Prepared in cooperation with the
Manned Spacecraft Center
National Aeronautics and Space Administration

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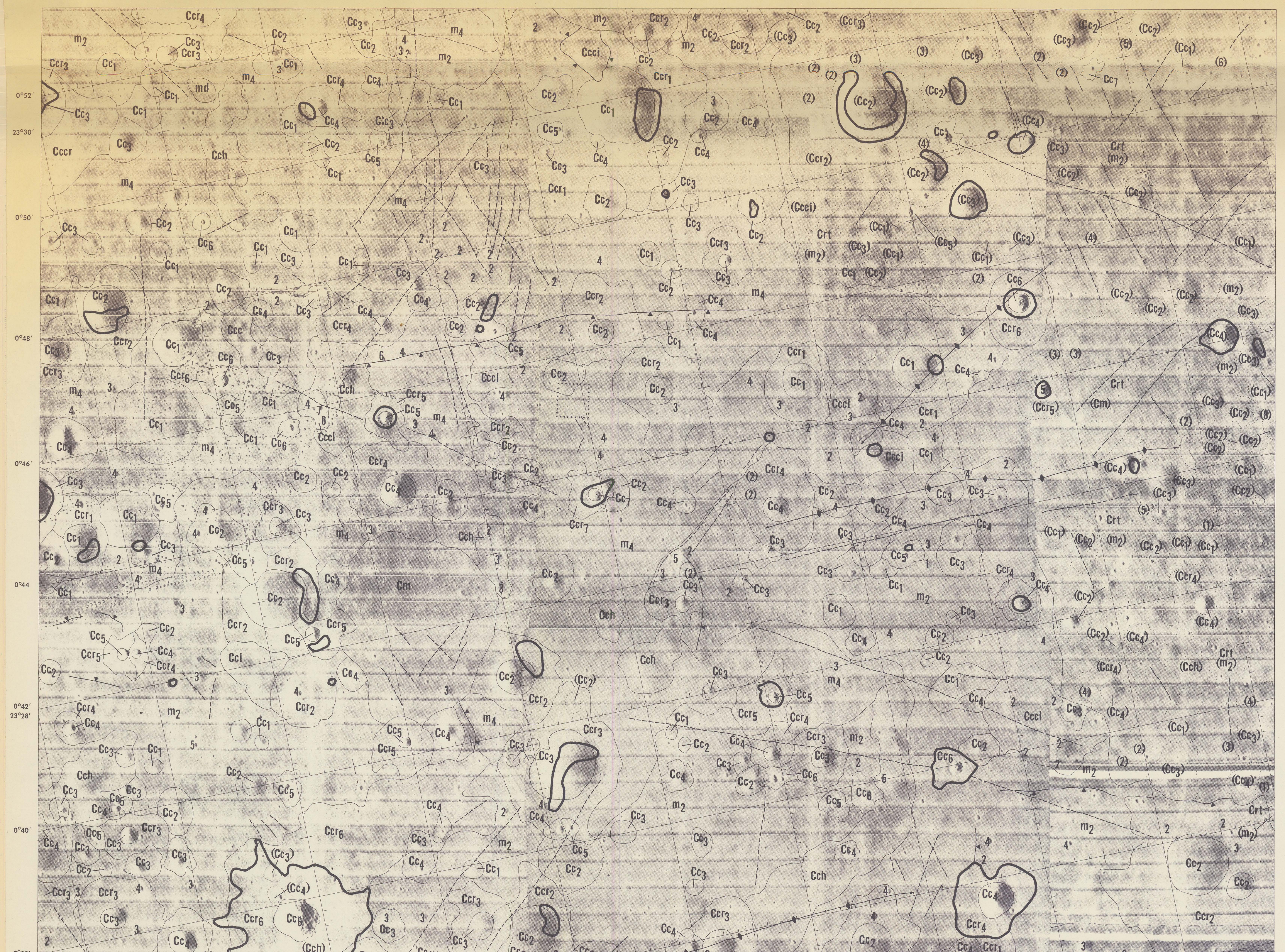
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
OPEN FILE REPORT



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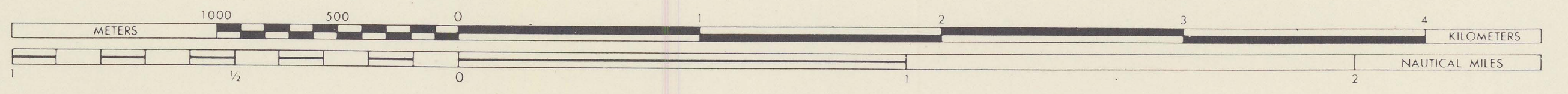
Principal sources of geologic information: Lunar Orbiter II, IV, V photographs (Langley Research Center, NASA, 1966, 1967); albedo data from full-Moon plates 5818 and 5819 taken at U.S. Naval Observatory, Flagstaff, Ariz.

