Summary of Lunar Stratigraphy— Telescopic Observations

By DON E. WILHELMS

CONTRIBUTIONS TO ASTROGEOLOGY

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CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY OF LUNAR STRATIGRAPHY—TELESCOPIC OBSERVATIONS

By DON E. WILHELMS

ABSTRACT

The geology of much of the moon has been mapped from the earth by means of telescopic photographs and observations. This mapping is based on the premise that the lunar crust is composed of material units that can be defined by physical properties and ranked in order of relative age by application of the principles of stratigraphy. Units are ranked locally by their superposition and transection relations and both locally and regionally by subordinate criteria such as density of superposed craters and degree of topographic freshness.

A moonwide stratigraphic column of material units has been divided into approximate and tentative time-stratigraphic units, whose type areas are near the craters Copernicus, Eratosthenes, and Archimedes. The oldest time-stratigraphic unit is the pre-Imbrian (not a formal system), followed by the Imbrian, Eratosthenian, and Copernican Systems.

Pre-Imbrian materials have a subdued topography and are highly cratered. Most are associated with craters and circular multiringed mare basins. Many pre-Imbrian craters originally may have resembled the young crater Copernicus but are now modified. The formation of each multiringed mare basin was a major event which obliterated the earlier geologic record over a large area and started a new stratigraphic sequence. On the basis of density of superposed craters and general freshness of appearance, the sequence of formation of some pre-Imbrian multiringed basins is believed to be, from oldest to youngest: Fecunditatis, Serenitatis, Nectaris, Humorum, Crisium (or Crisium-Humorum). Other less distinct basins are also pre-Imbrian in age.

Deposits called the Fra Mauro Formation that partly surround another fresher appearing mare basin, the Imbrium basin, are used to define the base of the Imbrian System. The Fra Mauro apparently forms a blanket that grades in texture and thickness away from the basin, and otherwise resembles the ejecta of craters such as Copernicus that are believed to have been produced by impact. Accordingly the Fra Mauro is believed to be ejecta from the impact that formed the Imbrium basin. Structures radial to and concentric with the basin also apparently were formed at the same time as the basin. The Fra Mauro and the structures divide the materials in a vast area of the earthward hemisphere into pre-Imbrian and younger units. A deposit like the Fra Mauro Formation covers a similarly vast area around the younger Orientale basin on the west limb of the moon. Similar material units may also have surrounded Humorum and the other circular pre-Imbrian basins, but greater degradation hinders their recognition.

Sufficient time elapsed between the formation of each mare basin and the completion of its flooding by the dark smooth material called mare material for extensive units to form. Those units in or near the Imbrium and Orientale basins are of Imbrian age, whereas those in the pre-Imbrian basins may be either pre-Imbrian or Imbrian in age. The most common units are crater materials and light plains-forming materials. Crater materials include those of Archimedes in the Imbrium basin and of Gassendi in the Humorum basin. Light plains-forming materials of Imbrian age include the Apennine Bench Formation on the shelf south of Archimedes and the Cayley Formation in troughs surrounding the Imbrium basin. Most light plains-forming materials are confined to depressions or low plateaus. Other light materials of probable Imbrian age form undulating or rolling topography and elevated plateaus.

The top of the mare material between the craters Eratosthenes and Archimedes has been used to define the top of the Imbrian System. Most mare material is Imbrian in age, but some is post-Imbrian. The youngest mare materials are the darkest and least cratered; the oldest are almost as light and as heavily cratered as the light plains-forming materials. Indeed, mare and light plains materials may be compositionally similar, though different in age. Mare materials were once called the Procellarian System and when this name was dropped, the Procellarum Group. The latter name as well as the two series of the Imbrian System, the Apenninian and Archimedian, should be dropped.

Materials whose age relative to Imbrian mare material is doubtful have been designated "Imbrian or Eratosthenian." They include crater materials, dark terra-mantling materials, and materials that form domes, cones, sinuous rilles, and prominent stringy ridges. The dark mantling units occur mainly at the margins of maria and may be partly interbedded with mare materials.

The two youngest lunar time-stratigraphic systems, the Eratosthenian and Copernican, have been defined on the basis of the physical properties of crater materials. Materials of rayless craters that are superposed on Imbrian mare material are assigned an Eratosthenian age; some superposed on terra are also doubtless Eratosthenian but are not telescopically distinguishable from Imbrian crater materials. Materials of craters that have rays or dark halos are considered Copernican in age; they also appear fresh and have a high thermal anomaly at eclipse. Some noncrater materials are also assigned Eratosthenian and Copernican ages. They include

some mare materials, a dark terra-mantling deposit, a possible light mantling deposit, a light plains-forming deposit, and several kinds of probable constructional deposits. Bright slope material apparently indicates fresh exposures of underlying units and is considered Copernican in age. Many other young deposits of various relief forms and albedo are known. Similar deposits probably were formed in earlier periods but have been obscured by mass wasting, meteorite impact, and mantling by younger materials.

The ultimate goal of lunar geologic mapping, after material units are recognized, is genetic classification. Most of the near-surface lunar crust is probably composed of complexly interfingering deposits of volcanic and impact origin, modified by mass wasting. Most mare and some light plains-forming materials are believed to be volcanic flows because they terminate against higher topographic forms and because some mare materials have lobelike scarps resembling flow fronts. The dark mantling materials and some light ones are probably free-fall tuff or ash-flow tuff. Materials of some craters, such as those alined in chains, are almost certainly of volcanic origin. Craters that have extensive ejecta blankets, fields of satellitic craters, and extensive ray patterns are probably of impact origin. The circular mare basins are also believed to be of impact origin because of their resemblance to the large probable impact craters and because of the great areal extent of their related structures.

INTRODUCTION

The U.S. Geological Survey, on behalf of the National Aeronautics and Space Administration, is engaged in a program of systematic lunar geologic mapping based on extension of terrestrial stratigraphic methods and principles. This paper summarizes the stratigraphy that was developed while lunar geology was being mapped from telescopic observations, before extensive study of photographs taken by spacecraft began. The period covered is from 1960, when the program was begun by E. M. Shoemaker, to late 1967, when 36 quadrangle maps at a scale of 1:1,000,000 had been completed (fig. 1).

The term "geology," whose roots refer to the study of land or ground as well as of the planet earth (Ronca, 1965), is retained for this study of the moon to emphasize the similarity in basic approach with terrestrial geology and to avoid proliferation of terms.

The principal objectives of the telescopic reconnaissance mapping were to delineate the major elements of lunar stratigraphy and structure on the near side of the moon, to develop principles and techniques for remote geologic mapping, and to provide the type of geologic framework essential for effective targeting of Ranger, Surveyor, and Lunar Orbiter spacecraft. The telescopic work also helped to narrow the range of possible origins for the major lunar features—especially the maria, mare basins, and large craters—and demonstrated their diversity. Speculation about origins has been deliberately held in check, however, by means of the mapping methods and conventions; so the maps should retain their validity even though concepts concerning formative processes change. The maps will serve as a framework in which later, more refined data about origin, composition, and absolute age can be evaluated.

Lunar geologic mapping is based on the concept that the crust of the moon, like that of the earth, is neither homogeneous nor randomly heterogeneous but is composed of material units, each having a limited range of properties and a limited lateral and vertical extent. The relative uniformity of a unit

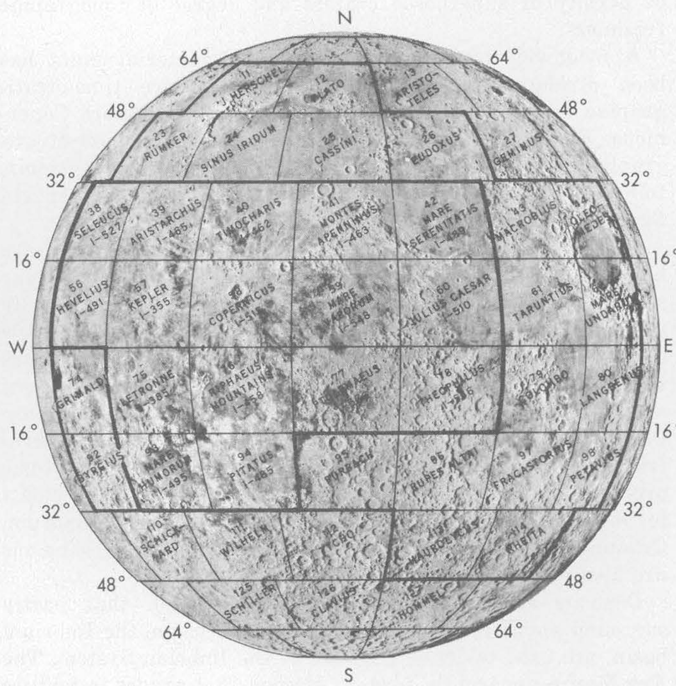


FIGURE 1.—Index map showing the status of mapping at 1:1,000,000 scale as of late 1967. Maps of the area in heavy outline are either published or in press, and the stratigraphy portrayed is discussed in detail in this report. Preliminary maps of the area in medium-weight outline were completed and released in the open files. Number below quadrangle name is the map number in the Geologic Atlas of the Moon, published by the U.S. Geological Survey. Number above quadrangle name is the chart number in the Lunar Astronautical Chart (LAC) series prepared by the U.S. Air Force Aeronautical Chart and Information Center (ACIC), St. Louis, Missouri. The LAC charts (part of one is shown in fig. 7) serve as bases for the geologic maps. Quadrangles were called regions in the first 10 geologic maps published.

suggests that it was formed under a limited set of conditions and within a limited time. The age relations of these units can be determined from their spatial relations because the principles of sequence are as valid on the moon as on the earth: in a depositional sequence that has not been overturned, younger rocks overlie older rocks; intrusive rocks are younger than the rocks they intrude; rocks cut by faults are older than the faults. Because these relations are commonly revealed in the pattern of the units and their contacts at the surface, they can be observed on photographs of the surface and mapped. Photographs may show the overlap or embayment of an older unit by a younger unit, or the contact of a younger unit transecting the contact between two older units. This concept of discrete mappable units occupying specific stratigraphic positions reduces the enormous complexity of a planetary crust to comprehensible proportions and allows much to be learned through remote means about the crust's structure, history, and formative processes.

The first section of this paper discusses the general principles by which lunar stratigraphic units are recognized, ranked in order of relative age locally, assigned to a moonwide time scale, and portrayed on maps. The second and longest section is a detailed description of the composite lunar stratigraphic column, as derived from telescopic observations. Criteria for recognition, present and prior nomenclature, and map conventions are discussed for nearly all stratigraphic units appearing on the maps that were published or in press as of late 1967. The status of definitions of units is clarified; some units are defined formally for the first time, others redefined, and others abandoned. The descriptions of this second section are closely tied to the lunar geologic quadrangle maps, although the introductory and general parts can be followed without reference to the maps. The last section is an interpretive summary of the stratigraphy previously discussed.

A photomosaic of the lunar near side (fig. 2) is given herein to show the areas that are illustrated in figures 3–14.

PREVIOUS WORK

This summary of lunar stratigraphic work by the U.S. Geological Survey is a sequel to several shorter summaries. Shoemaker (1962) and Shoemaker and Hackman (1962) established the stratigraphic system upon which the present system is based. Their pioneering studies concentrated on the region surrounding the craters Copernicus, Eratosthenes, and Archimedes. McCauley (1967b) discussed the geology of a larger region and reviewed changes in stratigraphic thinking that had occurred since the early work, especially the clarification of rock-stratigraphic and time-stratigraphic concepts. Another regional study appeared in the form of a 1:5,000,000-scale map which summarized the geology shown in preliminary 1:1,000,000-scale maps of the equatorial belt (lat 32° N.–32° S., long 70° E.–70° W.) (Wilhelms and Trask, 1965a; Wilhelms, Trask and Keith, 1965).[1]

Before the present program began, the Survey prepared three synoptic full earthside maps at a scale of 1:3,800,000 for the U.S. Army Engineers (Hackman and Mason, 1961; Mason and Hackman, 1962). In addition to delineating the major lunar physiographic provinces and discussing the inferred engineering characteristics of the surface, Hackman and Mason presented a generalized photogeologic map showing three stratigraphic units.

The only other systematic lunar geologic mapping known to the author is that of the Soviet scientists Khabakov (1962, p. 275–303) and Sukhanov, Trifonov, and Florenskiy (1967). Khabakov derived the order of formation of lunar features on most of the near side by an approach similar to the Survey's but emphasized landforms rather than stratigraphic units. Sukhanov and his colleagues based their mapping more directly on stratigraphic principles but believed that differences among units resulted mostly from differing structural patterns. Their work incorporated the results and stratigraphic systems of both the Survey and Khabakov.

Other geologically oriented lunar studies known to the author differ from the programs of the Geological Survey and of the Soviets referred to in three principal respects: (1) they are not based on systematic mapping, (2) they incorporate the historical perspective less systematically, although many do consider it, and (3) they concentrate on interpretations rather than descriptions, commonly to advocate either an impact or volcanic origin of most or all lunar craters on the basis of theory or comparison with terrestrial analogs.

Two early Survey geologists who studied the moon were Gilbert (1893) and Shaler (1903). Gilbert argued for an impact origin for most craters and for the moon's largest feature, the basin of Mare Imbrium, but did not exclude a volcanic origin

[1] A new map at a scale of 1:5,000,000, based principally on Lunar Orbiter IV photographs and covering a larger area, has been prepared (Wilhelms and McCauley, 1969.

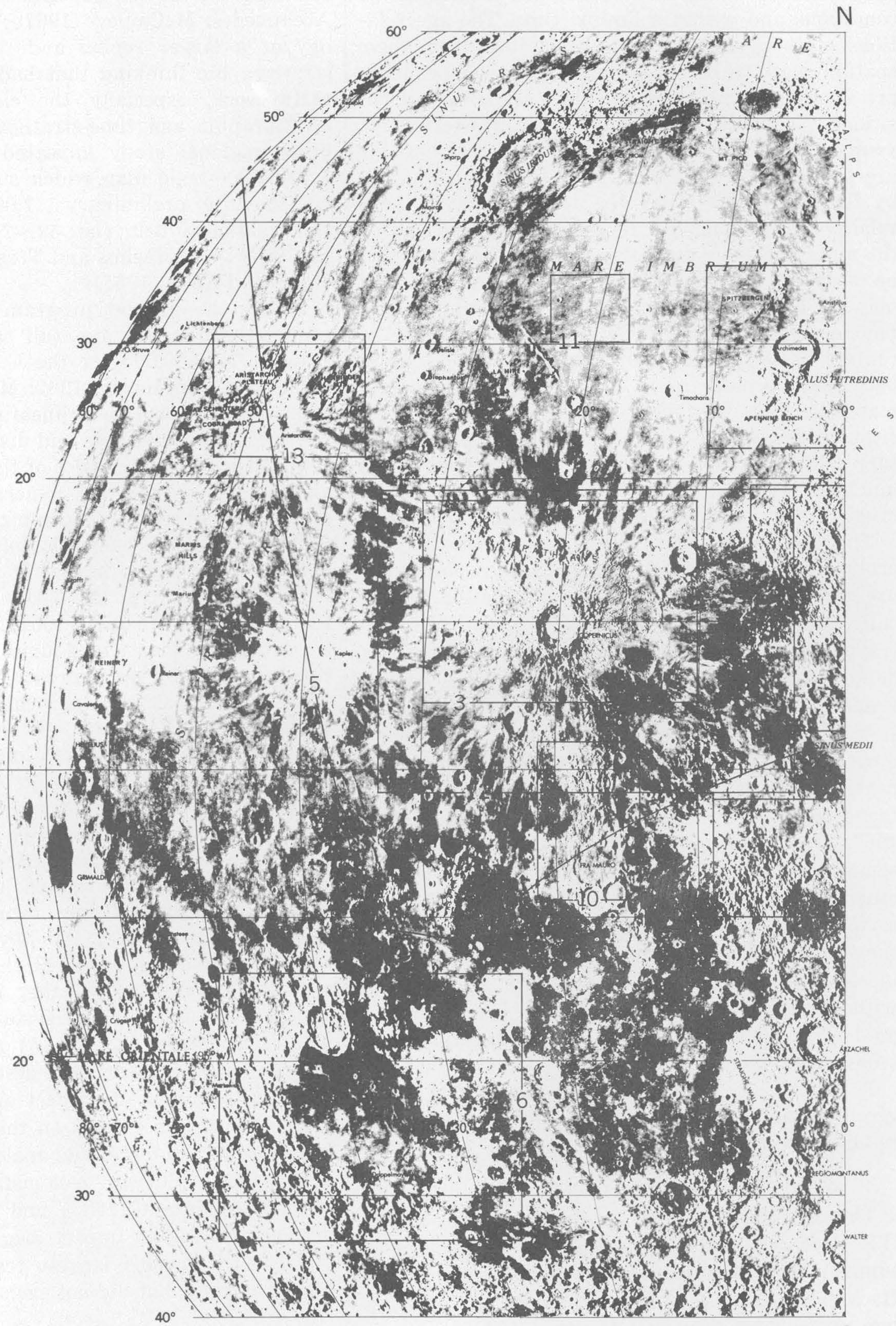


FIGURE 2.—Photomosaic of the lunar near-side showing areas covered by illustrations in this report.
Information

Base modified from LEM–1A (2d ed., Nov. 1962), published by Air Force Aeronautical Chart and Center.

for some features. Shaler and the non-Survey geologists Spurr (1944, 1945, 1948, 1949) and von Bülow (1957), among others, assumed an internal origin for nearly all lunar features and in their elaborate works gave scant attention to the alternatives. Perhaps the clearest early statement of stratigraphic principles applied to the moon was by the stratigrapher Barrell (1927), but he seems to have done no systematic work. Spurr devised a highly subjective time scale. The geologist Dietz (1946), the astrophysicist Baldwin (1949, 1963), and the photogeologist Hackman (1961), all proponents of the impact hypothesis, pointed out that lunar craters exhibit varying states of apparent preservation which permit an assessment of relative age. Numerous papers deal with relative ages based on crater population studies (for example, Dodd and others, 1963; Baldwin, 1964; Hartmann, 1967). Among the important recent works of wide scope are books by Baldwin (1949, 1963) and the astronomer-geologist Fielder (1961, 1965) and a paper by the astronomer Kuiper (1959).

ACKNOWLEDGMENTS

The work described here is the product of a collective effort and is by no means solely that of the writer; all lunar geologists of the Geological Survey have contributed to our knowledge of lunar stratigraphy through their maps, reports, and oral discussions. In particular, E. M. Shoemaker, J. F. McCauley, R. E. Eggleton, Harold Masursky, and the writer have been active in systematizing the stratigraphy. The following colleagues read the manuscript critically and contributed many valuable and appreciated suggestions: J. F. McCauley, G. W. Colton, H. G. Wilshire, M. H. Carr, and J. E. Carlson of the Geological Survey and T. A. Mutch and R. S. Saunders of Brown University.

APPLICATION OF STRATIGRAPHIC PRINCIPLES TO THE MOON

PROPERTIES AND SEQUENCE OF LUNAR MATERIAL UNITS

Material units of the lunar crust display various topographic and surficial properties that can be studied by visual observation or by means of instruments, through the telescope and on photographs. These units are mapped by outlining areas that have a simple combination of such properties. Properties can be combined in various ways to define units, and geologic judgment is necessary to select units that are stratigraphically significant. The most meaningful units on earth are three-dimensional bodies that are either tabular and layered or uniform and nonlayered. Therefore, properties for lunar units are sought that (1) represent units of finite thickness, rather than a surficial skin, and that (2) reflect lithology, rather than the effects of postformational processes. Most importantly, every effort must be made to recognize those units which were formed in a discrete time interval relative to adjacent units. Where true units cannot be recognized, as in complex, poorly photographed or heavily modified terrain, two-dimensional units are mapped which at least do not impose premature interpretations.

Of all the properties by which lunar material units can presently be defined, topography is the one that most directly reflects meaningful properties of three-dimensional rock bodies underlying the surface. Topography is best revealed by shadows cast by a low sun—that is, near the terminator—and disappears near full moon, when no shadows are cast (compare figs. 3 and 12). In general, simple overall geometric form and lateral uniformity or regular gradation of texture suggest uniform lithology, although they may also reflect a common structural or erosional history. True units can be confidently identified if they have a topographic texture that appears to be a primary depositional pattern. Such patterns include flow lobes, flow lineations, and hummocks that coarsen toward a likely source, such a crater. Additionally, the thickness of some units can be estimated from the extent to which they bury craters and valleys (Marshall, 1961; Eggleton, 1963). It is important to stress that in lunar geologic mapping as in all geologic mapping, materials are the things actually mapped and not topographic forms—crater materials, not craters; plains-forming materials, not plains.

