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STRATIGRAPHIC BASIS FOR A LUNAR TIME SCALE†

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INTRODUCTION

THE impending exploration of the Moon and geologic mapping of its surface raise the need for an objective lunar time scale. Photogeologic mapping already in progress has made this need immediate, and at the same time furnishes the stratigraphic foundation on which the broad framework of a lunar time scale may be based. This paper is a report of progress in meeting this need. Five major stratigraphic subdivisions will be described which have been adopted for use in detailed photogeologic mapping at a scale of 1 : 1 000 000.

The geological law of superposition is as valid for the Moon as it is for the Earth, but at the present time the application of this law to the Moon is restricted to the study of the relation of surface features as they are seen through the telescope or as they may be photographed from the Earth or a space vehicle. The chronologic relationships of many of the visible features of the lunar surface, nevertheless, can be unambiguously determined.

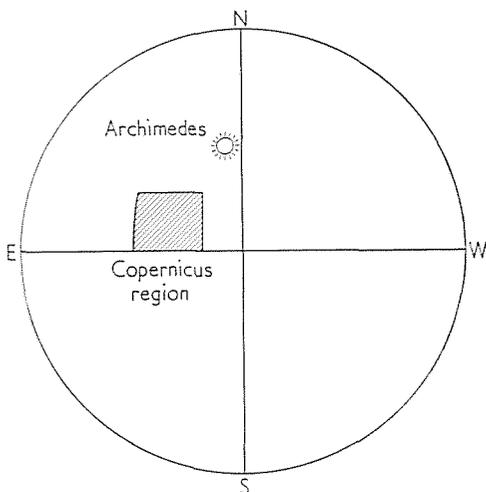


FIG. 1. Index map of the Moon showing location of the Copernicus region.

The lunar surface is locally built up of an intricate and complexly overlapping set of layers of ejecta from craters, material underlying the crater walls and floors, and material that occupies the maria. The composition and

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thickness of these layers are not known, though reasonable estimates can in some cases be made of the thickness. These are specific problems for future exploration. The existence of the layers, however, can be recognized, and their stratigraphic succession provides the basis for a relative time scale for events in the history of the Moon. Determination of the absolute age of points or events in this time scale, again, is a problem for the future.

A region around the crater Copernicus was selected for initial detailed investigation of the stratigraphy. This region is favorably located near the center of the lunar disk (Fig. 1) and is one where the relative succession of many stratigraphic units can be worked out. For this reason the Copernicus region has become a type area from which we are extending or tracing a number of major units by photogeologic mapping.

EJECTA FROM COPERNICUS

Copernicus is a somewhat polygonal crater about 90 km across (Fig. 2), and about 3500 m deep, measured from rim crest to floor; the rim rises about 1000 m above the surrounding lunar surface. The interior walls of the crater comprise a series of terraces, scarps, and irregular sloping surfaces that descend stepwise from the crest to the crater floor, a roughly circular area of generally low relief 50 km in diameter. A few low peaks rise above the floor near the center of the crater.

The outer slopes of the rim are characterized by a distinctive topography. Rounded hills and ridges are combined in a hummocky array that consists of humps and swales near the crest of the rim and passes gradually outward into a system of elongate ridges and depressions with a vague subradial alignment. The relief of the ridges gradually diminishes until it is no longer discernible at a distance of about 80 km from the crest of the rim. Beyond this distance the rim passes gradationally into the ray system.

The ray system, which extends out more than 500 km from Copernicus, consists mainly of arc-like and loop-shaped streaks of relatively highly reflective material on a generally dark part of the Moon's surface. In certain photometric characteristics the rays are essentially an extension of the crater rim and cannot be sharply delimited from it. The major arcs and loops can be locally resolved into an echelon feather-shaped element, ranging from 15 to 50 km in length, with the long axes of the element aligned approximately radially with respect to the center of the crater.

Within the rays, and preponderantly near the concave margins of the major arc and loops, numerous elongated depressions or gouge-like craters in the lunar surface may be seen that range in length from the limit of telescopic resolution to about 8 km (Fig. 3). Visible depressions or gouges lie at the proximal ends of many ray elements, though there is not a correspondence of one gouge for each distinguishable ray element. At very low angles of illumination the Moon's surface along the rays can be seen to be roughened ([1], p. 289, 291). The roughness is due, at least in part, to the presence of the gouge-like craters and very low rims around these craters.

A full explanation of the ray pattern and associated gouge-like craters can be given in terms of the ballistics of material ejected from Copernicus [2]. In this explanation the gouges are formed mainly by impact of individual large fragments or clusters of large fragments ejected from Copernicus and the ray elements are splashes of crushed rock derived chiefly from the impact of these fragments. The ray system may thus be conceived as a discontinuous

thin layer of ejecta derived partly from the main central crater and partly from the local gouges.

