GEOLOGIC MAPS OF EARLY APOLLO LANDING SITES

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GEOLOGIC MAPPING OF APOLLO SITES

The U.S. Geological Survey is publishing geologic maps of potential early Apollo landing sites on the Moon at scales of 1:100,000 and 1:25,000 as part of its Geologic Atlas of the Moon. 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.* The 1:25,000-scale maps show the details of each landing site and its immediate vicinity. The maps were constructed primarily by study and annotation of Lunar Orbiter photographs; stereoscopic coverage was available for some parts of each one. The Langley Research Center of the National Aeronautics and Space Administration provided the photographs. Base materials for the maps are photomosaics prepared by the Army Map Service and the Aeronautical Chart and Information Center of the U.S. Air Force.

Geologic maps of the Moon at relatively large scales such as 1:100,000 and 1:25,000, like those at small scales, are based on the same fundamental principles employed in mapping terrestrial geology. In general, materials that apparently formed under the same conditions and at approximately the same time are grouped into units, and the relative ages of the units are estimated as closely as practical. The surface of the Moon is heterogeneous. It features were apparently shaped both by impact of objects from space and by 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, 1-10 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-scale maps. The increased difficulty in subdividing lunar surface materials at larger scales probably is caused by the impact of meteoritic particles and, possibly, of high-energy solar particles and radiation, all of which 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, 1967, 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 1:1,000,000-scale reconnaissance maps and Apollo maps are assigned to time-stratigraphic divisions in the standard lunar stratigraphic column (Shoemaker and Hackman, 1962; Shoemaker, 1962; Wilhelms, 1966; McCauley, 1967), although this becomes more difficult at the larger scales of the Apollo maps. Time-stratigraphic units are planet-wide groups of rocks that were formed during specific time intervals. Development of a lunar stratigraphic column began with the mapping of the Mare Imbrium region, where a series of well-defined rock 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 the table below (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, 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 time-stratigraphic unit, the system, to which that unit is assigned; the small letters are descriptive abbreviations that indicate the lithogenetic nature of the unit (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.

* The Geological Atlas of the Moon comprises several categories of maps all published as part of the Miscellaneous Geologic Investigations of the U.S. Geological Survey. In order of increasing map scale the categories are: (1) A synoptic compilation of the Earthside exclusive of the limb regions incorporating the results of larger scale maps; to be published at a scale of 1:5,000,000. (2) Reconnaissance maps compiled largely from Earth-based telescopic photographs and direct telescopic observations, and published on USAF Aeronautical Chart and Information Center (ACIC) bases at a scale of 1:1,000,000. (3) Ranger maps—compiled from photographs returned by the Ranger spacecraft and published on ACIC bases at scales ranging from 1:5,000 to 1:250,000. (4) Apollo landing site maps.

Materials of most small features on the lunar surface (largely craters less than 100 meters 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_5 is material of a relatively young Copernican crater, Cc_1 of a relatively old Copernican crater).

CRATER MATERIALS

Like most of the Moon, every site is densely covered with craters whose sizes extend downward to the limit of photographic resolution. The craters form a continuum from sharp and fresh-appearing to highly subdued. In order to estimate the relative ages of craters, the following fundamental assumptions must be made: (1) when first formed, most craters appear fresh; (2) crater forms are progressively degraded, or subdued, with time, the smaller craters at a more rapid rate than the larger; (3) the rate of crater degradation is approximately the same everywhere on the Moon. These fundamental assumptions were used to construct the graph in figure 1. The overall slopes of the lines on the graph were fixed by the types of craters occurring on geologic units of well-established age; for example, craters having 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 and unrayed craters of the same size are assigned to the Eratosthenian. The six subdivisions within the Copernican System were chosen solely for convenience.

