.

The resolution of the last Ranger VIII frames is sufficient to permit a preliminary morphological classification of mare craters and depressions and a determination of the stratigraphic relationships of materials associated with these craters. Figure 39 is a geologic map of materials present in the area covered by B-camera frame 90. Some additional data from the last A- and P-camera frames were used in the compilation of this map. The stratigraphic relations and possible origins of the features shown are discussed below; they will be used later to illustrate the planning of a manned geologic investigation of the area.

a. Stratigraphy

The many craters observed on the last frames of Ranger VIII can be assigned to six morphological categories: (1) sharp-rimmed craters, (2) convex-rim craters, (3) funnel craters, (4) dimple craters, (5) low-rim craters, and (6) indefinite-rim craters. The materials associated with these craters. Figure 39 is a geologic map of material of crater with which they occur. The smooth-appearing material between recognizable craters has been mapped as mare surface material; it undoubtedly contains many unresolved small craters. Although the relative ages of many of the crater materials are indicated by their overlap relations their place in the standard lunar time scale of Shoemaker and Hackman (Ref. 22) is uncertain. Craters with bright rim material are assumed to have formed during the Copernican Period. The mare material is classed as Imbrian; it is probably covered by a thin layer of surficial debris of younger age. The large, indefinite-rim craters are classed as Imbrian or Eratosthenian. All other materials are given an indeterminate Copernican or Eratosthenian age.

Imbrian System. The mare surface material is assigned to the Imbrian System. Any surficial deposits of impact-shattered debris that may be present are probably mostly derived from local lava flows or ash deposits of the Procellarum Group.

Materials of Imbrian or Eratosthenian age. Materials on the rims and walls of poorly defined craters and depressions in the mare material are mapped as indefinite-rim crater materials. The crater rims are gently convex upward but are very low. The walls have very low slopes. The shape and general alignment of the craters suggest that they may be degraded composite secondary craters (Ref. 1, p. 81). On the other hand, they may be structurally controlled subsidence features of the mare, as subsidence features with similar shapes are present on the surfaces of both lava flows and mire ardente deposits on Earth. A strong northwest alignment of the large indefinite-rim craters is parallel with the alignment of rows of small depressions and lineaments in the southeast part of the map area; the craters and lineaments may be related. The origin of the indefinite-rim crater materials is uncertain, and they cannot be assigned an age more definite than the general one of Imbrian or Eratosthenian.

Materials of Eratosthenian or Copernican age

Materials of low-rim craters. Two craters in the map area are circular in outline, with well defined but very low rims (one is the large, nearly flat-floored crater appearing in the southeast corner of the map). The material of these craters is mapped as low-rim crater material. The slopes of the outer rims are all less than 5 deg; the steepest slopes on the walls are approximately 15 deg. Blocky crater-wall material in the large, low-rim crater appears to consist partly of relatively coherent, possibly solid blocks imbedded in the wall. These blocks may be fragments of the crater wall broken off by impact or fragments of an impacting body that have come to rest on the wall. From its subdued form, however, the crater appears to be of such an age that original irregularities of this type would have been worn down by
Fig. 38. Ranger VIII B-camera photograph 90, showing representative potential landing area in Mare Tranquillitatis.
Fig. 39. Geologic map of area shown in Ranger VIII B-camera photograph 90, illustrating...
meteorite and secondary-particle bombardment. It therefore seems more likely that the blocks are the partially exposed fragments of a coarse, allogenic breccia in the crater-wall material. The exposure was probably caused by the slumping of material down the crater wall, which, in turn, could have been initiated by low-intensity seismic activity or by nearby impact. Crater-bench material in the low-rim craters may also have been formed by the downslope movements of weakly coherent wall material.

Materials of concave-rim craters. Materials of craters with low, poorly defined rims that are convex upward are classed as concave-rim crater materials. These craters, whose walls are as steep as 15 deg, are probably eroded or degraded forms of sharp-rim, funnel, and dimple craters. There is a continuous gradation in characteristics between the convex-rim and the small indefinite-rim craters; materials of the former, however, stratigraphically overlap and are younger than many of the larger indefinite-rim craters.

Funnel-crater material. The funnel craters in the map area are rimless, steep-walled, funnel-shaped depressions; the slopes of the walls are nearly uniform from the crater lips to the bottoms of the craters. Slopes of the crater-wall material are greater than 15 deg. The shape of the funnel craters and their local association with a shallow linear depression suggest an origin either by upward discharge or by downward drainage of weakly coherent fragmental material through fissures in the mare material.

Dimple-crater material. The dimple craters have walls that are convex upward and come nearly to a point at depth. They resemble the funnel craters and may have been formed by drainage through narrow orifices. Both funnel and dimple craters probably developed by the drainage of finely divided solids rather than fluids, as they are younger than the large, low-rim crater in the southeast corner of the map area, which was probably formed by impact into solid mare material. It is also possible that the dimple craters were formed from sharp-rim craters by mass movement on the crater walls.

