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Lunar Orbiter Photographs: Some Fundamental Observations

Preliminary study reveals details of craters, crater distributions, and the major types of terrain.

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Lunar Orbiters I, II, and III have photographed over 600,000 square kilometers (8 percent) of the earth-side hemisphere of the moon. Most of the photographs are vertical and cover portions of the front side of the lunar disk. Each vertical moderate-resolution frame of the front side covers approximately 1000 square kilometers and has an identification resolution of 10 to 20 meters. Each vertical high-resolution (telephoto) frame of the front side covers approximately 55 square kilometers and has an identification resolution of 2 to 3 meters. Preliminary evaluation of the more than 1000 photographs taken by the first three Lunar Orbiters revealed many topographic features in remarkable detail; the amount of new information about the lunar surface conveyed by these photographs is truly staggering. Some of the most significant recurring features are described here.

The moon's surface is covered with craters of every size. If one mentally removes the craters from the topography, there remain three broad categories of terrain: (i) level, (ii) gently rolling, with slopes less than 10 degrees, and (iii) rough, with slopes greater than 10 degrees. Because the objective of Lunar Orbiters I, II, and III was to find relatively smooth landing spots for Apollo astronauts, the photographs they returned were mostly of level areas, but there were also many of gently rolling and rough terrain. Most of the level terrain is in the dark plains of the lunar maria; most of the gently rolling and rough terrain and many level areas are in the relatively bright lunar terrae in a very complex arrangement of mountain ranges and intervening basins.

In this article we first discuss the typical lunar scenes shown on high-resolution photographs of the three types of terrain. We then describe a class of craters designated "fresh," which are clearly shown in some detail on the high-resolution photographs, and which we feel are of considerable significance. We cite evidence to show that fresh craters are gradually destroyed and darkened with time. We conclude with a brief discussion of the moderate-resolution photographs, which show a much more varied scene than the high-resolution frames do.

Level and Gently Rolling Terrain

High-resolution photographs of level and gently rolling terrain show, without exception, that the lunar surface is dotted with a great many small, perfectly circular craters ranging in diameter from 50 meters down to the limit of resolution. Most of these small craters are cup-shaped, with distinct rims, but there are also many with very shallow interiors and indistinct rims (Fig. 1) and a few that are only shallow, rimless depressions. By and large, the small circular craters appear topographically sharper than craters more than 50 meters in diameter. Preliminary photogrammetric measurement of 400 craters appearing on Lunar Orbiter I photographs of the Surveyor I landing area shows that approximately 13 percent of the craters with diameters of less than 50 meters have maximum slopes in excess of 20 degrees.

The small circular craters are present on all level and gently rolling lunar surfaces examined so far—on maria and terrae, and on rayed and unrayed areas. In many high-resolution photographs they seem to be randomly distributed, but when one examines the entire suite of photographs it is clear that there are some elements of nonrandomness in the distribution. On some photographs there is an obvious clustering of as many as 50 of the small craters (Fig. 2); also, the measured frequency of craters per unit area differs widely from one broad area sampled by Lunar Orbiter to another. The areal density of craters with diameters between 10 and 20 meters generally ranges from 200 to 500 per square kilometer but is locally as low as 100 and as high as 700. However, many samples of the crater population in relatively small areas (1 square kilometer) yield a random distribution at a 5-percent confidence level when subjected to standard chi-square tests. A random distribution of the small craters suggests that they are mainly primary impact craters formed by the impact of objects from space. The elements of nonrandomness in the population indicate that craters of some other origin are also present. These may be secondary impact craters, which are formed by the impact of fragments ejected from primary craters of either impact or volcanic origin, or they may be

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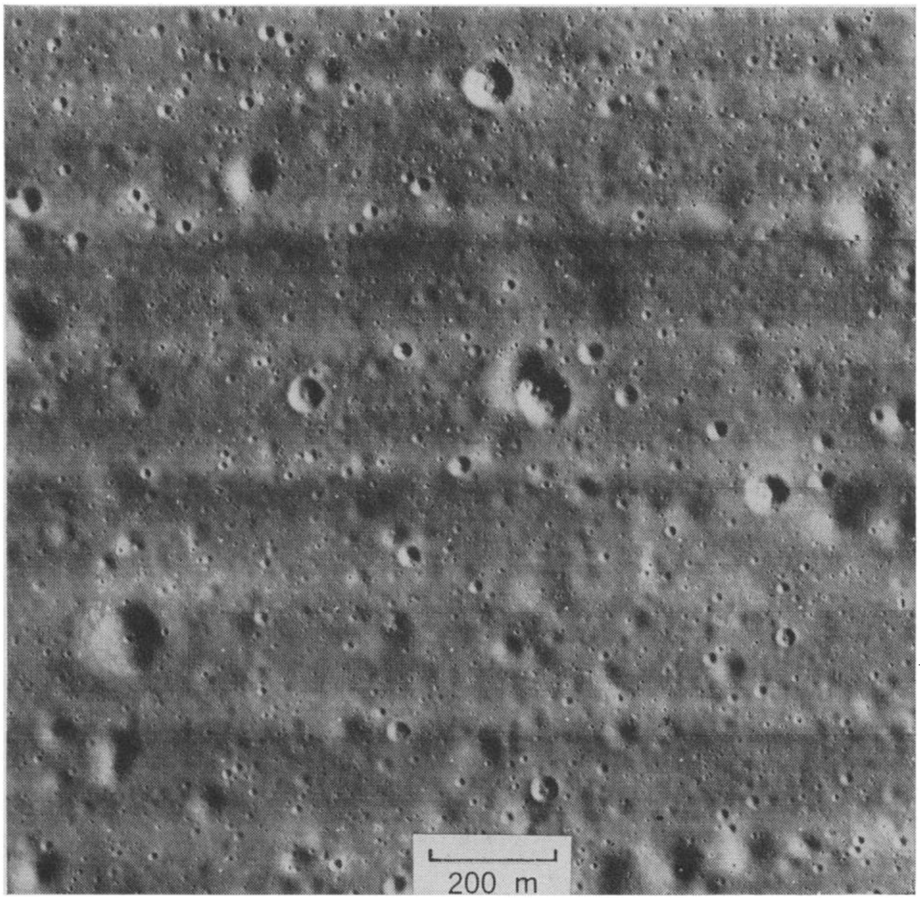