The radial frequency distribution of gouges shows a sharp mode near 160 km from the center of Copernicus. At greater distances the frequency drops off rapidly, and toward the outer extremity of the ray system the frequency drops gradually to zero. If we come closer to Copernicus from the

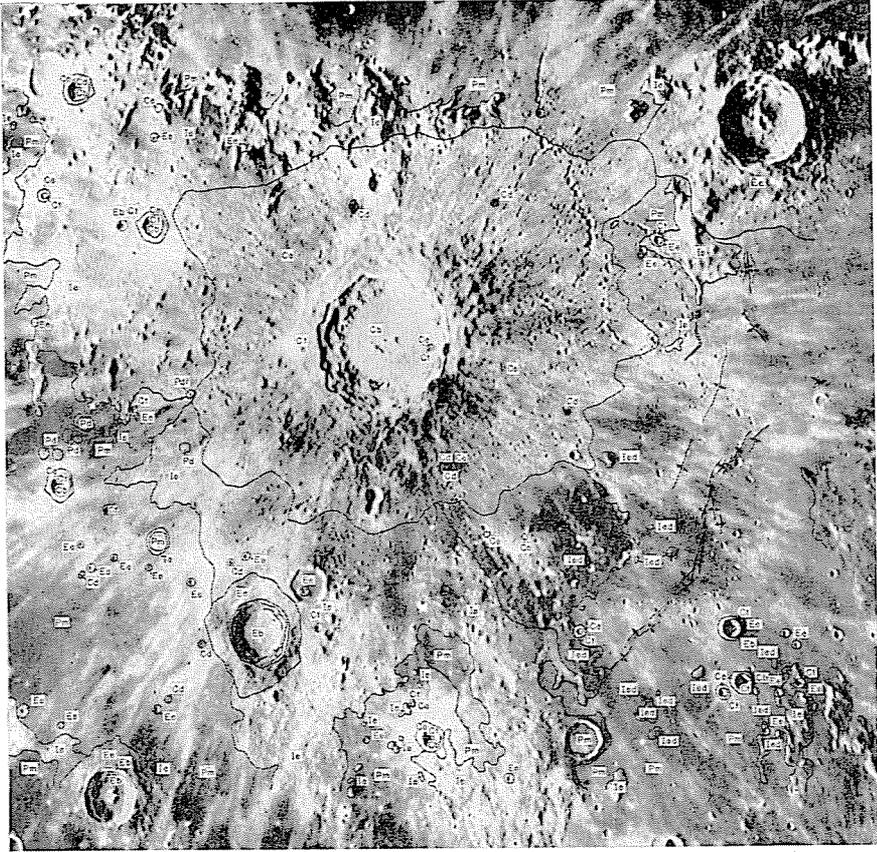


FIG. 3. Annotated photograph of the Copernicus region. Photograph taken by F. G. Pease at the 100-in. Hooker telescope in 1929, Mount Wilson Observatory.

modal distance, the frequency drops off very rapidly, evidently owing chiefly to the fact that toward the main crater the gouges in the pre-existing lunar surface tend to be covered up or smothered under an increasingly thick deposit of material making up the crater rim. The smothering effect begins about 80 km from the edge of the crater, about where the relief of the sub-radial ridges can first be seen, and from this distance inward there is essentially a continuous blanket of ejecta. The thickness of this blanket ranges from a feather edge at its outer extremity, beyond which the pre-existing lunar surface is exposed between the rays, to a maximum that probably does not exceed about 1000 m, the height of the rim.

EJECTA FROM OTHER CRATERS

Scattered over the lunar disk are many other craters the size of Copernicus and smaller that have similar hummocky rims. In general, the ratio of the width of the hummocky terrain to the diameter of the crater decreases with decreasing size of the crater. Around some craters almost all the rim terrain is made up of a nearly random arrangement of hummocks typical of the rim crest at Copernicus; around others the rim is marked by a strong radial or subradial pattern of low ridges typical of the peripheral zone of the rim of Copernicus. Visible gouges surround the rims of all such craters approaching Copernicus in size. The interior walls of these craters are almost invariably terraced, the floors are irregular, and nearly all have a central peak or peaks.

Many craters with this group of characteristics are the foci of prominent ray patterns, but many others, such as Eratosthenes (Fig. 2) lack rays entirely. Where they are not overlapped by Copernican rays, the rim and floor of Eratosthenes have relatively low reflectivity or albedo. Wherever a rayless crater like Eratosthenes or a crater with very faint rays occurs in an area with bright rays from some other crater, the bright ray pattern is in all cases superimposed on the darker crater or on the faint ray pattern. From this sequence and from the fact that both craters with rays and rayless craters are widely distributed over the surface of the Moon, we infer that some process or combination of processes is at work on the lunar surface that causes fading of the rays and other parts of the Moon's surface with high reflectivity.

It can be shown that the exterior ballistics for a lunar crater, the velocities and angles at which fragments are ejected, are independent of the size of the crater and the volume of material thrown out [2]. A fragment ejected at a given velocity and angle of elevation will go just as far from a small crater as it will from a large crater. A small volume of material ejected from a small crater, therefore, tends to be as widely distributed as a large volume of material from a large crater. But since the smaller volume is distributed over a comparable area, the lateral and vertical dimensions of the continuous layer of ejecta must obey different scaling laws than the dimensions of the crater.

The ratio of maximum thickness of the ejecta layer on the rim to the diameter of the crater and the ratio of the extent of the continuous ejecta layer surrounding the crater to the diameter of the crater should decrease with decreasing size of the crater. There may be a lower limiting size of craters on the Moon around which only scattered fragments and no continuous layer of ejecta will be found. These scaling relations are partly confirmed by the rim heights and the extent of the rim material of the smaller lunar craters. The width of the visible hummocky terrain diminishes rapidly with decreasing crater diameter so that craters of 15 km diameter and smaller are encompassed only by narrow belts of continuous rim deposits generally less than 5 km wide. An example of such a crater is Hortensius (Fig. 2). Major rim deposits are associated only with the larger craters.