Linear-depression material. This material is confined to the narrow, roughly linear depression in the large, low-rim crater in the southeast part of the map area. Several funnel craters appear to be related to this depression, and both the depression and the craters may have developed by subsidence along a fissure (although there is a possibility that they are small eruptive features related to outgassing of the cooling mare at depth). Inasmuch as the linear depression post-dates the large crater, it is probably not directly related in origin to the emplacement of the mare material.

Bright crater-wall material. The many small craters in the area have been mapped as (1) bright-walled craters or (2) craters too small to be classified. (The latter are shown by a structural symbol.) The bright-walled craters have maximum diameters near the lower limit of size at which the shapes of the craters can be defined; were they larger, they could probably be placed in one of the other morphological groups. Although the sunlit walls of the craters are bright, it is not known to what extent this brightness is due to their relatively steep inclination toward the Sun. The circular shape and steep walls of these craters suggest that they are small impact craters.

Materials of sharp-rim craters. A variety of materials associated with well defined, generally circular craters are mapped as sharp-rim crater materials. The outer rims of these craters are concave outward, and the rim crests are cusp-shaped. The inner walls are concave upward, with slopes greater than 15 deg near the rim crests. Some of the craters have well defined floors. A lobe of hummocky material appearing on the floor of one sharp-rim crater has probably been derived from the crater wall by slumping. Most of these craters have rim materials of the same albedo as the surrounding mare surface material, and most are probably primary- or secondary-impact craters.

Copernican System. Sharp-rim craters of the Copernican System are identical to those assigned to a Copernican or Eratosthenian age, except that the crater-rim materials in the former are markedly brighter than the surrounding mare surface material.

b. Structure

Two types of structural features are recognizable in the map area: (1) a general, northwest-trending alignment of indefinite-rim craters and depressions and (2) lineaments in and on the rim of the large, low-rim crater in the southeast corner of the area. The latter are rows of very gentle, irregular linear depressions approximately 10 m wide. Both northwest-trending and northeast-trending sets of lineaments are present. Where the two sets intersect, the so-called "tree-bark" structure, or patterned ground, is produced. Irregularities in the trends of the lineaments suggest that the lineaments may be more closely related to the internal structure of the crater materials on which they occur than to regional structures within the mare. The mapping of larger areas
by means of orbital photographs should give a clearer picture of the regional relations of lineaments and patterned ground.

2. Early Apollo Explorations

Ranger VIII photograph B90 (Fig. 38) illustrates a part of Mare Tranquillitatis that is of a size accessible on foot from a landed Apollo Lunar Excursion Module or from any other stationary vehicle on the lunar surface. The geologic features and units in Fig. 39 are probably typical of this and other mare surfaces.

Early manned exploration of an area such as that shown in Fig. 39 will have as its major scientific goals: (1) the representative sampling of materials of the local geologic units on the mare surface and of exotic rock fragments, (2) the investigation of the physical properties and composition of the various surface units, (3) the sampling of materials derived from depth in the mare, (4) the investigation, sampling, and photography of details of the fine structure not identifiable from pre-mission photographs, and (5) the identification and measurement of subsurface structure.

The fundamental constraints on achieving the above goals during Apollo exploration are: (1) the limited number of man-hours available for scientific tasks, (2) the limited mobility of a man in a spacesuit, (3) the restricted weight and characteristics of scientific gear that can be transported to the Moon and during a traverse, and (4) the weight of samples that can be returned to Earth. Assumptions concerning these constraints that may be made for the purpose of planning the scientific phases of the missions are given below. Some of these assumptions are optimistic; they are based, however, on what the writer feels is a reasonable extrapolation from the current status of the development of Apollo systems.

a. Exploration Time and Astronaut Mobility

Current estimates of the time available for surface activities during early Apollo landings average about 15 man-hours divided among three excursions of no more than 3-hr duration each. These figures are largely a function of the capacities of the Lunar Excursion Module and astronaut life-support systems. Such a division of time could include one extravehicular excursion by one man and two excursions by two men working together.