SCALE 1:25,000

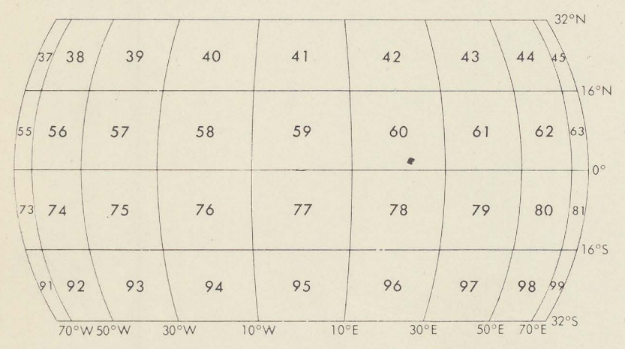


PRELIMINARY GEOLOGIC MAP OF ELLIPSE II-6-1 AND VICINITY

By
M. J. Grolier
1967

Mercator Projection

SITE LOCATION DIAGRAM KEYED TO LAC



General Geology

Site II P-6, which is in the southwestern part of Mare Tranquillitatis, is a mare area crossed by ridges and rays. Ellipse II-6-1 is north of the equator in the southwestern quadrant of the site. The geologic map described here includes the ellipse and a contiguous band that is 1 km and more in width.

Two of the four mare units mapped at the scale of 1:100,000 in site II P-6 (Grolier, 1967) occur in ellipse II-6-1. Within site II P-6, mare ridges are resolvable at telescopic resolution and are visible on Lunar Orbiter moderate-resolution photographs; however, these ridges do not extend into the ellipse. Part of a ray from Theophilus, a Copernican crater about 320 km to the southeast, extends northwestward across the eastern part of the ellipse.

Four mare units (m_1, m_2, m_3, and m_4) are shown on the geologic map of site II P-6 at the 1:100,000 scale (Grolier, 1967). Two of these (m_2 and m_4) are shown on the 1:25,000-scale map. They are probably volcanic flows mantled by a surficial fragmental layer. The other mare unit (Cm) is exposed in subcircular areas, which are surrounded discontinuously by small subdued craters. That unit (Cm) had not been distinguished from mare units m_2 and m_4 at the 1:100,000 scale.

The subcircular areas are perhaps "volcanic sinks" mantled with a surficial fragmental layer but otherwise resembling small terrestrial calderas or very large feeder dikes. Alternatively, they may be remnants of old and rather large impact craters, partly filled with mare material (Cm) which may have been emplaced after the Cc_2 and Cc_3 craters formed but certainly before the Cc_4 and Cc_5 craters formed. (Rim material of Cc_2 and Cc_3 craters appears to be truncated by mare unit Cm whereas that of Cc_4 and younger craters extends onto the mare unit.) This mare material (Cm) is relatively level, and its surface is pitted by craters that are mostly less than 75 meters in diameter.

The materials of all craters more than 75 meters in diameter are indicated on the map, and relative ages are assigned on the basis of morphology and crater diameter, as shown in figure 1. All craters in the map area are of Copernican age: Cc_1, oldest; Cc_8, youngest. Most of the craters are probably due to impact; however, some may be of internal origin. Crater materials are subjected to cratering after their formation, and a surficial fragmental layer develops on them as on the mare. Impact craters probably consist of loose, fragmental mare material. Some small particles may represent material compressed into hard rock by shock. Some of the mineral constituents of the fragments probably are shock metamorphosed.

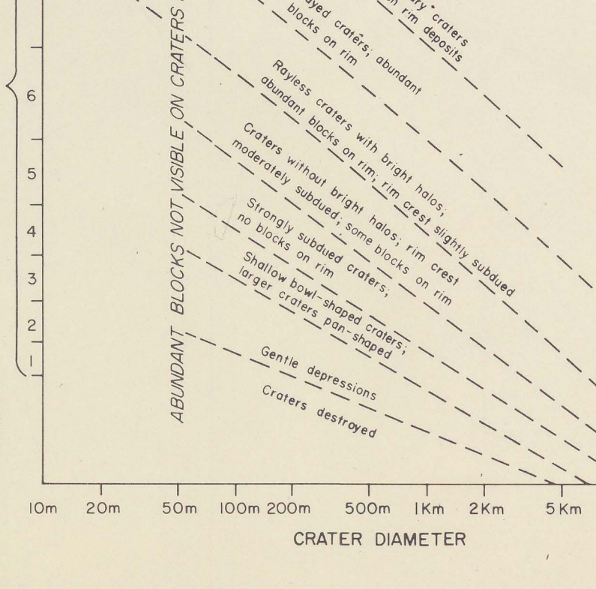


Figure 1.--Assumed relations among crater diameter (from rim crest to rim crest), crater properties, and crater age. Width of intervals on ordinate carries no implication as to lengths of intervals of lunar geologic time.