STRATIGRAPHY OF THE COPERNICUS REGION

In the Copernicus region the surface of the Moon is underlain mainly by an overlapping series of deposits surrounding major craters. The materials have been grouped into five stratigraphic subdivisions; from oldest to

youngest these are (1) pre-Imbrian material, (2) the Imbrian system, (3) the Procellarian system, (4) the Eratosthenian system, and (5) the Copernican system. These stratigraphic subdivisions correspond to five intervals of time which we will call periods. A brief description of the stratigraphic relations and surface characteristics of each system is given in the following pages. A more detailed description of each system and its photometric properties will accompany reports on specific regions that are currently being mapped by the U.S. Geological Survey.

PRE-IMBRIAN MATERIAL

No material of pre-Imbrian age can definitely be shown to be exposed in the Copernicus region, but pre-Imbrian rocks may crop out on ridges and hills in the Carpathian Mountains and on scattered ridges and hills east†, west, and south of Copernicus in areas indicated on the map (Fig. 2). The overlying Imbrian system, if present on these ridges, appears to be very thin. The Imbrian system can be inferred with high confidence to overlie a surface of complex relief that includes ridges, valleys, and craters. Rocks which underlie the Imbrian probably have diverse origins and a complex history. Because craters are a conspicuous component of the pre-Imbrian terrain, it is likely that the pre-Imbrian includes many crater rim deposits like those associated with craters of younger age. The overlying Imbrian system thins rapidly south of the Copernicus region, and pre-Imbrian material is probably widely exposed in the southern hemisphere of the Moon. Detailed mapping in the southern regions may show that the pre-Imbrian can be divided into many separate mappable stratigraphic units.

IMBRIAN SYSTEM

The Imbrian system is the oldest widely exposed stratigraphic unit in the Copernicus region. It is continuously exposed from the Carpathian Mountains southward to a group of hills or low mountains north of Hortensius and in a broad area south of Copernicus between the longitudes of Reinhold and Gambart. The topography developed on the Imbrian is unique. It is a gently rolling surface studded in most places with close-spaced low hills and intervening depressions generally ranging from 1 to 4 km across. Isolated larger hills and elongate ridges occur, but these may, in the main, merely reflect buried pre-Imbrian topography. The numerous small-scale topographic features impart a shagreen appearance to the Imbrian as it is seen through the telescope or on photographs with high resolution at certain angles of illumination.

Most of the Imbrian has an albedo intermediate between the extremes of the range of lunar albedo, but locally, north of Gambart (shown as II ed on the map, Fig. 2) and in isolated exposures in Sinus Aestuum and to the west, the Imbrian has a very low albedo. These areas of low albedo are some of the darkest places on the Moon.

The surface on which the Imbrian rests in the Copernicus region appears to include prominent linear ridges and intervening valleys in the Carpathian Mountains and the area south-east of the Carpathian Mountains and includes a few recognizable pre-Imbrian craters such as Stadius that are nearly filled

† In this report east and west will be used according to astronomical convention as shown in Fig. 1.

with Imbrian and younger strata. In most of the area between Reinhold and Gambart and north of Gambart the pre-Imbrian is apparently so deeply buried that this buried surface has little influence on the topography developed on the Imbrian, except possibly at a few isolated hills. Gambart, a crater north-west of Reinhold (Reinhold B), and a crater north of Copernicus (Gay-Lussac) are partly filled with Imbrian, but it is not clear whether these craters are pre-Imbrian in age or should be assigned to the Imbrian period. Unlike most craters partly filled with Imbrian material the rims of these three craters are not broken or displaced by linear trenches, which are part of a system of linear features referred to by Gilbert ([3], p. 275-279) as Imbrian sculpture, features which characterize part of the pre-Imbrian terrain. The Imbrian may be a few thousand meters thick where it fills or partly fills some of the pre-Imbrian craters and the valleys in the Carpathian Mountains, but it is evidently thin and perhaps locally absent where it covers or laps against the crests of old crater rims and certain high ridges, as indicated by relative sharpness of form of these features.

The Imbrian is extensively exposed in a very large region around the southern margin of Mare Imbrium and is probably related in origin to the great topographic basin which the mare occupies. Essentially the materials of the Imbrian system form an immense sheet partly surrounding Mare Imbrium. Gilbert ([3], p. 274-277), Dietz ([4], p. 373), Baldwin ([5], p. 210-212), Urey ([6], p. 221), and Kuiper ([7], p. 1104; [1], p. 290-295) have interpreted, each in a somewhat different way, part of the material which we recognize as the Imbrian system as ejecta from some place in the region occupied by Mare Imbrium. On the basis of its distribution and surface characteristics we concur with the interpretation of this material as ejecta, but the recognition of the Imbrian system is independent from the problem of its mode of origin and source. It has been named Imbrian for the extensive exposures that partially surround Mare Imbrium.