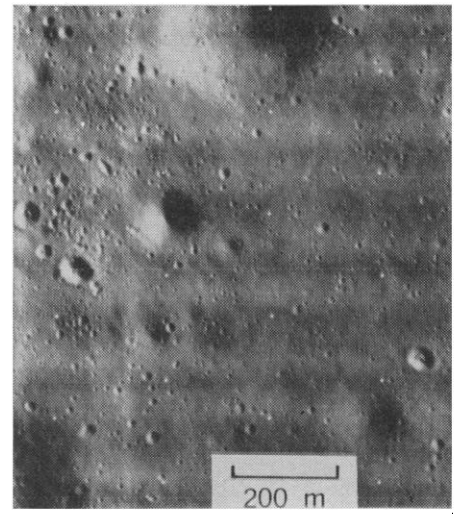


Fig. 1 (left). Scene typical of high-resolution photographs of level or gently rolling terrain. This is an area near the Surveyor III landing point, approximately 23°W, 3°S. North is at top in all photographs.

Fig. 2 (above). Cluster of small circular-to-slightly-elongate, relatively sharp craters 50 meters in diameter and smaller. Approximately 35°E, 3°N.

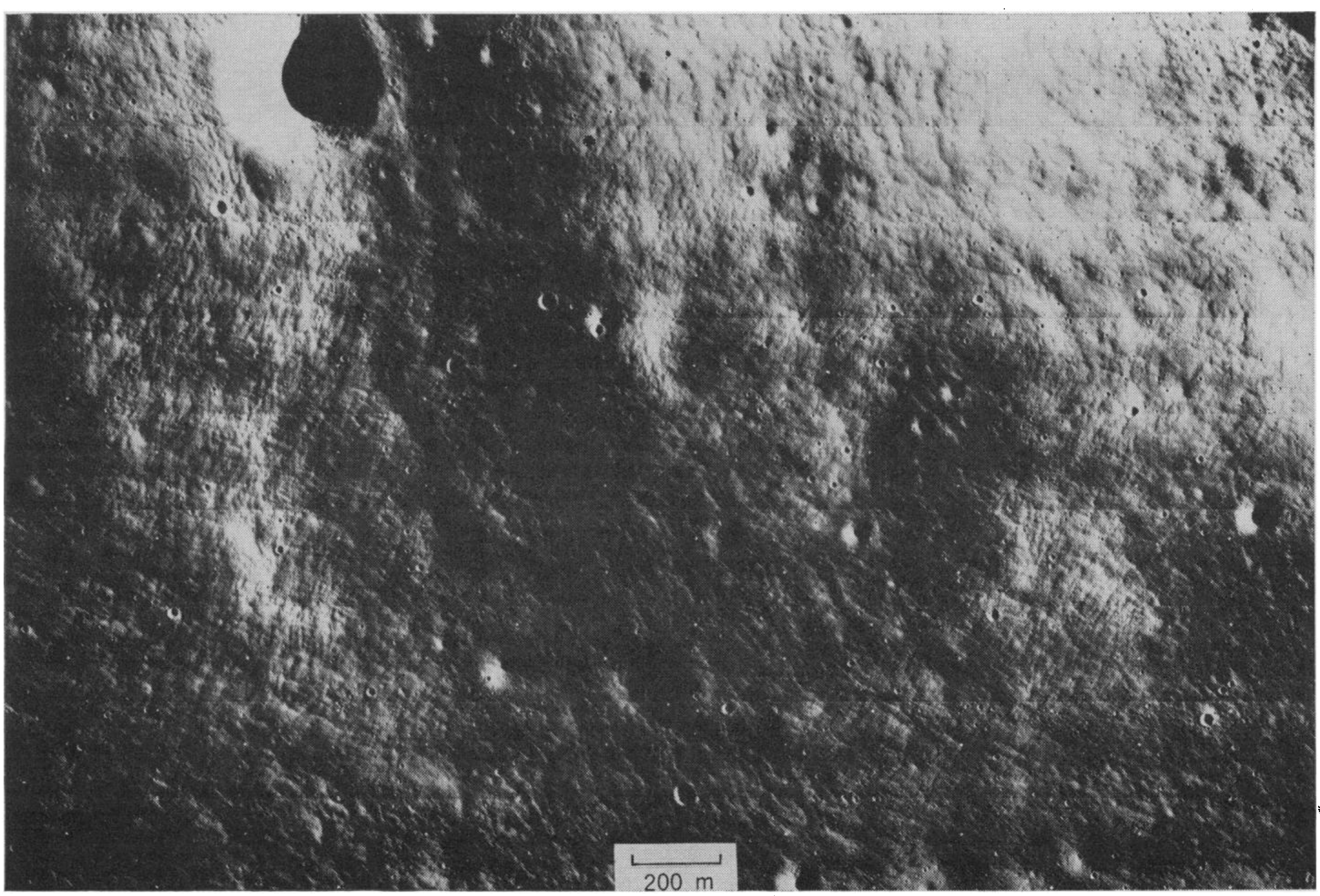


Fig. 3. Scene typical of high-resolution photographs of rough terrain. The slopes are covered with closely spaced troughs and ridges; sharp craters are present but shallow craters are sparse. Approximately 6.5°E, 4°N.