Properties of the uppermost surface materials may also reflect underlying lithology, just as the properties of many terrestrial soils are related to the composition of the underlying bedrock. The correlation may be only indirect, as with many soils, because external processes such as impact cratering, mass wasting, and radiation may have altered the original properties. Some distinctive properties can be used to characterize units even when the properties are poorly understood. The property most commonly used is reflectivity of incident light (brightness) in the visual spectrum, expressed either in relative terms or as a numerical value of albedo, the reflectivity at full moon. Brightness differences are enhanced while topographic differences disappear as the sun angle increases and fewer shadows are cast. Albedo is commonly highest on steepest slopes, so that the brightest units at full moon appear roughest at low sun. However, there are also rugged dark units, as well as both light and dark plains units.[2]

Another informative and thoroughly mapped property is radiation in the thermal region of the infrared at eclipse (Shorthill and Saari, 1966; Saari, Shorthill, and Deaton, 1966). Eclipse infrared values have been interpreted in different ways but appear to correlate mainly with freshness of exposure (U.S. Geological Survey, 1967, p. A132). Radar reflectivity may have similar meaning but has not been compared systematically with lunar geologic units. Reflectivity in other nonvisual wavelengths, color (Whitaker, 1966, p. 79–85), and polarization (Wilhelms and Trask, 1965b) are useful for delineating some units.

Two examples will show how lunar material units believed to be true three-dimensional rock units are recognized and how superposition and transection relations between them are deduced. First, the units which make up the maria have a flat surface and low albedo, which, taken together, distinguish the maria from other lunar surface areas. Surfaces with these characteristics extend laterally for great distances on the moon's near side. In many places these flat, dark surfaces terminate abruptly against the rugged, generally lighter terra and continue into the intervening valleys (fig. 3). The most reasonable interpretation of this pattern is that the mare surfaces are formed by layers of material emplaced in a fluidlike state and that the mare material is younger than the terra it embays.

Crater rim materials, another important class of lunar materials, are the second example. Rim material is defined as all material with positive relief from the rim crest outward. In young craters like Copernicus (fig. 3) the texture of rim material suggests that at least the surface material was deposited in a layer. The rim material deposits form generally uniform belts surrounding the crater and are regularly gradational outward. Near the rim crest is a high ring whose surface is randomly hummocky or has a pattern of branching convex-outward arcs; farther from the rim crest (starting at one-quarter to one-third crater diameters), the rim material has less relief and is characterized by radial ridges and grooves. This radially symmetric pattern indicates that the formation of rim material is related to the formation of the crater and that the material probably consists of ejecta from the crater which may be of either impact or volcanic origin. The rim material of an impact crater consists of debris ejected while the crater is being formed; it probably covers upthrust rock. The ejecta from a caldera consists of volcanic material erupted before and during collapse. Ejecta from a maar, also volcanic, is erupted sporadically over a period of time. The age of the rim deposits relative to other materials can be deduced from the map pattern. Where younger than other materials that surround the crater, the rim material forms an unbroken roughly circular pattern with a fringed or lobate boundary, and the concentric morphologic belts or facies are uninterrupted. Where older, it forms a circular map pattern interrupted by the younger materials, and parts of one or more of the rim facies may be missing at the surface. The pattern of the Archimedes rim material illustrates both relations (fig. 4). The part of the rim material on the Apennine bench shows a continuous pattern, which indicates that it is superposed on the bench and is younger. However, parts of the rim are covered by mare material, and Archimedes is therefore older than the mare surface material. This age relation is further confirmed by the presence of mare material inside the crater.

Additional evidence for the ages of crater materials relative to adjacent material is provided by satellitic craters—small elongate or composite craters which surround a large circular crater and probably were formed nearly simultaneously with it. Most of these large craters surrounded by satellitic craters seem to have formed by impact, and the satellitic craters seem to have formed by secondary impact of material ejected from them (Shoemaker, 1962). However, the stratigraphic meaning of the superposition relations is the same under any interpretation, provided that the satellitic craters were formed at about the same time as the parent craters. The satellitic craters of Copernicus are clearly superposed on the surrounding mare surface and thus are younger than the mare material; those of Archimedes are present on and are therefore younger than the bench material, but are obliterated by and are older than the mare material.

Stratigraphic columns can be constructed locally by the methods just described with little recourse to genetic interpretations. A fairly detailed sequence has been worked out in the Archimedes area (fig.

[2] The term "mare" (plural; maria) is used to describe the dark plains; the antonym "terra" (plural, terrae) is used to describe light plains and both light and dark rugged terrain, but not individual craters. These terms are descriptive not positional, and mare material sometimes occurs as small patches in predominantly terra regions, and vice versa.

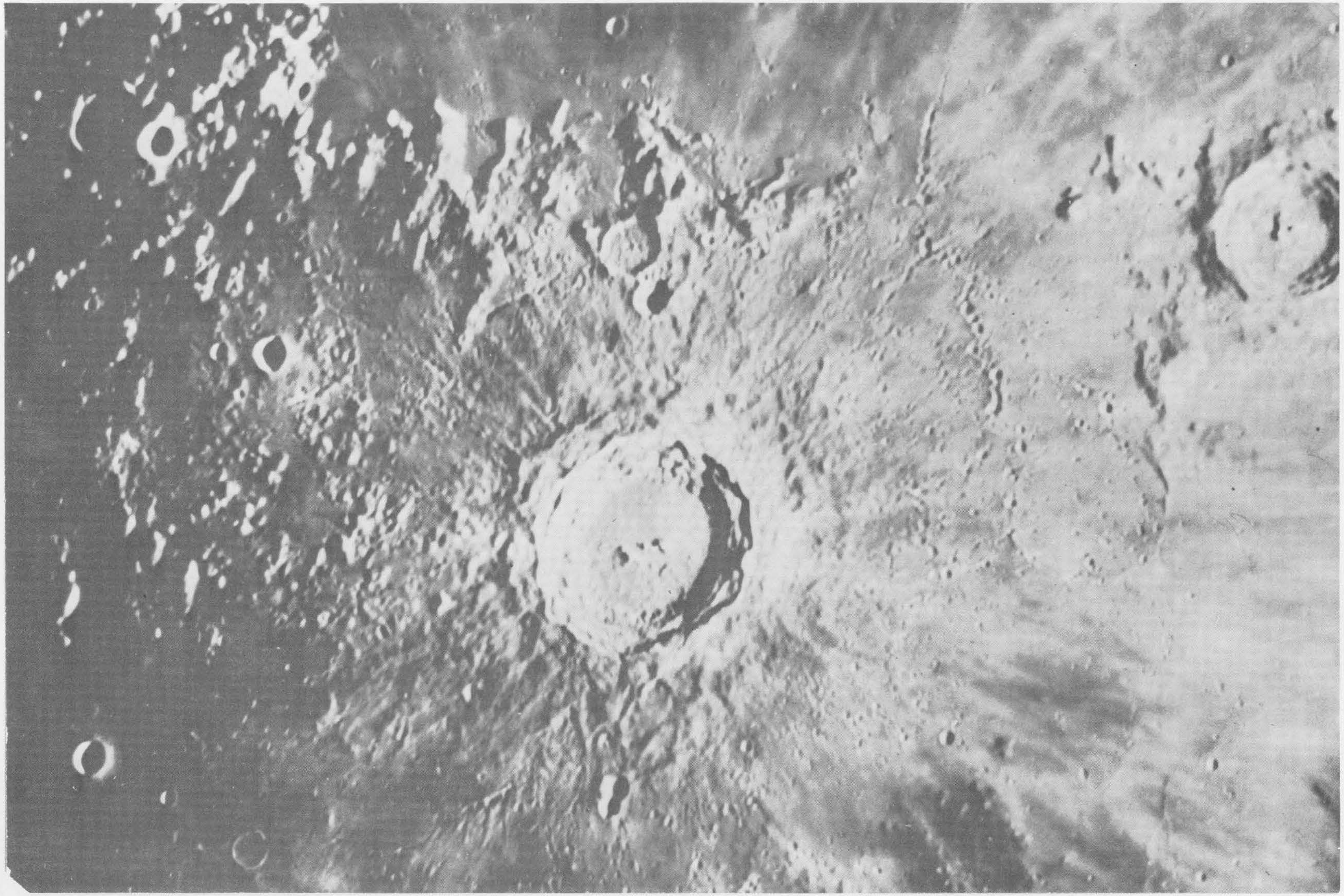


FIGURE 3.—Craters Copernicus (center), 90 km in diameter, and Eratosthenes (upper right), 60 km in diameter; Carpathian Mountains (Montes Carpatus) above Copernicus and Apennine Mountains (Montes Apenninus) above Eratosthenes. Both mountain ranges, part of a high terra ring surrounding Mare Imbrium (see figs. 2, 5), are embayed by the younger mare material. Rim and ray materials of Copernicus exhibit radial symmetry and are younger than the mare material. Geology of this area was mapped by Schmitt, Trask, and Shoemaker (1967) and by Carr (1965b). North is at top and east at right in this and all ensuing photographs, analogous to the orientation of terrestrial maps, the so-called astronautical convention. Unpublished photograph 1196 taken with the 61-inch reflector at Catalina Observatory, University of Arizona Lunar and Planetary Laboratory. Photographs taken with the Catalina telescope were unpublished at this writing, but many are now available in an atlas (Kuiper and others, 1967).

4) (Hackman, 1964, 1966; Shoemaker, 1964). The oldest recognizable unit is the rugged and stratigraphically complex terrain called "undivided material" of pre-Imbrian age in and northwest of the Apennine Mountains ("Apennines" in fig. 2). This undivided material is partly covered by the Fra Mauro Formation, a distinctively textured unit (p. 23–27). Next is the smooth flat light-colored material of the bench (Apennine Bench Formation), which embays the rugged terrain as does mare material. Following the light plains material are the crater material of Archimedes and the dark mare material. Youngest are materials of two rayed craters (Aristillus and Autolycus, of Copernican age) which, like the materials of Copernicus, clearly overlie the mare material.

Secondary criteria are employed to supplement superposition and transection relations in determining relative ages. These criteria include the density of superposed craters and the apparent freshness of units. Older units generally have more and larger superposed craters than younger units of the same gross morphology and composition, except where superposed craters are locally and anomalously concentrated. If the morphology of craters of similar size is assumed to have been originally the same, the materials of craters with subdued rims are older than those of craters with sharp rims in the same size category.

The value of a stratigraphic analysis is well illustrated by the preceding example. Archimedes is in the Imbrium basin, the largest mare basin, and much of the history of this basin was deduced from the stratigraphic relations in and around Archimedes. These relations show, for example, that the mare material filling the Imbrium basin is younger than the basin itself—sufficiently younger for the Apennine Bench Formation and materials of Archimedes to have been formed before emplacement of the mare material.

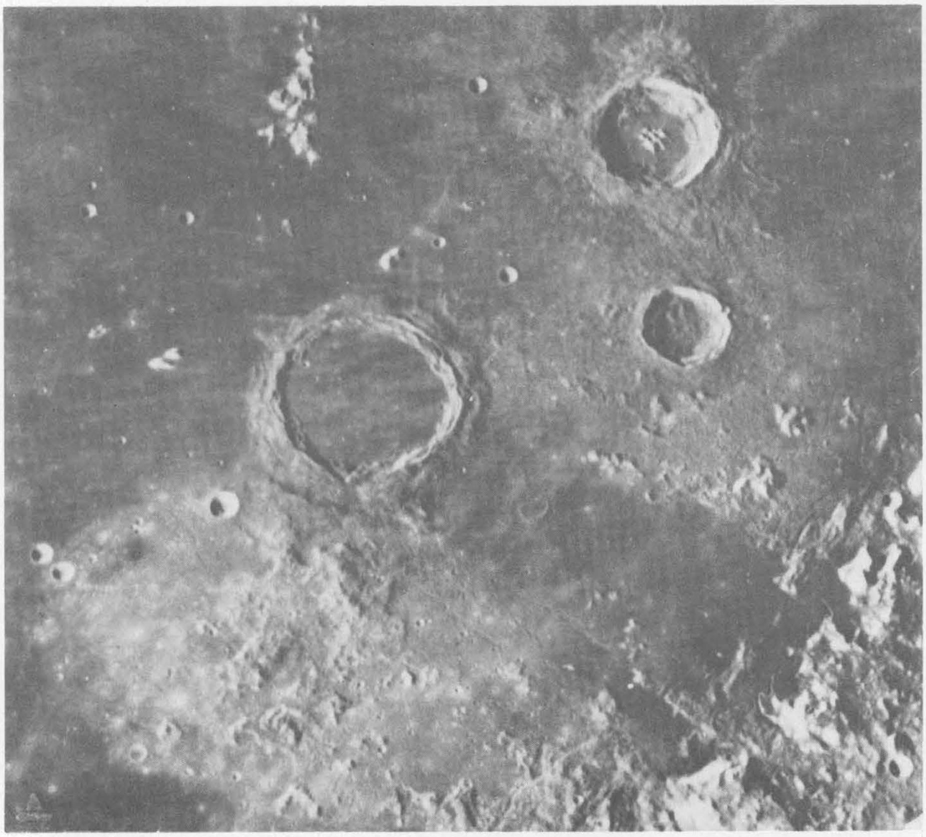
LUNAR TIME-STRATIGRAPHIC AND GEOLOGIC-TIME UNITS

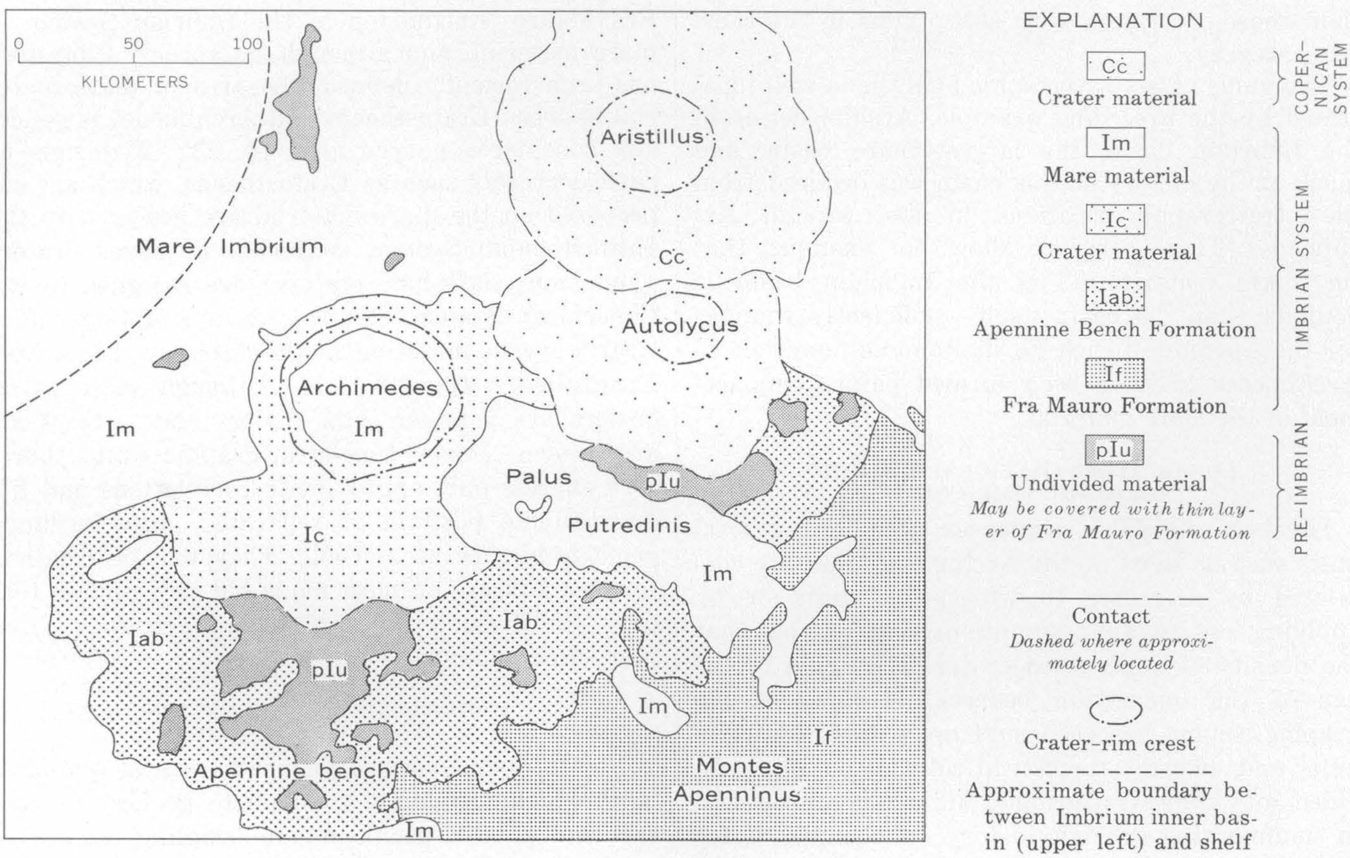
Local stratigraphic sequences of lunar material units such as those of the Archimedes area are correlated by reference to widespread units or by applying less certain assumptions, for example, that the density of superposed craters is related to the age of the underlying bedrock. A lunar stratigraphic column has been built up of lunar material units and, like the terrestrial column, has been divided into time-stratigraphic units for convenience in summarizing geologic history (Shoemaker, 1962, p. 344–351; Shoemaker and Hackman, 1962). Following terrestrial convention, the major time-stratigraphic units are designated systems and their subdivisions, series. The corresponding geologic-time units are periods and epochs, respectively. The three systems recognized at present, from oldest to youngest, are the Imbrian, Eratosthenian, and Copernican. (One system fewer than proposed by Shoemaker and Hackman, who included a Procellarian System.) Materials older than the Imbrian System are not yet assigned to systems and are designated simply as pre-Imbrian. The Imbrian System has been divided into two series, the Apenninian and Archimedian (Shoemaker, Hackman, Eggleton, and Marshall, 1962). These series have been used on some maps but have never been formally proposed; the author recommends that they be abandoned (p. 32–33).

The systems are defined in type areas in the regions where lunar stratigraphy was first worked out, near the craters Copernicus, Eratosthenes, and Archimedes. (Type area is a necessary lunar substitute for the terrestrial type section.) The base of the Imbrian System is the base of the Fra Mauro Formation, the unit at the surface in much of the Apennine Mountains, Carpathian Mountains, and the highland between the craters Copernicus and Fra Mauro. At the top of the Imbrian System is mare material, and although no specific type area has been formally defined, the area of mare material between Eratosthenes and Archimedes is generally considered a type area (p. 23). Materials of rayless craters such as Eratosthenes, which are superposed on the mare material are assigned to the Eratosthenian System. Materials of rayed craters (and many dark-halo craters) are assigned to the Copernican System, because the rays of Copernicus clearly overlie materials of the nearly rayless crater Eratosthenes (figs. 3, 12). Although most rayed craters are younger than rayless ones, exceptions are known. Lunar time-stratigraphic units therefore express only approximate correlations and the approximate position of separated units in lunar geologic history as a whole. They will be retained for this purpose on most maps but will remain tentative until moonwide correlations are made from spacecraft photographs.

SEPARATION OF OBSERVATION AND INTERPRETATION

The foregoing discussion needs several qualifications which are partly common to geology in general and partly specific to the fledgling science of




0
50
100
KILOMETERS
Mare Imbrium
Aristillus
Cc
Autolycus
Archimedes
Im
Im
Palus
pIu
Putredinis
Ic
Im
Iab
Iab
pIu
Im
If
Apennine bench
Montes
Apenninus
Im
EXPLANATION
Cc
Crater material
COPER-NICAN SYSTEM
Im
Mare material
Ic
Crater material
Iab
Apennine Bench Formation
If
Fra Mauro Formation
IMBRIAN SYSTEM
pIu
Undivided material
May be covered with thin layer of Fra Mauro Formation
PRE-IMBRIAN
Contact
Dashed where approximately located
Crater-rim crest
Approximate boundary between Imbrium inner basin (upper left) and shelf

lunar geology, which at this writing was still based solely on remote data. To control premature speculation, the three operations discussed above must be clearly separated: objective delineation of units, interpretation of these in terms of underlying materials, and correlation of separated units. The means for distinguishing fact from inference while conveying both are (1) the concurrent use of several conceptual types of geologic units and (2) the conventions, explanation, and text on the geologic map.

TYPES OF GEOLOGIC UNITS

A continuing problem in terrestrial stratigraphy has been premature inferences about the ages of material units. To achieve greater objectivity, the Stratigraphic Code (American Commission Stratigraphic Nomenclature, 1961) has distinguished between rock-stratigraphic units, material subdivisions of the crust that are distinguished solely on the basis of lithologic properties, and time-stratigraphic units, material units which include all rocks formed in a specific interval of time. Rock-stratigraphic units are the practical mapping units and are the basis for defining time-stratigraphic units. A third unit is a nonmaterial subdivision—the geologic-time unit, which is defined in terms of time-stratigraphic units. An effort to clarify the distinction among these three types of units for lunar stratigraphy was undertaken by lunar geologists of the Geological Survey in late 1963, and a stratigraphic classification parallel to the terrestrial one is now in use. (See McCauley, 1967b.)