PROCELLARIAN SYSTEM

The Procellarian system in the Copernicus region forms the relatively smooth dark floors of the Oceanus Procellarum, Mare Imbrium, and Sinus Aestuum and rests stratigraphically on the Imbrian system. It is the material which partly fills the topographic depressions of the Oceanus Procellarum and the maria. The name is taken from the Oceanus Procellarum which is by far the largest area of exposure of the Procellarian on the Moon. The albedo of the Procellarian is everywhere relatively low, but is by no means uniform. Determination of the photometric characteristics of the Procellarian in the Copernicus region is complicated by the presence of the superimposed Copernican rays. In areas between the rays the albedo of Procellarian is lowest east of Landsberg and just north of Hortensius and highest in Sinus Aestuum. At no place is the albedo of the Procellarian as low as that of the dark Imbrian material north of Gambart, but in general the Procellarian has a lower albedo than most of the Imbrian system and most of the other stratigraphic units on the Moon.

Relief on the Procellarian is exceptionally low compared to most other parts of the lunar surface, but the surface of the Procellarian is not featureless. Characteristic topographic forms intrinsic to the Procellarian include ridges, some of them probably more than 100 m high, and low conical and

dome-shaped hills up to 100 to 200 m high and 5 to 10 km across. Rarely do the slopes on any of these features exceed about 5° .

Individual ridges are typically 15 to 30 km long and they occur both singly and in complex en echelon systems, such as one extending into Sinus Aestuum that is nearly 200 km long. The ridges have commonly been interpreted as folds by previous investigators and are shown symbolically as anticlines on the map, but the structure of the ridges may be more complex or even entirely different than ordinary anticlines. By telescopic examination Kuiper ([1], p. 302) has found protrusions and fissure-like depressions on their crests.

Many of the low hills, which are referred to in the lunar literature as "domes", have small craters in their summits; within the limits of telescopic resolution some of these features resemble small terrestrial basaltic shield volcanoes and are so interpreted in the cross-sections accompanying the map. The surfaces of many of the "domes", however, unlike most shield volcanoes, are distinctly convex. The margins of the "domes" are topographically distinct and can be readily mapped, but it is not certain whether they are formed of material that is superimposed on the other Procellarian material or whether the domes are merely structural features in the Procellarian. Most of the dome material appears to be photometrically indistinguishable from the rest of the Procellarian.

In the Copernicus region the Procellarian rests nearly everywhere on the Imbrian system, and the surface of contact has considerable relief. Many isolated exposures of Imbrian occur on hills where the Imbrian rises above the level of the Procellarian in the midst of areas generally covered by the Procellarian. Elsewhere the Procellarian extends along comparatively narrow channelways or corridors into areas of general Imbrian exposure. Local completely isolated exposures of the Procellarian occur within craters such as Gambart. The thickness of the Procellarian, as judged from the extent and distribution of partly buried pre-Procellarian features, is probably nowhere greater than a few thousand meters in the Copernicus region. In other regions of the Moon it may be thicker (compare with Marshall [8]).

In the past the Procellarian material has very generally been interpreted to be volcanic, but recently the hypothesis has been advanced (Gold [9]; Gilvarry [10]) that the material referred to here as the Procellarian system is composed entirely of dust or fragmental debris derived by nonvolcanic processes. Except for the volcano-shaped domes, only a few features of form and scale characteristic of terrestrial lava fields have been found on the Procellarian. An irregular extension of the Procellarian between Gambart and Reinhold resembles a large lava flow, and a low scarp near the terminus may be a secondary flow front, possibly indicative of more than one surge of fluid. The exact nature of the scarp is not known however. It is a low rise on the surface of the Procellarian and could be a flow front, a monocline, or related in some way to the ridges that occur elsewhere on the Procellarian. Whatever the origin of the Procellarian system, it can be shown that the Procellarian is definitely older than a large number of strata that are superimposed upon it.

ERATOSTHENIAN SYSTEM

The Eratosthenian system comprises the rim deposits surrounding Eratosthenes, Reinhold, Landsberg, and a number of smaller craters and the

material that occupies the floors of these craters. Eratosthenian deposits rest on the Imbrian and Procellarian systems and locally may rest on pre-Imbrian material. Individual deposits surrounding each of the three largest Eratosthenian craters rest on both the Imbrian and the Procellarian. The most extensive of these deposits is associated with the crater Eratosthenes, from which the name for the system is taken. A pattern of numerous gouges in the Procellarian in both Mare Imbrium and Sinus Aestuum on either side of Eratosthenes (Fig. 3) shows conclusively that ejecta from this crater are superimposed on the Procellarian.

Eratosthenian deposits are characterized and can be distinguished photometrically from nearly all stratigraphically higher deposits of the Copernican system by their low to medium albedo. Where it is not overlapped by Copernican rays, the rim of Eratosthenes has a lower albedo than the Procellarian system in the adjacent parts of Mare Imbrium and Sinus Aestuum. The albedo of the rim deposit of Reinhold is about the same as that of the immediately adjacent part of the Procellarian system and distinctly lower than the albedo of the nearby Imbrian system, on which most of the Reinhold ejecta rest. Eratosthenian deposits around Landsberg have nearly the same albedo as nearby Imbrian exposures, which is distinctly higher than the albedo of the adjacent Procellarian.

The topography of the Eratosthenian deposits varies with the size of the individual craters with which they are associated. Upper slopes of the rim of Eratosthenes are irregularly hummocky, but low subradial ridges are present near the outer extremity of the ejecta blanket. The rim deposits of Reinhold and Landsberg are entirely hummocky. Rims of the smaller Eratosthenian craters are narrow and smooth at the scale observable through the telescope. The thicknesses of the rim deposits range from a feather edge to maxima that probably do not exceed the height of the crater rims above the surrounding terrain, about 600 m in the case of Eratosthenes, the largest Eratosthenian crater in the region.

