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INTERAGENCY REPORT: ASTROGEOLOGY 17

GEOLOGIC MAPS OF EARLY APOLLO LANDING SITES OF SET C

By

N. J. Trask

October 1969

Prepared under NASA Contract T-66353G

This report is preliminary and has not
been edited or reviewed for conformity
with U.S. Geological Survey standards
and nomenclature.

Prepared by the Geological Survey for the
National Aeronautics and Space
Administration

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ABSTRACT

Comparison of the five potential early Apollo landing sites of set C reveals significant geologic similarities and differences. No two sites are identical; the geology of each should be considered in the interpretation of returned lunar samples and observations. Geologic maps of each site have been prepared at scales of 1:5,000, 1:25,000, and 1:100,000.

Features emphasized on the 1:5,000-scale maps are common to all the sites and include mainly the widespread lunar regolith and small craters of varied age and origin. Because they cover the lunar surface and because mobility will be limited on early missions, these ubiquitous features will be the main objects of scientific inquiry during the first manned landings.

Regional geologic differences among the sites are more apparent on the 1:25,000- and 1:100,000-scale maps. Mare materials in sites 2 and 3 belong mainly to the Imbrian System; the materials in site 3 appear to be younger than those in site 2. Mare materials in sites 4 and 5 belong entirely to the Eratosthenian System. Most materials in site 1 have been assigned to the Copernican System. They consist of a young mantle of relatively low-cohesion material that covers an older cratered terrain, probably part of the terrae. Typical mare material occurs only in the eastern extremity of site 1. Ray materials and secondary impact craters related to large rayed primary impact craters are present in several of the sites.

INTRODUCTION

The U.S. Geological Survey has prepared geologic maps of potential early Apollo landing sites at scales of 1:100,000, 1:25,000, and 1:5,000. The 1:100,000-scale maps show the regional setting of each landing site and can be compared to smaller scale reconnaissance geologic maps which cover most of the earthside hemisphere of the Moon.[1] The 1:25,000-scale maps show the details of each landing ellipse and its immediate vicinity. The 1:5,000-scale maps show small details in the central part of each landing ellipse. Five sites in the lunar equatorial belt (fig. 1)--set C--are potential targets for a landing on the early missions. They are on either side of the 0° meridian to provide alternate sites during a given month in case of delays. Sites 4 and 5, north and south of the equator, are accessible at different times of the year. The 5 sites were picked from a group of some 25 photographed by Lunar Orbiter. Earlier, longer lists of sites were labeled A and B.

This report describes the geology of the five sites of set C. Features common to all sites are discussed in one section and the special features of each site in a subsequent section. These are both preceded by a discussion of how the sites were mapped.[2]

ACKNOWLEDGMENTS

This work was performed under contract T-66353G from the National Aeronautics and Space Administration. The raw material for the study was the magnificent series of Lunar Orbiter photographs obtained over the period from August 1966 to August 1967 by the Langley Research Center, NASA. Base materials for the maps are photomosaics prepared by the Army Map Service and the U.S. Air Force's Aeronautical Chart and Information Center. The cooperation and assistance of John Dietrich and James Sasser of the Manned Spacecraft Center, NASA, are gratefully acknowledged. Farouk El-Baz, Bellcomm, Inc., provided many helpful suggestions.

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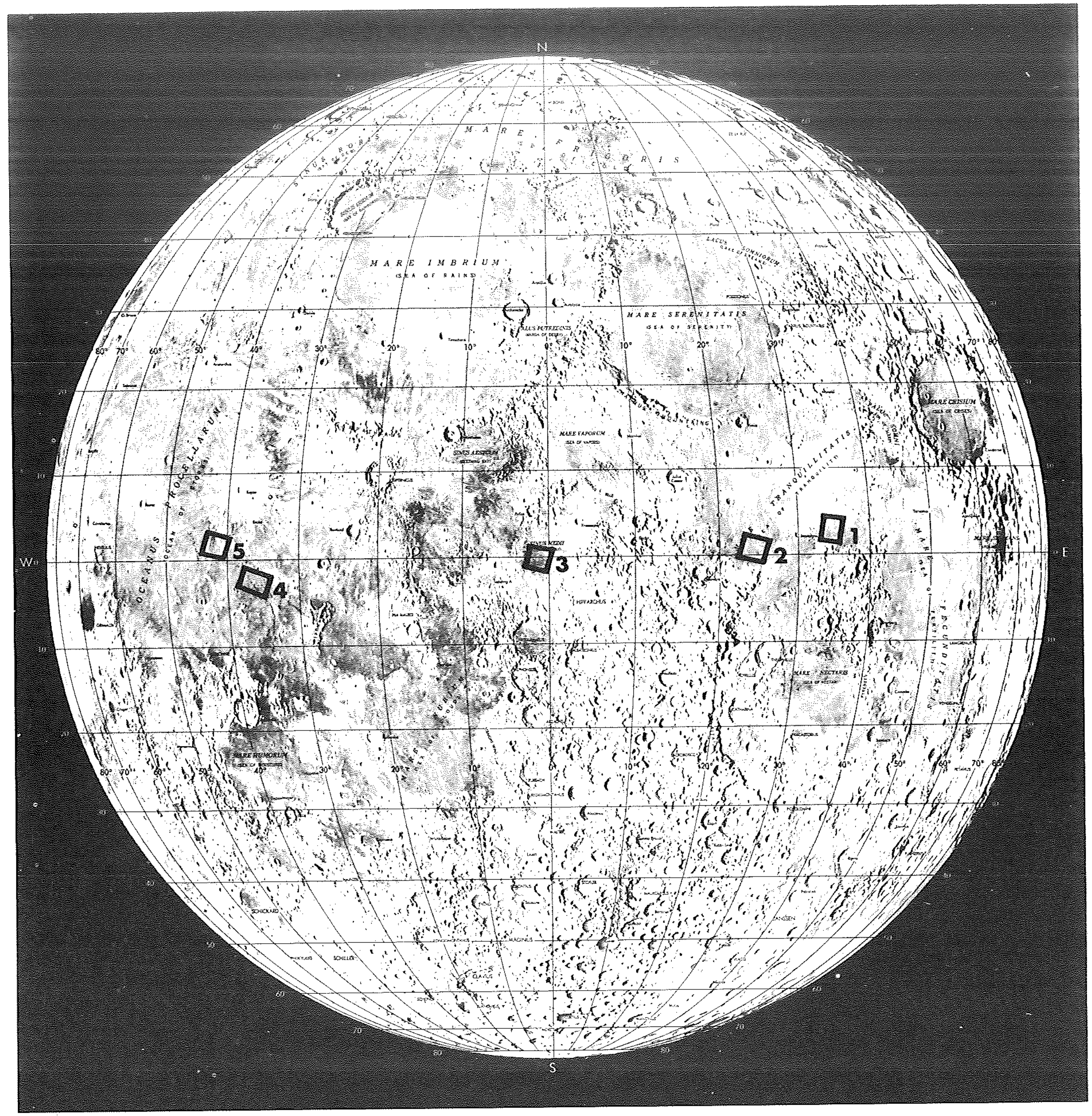
[1] Maps published as part of Miscellaneous Geologic Investigations series of the U.S. Geological Survey, at scales of 1:1,000,000 and 1:5,000,000.

