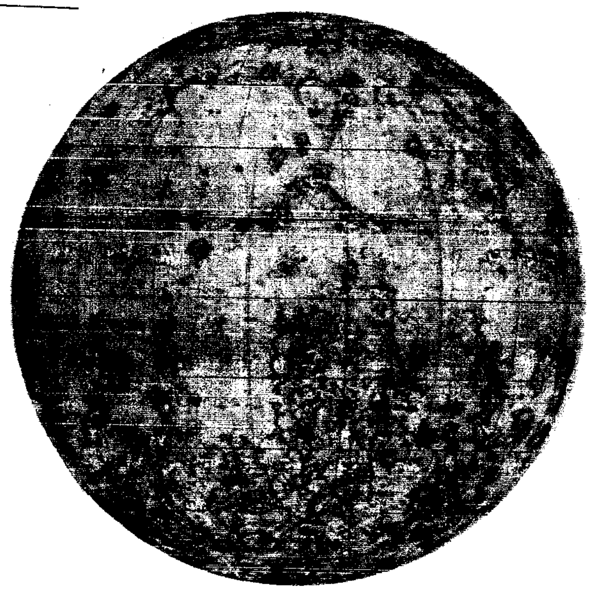
R-66

ASTROGEOLOGIC STUDIES

ANNUAL PROGRESS REPORT

August 25, 1962 to July 1, 1963



PART A

LUNAR AND PLANETARY INVESTIGATIONS

UNEDITED PRELIMINARY DATA

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

ASTROGEOLOGIC STUDIES

ANNUAL PROGRESS REPORT

August 25, 1962 to

July 1, 1963

PART A: LUNAR AND PLANETARY INVESTIGATIONS

May 1964

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It should not be quoted without permission.

This report concerns work done on behalf of the National Aeronautics and Space Administration.

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

ILLUSTRATIONS

TABLES

INTRODUCTION

This Annual Report is the fourth of a series describing the results of research conducted by the U. S. Geological Survey on behalf of the National Aeronautics and Space Administration. This report, which covers the period August 25, 1962 to July 1, 1963, is in four volumes corresponding to four main areas of research: Part A, Lunar and Planetary Investigations; Part B, Crater and Solid State Investigations; Part C, Cosmochemistry and Petrography; and Part D, Studies for Space Flight Program. An additional volume presents in abstract form summaries of the papers in Parts A, B, C, and D.

The major long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the Moon's crust, to work out from these the sequence of events that led to the present condition of the Moon's surface, and to determine the processes by which these events took place. Work being carried out that leads toward these objectives includes a program of lunar geologic mapping; studies on the discrimination of geologic materials on the lunar surface by their photometric, polarimetric, and infrared properties; field studies of structures of impact, explosive, and volcanic origin; laboratory studies on the behavior of rocks and minerals subjected to shock; study of the effect of stress history on the solid state properties of rocks; study of the chemical, petrographic and physical properties of materials of possible lunar origin and the development of techniques for their microanalysis and nondestructive analysis; and engineering studies in aid of the design of space flight experiments and the planning of space missions.

Part A: Lunar and Planetary Investigations (with map supplement), contains the preliminary results of detailed geologic mapping on a 1:1,000,000 scale of a major part of the equatorial belt of the Moon. Detailed geologic relations in certain areas and some regional geologic problems are discussed.

These discussions are facilitated by the designation of geologic materials by geographic names. Insofar as possible, the same rules that govern formal terrestrial stratigraphic nomenclature have been followed. However, the stratigraphic names proposed in this report should be considered to have informal status. Future publication of this nomenclature in a map series of the U. S. Geological Survey or in an outside journal will be considered as the formal presentation of the stratigraphy.

Part B: Crater Investigations, includes a study of a naturally occurring analogue of a secondary cratering event; a report on the progress of shock equation of state studies; reports on the high pressure polymorphs of silica, stishovite and coesite; and preliminary reports on field investigations conducted on meteorite craters of Campo del Cielo, Argentina, and the crypto-explosion structure of Flynn Creek, Tennessee.

Part C: Cosmochemistry and Petrography, includes reports on the chemistry of tektites, their behavior during heating, the nature of the magnetic spherules visible in some tektites and evidence for their presence in submicroscopic sizes in others. Reports on metallic iron and copper in stony meteorites are also included.

Part D: Studies for Space Flight Program includes reports on the determination of lunar slopes by photometric methods; a method for outlining isotonal areas on the lunar surface; a derivation of the expected frequency of small craters on the lunar surface; and a report on the change of effective strength of target materials with crater size. Reports on a search for matter in the Earth-Moon libration regions, infrared studies, x-ray fluorescence of tektites, photogrammetry of small craters, and computer analysis of the pattern of varying albedo over the lunar terrain are also included.

N66 86922

STRATIGRAPHY AND STRUCTURE OF THE MONTES APENNINUS QUADRANGLE OF THE MOON

by Robert J. Hackman

Introduction

The geology of the Montes Apenninus Quadrangle of the Moon was mapped in 1961 and 1962, and revised in 1963 by use of photographs supplemented by visual telescopic observations; the 26.5-inch refracting telescope of the Leander McCormick Observatory, University of Virginia, made available through the courtesy of Dr. V. Osvalds and Dr. L. W. Fredrick. This report summarizes the principal additions and changes introduced in the revision of the preliminary map (Hackman, 1963).

Stratigraphy

Five major stratigraphic subdivisions, corresponding to five periods of lunar history, were previously recognized in the Apennine region (Hackman, 1963). They were first recognized in the Copernicus region (Shoemaker and Hackman, 1960 and 1962; Shoemaker, 1962) and extended to the Kepler region (Hackman, 1962) and the Letronne region (Marshall, 1963). The Procellarian System has subsequently been reduced to group status in the Archimedian Series of Imbrian age. From oldest to youngest, the four major stratigraphic subdivisions in this region are: (1) pre-Imbrian material, (2) Imbrian System, (3) Eratosthenian System, and (4) Copernican System. Subdivision of these units mapped in the Apennine region are shown in figure 1.1.