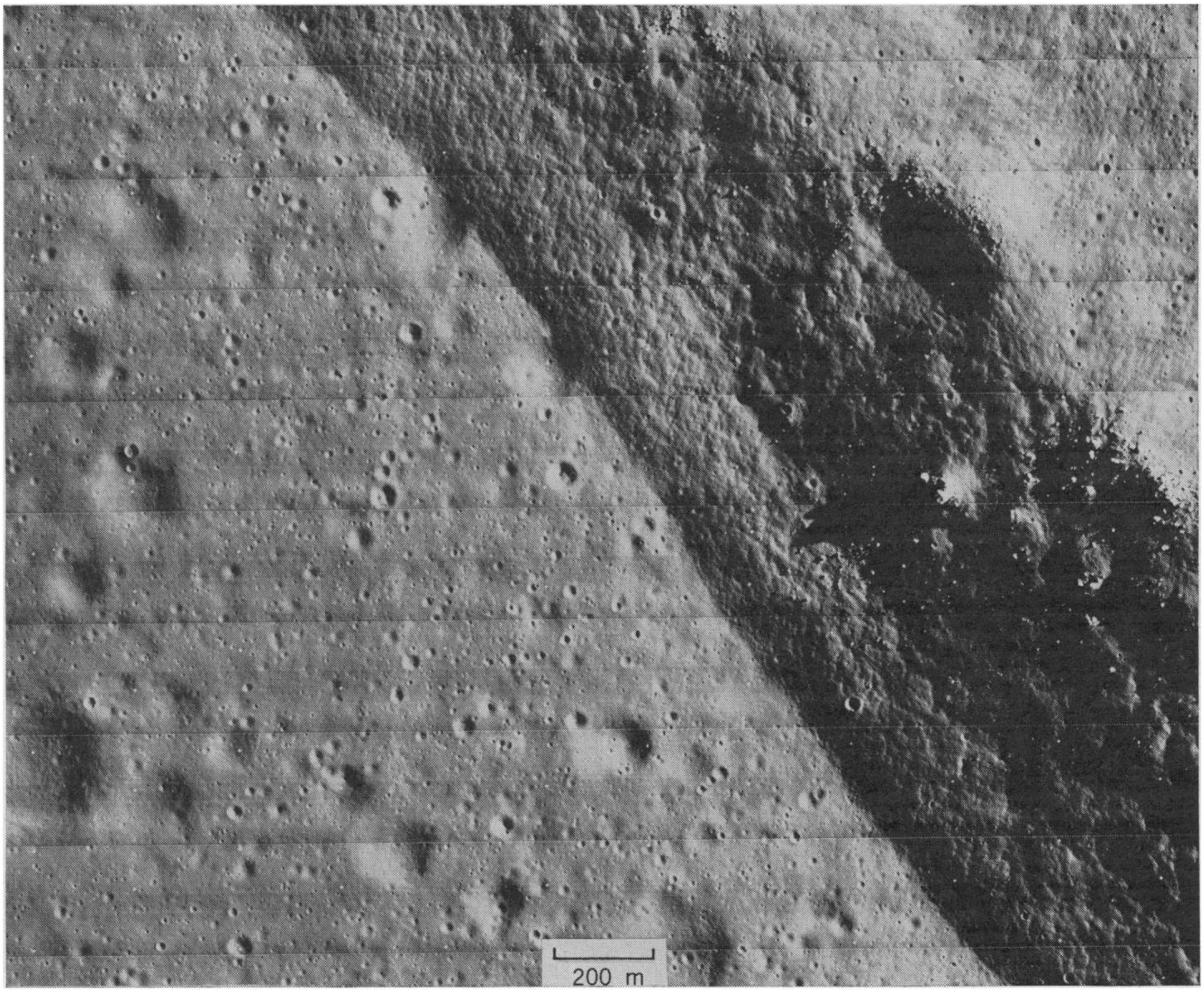


Fig. 4. High-resolution photograph showing typical relations among convex-upward terrace, mare, and steep slope of the crater Flamsteed P northeast of Surveyor I.

