*Photointerpretation of the Lunar Surface**
(with fold-in map supplement†)

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ABSTRACT: *Photographs of the Moon taken at different libration positions have an angular difference of perspective, and hence stereoscopic photo interpretive methods may be applied to studies of the lunar surface. The common interpretation elements of shape, size, texture, pattern, position and shadow are important criteria in the study of the Moon, just as they are in the study of the Earth's surface, although the photo interpreter must adapt to the novelty of extremely small-scale photography and must modify certain of the procedures and instruments used for conventional aerial photographs.*

The dominant features of the lunar landscape are nearly circular craters, thought to be the result of meteoroid impact, and great lowland areas now flooded with dark material believed by many to be lava fields. Relative ages of the lunar features may be determined from the degree of dissection of crater rims, and from the relative positions of craters with respect to the lowland and highland areas. In places the lunar surface is cut by conspicuous faults more than a hundred miles long. Many of these features, which bear on an understanding of the Moon's surface and its development, have been compiled on generalized geologic and physiographic maps at a scale of 1:3,800,000. More detailed studies are being made and maps are being compiled at a scale of 1:1,000,000 for target areas for future lunar probes.

INTRODUCTION

PHOTO interpretation of the lunar surface is the first step in geological exploration of the Moon. Many photographs from different observatories have been examined stereoscopically to obtain physiographic and geologic data. Before discussing the application of photo interpretation to the lunar surface, however, brief consideration will be given to the general features of the Moon, the scale and resolution of lunar images as seen through the telescope and on lunar photographs, the phases of the Moon and how the Moon's movement around the earth permits the taking of stereoscopic pairs of photographs.

GENERAL FEATURES OF THE MOON

Some of the most striking features on the Moon are the dark-colored lowlands, the lighter-colored crater-scarred highlands, and the light-colored rays associated with certain craters (Figure 1).

An appreciation of the scale of lunar features may be obtained from the dimensions of the broad lowland Mare Imbrium, which is approximately 700 miles across. The ray crater Copernicus is about 56 miles across, and the crater Abulfeda is 39 miles in diameter (Figure 2). All of metropolitan Washington, D. C. and its suburbs could be placed on the floor of Abulfeda, and there would still be some room left over. The crater Ptolemaeus (Figure 2) is 90 miles across; the state of Connecticut would just about fit inside it.

The smallest object that can be seen on the best lunar photograph is about half-a-mile across. A building the size of the Pentagon would not be visible on the best telescopic photography of the Moon. In contrast, the smallest object that can be seen through the telescope under optimum viewing conditions is about an eighth of a mile across or about one-fourth the size of the smallest object resolved on the best lunar photographs.

PHASE AND FACE OF THE MOON

The phase of the Moon, which is determined by the direction of illumination, in-

* Reproduced essentially as presented at the 27th Annual Meeting of the Society, Shoreham Hotel, Washington, D. C., March 19–22, 1961. Publication authorized by the Director, U. S. Geological Survey.

† This map may be purchased from the American Society of Photogrammetry, 1515 Massachusetts Ave., N. W., Washington 5, D. C. $1.00 postpaid in the United States. Foreign mailing extra.

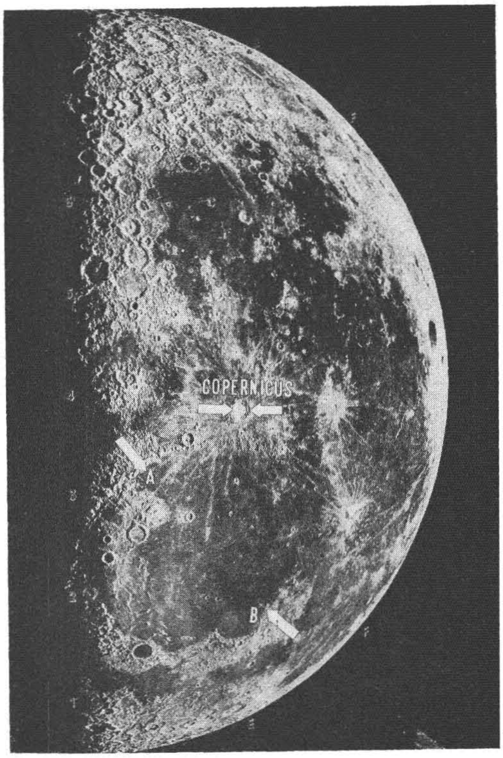


FIG. 1. Photograph of the quarter moon showing general scale of lunar features. Distance A to B, across Mare Imbrium, is about 700 miles. Ray crater Copernicus is 56 miles across.

fluences the appearance of the Moon and stereoscopic study of lunar features. A complete cycle of phases includes, in succession, new moon, crescent, 1st quarter, gibbous, full, gibbous, 3rd quarter, crescent, and finally new moon again. Regardless of phase, the Moon always shows essentially the same side to the Earth. This is due to the fact that the Moon rotates on its axis while revolving in its orbit around the Earth, and because the period of rotation is equal to the period of revolution. This movement of the Moon around the Earth may be likened to a man walking around a globe that is in the center of a room and always keeping his face toward the globe. In moving around the globe once (one revolution) he would have made one complete rotation with respect to the room. Viewed from the globe, only his face would be visible, never the back of his head.