Some craters with a convex rim and rim deposits whose width equals or exceeds that of the central depression may be volcanic. Such craters occur in the extreme southwest corner of the map area. If they are volcanic, they probably consist of basaltic volcanic ejecta.

Two sets of lineaments trend northeast and northwest across the mare; a third set, in the northwestern part of the map area, trends almost northward. Two very low mare ridges and a prominent escarpment trending almost eastward make up, with the lineaments, the structural elements of the ellipse.

The mare material in Mare Tranquillitatis is of Imbrian age (Morris and Wilhelms, 1967). None of the craters in site II P-6 mapped at the 1:100,000 scale are older than Eratosthenian. The oldest, Sabine D and E, might be older than the mare material which surround them, but there is no morphologic evidence within the site to assign with certainty a lower age limit to the main mare units. An age ranging from late Imbrian to early Eratosthenian is being suggested for Mare Tranquillitatis by two geologists (H. A. Pohn and T. W. Offield, 1967, oral commun.) who are systematically analyzing the relative ages of large lunar craters.

Within and around ellipse II-6-1, the ejecta of craters more than 75 meters in diameter covers about 25 percent or more of the mare surface. Five to seven percent of the rest of the mare is covered by materials of craters in the 5-75 meter range, and Ranger and Surveyor photographs have shown that the cratering process is manifested by craters whose smallest size is limited only by photographic resolution.

Because all resolvable craters at the 1:25,000 map scale are Copernican, the surficial material in ellipse II-6-1--the regolith that mantles mare and crater materials--is probably entirely of Copernican age.

General alinement of craters on and along low mare ridges in the east-central and southern parts of the area suggests structural control, and many craters are alined along lineaments in the northeastern part of the area. However, more evidence is needed to state with certainty that these craters are structurally controlled.

Engineering Geology

Regional relief in the map area probably does not exceed 200 meters; the terrain generally slopes gently eastward. Local relief occurs primarily in and around craters, and to a lesser degree between low mare ridges and troughs. The depth-to-diameter ratio of most fresh craters of impact origin is about 1:4. The largest fresh crater, 375 meters in diameter, is a Cc_6 crater in the southwest part of the map area. It is probably about 90 meters deep. Some subdued craters (Cc_1-Cc_3) are much larger and are probably more than 100 meters deep.

The engineering properties of the lunar surface in ellipse II-6-1 can be evaluated from data returned by Surveyor V, which landed in the northwestern part of site II P-6, about 25 km northwest of the ellipse, in mare unit m_2 (Grolier, 1967). The spacecraft was not equipped with strain gages or with a surface sampler. However, the interaction of its footpads with the lunar surface was similar to that of Surveyor I (site III P-12) and Surveyor III (site III P-9), suggesting that the surficial fragmental layer is texturally similar to that in the other two Surveyor landing sites. This layer probably consists of weakly cohesive, very slightly compressible, granular material whose engineering properties are as follows (Jaffe and others, 1967, p. 3, 5): Cohesion, 1.5×10^5 to 7×10^5 dynes per cm^2; angle of internal friction, 35° to 40°; and static bearing capacity, 2×10^5 to 6×10^5 dynes per cm^2. The surface roughness of the ellipse, in terms of rocks lying on or protruding through the surface, appears comparable to that of the Surveyor V landing site. Where mare units m_2 and Cm are modified by ray material from Theophilus, surface roughness may be greater than around Surveyor V. Mare unit Cm is less densely cratered than mare unit m_2 material at the Surveyor V landing area.

The thickness of the surficial fragmental layer in the ellipse cannot be estimated by the method of Oberbeck and Quaide (1967) because of the scarcity of fresh craters in which internal structure is present. However, craters up to 20 meters in diameter within 200 meters of the Surveyor V spacecraft are surrounded with fields of blocks and boulders. Assuming a depth-to-diameter ratio of 1 to 4, a "ratio characteristics of small primary lunar craters, the presence of blocks on the rims of these craters indicated that the depth to blocky or coherent material is locally not greater than about 5 meters" (Shoemaker and others, 1967, p. 645, 646). Probably, the older the mare material, the thicker the surficial fragmental layer, because of a more prolonged churning of the mare surface by successive impacts. The surficial fragmental layer probably is not much more than 5 to 8 meters thick, at least in the oldest mare unit m_2, which includes the Surveyor V landing site (Grolier, 1967).