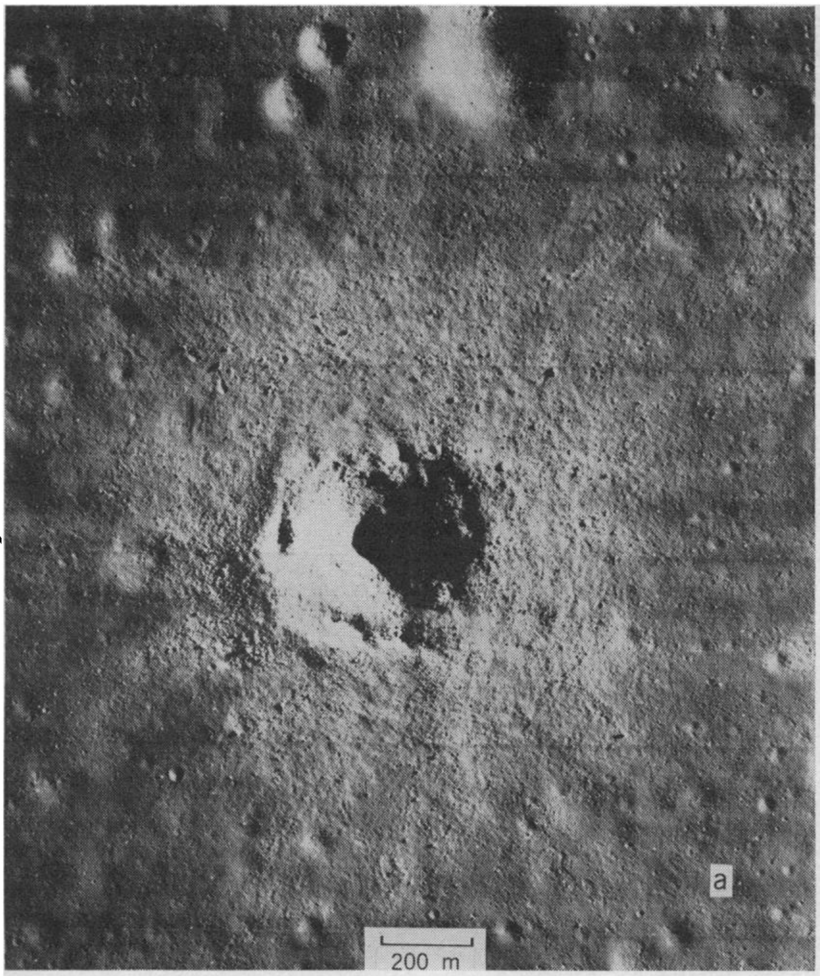
craters formed by endogenous processes such as volcanism. The small craters are similar in size to the spatter cones or cinder cones that occur around terrestrial volcanoes; however, they do not occur next to any obvious volcanoes, calderas, or fissures but are scattered ubiquitously over almost all larger topographic features. It seems most reasonable, therefore, to conclude that they are impact craters—some primary and some secondary.

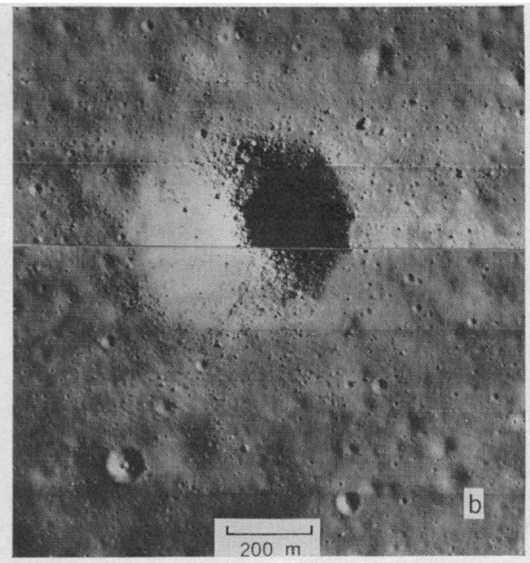
In level and gently rolling terrain the small craters are superposed on larger craters (Fig. 1). With the exception of the class of craters which we term "fresh," which are described below, the great majority of the craters larger than 50 meters in diameter have shallow floors and gently sloping interiors. The rim crests are broadly rounded, and the ground outside the rim crests is indistinguishable from level or very gently undulating areas between large craters. Completely rimless depressions are also common. The scene portrayed in virtually all the high-resolution photographs of level or gently rolling terrain is similar to that in the final full A and B frames of the Ranger series.

Rough Terrain

Rough terrain has fewer craters than level or gently rolling terrain. Craters in the 50- to 500-meter range are markedly few in number on rough terrain, and craters less than 50 meters in diameter are fewer by a factor of 2 to 3. The most striking aspect of rough terrain is the presence of narrow, roughly parallel ridges and troughs (Fig. 3). The wavelength of the furrows ranges from 3 to 10 meters. In places the trend of the furrows is parallel to the gross direction of the topographic contours, suggesting control by the directions of local slopes; elsewhere the trend is oblique to the contours, suggesting structural control for some of the ridges and troughs. Intersecting sets are present in some locations, and the trends of these sets commonly coincide with regional lineament patterns (*1*). Parallel ridges and troughs are most extensively developed on rough terrain but are also present in patches on the slopes of gently undulating terrain and on the interior slope of many shallow craters and depressions in otherwise level terrain. In these depressions the ridges are both parallel to and oblique to the topographic contours.