Pre-Imbrian material includes all rocks older than the Imbrian

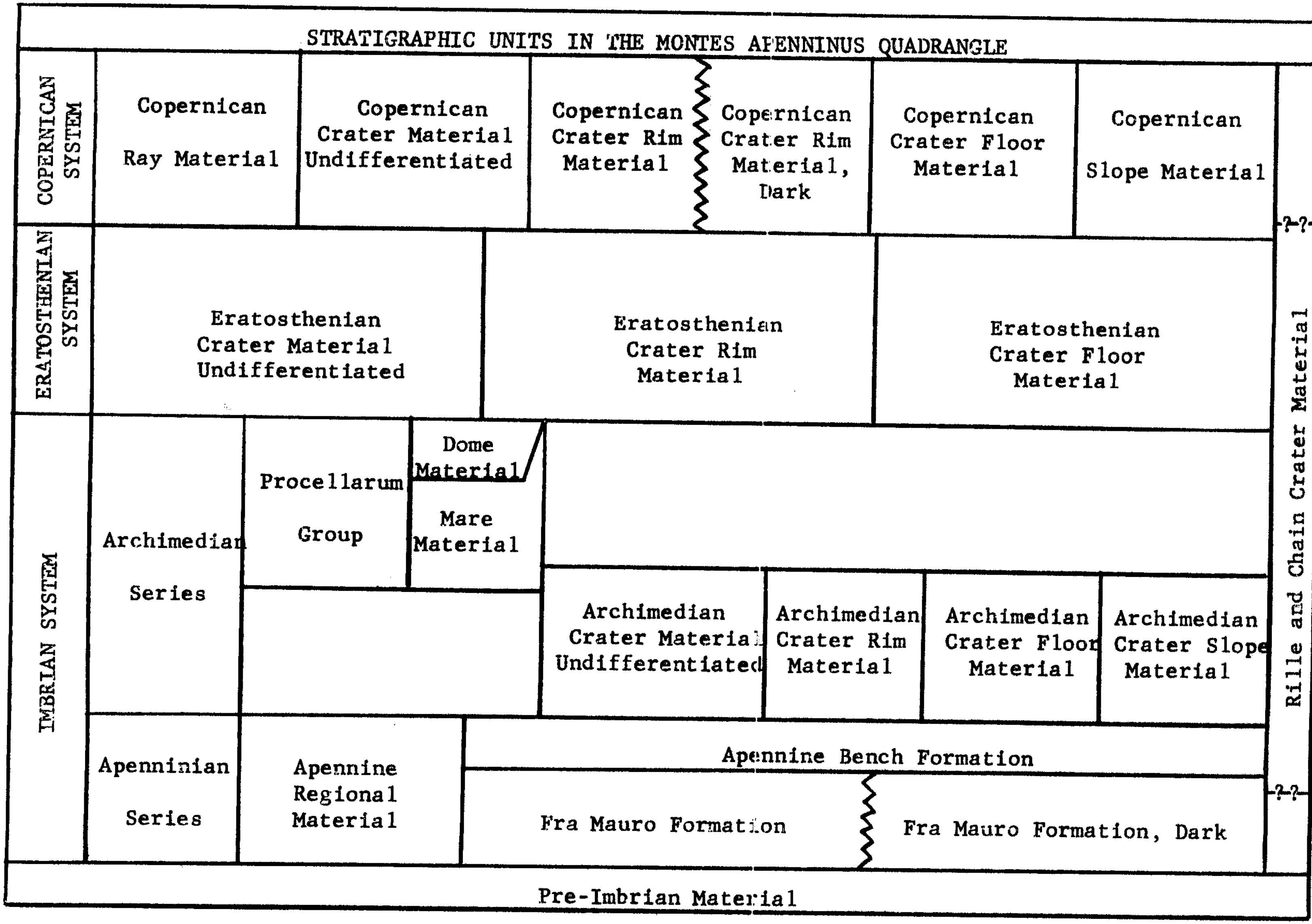


Figure 1.1. Stratigraphic units in the Montes Apenninus Quadrangle.

regional material (see below). In the Apennine region some pre-Imbrian material may be exposed near the tops of sharp ridges and in the faces of some steep slopes. These areas have a higher albedo than the surrounding material. It is possible that these brighter areas may be chiefly younger slope material, but, since such areas actually cross ridge crest, it seems likely that they may include outcrops of pre-Imbrian material.

The Imbrian System has two major subdivisions, the older Apenninian Series and the younger Archimedian Series. The Apenninian Series includes the older Fra Mauro Formation and the younger Apennine Bench Formation. The type locality of the Fra Mauro Formation is designated as the Fra Mauro region south of Copernicus and the type locality of the Apennine Bench Formation is in the Apennine Bench west of Copernicus.

The Fra Mauro Formation is the oldest widely exposed stratigraphic unit in the Apennine region. Fra Mauro material is a regional deposit that ranges in thickness from a few meters to a few thousand meters and probably is heterogeneous in composition. Two facies of the Fra Mauro Formation are present in the Apennine region; a light hummocky facies and a dark hummocky facies. The topography of both is characterized by numerous close-spaced hills and depressions.

The Apennine Bench Formation, in contrast to the hummocky Fra Mauro Formation, is characterized by considerably less local relief, and underlies the smooth, or in places rolling, topography of the part of the Apennine Bench. Its albedo is more uniform than that of the Apennine Bench.

Its albedo is more uniform than that of the older Fra Mauro Formation, which it overlaps, and is markedly higher than that of the younger mare material that overlies it. It occurs in shallow depressions in the Apenninian terrain.

The Archimedian Series of the Imbrian System includes the older Archimedian Crater Material and the younger Procellarum Group. The type locality of the Archimedian Crater Material, formerly making up all of the Archimedian Series, is the crater Archimedes in the Apennine region (Shoemaker et al., 1961). The type locality of the Procellarum Group, formerly the Procellarian System, is now designated as that part of Oceanus Procellarum included in the Kepler region, although the group was first described in the Copernicus region (Shoemaker and Hackman, 1962).

Archimedian Crater Material consists of crater rim, slope, and floor materials, and secondary crater materials that were formed after the deposition of the Apenninian Regional Material, but before the deposition of the extensive Procellarum Mare Material. Rim material of the crater Archimedes (ejecta blanket) is locally superposed on Appenninian Regional Material of the lower Apenninian Bench; elsewhere it is partially covered by mare material, as is the floor of Archimedes. Numerous small secondary craters are found superposed on the Apennine Bench beyond the rim material. Other examples of Archimedian material are found on the rim of the crater Wallace and of a small crater with an incomplete rim southwest of Archimedes.

The Procellarum Group includes two distinct mappable units, mare material and dome material. Dome material is found only on the maria and may be slightly younger than most mare material. The surface developed on mare material has a much lower relief than most other parts of the lunar surface, but is not featureless. It is characterized by low ridges and scarps and very small craters. Dome material makes up low dome-shaped hills found scattered on the mare surface. Under very low sun illumination the dome material can be seen to be slightly rougher than the mare material. The albedo of both the mare and dome material is variable, but everywhere low.

The Eratosthenian System includes the rim and floor material of rayless craters which are superposed on material of the Procellarum Group or the associated secondary craters which are superposed on the Procellarum Group. The most extensive deposits in the Apennine region include part of the rim material of the crater Eratosthenes in the southwest corner of the region; part of the type locality. In the southwest corner of the region, a small Eratosthenian crater, Wallace K, is superposed on some dome material.

The Copernican System includes rim, floor, and slope material and rays of all ray craters. Copernican slope material also occurs on steep slopes outside of Copernican craters. Ray material and secondary craters from Copernican craters outside the Apennine region are also present in the area. This material is associated mainly with the crater Copernicus (to the southwest), Aristillus (north of Autolycus), and Timocharis (west of Feuillée and Beer). Some ray material and secondary craters in the area may be related to other large Copernican craters at considerable distances from the area.

Structure and structural history

Structures were formed in the Apennine region in each of the time periods corresponding to the stratigraphic systems discussed above.

All pre-Imbrian structures in the Montes Apenninus Quadrangle have been considerably modified by the event that produced the basin now occupied by Mare Imbrium. The largest of these older structures is the basin now occupied by Mare Serenitatis, which is joined to Mare Imbrium by a 60 kilometer breach in the Imbrian ring mountains. The mountains to the south of this break are the Apennines and, to the north, the Caucasus. The material making up these two mountain ranges impinges upon the western edge of Mare Serenitatis. Although considerably modified by Imbrian event, and mantled by Apenninian Regional Material, the Haemus Mountains are probably part of the original rim of the southwestern edge of Mare Serenitatis.

Some of the irregular low areas now filled with mare material and found on the southeastern slope of the Apennine Mountains may be remnants of pre-Imbrian craters which have been faulted, fractured, and later filled. With the exception of the Serenitatis structure, which may be considered a very large crater, no smaller pre-Imbrian craters can be positively identified in the Apennine region.

Some of the linear features found in the eastern and southeastern part of the Quadrangle may be localized over concealed faults formed at the time the Serenitatis structure was formed.

In the Imbrian Period the most prominent linear ridge-and-valley topography (Imbrian sculpture) of the Apennine, Caucasus, and Haemus Mountains was formed. The time of development of this topography was previously assigned to the end of the pre-Imbrian Period, just prior to the deposition of Apenninian Regional Material, but is now defined as beginning the Imbrian Period. The Imbrian sculpture, the uplift of the Apennines and other border mountains, and the structures within them were probably produced mainly by the event which formed the basin occupied by Mare Imbrium. This event evidently also produced the Fra Mauro and Apennine Bench Formations, which were deposited upon the new structures immediately after, or possibly partially during, their formation (Shoemaker, 1962, p. 349).

Some displacement may have occurred along some of the scarps along the steep front of the Apennine Mountains during Archimedian time. No displacement is noted in mare material where it overlies these structures. However, certain rilles, wholly or partly in mare material, such as Rima Archimedes VI and Rima Bradley, are parallel or aligned with the Imbrian sculpture and may be due to reactivation of old structures. Arcuate rilles such as Rima Sulpicus Gallus I, II, and III, and sinuous rilles such as Rima Hadley and Rima Conon are also present in the area. These rilles may be tension fractures. The rille, Rima Archimedes I, at its western end near the crater Beer, joins a chain of craters believed to be of volcanic origin. The age of these craters cannot be positively determined, but they are probably post-Archimedian and pre-Copernican.

The principal events of the Eratosthenian and Copernican Periods were the formation of craters and associated secondary craters; some rilles may have formed during these periods.

References

Hackman, R. J., 1962, Geologic map and sections of the Kepler region of the Moon: U. S. Geol. Survey Misc. Invest. Map I-355.

Hackman, R. J., 1963, Stratigraphy and structure of the Apennine region of the Moon: U. S. Geol. Survey Astrogeologic Studies, Annual Progress Report, Aug. 25, 1961 to Aug. 24, 1962, Part A, p. 2-10 (Map in pocket).

Marshall, C. H., 1963, Geologic map and sections of the Letronne region of the Moon: U. S. Geol. Survey Misc. Invest. Map I-385.