[2] A new site, 7, was added to the list after preparation of this report and is now being mapped. It is located at long 23° 30' W., lat 3°00' S. and includes the Surveyor III landing site.


N
S
W
E
MARE FRIGORIS
MARE IMBRIUM
(SEA OF RAINS)
MARE SERENITATIS
(SEA OF SERENITY)
MARE CRISIUM
(SEA OF CRISES)
MARE VAPORUM
(SEA OF VAPORS)
TRANQUILLITATIS
OCEANUS PROCELLARUM
MARE NECTARIS
(SEA OF NECTAR)
MARE HUMORUM
1
2
3
4
5

LANDING SITE NUMBER (official designation appears on 1:5,000-scale map)	5	4	3	2	1
LUNAR ORBITER SITE NUMBER (appears on 1:100,000-scale map)	II P-13	III P-11	II P-8	II P-6	II P-2
OLD ELLIPSE NUMBER (appears on 1:25,000 scale map)	West One	West Two	Central One	East One	East Two
LONGITUDE:	41° 40' W.	36° 25' W.	1° 20' W.	23° 37' E.	34° 00' E.
LATITUDE:	1° 40' N.	3° 30' S.	0° 25' N.	0° 25' N.	2° 40' N.
LOCATION:	Oceanus Procellarum		Sinus Medii	Mare Tranquillitatis	
	Southwest of Kepler	Northeast Wichmann R		South-southwest	South-southeast
LAC CHART:	Kepler 57	Letronne 75	Mare Vaporum 59	Julius Caesar 60	Taruntius 61
AIC CHART:	Maestlin 57D	Wichmann 75B	Pallas 59D	Arago 60C	Maskelyne D 61D

Figure 1.--<u>Location of five early Apollo landing sites of set C.</u>

The authors of the 15 maps covering the five sites at three scales are listed in table 1. Without the long hours spent in preparing the maps, this summary would not have been possible; however, responsibility for statements made in this report rests solely with myself. Personnel of the U.S. Geological Survey who participated in the analysis of Orbiter photographs of the five sites, in addition to those listed in table 1, were H. J. Moore II, T. A. Mutch, H. A. Pohn, R. S. Saunders, and H. G. Wilshire. Harold Masursky, U.S. Geological Survey, provided continuing advice and encouragement.

GEOLOGY OF THE MOON, GENERAL

Geologic maps of the Moon at relatively large scales, like those at small scales, are based on the same fundamental principles of superposition and intersection employed in mapping terrestrial geology. In general, materials that are believed to have formed under the same conditions and at approximately the same time are grouped into units, and the relative ages of the units are estimated. The surface of the Moon is heterogeneous. Its features were apparently shaped both by impact of objects from space and effusion of material brought up from the Moon's interior by some form of volcanism.

The fundamental geologic units of the Moon are portrayed most easily at the smallest map scales. The differences between the maria and terrae and between rayed and unrayed areas show up readily on photographs of the entire disk. Basic subdivisions of the maria and terrae are on the order of tens of kilometers across and are shown conveniently on the reconnaissance geologic maps at a scale of 1:1,000,000. Additional subdivisions, 1 to 10 km across, can be shown on 1:100,000-scale maps, but the boundaries of most of these are indefinite. Except for a few minor units, no additional basic subdivisions of the surface materials can be made on the 1:25,000- or 1:5,000-scale maps. Lunar surface materials become progressively harder to subdivide at larger scales,

Table 1.--Authors of geologic maps of Apollo landing sites of set C

Map area	Scale: 1:100,000	Scale: 1:25,000	Scale: 1:5,000
Orbiter II P-2	M. H. Carr		
Ellipse East Two (II P-2)		D. E. Wilhelms	
Site 1 (East Two) (selected geologic features)			D. E. Stuart-Alexander
Orbiter II P-6	M. J. Grolier		
Ellipse East One (II P-6)		M. J. Grolier	
Site 2 (East One) (selected geologic features)			M. N. West
Orbiter II P-8	L. C. Rowan		
Ellipse Central One		N. J. Trask	
Site 3 (Central One) (selected geologic features)			N. J. Trask and G. G. Schaber
Orbiter III P-11	David Cummings		
Ellipse West Two (III P-11)		M. N. West and P. J. Cannon	
Site 4 (West Two) (selected geologic features)			P. J. Cannon
Orbiter II P-13	M. H. Carr and S. R. Titley		
Ellipse West One (II P-13)		S. R. Titley and N. J. Trask	
Site 5 (West One) (selected geologic features)			Jerry Harbour and R. E. Sutton

probably because impacting meteoritic particles and, possibly, high-energy solar particles and radiation tend to blur the differences between surface materials that are thin or limited in extent.