Topographic profiles show that poor-





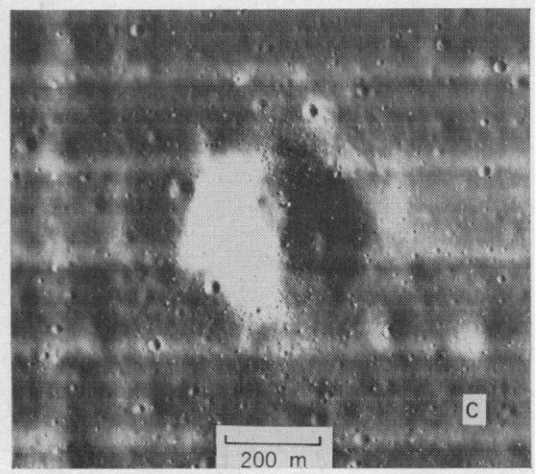
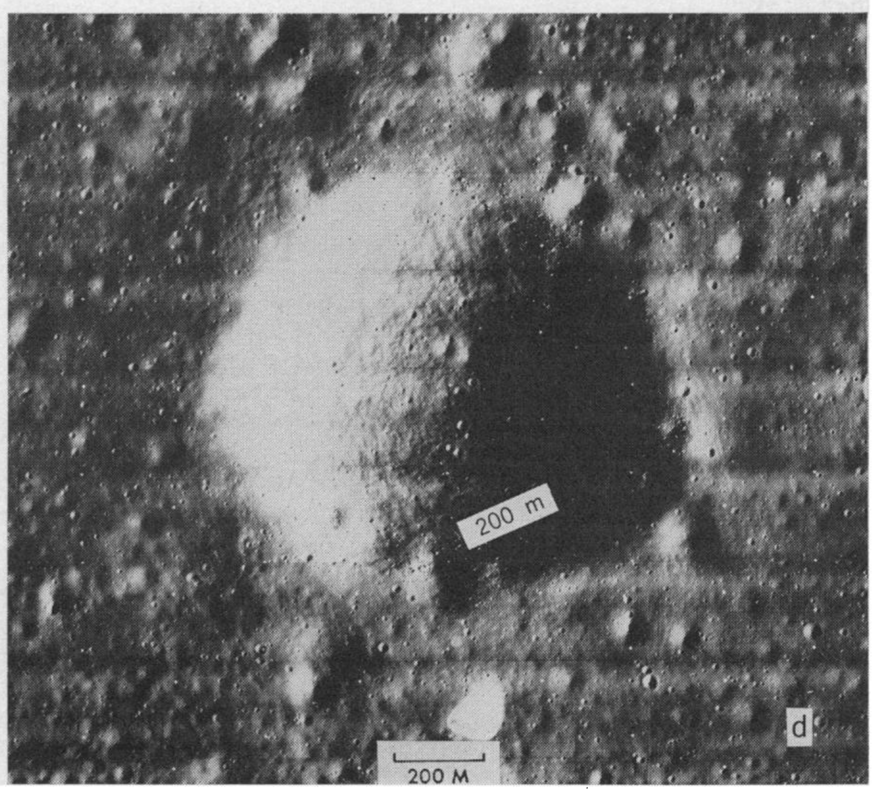


Fig. 5. (a–d) Continuum of crater types from very fresh to highly subdued. The number of blocks in the rim material and the albedo of the rim material decreases, the interiors of the craters become smoother, and the steepness of the interior and exterior slopes decreases throughout the sequence.



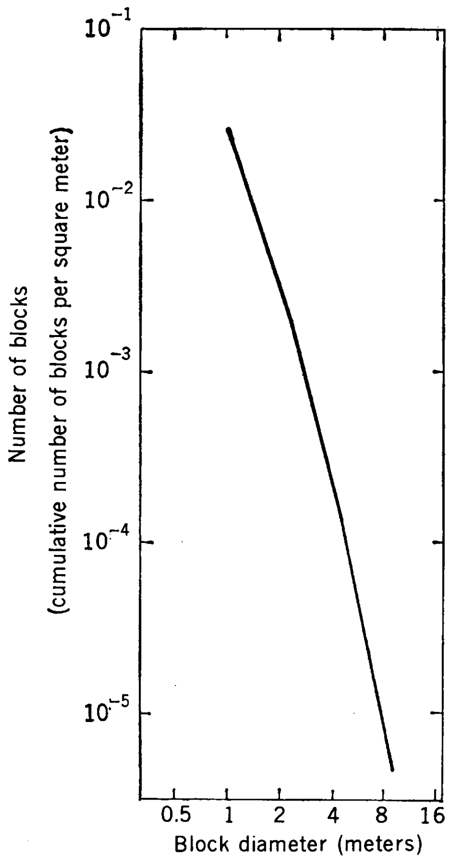


Fig. 6. Size-frequency distribution of blocks around a typical fresh crater 350 meters in diameter at approximately 18°E, 1°S. [Distribution determined by F. G. Robertson, U.S. Geological Survey]