Shoemaker, E. M., 1962, Geologic interpretation of lunar craters, in Kopal, Zdenek, ed., Physics and astronomy of the Moon: New York, Academic Press, p. 283-358.

Shoemaker, E. M., and Hackman, R. J., 1960, Stratigraphic basis for a lunar time scale (abs.): Geol. Soc. American Bull., v. 71, p. 2112.

Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, in Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--International Astronomical Union symposium 14: New York, Academic Press, p. 289-300.

Shoemaker, E. M., Hackman, R. J., Eggleton, R. E., and Marshall, C. H., 1961, Lunar stratigraphic nomenclature: U. S. Geol. Survey Astrogeologic Studies, Annual Progress Report, Feb. 26, 1961 to Aug. 24, 1961, p. 114-116.

N 66-86923

THE GEOLOGY OF THE TIMOCHARIS QUADRANGLE

by Michael H. Carr

Introduction

The Timocharis Quadrangle lies in the northeast quadrant of the lunar disc, is bounded by latitudes 16°N and 32°N and by longitudes 10°W and 30°W, and covers an area of 268,100 sq. km. (Plate 2). Most of the quadrangle lies within the Imbrium Basin, the southern boundary of the basin almost coinciding with the southern boundary of the quadrangle. The southern two-thirds of the quadrangle lies between the rim of the Imbrium Basin and the inner ring of Mare Imbrium, a broken ring of features with higher elevations than the regional mare surface. Thus, much of the area lies in a position structurally analogous to the lower Apenninian Bench to the east (Hackman, 1963). The four largest craters within the quadrangle are Timocharis (35 km in diam.), Lambert (30 km), Euler (27 km) and Pytheas (19 km). South of the map area are two large craters, Copernicus and Eratosthenes, and ejecta from both of these craters are found within the map area. Because most of the quadrangle lies within the Imbrium Basin, the dominant geologic unit in the area is mare material (Procellarum Group). Older rocks crop out in isolated patches within the Imbrium Basin and also to the south in the Carpathian Mountains. Younger rocks crop out around craters on the mare surface.

Summary of stratigraphy

Materials of Imbrian, Eratosthenian and Copernican age have been identified in the area using the criteria established by Shoemaker and Hackman (1962). No Pre-Imbrian material has been definitely recognized although some may crop out on scarp fronts and ridges in the Carpathian Mountains and in isolated peaks within the Imbrium Basin.

The Imbrian System is divided into two series, the Older Apenninian Series and the younger Archimedian Series. The Apenninian Series is represented in this area by the light hummocky facies of the Fra Mauro Formation. This formation can be traced laterally, from its type area near Fra Mauro, northward into the map area, where it is exposed as a continuous blanket in the Carpathian Mountains. Some material that crops out locally within the Imbrium Basin has also been mapped as Fra Mauro Formation on the basis of its resemblance to the Fra Mauro Formation exposed in the Carpathian Mountains. The general characteristics of the Fra Mauro Formation have been described elsewhere (Eggleton, 1963, this report; Hackman, 1963).

The Archimedian series is represented by materials associated with the crater Tobias Mayer and by mare material (Procellarum Group). To the north of the map area it is possible to divide the Procellarum Group into a dark and a light facies. Within the map area, however, ray material masks much of the mare so that the albedo of the facies boundaries distinguished to the north cannot be traced with certainty southward into the map area. Thus, the mare material has been left undifferentiated. In spite of this, slight differences in the albedo of the mare are discernable within the Timocharis region. The mare around Pytheas and north and east of Euler appears darker than the mare between Timocharis and Eratosthenes.

Dark hummocky material, resembling the dark facies of the Fra Mauro Formation, is exposed in the southwest corner of the quadrangle. Patches of this material crop out along a scarp that cuts the wall of the crater Tobias Mayer. The dark hummocky material is exposed in both sides of the scarp yet is not cut by the fault. The material thus appears to be younger than the scarp, which is itself post-Archimedian. This unit cannot therefore be dark Fra Mauro material and has been tentatively included in the Archimedian Series.

Numerous Eratosthenian and Copernican craters are found on the mare surface. These craters are all younger than the mare, and the Copernican craters are distinguished from Eratosthenian craters by having bright ray material associated with them. Eratosthenes, the type Eratosthenian crater, actually has a faint radial ray system, and is for mapping purposes considered to have the brightest rays possible for an Eratosthenian crater. Craters with ray systems brighter than Eratosthenes are mapped as Copernican. Craters lacking rays or with rays darker than Eratosthenes are mapped as Eratosthenian. The most prominent Eratosthenian crater in the map area is Lambert. Prominent Copernican craters are Timocharis, Euler, and Pytheas.

Material associated with these craters has been divided, where possible, into floor material, rim material, and central peak material. Crater rim material has been mapped solely on the basis of its topographic expression. The Copernican craters Timocharis, Euler, and Pytheas are each surrounded by asymmetric areas of high albedo. These areas do not coincide with the areas of crater rim material as they are expressed topographically. In these cases the topographic boundary rather than the albedo boundary has been chosen to delineate the crater rim material. In the case of small craters, where the topographic features of the crater rim material are not visible, the albedo boundary was used to map the crater rim material.

Rays as an index of age

Craters younger than the mare material have previously been subdivided into Copernican and Eratosthenian craters (Shoemaker and Hackman, 1962) on the basis of the presence and absence of rays. Shoemaker and Hackman suggested that, in general, bright rayed craters are younger than rayless and faint rayed craters. They also suggested that rays are progressively destroyed with time so that all gradation between bright rayed and rayless craters should exist. Their contentions are partially substantiated by the relationships between the large craters in the vicinity of the map area and by comparison of secondaries from Copernicus and Eratosthenes. Some doubt is, however, thrown on the general application of Shoemaker and Hackman's conclusions by the presence of numerous post-Copernicus rayless craters in the Timocharis quadrangle.

To examine the validity of the suggested inverse correlation of brightness of rays with age, the time relationships between six craters will be examined. These craters are Copernicus and Eratosthenes, which lie to the south of the map area, and Timocharis, Lambert, Euler, and Pytheas which lie within the map area. Copernicus and Pytheas are the two brightest craters in the group, followed by Timocharis and then Euler. These four craters all have distinct ray patterns. Eratosthenes has a very faint and indistinct radial ray system. Lambert has no discernible rays. Rays from Copernicus are superimposed on crater rim material of both Lambert and Eratosthenes. Thus Copernicus is unambiguously younger than both Lambert and Eratosthenes. To the northeast of Pytheas, crater rim material from Pytheas appears to abruptly terminate a Copernicus ray, suggesting that Pytheas is younger than Copernicus. The relations between Copernicus, Timocharis and Euler are indistinct. Copernicus is then demonstrably younger than the two darkest craters in the group and older than the very bright crater Pytheas. These time relations are all consistent with Shoemaker and Hackman's conclusions.

Secondary craters from Copernicus are commonly topographically distinguishable from Eratosthenes secondaries. The distinction between the two types will be discussed in detail subsequently, but in summary, Copernicus secondaries have distinct outlines, low rims, and, if the crater is composite, the rims are markedly cuspate (fig. 2.1). In

Figure 2.1. Secondary crater of Copernicus

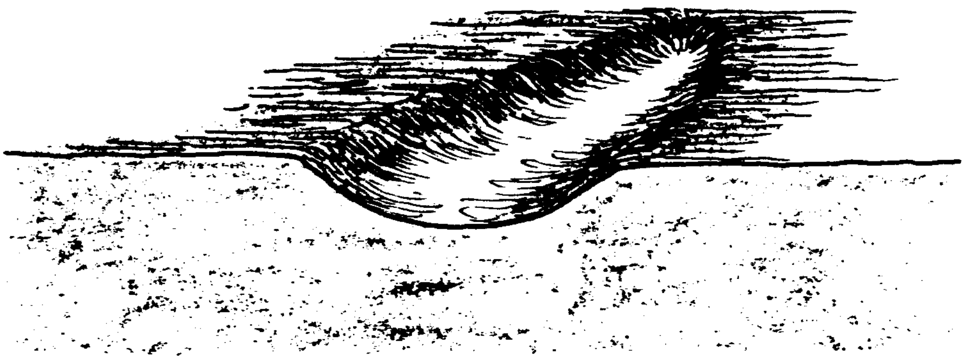


Figure 2.2. Secondary crater of Eratosthenes

contrast, Eratosthenes secondaries (fig. 2.2) have indistinct outlines, do not have cuspate rims, and are shallower than Copernicus secondaries. These differences suggest that small craters are gradually destroyed, the Eratosthenian secondaries representing a stage of partial destruction. The very dark crater Lambert is totally lacking in observable secondaries and may represent the final stage of secondary crater destruction.