The floors of the larger Eratosthenian craters have small-scale topographic features and photometric characteristics similar in some respects to the rim deposits. The floors have been outlined and designated somewhat arbitrarily as breccia on the map to differentiate the material that underlies the crater floors from the ejecta of the rims, which presumably have been thrown out. In the cross section, which is necessarily speculative, the breccia is interpreted as a deep lens under the crater by analogy with large terrestrial impact craters (Shoemaker [2]).

The deposits around the various craters in the Copernicus region that have been grouped in the Eratosthenian system probably have a wide range in age, but all can be shown to be post-Imbrian and most of the deposits rest partly or entirely on the Procellarian and thus are post-Procellarian. Nearly all of the Eratosthenian deposits are partly overlapped by Copernican rays and are therefore pre-Copernican.

COPERNICAN SYSTEM

The Copernican system, the stratigraphically highest system in the Copernicus region, includes several mappable units. The most extensive units of the Copernican system are the rays and rim deposits of the crater Copernicus and the rays of several smaller craters, notably Hortensius and a bright ray crater east of Gambart. Other units in the Copernican system

have been termed breccia, talus, and dark ejecta. As in the Eratosthenian craters, the material that occupies the more or less level floors of the larger Copernican craters has been mapped separately and somewhat arbitrarily as breccia. The term talus has been applied to all material of high albedo on smooth steep slopes. Among the stratigraphically highest units in the region are the dark rim deposits of certain small craters that are superposed on the ejecta blanket and rays of Copernicus. Because of their stratigraphic position these dark deposits have been included in the Copernican system although they contrast photometrically with the other Copernican units. Various units of the Copernican system rest on all the other stratigraphic systems in the Copernicus region.

The albedo of all units of the Copernican system, except for the small dark rim deposits, ranges from medium to high and is higher than the albedo of any of the other stratigraphic system. The wall of the ray crater east of Gambart (Gambart A) is one of the brightest places on the surface of the Moon, but in some places the Copernican units have only slightly higher albedo than adjacent systems. The ejecta blanket around Copernicus is mottled with streaks and patches of lower albedo than the average for the blanket, which is considerably lower than the albedo of the rim deposit of Gambart A.

The rays present a peculiar problem in cartography because they have no well-defined boundaries. Their diffuse margins are probably areas where fragments of Copernican ejecta are scattered individually over the lunar surface and much pre-Copernican material is exposed. The measurable albedo at any place on the rays would therefore contain the integrated effect of Copernican ejecta and whatever pre-Copernican material is present at the surface. The rays have no determinable thickness and their topography is thus the pre-Copernican topography modified locally by the presence of gouges. For these reasons a stipple pattern overprinted on the pre-Copernican units was chosen to represent the ray material on the present map.

Units mapped as talus in the Copernicus region occur only on slopes exceeding 20° . Most such slopes occur on the walls of the smaller craters, and nearly all slopes this steep have a high albedo, regardless of the age of the crater or the albedo of the ejecta surrounding the crater. This correlation between albedo and slope suggests that fresh material of a high albedo is being continuously or intermittently exposed by mass movement on the slopes; hence, it has been termed talus. Similar material probably occurs along steep scarps characterized by higher than average albedo that separate terraces on the walls of Copernicus, but for the sake of clarity of the map have not been shown. The bases of the scarps are indicated by symbols for faults.

The Copernican dark rim deposits, which form small diffuse haloes around craters ranging from 1 to 5 km across, have been tentatively interpreted by us as dark colored volcanic ash [11, 2]. They are unusual features which are peculiar to the Copernicus region and a few other widely separated localities on the Moon. One small crater is present in the southern hemisphere of the Moon (Buch B) around which there are both bright and dark rays. Only for these few deposits and some exceptional dark streaks and haloes in Copernican ejecta blankets does the albedo fail as a criterion for the recognition of Copernican material.

The individual deposits assigned to the Copernican system probably range

widely in age but all are superimposed on pre-Copernican strata or on the ejecta from Copernicus itself. Rays from Copernicus are superimposed at one place or another on all exposures of pre-Copernican units in the Copernicus region except for a few small isolated areas of outcrop of pre-Imbrian, Imbrian, and Eratosthenian material. The rays and rim deposits of two small bright ray craters and from several dark halo craters are, in turn, superimposed on the ejecta blanket of Copernicus. The stratigraphic relations between the rays of Copernicus and bright rays of certain other Copernican craters such as Hortensius and Gambart A have not yet been demonstrated conclusively, but the very bright rays of Gambart A appear to be superimposed on the somewhat darker rays of Copernicus.

RILLS AND CHAIN-CRATER MATERIAL

Rills, which are long narrow trenches in the lunar surface, and craters aligned in a chain or a row that passes laterally into a rill, occur in Sinus Aestuum and Mare Imbrium. These features are developed on the Procellarian and are overlapped by Copernican rays and locally by the ejecta blanket. Their age is not definitely established, as they could be either late Procellarian or Eratosthenian or possibly early Copernican. The chain craters have distinct raised rims but the extent of any ejecta that may have been derived from them has not been determined. The material on the floors of these craters and in the rills is shown on the map as a unit separate from the surrounding Procellarian material, but the areas of exposure are so small that it is difficult to discriminate the material photometrically from the Procellarian.