All five successful Surveyors provided evidence of a layer of surficial debris--termed the lunar regolith (Shoemaker and others, 1967a, p. 41)--in the immediate vicinity of the landing sites. Indirect evidence that the regolith occurs everywhere on the Moon has been provided by Lunar Orbiter photographs. Thus, the original surfaces of all lunar geologic units, except the very youngest, have probably been greatly modified by development of this debris layer. The 1:1,000,000-scale reconnaissance maps attempt to show the geologic units beneath the regolith. On the geologic maps of the Apollo sites, many of the units represent crater materials which are contemporaneous with and have contributed to the regolith; these are shown on a background of basic subdivisions of the mare and terra materials that are interpreted to underlie the regolith.

Geologic units on the 1:1,000,000 maps and on the Apollo maps at 1:100,000 and 1:25,000 are assigned positions in the standard lunar time scale (Shoemaker and Hackman, 1962; Wilhelms, 1966; McCauley, 1967). The 1:5,000-scale maps show the regolith itself which does not have a discrete age and is not assigned to a time-stratigraphic division. The many craters shown at 1:5,000 are also not assigned to the time-stratigraphic divisions both for the sake of clarity and because it is difficult to estimate the relative ages of small craters.

ASSIGNMENT OF MATERIALS TO TIME-STRATIGRAPHIC UNITS

Definitions and Conventions

Time-stratigraphic units are planetwide groupings of rocks that were formed in a specific interval of time. The lunar stratigraphic column has been worked out for the region around Mare Imbrium, where a series of well-defined map units is visible (Shoemaker and Hackman, 1962). Some of these units can be correlated with similar-appearing units in other parts of the Moon. The major time-stratigraphic divisions are called systems; each system corresponds to a period of time marked by a major event in the Mare Imbrium region, as listed in table 2.

Table 2.--Lunar stratigraphic and time divisions, as shown on 1:1,000,000-scale maps (top to bottom--most recent to oldest)

PERIOD (SYSTEM)	EVENTS
Copernican	Formation of large ray craters (such as Copernicus)
Eratosthenian	Formation of large craters whose rays are no longer visible (such as Eratosthenes)
Imbrian	Deposition of most of the mare material. Formation of pre-mare craters (such as Archimedes) Formation of the Imbrium basin

Materials interpreted as predating the formation of the Imbrium basin (other mare basin materials and crater materials) are designated pre-Imbrian and are not assigned to systems.

Geologic units are arranged in the map explanations with the youngest units at the top and the oldest units at the bottom. The distinguishing characteristics of each unit are given first, followed by an interpretation of the origin of the unit. The units are grouped in systems on the 1:100,000- and 1:25,000-scale maps, as shown by (1) the brackets along the right-hand margin of each explanation, and (2) the names of the systems in large capital letters. The capital letter in the symbol used for each unit stands for the system to which that unit is assigned; the small letters are descriptive abbreviations that indicate the type of material (thus Ec, Eratosthenian crater material; Im, Imbrian mare material). All three systems are represented in some

Apollo landing sites, only the Eratosthenian and Copernican in others. Pre-Imbrian or possible pre-Imbrian materials occur in a few sites.

Materials of most small features on the lunar surface (largely craters less than 100 m in diameter) belong to the Copernican System. Numbers have therefore been added to the symbols used for most Copernican units in order to provide a finer breakdown by relative age. The highest numbers are for the youngest units (thus, Cc_6 is material of a relatively young Copernican crater, Cc_1 of a relatively old Copernican crater).

Assignment of Crater Materials

Assignment of crater materials to the time-stratigraphic units (systems) is critical both because craters are the most widespread and readily mapped features seen on Orbiter photographs and because the relative ages of surfaces of regional extent can be estimated partly on the basis of the oldest craters developed on them. A continuum of crater types from sharp and fresh-appearing to highly subdued is present on most level and gently rolling surfaces on the Moon. The relative ages of craters are estimated on the basis of the following assumptions: (1) When first formed most craters appear fresh, (2) crater forms are progressively degraded, or subdued, with time, and smaller craters are more rapidly subdued than larger ones, and (3) the rate of crater degradation is approximately the same at all points in similar types of terrain on the Moon. These assumptions were used to tentatively assign ages to craters on a variety of surfaces whose relative age could be determined on independent grounds. The oldest craters on relatively old surfaces turned out to be older than the oldest craters on relatively young surfaces, a result which strengthens the validity of the assumptions. This outcome also implies that the function relating the number of craters produced to crater diameter is nearly the same for all surfaces at any given time, a situation most likely to obtain if most craters now visible on the lunar surface are of primary impact origin. These assumptions were used to construct figure 2, which provided the basis for mapping most craters on the 1:100,000- and 1:25,000-scale maps. The overall slope of the lines on the graph was fixed by the types of craters occurring on geologic units of well-established age; for example, craters in the form of gentle depressions are as much as 1 km across on the Imbrium basin ejecta blanket, which marks the base of the Imbrian system. The graph was also made to fit the 1:1,000,000-scale reconnaissance maps on which rayed craters as small as 3 to 5 km are assigned to the Copernican System and unrayed craters of the same size are assigned to the Eratosthenian. The six subdivisions within the Copernican System were chosen solely for convenience. Only the largest craters in each 1:100,000 and 1:25,000 map area are outlined by geologic contacts; intermediate-size craters are marked with numbers or letters only; the smallest craters are unmapped.