Sinuous rills also appear to be progressively destroyed. Fresh sinuous rills, e. g., Schröter's Valley (Moore, this report) and Hadley's Rille (Hackman, this report) are sinuous depressions with well defined outlines and steep walls. They commonly terminate in a depression with a diameter greater than the width of the rill. The subdued feature, Rima La Hire 1, just west of La Hire, is thought to be a partly destroyed sinuous rill. It has a large terminal depression of diffuse outline and gently sloping walls. The rill itself also has gently rounded sloping walls. The whole feature is so shallow that it is barely discernible under optimum lighting conditions. The contrasts between Rima La Hire 1 and fresh sinuous rills are thought to be indicative of a destructive mechanism similar to that suggested for secondary craters.

The mechanism whereby the topography of small craters, sinuous rills, and perhaps other lunar features, becomes modified may be either erosion or burial or a combination of both these processes. No matter which case, such a mechanism would tend to destroy the rays and support the conclusions of Shoemaker and Hackman that rays are progressively destroyed with time.

The only evidence in the map area which sheds doubt on the validity of the use of rays as an index of age is provided by the Copernican dark halo craters. These are craters which are younger than Copernicus and which are surrounded by diffuse dark haloes. Shoemaker (1962), in studying the Copernicus region, suggested that these craters may be lunar analogues of terrestrial maars. The largest such crater in the Copernicus region is Copernicus H with a diameter of 5 km. In the Timocharis quadrangle are several craters younger than Copernicus which have dark haloes, e.g., Draper, Draper C, Eratosthenes E and D. These range in size up to 9 km diameter, and are topographically indistinguishable from typical bright rayed Copernican craters. Dark craters have been mapped as Copernican dark halo craters only when they are demonstrably younger than Copernican ray material. Where ray material is absent, no criteria are available for distinguishing between the older Eratosthenian craters and the younger Copernican dark halo craters. Thus some craters in rayless areas mapped as Eratosthenian craters may actually be dark craters of Copernican age.

We can conclude that although most young craters have bright rays and rims, some young craters do not. If rays are present they appear to be progressively destroyed with time. Hence, the presence of rays is indicative of a young crater but the absence of rays is not necessarily indicative of an old crater.

Structures of large craters

Out of three hundred craters listed by Baldwin (1963) as having central peaks only nineteen have summit pits, yet the four largest craters in the Timocharis quadrangle, Lambert, Euler, Pytheas, and Timocharis, all have central peaks with summit pits. Thus, the large craters in this area are not typical lunar craters.

The central peak of Timocharis is a circular cone connected by a spur to the north rim of the crater. In the center of the central peak is a circular crater. The albedo of both the central peak and the spur is higher than the albedo of the surrounding crater floor material but similar to the albedo of the crater rim material. Hummocky crater rim material extends for approximately one crater radius from the rim crest of Timocharis. Beyond this, faint radial ridges indicate the presence of crater rim material for a distance of approximately another crater radius. The faint ridges are more easily seen to the north and south of the crater where the ridges are at right angles to the incident light than to the east and west where the ridges are parallel to the incident light. On the north, west, and south only part of the hummocky crater rim material has a high albedo. To the east the area of high albedo extends even beyond the faint radial ridges.

Lambert has an irregular central peak, elongated in a north-south direction. In the center of the peak is an irregular depression approximately 4 km in diameter and to the northwest is a circular crater 1 km in diameter. A faint lineation with a N.W.-S.E. trend has been seen on the central peak. The whole central peak has an albedo that is higher than that of any other part of the main crater. Northwest of the central peak, within the main crater, is a circular smooth area with an albedo similar to mare material. This has been mapped as crater floor material but may actually be mare material. Hummocky crater rim material extends for approximately one crater radius out from Lambert's rim crest but no radial ridges are visible beyond the hummocky material. Crater rim material just inside the rim crest on the east, north, and west has a slightly higher albedo than the rest of the crater rim material. The crater rim is broken in two places by a N.E.-S.W. scarp and a crater chain is found on the southern flank of the crater.

The central peak of Euler is in the form of a north-south ridge. On the ridge are possibly two craters 0.5 km in diameter. The albedo of the ridge is higher than that of the crater floor material but similar to the albedo of the material at the crater rim crest. The albedo of the crater rim material is high at the rim crest and to the south and west of the crater, but moderate elsewhere. On the southeast flank of the crater is a crater chain.

Pytheas has a hummocky, irregular, composite central peak and lacks smooth floor material. On the central peak are three small craters. The crater rim material is distributed asymmetrically about the crater, being more prominent to the N.N.W. East of the crater, within the crater rim material, are several linear depressions. The whole crater has a very high albedo.

From the description of the craters above the following general statements may be made:

1. All the large craters within the quadrangle are unusual in that they have central peaks with summit pits.

2. The central peaks have albedos as high, if not higher, than any other part of the crater.

3. The albedo of the floor material is generally lower than that of the rim material and central peak material.

4. Topographically there is little resemblance between the different central peaks, in spite of them all being cratered.

5. In Copernican craters the areas that are covered by crater rim material are not coincident with the areas of high albedo.

6. The crater rim crests are generally brighter than the rest of the crater rim material.

7. The areas of high albedo around Copernican craters are more asymmetric than the areas of crater rim material.

It may be assumed that the craters discussed above were caused by impact, volcanism, or a combination of these two processes. The main features of the craters are thought to have resulted from impact as all these craters have some features indicative of impact such as elevated hummocky rims, radial ridges, secondary craters, rays, etc. Some features of the craters are, however, inconsistent with the theory that the present morphology results only from impact.

Central peaks can be produced during impact by motion of mobilized material toward the center of the crater immediately subsequent to impact. An irregular depression, such as that on Lambert's central peak, could conceivably also be formed by this mechanism, but it is unlikely that circular craters could be formed in this way. To explain the circular craters on the central peaks by an exclusively impact mechanism, two possibilities are suggested: (1) the central peak craters are produced by material ejected from the main crater, i.e., the central peak craters are secondaries; and (2) the central peak craters are produced by primary impacts subsequent to the formation of the main crater. The first possibility is rejected on theoretical grounds (Shoemaker, 1962) and on the basis of the lack of any experimental evidence of secondary craters within primary craters. The second possibility is considered unlikely for the following reasons: (1) it is improbable that random impact would produce the large crater in the exact center of Timocharis; (2) the crater to the northwest of Lambert's central peak is on a cone suggesting a non-impact origin; (3) the density of craters on the central peak of the very young crater Pytheas appears too large for the impact theory.

These considerations suggest that although the main craters are probably produced by impact the cratered central peaks may be produced by volcanism. The volcanism may be induced by the impact but occur much later than the impact. The cone-shaped form of Timocharis central peak, its large circular crater, the crater cone on Lambert's central peak, and the mare-like filling on the floor are all suggestive of volcanism. The high albedo of the central peaks could indicate that the rocks on the central peaks are younger than those in the crater rims and floors. The reason for the prevalence of craters with pitted central peaks in this area is not known but one possible explanation is that the thermal gradient in the area is steeper than is normal for the Moon.

Secondary craters

The mechanics of secondary crater formation and the morphology of Copernicus secondary craters have been discussed in detail by Shoemaker (1962). Secondary craters from both Copernicus and Eratosthenes are found in the Timocharis Quadrangle and are generally associated with ejecta from their parent crater. The ejecta from Copernicus is in the form of rays, that from Eratosthenes is in the form of both faint rays and a continuous blanket.

The Copernicus rays in some places are formed of local elements elongate in a direction radial to Copernicus but arranged *en echelon* so that the ray itself is at an angle to the radial direction. In other places, the ray material forms streaks radial to Copernicus or plumes broadening out with increasing distance from Copernicus. Most Copernicus secondaries lie on the ray material (fig. 2.3). They tend to lie on the narrow end of the plumose rays and on the Copernicus side of the rays at an angle to the radial direction.