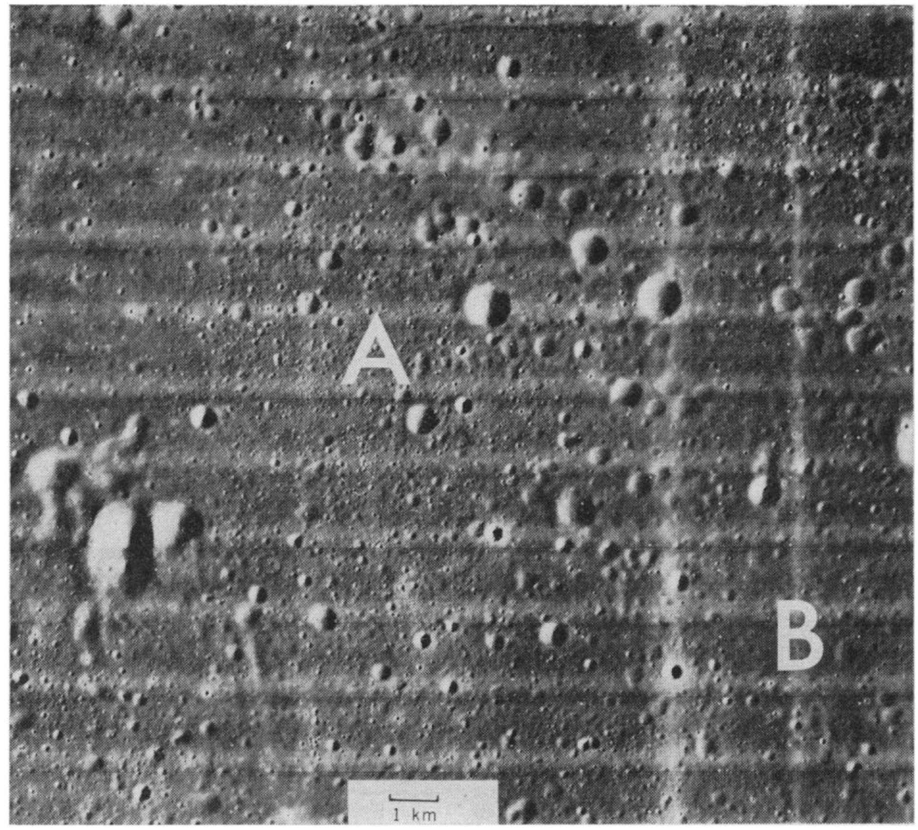


Fig. 8. Moderate-resolution photograph of a part of the southeastern region of Mare Tranquillitatis, showing (i) nonrandomness of crater distribution and (ii) areas in the maria having anomalously low crater frequency. Areas *A* and *B* correspond, respectively, to curves *A* and *B* of Fig. 9.

ly defined terraces or benches 200 to 400 meters wide commonly occur at the base of steep slopes. They are especially prevalent at the contact with the mare (Fig. 4), but they also occur at the base of steep slopes on rough terrain. The terraces are level or slope gently where they abut steep slopes, and they become steeper away from the slopes and toward the mare or other level ground; in profile, the terraces are thus convex upward (Fig. 4). The contact of terrace with mare is generally sharp; the contact with the slope above it is gradational. The crater frequency over all parts of the terrace is lower by a factor of 3 to 4 than the frequency on the adjacent level terrain and is similar to the frequency on the steep adjacent slope. Most of the craters on the terraces are of the sharp circular type; large shallow craters are virtually absent. Alternating ridges and troughs, similar to those on slopes in rough terrain, are also common. The trend of the troughs and ridges is generally parallel to the long dimension of the terrace, but faint lineaments are also present at an angle to the long dimension and apparently control the trend of some of the troughs and ridges (Fig. 4). The lineaments oblique to the long direction of the terrace are confined to the terrace and adjacent slope and do not extend onto the maria. The terraces are all similar to a prominent terrace noted on Orbiter I photographs at the base of the wall of the crater Flamsteed P (also referred to as the Flamsteed ring) (*2*). The origin of these terraces has not been finally settled (*2*), but we feel that the observations are most consistent with erosion of material from steep slopes and deposition at their bases.

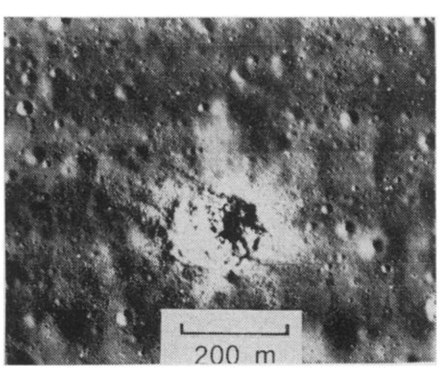


Fig. 7. Irregularly shaped fresh crater with shallow blocky floor. Approximately 43.5°W, 2°S.

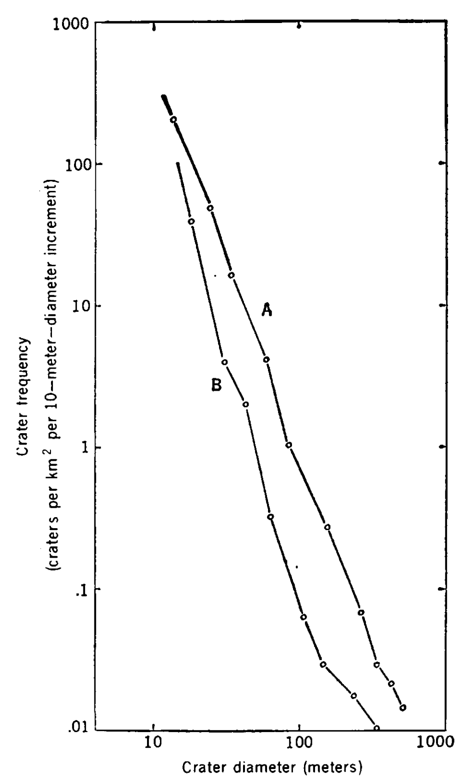


Fig. 9. *A*, Typical size-frequency curve for craters in the maria; *B*, size-frequency curve for craters in a mare area having anomalously low crater frequency. Areas represented by *A* and *B* are shown in Fig. 8. Counts were obtained from both moderate- and high-resolution photographs.

Fresh Craters

We classify as "fresh craters" those that have material on the exterior slope which appears clearly different from adjacent material of the intercrater areas (Fig. 5a). Fresh craters are rare but arrest the attention of all users of the high-resolution Orbiter photographs and are, we feel, of great significance. Those larger than 100 meters in diameter are most clearly shown. The most conspicuous feature is the profusion of angular blocks both on the floors and on the exterior slopes (Fig. 5, a and b) and occasionally on the interior slopes (Fig. 5b). The maximum block size varies with the size of the crater; the largest block recognized on the photographs of Orbiters I, II, and III is 80 meters in diameter, near the crater Dionysius, which is about 15 kilometers in diameter. The blocks are most abundant on the floors and on the exterior slopes close to the rim crest; their numbers gradually diminish away from the rim crest. Scattered isolated blocks have been observed as much as two crater diameters from the rim crest. At distances beyond one crater diameter, the blocks are not symmetrically disposed around the crater but are concentrated in ray-like extensions of the main block field. Around a typical fresh crater the number of measurable blocks per unit area varies with block diameter according to an inverse power function (Fig. 6). Detectable blocks in the areas between fresh craters are extremely rare.