Although the system outlined by figure 2 gives a general idea of the relative ages of craters, it cannot be used to assign precise crater ages. Therefore, categories Cc_1 through Cc_6 are informal designations and are not proposed as formal subdivisions or series within the Copernican System. One difficulty is that all newly formed craters in the same size class probably do not have the same morphologies and depth/diameter ratios. Craters of internal origin and secondary impact craters may well be initially shallower relative to their diameter than primary impact craters of the same diameter, and their rim crests may be initially more subdued than those of primary impact craters. Attempts have been made on the geologic maps to show those craters interpreted most confidently as secondary impact craters and craters of internal origin--such as clearly alined groups of craters of the same apparent age--separately from the rest of the crater population. In estimating the ages of these special types, account is taken of the possibility that their initial forms may have differed significantly from those of young primary impact craters. Most

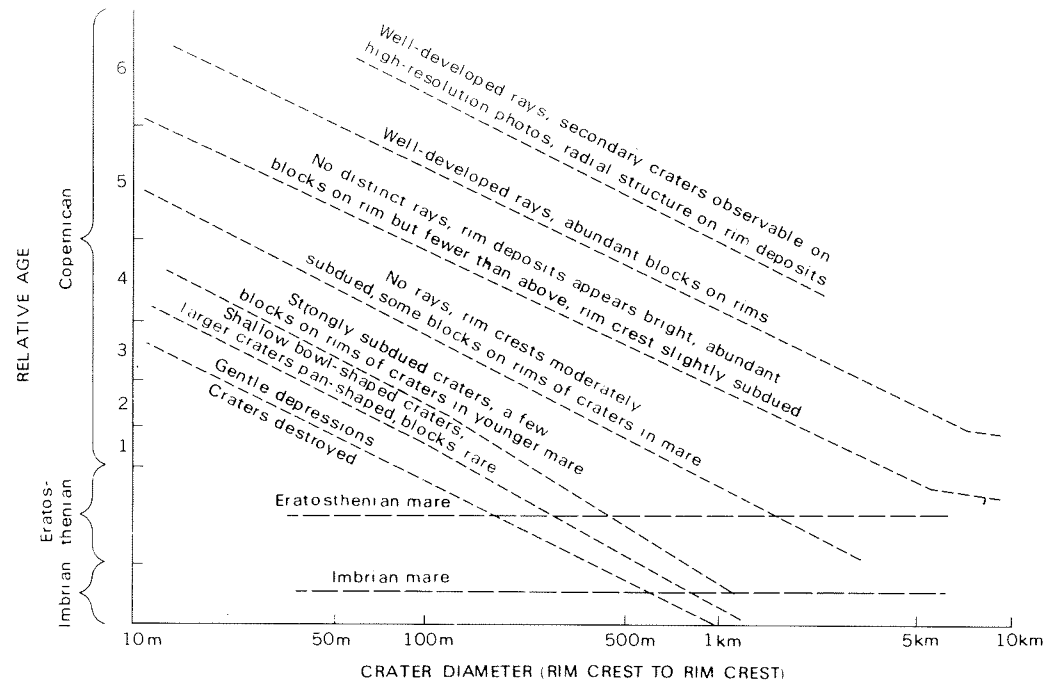


Figure 2.--Relationships between crater morphologies, crater diameters, and postulated ages.

single round craters are placed in the main sequence of crater classes shown in the right-hand column of each explanation; however, some of these craters may also have formed by secondary impact or by internal processes and thus may have been assigned to the wrong age category because their original configurations differed from those of fresh primary impact craters.

Another difficulty inherent in the crater-age assignment system is that physical properties of the lunar materials may also influence the initial morphology of a crater. In some units, a clear deficiency of craters with sharp, blocky rims suggests that the materials of these units may be less cohesive than other lunar materials. Craters in these less cohesive materials will appear to be subdued even when first formed.

Topography also exerts an influence on the rate of crater aging. On sloping surfaces, such as mare ridges, downslope movement of material appears to destroy craters faster than they would be destroyed on level or gently rolling terrain. Craters on ridges, therefore, are probably younger than the maps indicate. Locally, the rate of crater degradation may be temporarily augmented owing to the presence of a blanket of volcanic material. Thus, a crater degraded slowly by continuous bombardment of small meteoritic particles will be indistinguishable from one degraded rapidly by a volcanic blanket.

Despite these uncertainties, craters assigned to the Imbrian, Eratosthenian, and oldest Copernican (Cc_1) are almost certainly relatively old members of the total population because they are dotted with many small craters (3-20 m in diameter). Similarly, craters assigned to the middle and upper Copernican (Cc_2-Cc_6) must represent a sequence of decreasing age since they have progressively fewer such small superposed craters. In any local area on the same geologic unit, the crater designations are probably a reasonably accurate indication of relative age, but correlations between areas are less certain.

Assignment of Mare Materials

Mare units are distinguished on the Apollo site maps mainly on the basis of differing crater populations, which in turn appear to be related to age, mechanical properties of the materials, or mode of emplacement. Whether the units also have differing chemical or mineralogical properties cannot be determined at present. A limited amount of information on the chemical properties of the maria has been provided by the Surveyor alpha particle scattering experiments (Turkevich and others, 1968, 1969). Analyses of typical mare material at one point in Sinus Medii and at another in Mare Tranquillitatis indicated a chemistry similar to that of iron-rich basalt with an exceptionally high content of titanium at the latter site. The mare materials apparently vary both in age and composition from place to place, although the contacts between contrasting materials have been rendered indistinct by the development of the lunar regolith.

The oldest craters that have formed on the mare material in sites 4 and 5 (Oceanus Procellarum) are Eratosthenian; and in site 5, craters assigned to the Eratosthenian are partly covered by the mare material. These mare materials are therefore assigned to the Eratosthenian System. Fresh-appearing domes and mare ridges, suggestive of relative youth, are also present in sites 4 and 5. The oldest craters in site 3 (Sinus Medii) are likewise Eratosthenian, but gentle depressions and subdued craters attain larger sizes than in sites 4 and 5 and therefore are older according to the age relationships illustrated in figure 2. Thus, the mare material in site 3 is estimated to be latest Imbrian in age. Large Imbrian craters are present on the mare material of site 2 (Mare Tranquillitatis), which is accordingly mapped as Imbrian, older than that in site 3. These surfaces of increasing age can be thought of as successively lower horizontal lines on figure 2, with gentle depressions attaining greater sizes on the older surfaces. Note that the ages assigned to the mare materials apply only in and around the landing sites and not to entire maria.