The lunar parallel to the terrestrial rock-stratigraphic unit is the lunar material unit. It is here defined as a subdivision of the materials in the moon's crust exposed or expressed at the surface and distinguished and delimited on the basis of physical characteristics. Although lunar material units and rock-stratigraphic units are thus parallel in definition and purpose by being objective practical mapping units independent of inferred geologic history, they differ in enough ways to make the special lunar term desirable. First, the Stratigraphic Code implies that rock-stratigraphic units have a finite three-dimensional extent that is known to some degree, whereas the third dimension of lunar material units is generally inferred. Second, rock-stratigraphic units are defined mainly by lithology, whereas many distinguishing properties of lunar material units may prove to be secondary; certain of their features may have been superposed by structural, erosional, impact, or other processes. Third, lunar material units are probably more complex than most terrestrial rock-stratigraphic units; even relatively simple lunar material units may consist of an overlapping sequence of related rock units that on earth would be called a complex, or even of unrelated rocks of similar visible properties. Such a complex lunar material unit may be a tectonic unit, analogous to the Colorado Plateau for example.

These differences resulting from uncertainties about lunar materials require that the definition of lunar material units be free of inferences not only about age and origin but also about intrinsic lithology and subsurface form. This is not to say that inferences should not be made about lunar units, only that they be kept separate from definitions. Criteria selected to define units, regardless of the degree of interpretation that contributed to their selection, must be objective and recognizable by other geologists. All lunar material units are subject to revision. The simpler the combination of defining properties—where topographic and surficial properties coincide—the greater the confidence that a valid unit has been recognized. However, as noted above, the units are probably more complex than presently depicted, and their components may be recognized in the future. Properly defined units will serve as a springboard for new work, whereas premature time-stratigraphic or other inferences will retard recognition of true units.

MAP CONVENTIONS

Conventions and explanations of lunar geologic maps are parallel to those of terrestrial maps but are specially treated to separate interpretation from observation. In the explanation for each unit, one paragraph labeled "characteristics" defines and describes the unit, while a second labeled "interpre-

FIGURE 4.—Upper: Vicinity of the crater Archimedes. Photograph (L–35) taken with the 120-in. reflector, Lick Observatory. Part of the excellent series taken by G. H. Herbig and one of the best telescopic photographs ever made. Features as small as 130 meters in diameter are detectable, and the shape of features as small as 200 meters can be discerned. Lower: Geologic sketch map of area in upper view (after Hackman, 1966). Archimedes is younger than the materials of the Apennine bench (including rugged materials and the plains-forming Apennine Bench Formation) but older than the mare materials of Mare Imbrium and Palus Putredinus. The Apennine Mountains (Montes Apenninus) are part of the high arc surrounding the Imbrium basin, and the Apennine bench is part of the shelf.

tation" suggests a lithology, form at depth, history, and an origin that seem consistent with the characteristics. Interpreted relative age is shown by the order of units in the explanation. Geologic sections combine the interpretations of relative age and form at depth. A text summary accompanies the most recent maps.

Stratigraphic nomenclature and map conventions reflect the state of knowledge about lunar units. Units interpreted as true three-dimensional rock units are given either formal names derived from geographic place names (for example, Apennine Bench Formation) or informal but specific descriptions followed by the word "material(s)" (for example, mare material). Formal names may also be terms of convenience for units not confidently interpreted as rock units. If individual rock units which contribute to the observed character of a lunar material unit are not recognized, the unit is noncommittally designated by a terrain description followed by the word "material(s)," such as "hummocky material," "regional pitted material," or "ridge material." All names are objective, not interpretive—"crater rim material," not "impact ejecta" or "volcanic rocks."

Two or more superposed lunar material units are commonly recognized. The unit that contributes the surficial properties, such as albedo, may not appear to be the unit that contributes the dominant topography, because boundaries between albedo and topographic properties do not coincide. Alternatively, two superposed units, such as materials of two craters, may both contribute to the surface topography. If two superposed units are present, the one regarded as most significant is shown in color. This unit ordinarily is the youngest unit that contributes noticeable topographic expression, but it may be an albedo unit (a dark or light patch) whose topographic expression is that of an underlying unit. Opinions differ about which unit should be stressed. The choice of surface unit depends largely on the scale of mapping. For example, at telescopic resolution, the rim material of an old crater in the southern highlands is prominent, and on maps of 1:1,000,000 scale it is the unit mapped. But if spacecraft photographs show that the rim has a mantled appearance, then various mantling materials may be the units mapped on larger scale maps based on these photographs. Two superposed units commonly are shown by dotted contracts and sympols in parentheses for the underlying unit or by an overprint pattern for the overlying unit. Buried contacts are drawn at the limit of observed topographic expression, not at the inferred or projected limits. Some units are designed to show both the underlying and overlying layers. (See section entitled "Terra units of the Theophilus quadrangle".)

A lunar map unit commonly represents several occurrences of like materials, such as crater materials or ponds of plains material, each of which may have formed at a different time but within a given interval of time. Each individual occurrence of such material is regarded as a formation, as it would be on earth, but for convenience all are given the same name. Accordingly, two occurrences of the same unit may be separated by a contact (for example, where materials of one Copernican crater are superposed on those of another); this is not done on terrestrial maps. The symbol for a lunar map unit, like its terrestrial counterpart, consists of an abbreviation of the system to which it is assigned (capital letter) and an abbreviation of the formal or informal name (lowercase letters). Units that may belong to either of two systems are given symbols with two capital letters, representing both systems (youngest first). If the age of a unit is unknown or only approximately known, capital letters are omitted.

Detailed discussion of structural symbols is beyond the scope of this paper; suffice it to say that they too follow terrestrial precedent with allowances for lunar uncertainties. Mapped lunar features that resemble terrestrial features include faults (some quite definite and some inferred), lineaments (indistinct linear depressions), probable slump blocks, and circular and irregular depressions. Peculiar lunar features include riverlike sinuous rilles and mare ridges, scarps, and troughs. (Sinuous rilles and some linear rilles have been shown as geologic units instead of as structures on some maps.) The buried craters not shown by concealed contacts are shown by a rim-crest symbol. Lunar geologic sections contain additional interpretive symbols for breccia lenses and igneous intrusions.

LUNAR STRATIGRAPHIC COLUMN

Most of the remainder of this paper is a systematic review of lunar material units which have appeared on U.S. Geological Survey 1:1,000,000-scale maps. The units are grouped into time-stratigraphic units as they are on the maps. The oldest units, of pre-Imbrian and Imbrian age, are discussed first. These include the major lunar stratigraphic datum planes, areally extensive units associated with mare basins. Less space is devoted to units of Eratosthenian and Copernican age, which are mainly of local extent. These units, which are younger than the main mare basin filling, have greater morphologic variation than the older units. Miscellaneous units, which are also mostly young and varied but which are usually not assigned ages, are described in a separate section. Crater materials, the dominant lunar materials, are found in all lunar time-stratigraphic units and are discussed repeatedly. A special section is devoted to crater material subunits, which account for a large percentage of the units on Survey lunar geologic maps.

GENERAL OBSERVATIONS

Many basins that contain mare material are large complex circular structures hundreds of kilometers in diameter consisting of an inner basin and several outer concentric troughs separated by raised rings (Hartmann and Kuiper, 1962; Baldwin, 1963)[3]. These circular multiringed mare basins are the largest features on the moon and dominate its stratigraphy and structure. The formation of one is a major event which largely obliterates the earlier stratigraphic record in its vicinity and starts a new stratigraphic succession. The time of formation of the basins relative to one another has been estimated by the freshness of structures surrounding the basins and by the density of craters superposed on these structures. Tentatively, the sequence of basins, from oldest to youngest, appears to be: Fecunditatis (the northern, larger part), Serenitatis, Nectaris, Humorum, Crisium, Imbrium, Orientale; or Crisium may have preceded Humorum. The first five are pre-Imbrian in age, and the last two are Imbrian; the Imbrian Period began with the formation of the Imbrium basin (fig. 5). Imbrium is a large basin whose associated stratigraphic units and structures dominate a huge area of the moon's earthward side and to which the rest of the earthside stratigraphy is referenced. The deposits of the younger Orientale basin form another important datum plane on the west limb, an area less fully studied by telescope because it is only partly visible from earth. Other basins whose circular multiringed form is less clear, such as Nubium and Tranquillitatis, may each consist of a circular ringed basin or of two or more coalescing but separately formed basins. Oceanus Procellarum is an irregular generally depressed mare-covered area. Parts of several discrete apparently multiringed basins occur within this area, and others are probably present beneath the mare surface. It is not known whether Oceanus Procellarum as a whole is localized in a giant multiringed basin.

The stratigraphic sequence in each circular multiringed basin is grossly similar to the sequence established in the Archimedes area for the Imbrium basin, although the units vary in age from basin to basin (table 1). At the base of each local section are the materials formed before the basin. These materials are exposed in the raised rings surrounding the basin that probably were uplifted when the basin was formed (figs. 3, 4, 5, 6). The individual preuplift units in these rings are now unrecognizable, but presumably they were much like units of that terra in the southern highlands not affected by basin formation.

Partly covering these rings are materials believed to be deposits of debris ejected from the basin during its formation. Materials interpreted as ejecta are seen around three basins—Imbrium, Orientale, and Humorum (fig. 6)—and patchy hummocky materials near other basins may also consist of ejecta.

Two kinds of units that are younger than the basin-related materials are light plains-forming materials and crater materials. The light plains-forming materials fill troughs between the raised arcs and cover the shelves of the basins (figs. 4, 5, 6). In the Archimedes area of the Imbrium basin (fig. 4), these materials are older than the crater Archimedes, but in most areas there is a complex overlapping sequence of plains-forming and crater materials.

Next younger in all basins, and covering part of the lighter plains-forming materials in the troughs and shelves and filling the inner basin, is the widespread dark plains-forming material called mare material. Mare material (formerly designated the Procellarum Group) was once thought to be approximately the same age in all basins, but more and more exceptions to this are being found. Lastly, crater materials and other materials of the Eratosthenian and Copernican Systems overlie or are interbedded with the mare material in all basins.

Craters—young and old, large and small—are the moon's dominant features. Many topographic features are recognized as parts of craters after allowance is made for faulting and partial burial.

Materials of all large and of many small craters that are circular or roughly circular and have raised rims and concave-upward flanks are normally assigned to systems. Craters older than the Fra Mauro Formation are pre-Imbrian. Craters younger than Fra Mauro but older than most of the mare

[3] Circular multiringed basins without mare material are called thalassoids—sealike. Several occur on the moon's averted side (Lipsky, 1965).

material are Imbrian. Rayless craters on the mare material are Eratosthenian. All bright-rayed and some dark-halo craters are Copernican. Many craters whose stratigraphic relations cannot be directly determined must for the present be dated subjectively by apparent freshness. There seems to be an age progression from the very fresh craters like Copernicus to subdued craters like many in the southern highlands. Fresh craters have high sharp rims, deep floors, well-developed hummocky and

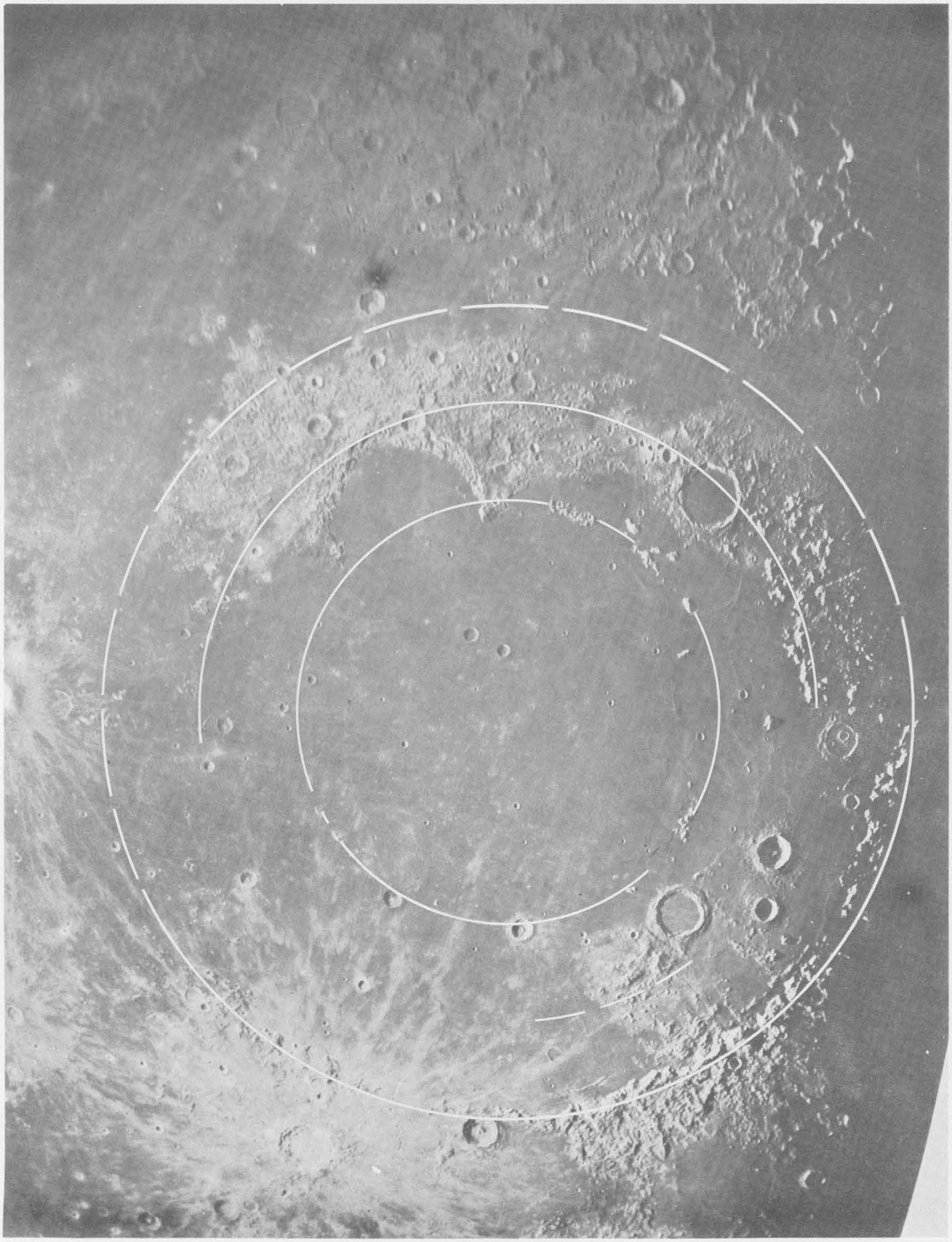


FIGURE 5—(Explanation on opposite page)

radial rim-material facies and extensive fields of satellitic craters. Subdued craters have low rounded rims, shallow broad floors, and only a narrow ring of rim material. Crater materials dated only by freshness are placed in three broad overlapping categories: pre-Imbrian, pre-Imbrian or Imbrian, and Imbrian or Eratosthenian. The overlap of the three designations assures that a crater unit cannot be seriously misassigned.

Crater materials of several other types, whose differences in appearance apparently are not due entirely to differences in age, are not assigned to systems. These include materials of irregular high-rimmed craters, low-rimmed round or slightly elongate craters, and craters alined in chains or along rilles, such as Hyginus rille (fig. 7).

Round or irregular depressions are commonly mapped by depression symbols or sometimes by the interpretive convention of arcuate faults and not as material units.

PRE-IMBRIAN UNITS

Rocks older than the Fra Mauro Formation, the basal unit of the Imbrian System, are complex and have been mostly left undivided; only a few distinctive units have been mapped. The main pre-Imbrian units are undivided materials in raised arcs concentric with mare basins, complex units in interbasin areas, and crater materials. Near the Imbrium basin, rocks are recognized directly as pre-Imbrian in age where they appear to be buried by the Fra Mauro Formation, or indirectly, where they are cut by elements of Imbrian sculpture (see fig. 8), which are believed to be mostly contemporaneous with the Fra Mauro. Farther from the Imbrium basin, units are dated and correlated with units that are near the Imbrium basin chiefly by comparison of crater densities; units whose density of superposed craters is greater than that of the Fra Mauro are inferred to be pre-Imbrian. Additionally, pre-Imbrian "crater material" is distinguished from Imbrian crater material on the basis of its more subdued topography; pre-Imbrian craters have broad shallow floors and crater-pocked low narrow rims.

The Imbrium basin, like all large circular mare basins, is surrounded by several concentric belts of alternating ridges and troughs (fig. 5). The most prominent topographic ring is composed of rugged arcuate mountain ranges named in different areas the Carpathians (fig. 3), Apennines (figs. 3, 4), and Caucasus. The subsurface material of the rugged ring is by definition pre-Imbrian, because the surface material, except for a few apparent pre-Imbrian islands, is the Fra Mauro Formation, which defines the base of the Imbrian System. This pre-Fra Mauro material is no doubt a complex assemblage of rocks and where exposed has been mapped by most workers as "undivided (undifferentiated) material" of pre-Imbrian age (table 1).

Although the materials in the ring surrounding the Imbrium basin are pre-Imbrian, the ring probably owes its present form to structural deformation in the Imbrian Period. Most of this deformation probably occurred at the beginning of the Imbrian Period when the basin was formed. Under the impact hypothesis the basin was formed nearly instantaneously, and the ring was uplifted by shock waves from the impact and immediately covered by the Fra Mauro Formation, which consists of the ejecta from the impact. Renewed movement and degradation have modified the ring to an unknown degree.

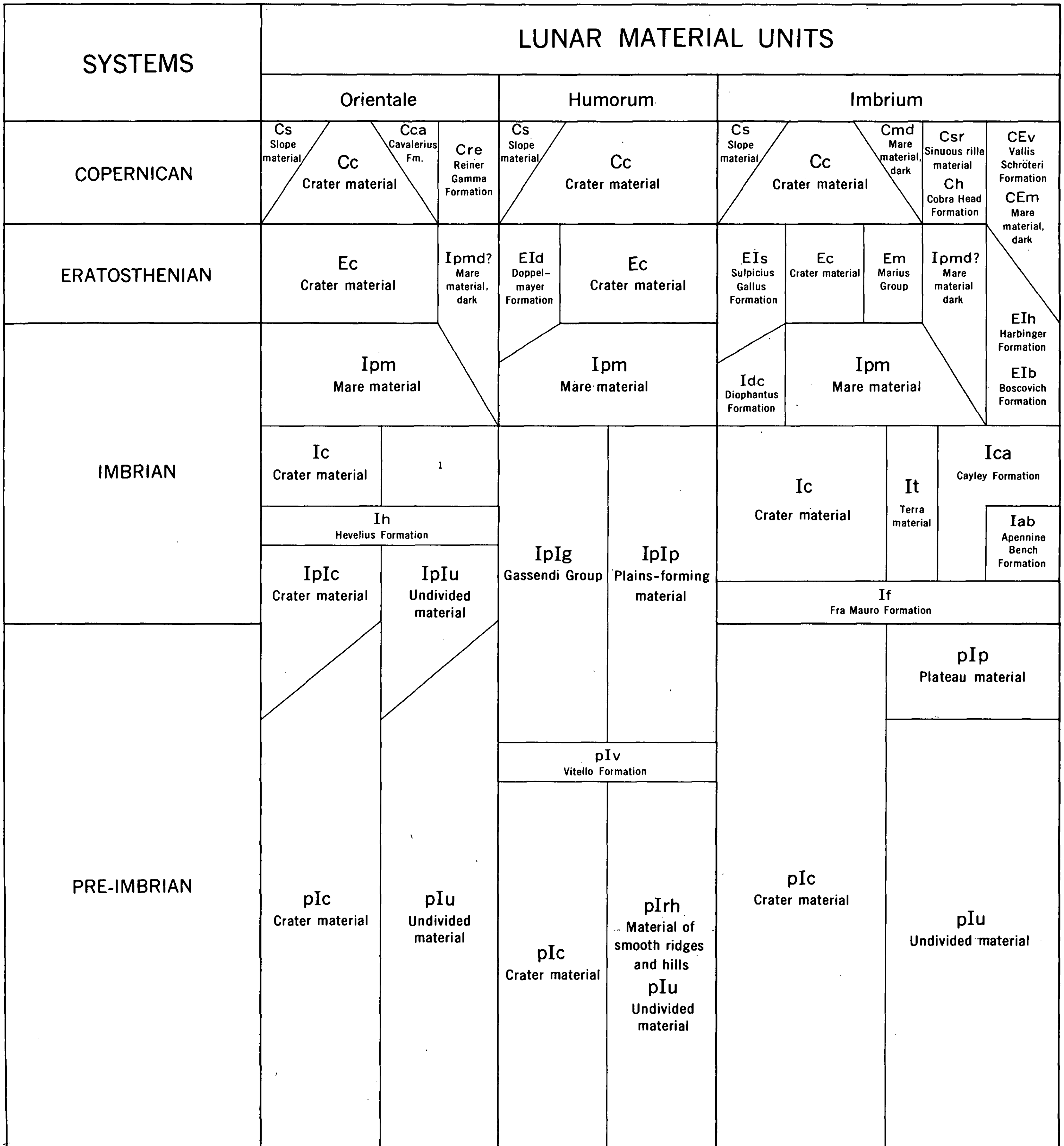
Much terrain near the Imbrium basin is transected by a system of scarps, ridges, and troughs radial to the center of the basin. These features are collectively termed "Imbrian sculpture" (figs. 5, 8) (Gilbert, 1893; Hartmann, 1963). Gilbert and several others believed that the troughs and ridges were sculptured by flying debris from the Imbrium impact, but the morphology of the so-called sculpture can more convincingly be explained as a series of fault-bounded horsts and grabens. "Sculpture" remains a convenient term for the set of features radial to the Imbrium basin. Similar sculpture is present around other basins (Hartmann, 1964).