One of the processes by which lunar craters become degraded is mass wasting. Some of the craters in ellipse II-6-1 are more than 100 meters deep and were probably even deeper when first formed. A layer of debris derived from the walls and structural terraces accumulates on the floor and the lower walls of craters and is continually churned by impacts. Thus, the combined colluvial layer and overlying surficial fragmental layer on the crater floor is probably much thicker within large subdued Cc_1 and Cc_2 craters than on the mare, perhaps by at least one order of magnitude.

The rim material of most craters probably consists of multiple layers (underlying mare surficial layer, impact or volcanic ejecta, and the surficial layer developed on the ejecta). When fresh, these layers are probably thicker than the surficial fragmental layer on the mare, but with time their thickness is reduced by mass wasting.

The chief engineering hazards are craters and block fields. Materials of all craters more than 75 meters in diameter are outlined on the map, but the number of craters from 5 to 75 meters alone exceeds the craters mapped by at least one order of magnitude (Natl. Aeronautics and Space Adm., 1967, p. 49-50). All block fields containing blocks larger than 2 meters in diameter are outlined on the map; they all are restricted to parts of craters or crater rims. Smaller blocks probably occur around many smaller craters with raised rims (as shown on Surveyor V photographs), and also in the area covered by discontinuous ray material from Theophilus.

Many of the lineaments are defined by small scarps on the mare, and like steep-walled craters, they constitute trafficability hazards. Another such hazard lies in the possible presence of numerous small, fault-controlled scarps that cannot be resolved on Orbiter photographs.

A potential hazard to lunar construction, but perhaps not a landing or trafficability hazard, is permafrost. Waters (1967, p. 55) recently suggested that a permafrost layer may occur 1 or 2 meters below the lunar surface. Lunar permafrost might form by the freezing of volcanic water or other endogeneous volatile substances. The surficial fragmental layer in ellipse II-6-1 would be thick enough for the formation of permafrost.

Scientific Possibilities

The primary scientific objective ought to be the sampling of the surficial fragmental layer and the rocks protruding through it or lying on it. The diversity in dimension, texture, and probably in composition of these rocks is shown on many of the Surveyor photographs.

The youngest craters (Cc_6 to Cc_8), which are smaller than 50 meters in diameter and therefore not outlined on the map, will yield much information on impact debris and cohesive material derived from the mare substratum. The block fields and the blocks within the fields around small young craters probably are relatively small--a distinct advantage to trafficability.

The rim materials of all craters Cc_4 or older display the same density of superposed craters as the adjacent mare. The implication is that the steady state in the impacting process has not yet been reached for craters Cc_5 or younger. Therefore, the stability of rock aggregates and of rock compressed by shock could be estimated from the percentage of rock types, systematically collected on Cc_5 craters or younger. Shock-compressed rock derived from terrestrial impact craters is more fragile and disintegrates at a faster rate than coherent fragments derived from bedrock (D. Roddy, oral commun.). By analogy, shock-compressed rock on the Moon may also disintegrate at a faster rate.

Study of high-pressure and high-temperature minerals produced by shock has shown that some are stable for very long periods of geologic time, even when no longer in equilibrium with their environment (E. C. T. Chao, oral commun.). Some minerals may be vitrified by shock; conceivably, different mineral glasses have different rates of devitrification. Sampling of crater materials of different ages may yield information on devitrification rates. Likewise, the outer skin of surficial lunar rocks may supply information on the residue of proton bombardment.

Sampling of large blocks, 2 meters or more in diameter, if feasible, may provide stratigraphic evidence if they were excavated from a greater depth in the lunar substratum than ejecta of smaller size. Comparison of the morphology of big blocks on the rim of large subdued Cc_1 and Cc_2 craters (as in the northern part of the area) with the morphology of blocks on the rims of large young Cc_6 craters (as in the southwest part of the area) may lead to better understanding of the processes of lunar erosion.

Material deep under overhangs or beneath large blocks should be probed for lenses of ice or other frozen volatiles. Photography of the landscape traversed and of the rocks sampled is an integral part of the geologic investigation.

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Contact

Dashed where uncertain.

(Cc4)

Concealed contact

Dots show limit of buried unit, where topographically expressed. Buried unit indicated by symbol in parentheses.

(3)

Buried small crater

Lineament

Very gentle scarp or gentle narrow trough in mare.