LIBRATION AND STEREOSCOPIC PHOTOGRAPHS

It may be asked how stereoscopic pairs of photographs are obtained if the Moon shows only one face. If telescopic photographs were taken of the Moon from opposite sides of the Earth, the angular difference in view would be about $1\frac{3}{4}$ degrees, much too small for good stereoscopic viewing. Fortunately the Moon has apparent oscillations which enable us to see a little more around the edge at one time than at another. These oscillations, called libration, provide the means of obtaining stereoscopic pairs of lunar photographs.

At times it is possible to see as much as $6\frac{1}{2}$ degrees beyond the north pole of the Moon and at other times $6\frac{1}{2}$ degrees beyond the south pole. This latitudinal change in view of the Moon is called latitudinal libration. This is observed because the Moon's axis is inclined $1\frac{1}{2}$ degrees to the plane of its orbit, which in turn is inclined 5 degrees to the plane of the Earth's orbit (the ecliptic).

There is also a longitudinal change in view of the Moon; this is called longitudinal libration. It is caused by acceleration of the Moon in its elliptical orbit according to Kepler's second law while the rate of rotation remains nearly constant. Longitudinal libration allows viewing about 8 degrees more of longitude on either side of the Moon than may be seen at mean libration. Photographs taken at different librations appear the same as though they were taken from different points in space. With a sufficiently long base line (Figure 3) lunar photographs can be viewed stereoscopically with sufficient depth perception for stereoscopy to be of use in photo interpretation.

PREPARING LUNAR PHOTOGRAPHS FOR STEREOSCOPIC VIEWING

Many lunar photographs can be prepared for stereoscopic viewing in a manner some-

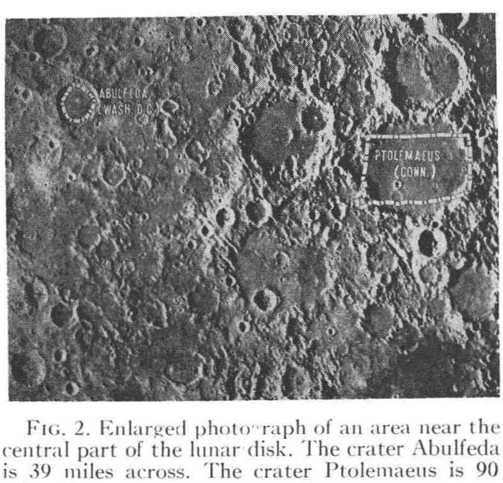


FIG. 2. Enlarged photograph of an area near the central part of the lunar disk. The crater Abulfeda is 39 miles across. The crater Ptolemaeus is 90 miles across.

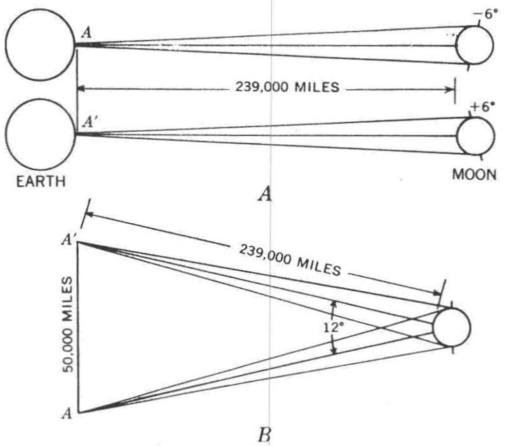


FIG. 3A. Diagram showing relation of the Earth to the Moon at two different librations; 3B. Diagram showing how photographs of the Moon at two librations are the same as though taken from two different points in space.

what similar to the method used for preparing terrestrial vertical aerial photographs. The geometric center of the lunar disk for each pair of photographs is located by geometric construction or by use of a circular template (points *A* and *B*, Figure 4). The conjugate image-point of these centers are located on the respective photographs, and the four points are alined in the *x*-direction for stereoscopic viewing. Enlarged lunar photographs can be cut into sections, and by use of reference points indicating the shift of the geometric center to the mean libration center, the sections can be properly oriented for stereoscopic viewing.

THE STEREOSCOPIC MODEL

Because of different base-height ratios in steoreoscopic pairs of lunar photographs taken at different libration positions, the apparent surface relief will vary from one model to another. The effect of different base-height ratios is so marked that even the curvature of the Moon's surface is noticeably different from one model to another. Yet the relative spatial relationship of one feature to another within the vertical dimensions of the model generally can be ascertained. With photographs having 12 degrees or more difference of libration, relief of 1,000 feet or more can be discerned in normal stereoscopic models. Relief of features only 100 to 200 feet high