The assumption that much of the Imbrian sculpture originated when the basin was formed has been used to date the transected units. Under any hypothesis of origin, the close geometric relation

FIGURE 5.—Mare Imbrium and its multiringed basin. Three concentric rings are outlined by the circles: an island ring approximately 670 km in diameter around the inner basin, a middle ring approximately 950 km in diameter including the Alpes and the rugged terra on the Apennine bench south of Archimedes, and an outer ring, 1,340 km in diameter, whose highest part is the Apennine Mountains ("Apennines" in fig. 2). Mare materials occupy depressions related to the basin, notably the long concentric trough north of the basin (Mare Frigoris). Note the radial troughs and ridges composing the "Imbrian sculpture." (See fig. 8). Rectified photograph and concentric circles by Hartmann and Kuiper (1962), courtesy of Lunar and Planetary Laboratory, University of Arizona. (Other rectified photographs are available in an atlas by Whitaker and others, 1963.)

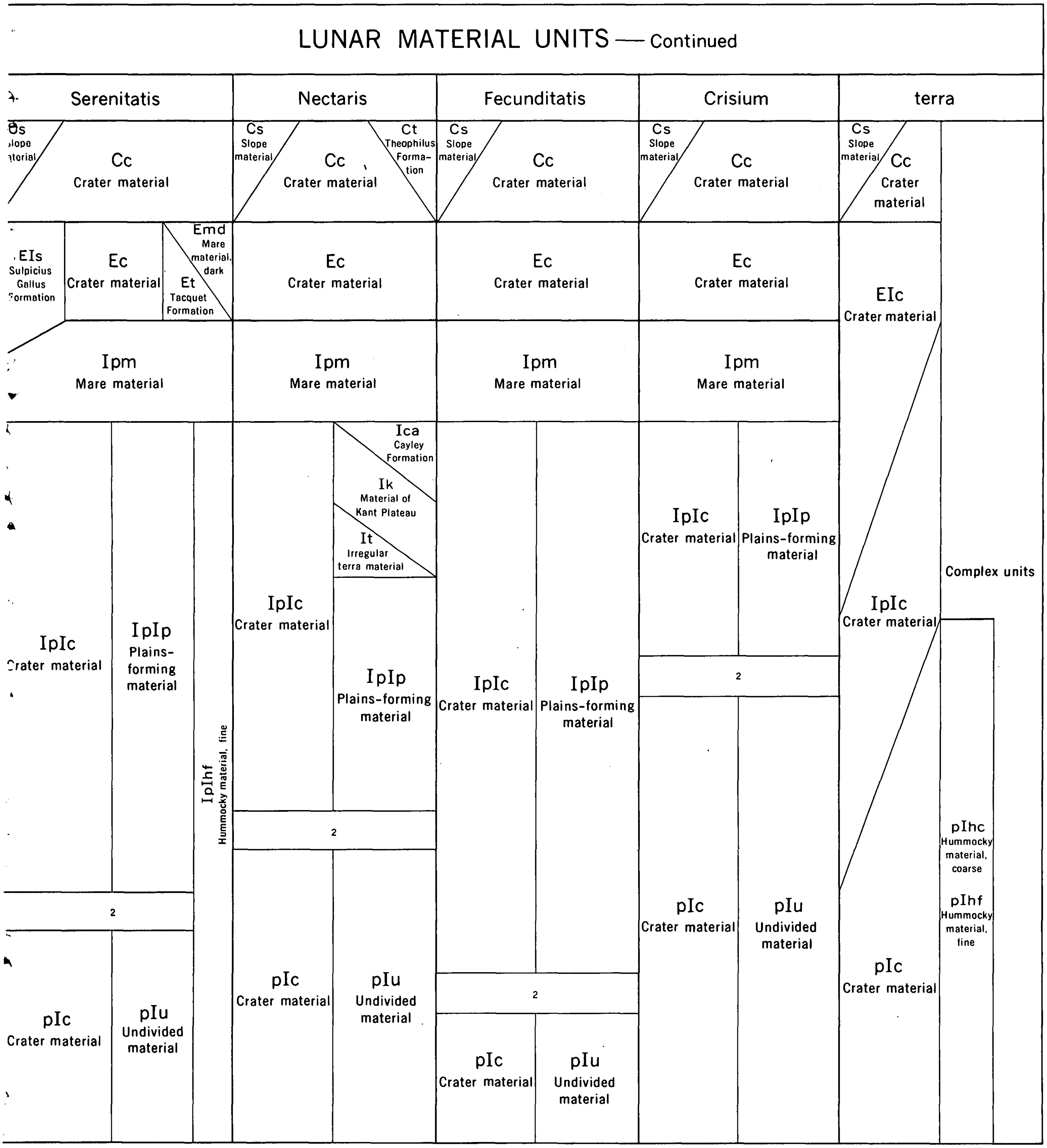
TABLE 1.—*Composite lunar stratigraphic columnar*

[Symbols are those that have been used on published maps. Subunits and satellitic crater materials are not shown. Units are arranged according to the mare to have been formed contemporaneously with each basin are shown in narrow horizontal boxes (for example, the Fra Mauro Formation); the relative positions



section showing most units discussed in text

basin they are nearest, but many units are not genetically related to the basins; units not near one of the basins named are listed under terra. Units believed of these boxes therefore indicate the estimated relative time of formation of the basins]



(Unit page references on next page)

PAGE REFERENCES TO PRINCIPAL TEXT DESCRIPTIONS OF UNITS

Crater units younger than Imbrian mare material:

Cc	Crater material (light-rayed) (36)
	Dark-halo crater material (Ccd) (36) has same stratigraphic position
Ec	Crater material (36)

Miscellaneous units younger than Imbrian mare material:

Cs	Slope material (39)
Cca	Cavalerius Formation (37)
Cre	Reiner Gamma Formation (37)
Cmd	Mare material, dark (32, 37)
Csr	Sinuous rille material (38)
Ch	Cobra Head Formation (38)
Ct	Theophilus Formation (37)
CEv	Vallis Schröteri Formation (38)
CEm	Mare material (32, 37)
Em	Marius Group (37)
Emd	Mare material, dark (32, 37)
Et	Tacquet Formation (37)

Units partly contemporaneous with Imbrian mare material:

EIc	Crater material (33)
EId	Doppelmayer Formation (33)
EIs	Sulpicius Gallus Formation (33)
EIh	Harbinger Formation (35)
EIb	Boscovich Formation (35)
Idc	Diophantus Formation (28)
Ipmd?	Mare material, dark (30); may be younger than Imbrian mare material

Mare material of Imbrian age (formerly called Procellarum Group):

Ipm	(29)

Crater units younger than the basins but older than the mare material:

Ic	Crater material (including that of Archimedes) (28)
IpIc	Crater material (22)
IpIg	Gassendi Group (23)

Plains-forming and other noncrater units younger than the basins but older than the mare material:

It	Terra material (28)
	Irregular terra (29)
Ica	Cayley Formation (27)
Iab	Apennie Bench Formation (27)
Ik	Material of Kant Plateau (29)
IpIp	Plains-forming material (22) (not yet shown on published maps near Nectaris, Crisium, and Fecunditatis basins)
(1)	Plains-forming unit of Imbrian age present but not yet named on published maps

Units contemporaneous with formation of basins:

Ih	Hevelius Formation (28)
If	Fra Mauro Formation (23)
pIv	Vitello Formation (22)
(2)	Basin-contemporaneous units not yet named on published maps

Units older than the basins:

IpIc	Crater material (22)
IpIu	Undivided material (19)
pIc	Crater material (15)
pIp	Plateau material (18)
pIu	Undivided material (15, 22)
pIrh	Material of smooth ridges and hills (22)

Other units:

IpIhf, pIhf	Hummocky material, fine (22)
pIhc	Hummocky material, coarse (22)

between the radial sculpture pattern and circular basin implies a genetic relation. This relation is easily explained by the impact hypothesis, which additionally implies a temporal relation. Most of the faults were probably produced by the shock proceeding outward from the basin-forming impact (Shoemaker, 1962, p. 349); however, some faults probably were preexisting fractures and were only emphasized by the impact, and others may have been rejuvenated since the impact (Masursky, 1964, p. 128–129; Howard and Masursky, 1968). Therefore, a crater or other feature that is close to the Imbrium basin and is cut by many basin-radial fractures is likely to be pre-Imbrian, even though one or two such fractures do not prove pre-Imbrian age. This assumption is particularly helpful because the Imbrian sculpture pattern can be traced farther from the basin than the Fra Mauro Formation.

One sculptured pre-Imbrian unit of possible depositional origin has been described on published maps. Pre-Imbrian crater remnants are less common on terrain northwest of Ptolemaeus and west of Herschel (fig. 8) than in much of the southern highlands. The missing pre-Imbrian craters may have been buried by thick deposits, mapped as "plateau material," before the terrain was faulted by Imbrian sculpture (Howard and Masursky, 1968).

Extensive pre-Imbrian materials beyond the limits of the Fra Mauro Formation and Imbrian sculpture occur in arcs concentric to other basins. Examples are the Altai Scarp (Rupes Altai) and several lower arcs around the Nectaris basin, and two prominent arcs bounded by steep jagged scarps around the Crisium basin (Hartmann and Kuiper, 1962; Wilhelms, Masursky, Binder, and Ryan, 1965, summarized in U.S. Geological Survey, 1966, p. A124). Arcs around three other circular basins—Serenitatis, Fecunditatis, and Humorum (fig. 6)—are less well defined. The Fra Mauro Formation has not been identified on any of these arcs; so there is no direct means of estimating their age. However, the number of large craters superposed on the arcs is so much greater than on the surface of the Fra Mauro that, unless the formation of craters was localized along the arcs, the arcs must be pre-Imbrian. Further evidence for the age of the arcs, although still more indirect, is provided by their relatively subdued topography. Among the pre-Imbrian structures, only the Altai Scrap and the arcs of Crisium approach the Apennines in elevation and ruggedness.[4] Like the Apennines and other elements of the main Imbrium ring (see fig. 5), the

[4] The structures associated with the Orientale basin are fresher than those of the Imbrium basin; this and other evidence suggests that the Orientale basin is Imbrian in age. Undivided ring materials near Orientale must therefore be called "pre-Imbrian or Imbrian."

FIGURE 6.—Mare Humorum. Large crater at top is Gassendi (G), 110 km in diameter. Gassendi transects one of the concentric structures of the Humorum basin and so is younger than the basin. It is embayed, however, by mare material and thus is older than the mare. Type area of the Vitello Formation (pIv) is in the lower right corner, southeast of the sharp 40-km diameter crater Vitello (V). Rugged terrain to left of Gassendi may also be the Vitello Formation. Premare light plains-forming material (IpIp) occurs in patches. Dark material at bottom is Doppelmayer Formation (EId); right-hand (east) occurrence of this formation overlies part of the rim and interior of the crater Doppelmayer. Note ridges (r) and mare-filled trough (arrow) concentric with the basin. Inner basin probably lies between southernmost part of Gassendi rim and northernmost part of Doppelmayer rim. Geology of this area was mapped by Titley (1967). (Photograph 1607, Catalina Observatory.)

FIGURE 7.—Hyginus rille (Rima Hyginus) and its chain of regularly spaced uniform-sized craters. Part of lunar chart LAC 59, typical of the base charts produced at a scale of 1:1,000,000 by the Air Force Aeronautical Chart and Information Center (ACIC). Compiled from many photographs with critical detail added from visual telescopic observations; detail is shown better than on any single earth-based photograph and about as well as can be seen visually with a large telescope under good conditions. Each grid square is 2°, or about 60 km on a side.

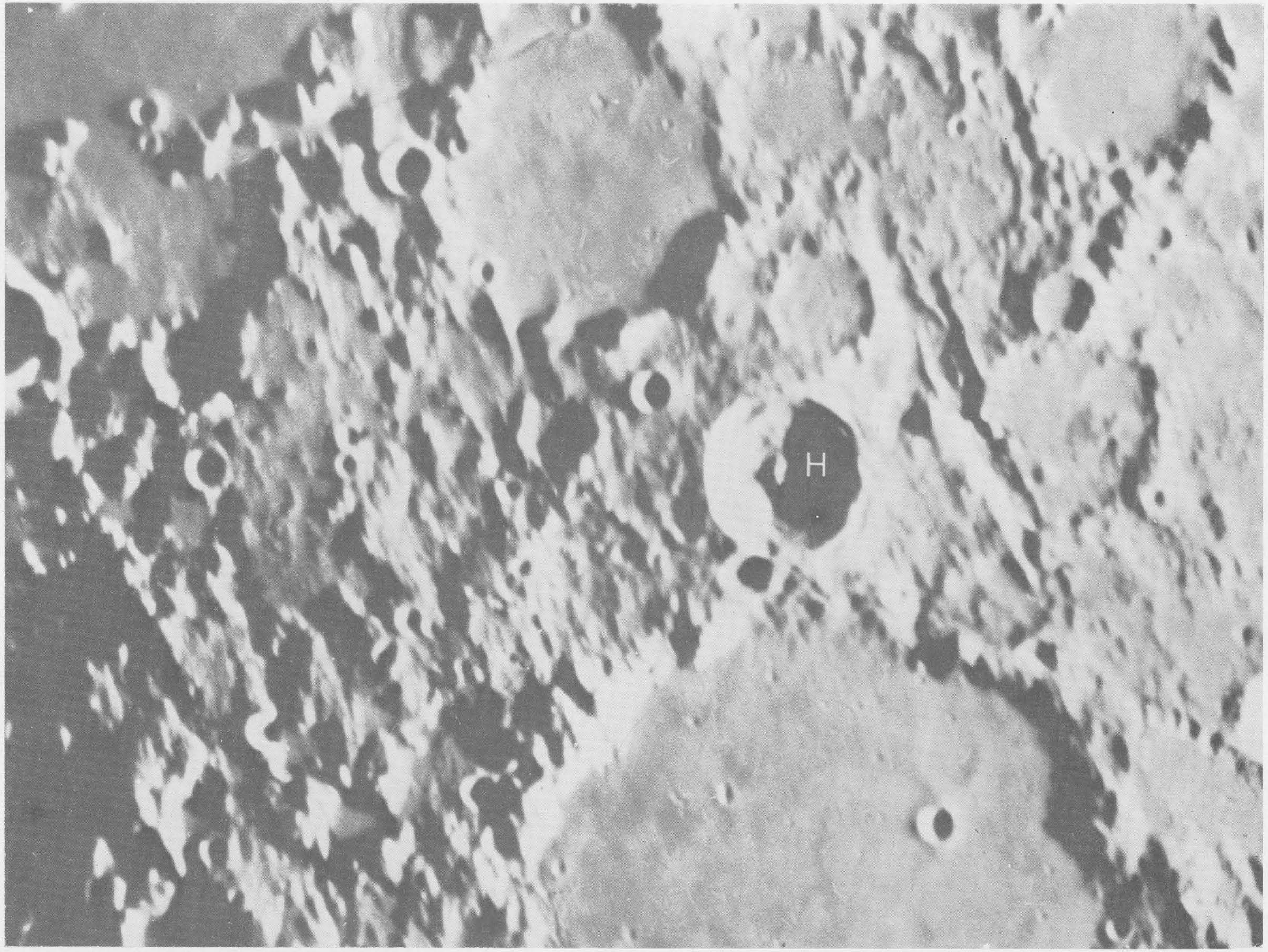


FIGURE 8.—Central part of moon showing "Imbrian sculpture" trending N. 30° W., radial to the Imbrium basin. Large flat-floored crater at bottom of picture is Ptolemaeus, 145 km in diameter; fresh crater to right of center is Herschel (H), 40 km in diameter. The rims of Ptolemaeus and of many other flat-floored craters are cut by the Imbrian sculpture, but the floors of these craters and the rim of Herschel are not cut. The flat floor material is assigned to the Cayley Formation of Imbrian age; Herschel is still younger. Sculptured terrain west of Herschel and northwest of Ptolemaeus where few old craters are present may be formed by a discrete pre-Imbrian plateau unit. Geologic map of this area by Howard and Masursky (1968). (Photograph 1907, Catalina Observatory.)

pre-Imbrian basin rings must have received their topographic configuration at the time of basin formation. These materials are designated mostly as "undivided" (or undifferentiated); those around the Humorum basin are designated "material of smooth ridges and hills" (Trask and Titley, 1966; Titley, 1967).

The surface materials on these rings differ from basin to basin and are interpreted with varying degrees of confidence. Hummocky material partly resembling the Fra Mauro Formation and also tentatively interpreted as ejected debris is present in patches around the Humorum basin (fig. 6) (Titley and Eggleton, 1964, summarized in U.S. Geological Survey, 1965, p. A131–132). This material was named the Vitello Formation (Trask and Titley, 1966; Titley, 1967). Terrain around the basins of Crisium, Serenitatis, Nectaris, Fecunditatis, and other maria is complex, and the recognition of significant units must await interpretation of Orbiter photography. A few patches of hummocky material have been mapped and assigned pre-Imbrian or noncommittal pre-Imbrian or Imbrian ages. Examples that have appeared on published maps are "hummocky material, fine (pre-Imbrian) and "hummocky material, coarse" (pre-Imbrian), near Mare Nubium but not clearly related to any multiringed mare basin (Trask and Titley, 1966), and "hummocky material, fine" (pre-Imbrian or Imbrian) near the Serenitatis basis (Carr, 1966a). If extensive hummocky material like the Fra Mauro ever surrounded the pre-Imbrian multiringed basins, it is either buried or its characteristic hummocky texture has been obliterated (by mass wasting, meteorite bombardment, and (or) a cover of presently unrecognized volcanic materials).

PRE-IMBRIAN AND (OR) IMBRIAN UNITS

Many lunar units are designated "pre-Imbrian or Imbrian," meaning that they are older than the youngest units of the Imbrian System but that their relation to units at the base of the Imbrian is unknown. Other units are designated "pre-Imbrian and Imbrian," meaning also that they are older than the youngest Imbrian units but that some individual occurrences of the unit are older and some younger than the oldest Imbrian units. Most mapped pre-Imbrian and (or) Imbrian units are associated with pre-Imbrian multiringed mare basins and are younger than the basins but older than the mare material filling the basin. Their stratigraphic relations to the basins are therefore similar to the relation of Imbrian units to the Imbrium basin.

The blanket designation "pre-Imbrian or Imbrian" has come into wide use in lunar geologic mapping because the base of the Imbrian System is marked over less area of the moon than the top of the system. Outside the limits of the Fra Mauro Formation and the Imbrian sculpture, the age of material cannot be confidently determined relative to the base of the Imbrian System. The approximate top of the system is marked by the widespread mare material, much or possibly most of which is Imbrian. Many units are in contact with the mare material or can be dated relative to it by density of superposed craters. Some units that cannot be dated this way are designated "pre-Imbrian or Imbrian" because they do not seem as fresh as known postmare units (for example, terra dome material and slope material (Trask and Titley, 1966).

"Crater material" is a common "pre-Imbrian or Imbrian" unit. This broad age designation may seem nearly meaningless but it is useful for those craters which are much less fresh than Eratosthenes and other Eratosthenian craters and which have more superposed small craters, but are not quite as cratered, subdued, and degraded as craters that are definitely pre-Imbrian.

Another common unit of "pre-Imbrian or Imbrian" age, "plains-forming material," forms light flat smooth surfaces and resembles the Apennine Bench and Cayley Formations of Imbrian age. (See p. 27.) It occurs over much of the lunar surface, mostly in depressions and commonly in the troughs surrounding each pre-Imbrian multiringed mare basin and on the shelf between the inner basin and the first high ring. Light plains embay the rugged terrain of the circumbasin structures and are ordinarily not cut by the same faults which cut these structures; therefore the plains material is younger than the basins. Although this plains material near pre-Imbrian basins resembles the Cayley Formation, it cannot be dated relative to the Fra Mauro Formation or Imbrian sculpture and so cannot be correlated with the Cayley. Because of this uncertaintly that it is Imbrian in age, it is designated "pre-Imbrian or Imbrian" (Carr, 1966a; Trask and Titley, 1966; Titley, 1967).