Scarp

Barbs point downslope. Gentle mare scarp or mare ridge escarpment. Interpretation: May be fault or flow front.

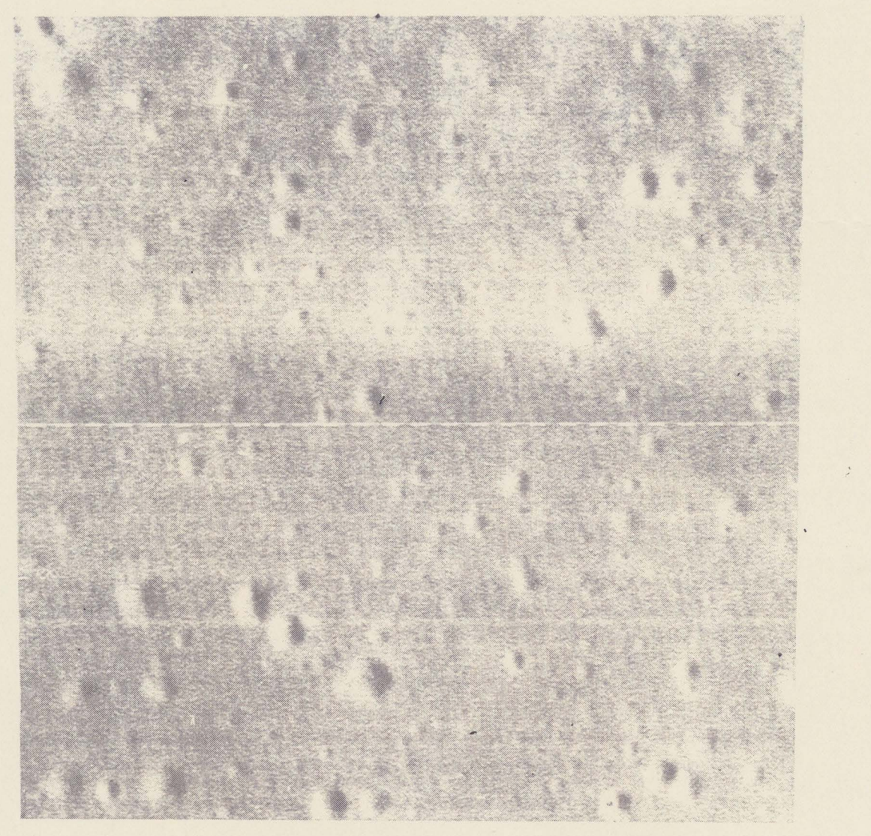
Very low mare ridge

Block field

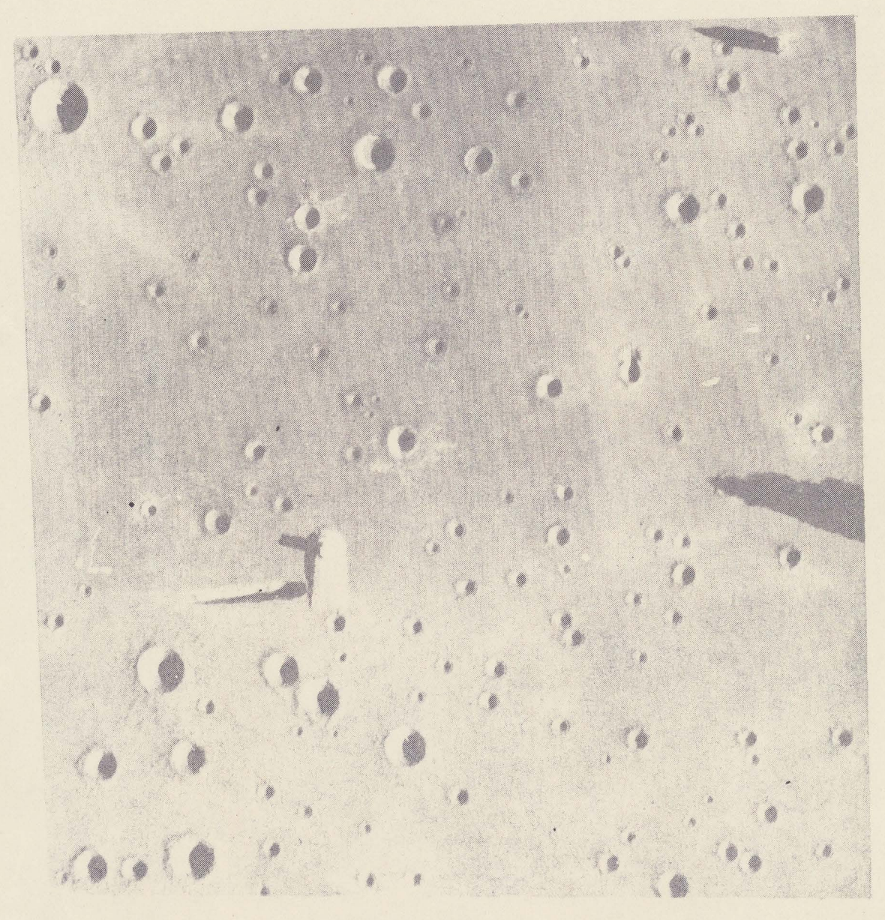
Area where blocks larger than 1 meter in diameter are abundant.