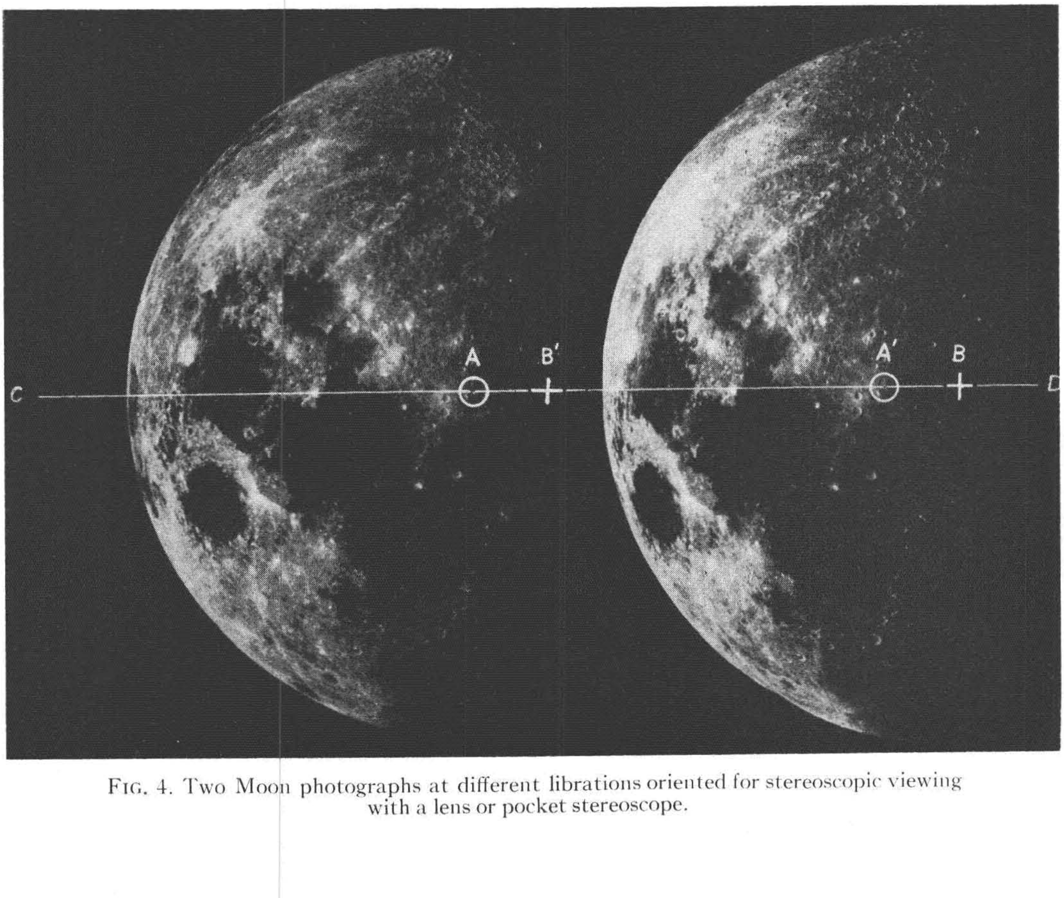


FIG. 4. Two Moon photographs at different librations oriented for stereoscopic viewing with a lens or pocket stereoscope.

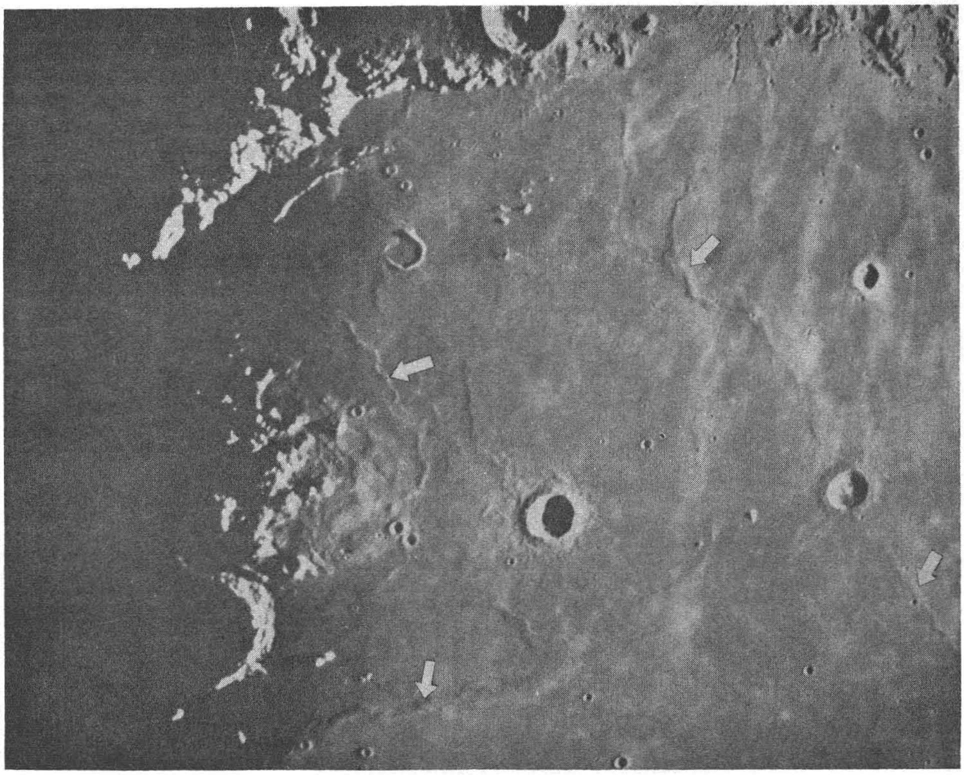


FIG. 5. Photograph showing wrinkle ridges in maria. Although not visible in the stereoscopic model, such features, 100 to 200 feet in relief, are visible under very low sun because of the shadows they cast on the lunar landscape.

cannot be discerned stereoscopically with existing photographs, but the presence of features with much less relief is clearly shown on photographs taken with the sun at a low angle, because of the shadows cast on the lunar landscape and differences in intensity of the scattered sunlight. Ridges in some of the maria are examples of low relief features visible because of intensity differences (Figure 5).