The albedo of the blocks is higher than that of the undisturbed material between the fresh craters; they are thus similar to many of the blocks observed by Surveyor I (*3*). Additional material with relatively high albedo is present between the detectable blocks on the floors and rims of the fresh craters. This material undoubtedly consists of blocks smaller than those that can be seen on the Orbiter photographs but typical of the blocks photographed by Surveyor and probably mixed with still finer debris.

Fresh craters over 50 meters in diameter vary in outline from slightly irregular to markedly polygonal (Fig. 5, a–c). The floors of fresh craters 50 to 300 meters in diameter are highly irregular, and those of some craters are anomalously shallow (Fig. 7). Fresh craters less than 50 meters in diameter and those more than 300 meters in diameter are more nearly cup-shaped, like telescopically observed craters in the size range 5 to 20 kilometers. The variations in morphology with diameter were first noted independently by several workers (*4*) and may be a reflection of layering in the uppermost portion of the lunar crust, because the depth of material affected by the craters also varies with crater diameter. The craters with irregular and shallow floors in the diameter range 50 to 300 meters appear to be strongly affected by the material at depths of from 10 to 50 meters. Further studies along these lines are under way and will require precise measurements of crater profiles.

Craters that produce anomalously high infrared signals during lunar eclipse have received considerable attention in recent years, since it was discovered that there are hundreds of such craters (*5*). The thermal signals, in combination with geologic evidence, have indicated that such craters are relatively young and have not been eroded and blanketed with debris such as is responsible for the highly insulating properties of the older lunar surfaces (*5*). Several of these craters, including Gambart C, Moltke, Mösting C, and Dionysius, have been photographed by Lunar Orbiter. All are fresh and have angular blocks on their rims (see cover). The interiors of these craters are mostly in shadow or in overexposed areas on the photographs, but some blocks and fine-grained debris

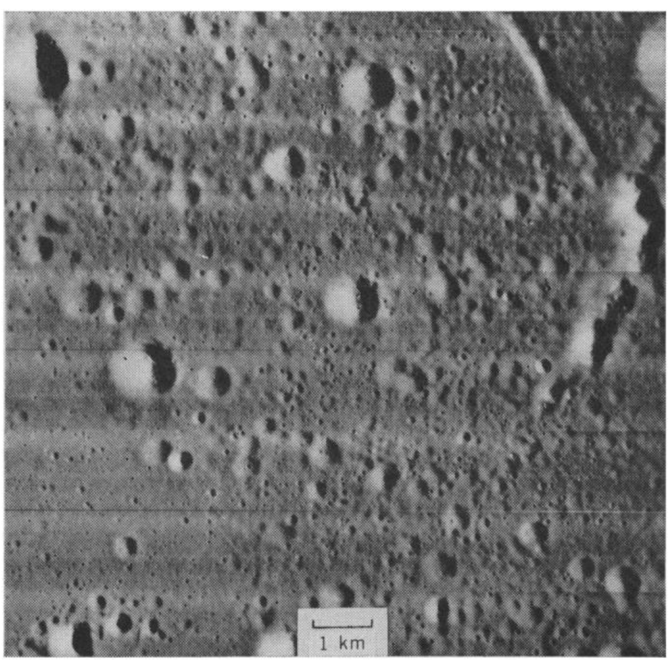


Fig. 10 (above). Moderate-resolution photograph of a level area (approximately 41°W, 2°N) in the terra southwest of Kepler, in which the frequency of craters in the size range 50 to 400 meters is very high.

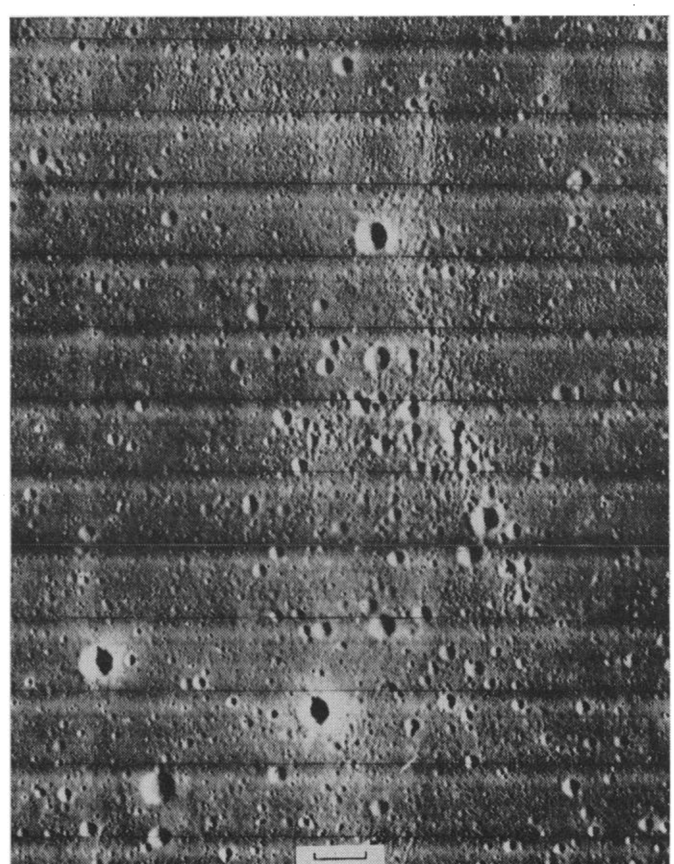


Fig. 11 (right). Moderate-resolution photograph of an area (approximately 41°W, 1°N) southwest of Kepler. Areas with high crater frequency are on the rays of Kepler.

with relatively high albedo are visible, along with a strong pattern of intersecting lineaments.