Simulated cratered area

Square area outlined by dots on the map was selected for simulation at Cinder Lake, about 10 miles northeast of Flagstaff, Ariz., because of its relatively low crater density and small diameter of its craters. The area in site II P-6 and the simulated area are shown below for comparison at the approximate scale of 1:2,540. Approximate North is at top of pictures.



Area in ellipse II 6-1 approximately 262 meters by 262 meters.



Area of about the same dimensions simulated at Cinder Lake, Arizona.

Cm

Mare material

Characteristics
Very gently undulating material, restricted to two subcircular areas, in the northeastern and west-central parts of the map. Cc_3 and older craters appear truncated by mare material, whereas ejecta of Cc_4 and younger craters extend onto it. Structural control of this subcircular area is suggested by its being wedged between two low mare ridges; lineaments trend northeastward across it. There is a lack of craters larger than 75 meters in diameter.

Interpretation
Volcanic material at the top of a "volcanic sink," possibly resembling terrestrial calderas or very large feeder dikes. The apparent structural control, perhaps along the northeast component of the lunar grid, suggests a nonrandom process of formation. An alternate interpretation of the subcircular area is that it represents a crater, older than the latest episode of volcanic activity on the mare, and partly filled with mare material. The area in the northeastern part of the map is perhaps thinly mantled with ray material from the crater Theophilus.

Interpreted engineering properties
Fragmental material at the surface probably extends to a depth of 4-6 meters. The surface generally slopes less than 5°. The density of craters 5-75 meters in diameter is less than 5 percent. Blocks less than 2 meters in diameter are likely to occur in scattered areas mantled with Theophilus ejecta.

Scientific interest
The low density of craters larger than 75 meters in diameter may be related to late emplacement of the mare material, or to a faster rate of crater erosion related to subsidence of material in caldera or feeder dike.

Crt

Ray material

Characteristics
Band, 1-3 km wide, or material slightly brighter than adjacent material. This band is the western part of a wider band (5-10 km) mapped in site II P-6 at the scale of 1:100,000 (Grolier, 1967).

Interpretation
Probably a discontinuous and thin layer of ejecta over mare units m_2 and Cm_2. This ray material is traceable to the crater Theophilus 320 km south of the site.

Interpreted engineering properties
The slightly greater brightness of the material perhaps is due to a greater surficial roughness than in surrounding mare. This surficial roughness may be caused by blocks smaller than 2 meters in diameter, yet large enough to constitute trafficability hazards.

Scientific interest
The effect of crater ejecta on the lunar surface, hundreds of miles from the primary impact crater, is not always clear; ray material from Theophilus perhaps is fine enough for its cratering effect on the mare surface to be negligible.

Cch

Chain crater material, irregular

Characteristics
Materials of shallow Cc_1 and Cc_2 craters, generally more than 125 meters in diameter, alined most commonly northeastward. Blocks larger than 2 meters are absent. Patterned ground is conspicuous.

Interpretation
Probably materials of secondary impact craters. The chain-forming craters mostly are subdued and of early Copernican age.

Interpreted engineering properties
The thickness of the surficial fragmental layer probably is thicker than on the adjacent mare.

Scientific interest
Some of the crater chains are oriented northeastward. Structural control along one direction of the lunar grid perhaps could be checked in the field.

Ccci	Cccr

Crater cluster material, irregular

Characteristics
Ccci, crater materials, undivided. Material of shallow contiguous craters, generally 125 meters or more in diameter, and of irregular outline. Clusters consist of subdued Cc_1 and Cc_2 craters. Only block field is in the largest cluster in the northwestern part of the map. Patterned ground is conspicuous.
Cccr, crater rim material. Relatively smooth material, probably consisting of crater ejecta. Slopes are generally less than 15 degrees. Superposed craters are less than 75 meters in diameter. Blocks less than 1 meter in diameter may occur near the rim crest.

Interpretation
Materials in impact craters and associated ejecta blankets; some material may be of secondary impact origin.