THE LUNAR TIME SCALE

Reconnaissance studies indicate that the stratigraphic systems recognized in the Copernicus region can be correlated and mapped over most of the visible hemisphere of the Moon, and the systems have been traced by photogeologic mapping from the Copernicus region into the contiguous regions. A lunar time scale corresponding to the stratigraphic systems described and extending from the beginning of lunar history to the present is therefore proposed as follows:

- Present time
- Copernican period
- Eratosthenian period
- Procellarian period
- Imbrian period
- pre-Imbrian time
- Beginning of lunar history.

The periods are defined as consecutive.

The beginning of the Imbrian period is defined as the moment of deposition of the stratigraphically lowest material in the Imbrian system. This material lies at the base of the great Imbrian sheet extending south of Mare Imbrium. All of lunar history prior to this moment makes up pre-Imbrian time, an historical interval that may be divisible into formal periods in future investigations.

The end of the Imbrian period and beginning of the Procellarian period is the moment of deposition of the stratigraphically lowest material of the

Procellarian system. Considerable evidence indicates that the Imbrian period occupies a significant interval of absolute time in lunar history. The rim deposit around the crater Archimedes (Fig. 1), for example, overlies the Imbrian sheet and is in turn overlain by the Procellarian. Numerous other craters outside the Copernicus region were formed during the Imbrian period, and the ejecta from them are part of the Imbrian system.

The end of the Procellarian period and beginning of the Eratosthenian period is defined as the moment when deposition or emplacement of the stratigraphically highest material in the Procellarian system ended. Statistical studies of the distribution of Eratosthenian and Copernican craters on the Procellarian [12] suggest that the top of the Procellarian system is about the same age wherever the Procellarian occurs on the Moon. The absolute time interval occupied by the Procellarian period is probably relatively short.

The end of the Eratosthenian period is operationally defined as the moment of deposition of the faintest rays that can be discriminated photometrically by their higher albedo. Implicit in this definition is the working hypothesis that the albedo of all rays has decreased with the passage of time, that the rate of decrease is a monotonic function of time and similar for all bright rays, and that the photometric properties of the rays approach those of the material on which they are deposited so that the rays ultimately disappear. A corollary of this working hypothesis is that many or most Eratosthenian craters, such as Eratosthenes, were once the foci of rays that have disappeared. All Eratosthenian craters, are by definition, devoid of rays. The local relative stratigraphic sequence of all Eratosthenian and Copernican craters so far mapped or studied is consistent with this working hypothesis.

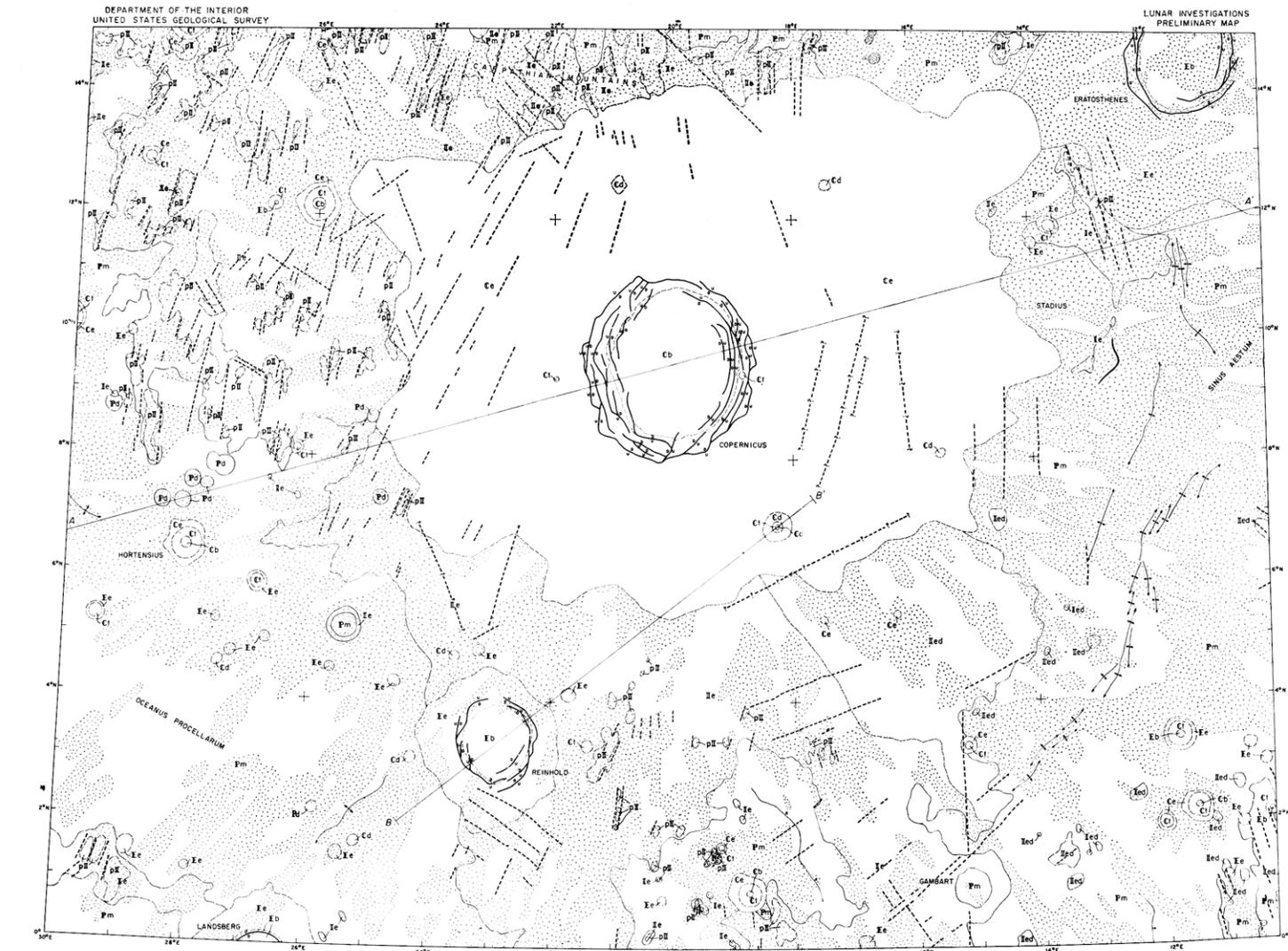
The Copernican period is taken as extending to the present. Studies of crater frequency distribution, which will be reported elsewhere, suggest that the Eratosthenian and Copernican periods, taken together, correspond to the greater part of geological time and that the Copernican period represents somewhat less than half of this total interval. If this is so, the earlier periods are comparatively compressed intervals in absolute time, but ones of considerable activity in the development of the lunar surface features.