The slightly different designation "pre-Imbrian and Imbrian" has a more definite meaning. This age designation refers to groups of crater materials which, like the pre-Imbrian or Imbrian plains-forming unit, are younger than a pre-Imbrian multiringed basin but older than the mare material which fills the basin. The position of these crater materials in the local basin stratigraphy is thus analogous to that of Archimedes materials in the Imbrium basin stratigraphy—younger than the basin but older than the basin-filling mare. The difference in designation between the "pre-Imbrian or Imbrian" of the plains unit and the crater unit is that while no individual crater can yet be accurately dated, there is reason to believe that some are pre-Imbrian and some are Imbrian in age because craters are more numerous per unit area near the basins than Imbrian-age Archimedes-type craters are near the Imbrium basin. Examples of their groups are the craters Fracastorius in the Nectaris basin and Gassendi in the Humorum basin (fig. 6). Only the Gassendi Group has been formally named (Titley, 1964, p. 67; U.S. Geological Survey, 1964, p. A141–142 (brief mention); Trask and Titley, 1966 (definition); Titley, 1967). (The section in this report entitled "Crater material subunits" discusses the nomenclature and subdivision conventions of the Gassendi Group.)

Separate colors are used for those crater materials designated "pre-Imbrian or Imbrian" and those designated "pre-Imbrian and Imbrian." In map explanations, the former are shown to the left of the main column, and the latter are incorporated in the main column below the mare material and above units formed contemporaneously with the multiringed basins.

IMBRIAN SYSTEM

DEFINITION AND GENERAL FEATURES

The name "Imbrian System," derived from Mare Imbrium, has been applied in several different ways and has not been formally defined. The name was restricted first to the hummocky blanket surrounding Mare Imbrium (Shoemaker and Hackman, 1962, p. 293–294), now called the Fra Mauro Formation. Next, in an informal publication (Shoemaker, Hackman, Eggleton, and Marshall, 1962) the system was enlarged to include two series, the Apenninian (the hummocky regional blanket) and Archimedian (crater materials), a usage which persisted through the publication of two quadrangle maps (Kepler region, Hackman, 1962; Letronne region, Marshall, 1963). Following a meeting of lunar mappers in November 1963, rock-stratigraphic terms were separated from time-stratigraphic terms. The materials of the Procellarian System, formerly the system next younger than Imbrian, became the rock-stratigraphic (lunar material) unit Procellarum Group and the top of this group was taken as the top of the Imbrian System. The Fra Mauro Formation was named and remained as the base of the Imbrian System. The two series were retained; the Fra Mauro and Apennine Bench Formations belonged to the Apenninian Series and the Archimedes-type craters and the Procellarum Group belonged to the Archimedian Series. Because the base of the Imbrian System is the Fra Mauro Formation and the top is mare material, the system includes essentially all the rocks formed between the time of formation of the Imbrium basin and the time of completion of most of its filling.

Confusion has persisted about the definition of the top of the Imbrian System. Neither the type area of the former Procellarian System, presumably in the Copernicus quadrangle, nor the type area of the Procellarum Group, informally established in the Kepler quadrangle, was explicitly established as the type area of the top of the Imbrian System. (These type areas are further discussed in the section on nomenclature of the mare material.) This is fortunate because the mare material in the Copernicus quadrangle and in all but the western part of the Kepler quadrangle is nearly obscured by ray material and therefore is not a satisfactory type for the system. Furthermore, the western part of the Kepler quadrangle is far from the Copernicus-Eratosthenes-Archimedes region, where the general lunar stratigraphy was first worked out. The mare material in the latter region that is least obscured by rays is that between Eratosthenes and Archimedes; this region between Eratosthenes and Archimedes appears to be the most satisfactory type area for the top of the Imbrian System. Units in this area can be confidently assigned to either the Imbrian or Eratosthenian Systems. Accordingly, many mappers have used it as an informal type area, but it is not now proposed as a formal type area because Orbiter photographs may reveal unsuspected complications.

FRA MAURO FORMATION

The terra surrounding the Imbrium basin has a hummocky surface which is generally similar in appearance in belts concentric with the basin but changes progressively with distance from the basin, from coarsely hummocky and complexly structured to relatively smooth (fig. 9) (Eggleton and Marshall, 1962). Within these belts, the terrain underlying the surface appears heavily mantled close to the basin and progressively less mantled farther from it. This regularity suggests that the surface material is a true rock-stratigraphic formation; that is, the hummocky morphology is intrinsic to the unit, and the unit forms a laterally continuous bed of rock, even where covered by younger rocks.

This unit, after passing through a series of name changes, is now called the Fra Mauro Formation. Along with some now-excluded smooth materials, the present Fra Mauro was originally called the Imbrian System, because of its relation to the Imbrium basin (Shoemaker and Hackman, 1962,

p. 293, 294); it was thus equated with a time-stratigraphic system. Later (Shoemaker, Hackman, Eggleton, and Marshall, 1962; Hackman, 1962; Marshall, 1963) it was called the "regional material of the Imbrian System" and was equated with the time-stratigraphic unit, the Apenninian Series. This older of two series of the Imbrian System was named after the Apennine Mountains, where the unit is well developed. But basic units, in stratigraphic practice, should not be time stratigraphic units (American Commission Stratigraphic Nomenclature, 1961); therefore the Fra Mauro Formation was later established by Eggleton, in a preliminary open-file report (1964, p. 51–55), with specific type areas and more exact physical definitions. This definition began the divorce of the Fra Mauro from the Apenninian Series. Eggleton, however, still regarded Apenninian Series as the basic designation for the circum-Imbrium blanket that contained the Fra Mauro Formation and the probably younger Apennine Bench Formation as subunits.

DEFINITION

The Fra Mauro Formation is defined here because its first definition (Eggleton, 1964) was not printed in a recognized scientific publication and its first published description lacked a definition (Eggleton, 1965). In another publication (U.S. Geological Survey, 1964, p. A141), the unit was referred to by name but not described. The type area (fig. 10) is here designated a rectangle bounded by lat 0° and 2° S. and long 16° W. to 17½° W. (LAC 76, 2d ed.), north of the crater Fra Mauro for which the formation is named. (Fra Mauro is a pre-Imbrian crater buried by the formation.) This area is the eastern three-quarters of Eggleton's type area of the hummocky member. Eggleton defined two members—one hummocky and the other smooth—and referred to them as facies. Characteristics in the type area (mostly in Eggleton's words) are: abundant, close-spaced, low, rounded, subequidimensional or north-south elongated hummocks generally 2–4 km across. (A hummock is a low somewhat irregular hill; the term "hummocky," commonly used in the lunar literature, refers to the presence of many such hills which together give an impression of disorder.) This definition of the Fra Mauro Formation includes all material in the rectangle (except crater materials) because the uniformity of the hummocks and intervening depressions suggests that they are intrinsic to a single depositional unit; that is, they would develop even if the formation were deposited on a smooth surface. A supplementary reference area is between lat 3° S. and 4½° S. and long 17° W. and 18° W. The topography of this area is similar to that of the type area, although slightly rougher. The top of the Fra Mauro Formation is near the present surface, but the formation is probably overlain by a regolith of fragmental materials and crater materials derived from the Fra Mauro itself; locally the Fra Mauro may be covered by presently unrecognized volcanic or other rocks. The depth of the base in the vicinity of the type area was estimated by Eggleton (1963) to average 550 meters; the depth varies because the subjacent terrain (pre-Imbrian crater materials and undivided materials) has high relief. This rugged pre-Imbrian terrain protrudes through the surface in places outside the type and reference areas and may also do so, unrecognized, within them. (Where the Fra Mauro is believed to be thin, a lined pattern has been overprinted on its map color.) Exposure of the formation is limited laterally, outside the type and reference areas, by dark (mare) and light (Cayley?) plains, which embay Fra Mauro along a sinuous contact and probably bury parts of it. Exposures separated from the type area by younger units cannot be correlated with certainty. However, the Apennine Mountains contain extensive exposures partly resembling those in the type area, and the Fra Mauro Formation is believed to extend all around the Imbrium basin.

MEMBERS

The definition of the Fra Mauro presented here excludes many smooth materials that had earlier been included in the "Imbrian System," "regional

FIGURE 9.—The terra peninsula beginning at the Apennine Mountains (top) is surrounded by Sinus Aestuum (left), Mare Vaporum (right), and Sinus Medii (bottom). Notice the gradational change in the surface of the terra from coarsely hummocky in the Apennines to relatively smooth near Sinus Medii. This terra material is the Fra Mauro Formation and the smooth material (in box) is the reference area for the smooth member of the Fra Mauro. The gradation in texture away from the Apennines is comparable to the gradation in texture of crater rim material away from a crater. Note also the dark smooth terra east of Sinus Aestuum which is part of the Sulpicius Gallus Formation. North-south dimension of photograph is approximately 500 km. (Photograph 2668, Catalina Observatory.)

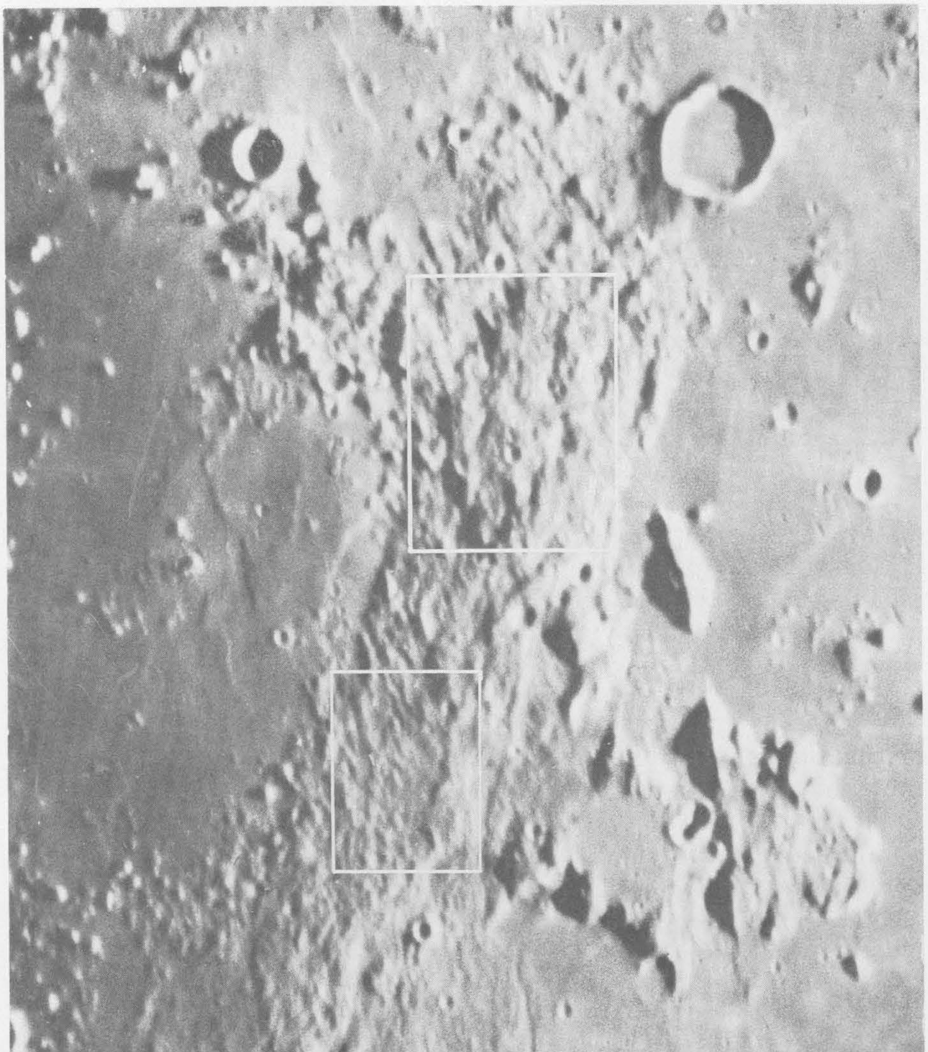


FIGURE 10.—Type area of the Fra Mauro Formation (upper box) and reference area (lower box). Large crater is Fra Mauro, 95 km in diameter. Fra Mauro Formation grades from hummocky in the north (nearest Imbrium basin) to smooth in the south; some of southern smooth material could be a younger unit. (Photograph 1994, Catalina Observatory.)

material of the Imbrian System," or the "Apenninian Series" (Eggleton and Marshall, 1962), but that are now mapped mostly as the Apennine Bench and Cayley Formations (Wilhelms, 1965, summarized in U.S. Geological Survey, 1965, p. 123). Eggleton's type area of the smooth member is explicitly excluded from the definition of the Fra Mauro given here; as Eggleton realized, the smooth material may be younger, unrelated material, possibly of the Cayley Formation. However, some relatively smooth material that is laterally continuous and gradational with the hummocky material is still correlated with the Fra Mauro Formation and is mapped as the "smooth member." The surface of this material has very low ripplelike hummocks or sinuous ridges and is not as smooth as the Cayley Formation. Most of this material is farther from the basin than the hummocky material, but some is on high ground nearer to the basin. A reference area for the probable smooth member is in the Mare Vaporum quadrangle between lat 7° N. and 8½° N. and long 0° and 1½° W. (fig. 9). This material is gradational with hummocky material in the Apennine Mountains that resembles the type Fra Mauro. Some patches of smooth blanketing material that are detached from exposures of hummocky material are also tentatively mapped as smooth Fra Mauro (for example, in other parts of the Mare Vaporum quadrangle, Wilhelms, 1968).

Where members are mapped, the hummocky material is designated the "hummocky member." In the Ptolemaeus quadrangle an additional "ridged member" was mapped, and an Imbrian unit called "smooth material" was tentatively correlated with the smooth Fra Mauro Formation (Howard and Masursky, 1968). On two published maps (Eggleton, 1965; Hackman, 1966) and several preliminary maps, a dark hummocky facies is recognized, but most mappers now regard the dark coloration as that of a superposed unit of probable volcanic origin, the Sulpicius Gallus Formation (discussed under "Imbrian or Eratosthenian Systems").

INTERPRETATION

The Fra Mauro Formation, like all lunar material units, can be delineated objectively on the basis of physical properties, and age relations can be determined objectively from superposition and transection relations. However, the thought process that led to its recognition as a unit involved an interpretation of its origin. The interpretation was based on the observation that Mare Imbrium occupies a basin that has many similarities to large craters. This basin is circular and is surrounded by rings of rugged topography. The surface material of these rings, the Fra Mauro, resembles rim material of fresh young craters in that its inner part is coarsely hummocky and its outer part smoother. It seems to be thickest close to the basin where very few old craters are visible, probably because the Fra Mauro mantles pre-Imbrian craters progressively more deeply toward the basin. The crater Julius Caesar is most heavily mantled by the Fra Mauro on slopes facing the Imbrium basin, as it would be if debris traveling in low trajectories piled up against obstacles (Morris, 1964; Morris and Wilhelms, 1967). The outer part of the Fra Mauro is lineated radially to the basin, as is the outer part of crater rim material (Wilhelms, 1965). Since large craters are probably produced by impact, the Fra Mauro material is interpreted to be the ejecta from a great impact which excavated the Imbrium basin.

CAYLEY AND APENNINE BENCH FORMATIONS

Light plains-forming material is abundant and widely distributed on the moon's surface. Much of this material in the central and northern parts of the near side is believed to be of Imbrian age because it is younger than the Fra Mauro Formation and Imbrian sculpture (fig. 8); however, it is apparently older than the Imbrian mare material. One occurrence, mentioned previously (p. 9), is the light plains-forming material on the Apennine bench near the crater Archimedes (fig. 4); this material is called the Apennine Bench Formation (Hackman, 1964, 1966 (definition); U.S. Geological Survey, 1964, p. A141 (brief mention)). Another occurrence of the material is in a circum-Imbrium trough near the crater Cayley (lat 4° N., long 15° E.) (Wilhelms, 1965; Morris and Wilhelms, 1967). The material there is unaffected by the Imbrian sculpture which has greatly modified the adjacent terrain. The material appears to be embayed by the mare material of Mare Tranquillitatis and has a higher crater density than the mare. Except for the material assigned to the Apennine Bench Formation, all lunar plains-forming materials in the central part of the near side that resemble this material and that are of demonstrable Imbrian age are designated the Cayley Formation (U.S. Geological Survey, 1966, p. A123 (brief mention); Morris and Wilhelms, 1967 (definition)).

Most of the material of the Cayley Formation, like other plains-forming material, is smooth and level and occurs in depressions. Contacts are sharp in places, gradational elsewhere. Where contacts are sharp, the Cayley may consist mostly of flows; where contacts are gradational, it may consist largely of free-fall tuff interbedded with mass-wasted debris and be modified by downslope movement.

Many occurrences of smooth, level Cayley Formation merge without a detectable discontinuity in albedo into tracts of subdued topography. These tracts may be covered with thin layers of material that is either identical with level Cayley or is a pyroclastic facies of it. On the basis of this interpretation, some tracts of gentle relief are designated the "hilly member" of the Cayley Formation (Milton, 1968; Wilhelms, 1968). Alternatively, the gentle hilly terrain may be mapped as undivided Cayley Formation, and the units believed to be buried and to produce the hilly character may be shown by dotted contacts and symbols in parentheses. In one place, where the buried terrain consists of round hills, a special pattern was used, to depict this on a map (Howard and Masursky, 1968).

Tracts of moderately rugged as well as gentle relief mapped as Imbrian "terra material" in the Ptolemaeus quadrangle may also be covered by material correlative with the Cayley (Howard and Masursky, 1968). Similar terrain assigned to the Imbrian System and mapped as "terra material, undifferentiated" in the Julius Caesar quadrangle (Morris and Wilhelms, 1967) is also believed to include a mantling material, but not necessarily a facies of the Cayley Formation.[5]

The Cayley Formation very likely includes materials that differ in age and lithology. Much of the material that is lumped as Cayley in telescopic mapping has been divided into numerous units on maps made from Ranger photographs (Milton and Wilhelms, 1966; Carr, 1966b; McCauley, 1966). Even at telescopic resolution, differences in albedo and crater density are apparent from area to area. Post-Imbrian materials may be present within some areas mapped as Cayley; at high telescopic resolution small areas are seen which are less densely cratered than most mare surfaces. Accordingly, either subdivision of the Cayley Formation or introduction of new units will be required on future large-scale maps.

CRATER MATERIALS

The crater Archimedes (figs. 4, 5) is not overlain by Fra Mauro Formation nor is it cut by Imbrian sculpture, although it is in the Imbrium basin; it is thus younger than the basin and the Fra Mauro. On the other hand, Archimedes is embayed and filled with mare material, and thus is older than the upper strata of the mare material. Another criterion for this postbasin premare age is the presence of satellitic craters on the Apennine Bench Formation and their absence on the mare. The materials of Archimedes and other craters younger than the Fra Mauro Formation and older than Imbrian mare material were previously called the Archimedian Series (see section entitled "Apenninian and Archimedian Series") but now are identified as "Imbrian crater materials" (see section on "Crater material subunits" for subdivision conventions). Such materials may be contemporaneous with, younger than, or older than the Cayley Formation. Some crater materials believed to be contemporaneous with the mare material (Procellarum Group) have been named the Diophantus Formation (Moore, 1965).

MATERIALS NEAR THE ORIENTALE BASIN

The surface surrounding the Orientale basin, whose center lies on the west limb of the earthside disk, resembles the surface of the Fra Mauro Formation (McCauley, 1964). It is coarsely hummocky close to the basin and smoother farther from it; available photographs show no hummocks beyond about 900 km from the basin center (compared with about 1,000 km from the Imbrium basin center for the Fra Mauro). Prebasin craters seem to be almost completely filled close to the basin and progressively less filled farther from it (as seen on Zond 3 photographs of the averted hemisphere. See McCauley, 1967b.)[6] The density of craters near the Orientale basin is much less than on the surrounding terra.

The material underlying this surface has been separated into two units that are believed to consist of blanketlike deposits. The inner hummocky unit is not yet formally named. The smoother, probably laterally continuous unit is the Hevelius Formation (McCauley, 1967a). Preliminary crater counts suggest that these units are younger than the Fra Mauro (McCauley, 1967b). The Hevelius is embayed by dark mare material of questionable Imbrian age and is therefore tentatively assigned an Imbrian age. The inner hummocky material, and tentatively the Hevelius Formation, are interpreted as debris ejected by the impact which formed the Orientale basin. The Hevelius would, therefore, be genetically similar to the smooth member of the Fra Mauro Formation. (Like the Fra Mauro, it may consist locally of bedrock older than its source basin and of presently unrecognized younger volcanic units.)

[5] Another mantled unit assigned to the Imbrian but called "rugged terra" and including only terrain resembling the more rugged parts of the units in the Ptolemaeus and Julius Caesar quadrangles, was mapped in the Theophilus quadrangle by Milton (1968). See the section "Terra units of the Theophilus quadrangle."

[6] After this was written, Lunar Orbiter IV provided photographs of Orientale far superior to those of Zond 3.

The relative youth of the units is supported by the apparent youth of the Orientale basin; the scarps concentric with the basin appear very fresh, and there is comparatively little mare fill in the basin or along the base of the scarps. Indirect evidence suggests that the units formed before Eratosthenian time. Sculpture or stringers of ejecta are absent on mare material of probable Imbrian age as little as 1,000 km from the basin center, although they should be present if the basin were postmare because at this distance from the center of the Imbrium basin the Fra Mauro Formation is abundant and Imbrian sculpture prominent.