Interpreted engineering properties
Surficial fragmental layer probably thicker than in any of the mare units, because of faster mass movement of debris down crater walls and slopes of the rim, and also because the originally fragmental ejecta was churned by subsequent impacts. For the same reasons, the material of the surficial fragmental layer on the smaller irregular craters may be more finely divided than on the mare. In the largest irregular crater, blocks and patterned ground may constitute landing and trafficability hazards.

Scientific interest
The irregular outline of some cluster-forming craters may be due to deformation along the main directions of the lunar grid, rather than dependent on the dynamics of impact.

md

Mare dome material

Characteristics
Material of subcircular mare dome, about 200 meters in diameter and slightly elongated to the northwest. The material forms a slight bulge in the surface of mare unit m_4, and apparently is not directly related to a linear mare ridge.

Interpretation
Material of small volcanic plug, mantled with surficial fragmental layer.

Interpreted engineering properties
Surficial fragmental material derived from dome material perhaps is denser and more felsic than fragments of ordinary mare material.

Scientific interest
Very small mare domes either are primary depositional (volcanic) features or they might result from differential erosion of mare material.

Crater materials

NOTE: Crater materials occupying larger areas, including deposits outside the rim crest, are outlined by geologic contacts; materials occupying smaller areas are assigned numbers only.

Characteristics

8

8, crater materials, undivided. Rim crest diameter 75-125 meters. Includes very bright or dark ray material; crater density on rim less than that of surroundings; crater rim crest sharp.

7	Cc7

7, crater materials, undivided. Rim crest diameter 75-125 meters. Includes very bright ray material; floor material hummocky; crater density on rim less than that of surroundings; crater rim crest slightly subdued.
Cc_7, crater materials, undivided. Rim crest diameter 125-400 meters. Includes bright ray material; no blocks resolvable in rim or wall deposits; structure abundant in floor; crater rim crest slightly subdued.

6	Cc6	Ccr6

6, crater materials, undivided. Rim crest diameter 75-125 meters. Includes bright halo material; crater density on rim less than that of surroundings; crater rim crest slightly subdued.
Cc_6, crater materials, undivided. Rim crest diameter 125-400 meters. Includes bright halo material; blocks moderately abundant in wall material; strong structure occurs in floor; crater density on rim less than that of surroundings; crater rim crest slightly subdued.
Ccr_6, crater rim material. Wider than 125 meters. Abundant blocks throughout for largest craters, blocks occur around rim crest of craters less than 150 meters in diameter; crater density less than that of surroundings.

5	Cc5	Ccr5

5, crater materials, undivided. Rim crest diameter 75-125 meters. Unit not bright; crater density on rim slightly less than that of surroundings; crater rim crest subdued.
Cc_5, crater materials, undivided. Rim crest diameter 125-400 meters. Unit not bright; blocks present in wall material; slightly subdued structure occurs in floor; crater density on rim slightly less than that of surroundings; crater rim slightly subdued but well defined and raised.
Ccr_5, crater rim material. Wider than 125 meters. No blocks present; crater density less than that of surroundings.

4	Cc4	Ccr4

4, crater materials, undivided. Rim crest diameter 75-125 meters. Unit not bright; crater density on rim same as that of surroundings; associated crater has shape of shallow bowl; crater rim crest slightly raised.
Cc_4, crater materials, undivided. Rim crest diameter 125-400 meters. Unit not bright; no blocks or few blocks present in and around most craters, large block fields in others; concentric structure very slight in rim deposits of some craters; associated crater has conical shape or shape of shallow bowl; crater rim crest subdued.
Ccr_4, crater rim material. Wider than 125 meters. Conspicuous block fields present in rim deposits of some craters; crater density slightly less than that of surroundings.

3	Cc3	Ccr3

3, crater materials, undivided. Rim crest diameter 75-125 meters. Associated crater is gentle pan-shaped depression.
Cc_3, crater materials, undivided. Rim crest diameter 125-400 meters. Few blocks present in rim deposits, abundant blocks in wall; patterned ground occurs in wall; crater density in rim same as that of surroundings; associated crater has shape of shallow bowl; crater rim crest subdued.
Rim crest diameter 400-800 meters. Few blocks present in floor and wall material; concentric structure slight in rim; crater density on rim same as that of surroundings; associated crater has shape of shallow bowl.
Ccr_3, crater rim material. Wider than 125 meters. No block fields present except in higher part of rim; crater density about the same as that of surroundings. In southwestern part of map, rim material of two craters is wider than the crater diameter.