Many lunar photographs with different low angles of illumination are needed in photo interpretation work. Generally, Moon photographs with shadows in opposition cannot be successfully viewed stereoscopically. In some cases, however, opposing shadows may be an aid in interpretation (Figure 6). A positive interpretation of the two linear features, *A* and *B*, shown in Figure 6, cannot be made on any one of the photographs, but shadow patterns on both photographs together permit a reliable interpretation to be made. *A* is a low escarpment and *B* is an elongated valley or trough.

The appearance of features on the surface of the Moon varies considerably under different angles of illumination (Figure 7). Rays emanating from certain craters are conspicuous features of the full moon but details of topography are generally obscure. On photographs of the quarter moon the rays are inconspicuous, but topographic details stand out, especially along the sunset belt. By viewing such a pair of photographs stereoscopically, both the details of topography and the distribution of the ray material can be seen at the same time. The photo interpreter is thus able to extract considerably more information by viewing stereoscopically many pictures taken at different phases than could be obtained from photographs of any one phase.

PHOTO INTERPRETATION

The criteria of size, shape, texture, patterns, position and shadow are valid in photo interpretation of the Moon just as they are of the Earth, and the geologic law of superposition of rock units is also applicable to a study of the Moon. But in applying interpretation procedures to the Moon that were initially developed for terrestrial applications, the interpreter is limited by the small scale of lunar photographs. Furthermore the relative

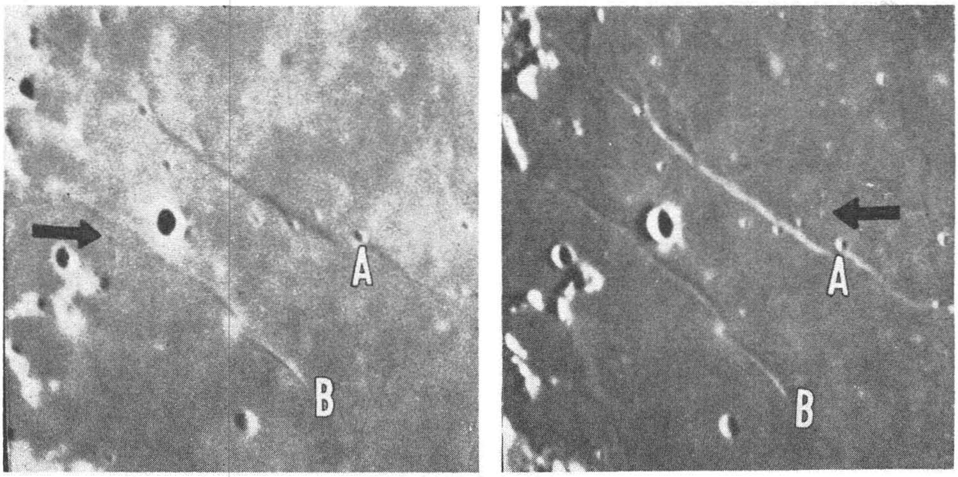


FIG. 6. Two photographs (not a stereo pair) showing how opposing shadows are an aid in interpretation. Arrows indicate direction of low sun illumination. A positive interpretation of the linear features, *A* and *B*, cannot be made on any one photograph. Comparison of shadow patterns on the two different photographs, however, shows *A* is a low escarpment, *B* an elongated valley or trough.

importance of the criteria may be much different in study of the Moon. Features sculptured by running water, for example, which are so prominent in the terrestrial landscape, are lacking on the Moon.

CRATERS

The dominant surface features of the Moon are nearly circular craters which most American specialists believe are chiefly the result of meteoroid impact. Some of the

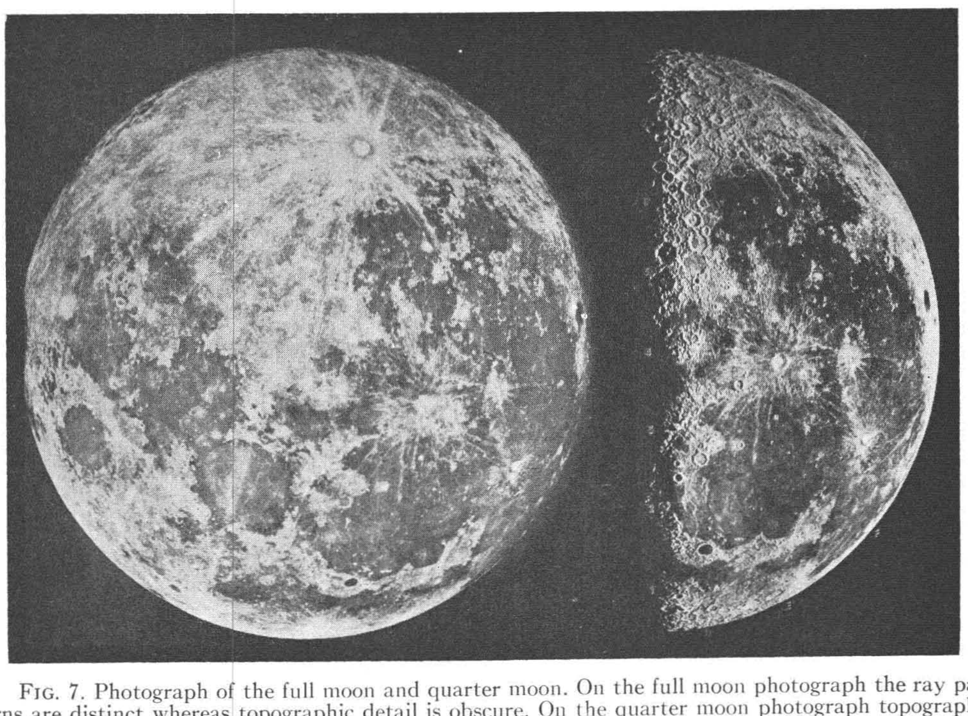


FIG. 7. Photograph of the full moon and quarter moon. On the full moon photograph the ray patterns are distinct whereas topographic detail is obscure. On the quarter moon photograph topographic detail is conspicuous, especially along the terminator (sunset zone), whereas many of the ray patterns are only poorly seen.