TERRA UNITS OF THE THEOPHILUS QUADRANGLE

The first published map on which an analysis was attempted of extensive terra tracts outside the immediate influence of mare basins is the Theophilus quadrangle (Milton, 1968). (See also Milton, 1964, summarized in U.S. Geological Survey, 1965, p. A131.) Besides the light and level or gently undulating plains materials of the Cayley Formation and a few patches of possible Fra Mauro Formation, two main categories of terra units are recognized. One category is called "irregular terra," a name which conveys an appropriately uncertain interpretation. The units are "rugged terra,"[7] "rugged terra of crater rims," and "furrowed terra." These units differ from most lunar material units in that they probably reflect more than one superposed rock unit. Rugged terra of crater rims, for example, is characterized by the gross form of a crater; but the crater may be either pre-Imbrian or Imbrian in age, whereas the Imbrian age assigned to the terra unit applies to a light-colored surficial blanket. The crater may be of impact origin; and the blanket, volcanic. The blanket may be the same as that which covers other units.

The other category of terra units is "materials of Kant Plateau," another noncommittal name. This name is applied to terrain having positive relief that occurs in an arc concentric with the Mare Nectaris basin. Units are labeled "smooth," "pitted," "rugged," and "rugged bright." Unlike the irregular terra units, where subjacent relief is conspicuous, only the broad elements of subjacent topography are detectable. The positive relief and the surface textures suggest that Kant Plateau materials are depositional in origin; they may consist of various volcanic materials that tended less to flow into depressions or otherwise conform to preexisting topography than do those of the Cayley Formation and the "irregular terra" units. Alternatively, the Kant Plateau could be mainly or entirely a tectonic feature.

A lower age limit of Imbrian is assigned to both irregular terra units and materials of Kant Plateau because they apparently cover the Fra Mauro Formation. However, the upper limit is very uncertain, and the upper parts of the units may extend into the Copernican System. The relative ages are also uncertain, and the units are arranged in the explanation of the Theophilus map according to the degree to which they mask underlying topography: from bottom to top, Fra Mauro Formation, irregular terra materials, materials of Kant Plateau, and Cayley Formation.

Alternative units are being recognized in the terrae of other areas, and this work may clarify the nature, ages, and origins of terra material. But the undistinguished appearance of much terra suggests that meaningful rock-stratigraphic units may never be recognized at the telescopic scale.

MARE MATERIAL (FORMERLY PROCELLARUM GROUP)

Areas that appear dark, flat, and smooth through the telescope and that locally have characteristic ridges (fig. 6) and domes are underlain by mare material, a widespread unit mentioned often in preceding sections. In this section, the properties that distinguish mare materials and its subdivisions and the history of its stratigraphic nomenclature are discussed. The author considers the name Procellarum Group, commonly applied to most mare material but never formally proposed, abandoned. (See discussion under the section "Nomenclature".)

Several physical characteristics set mare units apart from other smooth, flat material units, such as the Cayley Formation, and also lead to internal subdivisions. The most obvious properties on telescopic photographs are crater density and albedo. Commonly, these two properties are related; the more craters, the higher the albedo (the lighter the surface). Crater density—and possibly albedo—are secondary characteristics that are partly a function of age. Some materials which appear to embay others or lie as pools within them are darker and less cratered than those that they appear to overlie; for example, the sparsely cratered material of Palus Putredinis embays both the Apennine Bench Formation and lighter, more cratered, mare material (fig. 4).

[7] Imbrian terra material given the same map symbol as rugged terra was mapped in two adjacent quadrangles, Julius Caesar (Morris and Wilhelms, 1967) and Ptolemaeus (Howard and Masursky, 1968), but includes relatively featureless as well as rugged terrain. (See p. 28.)

The reasons for albedo variation are not well understood, and the intrinsic albedo of lunar materials is unknown. Plains-forming materials may be dark like mare materials when young, then become lighter through cratering, mass wasting, and other processes which expose light blocky materials. Processes similar to this "aging" can also occur instantaneously when crater rays are formed by secondary impact. (See section "Eratosthenian and Copernican Systems, Crater Materials.") Albedo may also be partly a function of chemical composition.

Mare materials are almost certainly bedded. Commonly, the contact between surface units is lobate, and this fact suggests encroachment on one flat-lying layer by arcuate flow fronts of another. A few such arcuate contacts are topographic scarps that convincingly resemble terrestrial volcanic flow fronts (fig. 11). Some of these scarps coincide with slight color changes, which can be enhanced by compositing photographs taken through ultraviolet and infrared filters (Kuiper, 1965, p. 29–33, including map by R. G. Strom, fig. 18; Whitaker, 1966, p. 79–95).

Most mare surfaces are flat, and they terminate abruptly at the slightest rise in topography. This fact, along with the steepness of the scarps mentioned above, has been taken as evidence that mare material is composed of lava flows. However, some smooth dark material that overlies barely perceptible craters (ghosts) and other features is apparently gradational to flat mare material and has been mapped as mare. This mare material may be composed of free-fall pyroclastic material or of ash-flow tuff, which is implaced as fluid flows (O'Keefe and Cameron, 1962, p. 281–284; O'Keefe, 1966). Both kinds of material may compact differentially upon cooling; so the topography of the surface resembles the subjacent topography, but in more subdued form. Free-fall tuff, ash-flow tuff, and lava may all be mare materials. A lunar mare may well be as complex stratigraphically as a terrestrial volcanic province.

NOMENCLATURE

As lunar geologic studies have progressed, mare material has been increasingly subdivided. At the outset of the mapping program, mare material was thought to have approximately the same age everywhere, except in relatively young Mare Crisium, on the basis of crater counts from the poor-resolution photographs then available (Shoemaker, Hackman, and Eggleton, 1962). The mare material was assigned time-rock status as the Procellarian System (Shoemaker and Hackman, 1962, p. 294; Shoemaker, 1962, p. 346); the type area was unstated but presumably was in the Copernicus quadrangle, where the study concentrated. Subsequently, differences of crater density and albedo became apparent, and certain crater rim materials were found to be superposed on mare material in one sector but overlapped by it in another (for example, Manilius, lat 14°30′ N., long 9° E.). To handle such complexities, and to follow correct stratigraphic practice by avoiding premature age assumptions, the Procellarian System was replaced by rock-stratigraphic (lunar material) units. At first, the only such unit defined was the Procellarum Group. This name was first mentioned in a preliminary open-file report (Hackman, 1964, p.4), and "that part of Oceanus Procellarum included in the Kepler region" (now quadrangle) was designated the type area. The unit was not formally defined, although the name was used thereafter and the redefinition of the system to group was referred to in a formal publication (U.S. Geological Survey, 1964, p. A141).

The Procellarum Group consisted of the units "mare material" and "dome material" and of other materials with relief (discussed below), each of which constituted an informal formation. "Mare material" was called "flat mare material" on some maps and "smooth mare material" on others. In many areas flat mare material was further divided into members on the basis of albedo differences. Commonly four members have been mapped whose symbols bear numerical suffixes. Member 1 has the highest albedo (lightest); member 4, the lowest albedo (darkest). The type areas for these members are in Mare Serenitatis, where there is less ray cover to obscure the relations among members than in Oceanus Procellarum (Carr, 1966a). However, distant units do not always match these types exactly. Furthermore it is difficult to compare albedos exactly. Many contacts are sharp, but some are blurred and may not represent true edges of beds; these are shown by a special contact symbol (Carr, 1966a). A simpler classification of "light" and "dark" has been used in some areas (McCauley, 1967a; Moore, 1967; Howard and Masursky, 1968), and it is more satisfactory in rayed areas than the fourfold classification. In both of these classifications, the darker members were interpreted as younger than the lighter because at least some dark materials embay areas of light materials and have fewer superposed craters.

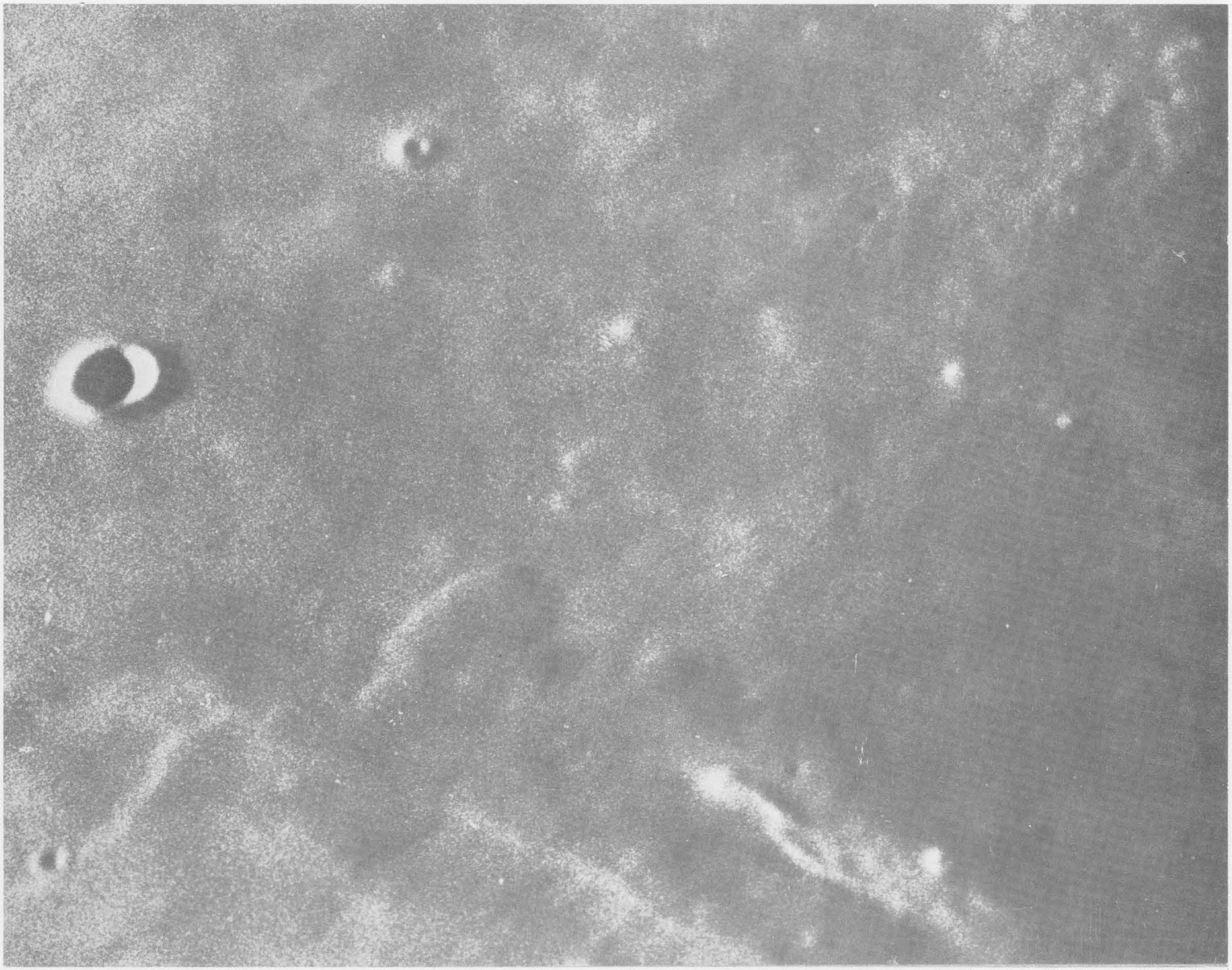


FIGURE 11.—Flow lobes in Mare Imbrium. Largest crater is Carlini, approximately 11 km in diameter. (Photograph 2862, Catalina Observatory.)

Unfortunately, and contrary to intentions, a time-stratigraphic significance is still attached to the Procellarum Group, and it has been used as a synchronous stratigraphic datum much as was the Procellarian System. Nearly all maps show the age of the Procellarum Group as Imbrian. Most mare material may well be of this age—that is, as old or older than the material between the craters Eratosthenes and Archimedes. (As discussed in the section "Imbrian System," no formal type area has been established.) However, many authors are aware that some mare material is younger than Imbrian, although they have shown the age as Imbrian; McCauley (1967a) and Moore (1967) considered a Copernican age possible for some of the dark mare material.

Where authors chose to show post-Imbrian ages, they mapped other material units and dropped or restricted the name Procellarum Group. The name "mare material, dark" was used by Carr (1966a) for extremely dark material at the east edge of Mare Serenitatis which is assigned an Eratosthenian age because it is younger than most mare material yet older than Copernican-age crater rays. Moore (1967) used the same designation for dark material that covers part of the Copernican crater Lichtenberg and is therefore itself Copernican. Wilhelms (1968) recognized the same four mare material subunits in the Mare Vaporum quadrangle as in Mare Serenitatis, but concluded that the two darker subunits are post-Imbrian because they are very smooth and because one occurrence embays the Eratosthenian or Copernican crater Manilius. These units were therefore mapped as "Eratosthenian or Copernican mare material." The two lighter, more cratered (probably Imbrian) units were assigned to the Procellarum Group.

The name Procellarum Group has thus become equated, in practice, with Imbrian mare material. This usage is both incorrect and unnecessary. A lunar material unit of a certain albedo range cannot always be assigned a particular age because albedo probably is not always related to age. Nothing would be gained by redefining the group to remove these objections, and the name Procellarum Group is considered dropped and all material traditionally called mare is simply considered as the lunar material unit "mare material." Subdivision on the basis of albedo or other physical properties may continue to be desirable. Where spacecraft photographs are available, accurate relative age ranking and assignment to time-stratigraphic units possibly can be achieved.

MARE MATERIALS WITH TOPOGRAPHIC RELIEF

The mare materials discussed above form completely or nearly flat surfaces. A common material assigned to the Procellarum Group that does not form a flat surface is "dome material" or "mare dome material." Domes are low and round or elliptical in plan and have convex-upward profiles; some have summit craters. Their surface is similar in fine texture and albedo to that of flat mare, and all known domes are in contact with flat mare. The contact between most domes and adjacent mare is marked by a sharp topographic break. Such domes, especially those with summit craters, resemble terrestrial shield volcanoes and are probably volcanoes superposed on the mare surface. Other domes merge gradually into the adjacent mare and may overlie subsurface intrusions, probably laccoliths. Both kinds of domes may be younger than the uppermost strata of the flat mare material nearby, but unseen domes are probably buried by flat mare. Domes and flat mare are doubtlessly related genetically as well as spatially and texturally. Some of the possible laccoliths are transitional to mare ridges, which may overlie sills or dikes.

Certain other domes and one additional minor unit are mapped as part of the Procellarum Group. Several domes having rough summits or discrete summit hills are known and have been mapped separately from other domes in one area, as "rough dome material" (Moore, 1965). Second, "hummocky material" (or variations on the name) has been mapped tentatively as another formation of the Procellarum Group in some areas because of its low albedo (Carr, 1965b; Moore, 1965; Howard and Masursky, 1968). Such material may be clusters of small subresolution domes. The ridges that are characteristic of maria are mapped as structures, but might appropriately by shown as geologic units on future maps.

APENNINIAN AND ARCHIMEDIAN SERIES

In many reports and maps of the Geological Survey, the Imbrian System has been divided into the Apenninian and Archimedian (Archimedean) Series. At present the base of the Apenninian Series is defined as the base of the Fra Mauro Formation and the top as the top of the Apennine Bench Formation (Hackman, 1966). The Archimedian Series includes all post-Apenninian Imbrian materials. These series were not explicitly defined by Hackman but he employed them this way on his map; his definition appears only in an open-file report (Hackman, 1964, p. 4).

The original definitions of the series, also not published formally, were somewhat different (Shoemaker, Hackman, Eggleton, and Marshall, 1962). The Apenninian Series included only the "regional material of the Imbrian System," now called the Fra Mauro Formation. The Archimedian Series comprised only the crater-rim materials that are superimposed on the Apenninian Series and are overlapped by the Procellarian System. Thus the two units defined as series were in fact lunar material units.

As presently defined these series are practical units only near Archimedes and the Apennine bench (fig. 4), because only there can material units be assigned to them; elsewhere, the age of a plains-forming unit or crater materials relative to the age of the Apennine Bench Formation or the crater Archimedes cannot yet be determined. At best, all that is known is that they belong to the Cayley Formation or are Archimedes-type craters (that is, they resemble the type Cayley or the crater Archimedes and are younger than the Fra Mauro Formation and older than the youngest mare material). Therefore these series names should be dropped.

An alternative is to return to the original definition of the Apenninian Series by restricting it to the Fra Mauro Formation and to place all the remaining Imbrian material units in the Archimedian Series. This classification, however, would serve no practical purpose and would divide the time-stratigraphic column too unevenly. There would be only one formation in the one series—Fra Mauro—and all the light-plains materials, Archimedes-type craters, and mare material in the other. Furthermore, if the Fra Mauro Formation is correctly interpreted as consisting of the ejecta produced by a single impact, the two series could represent vastly disparate time spans—minutes on the one hand, tens of millions of years on the other.

IMBRIAN OR ERATOSTHENIAN SYSTEMS

Materials that cannot be dated relative to Imbrian mare material but are believed to be moderately young are designated "Imbrian or Eratosthenian." These include crater materials, dark terra-mantling materials, and materials with probably intrinsic positive relief. Materials of craters that resemble known Eratosthenian craters but are superposed on terra instead of mare are by convention mapped as "Imbrian or Eratosthenian crater material"; such craters are topographically sharp and rayless.

DARK TERRA-MANTLING UNITS

An important type of "Imbrian or Eratosthenian" material is as dark or darker than mare and occurs mainly on the terra near the margins of mare basins. Material of this kind adjacent to Mare Serenitatis was named the Sulpicius Gallus Formation (Carr, 1966a). Large conspicuous areas of similar materials adjacent to Mare Vaporum and Sinus Aestuum (Wilhelms, 1968) and near Copernicus (Schmitt and others, 1967) also have been mapped as Sulpicius Gallus (fig. 9, 12). Similar material adjacent to Mare Humorum (fig. 6) is called the Doppelmayer Formation (Titley, 1967).

Several patches resembling the Sulpicius Gallus Formation were formerly regarded as a dark hummocky facies of the Fra Mauro Formation (Hackman, 1966). However, the dark material is now believed to be a thin surficial covering, because its relief is either similar to or more gentle than that of adjacent materials; ridges, craters, and other topographic forms that pass under the contacts are only slightly subdued. This weak topographic expression suggests that the mantling material is largely pyroclastic. The type Sulpicius Gallus is thickest along rilles, which are probably its source (Carr, 1965a). The source for other exposures of the formation may be small craters and domes which are seen as dark spots on very high resolution full-moon photographs (Wilhelms, 1968).

Embayment relations suggest that the rugged parts of the Sulpicius Gallus Formation are mainly older than the mare material. However, parts of the Sulpicius Gallus and much of the Doppelmayer Formation appear to be contemporaneous with or younger than the mare, because flat material and adjacent rugged material have the same low albedo. This suggests that a mantle of Sulpicius Gallus or Doppelmayer extends over both the rugged terrain and the flat mare.

Such flat areas would not be distinguishable from mare if they were not laterally gradational to rugged areas of Sulpicius Gallus or Doppelmayer. Mare material and dark mantling material may therefore be basically similar and differ only in proportions of constituent rock types; mare material, which tends to accumulate in available depressions, may consist predominantly, but not entirely, of flows, whereas the mantling type may consist predominantly of free-fall ash. Some dark mare units may be old flows with only a young thin ash cover.