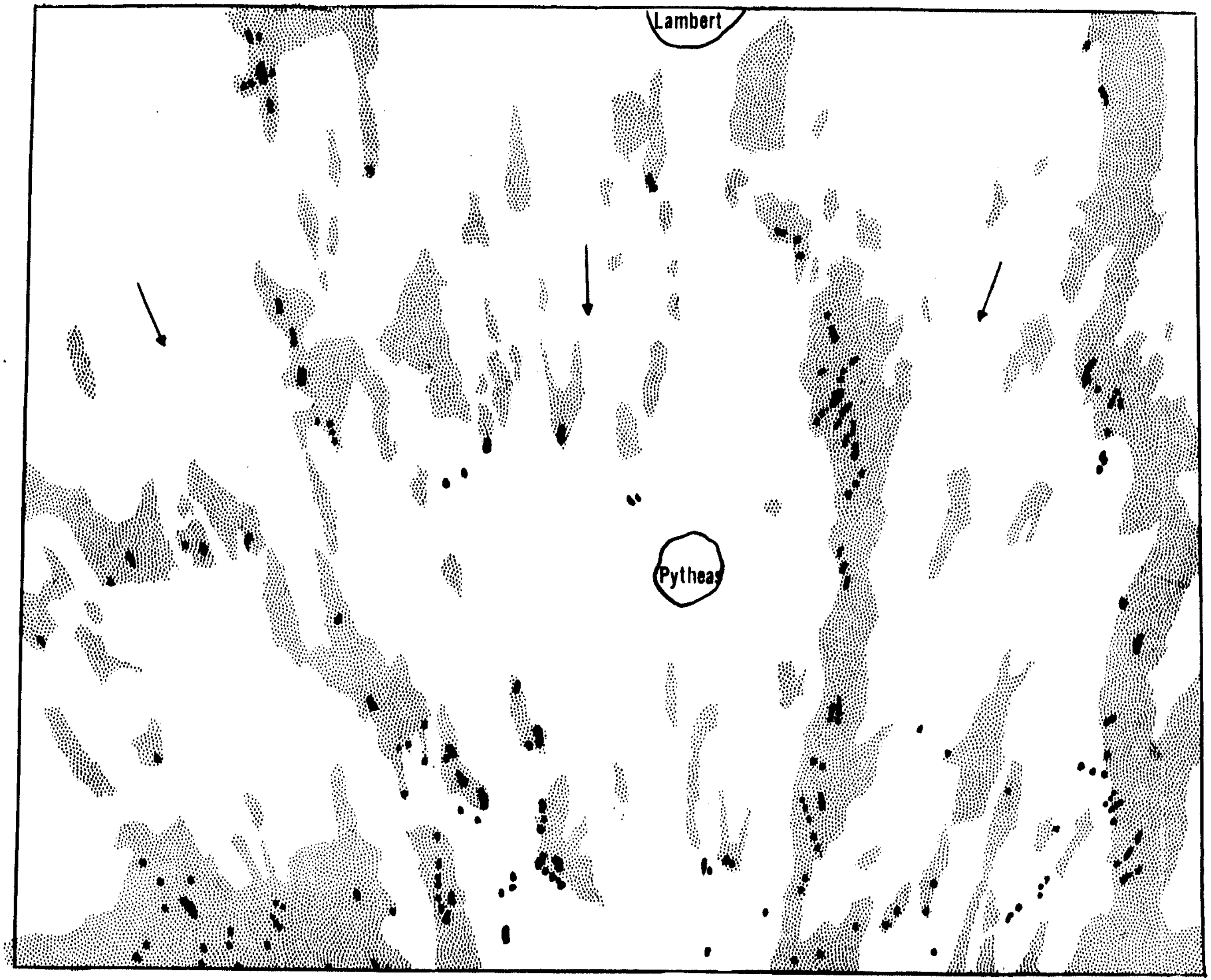


Figure 2.3. Relationship between the Copernicus secondary craters and Copernicus rays in the region of Pytheas. Black dots indicate position and shape of the secondary craters, stipple pattern indicates the area covered by ray material. The arrows are radial to Copernicus.

The Copernicus secondiaries (fig. 2.1) generally have low rims or no observable rims. They commonly are irregularly shaped but have distinct outlines. Many have cuspate outlines and appear to have formed from several intersecting craters. Others form lines of non-intersecting craters radial to Copernicus.

Most of the Eratosthenes secondaries lie on the ejecta blanket of Eratosthenes and are generally morphologically distinguishable from Copernicus secondaries (fig. 2.2). The Eratosthenes secondaries have diffuse indistinct outlines and commonly merge almost imperceptibly into the radial ridge and furrow topography of the ejecta blanket. Many are elongate radial to Eratosthenes. The crater rims are never cuspate in outline and the rim crests are rounded. The Eratosthenes secondaries are generally shallower than Copernicus secondaries of equivalent size.

References

Baldwin, R. B., 1963, The measure of the Moon: Chicago, Univ. of Chicago Press, 488 p.

Eggleton, R. E., 1963, Thickness of the Apenninian Series in the Lansberg region: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A, p. 19-31.

Eggleton, R. E., 1964, Notes on the geology of the Riphaeus region of the Moon: U. S. Geol. Survey Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A.

Hackman, R. J., 1963, Stratigraphy and structure of the Apennine region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A, p. 2-9.

Hackman, R. J., 1964, Stratigraphy and structure of the Montes Apenninus region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A.

Moore, H. J., 1964, Aristarchus region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A.

Shoemaker, E. M., 1962, Geologic interpretation of lunar craters, in Kopal, Zdenek, ed., Physics and astronomy of the Moon: New York, Academic Press, p. 283-358.

Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, in Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--Symposium no. 14 of the International Astronomical Union: New York, Academic Press, p. 289-300.

N66-86924

PROGRESS IN MAPPING THE TARUNTIUS QUADRANGLE

by D. E. Wilhelms

Introduction

The Taruntius Quadrangle (fig. 3.1) lies in the eastern part of the lunar disk and is bounded by latitudes 30°E and 50°E and longitudes 0° and 16°N. The mapping, which is about one-third complete, is based on about 22 hours of useful seeing on the Lick 36-inch refractor and Kitt Peak 60-inch solar reflecting telescope. Many new problems of lunar stratigraphy are presented by the relations of the materials exposed in the quadrangle. There are also new structural problems, particularly concerning the nature of many craters in the highlands, which are unlike any closely studied before.

Stratigraphy

The following is a preliminary stratigraphic column for the Taruntius:

System	
Copernican	Materials associated with ray craters Inner-ring material of Taruntius Crater
Eratosthenian	Materials associated with rayless craters younger than mare material
	Domes and broad ridges
Imbrian	Smooth, dark mare material
? ?	Wavy, light mare material ?
Imbrian (?) or pre-Imbrian (?)	Palus Somni material
? ?	Regional material ? ?
pre-Imbrian	Older regional and crater material