Although the system outlined by the graph of figure 1 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 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

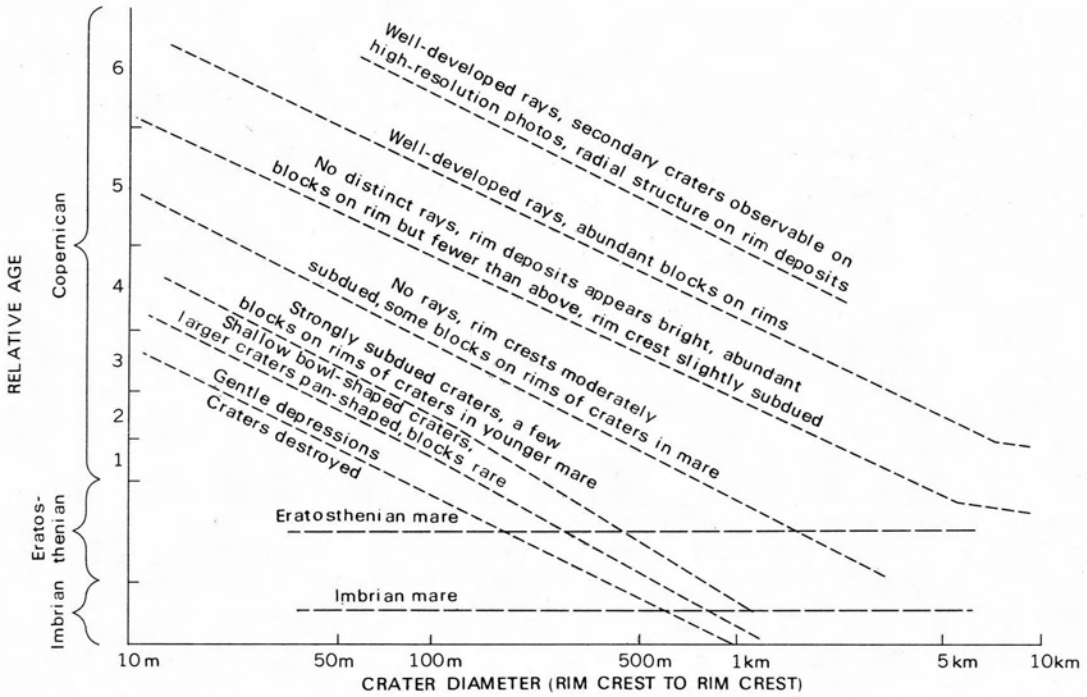

Figure 1.--Graphs showing assumed relations among diameters, properties, and ages of craters: Categories are intergradational. Horizontal lines are isochrons indicating variations in crater populations on surfaces of increasing age.

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 to 20 m in diam.). 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.

Only the largest craters in each map area are outlined by geologic contacts, intermediate - size craters are identified by numbers or letters only, and the smallest craters are unmapped. Some of the intermediate craters are surrounded by mappable rim deposits, but outlines have been omitted to ensure legibility. Many of the older craters, including some outlined by geologic contacts and some shown only by numbers and letters, lack mappable rim deposits on Orbiter photographs, possibly because such deposits are finer grained than the limit of resolution.

The craters of greatest scientific interest are those large enough to have penetrated bedrock beneath the regolith and young enough so that the resulting ejecta deposits can be clearly differentiated. There may be little to distinguish crater deposits from adjacent regolith around craters too small to have penetrated the regolith and around very old craters. Samples that display shock phases or volcanic textures and compositions 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 the exposure ages of crater materials are determinable, samples from craters of various ages could 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. In all likelihood, the craters investigated by astronauts on early Apollo missions will be smaller than those shown on the 1:25,000-scale maps, but figure 1 can be used to estimate the age of any crater that has penetrated bedrock beneath the lunar regolith.

Among the special types of craters in each site, those interpreted as produced by secondary impact are probably of the greatest significance. Included in this category are most craters mapped under the heading of crater cluster. Some of these clusters appear to be clearly related to a primary impact crater: they are concentrated along lines roughly radial to a larger, primary crater, or they lie along bright rays (visible on telescopic full-Moon photographs) that emanate from a primary crater. Bedrock samples quarried from considerable depth by the impact that formed the primary may be present in and around these clusters. Clusters that apparently were formed by the impact of fragments ejected during formation of the crater Tycho occur in several of the sites.