The Eratosthenian mare materials in Oceanus Procellarum appear to be confined to small patches, which were chosen as potential landing sites because they appeared dark and smooth on telescopic photographs.

Southern Mare Tranquillitatis has in general fewer craters 50 to 125 m in diameter than the younger mare material in parts of Sinus Medii and Oceanus Procellarum. This seeming paradox suggests that the rates of crater production and (or) degradation have not been exactly the same on all surfaces. The excess craters on the younger mare surfaces may have formed endogenetically or by secondary impact; alternatively, craters may be missing in southern Mare Tranquillitatis because of burial by a layer of younger material or because of especially rapid degradation; or a combination of all these processes may have produced the crater populations presently observed.

Assignment of Terra Materials

Site 1 is the only one with extensive terra materials. Much of this material has a slightly higher albedo than adjacent typical mare material, though not as high as typical terra material. The terrain occupied by the terra material is gently undulating, like some terra elsewhere, but has greater relative relief than typical mare material. The crater population includes several large subdued craters of apparent Imbrian and Eratosthenian age, which are interpreted as buried, and there is a very marked deficiency of craters of intermediate sizes (50-200 m in diameter) and ages (Ec-Cc_1). The areal distribution of this material and its relation to the mare material (discussed on p. 19-20) suggest that its age is Copernican.

SCIENTIFIC SIGNIFICANCE OF FEATURES COMMON TO ALL SITES

Features common to all sites--the regolith, craters and certain other landforms--are discussed briefly in this section. More detailed descriptions are given in the Definitive Experiment Plan of the Apollo Lunar Geology Investigators, April 1968.

Regolith

The regolith appears to be present everywhere on the Moon and presumably will be studied and sampled on all missions, including those with very limited time for Extra Vehicular Activity (EVA). The significance of early samples of the regolith, the first materials known definitely to have come from the Moon, is obvious. Most investigators believe that the regolith at any locality is composed partly of fragments of the underlying bedrock and partly of material transported ballistically from greater distances on the Moon (Shoemaker and others, 1967a, p. 21). Underlying bedrock units, not the regolith itself, are shown on the 1:100,000- and 1:25,000-scale maps. On the 1:5,000-scale maps the regolith is divided into units, according to the bedrock units which underlie it. The symbols for the regolith on each 1:5,000-scale map are abbreviations of the symbols used for the bedrock units on the 1:25,000-scale map of the same area. The regolith probably develops in such a way that the contacts between subunits of the regolith will be broad zones rather than sharp lines; and since the bedrock units are distinguished mainly by differing crater populations, which may not correspond to differences in composition, there may be no differences at all in materials on either side of these contacts. The significance of the various bedrock units in the different sites is discussed in a later section describing the geology of the five sites. During a single early mission, sampling will probably be limited to the regolith above only one bedrock unit.

Craters

The next most ubiquitous materials on the surface are those associated with specific craters. The craters occur in all sizes down to those a centimeter or so across, as photographed by Surveyor. All mappers and most other workers agree that the greatest scientific interest attaches to those craters large enough to have penetrated bedrock beneath the regolith and young enough so that the resulting ejecta deposits can be clearly differentiated (Apollo Lunar Geology Experiment, Definitive Experiment Plan, p. 7.8). Around craters too small to have penetrated the regolith and around relatively old craters, Surveyor and Orbiter photographs suggest that there may well be little distinction between the crater deposits and the adjacent regolith. Samples that display shock phases or volcanic textures will be of value for deciphering crater origins only if their parent craters can be definitely identified. Also, of all the fragmental material on the surface, blocks ejected from young craters have most clearly been derived from the underlying bedrock unit. These bedrock samples should be less contaminated by debris derived from more distant parts of the Moon than samples from intercrater areas which have been recycled through the regolith one or more times. If exposure ages of crater materials are determinable, samples from craters of various ages might be used to assess the history of radiation on the lunar surface and would be helpful for assigning absolute ages to the lunar geologic time scale.[3]

Crater materials have been mapped according to interpreted relative age on the 1:100,000- and 1:25,000-scale maps. For cartographic convenience, the mapping has included craters of smaller diameters for the younger craters than for the older craters on both the 1:100,000- and 1:25,000-scale maps. The younger craters, however, are widely spaced on the 1:25,000-scale maps; thus, craters visited on the early Apollo missions will probably fall in the unmapped category. All relatively young craters larger than several meters in diameter have therefore been shown on the 1:5,000-scale maps, though by different conventions. Craters surrounded by resolvable blocks (eight or more), craters surrounded by

[3] M. J. Grolier has further suggested that the ejecta around a fresh crater may have several components and that the components may disintegrate at different rates. After observations had been made on a number of craters, it might be possible to estimate crater ages quickly from the relative abundance of different components in the ejecta surrounding them.

bright halos, and craters with very sharp rims are all shown by special symbols. Although all of these craters are relatively young, some of the larger ones may be older than some very small unmapped craters (fig. 2).

It is difficult to estimate the relative ages of the very small craters on Orbiter photographs from the presence or absence of blocks for at least three reasons: (1) Blocks may be present but smaller than the limit of photographic resolution. (2) They may be absent because the crater did not penetrate bedrock. (3) They may be absent because any blocks which the crater may have originally had on its rim have been subsequently pulverized and destroyed. Also, variations in photographic quality are most serious when examining the smallest features. If it is decided on a given mission to sample ejecta from craters with a spectrum of ages, then samples from a small bright-halo crater, an intermediate-size sharp-rimmed crater, and a large blocky-rim crater would probably yield the range of materials desired. However, visual estimates of relative age made by the astronauts on the ground might well be an essential step in obtaining such a suite of samples.