The mobility of the astronaut outside the spacecraft will be governed by the mechanical properties of the surface, the characteristics of the spacesuit and the life-support system, and the nature of the scientific gear that must be transported. Although the distances that an astronaut can traverse under various conditions have not been determined with any degree of certainty, some estimates can be made. Allowing 0.5 hr for egress, equipment checkout, and ingress, the maximum useful time for surface exploration during an excursion would be about 2.5 hr. Tests conducted by the Manned Spacecraft Center of the National Aeronautics and Space Administration and by the U. S. Geological Survey suggest that average geologic traverse speeds (including time for descriptive and other activities) over rolling, loosely aggregated terrain may be approximately 10 m/min. Thus, maximum traverse lengths on the order of 1500 m can probably be anticipated during any given excursion, provided that sampling, photographic, and descriptive operations can be carried out efficiently.

b. Scientific Exploration Equipment

The following equipment can probably be available for early Apollo surface exploration:

1. Television camera
   (a) Hand-held
   (b) Confined to use within 30 m of the Lunar Excursion Module by the camera cable
   (c) 0.625 frame/sec, 1280 lines/frame
   (d) Recording orientation system

2. Exploration staff
   (a) Surveying, stereometric, spectrophotometric, and photometric film camera
   (b) Orientation system for recording camera orientation and the geometry of structural features
   (c) Detachable scraper-pick-hammer combination
   (d) Gamma-ray flux meter (visual readout)
   (e) Penetrometer (visual readout)
   (f) Stadia markings

3. Instrument and sample carrier
   (a) Rack for field-sample containers
   (b) Rack for special-purpose-sample containers
   (c) Scoop-pick-hammer combination
   (d) Sample orientation device
   (e) Small, single-lens camera
   (f) Holder for television camera
   (g) Holder for photogeologic map, photograph, and traverse plan

4. Active seismic gear

5. Emplaced scientific station instruments
c. A Representative Scientific Mission Profile

The local geology, such as that shown in Fig. 39, is of prime importance to the detailed planning of a nominal scientific mission in the area to be explored. The observed distribution of craters, depressions, positive-relief features, and geologic units—together with previous inferences on the origin of the lunar features, based on terrestrial field and laboratory research—should govern the selection of geologic and geophysical traverse locations. However, traverse plans based on geologic analysis of photographs and other data acquired before the mission should not be so restrictive that they prevent the examination of the unexpected.

Figure 39 illustrates representative traverses that permit the systematic sampling, photography, and description of each major type of geologic unit or feature present within walking distance of an arbitrarily chosen landing point. In addition, it is expected that on each traverse, samples can be obtained of material derived from impact events in rocks far removed from the landing site. An analysis of the geology suggests several areas of interest for subsurface exploration by seismic-refraction methods to determine the thickness of surficial fragmental debris on the relatively level parts of the mare and across the shallow mare depressions. Seismic data could also be obtained on the thickness of crater-rim materials, such as the unit around the large southeast crater. The traverses shown are intended to illustrate how efficient exploration of a previously unknown area can be planned on the basis of a geologic map. A similar use of photographic data is made in terrestrial geologic field work. Deviations from the planned traverse are expected to occur where important new features are observed below the identifying resolution of the available photographic base.

First excursion. The first excursion (not shown in Fig. 39) of the hypothetical mission on Mare Tranquillitatis is planned for one man and is confined to an area within approximately 100 m of the Lunar Excursion Module. The principal geologic target for this excursion is a part of the mare surface that is relatively free of resolved craters. A detailed television and sampling survey of the landing site is to be carried out first, using the television camera mounted on the instrument and sample carrier. The television survey is directed toward obtaining photometric and photogrammetric data on the materials and features of the landing site in the immediate vicinity of the Lunar Excursion Module. The overall survey should provide data on the nature of any crater formed by the rocket effluent during landing of the Module, samples taken from the bottom of this crater and progressing outward to the undisturbed material, and samples of apparently exotic materials in the vicinity of the Module. Large samples that are required for special purposes and can be found near the landing site should be obtained during the first excursion. Such samples might include material newly exposed by the rocket effluent; specially preserved samples of the mare surface, to be used for textural studies; and specimens for biological tests.

An active seismic experiment could be carried out during the first excursion to determine the mare subsurface structure and the properties of rocks found in the relatively uncratered part of the surface. Also of particular interest would be a seismic-refraction profile across the indefinite depression to the northeast of the landing site (Fig. 39), in order to determine whether depressions of this class are original shallow features of the mare or filled-in craters.

The emplaced scientific station should be set up during the first excursion on favorable ground near the Lunar Excursion Module, but at sufficient distance to be undisturbed by the later ascent of the upper stage.

Second excursion. In the second excursion (long-dashed traverse in Fig. 39), features to the south-southeast of the landing site will be sampled and examined. This is planned as a two-man excursion, with one astronaut performing most of the descriptive and photographic operations that utilize the exploration staff; using the instrument and sample carrier, the other astronaut will concentrate on the systematic sampling of materials described and photographed by the first astronaut.

The geologic targets for the second excursion include an average-size indefinite crater; the rim and wall materials of the large, low-rim crater southeast of the landing site; a large dimple crater and the bench units within it; a small, bright-walled crater; and the lineaments and patterned ground on the rim of the large, low-rim crater.