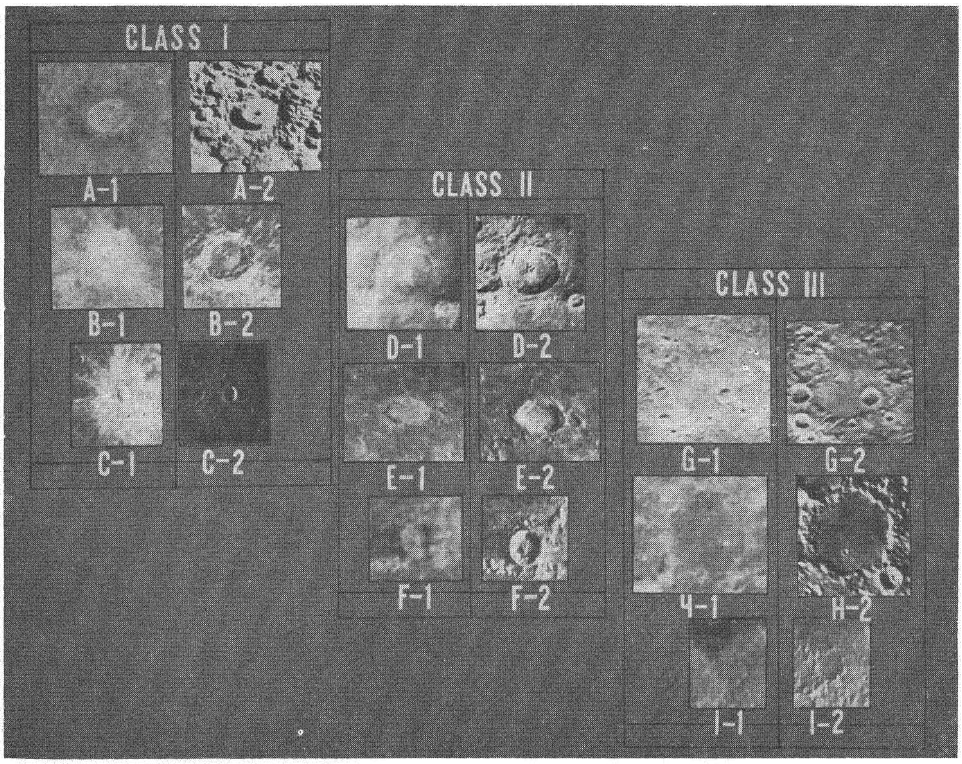


FIG. 8. Photograph showing three classes of lunar craters. Each crater is shown twice—once under high sun illumination and once under low sun illumination. Craters of Class I are the youngest; those of Class III are among the oldest.

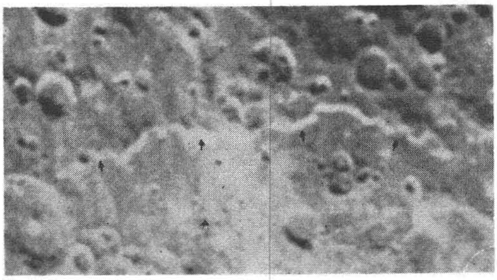
large basins now filled with dark material are believed to have been formed by impact of bodies of asteroidal size. Infall of meteoroids has probably been going on throughout lunar history. Even though erosion by water is absent, some process of modification has apparently changed the appearance of the older craters with respect to the younger ones. This change can probably be attributed to such factors as solar radiation, extreme temperature changes, micro-meteorite bombardment, Moon-quakes, and burial of older features with thin layers of material ejected from younger craters.

Three general classes of craters may be recognized (Figure 8). Those which are at the foci of bright radiating streaks, called ray craters, are the most conspicuous craters on the lunar surface at full moon (Class I, Figure 8). The rays are believed to be discontinuous thin layers of highly reflective material derived primarily from the craters from which they radiate. These are among the youngest craters on the Moon. Although the rays show up under high sun, they are rarely visible at very low sun. At low sun the topographic details of the craters are clearly visible.

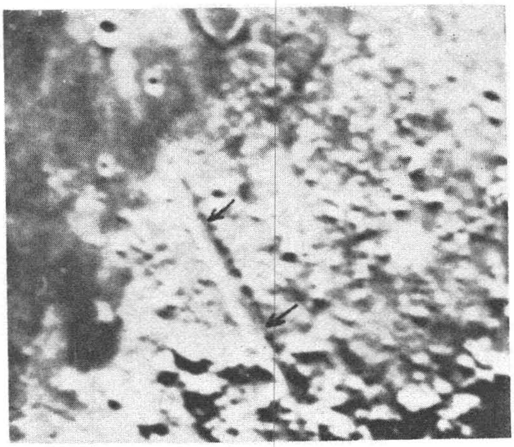
Craters of Class II exhibit topographic features at low sun similar to those of Class I, but under high sun exhibit no ray patterns. Crater D-1, a Class II crater, is overlapped by a ray from a prominent ray crater (Figure 8). The rays evidently darken and disappear with time, and craters of Class II are older than the ray craters. The light band inside the rim of crater D-1 may be due to the high reflectivity of fresh, broken rock of an active talus slope. As the craters become older, even talus slopes apparently stabilize and darken, as such light bands are rarely visible in the oldest craters.