The deposition of most individual deposits of ejecta probably occurs in extremely small fractions of the total span of lunar history, and the precise position of the type Eratosthenian deposits of the Copernicus region and the type Copernican deposits within the Eratosthenian and Copernican periods, as defined, is not known. The number of small bright ray craters superimposed on the ejecta blanket of Copernicus suggests it was formed in the later third of the Copernican period. Further studies are expected to show that it is possible to subdivide the Copernican period and correlate Copernican ejecta according to the albedo of the rays.

The causes of the fading of the rays are not known, but two processes acting on the lunar surface may be expected to contribute to the lowering of their albedo: (1) solar ultraviolet irradiation and cosmic ray bombardment, and (2) micrometeorite bombardment. High energy radiation is known to lower the albedo of some silicate and other rock-forming materials, and the processes of bombardment by micrometeorites and small meteorites serve to mix the bright ejecta forming the rays with underlying and adjacent materials of the lunar surface.

REFERENCES

1. Kuiper, G. P. The exploration of the Moon. In "Vistas in Astronautics 2nd annual astronautics symposium", Pergamon Press, New York, 2, 273-312 (1959).
2. Shoemaker, E. M. Interpretation of lunar craters. In Kopal, Zdeněk, ed. "Physics and Astronomy of the Moon," Academic Press Inc., New York and London (1962).
3. Gilbert, G. K. *Bull. Phil. Soc. Wash.*, **12**, 241-292 (1893).
4. Dietz, R. S. *J. Geol.* **54**, 359-375 (1946).
5. Baldwin, R. B. "The Face of the Moon", Chicago University Press, Chicago, p.239 (1949).
6. Urey, H. C. *Geochim. et Cosmochim. Acta*, **1**, 209-277 (1951).
7. Kuiper, G. P. *Proc. Nat. Acad. Sci., Wash.* **40**, 1096-1112 (1954).
8. Marshall, C. H. Thickness of the Procellarian System, Letronne region of the Moon. In "Short Papers in the Geological Sciences", U.S. Geol. Survey Prof. Paper 424 (In press.)
9. Gold, Thomas. *Mon. Not. R. Astr. Soc.* **115**, 585-604 (1955).
10. Gilvarry, J. J. *Astrophys. J.* **127**, 751-762 (1958).
11. Hackman, R. J. Generalized photogeologic map of the Moon. In "Engineer Special Study of the Surface of the Moon", U.S. Army, Office of the Chief of Engineers (1960).
12. Shoemaker, E. M., Hackman, R. J. and Eggleton, R. E. Interplanetary correlation of geologic time. *Proc. Amer. astronaut Soc.*, 7th Annual Meeting. (In press.)