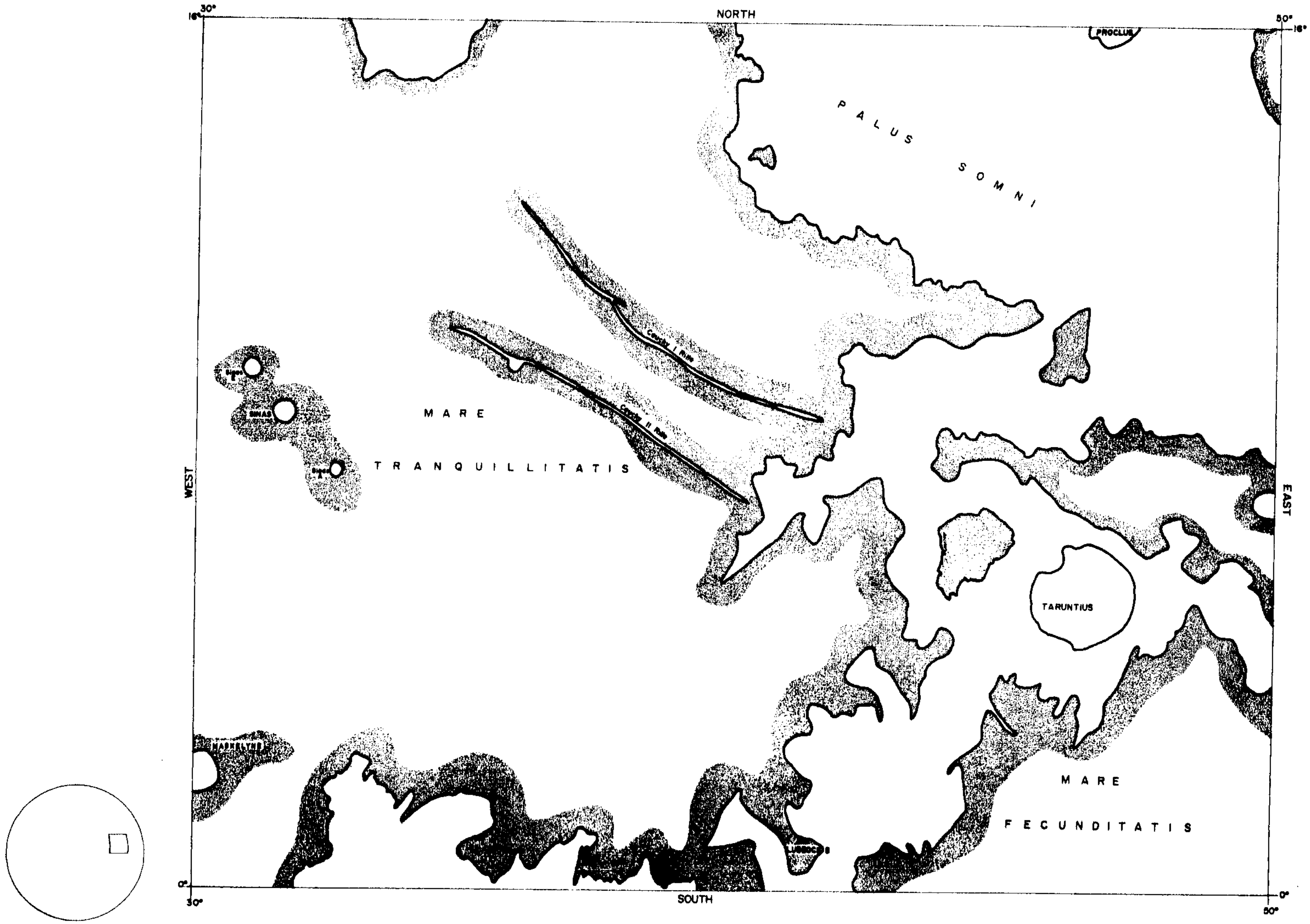


Figure 3.1. The Taruntius Quadrangle.

Pre-Imbrian System

Rocks that crop out over most of the highland area of the Taruntius Quadrangle are tentatively designated as older regional and crater material. This material is partially overlain by younger regional material and the Palus Somni material. The older regional and crater material is complex in composition and is not a simple geologic unit. It is characterized by rugged topography and craters and ridges of irregular shape. The older regional material is tentatively dated as pre-Imbrian because it is cut by straight rilles approximately parallel to the Imbrian sculpture. These rilles may be produced, however, by reactivations in Imbrian time along the sculpture trend. There is a decided paucity of circular, hummocky-rim craters, which are numerous in the central part of the Moon.

Imbrian (?) or pre-Imbrian (?) System

Regional material

The strip of upland extending from Lubbock S to Palus Somni and separating Mare Fecunditatis from Mare Tranquilitatis, contains large relatively smooth areas only slightly lighter than the maria. In places, irregular crater, ridge, and rille topography like that of the older regional material appears to be mantled by a blanket-like covering. This covering is also seen in the southern part of Palus Somni. There may be more than one such smooth unit, but there is no evidence for this at present, and all such material is tentatively designated as "regional material" of Imbrian age. Irregular craters like those in the older material have locally been cut through the blanket.

Palus Somni material

Filling large, irregular depressions in Palus Somni, but of more local extent than the regional material, is very smooth material of a distinctive albedo midway between that of the maria and highland. In several cases, groups of small craters have been observed at the contacts of this material with neighboring ridges and cones; these craters may have been the source of this material. Several levels of the material have been mapped in some of its basins, but correlation between basins has not been established.

Imbrian System

Mare material

All the units discussed above are unconformably overlain in places by mare-like material of two distinct types. The type which is believed to be the older is slightly lighter and has a more wavy surface than the other. It lies in the southeast corner of Mare Tranquilitatis, between dark, smooth, more typical mare on the west and the smooth regional blanket material on the east, and is intermediate between these two materials in albedo and surface texture. The "waviness" is gentle, appearing as though broad and subdued mare ridges cover about half the area. The origin of the waviness is not known, but many exposures of older rough terrain protrude through the mare surface in this area, and it may reflect mantled, shallowly buried terrain. There are many more small craters on the wavy, light mare material than on the darker, smoother mare; these craters have a non-random distribution and many are probably volcanic. The correlation of the mare units with the type Procellarum Group is uncertain; possibly both correlate with parts of it.

Domes

The Taruntius Quadrangle probably contains more domes than any other lunar quadrangle. They have been observed only in regions covered by the dark, smooth, younger mare material. They are gently convex upward in cross section. Most are symmetrical in plan, and the majority are nearly circular. However, some irregular dome-like features are present which may be transitional between domes of the type described and broad mare ridges. The majority have summit craters, but one has a small hill at its summit lighter than the rest of the dome. One elliptical dome has a chain of craters along its crest. Most of the domes occur in a belt roughly parallel to the Cauchy rilles (see below). No evidence has been found of their age, other than thay they appear to be superimposed on the mare material, or of their nature, whether shield volcanoes or laccoliths.

Eratosthenian System

There are a few Eratosthenian craters in the mare and highland areas of the quadrangle. Satellitic craters have been observed around only one, Maskelyne (which has a suggestion of rays and may be Copernican). Several of the craters in the mare areas are circular and have raised rims, but are located along mare ridges (Sinas, Sinas A, Sinas E, etc.); this preferred distribution suggests the possibility that they are volcanic in origin, in spite of their resemblance to impact craters. Some craters in the maria have no discernible rim and may be maars.

Copernican System

Only a few Copernican craters of any size have been seen in the area. The southern half of the very bright crater Proclus and part of its asymmetric ray system lies within the boundaries of the quadrangle. Most interesting is the 60-km diameter Taruntius. This crater has been observed under good lighting conditions only once, and at that time a field of satellitic craters was located north of it, and the rim was seen to be hummocky near the crest and to consist of radial ridges and grooves farther out. Inside the crater and concentric with its rim are both a sharp ridge and a rille which cross at one point. Three craters in the southern rim flank lie at the heads of partially sinuous rilles. The satellitic craters and the topography of the rim indicate that the main crater may be of impact origin.

Structure

The majority of the linear structural features of the area--rilles, chain craters, scarps, and lineaments of uncertain nature--lie roughly parallel to the Imbrian sculpture, although they are not as well developed as that sculpture is west of Mare Tranquilitatis. However, it is not certain that these structures are related genetically.

The Cauchy Rilles are two prominent features of this trend in Mare Tranquilitatis. The northern rille has a smoothly curved cross section. The southern rille is similar for part of its length, but elsewhere is a south-facing scarp. The block between the two rilles slopes north. The smooth bottom of the rilles suggests the possibility that the trough was formed before part of the mare material, which lies draped across the rilles. If extended, the rilles would be tangential with the rim of the crater Taruntius. Some of the domes may be localized along a deep continuation of the southern rille.

N 66-86925

STRATIGRAPHIC RELATIONS IN THE VICINITY OF THE CRATER JULIUS CAESAR

by E. C. Morris

Preliminary geological mapping of the Julius Caesar Quadrangle has revealed that the western half of the quadrangle is nearly everywhere covered with a blanket of material identified as the Apenninian Series. This unit, defined by Shoemaker and Hackman (1962), and Shoemaker, et al. (1962), consists of a great sheet of material surrounding Mare Imbrium. In some areas of the upland regions the Apenninian is characterized by a hummocky topography, and in other areas it has a smoother surface containing a high population of small, post-Apenninian craters. The Apenninian was deposited on a varied topographic surface, which is generally apparent in spite of the Apenninian blanket. Within the Julius Caesar Quadrangle, pre-Apenninian craters smaller than 10 km diameter are almost completely buried and appear as shallow, low-rimmed depressions. Larger buried craters characteristically have rims which are broken by linear ridges and valleys that are radial to Mare Imbrium.

Julius Caesar is the largest (approximately 80 km), buried, pre-Apenninian crater of this type. The approximate inner and outer rim boundaries of Julius Caesar are shown on plate 7. The western half of the crater rim is buried beneath a cover of Apenninian that has the appearance of having been "plastered" against the rim of the crater along ballistic trajectories originating within Mare Imbrium. The build-up of material along the rim may have provided a barrier to the emplacement of material within the crater at the northwest end, but allowed filling of the crater progressively to a greater extent toward the southeast. The crater has a sloping floor which rises southward to a level above the height of the old rim. The deeper part of the crater, however, lies north of the line of trajectories from Mare Imbium which suggests that the crater may have had partial filling from a source in Mare Serenitatis prior to emplacement of Apenninian material. The northern third of the crater, which lies within the "ballistic shadow" of the rim, was subsequently filled with younger Procellarum mare material. Although the boundary between the smooth Apenninian and the Procellarum within the crater is not everywhere distinct, the Apenninian characteristically has a higher albedo, a rougher surface texture, and a higher small-crater population than the Procellarum.