Craters of Class III, the oldest (Figure 8), have been considerably modified and their walls have been dissected. In many places younger craters are superposed upon them. Under a high sun these old craters can be seen only with difficulty.

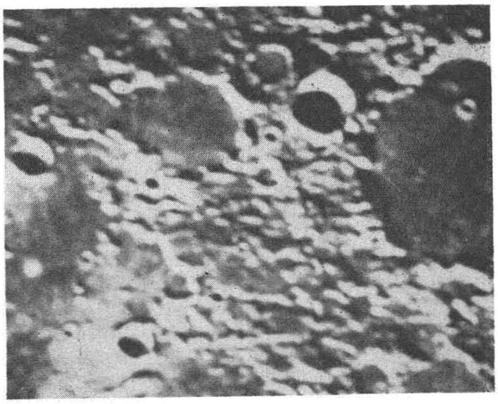
A sequence of craters exhibiting progressively modified features can be recognized that spans the range of age from bright young ray craters to the oldest recognizable



A



B



C

FIG. 9. Photograph showing lunar fractures. *A* shows the Altai Scarp; *B* shows the Alpine Valley; *C* is a complexly faulted area southeast of Mare Imbrium.

craters. The classification of lunar craters by age leads to certain inferences concerning the geologic history of the Moon.

FRACTURES

The surface of the Moon exhibits an intricate system of scarps and linear features that are interpreted as faults and fractures. Among the more conspicuous fault scarps is the Altai scarp (Figure 9A), an arcuate feature concentric with Mare Nectaris. Vertical relief along this fault is approximately one mile. Also conspicuous is the Alpine Valley, approximately 83 miles long, 3 to 6 miles wide and in places 10,000 feet deep (Figure 9B), which is interpreted as a graben, or down-dropped fault block. Besides the more conspicuous faults there are many subtle lineations, interpreted to be fractures, that are visible on lunar photographs and best seen in the stereoscopic model. Because of differences of appearance that are dependent on the angle of illumination, not all the fractures and lineations can be seen on one pair of photographs, but by viewing many photographs of the same area taken at different sun angles, a more complete fracture pattern can be worked out. In a complexly faulted area southeast of Mare Imbirum, two types of craters are visible (Figure 9C), one type with continuous unbroken rims and the other with fractured rims. The fractured craters are older than the fractures, whereas the craters with unbroken rims are younger.

MARIA

Conspicuous dark areas seen on the face of the Moon are called maria—they are the seas of the early astronomers. These vast smooth-looking dark surfaces, with scattered ridges rising as much as a few hundred feet above the general surface, have been commonly interpreted as lava fields. Domelike hills resembling shield volcanoes occur in certain areas on the maria. The material of the maria has filled many of the large lunar basins, some of the adjacent lowlands, and some of the craters. Many young craters are superposed on the basin material and are approximately uniformly distributed, which suggests that the material of the maria is everywhere about the same age. Using the vast surfaces of the maria as a datum or reference, many lunar events and features can be dated as older or younger than the period in which the maria were formed.

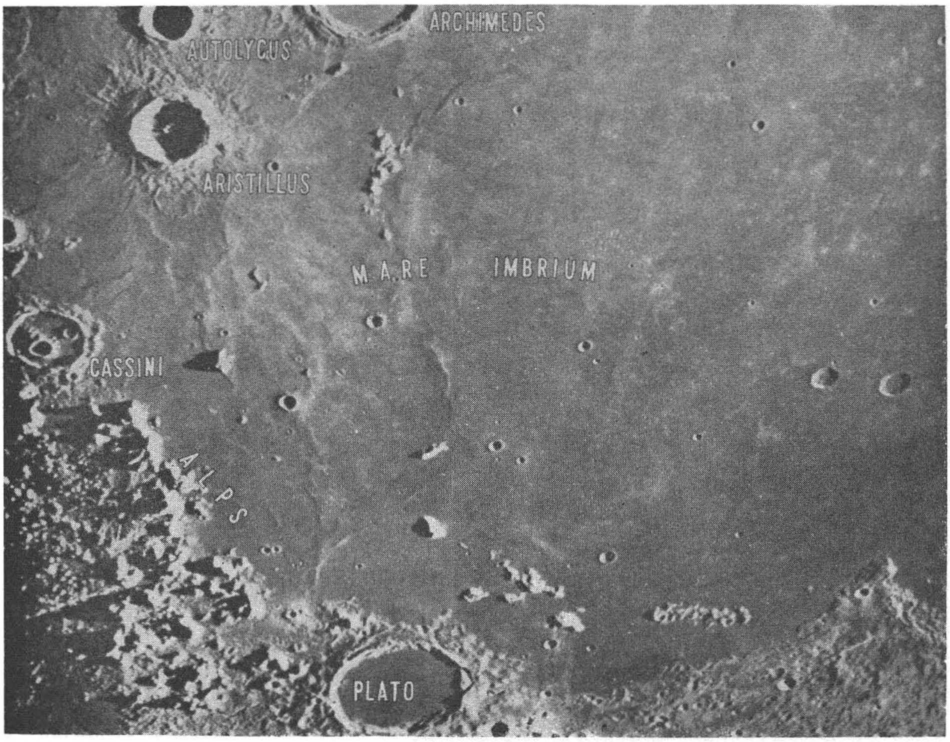


FIG. 10. Photograph of part of Mare Imbrium and surrounding craters showing lunar features of different ages (see text for explanation).