A continuum of crater types, from the sharpest fresh craters to shallow subdued depressions and rimless depressions, appears on the high-resolution photographs (Fig. 5, a–d). The continuum indicates that many of the shallow craters were once fresh and sharp but have undergone erosion and modification, although it does not follow that all such craters have evolved in this way. In craters that are well advanced through the destructive sequence the original sharp outlines of the freshest craters have been partially rounded off and the interior and exterior slopes are less. Blocks are usually missing on the exterior slope, but a series of generally concentric, low ridges is present close to the rim crest, and the albedo of the rim material is still higher than that of the surroundings. Also, the rim has few small, circular craters. Apparently, on the moon a process, or processes, acts to cause (i) disappearance of blocks either by comminution or burial; (ii) erosion of sharp topography, such as crater rim crests, and destruction of the typical topographic form of fresh craters; and (iii) darkening of material on the exterior slopes of fresh craters, so that its albedo becomes the same as that of the undisturbed material at a distance from the crater.

It is noteworthy that, in addition to occurring in and around fresh craters, angular blocks up to 15 meters in diameter are present along the crests of numerous ridges within the maria and at the top of steep escarpments in the terrae. The blocks appear identical with those associated with craters. Along mare ridges, they have higher albedo than the adjacent mare material.

Moderate-Resolution Photographs

The moderate-resolution photographs, which in typical format are one-third the size of the high-resolution frames, cover much larger areas and show elements of the lunar topography previously recognized by telescopic observations —plains, hills, ridges, domes, escarpments, rays, and craters with a great variety of shapes and sizes.

The density of craters 100 meters or more in diameter on the moderate-resolution photographs varies with location on the moon between narrow but significant limits, and a glance shows that there are many nonrandomly distributed craters within the total population (Figs. 8 and 9). Craters less than 500 meters in diameter on level or gently rolling terrain display a continuum of morphologies, from fresh craters with sharply raised rims to gentle depressions. On rough terrain there are no shallow subdued craters and gentle depressions. As is well known, the boundary between maria and terrae is not the same as the boundary between level terrain and terrain with relief; many areas of the terrae are as level as any in the maria. Level areas of the terrae are more heavily cratered than the maria, in places appearing "saturated" with craters in the size range 100 to 500 meters (Fig. 10). In some gently rolling areas of the terrae, shallow craters are surprisingly few.

On the maria the crater frequency, from the smoothest to the most cratered area, varies by almost an order of magnitude. Areas with as few craters as are shown by curve *B* of Fig. 9 are rare (*6*); some of them are as large as 25 square kilometers. Many crater-frequency curves are like curve *B* in having a steeper slope in the diameter interval 10 to 30 meters than at larger diameters.

Several well-defined rays—streaks that emanate from large craters and have a higher albedo than their surroundings—are shown by the moderate-resolution photographs. Most rayed areas are highly cratered; craters that are apparently intrinsic to the rays range from 50 to 500 meters in diameter in those rayed areas that have been photographed (Fig. 11). Many of the craters on rays are of irregular shape, commonly elongate parallel to ray trends. Although almost all rays are covered with craters, the converse—that all heavily cratered areas are rays—apparently does not hold. In several of the sites photographed by Lunar Orbiter, heavy concentrations of craters are not distinguished, by increased level of brightness, from the surroundings, on full-moon photographs. The intercrater areas of many rays are characterized by series of closely spaced ridges and troughs that are parallel to ray trends.

Summary

High-resolution photographs returned by Orbiters II and III typically show a surface pitted with small, perfectly circular craters as much as 50 meters in diameter, some of which are strongly clustered; these are superposed on larger, generally shallower craters and must be a mixture of primary and secondary impact craters. Rough terrain is less heavily cratered but is crossed by numerous closely spaced troughs and ridges up to 3 meters high. Terraces, which commonly occur at the base of steep slopes, are also crossed by these troughs and ridges and have relatively few craters. Fresh craters—craters whose exterior slopes are covered with material different from that of the intercrater areas—are rare and are surrounded by angular blocks up to 80 meters in diameter, in varying numbers; these craters apparently undergo gradual destruction to shallow gentle depressions. The frequency of craters 100 meters and more in diameter varies widely, even on level terrain; some of the highest concentrations of craters occur on rays.

The highly successful Lunar Orbiter program, which made these observations possible, has fulfilled one of its missions, that of searching for relatively level and smooth areas that might be suitable for early manned landings. The task of extracting the scientific content of the photographs is just beginning. Image enhancement and electronic improvement of selected photographs are under way. With careful analysis, the photographs should provide strong constraints on proposed theories of the origin of lunar surface materials and features. We feel that the observations described provide a start in this direction.

References and Notes

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6. The size-frequency data for the craters are normalized to equal areas and to equal increments of diameter and plotted incrementally, according to the suggestion of C. R. Chapman and R. R. Haefner [*J. Geophys. Res.* **72**, 549 (1967)].
7. The Lunar Orbiter Project is managed by Langley Research Center, Hampton Station, Virginia. The generous assistance and cooperation of all Langley personnel connected with the project are gratefully acknowledged. We thank D. J. Milton and M. R. Brock for critically reviewing the manuscript. Publication of this article is authorized by the director of the U.S. Geological Survey.