Craters interpreted on the maps as being of internal origin include irregularly shaped craters, those whose shapes appear to be strongly controlled by lineaments, chain craters, craters at the summits of low domes, and dimple craters (those with walls strongly convex upward and very low rims). Most of these craters appear to have been subdued by the superposition of younger smaller craters.

MARE AND TERRA MATERIALS

The properties which distinguish the various mare and terra units on the Apollo site maps are mainly differing crater populations which in turn appear to be related to age, mechanical properties of the materials, or mode of emplacement. Whether the chemical or mineralogical properties of the units also differ cannot be determined until manned or unmanned traverses are made. A limited amount of information on the chemical properties of these materials is available from the Surveyor alpha particle scattering experiments (Turkevich and others, 1968). Analyses at two points in typical mare material indicate a chemistry similar to that of iron-rich basalt; analyses at a single point on the ejecta blanket of the crater Tycho on the southern lunar highlands also indicate a basaltic chemistry, though with somewhat less iron than the mare material. These analyses, together with substantial photographic evidence of volcanic landforms, indicate that volcanic rocks are widespread on the Moon; the mare materials are probably made up mostly of volcanic materials. These materials undoubtably vary both in age and composition from place to place, although the contacts between contrasting materials have been blurred by the development of the lunar regolith.

The oldest craters that have formed on the mare material in the three early Apollo landing sites in Oceanus Procellarum (Maestlin G, Wichmann CA, and Flamsteed K regions) are Eratosthenian; and in the Maestlin G region and near the Flamsteed K region, craters mapped as Eratosthenian are partially buried by 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 these three sites in Oceanus Procellarum. The oldest craters in the site in Sinus Medii (Oppolzer A region) are also Eratosthenian, but subdued craters and gentle depressions are larger than in sites to the west and therefore are older (fig. 1). The mare material in the Oppolzer A region is therefore estimated to be latest Imbrian in age. Large Imbrian craters are present on the mare material in the Sabine D region in southwestern Mare Tranquillitatis, which is accordingly mapped as Imbrian, older than that in the Oppolzer A region. These surfaces of increasing age can be thought of as represented by successively lower horizontal lines on the graph of figure 1. On an older surface, crater degradation has operated for a longer period than on a younger one, and gentle depressions are therefore larger. 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.

The crater population in southern Mare Tranquillitatis has relatively fewer intermediate size craters (50 to 125 m in diameter) than the population on the mare material mapped as younger in Sinus Medii and Oceanus Procellarum in the vicinity of the landing sites. This seeming paradox must mean 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 be of internal origin or may be secondary impact craters; the 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 of these factors may have produced the crater populations presently observed.

Compared with the dark, level plains of the lunar maria, most of the lunar terrae are light and rugged. Isolated patches of terra materials occur in several of the sites, but the Maskelyne DA region in southwestern Mare Tranquillitatis is the only one with extensive terra materials. Much of this material is assigned to the Copernican System. It occurs on a gently undulating surface with more relative relief than the typical mare material in the other five sites but generally is smoother and less cratered than any other materials in the early Apollo landing sites. The crater population of the Copernican terra material includes several large subdued craters of apparent Imbrian and Eratosthenian age which are interpreted as buried. There is a very marked deficiency of craters of intermediate sizes (50-200 m) and ages (Ec and Cc_1). This material appears to be a relatively young, thin layer of volcanic rocks or erosional debris which overlies an older, more heavily cratered surface. Thus, samples collected from the Maskelyne DA region may be more heterogeneous than those collected elsewhere.

OTHER GEOLOGIC UNITS AND STRUCTURAL AND TOPOGRAPHIC FEATURES

Among the other geologic features that have been mapped, ridges, scarps, and lineaments are the most common. Some of the mare ridges may consist of discrete bodies of extruded volcanic material which could provide important data on lunar volcanism. Scarps and lineaments are more difficult to map than the ridges 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. Sinuous scarps are of special interest because they may resemble terrestrial lava flow fronts and might give evidence of lunar volcanism. Other features of special interest are small (≈200 m diam.) domes and peculiar ring structures in the three sites in Oceanus Procellarum.

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