LUNAR HISTORY

From the relative ages of the Moon's features, an historical sequence of events can be determined by a study of lunar photographs. Consider, for example, the area around Mare Imbrium (Figure 10). When the basin occupied by Mare Imbrium was formed, older craters in a broad belt about 200 miles wide around the basin were obliterated. The Alps Mountains are a part of this belt. Between the time the basin was formed and the deposition of the maria material, the craters Plato, Cassini, and Archimedes were formed. These craters, flooded with maria material, are superposed on the rugged terrain around the basin where older craters were filled or destroyed. Therefore they must be younger than the Mare Imbrium basin and older than the material which fills it. After deposition of the maria material, craters such as Autolycus and Aristillus were subsequently formed and are now seen superposed on the mare.

A sequence of five events can be recognized in the Mare Imbrium area:

1. Formation of the Alps.
2. Formation of the pre-maria craters.
3. Deposition of maria material.
4. Formation of post-maria craters without rays, such as Autolycus
5. Formation of post-maria ray craters, such as Aristillus.

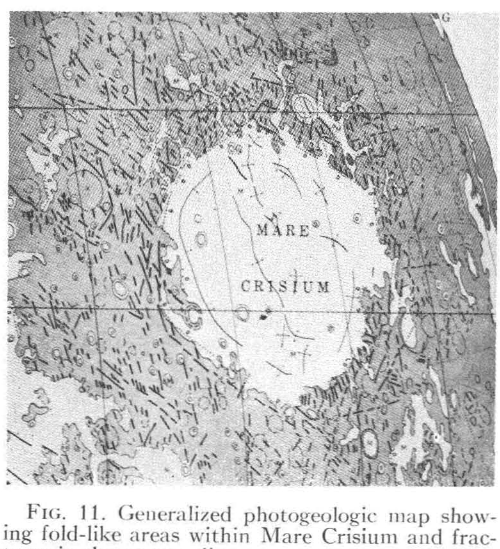


FIG. 11. Generalized photogeologic map showing fold-like areas within Mare Crisium and fractures in the surrounding area.

TABLE 1

DESCRIPTION OF MAJOR DIVISIONS AND DIVISIONS OF THE MOON*

Major division or division	*Location and characteristics (Only major division and division are described)*
LUNAR HIGHLANDS	Two-thirds visible surface of moon, almost completely covered with 30,000 distinguishable and perhaps a million or more other craters, many overlapping and impinging on others, and with small craters superimposed on large craters; diameters from 146 miles to below limit of visibility, about ½ mile; depths vary roughly with diameters and range from 20,000 ft. to probably a few ft.; also ejecta-covered, rugged, ring mountains encircling some maria. Rough surface except for many crater bottoms which are fairly level in whole or in part. Slopes generally 5° to 25°; most about 10°; some 20° to 25°; few slopes steeper.
Imbrium-Serenitatis Mountains	Two large ring mountain systems nearly encircling Mare Imbrium and Mare Serenitatis. Mountain blocks fractured in radial pattern; cut off in maria side by faults nearly encircling the maria. Rough surfaces of ejecta partly or wholly concealing eroded and fractured older surface, but not post-maria craters. Many steep slopes, especially near maria rims, where slopes are very steep toward maria, less steep away from maria.
Central and Southern Highlands	Almost one-third visible surface of moon, in center and south. Densely pocked with contiguous, overlapping, and superimposed impact craters ranging in diameter from 146 miles (Clavius) (Bailly may be 183 miles in diameter, but on limb and visible only during favorable libration) to below limit of visibility, about ½ mile; in rim height from 10,500 ft. (Barocius) to a few ft.; in depth from 20,000 ft. to a few inches. Rough surfaces almost everywhere; some crater bottoms smooth. Most surfaces in slopes, mostly about 10°, but ranging from 5° to 20°; some crater bottoms nearly level.
Crisium-Fecunditatis	Extensive area on E. limb. Densely pocked with old craters, including several large ones. Several maria partly interrupt central part, the largest being Mare Crisium. Surrounding Mare Crisium are radial faulted mountains which slope away from mare; shelf mountains and promontories extend into mare. Boundaries with other maria chiefly formed by embayments and are irregular. Some post-maria craters. Surfaces generally rough. Slopes mostly 5° to 15°, commonly about 10°, but slopes facing Mare Crisium slightly steeper.
Northern Highlands	On N. limb, N. of Mare Frigoris. Densely pocked with old craters, many with somewhat level bottoms; numerous pre-maria and a number of large post-maria craters. Several strong fracture patterns, in order of prominence extending NW.-SE., NE.-SW., N.-S. Surface generally rough. Slopes mostly 5° to 15°, commonly about 10°.
Procellarum Highlands	Along W. limb, W. of Oceanus Procellarum. Densely pocked with much altered old craters. Boundary with Oceanus Procellarum sinuous and poorly defined, with many re-entrants. Some post-maria craters. Mountains of uncertain nature along limbs. Surfaces rough to moderately rough. Slopes 5° to 15°, commonly 10°.
LUNAR LOWLANDS	Lowland areas widely distributed on Moon's visible surface, but more in N. than S., the larger areas termed maria. Plains material has occupied both large basins and adjacent lowlands. Older surface forms many islandlike highlands. Plains have low, sinuous ridges, moderate differences in elevation from one part to another, and some low domes and hills. Numerous scattered large and small craters superimposed on the maria. Slopes gentle in plains; steep on craters and included highlands.
Mid Lunar Lowlands	Group of connected lowland areas occupying about one-third moon's visible surface, principally in NW. quadrant, but extending S. and SE. into the other quadrants. Other characteristics the same as Lunar Lowlands.
Marginal Lowlands	Near E. limb. Flooded area and lowlands, possibly connected in part. Ring mountains nearly encircle control basin forming generally circular boundary; most boundaries irregular. Low ridges. Surface generally smooth except probably for many small post-maria pits and craters. Slopes generally 1° to 3°, ridges 1° to 4°; pits and craters steeper.
Australe Lowlands	Situated on SE. limb. Australe Lowlands beyond limb probably includes other maria areas like Mare Australe, a flooded lowland. Surfaces and slopes unknown, but probably similar to Mare Humorum.
Aestatis Lowlands	On W. limb of moon. All the maria in this division are flooded lowlands, not easily observed because of position on limb. Surfaces and slopes unknown but probably similar to Mare Humorum.