Besides individual circular craters, all sites contain a variety of special types of craters. Those interpreted as secondary impact craters are probably of the greatest significance. Included in this category are most craters mapped as "crater clusters" at all scales. Some of these clusters appear to be quite clearly related to a primary impact crater because they are concentrated along lines roughly radial to the larger crater and some of them lie along rays (visible on telescopic full-Moon photographs) that emanate from a primary. Rock excavated from considerable depth by the primary impact may be present in and around these clusters. Clusters interpreted as formed by ejecta fragments from the location of Tycho are present in sites 1, 3, and 4. Rays and secondaries from Theophilus are present near sites 1 and 2; secondaries from Copernicus near site 3 and secondaries from Kepler in and near site 5. Chances that a landing will be near any of these particular clusters are remote, however. Also interpreted as secondary impact craters are isolated elongate craters shown mainly on the 1:5,000-scale maps; in some sites these craters appear to have a consistent trend to the direction of elongation. In some, one end is deeper and wider than the other--the expected morphology of secondary impact craters. Some of these elongate craters are parallel to pervasive lineament directions and could be of internal origin, however.

Other craters interpreted on the maps as being of internal origin include irregularly shaped craters, those whose shape appears to be strongly controlled by lineaments, chain craters, craters at the summits of low domes, and dimple craters. Most of these craters appear to have been moderately to strongly subdued by the superposition of younger smaller craters. The best examples of dimple craters plainly do not belong to the main sequence that includes most craters in the sites; but there are all gradations from well-defined dimple craters with strongly convex-upward walls to shallow craters whose walls are only slightly convex upward and which may be simply a variant of the main sequence forms. Recognition of a dimple crater requires that the angle of Sun illumination be sufficiently high so that the interior of the crater can be observed. More dimple craters have been mapped in sites 2 and 3 than in the other sites; but the angle of Sun illumination of the Orbiter photographs of these sites was 8° to 10° higher than in the others, so it is doubtful if there are real differences in the number of such craters. The possibility that they may present hazards to mobility gives the dimple craters some importance. The usual interpretation of these craters is that they are formed by drainage of the loose material of the regolith into a subsurface opening or fracture. Some of the dimple craters in site 2 are too large to have formed by this mechanism and may be centers of volcanic eruption which later collapsed.

Other Landforms

Ridges, scarps and lineaments are the most common additional landforms which occur in and around all the landing sites. Most are very low and subdued; they are difficult to map because of the discontinuities in the Orbiter photographs at the framelet boundaries and because of spurious relief along the framelets introduced by the TV transmission system. Because the manned landings will be made under Sun angle illuminations considerably less than those under which the Orbiter photographs were taken, additional landforms and structural features, hitherto unrecognized, may be apparent to observers on the lunar surface. Sinuous scarps are of special interest since they may have some of the characteristics of terrestrial lava flow fronts and might give clear evidence of lunar volcanism. Several good examples are quite prominent on Orbiter V photographs of site 4, though unfortunately not near the center of the ellipse. A few poorer examples of such features have been mapped in most of the other sites.

SCIENTIFIC SIGNIFICANCE OF INDIVIDUAL SITES

This section summarizes the geology of the five early Apollo landing sites of set C. Emphasis is on the units interpreted to lie beneath the regolith and on how these units fit into the lunar geologic time scale. The areas discussed are those covered by the 1:25,000-scale maps and not the entire Orbiter site. The 1:25,000-scale maps of sites 3 and 4 contain, in addition to the original elliptical landing areas, smaller relocated sites (3R and 4R) that include special features of scientific interest. The names applied to the sites have changed repeatedly and are summarized in figure 1. In the discussion below, each site is identified first by its current name (for example, site 1); names used previously are shown in parentheses. The older names appeared on the geologic maps of the sites, which are currently available as open-file reports. The new names will appear on published versions of the same maps.

Site 1 (II P-2, East Two)

Of the five sites, site 1 in southeast Mare Tranquillitatis is unique in the complexity of the geologic relations within it, as shown by marked differences in both albedo and topography over short distances. Most of the site is covered by material interpreted as a mantle of relatively young deposits covering an older surface. The crater population on this terrain includes several subdued craters up to 700 m, but there is a marked deficiency of craters of intermediate size (50-200 m in diameter) and age (Ec and Cc_1) when compared to the population on typical mare material in the other sites. Such a crater distribution is consistent with the presence of relatively young near-surface material that incompletely erases the topography of an older cratered surface and has had little time to be cratered itself. The near-surface mantling material is mapped as Copernican terra mantling material (Ctm). The albedo of this material is higher than that of typical mare material and lower than that of typical terra material; the terrain it covers is gently undulating with more relative relief than typical mare material and is probably an old terra surface. A subdivision of the Copernican terra mantling material that occurs in the northeast portion of the landing site is even smoother and less cratered than the rest of the unit and is designated smooth terra mantling material (Ctms). It is the smoothest unit in the site and one of the smoothest on the Moon yet to have been photographed at high resolution.

East of the Copernican terra mantling material, the site contains level material with low albedo like that of typical mare material but with a crater population similar to that of the Copernican terra mantling material. This material is mapped as Copernican mare material (Cm). It grades to slightly more heavily cratered material mapped as Eratosthenian mare material (Em_1 and Em_2). Adjoining the Eratosthenian and Copernican mare material is a small tract of heavily cratered terrain resembling typical mare material elsewhere on the Moon; it is mapped as Imbrian mare material (Im). Across the relatively narrow transition zone from Imbrian to Copernican mare, there is a rapid decrease in the total number of craters and in the number of fresh blocky craters. The topography of the heavily cratered Imbrian mare can be seen in subdued form beneath the younger mare material west of the outcrop area of the Imbrian mare material. The Copernican, Eratosthenian, and Imbrian mare materials occur only in the eastern one-eighth of the present landing ellipse.