UNITS WITH INTRINSIC RELIEF

Some units mapped as "Imbrian or Eratosthenian" apparently have intrinsic relief. One is the

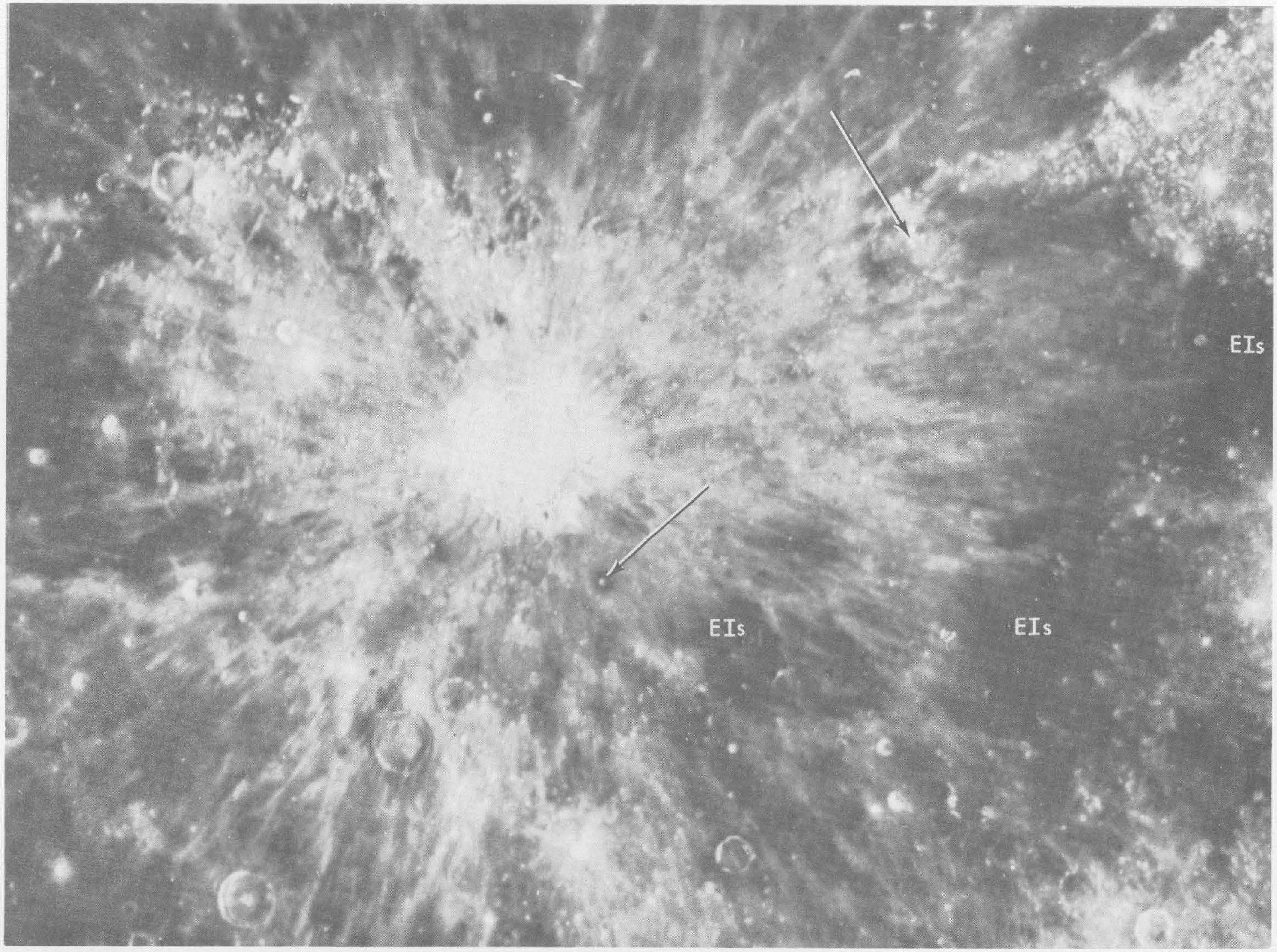


FIGURE 12.—Craters Copernicus (left center, 90 km in diameter) and Eratosthenes (its center marked by black and white arrow) under near-full-moon illumination. Copernicus has a bright, conspicuous ray system; Eratosthenes' rays are barely visible. The rays of Copernicus are clearly superposed on Eratosthenes. Several dark-halo craters younger than Copernicus are present; a conspicuous large one is Copernicus H, southeast of Copernicus about a crater diameter away (black and white arrow). Very dark patches are exposures of the Sulpicius Gallus Formation (EIs). Very bright crater walls and other slopes are Copernican slope material. Compare photograph with the low-illumination photograph of figure 3, in which relief is much more conspicuous. (Unpublished photograph 5818, U.S. Naval Observatory, Flagstaff, Ariz.)

FIGURE 13.—Aristarchus plateau, large parallelogram-shaped raised area in western (left) half of picture; Harbinger Mountains (Montes Harbinger) are the smaller complex in the eastern (right) half; large fresh crater is Aristarchus, 40 km in diameter; largest of the many sinuous rilles is Schröter's Valley (Vallis Schröteri). Note large cone (28 km long) with summit crater (arrow). Probable volcanic material of several kinds forms the plateau (Vallis Schröteri Formation, Cobra Head Formation, sinuous rille material) and Harbinger Mountains (mainly Harbinger Formation). Geologic maps of this area are by Moore (1965, 1967). (Photograph 369, Catalina Observatory.)

Harbinger Formation east of the Aristarchus plateau (fig. 13) (Moore, 1964, 1965). Some of this formation's relief is apparently formed by volcanic domes, cones, and craters, though some may be due to the underlying Fra Mauro Formation. The Harbinger Formation is also characterized by numerous sinuous rilles. What appear to be the high ends of these rilles terminate at craters within the formation; the low ends terminate on mare. The rilles may have been cut principally by flowing volcanic material; the direction of flow may have been controlled partly by structure. The Harbinger Formation is designated "Imbrian or Eratosthenian" because parts of it may interfinger with mare material, whereas other parts seem to embay mare; material that flowed out of the sinuous rilles may form part of the mare material. The Harbinger Formation is part of an extensive volcanic province near the crater Aristarchus (fig. 13; table 1); some formations of this province may be as young as Copernican (see p. 38).

Another unit having intrinsic relief is the Boscovich Formation in the Julius Caesar quadrangle (Morris and Wilhelms, 1967). This unit forms long stringy ridges approximately parallel with Imbrian sculpture; near it are terra domes of probable volcanic origin. The Boscovich and the domes may consist of viscous volcanic materials extruded from the sculpture fractures.

ERATOSTHENIAN AND COPERNICAN SYSTEMS

The next youngest lunar time-stratigraphic system after the Imbrian is the Eratosthenian, and the youngest is the Copernican. Although most mappers have separated the Eratosthenian and Copernican Systems, the two are discussed together here because of doubt that they can be validly separated in many areas. (See also McCauley, 1967b, p. 436.) Moreover, many of the units discussed here resemble units discussed above that are assigned "Imbrian or Eratosthenian" ages, and some of these may be as young as Copernican. The ages of most terra-mantling, plains-forming, and positive-relief materials are based on their superposition on crater materials and thus are only as reliable as the estimated ages of the craters.

Because time-stratigraphic systems adjoin without gaps, the base of the Eratosthenian System coincides with the top of the Imbrian System. The common boundary is not defined, but it is informally regarded as the top of the mare material between the craters Eratosthenes and Archimedes. (See introduction to the section "Imbrian System".)

CRATER MATERIALS

Chief among lunar material units of the Eratosthenian System are materials of fresh rayless craters. Chief among Copernican units are materials of rayed craters. (See the section "Crater material subunits" for subdivision conventions). Most Copernican craters have a high signal in the thermal region of the infrared during eclipse. The signal of most Eratosthenian craters is lower and commonly indistinguishable from the background (U.S. Geological Survey, 1967, p. A132).

Crater materials are shown as "Eratosthenian or Copernican" for several reasons: (1) if the craters do not have telescopically resolvable bright rays but have bright halos which may be formed of unresolved rays; (2) if they have bright halos or some rays but have only a low thermal signal at eclipse (Wilhelms, 1968); (3) if they are small and apparently rayless but do not contact rays of large Copernican craters and cannot be dated directly otherwise (Eggleton, 1965; Schmitt and others, 1967); however, such craters are mapped as Eratosthenian by most mappers.

The reason for making the presence or absence of rays an age criterion for craters is that rays appear to be among the most recent materials on the moon and are superimposed on most other materials; in the type example, the rays of Copernicus overlie the materials of the nearly rayless crater Eratosthenes (fig. 12) (Shoemaker and Hackman, 1962, p. 295–298; Carr 1964, p. 12–15). External processes such as micrometeorite mixing and solar radiation may cause rays to darken and disappear with time (Shoemaker, 1962, p. 345). Rays may be an expression of myriads of small secondary and tertiary impact craters, and they may fade when bright steep slopes of these satellitic craters become subdued. (Rays are shown with a stipple pattern on lunar geologic maps.)

The presence or absence of visible bright rays, however, is not entirely a function of age. If rays fade from mixing with darker materials, they would fade more readily around small craters than around large ones. Furthermore, there are rayless craters with circular dark halos—mapped as "Copernican dark-halo crater material"—clearly superposed on the ray and rim materials of light-ray craters (fig. 12) (Shoemaker and Hackman, 1962, p. 297–298; Carr, 1964, p. 16). Similar dark craters of Copernican age may well occur where there are no light Copernican rays by which to determine their relative age, and these craters may have been mapped erroneously as Eratosthenian. Any one or all of the following factors may explain the difference in brightness: (1) the nature or composition of the material in which the crater was formed—for example, there are more telescopically resolvable bright-rayed craters on some light terrae than on maria; (2) the presence of two superposed source layers—this may explain Dionysius (lat 3° N., long 17° 30′ E.), which has dark as well as bright rays (Smalley, 1965), and Tycho and many other craters that have both bright and dark halos; (3) material in which rays formed—a ray that is superposed on both light and dark materials is commonly brighter on the light materials; (4) differences in origin—some or all dark-halo craters may be of volcanic origin, and most light-rayed craters may be of impact origin; (5) later events, such as burial by ash fall. Probably the most accurate statement is that the presence of rays indicates a young crater, but the absence of rays does not necessarily indicate an old crater (Carr, 1964, p. 16).

There are serious reservations, therefore, about the assignment of craters to time-stratigraphic systems solely on the basis of the presence or absence of rays. Eventually, the younger subdivisions of the lunar time scale can be redefined on the basis of crater freshness or the dating of noncrater post-Imbrian rock units.

MANTLING MATERIALS

Some extensive units morphologically (and probably lithologically) like the Sulpicius Gallus and Doppelmayer Formations that apparently form a thin dark cover over subjacent terrain and add little relief of their own are assigned Eratosthenian and Copernican ages. The Cavalerius Formation of Copernican age (McCauley, 1967a) is superposed on rim material of the postmare crater Cavalerius, on the adjacent mare surface, and on Copernican rays. (The Cavalerius Formation is the unit on which the Soviet probe Luna 9 probably landed.) Several other units of probable Copernican age are so thin that subjacent topography is not modified at all. In order not to obscure the more important subjacent units on the map, the dark covering materials are shown with an overprint pattern, and the subjacent units are shown in color (Milton, 1968; Howard and Masursky, 1968). Darkening by other causes or the absence of bright covering may be shown similarly (Schmitt and others, 1967).

At least one thin unit of possible covering material, the Reiner Gamma Formation (lat 7° N., long 59° W., west of the crater Reiner and south of the Marius Hills) (also Copernican), is brighter than the adjacent material (McCauley, 1967a). This peculiar formation possibly consists of ash-flow tuff or an irregular area of surface alteration. Attention is now being given to other areas of light covering materials not associated with craters, but mapping conventions have not yet been established.

PLAINS-FORMING MATERIALS

As discussed above (p. 32), some post-Imbrian dark materials are probably mare materials; that is, they are dark and appear smooth and flat at telescopic resolution. Most of these young materials occur at the edges of mare basins and in smaller depressions of the terra. This is true both of "Copernican or Eratosthenian mare material" mapped in the Mare Vaporum quadrangle (Wilhelms, 1968) and of other materials that either have been assigned a possible Imbrian age (see p. 32) or are as yet unreported in the published literature. The darkest material yet recognized, mapped as "Eratosthenian mare material, dark" (Carr, 1966a), occurs along the east margin of Mare Sernitatis. On the other hand, the dark material mapped as "Copernican mare material, dark" that embays the rayed crater Lichtenberg in the Seleucus quadrangle (Moore, 1967) apparently issued from part of a very long linear midmare fracture. Rays of Lichtenberg and Copernicus are obscured along this fracture for hundreds of kilometers (Moore, 1967; U.S. Geol. Survey, 1967, p. A131).

Other, lighter materials also form plains. An example is the flat smooth-surfaced material which occurs in depressions in the rim material of the Copernican crater Theophilus (fig. 14). This material, obviously younger than the crater and therefore also Copernican in age, is the "smooth member" of the Theophilus Formation (Milton, 1964, p. 22; 1968). The topography of the crater rim material is subdued around the smooth plains, probably by thinner material ("hilly member") related to the plains-forming material.

UNITS WITH INTRINSIC RELIEF

Certain materials younger than the local mare material have much intrinsic relief. One is the Tacquet Formation along the southern edge of Mare Serenitatis (Carr, 1966a). This unit, assigned an Eratosthenian age, forms an elongate low bulbous dark ridge ("dark member") surrounded by lighter, and probably older, material with lower relief ("light member"). Rilles, some with raised rims which grade into the rest of the formation, run the length of the dark ridge and were probably its source. Low ridges in the light member oriented normal to the rilles may be flow lobes, and low scarps bounding the formation may be flow fronts. This unit is part of the young marginal belt of Mare Serenitatis, as are the two dark members of typical mare material of Imbrian age, the still-darker mare material of Eratosthenian age, and the Sulpicius Gallus Formation.

In the northwest quadrant of the moon there are two complexes of domes and other materials that superposition relations suggest are younger than the local mare material. One, assigned an Eratosthenian age, is the Marius Group west of the crater Marius (McCauley, 1965, 1967a; summarized in U.S. Geological Survey, 1966, p. A124). This unit consists of undulating plateau-forming material and at least two kinds of domes: one low and convex in profile like mare domes, and the other with steeper slopes that are concave in profile. By analogy with terrestrial landforms the domes are interpreted to be volcanic in origin. Some steep domes are superposed on low domes, as in certain terrestrial volcanic provinces, where the cause may be a change in either the bulk composition of the magma or in its volatile components.

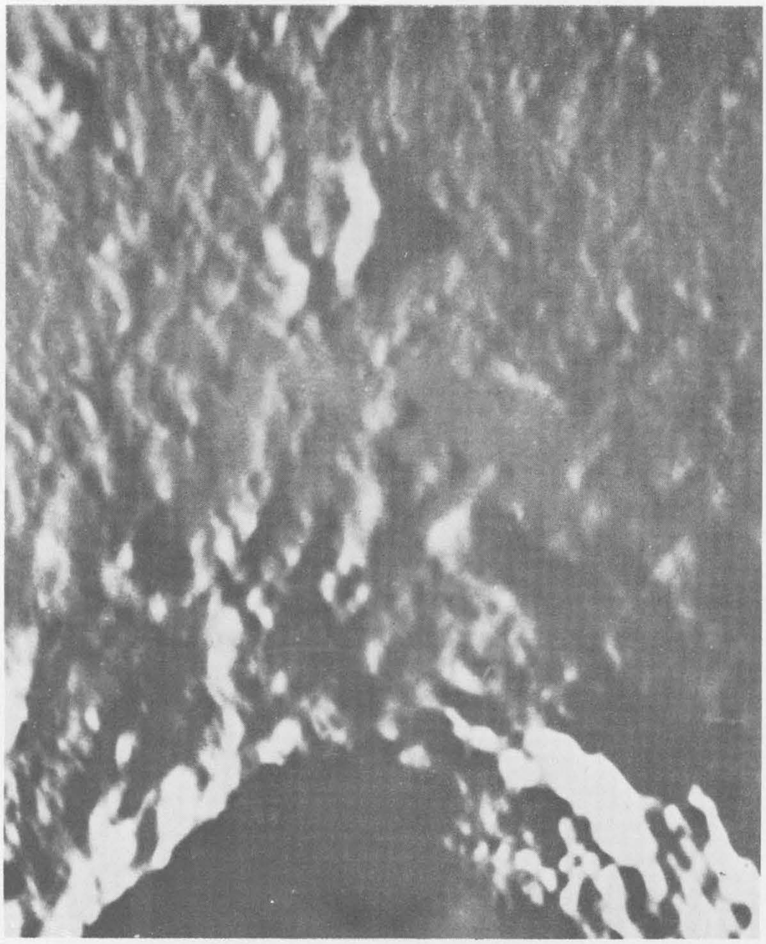


FIGURE 14.—Part of crater Theophilus (at bottom of picture). The crater's rim material extends over most of remainder of picture. In the center is the main occurrence of the Theophilus Formation (Milton, 1964, 1968), a plains unit lying on the rim material. Picture covers an area approximately 90 km east-west. (Photograph ECD 37 taken with 120-in. reflector, Lick Observatory.)

The other volcanic complex in the northwest quadrant of the moon, assigned "Eratosthenian or Copernican" age, is the Vallis Schröteri Formation in the Aristarchus plateau (Moore, 1965, 1967), an area also known as Wood's spot (fig. 13). In addition to containing thin blanketing material that does not visibly subdue the underlying topography, the formation includes plains-forming materials, domes, low-rimmed craters, and cratered cones; one elongate cone is 13 by 28 km. As in the Harbinger Formation, sinuous rilles head in the Vallis Schröteri Formation and terminate in the adjacent mare. The two formations are similar and probably represent continued volcanism of the same type.

The Vallis Schröteri Formation is transected by the feature for which the formation is named, Vallis Schröteri, the largest of all sinuous lunar rilles. The topographically higher end or head of the rille is a crater called the Cobra Head that is in a very large dome; the material of the dome is the Cobra Head Formation (Moore, 1965). This formation and the material in the floor of the rille (mapped as "sinuous rille material" by Moore 1965, 1967) are assigned a Copernican age because of their apparent topographic freshness. Like the other sinuous rilles, Vallis Schröteri may have been formed in part by erosion as fluid material flowed from the crater at the head (Cobra Head) to the low end of the rille. Since the low end is on the mare, the mare material (mapped as the Procellarum Group) may include materials of Copernican age that flowed from the rille.

SLOPE MATERIAL

The material on the walls of craters and on other steep slopes is commonly brighter under full-moon illumination than the adjacent materials (fig. 12), and some has the highest albedo of all lunar materials. Steepest and youngest slopes—where downslope movement of rock is most likely to occur—are commonly the brightest, suggesting that albedo is a function of the amount of fresh material exposed. This bright material is, therefore, assigned a Copernican age, even where it occurs in craters or on other features of pre-Copernican age. The bright slope material may consist mostly of mass-wasted debris. However, since it may also include freshly exposed bedrock, "Copernican slope material" may not be everywhere a rock unit by itself but rather an indicator of the freshest exposures of other rock units.

Trask and Titley (1966) mapped two additional slope units. One, assigned an Eratosthenian or Imbrian age, is brighter than the adjacent mare material, although not as bright as the Copernican slope material. The other, assigned an Imbrian or pre-Imbrian age, is not bright and was mapped to emphasize the slope of a long ridge.

MISCELLANEOUS UNITS

Up to this point, the units discussed have been assigned ages and given either formal (table 2) or informal names. All maps show a variety of additional small material units of distinctive morphology that normally are not assigned ages. These include materials of chain craters; materials of other types of craters discussed earlier that are not part of the main sequence of unclustered round craters; dark-halo crater material; pitted material; hummocky material; ridge material; material of cones with summit craters; and terra dome material, which is sometimes divided into light and dark. In map explanations, most of these are grouped with the structural symbols, apart from the main box explanation. This arrangement is followed because ages are commonly known only to within three geologic-time periods—Imbrian to Copernican or pre-Imbrian to Eratosthenian. Superposition relations, obvious on the map, show what is known about the ages of individual occurrences. Some large units, however, are assigned to specific systems. Some morphologic forms shown by structural symbols on most recent maps were shown on earlier maps as geologic units, such as sinuous rille material and linear rille material. A common inclusive unit on early maps is rille and chain crater material.

TABLE 2.—*Formally defined lunar stratigraphic names*

Name	*Publication*	*Page in this report*	*Age*
Apennine Bench Formation.	Hackman, 1966	27	Imbrian.
Boscovich Formation.	Morris and Wilhelms, 1967.	35	Imbrian or Eratosthenian.
Cavalerius Formation.	McCauley, 1967a	37	Copernican.
Cayley Formation.	Morris and Wilhelms, 1967.	27	Imbrian.
Cobra Head Formation.	Moore, 1965	38	Copernican.
Diophantus Formation.	Moore, 1965	28	Imbrian.
Doppelmayer Formation.	Titley, 1967	33	Imbrian or Eratosthenian.
Fra Mauro Formation.	Eggleton, 1964, 1965; Wilhelms, this report.	23	Imbrian.
Gassendi Group	Trask and Titley, 1966; Titley, 1967.	23	Pre-Imbrian and Imbrian.
Harbinger Formation.	Moore, 1965	35	Imbrian or Eratosthenian.
Hevelius Formation.	McCauley, 1967a	28	Imbrian.
Marius Group.	McCauley, 1967a	37	Eratosthenian.
Procellarum Group.[1]	U.S. Geol. Survey, 1964.	29	Imbrian.
Reiner Gamma Formation.	McCauley, 1967a	37	Copernican.
Sulpicius Gallus Formation.	Carr, 1966a	33	Imbrian or Eratosthenian.
Tacquet Formation.	Carr, 1966a	37	Eratosthenian.
Theophilus Formation.	Milton, 1968	37	Copernican.
Vallis Schröteri Formation.	Moore, 1965, 1967	38	Eratosthenian or Copernican.
Vitello Formation.	Trask and Titley, 1966; Titley 1967.	22	Pre-Imbrian.

[1] Abandoned.

ABANDONED NAMES

This section lists stratigraphic names that have been introduced casually but never defined formally nor used on published maps of the Geological Survey series discussed in this paper (table 3). The names in table 3 were introduced by Survey geologists in preliminary open-file reports to the National Aeronautics and Space Administration, and were then published as part of short informal stratigraphic summaries (U.S. Geological Survey, 1964, 1965, 1966). These names are now considered abandoned. Additional abandoned names, not listed here, appeared only in the preliminary reports and maps.