* Table 1—from information compiled by Arnold C. Mason and Robert J. Hackman, U. S. Geological Survey.

FIRST LUNAR PROJECT

The initial steps in photogeologic mapping of the Moon were the preparation of a map of the physiographic divisions and a generalized photogeologic map of the entire Moon. The physiographic divisions, shown on the map supplement (PLATE 1), have been delineated on the basis of gross topographic characteristics of the lunar landscape. Physiographic classification permits description and analysis of lunar terrain by areal units rather than by individual features (Table 1). Most of the names used were taken from previously named topographic features, but in some areas new descriptive names were required.

The generalized photogeologic map of the Moon shows structures such as faults, folds, domelike hills, and craters (Figure 11). The rocks have been divided into three age groups with reference to the maria.

Photo interpretation is being continued for selected parts of the lunar surface which are the target areas for the first lunar probes planned by the National Aeronautics and Space Administration. Photogeologic maps are being prepared at a scale of 1:1,000,000, about three-and-a-half times larger than the generalized photogeologic map already produced. This is the maximum scale at which maps may be prepared with acceptable accuracy because of the limited resolution of present-day lunar photographs. In addition to photogeologic studies, photometric, colorimetric, polarimetric, and radiometric techniques are being utilized to aid in the correlation of rock units and interpretation of some of their physical characteristics. The maps now being made provide a broad framework for more refined geologic studies of the Moon that will be undertaken when the first photo reconnaissance rocket sends back more detailed photographs.

ACKNOWLEDGMENTS

Information presented herein is based on studies initially undertaken by the U. S. Geological Survey for the U. S. Army Corps of Engineers, and now being continued under support of the National Space and Aeronautics Administration and the Corps of Engineers. The author is indebted to the Aeronautical Chart and Information Center, U. S. Air Force, for permission to use the photomosaic on which the Moon's physiographic divisions have been plotted. Photographs used as illustrations are mainly from the Lunar Atlas, U. S. Air Force, Volume 1.

*Photo Topography for the 1:1,000,000 Lunar Charts**

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ABSTRACT: *Lunar photography taken from earthbound telescopes presents unique problems in the determination of lunar heights and interpretation of surface features. These problems are minimized by techniques used at the Aeronautical Chart & Information Center (ACIC), St. Louis, Mo., in photo compilations of 1:1,000,000 scale lunar charts. Professor Zdenek Kopal, University of Manchester, England, has refined techniques for determining heights of lunar features through shadow measurements. This method combined with reduction of other measurements of the lunar surface by the Austrian Astronomer Schrutka-Rechtenstamm has permitted ACIC to compile lunar charts with 300 meter contours having a probable error of 100 meters in localized areas. Visual observations of the Moon for supplementing and confirming photo interpretation is being carried out at Lowell Observatory, Flagstaff, Arizona, by lunar cartographers. To support the ACIC lunar program, an exhaustive collection of lunar photography is being undertaken at Pic du Midi Observatory in the Pyrenees Mountains of Southern France with prolonged cine-photography of the whole of the visible Moon on 9 inch aerial film.*

THE GENERAL PROBLEM

EARTHBOUND photography comprises the only photographic source material now available for basic lunar mapping. At first thought it seems easy, given reasonably good photographs, to measure what one sees and then compile a lunar map. However, there are several major problem areas. One obstacle is that all photographs of the Moon taken from the Earth have various imperfections. The biggest cause of trouble is the Earth's atmosphere; its dust obscures the view and its turbulence produces small random variations in scale across the Moon's image. Another obstacle is the Moon's distance from the Earth. This distance of some 239,000 miles restricts conventional stereoscopic mapping even when maximum librated photography is used. Both of these factors, the Earth's atmosphere and distance from the Moon, pose some unique problems in determining lunar elevations and identifying surface features. Since these determinations are recognized to be of primary signifi-

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