Determination of the nature and age of the terra mantling material and possibly the materials beneath it is the main goal of a mission to site 1. The mantling material may be a cover of young terra volcanics, derived from craters of probable volcanic origin nearby; or it may be a sheet of mass-wasted debris, derived from more rugged terra, which is also nearby. Still a third, though less likely, alternative is that on the edge of Mare Tranquillitatis thin young mare material overlies terra material and that the two types of material have become mixed by impacts. Further discussion of these alternatives does not seem warranted at present, but it should be borne in mind that the interpretation eventually placed on returned samples may depend heavily on the geologic picture that is favored. The situation is a little like that in areas of complex metamorphic geology where stratigraphy and structure must be worked out simultaneously. The photographic evidence from Lunar Orbiter and the evidence from the samples and from astronauts' observations will have to be meshed to form a mutually consistent story.

Site 2 (II P-6, East One)

Site 2, in southwest Mare Tranquillitatis, lies entirely in relatively old (Imbrian) mare material. There are many large, subdued Eratosthenian and Imbrian craters 200 to 700 m in diameter. The number of intermediate-size craters, 50 to 125 m in diameter, is fewer than on mare material in the western and central sites. The mare material has been divided into two main units, Im_1 and Im_2; the younger unit, Im_2, has slightly fewer large Imbrian craters. A third unit, Im_3, occurs in very small patches between large craters; it appears to be slightly darker than the other mare units and to occupy slightly depressed areas. Its limited extent makes it impossible to date accurately, and it could be as young as Eratosthenian or Copernican.

The paucity of craters 50 to 125 m in diameter, compared with sites to the west, gives this site a subdued appearance. The apparently fine grain size of the regolith in this area, as indicated by Surveyor V (Shoemaker and others, 1967b, p. 17), may contribute to the subdued appearance. Craters formed in very fine grained material may not last as long as those in coarser grained material, particles of which can more readily interlock. Alternatively, the relatively low number of intermediate-size craters may be due to a blanket of relatively young material (Oberbeck and Quaide, 1968, p. 462) like that mapped in site 1, and a mixture of samples should be looked for in the regolith. The peculiar aspect of the site may be related to the fact that the spectral reflectivity curve of Mare Tranquillitatis shows a strong enhancement in the blue part of the visible spectrum (Kuiper, 1965, p. 27; McCord, 1969).

Determination of the age and nature of the Imbrian mare material is the prime object of a landing in the site. The presence or absence of a cover of younger material, such as pyroclastics, will bear on the interpretation of the radiometric ages and other chemical data and on the interpretation of materials in other areas which have a similar subdued aspect or reflect strongly in the blue part of the spectrum.

Site 3 (II P-8, Central One)

Most of the mare material in site 3, in Sinus Medii, is assigned to the upper Imbrian, slightly younger than the mare material in site 2. Subdued Eratosthenian craters are up to 600 m across, and there are abundant intermediate-size craters, 50 to 125 m across. At the western end of the site, the surface has a more subdued appearance--similar to but not as pronounced as that in site 2. The eastern contact of the subdued area is gradational and cannot be located precisely, but the presence of slightly different material to the west has been noted independently by several observers. The subdued mare material has been assigned to the Eratosthenian. It represents either a thin mantle of younger material, such as pyroclastics, or an area where the original properties of the mare material were somewhat different. If it is a thin layer of pyroclastics, the regolith in this area would probably yield samples of both the Imbrian and Eratosthenian units. The main goal of a mission to the site thus becomes to determine the nature and age of the Imbrian mare material and, in the western part of the site, the presence or absence of a younger blanket. A very low, narrow east-west ridge in the eastern part of the site is of interest as the only mare ridge within one of the original unrelocated early Apollo sites, but it will be difficult to study on a mission of short duration.

Site 3R, just to the north of site 3, is on the south edge of the more prominent, zigzag mare wrinkle ridge north of the ellipse. The nominal landing point is in Imbrian mare material. A 1-km traverse from the landing point reaches a well-defined terrace at the contact between the ridge and the mare material. The convex-upward terrace is similar to many others on the Moon at the base of steep slopes. Most opinion holds that the terrace is an accumulation of mass-wasted debris from the upper parts of the slope; confirmation or rejection of this hypothesis may be possible on a manned mission.

Site 4 (III P-11, West Two)

This site, east of Flamsteed P, is entirely within Eratosthenian mare material. Resolvable blocks are abundant around craters larger than 30 m, indicating relatively coarse-grained surficial material. The fragmental layer is apparently thinner in this site than in the other four (Oberbeck and Quaide, 1968, p. 452). Other indications of relative youth are the presence of several poorly defined to well-defined sinuous scarps suggestive of flow fronts and a widespread texture of low hummocks and hollows 5 to 10 m across suggestive of an original volcanic topography.

A few subdued craters 50 to 125 m across are surrounded by terrain with the hummocky topography which terminates in a sinuous scarp 100 to 800 m from the crater rim. The impression is strong that these craters are the source of the flow that forms the scarp and are probably of internal origin. The craters are sufficiently rare that there is little chance that a landing will occur near enough to enable their investigation; other subdued craters in the site in this size range, however, may also be of internal origin but are unidentifiable as such on available photography. This also holds true for similar craters in the other sites. Of interest in this regard is the recent work of Fielder and Fielder (1968), who generated a set of accurate crater statistics in the region of the well-developed flow fronts in the eastern part of Mare Imbrium (see also Kuiper, 1965, p. 31; Oberbeck and Quaide, 1968, p. 459; Schaber, 1969). The mare material in the region of the flows appears to be of Eratosthenian age. There are more subdued to slightly subdued craters 50 to 200 m in diameter on the upper or younger flow unit than on the lower or older unit. The excess craters do not appear to be secondary impact craters, and an endogenetic origin seems clearly indicated (Fielder and Fielder, 1968, p. 33). It appears that on relatively young topography that develops from lava flows, many craters may be of internal origin, but such craters are degraded and increasingly difficult to recognize on older surfaces.