TABLE 3.—*Stratigraphic names that have appeared in Geological Survey publications but have not been defined formally*

Name	*Author*	*Reference: U.S. Geol. Survey Research of the year indicated*	*Current published designation*	*Reason for abandoning*
Bond Formation.	H. A. Pohn	1966	Unpublished (probably will be called plains-forming material).	Not formally defined; no need for name.
Censorinus Formation.	D. P. Elston	1964 (see also Elston, 1964)	Unpublished	Not formally defined.
Cordillera Group.	J. F. McCauley	1964, 1965	Includes Hevelius Formation; part unpublished.	To be replaced by Hevelius Formation and possibly another formation.
Crüger Group.	J. F. McCauley	1964	Unpublished (probably will be called crater material).	Not formally defined; no need for name.
Humorum Group.	S. R. Titley	1964, 1965	Assigned to the Vitello Formation, material of smooth ridges and hills, and plains-forming material.	Distinctiveness of the three units.
Pyrenees Formation.	D. P. Elston	1964 (see also Elston, 1964)	Unpublished	Not formally defined.

The only stratigraphic names known to the author that have been proposed outside this mapping program and not used in it are those of Spurr (1944–49)—highly interpretive time units—Khabakov (1962, p. 288); Sukhanov, Trifonov, and Florenskiy (1967); and Dodd, Salisbury, and Smalley (1963). In the last report, the names Ptolemaic and Highlandian Series were proposed for units previously recognized by the Geological Survey.

CRATER MATERIAL SUBUNITS

A crater is a topographic form—a depression—but its rim, walls, floor, and other features are composed of material units. Materials of large craters are extensively subdivided on lunar geologic maps of 1:1,000,000 scale, and the subunits make up from one quarter to more than half the number of the map units. Material with positive relief outside the rim crest is mapped as "crater rim material"; the inclined parts inside, as "crater wall material"; [8] the generally level parts in the center, as "crater floor material"; and the single or multiple peaks at or near the center, as "crater peak material." Interior material similar in texture to rim material is sometimes mapped as rim material instead of wall material, especially in craters whose rim crests are indistinct. The level surfaces of arcuate terraces in the largest craters are also usually mapped as rim material because the terraces are interpreted to be slumped parts of the rim. (The original crater diameter was therefore less than the present rim crest-to-rim crest diameter.) Wall and floor material generally meet at a sharp break in slope. Where there is no break in slope, as in conical or bowl-shaped craters, the entire interior is mapped as wall material. Subunits are not mapped in small craters, and the contact between crater materials and adjacent materials is drawn at the outer most limit of positive relief, not at the rim crest. Subunits of large craters may not be mapped separately if they are indistinct, as in many old craters.

All materials of a single crater are collectively regarded as an informal formation, and each of the subunits discussed above as an informal member (fig. 15). These members may be divided into submembers, the more common of which are shown in figure 15. Additional members and submembers may be distinguished as the need arises. An outer rim facies in which some positive relief and many satellitic craters occur together has been called "cratered rim material" and mapped as a separate geologic unit (Trask and Titley, 1966), or it has been delimited by a special line symbol and given the color of the underlying unit (Schmitt and others, 1967). Examples of other special units are "ring material" forming circular ridges within two craters in the Pitatus quadrangle (Trask and Titley, 1966) and "ridge material" of the central ridge in the crater Alphonsus (Howard and Masursky, 1968). Units can also be divided on the basis of albedo where this property is believed significant: "rim material, dark"; "floor material, dark."

Crater materials are subdivided in order to call attention to differences in physical properties, relative ages, and probable origins among the subunits of a single crater and also among different craters. The near-surface rim material is interpreted as

[8] On two maps (Carr, 1965b; Hackman, 1966) this material was designated "slope material." On all maps including these, bright material on crater walls and other slopes is called slope material and assigned a Copernican age. (See section on "Slope material.")

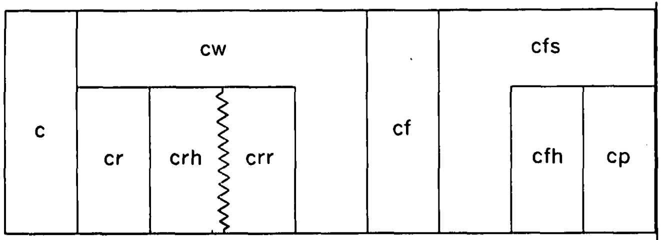


FIGURE 15.—Example of map explanation box showing approximately stratigrapric relation among crater material subunits. All materials of a single crater are regarded as an informal formation; each formation may be divided into members, and each member may be divided into submembers. Common submembers are illustrated above. The "c" represents the formation "crater material"; where it stands alone it represents undivided material (shown on left). The second lowercase letter stands for a member and the third for a submember, as follows:

cr, rim material
  crh, hummocky
  crr, radial — Laterally gradational facies of rim material recognized in some large craters.
  cw, wall material — (Includes floor material and peak material in some small craters; may also include rim material extending inside some craters.)
cf, floor material — (Includes peak material in some small craters.)
  cfs, smooth
  cfh, hummocky
cp, peak material

Boxes in lower row refer to materials formed contemporaneously with the crater. Wall material (cw) and smooth floor material (cfs), particularly, may continue to form after cratering. Peak material and hummocky floor material may do so also and are so shown on some maps.

The "c" may be replaced by letters representing the descriptive designation of craters (such as "sc" for satellite crater material and "ch" for chain-crater material). The "c" may also be replaced by letters representing informal but specific names (such as "a" for materials for the crater Alpetragius) or formal names (such as "g" for Gassendi Group). (Even though the letter refers to a group, not to a formation, the materials of each individual crater are still regarded as an informal formation; these formations together compose the formal group.) On a map, a capital letter representing an age assignment (C, CE, E, EI, I, IpI, pI) normally precedes the lowercase letters. (On early maps, crater subunit boxes were separate, not joined as in this figure, and did not show stratigraphic relations among subunits.)

ejecta of either impact or volcanic origin (p. 7). The surface texture and apparent areal extent (relative to rim-crest diameter) of rim materials are indicators of crater age and origin. Extensive rings of distinctively textured hummocky and radial rim facies and large fields of satellitic craters—all well displayed by Copernicus, for example—are probably characteristics of young impact craters (Shoemaker, 1962). In the absence of radial rim materials and satellitic craters, a subdued circular or polygonal ring of indistinctively textured material may represent either a crater that did not form by impact, or an old impact crater modified by mass wasting, superposed materials, and isostatic rebound (Masursky, 1964; Daneš, 1965). (Rim material of all craters, especially seemingly old ones, is gradational with the surroundings, and the contact may be difficult to map.)

Wall material is usually interpreted as fragments of rim and precrater rock which have moved downslope, although the unit as mapped may also include outcrops of these rocks. Downslope movement may continue for some time, after the formation of a crater, and the explanation boxes of many maps show wall material as partly younger than the rim material, although assigned to the same system (fig. 15). Material on crater walls is generally somewhat brighter than the rim material and where especially bright may be substantially younger than the crater. This brighter material is usually mapped as "Copernican slope material," rather than as wall material (see p. 39).

Floor material may have formed with the crater or afterwards. It is interpreted, alternatively, as the exposed original brecciated crater floor, as impact fallback, as material transported from the wall, as penecontemporaneous or substantially younger volcanic materials, or as a combination of these. Smooth floor material, in particular, may consist of volcanic materials emplaced some time after the crater formed and is shown as partly younger on many maps. Such material may not be related to the primary crater-forming event. Where smooth material in crater floors can be correlated with mare materials or other plains-forming units, it is mapped as these units and not as floor material. Crater peak material may be either material from depth that rebounded immediately after impact or volcanic material emplaced later.

The conventions described above are different from those used on the first two maps published at 1:1,000,000 scale (Hackman, 1962; Marshall, 1963), where only three main subunits were employed: "rim material," "floor material," and "Copernican slope material." In addition to material outside the rim crest, "rim material" included parts of the upper walls, the entire wall when the slopes were not bright, and the entire crater when no subunits were mapped. Rim material of the large crater Kepler was mapped on the basis of albedo, not topography. It was divided into a dark inner unit and a bright outer one, and the outer limit was placed at the limit of the continuous bright halo, which extends beyond the continuous positive relief of the radial rim material. Floor material included material of the central peak, as well as of the relatively flat interior.

Crater material subunits are now mapped differently, therefore, in the following respects: (1) More emphasis is placed on topography and less on albedo, (2) a hierarchical subdivision is established whose basic formational unit is "crater material," and (3) a wall unit is introduced to emphasize the differences between the interior and exterior crater materials and to deemphasize the albedo differences among interior materials. A cartographic dividend of distinguishing between rim and wall materials is that it aids portrayal of intersection and superposition relations between the crater materials and other units, for example, where a unit younger than the crater covers rim material but does not encroach on the wall material inside.

SUMMARY AND CONCLUSIONS

The geology of much of the moon's earthside surface was mapped from earth-based telescopic data before spacecraft photography became available. Lunar geologic mapping is based on the concept that the lunar crust, like the terrestrial crust, is composed of discrete material units. Relative uniformity of topographic and surficial properties is the basis for recognizing and mapping a unit and implies that most units are three-dimensional bodies having a limited range of lithology and age. The order in which such units were formed is determined by their superposition and transection relations and by secondary characteristics such as crater density and degree of topographic freshness. A composite column of such lunar material units, conceptually equivalent to terrestrial rock-stratigraphic units, has been divided into four approximate time-stratigraphic units. The oldest unit is the pre-Imbrian (not a formal system); all materials formed before the formation of the Imbrium basin are conveniently assigned to it. Next youngest is the Imbrian System, which includes all materials formed during and after the formation of the Imbrium basin but before the deposition of most of the mare material in the basin. The Eratosthenian System follows; it tentatively includes materials of rayless craters and some other materials superposed on the Imbrian mare material. The Copernican System is youngest and includes materials of rayed and dark-halo craters and materials contemporaneous with them.

Circular multiringed mare basins are the largest lunar features, and the formation of such a basin is a major event that obliterates the earlier record over a large area and starts a new stratigraphic sequence. Basins consist of an inner basin and several concentric alternately raised and depressed arcuate structures composed of deformed prebasin materials. The original form of these materials is unrecognizable, but they presumably resembled interbasin materials like those of the mainly pre-Imbrian southern highlands. These arcs were probably formed when the basin was formed but may have been later modified by renewed movement. They may be partly covered by basin ejecta. In pre-Imbrian time several mare basins were formed whose materials are now subdued, heavily cratered, faulted, and partly buried by younger materials. The estimated order of formation of some conspicuous pre-Imbrian basins from oldest to youngest is Fecunditatis, Serenitatis, Nectaris, Humorum, and Crisium (or Crisium-Humorum). The largest and youngest basin on the near side is the Imbrium basin, whose formation marks the beginning of the Imbrian Period and whose extensive etjecta(?) deposits (Fra Mauro Formation) and radial fracture system (Imbrian sculpture) are used to separate the materials of a vast area into pre-Imbrian and younger ages. Orientale is a still younger basin of Imbrian age, which similarly dominates a vast area centered on the west limb.

The principal deposits that were emplaced after the formation of each basin are light plains material, dark plains (mare) material, and crater materials, all of which interfinger complexly. Both kinds of plains-forming materials fill depressions such as the basins themselves and their peripheral concentric and radial depressions, whereas crater materials may be formed anywhere. Most light plains materials are older than most dark plains materials and may have evolved from originally dark plains through cratering and other processes. Light plains materials in or near the Imbrian basin (Apennine Bench and Cayley Formations) must be Imbrian in age, whereas those in the pre-Imbrian basins and on the terra between basins may be of either pre-Imbrian or Imbrian age. Many mare materials can be correlated with those mare materials that informally define the top of the Imbrian System and are therefore of Imbrian age. Hence mare material is an approximate stratigraphic datum common to all basins; however, mare materials do differ in age, and a substantial but undetermined percentage of dark mare material is younger than Imbrian. Much dark young mare material as well as young mantling and positive-relief materials are concentrated near basin margins. Filling of a basin by mare material only ends long after the basin was formed.

Craters and their deposits have formed throughout lunar history. Craters older than basins are all pre-Imbrian except some near Orientale. Pre-Imbrian craters are very numerous in areas such as the southern highlands where basins have not formed. Materials of craters such as Gassendi which are younger than the pre-Imbrian basins but older than the mare material that fills the basins are virtually all pre-Imbrian or Imbrian in age. Those craters such as Archimedes which are similarly related to the Imbrium and Orientale basins and their mare filling are Imbrian in age. Among relatively round craters with concave-upward rim-flank profiles, there seems to be a progression in morphology and age from subdued, probably old craters like many in the southern highlands to fresh, probably young craters like Copernicus. Rayless fairly fresh-appearing craters not in contact with the mare material may be either Imbrian or Eratosthenian in age; most rayless craters superposed on mare surface are assigned an Eratosthenian age. Rayed craters everywhere are assigned a Copernican age. All evidence points to the relative youth of rayed craters, but age designations of most rayless craters are only tentative. Rays seem to fade with time, but at varying rates, and they may never have been present around some craters. Indeed, some rayless and dark-halo craters are certainly very young, as indicated by superposition relations or pronounced thermal anomalies. Several classes of irregular, elongate, or low-rimmed craters and craters alined in chains (except those satellitic to large craters) are not assigned ages.

Additional types of material, mostly relatively young and of local extent, include dark blanketing materials (mapped as the Sulpicius Gallus, Doppelmayer, and Cavalerius Formations); materials of various domes, cones, plateaus, and other apparently constructional features (materials of Kant Plateau; Harbinger, Boscovich, Tacquet, Vallis Schröteri, and Cobra Head Formations; Marius Group); and sinuous rille materials. One moderately light plains-forming unit is Copernican in age (Theophilus Formation). Finally, bright slope material indicates fresh exposures of other units.

In general, young lunar material units have more textural detail than old ones. Much relatively old light-colored lunar terrain appears subdued, and this fact suggests that is has been eroded or blanketed by light-colored stratigraphic units (such as the hilly member of the Cayley Formation and various Imbrian terra units). The generally old terrain of the southern highlands is doubtless complex internally, but little detail is seen at telescopic resolution and this terrain is still poorly understood. A pre-Imbrian plateau-forming material and a few other distinct units, in addition to crater-material units, have, however, been recognized in the highlands.

Lunar stratigraphic studies were aimed, in their early stages, at recognizing material units, mapping their spatial relations, and establishing their sequence of formation. The ultimate goal, however, includes unraveling the origin of lunar materials. Evidence of the operation of general processes such as emplacement of flows or ejection of debris is provided by characteristics of topography visible at telescopic resolution. Details of processes and composition must, however, be inferred by drawing comparisons with terrestrial analogs of lunar features and from laboratory experiments and theory. The inferences made earlier in this paper will be summarized here.

Some craters form by volcanism and some by impact, and many impact craters have volcanic materials superposed on them. Chain craters that are uniformly sized and regularly spaced along a graben and low-rimmed, commonly elongate craters exactly centered at the tops of shieldlike mare domes must be volcanic. On the other hand, large craters such as Copernicus and Tycho are probably formed by impact. The pattern of secondary craters and the very long rays around such craters are explained in detail by ejection of fragments in a single sudden release of explosive energy from a point or line source in the parent crater. An explosion of sufficient energy could easily be generated by the impact of a relatively small object from space, and many such objects are known to exist in the Solar System and must have existed in the past. Not even the largest terrestrial volcanic explosion, however, has released sufficient energy suddenly enough to produce features of the scale observed on the moon.

In several respects mare basins are morphologically similar to large impact craters, and some basins are surrounded by deposits that resemble impact crater ejecta; for example, the Imbrium basin is surrounded by the hummocky, laterally gradational, and apparently blanketlike Fra Mauro Formation. These geometric similarities, in addition to the great areal extent of radial and concentric structures that were presumably formed when the basin was created, suggest that the basins (not their filling) formed by impact.

Volcanic materials appear to be common on the moon. Many domes and other constructional features are clearly of volcanic origin, and their variety of form suggests different magma compositions or modes of eruption. Sinuous rilles suggest the flowage of fluid material of some sort. The fact that many light and dark plains-forming materials have lobelike contacts and terminate abruptly against higher topographic forms suggests that they were emplaced as flows with the properties of a fluid. Basalt lava comes to mind because of the plateau basalts on earth, which are highly fluid, laterally extensive, and dark. The dark and possibly the light mantling materials, on the other hand, are more likely to be deposits of free-fall tuff. They grade to plains-forming materials in many places; thus, free-fall tuff may be interbedded with the plains flows. An alternative to these interpretations is that some or all plains and mantling materials are ash-flow tuff. Like plateau basalt, this material is extensive terrestrially and on the regional scale does not appear significantly different from basalt. Like free-fall tuff, ash-flow tuff compacts differentially upon cooling, and so the buried topography remains expressed, but in subdued form.

The role of erosional processes in the degradation of lunar landforms is not yet known, but the prevalence of subdued topography suggests considerable erosion. The light terra-mantling deposits may well be mostly mass-wasted debris. Meteorite impact presumably is an important erosional agent and probably produces a fragmental layer on exposed surfaces.

In brief, lunar materials are currently believed to fall into the following major genetic classes: (1) impact ejecta deposits from craters; (2) impact ejecta blankets from mare basins; (3) volcanic materials erupted from craters; (4) dark plains-forming (mare) materials composed chiefly of volcanic flows; (5) dark terra-mantling materials composed chiefly of pyroclastics; (6) light plains-forming material composed at least partly of volcanic flows; (7) light terra-mantling materials of mixed origin; (8) plateau-forming materials of volcanic or tectonic origin; (9) materials of volcanic domes that have gentle slopes; (10) materials of volcanic domes and ridges that have intermediate and steep slopes; (11) slope materials transported by mass-wasting.

All these materials were probably formed throughout lunar history; however, they are subject to degradation and change, and some have been recognized only in recent systems. Only mare-basin materials, crater materials, plateau-forming materials, and possibly light plains materials are now known to have formed in pre-Imbrian time. The same materials also formed in the Imbrian Period, as did dark plains-forming (mare) and terra-mantling materials. The light materials, especially those that form plains, may have evolved from the dark ones. Constructional volcanic features are known from the Imbrian and become common in the Eratosthenian and Copernican Systems; no doubt many old ones are also present but unrecognized because of degradation and burial. Crater materials also were formed in the Eratosthenian and Copernican Periods, and the features that reveal their origin are best preserved in these young craters; origins of many older craters may never be known. Materials have doubtless moved down slope in all periods, but only those active in the Copernican can be separated from the materials from which they were formed. The more thoroughly the Moon's surface is examined, the more small areas are found which can be distinguished from their surroundings by differences in texture, albedo, and crater density. Materials in most of these small areas are of post-Imbrian age, and the stratigraphy of the Eratosthenian and Copernican Systems doubtless will become increasingly complex as studies continue.

Geologic mapping has shown, therefore, that a variety of formative and destructive processes and a complex evolutionary history have produced a heterogeneous lunar crust. Contrary to a widespread presumption, no single origin—neither impact nor volcanism—adequately accounts for all craters and other features. Throughout its history the crust probably was repeatedly affected by volcanic activity and was constantly bombarded and deformed by the impact of bodies from space and of fragments of its own crust secondarily ejected from the craters thus formed. All surfaces are degraded by a process analogous to terrestrial erosion. This heterogeneity means that during future exploration, ground visits must be made to many representative points. We cannot expect one place to reveal the complete composition of the crust and the complete history of the moon. Synoptic spacecraft photography will be necessary to study regional differences and to extend the lunar stratigraphic framework which owes its beginning to earth-based telescopic studies. The simple but powerful methods of stratigraphy applied to photographs will continue to be the most economical means of deciphering the structure, history, and formative processes of the moon.

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PRELIMINARY LUNAR GEOLOGIC MAPS

Following are preliminary open-file geologic maps at a scale of 1:1,000,000 that have not yet been superseded by a published map. Dates shown refer to the Astrogeologic Studies Annual Progress report to the National Aeronautics and Space Administration of which the maps were a part.

July 1963–July 1964

Grimaldi quadrangle, by John F. McCauley (with text)

July 1964–July 1965

Byrgius quadrangle, by N. J. Trask (with text)
Cleomedes quadrangle, by A. B. Binder
Colombo quadrangle, by Donald P. Elston (text in July 1963–July 1964)
Fracastorius quadrangle, by Donald P. Elston
Langrenus quadrangle, by J. D. Ryan and D. E. Wilhelms
Macrobius quadrangle, by H. A. Pohn (with text)
Mare Undarum quadrangle, by Harold Masursky
Petavius quadrangle, by D. E. Wilhelms
Purbach quadrangle, by H. E. Holt
Rupes Altai quadrangle, by L. C. Rowan
Taruntius quadrangle, by D. E. Wilhelms

July 1965–July 1966

Cassini quadrangle, by N. J Page
J. Herschel quadrangle, by G. E. Ulrich
Maurolycus quadrangle, by N. D. Cozad and S. R. Titley
Plato quadrangle, by J. W. M'Gonigle and D. L. Schleicher
Rheita quadrangle, by Désirée E. Stuart-Alexander
Rümker quadrangle, by R. E. Eggleton and E. I. Smith
Sinus Iridum quadrangle, by G. G. Schaber

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