The eastern rim of the crater, and the area northeast to approximately 60 km, have a hummocky, rough surface typical of the hummocky facies of Apenninian.

References

Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, in Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--Symposium no.14 of the International Astronomical Union: London, Academic Press, p. 289-300.

Shoemaker, E. M., Hackman, R. J., Eggleton, R. E., and Marshall, C. H., 1962, Lunar stratigraphic nomencluature: U. S. Geol. Survey, Astrogeologic studies semiannual progress report, February 26, 1961 to August 24, 1961, p. 114-116.

N66 86926

THE GEOLOGY OF THE ARISTARCHUS QUADRANGLE OF THE MOON

by H. J. Moore

Introduction

The Aristarchus Quadrangle is the area between longitudes 16° to 32° N. and latitudes 30° to 50° W. Much of the region is occupied by parts of the Mare Imbrium and the Oceanus Procellarum. A few isolated hills and ridges with steeper slopes rise above the relatively smooth mare surface, and craters ranging from a kilometer (or less) to 40 kilometers in diameter are scattered across the quadrangle. In the west-central part of the quadrangle, abundant hills, craters, and small linear to serpentine depressions are present.

Stratigraphy

The rocks of the Aristarchus Quadrangle have been classified into 26 units based on differences in reflectivity or albedo, relief, geometrical form, and stratigraphic relationships. Relative ages of the units are inferred from superposition of one unit upon another, cross-cutting relationships of structures, albedo, and form. The criteria employed are listed in the accompanying explanation for the geologic map of the Aristarchus Quadrangle (see plate in Supplement folder), and by Shoemaker and Hackman (1962).

The materials exposed fall into three time-stratigraphic units: the Imbrian System, the Eratosthenian System, and the Copernican System. This classification is essentially the same as that used for the

Copernicus region (Shoemaker and Hackman, 1962, p. 290, fig. 2) except that the Procellarum System has been reclassified as a rock-stratigraphic unit, the Procellarum Group, and is now included within the Imbrian System. Correlations, interpretations, and age relationships for each unit are discussed below.

Imbrian System

Materials of the Imbrian System are divided into two time-stratigraphic units, the Apenninian Series and the Archimedian Series. The Fra Mauro Formation is the only rock-stratigraphic unit in the Apenninian Series present in the region. Seven units have been mapped in the Archimedian Series: 1) crater rim material of Archimedian age; 2) mare material, 3) hummocky mare material, 4) dome material, and 5) rough dome material of the Procellarum Group; 6) crater rim material, and 7) crater floor material of the Diophantus Formation.

The <u>Fra Mauro Formation</u>, the oldest unit currently recognized in the Aristarchus Quadrangle, is correlated with the Fra Mauro Formation of the type area (Eggleton, 1964) on the basis of albedo, texture, and stratigraphic position. In the Aristarchus region, the Fra Mauro Formation crops out only locally in isolated hills surrounded by mare material; to the east of the Aristarchus Quadrangle, in the Carpathian and Apennine Mountains, the Fra Mauro Formation is extensively exposed. Mare material of the Procellarum Group is superposed on the Fra Mauro Formation. This superposition is clearly illustrated north of the crater Aristarchus, where embayments in the Fra Mauro Formation are filled with mare material.

The Fra Mauro Formation in the Aristarchus Quadrangle is characterized by low to moderate reflectivity with generally moderate local contrast and gradual lateral variations. The topographic expression of the Fra Mauro Formation is generally rough throughout the quadrangle.

Crater rim material of the Archimedian Series occurs in the rim crests of craters with floors that are filled with younger mare material. In addition, the flanks of the craters are completely or partially inundated by mare material. Thus the craters are clearly older than at least some of the mare material. These craters are probably younger than the Fra Mauro Formation because there is no evidence for deposition of the Fra Mauro Formation on them.

This crater rim material is characterized by low to moderate reflectivity. Local contrasts in reflectivity are low to moderate and lateral variations are gradual. The ridge crests are hummocky. Crater rim material may be distinguished from the Fra Mauro Formation by the shape of the outcrop patterns of the crater rim materials which are circular to semi-circular.

Mare material of the Procellarum Group covers the major portion of the Aristarchus Quadrangle. Mare material may be correlated by tracing the same unit from the type area in the adjoining Kepler Quadrangle. Superposition indicates that the mare material is younger than the Fra Mauro Formation. Hummocky mare material is correlated with similar material in the Timocharis Quadrangle (Carr, 1964).

Mare material can be distinguished from the preceeding units by its smooth horizontal surfaces which abut against and inundate older units. In addition, the reflectivities of the mare materials are generally lower than those of the previous units. The reflectivity of hummocky mare material is a little lower than that of the normal mare material and the surfaces are distinctly rougher than the normal mare material.

Dome material of the Procellarum Group forms very subdued hills up to 10 kilometers across. In one case, the dome is capped by hills and was mapped as Rough Dome material. Some domes possibly are the result of extrusions prior to the formation of mare material; other domes may result from intrusions or extrusions contemporaneous with, and subsequent to, the formation of mare material. Thus, dome material may be either older, pene-contemporaneous, or younger than mare material.

Dome material has reflectivities as low as and lower than mare material. Dome material is distinguished from mare material on the basis of topographic expression. The dome materials in the Aristarchus Quadrangle occur on sub-circular to triangular domical hills up to about 10 kilometers across. The tops of the domes are gentle, but slopes near the margins of the domes steepen. The rough dome material has an albedo lower than the mare material and differs from other dome materials in that there are a number of small hills rising about 300 meters above the top of the dome. The albedo and texture of the rough dome material are clearly different from the nearby Fra Mauro Formation.

Crater rim and crater floor material of the Diophantus Formation. The crater Diophantus has all the characteristics of an Eratosthenian crater. However, the southwest part of its rim appears to be down-faulted and covered with mare material. The crater is thus older than some of the mare material. If the Procellarum Group is restricted to the older Imbrian System, then the Diophantus material cannot be classified as Eratosthenian.

The material associated with the crater Diophantus therefore has been grouped as a separate unit, the Diophantus Formation. The material associated with the crater Delisle appears to have similar but more obscure relations than those associated with Diophantus. The reflectivity is low to moderate; the local contrast in reflectivity is small to moderate; lateral variations are generally gradual. The formation is probably chiefly crushed rock with large blocks in hummocky layers.

Imbrian-Eratosthenian Systems

Six units have been recognized that may be Imbrian or Eratosthenian in age: crater rim material, crater floor material, crater material undifferentiated, rima (rille) and chain crater material, sinuous rima (rille) material, and materials in the Harbinger Mountains Formation.

<u>Crater rim material, crater floor material, and crater material undifferentiated</u> were mapped where craters without rays appeared to be only fairly well preserved but burial by mare material could not be established. The characteristics of these materials are nearly identical with those of Eratosthenian craters which are discussed below. The craters may have predated, accompanied, or post-dated mare material.

Rima (rille) and chain crater material and sinuous rima material are placed into the Imbrian-Eratosthenian Systems because cross-cutting or superposition relationships suggest that they are post-mare material. On the other hand, these rimae may have been the source for part of the mare material.

The reflectivity of the rima and chain crater and sinuous rima materials are generally low to moderate and the material occurs in narrow linear depressions associated with small craters and sinuous depressions.

The Harbinger Mountains Formation, here named from exposures near the Harbinger Mountains, includes material in and around craters associated with rilles. The broad hills are circular or elliptical areas of positive relief up to a few tens of kilometers across. The sinuous rima or rima complexes that are associated with the craters may cross-cut mare material. The reflectivity is low with gradual lateral variations and therefore cannot be separated from adjacent mare material on the basis of albedo; the formation grades imperceptibly into mare material. The Harbinger Mountains Formation is assigned to the Imbrian-Eratosthenian Systems. The formation probably consists of volcanic flows, ash falls, and ash flows.

Eratosthenian System

Materials associated with rayless craters that appear to be younger than mare material have been mapped as Eratosthenian. These materials have been subdivided into crater rim material, crater floor material, and crater material, undifferentiated.

Crater rim material reflectivities are low to moderate with small local contrasts. The rim material is hummocky near the rim crests and low hummocks and sub-radial ridges may be observed around the flanks. The reflectivity of crater floor material is low to moderate and topography is generally smooth or flat. Crater material, undifferentiated, includes craters with low to moderate reflectivities that are so small that the crater floor material cannot be mapped separately. The Eratosthenian crater materials are distinguished from those in the Eratosthenian-Imbrian Systems in that they have a fresher and better preserved appearance.