The mare material in site 4 has been divided into two main units on the 1:25,000-scale map: Em_2 has slightly fewer Eratosthenian craters than Em_1. A third unit, Em_3, is the best example of a flow unit surrounding a crater of probable internal origin; it is of too limited extent to be dated accurately and could be as young as Copernican. Unit Em_3 sits at the top of a well-defined mare scarp in the east-central part of the site. The scarp appears to be of tectonic origin and is significant both as a place where mare stratigraphy may be exposed and as a hazard for early manned landings. A Tycho ray (Crct, Crft) consisting of a series of subdued craters with abundant resolvable blocks crosses the landing ellipse at its west end. The main information to be gained from a landing in the site is the age and composition of the Eratosthenian mare material. In this site, details of the mechanisms of mare emplacement may be better shown than in the others because of the relatively fresh appearance of the material and the thin layer of surface material.

Site 4R is near the east edge of the northwest-trending Tycho ray at the west end of the ellipse. The nominal landing point is in typical Eratosthenian mare material. A 1-km traverse from the landing point reaches the northeast margin of the ray. Chances seem good that material derived from the terrae at the site of Tycho may be found in the surficial material developed on the ray. Samples of this exotic material may help determine the age of Tycho.

Site 5 (II P-13, West One)

This site southwest of Kepler also lies entirely within Eratosthenian mare material. As in site 4, there are more resolvable blocks around craters than in sites 1, 2, and 3, which suggests that the surficial material is generally coarser grained, as would be expected on a younger surface that was originally solid. Blocks are much more abundant in sites 4 and 5 than on the patches of Eratosthenian mare material in sites 1 and 3. Site 5 is surrounded by rays of the system around Kepler; on Orbiter photographs, the rays can be seen to consist of clusters of moderately subdued craters on lines radial to Kepler. Small weakly developed crater clusters and lineaments radial to Kepler occur within the site itself. Isolated subdued craters of intermediate size (50-125 m in diameter) and age (Ec-Cc_2) are present, and some of these may also be secondary impact craters of the Kepler field. Thus some material derived from depth at Kepler may be present in the surficial

Table 3.--Summary of geologic characteristics of Apollo landing sites of set C (see fig. 1 for locations)

Characteristics	Site 5 (II P-13, East One)	Site 4 (III P-11, West Two)	Site 1 (II P-8, Central One)	Site 2 (II P-6, East One)	Site 1 (II P-2, East Two)
Major stratigraphic unit in site	Eratosthenian mare material (Em)	Eratosthenian mare material (Em_1, Em_2, Em_3)	Imbrian mare material (Im, Iml)	Imbrian mare material (Im_1, Im_2, Im_3)	Copernican terra mantling material (Ctm, Ctms).
Other units in site exclusive of craters	Kepler ray material (Crfk)	Tycho ray material (Crct, Crft)	Eratosthenian mare material (Em). Mare ridge material (Imr).	--	Copernican mare material (Cm). Eratosthenian mare material (Em_1, Em_2). Imbrian mare material (Im). Pitted material (Eph, Epg). Terra material (IpIth, IpIts). Tycho and Theophilus ray material (Ccc_5, Ccc_1).
Remarks on stratigraphy	--	Unit Em_3 may be Copernican	Unit Em may be a thin cover of pyroclastics	Unit Im_3 may be Eratosthenian or Copernican. Whole site may have mantle of younger material	Discrete mantle of material overlies older cratered terrain of Imbrian or pre-Imbrian age. Age of mantle not certain.
Significant structural features	Lineaments radial to Kepler	Several flow fronts. Major scarp. Widespread hummocky texture may be volcanic	NW-trending and NE-trending lineaments in Iml and Imr	Flow fronts in SW corner. Weak scarps with a variety of orientations	A few sinuous scarps.
Essentials of crater population	No gentle depressions >200 m. Abundant craters 50-125 m.	No gentle depressions >200 m. Abundant craters 50-125 m.	Gentle depressions and subdued craters up to 600 m. Abundant craters 50-125 m.	Gentle depressions and subdued craters up to 700 m. Relatively few craters 50-125 m.	Gentle depressions and subdued craters up to 700 m. Relatively few craters 50-200 m.
Relative abundance of blocks	Abundant (0.2 x $10^{-3}/m^2$ >1 m across[1]	Abundant	Rare (0.0 x $10^{-3}/m^2$ >1 m across[2]	Rare	Rare.
Median thickness of regolith, from morphologies of small craters[3]	4.6 ≈5	3.3 3.0	4.6 4.8	4.6 6.2	4.6 ---
Nearest Surveyor	I, 120 km southwest	I, 200 km west	VI, on 1:25,000-scale map	V, 27 km northwest	V, 330 km west.

[1]H. J. Moore, unpublished data.
[2]Mapping Sciences Group, Manned Spacecraft Center, unpublished data.
[3]First number is from Oberbeck and Quaide (1968, p. 452). Second number determined by U.S. Geological Survey. Various individuals made the measurements, which may account for some of the inconsistency with the data of Oberbeck and Quaide.

material of the site, and fine-scale textural details related to the Kepler rays may be present. The chief goal of a landing in the site, however, is the determination of the age and composition of the Eratosthenian mare material.

SUMMARY

Early manned landings on the Moon will probably concentrate on those features that occur all over the planet--the regolith and small craters. Later exploration, whether manned or unmanned, will be directed broadly to working out a more complete geologic history of the Moon through landings and traverses across features of a variety of ages and probable origins. Each of the early Apollo landing sites discussed here differs from the other four in some respect. Differences and similarities among the sites are summarized in table 3. Crater population is probably the most distinctive characteristic of each site but does not correlate exactly with other characteristics. Site 3 has a crater population generally similar to that of sites 4 and 5 but has slightly older craters and lacks the abundant resolvable blocks of the western sites. Sites 4 and 5 have similar crater populations, but 5 lacks the hummocky texture and flow fronts of 4. Crater populations in sites 1 and 2 are similar, but a cover of young material has been mapped in 1 and not in 2. Appreciation of these differences will be essential to a complete interpretation of returned lunar samples and observations.

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