System

Copernican

Erastosthenian

Procellarian

Imbrian

pre-Imbrian

EXPLANATION

Stratigraphic Units

- Ray material**
Probably chiefly crushed rock. Forms thin patchy layers, in most places probably not more than a few feet thick. Initial surface probably very rough at the scale of feet and inches.
- Dark ejecta**
Probably basaltic or dark colored volcanic ash. Forms layers ranging from a feather edge to several hundred feet thick surrounding small craters (probably maar-type volcanoes). Initial surface probably smooth at the scale of feet and inches.
- Ejecta blanket**
Probably chiefly crushed rock with large blocks. Forms hummocky layers ranging from a few feet to about 3000 feet thick around small and large craters. Initial surface probably rough at the scale of feet and inches.
- Breccia**
Probably chiefly crushed rock with large blocks. Probably forms deep lenses inside of small and large craters. Topography is irregular to smooth. Initial surface probably rough at the scale of feet and inches.
- Talus**
Probably partially sorted accumulation of fragments ranging in size from dust to large blocks. Generally forms sheets mantling smooth slopes of about 30°. Initial surface probably rough at the scale of feet and inches.
- Ejecta blanket**
Probably chiefly crushed rock with large blocks. Forms hummocky layers ranging from a few feet to about 2000 feet thick around small and large craters. Initial surface probably rough at the scale of feet and inches.
- Breccia**
Probably chiefly crushed rock with large blocks. Probably forms deep lenses inside of small and large craters. Topography is irregular to smooth. Initial surface probably rough at the scale of feet and inches.
- Dome material**
Probably chiefly volcanic flows; may include volcanic ash. Common dark color and low slopes suggest dominantly basaltic composition. Forms cones up to 5 miles across and a few thousand feet high, generally with summit craters. Initial surface probably rough at the scale of feet and inches.
- Mare material**
Probably volcanic flows. Great extent and generally smooth topography suggest thick sheets of basalt or ignimbrite. Forms layers ranging from a feather edge to several thousand feet thick. Initial surface may have been rough or relatively smooth at the scale of feet and inches.
- Ejecta blanket**
Probably chiefly crushed rock and great blocks derived mainly from the region of Mare Imbrium. Forms a layer ranging from a few hundred to a few thousand feet thick. Layer is probably heterogeneous in composition either because of heterogeneity of source material or because of local alteration. Iled is darker than Iie and locally exhibits faint green coloration. Initial surface probably rough at scale of feet and inches.
- Pre-Imbrian rocks (undifferentiated)**
Probably includes breccia, layers of ejecta, and possibly volcanic or other igneous rocks. May in some places be covered with a thin mantle of Imbrian ejecta.

Surface Characteristics

- Generally smooth at the scale of miles. Topography controlled by relief on contact with underlying material. Probably smooth at the scale of feet and inches. Among the youngest material on the lunar surface; initial surface characteristics probably largely unmodified. Low reflectivity.
- Topography at the scale of miles varies from pitted to hummocky to smooth. Probably rough to very rough at the scale of feet and inches; initial surface characteristics probably fresh to partially modified. High to very high reflectivity.
- Topography at the scale of miles varies from pitted to hummocky to smooth. Probably smooth to slightly rough at the scale of feet and inches; initial small scale relief probably much reduced by small meteorite bombardment, insolation and mass movement. Low to moderate reflectivity.
- Volcano-shaped topographic forms. Probably smooth at the scale of feet and inches; initial small scale relief probably largely reduced by small meteorite bombardment, insolation and mass movement. Low to moderate reflectivity.
- Smooth plain broken by small meteorite and secondary impact craters and rounded ridges of several hundred feet relief. Probably smooth at the scale of feet and inches; initial small scale relief probably largely reduced by small meteorite. Low reflectivity.
- Hilly to locally smooth at the scale of miles. Topography characterized by numerous hills and depressions one to two miles across; locally controlled by relief on contact with pre-Imbrian rocks. Probably smooth at the scale of feet and inches; initial small scale relief probably largely reduced by small meteorite bombardment, insolation, and mass movement. Low to moderate reflectivity.
- Not well exposed.

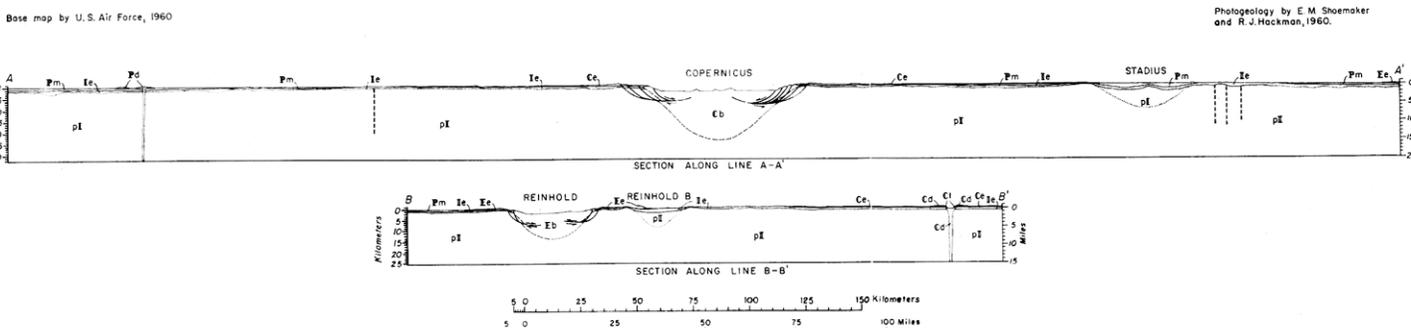
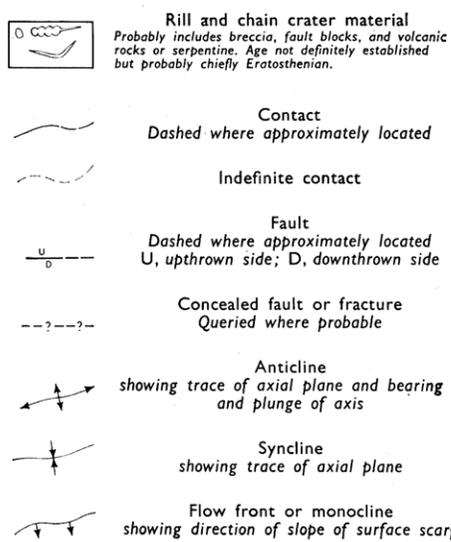


Fig. 2. Preliminary photogeologic map of the Copernicus region of the Moon.