2	Cc2	Ccr2

2, crater materials, undivided. Rim crest diameter 75-125 meters. Associated crater is very gentle depression.
Cc_2, crater materials, undivided. Rim crest diameter 125-400 meters. Blocks present in wall material; patterned ground in wall; associated crater is very gentle depression.
Rim crest diameter 400-800 meters. Blocks present on rim crest; patterned ground occurs in wall and floor material; crater density on rim same as that of surroundings; associated crater has shape of shallow bowl.
Ccr_2, crater rim material. Wider than 125 meters; occurs only around craters more than 400 meters in diameter. No block fields present except in higher part of rim material; crater density same as that of surroundings.

Cc1	Ccr1

Cc_1, crater materials, undivided. Rim crest diameter 125-400 meters. No blocks present in wall material; patterned ground occurs in wall and floor; crater density on rim same as that of surroundings; associated crater is pan-shaped depression.
Rim crest diameter 400-800 meters. Blocks present in wall material; patterned ground occurs in wall and floor; crater density on rim same as that of surroundings; associated crater is pan-shaped depression.
Ccr_1, crater rim material. Few blocks present in upper part of rim; crater density same as that of surroundings.

Interpretation
Poorly sorted fragments in and around primary and secondary impact craters; as in deposits of terrestrial impact craters, no more than 2 percent of the fragments are likely to be shock compressed or to contain high-pressure and high-temperature minerals resulting from shock. Volcanic deposits may occur where rim deposits are tongue shaped (Cc_4 craters in the northwest and southwest parts of the map) or where the rim deposit is much wider than the crater (Cc_3 crater in the extreme southwest part of the map). Morphology of craters is progressively modified by mass wasting, tectonism, and superposition of craters and ejecta with increasing age (Cc_1, oldest; 8, youngest).

Interpreted engineering properties
All block fields constitute landing and trafficability hazards. Most 8, 7, Cc_7, 6, Cc_6, 5, and Cc_5 craters are likely to have scattered blocks in and around them, up to 1 meter in diameter, and therefore, these craters are trafficability hazards. Depth to cohesive substrate in large subdued craters, Cc_3, Cc_2, and Cc_1, and on the rims of all craters is higher than on the mare.

Scientific interest
The rim material of many craters largely consists of fragments of mare material excavated from the mare substratum at the time of impact. The analysis of ejecta samples may help elucidate the lithology of the mare substratum, even though the latter cannot be sampled in place because of trafficability hazards down the walls and floors of craters. Shock-compressed rock fragments in the ejecta probably disintegrate faster than substratum fragments; the relative abundance of these two types of rocks around any one crater perhaps may be used as an index of crater age.

m_4

Mare material

Characteristics
Relatively level material with well-developed patterned ground. Less than 5 percent of the terrain is covered by craters, 5-75 meters in diameter. Craters larger than 125 meters cover about 10 percent of the unit.

Interpretation
Volcanic flows mantled with fragmental layer.

Interpreted engineering properties
Fragmental layer at the surface extends to a depth of 4-5 meters.

Scientific interest
Volcanic flows probably are among the youngest in site II P-6, and do not extend much beyond the area mapped at the 1:25,000 scale. Yet, patterned ground is conspicuous on an apparently young surface—a possible time of emplacement as old as late Eratosthenian.

m_2

Mare material

Characteristics
Gently undulating material in the southern third and eastern half of the map. Low mare ridges trend northeastward across this unit; they are parallel or subparallel to set of grooves and low scarps, which account for most of the relief on the mare. The swells and troughs of the patterned ground in and around shallow depressions [illegible] unit m_2. Less than 5 percent of the terrain is covered by craters, 5-75 meters in diameter. The crater density in this diameter range is similar to the other mare units. Craters larger than 125 meters are more abundant than in the other three mare units; they cover about 15 percent of the terrain. Lineaments are more abundant than in the other mare units.

Interpretation
Volcanic flows, covered in part with ejected debris from Theophilus and in part with superposed craters. Small indistinct scarps may mark the location of flow fronts.

Interpreted engineering properties
Fragmental material at the surface probably extends to a depth of 6-10 meters, greater than in other areas of the map. Blocks less than 2 meters in diameter are likely to occur in scattered areas mantled with Theophilus ejecta.

Scientific interest
Typical mare material, generally concealed under surficial fragmental layer, even along low scarps and low ridges. The material is likely to be exposed in place only in the walls of some Cc_4 and younger craters.

COPERNICAN SYSTEM

IMBRIAN OR ERATOSTHENIAN SYSTEMS

~~Moon (Ellipse area). Geol. 1:25,000. 1967.~~
~~sheet 2-6-1,~~
~~cop. 1.~~