Verbal descriptions of the features and materials along the traverse should record data that will not be provided by the returned photographs and samples and, especially, relate the photographs and samples taken to the observed fine structure of the mare. Among other information that will probably not be recoverable entirely from the photographs or returned samples will be the stratigraphic relations of geologic units, such as the mare-surface material and various crater-rim materials. Descriptions of
variations with depth and the interrelations of the lunar surface materials exposed in the walls of small, sharp-rim craters will be important for an understanding of the radiation and micrometeoroid impact history of the mare surface. Observations of the presence or absence of patterned ground, small craters, and bright or dark streaks on crater walls will provide information on the effectiveness of the processes of mass wasting on the lunar surface and, in turn, may offer clues to lunar seismic activity. Careful observation and description will probably be required to decipher the nature and origin of the blocky crater-wall material in the large southeast crater.

Stereometric, photometric, and spectrophotometric photographs taken along the traverse should emphasize the near field, here defined as the range from about 10 cm to a distance equal to the identifying resolution of pre-mission photographs. In the early Apollo missions, the near field will probably extend to about 5 m.

Sufficient near-field photographs should be taken to permit quantitative characterization of the geologic units shown in Fig. 39 and the subunits within them, with respect to their textures and photometric and spectrophotometric properties. This will make possible post-mission correlation and interpretation of units and subunits which will augment the visual interpretations made during the traverse. The stereo photographs will play a major role in documenting the crater-wall and rim textures and will provide data on the crater-wall slopes and the size-frequency distribution of craters less than 5 m in diameter. Photographs taken at various phase angles will help to determine the photometric functions for surfaces such as the wall of the large southeast crater. Also, the long focal-length lens of the camera may be used to obtain high-resolution photographs which will provide information on features not actually reached on the traverse, such as the linear depression and associated funnel craters crossing the wall of the large southeast crater.

Other instruments on the exploration staff will provide supplementary information on the structure and physical properties of the geologic units. The staff orientation system gives the data necessary for the photogrammetric and photometric control of the film-camera photographs; with this control, quantitative information may be obtained on structural features such as layers and fractures exposed in crater walls. Systematic penetrability measurements on the various units may yield data that will assist in determining the relative age or stratigraphic sequence of these units, as the processes of micro-

meteoroid bombardment and solar radiation probably affect the cohesiveness and bearing strength of exposed materials and the thickness of finely pulverized material probably increases with time. Penetrability measurements also provide engineering data of importance to post-Apollo vehicular traverses. Determination of the flux of gamma rays from various units may help to distinguish relative differences in chemical composition as a guide to the delineation and sampling of subtle geologic units. The detection of exotic fragments of unusual composition may be facilitated by use of the gamma-ray flux meter, especially if finely pulverized material coats most of the surface.

The traverse sampling activities, for the most part, should be designed to provide as varied and complete a collection of representative, exotic, and textural samples as can be obtained along the traverse. General grab sampling, coupled with data on the spatial relations of the samples, should provide a representative suite of materials from the geologic units encountered. Most of the exotic samples collected will probably have been derived from areas far removed from the landing site by ejection from impact craters elsewhere on the Moon, and will provide preliminary data on the nature of lunar materials other than those of the mare.

Samples of the rim material around the large southeast crater may provide a profile of mare material to a depth approximately equal to the crater depth. Samples from the blocky crater-wall material may yield relatively fresh, coherent pieces of mare material. The blocky crater-wall material may also be partially mantled with material related to the linear depression and funnel craters farther down in the main crater.

The sampling of profiles in the surface fragmental layer, exposed either in the walls of the sharp-rim craters or by digging, will be of major importance in determining the radiation, micrometeoroid impact, and, possibly, the volcanic history of the mare. Ideally, each recognizable geologic unit should be sampled, so that the effects of events that have taken place over as broad a span of lunar history as possible can be studied.

The locations of data and sample points and of photographic stations along the traverse are obtained by photographing the unit coordinate system defined by the Lunar Excursion Module, using the long focal-length lens of the film camera. Each survey photograph should also be accompanied by a stereo photograph of the near field,
for continual expansion of the photogrammetric coverage of the area. A similar procedure can be followed for locating necessary data and sample points out of view of the Lunar Excursion Module by utilizing the single-lens film camera to photograph the exploration staff from a known point, or the staff film camera to photograph the instrument and sample carrier situated at some known point.

Third excursion. The third excursion (short-dashed traverse in Fig. 39) will be operationally similar to the second, except that a final seismic profile is shot across one of the large indefinite craters southwest of the landing point. Such a profile would yield comparative data for further evaluation of the origin(s) of this type of depression.

The geologic targets for this excursion include a string of very small craters, a convex-rim crater, two large indefinite craters, and the rim materials and surface features of relatively dark and bright sharp-rimmed craters.

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