Copernican System

Materials associated with bright-rayed craters younger than the mare have been mapped as Copernican. The material includes light and dark crater rim material, crater floor material, and undifferentiated crater material. In addition to these units, the following units have been included in the Copernican System: the Cobra Head Formation, sinuous rima material, slope material, and satellitic crater material.

Crater rim and crater floor materials of the Copernican System are associated with bright ray craters. The reflectivity of both crater rim and crater floor materials is generally high to very high, although part of the materials may be relatively dark. The topography of the rim material is hummocky near the crest of the rim and low hummocks and sub-radial ridges are present on the flanks. The crater floor materials are partly flat and partly hilly. The topography of small craters appears smooth.

Crater material, undifferentiated, was mapped around very small bright craters with circular ray patterns concentric to the crater. The concentric and circular pattern of the rays was used to distinguish these materials from satellitic crater materials.

Slope material was high to very high in reflectivity and occurs on smooth slopes ranging between 20^{o} to 40^{o}.

Cobra Head Formation, here named, includes the materials forming the hill at the head of Schröter's Valley, a large sinuous rima (rille). The apex of the hill has a high albedo which is clearly related to the hill and craters thereon. The reflectivity is moderate to very high. The local contrast in reflectivity is moderate to large; lateral variations are commonly abrupt. Topography includes craters on smooth to weakly hummocky circular or elliptical area of positive relief up to 35 kilometers across. The formation, which probably includes volcanic ash falls, ash flows, and flows, is placed in the Copernican System because of the high reflectivity of the apex of the hill.

Sinuous rima (rille) material includes the material in Schröter's Valley. The material on the floor of Schröter's Valley has low to moderate reflectivity whereas the walls of the valley have a high reflectivity. The walls will be mapped as slope material in the future. This unit is assigned to the Copernican System on the basis of its fresh appearance and association with the Cobra Head Formation.

Satellitic crater material is associated with small, bright craters believed to result from the impact of fragments from larger primary impact craters. The craters are identified by their associated bright rays which extend away from the parent primary crater. Although this criterion is not wholly valid, the craters are too small to use any other criterion.

Questionable Units

The classification of the crater Krieger and its associated craters is questionable. Krieger could be a caldera with associated smaller craters because the concentration of craters is unusually high for such a small region. On the other hand, the areal relation of the craters with Mare Imbrium suggests they may be partly buried craters on a buried upland surface. In any event, Krieger should be placed in the Imbrian System since its floor is covered by mare material. The subdued form of the other larger craters associated with Krieger suggest that they are also Imbrian in age.

The classification of two craters west of Krieger (longitude 50° W., latitude 27° N.) is in doubt because they lie along a structural trend. In addition, the craters have low subdued rims and are unlike Eratosthenian craters. Because of the uniformity of their size and their alignment along a lineation, the craters may be volcanic.

The surface around the margins of Schröter's Valley is questionably placed in the Fra Mauro Formation. Although much of the surface is rough and hummocky like the Fra Mauro Formation, part is smooth. In addition, the albedo of the material is as low or lower than average mare material. Satellitic craters from Aristarchus (Copernican in age) are present on the surface. Perhaps this material, which may be like mare material, forms a thin veneer over the Fra Mauro material.

Structure

The structural features in the Aristarchus region may be grouped into six types: faults, fracture lineations, linear depressions, sinuous depressions, and mare ridges.

Faults

The crater rim material of the crater Diophantus is down-faulted on the southwest flank. Similar faults are believed to be present on the west flank of Delisle, the west side having moved down. The faults appear to be parallel with the margin of the Imbrium Basin and may be related to it. Additional faults are present in the area immediately north of the crater Aristarchus and Schröter's Valley. The large exposed block of Fra Mauro Formation north and west of Aristarchus is the result of faulting along breaks parallel to the block margins.

Lineations

The area north of Aristarchus exhibits three directions of fracture lineations. One set is parallel to a radial from the center of the Imbrium Basin, while the other two form 60° to 90° angles to the first fracture set. The strikes of the second sets are about N. 30°W. and N. 30° E.

Linear depressions

Linear rimae (rilles) appear to be parallel to lineations. One linear rima, directly north of Aristarchus, is parallel to the lineations radiating from Mare Imbrium. Another rima further to the north is parallel to one lineation ($\approx$ N. 30° W.) over the first part of its course, parallel to another lineation ($\approx$ N. 30° E.) over the second part of its course, and then the rima cuts across mare material in a northerly direction.

Sinuous depressions

Sinuous rimae (rilles) are well displayed west of the Harbinger Mountains and north of the crater Prinz. Other sinuous rimae are present to the northwest. Schröter's Valley, near the western margin of the region, is a large sinuous rima measuring about 5 kilometers across.

Interpretation of unique features

The features of the Aristarchus region worthy of special mention are: the sinuous rimae (rilles) with their associated material, the crater Diophantus, and the rough top dome.

The largest sinuous rima (rille) in the Aristarchus region is Schröter's Valley. Shröter's Valley is a sinuous depression about 200 kilometers long, up to 5 kilometers wide, and in part deeper than 300 meters. Only a portion of Schröter's Valley is present in the Aristarchus Quadrangle. Sinuous rimae (rilles) have been interpreted to be the result of erosion by nueé ardentes originating from the vicinity of craters or crater-like depressions (Cameron, 1963). The close association of craters on hills with sinuous rima extending in downslope directions fits well with Cameron's hypothesis. The size and depth of Schröter's Valley is the result of erosion by nuées ardentes, one wonders what rock type would permit such extensive and deep erosion?

The burial of the southwest flank of the crater Diophantus subsequent to faulting suggests that the formation of the mare material may have preceded and post-dated the formation of the crater. Additional evidence that the crater rim material of late Archimedian craters may be partially buried by mare material has been given by Eggleton (1964) where associated satellitic craters are inundated and infilled but the center of the crater is not filled with mare material.

The rough top dome may represent a domical structure with smaller extrusive breccia domes superposed on the larger dome, or ash cones on the dome, or possibly smaller extrusive glass domes on top of a large dome.

References

Cameron, W. S., 1963, An interpretation of Schröter's Valley and other lunar sinuous rilles: Astron. Jour., v. 68, no. 5, p. 275.

Eggleton, R. E., Notes on the geology of the Riphaeus Quadrangle of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to July 1, 1963.

References, Continued

Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, in Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--Symposium no. 14 of the International Astronomical Union: New York, Academic Press, p. 289-300.

PRELIMINARY GEOLOGY OF THE RIPHAEUS QUADRANGLE OF THE MOON AND DEFINITION OF THE FRA MAURO FORMATION

by Richard E. Eggleton

Introduction

The Riphaeus Quadrangle lies slightly southwest of the center of the visible lunar disc, extending from 0° S. to 16° S., and from 10° W. to 30° W. and covering about 300,000 square kilometers (see plate in Supplement Folder). This area includes materials of all the major stratigraphic units previously recognized by Shoemaker and Hackman (1962) in the adjoining Copernicus and Kepler regions and by Shoemaker et al. (1962) and Hackman (1963 and 1964). From oldest to youngest, these included: 1) materials underlying a regional blanket deposit around Mare Imbrium, 2) the regional blanket itself, 3) crater rim material and crater floor material of craters superposed on the blanket, but older than the top of the extensive deposits of the dark lunar maria, 4) the dark mare material, 5) materials of most younger craters lacking bright ray material, and 6) crater materials and ray materials of the bright-rayed craters.

This report is chiefly a brief sketch of work so far completed in the geologic study of the Riphaeus Quadrangle, stressing unusual features that are not conspicuous on the map or that differ from features treated in previous similar studies of lunar geology (Shoemaker, 1962; Shoemaker and Hackman, 1962; Eggleton and Marshall, 1962; Hackman, 1962, 1963, and 1964; and Marshall, 1963). In addition, because it is now expeditious to establish formations within the Apenninian Series as a result of progress in lunar geologic studies, a definition of one of these, the Fra Mauro Formation, is included below.

Pre-Imbrian materials

The oldest materials in the Riphaeus Quadrangle underlie the regional blanket deposit around Mare Imbrium and are referred to as pre-Imbrian in age. They are mainly crater materials, but are also inferred to include a considerable expanse of mare-like material. Within a belt a few hundred kilometers wide, adjacent to at least the southern to eastern sides of Mare Imbrium, these pre-Imbrian materials are seen to be widely covered by the more extensive younger units and are inferred to be mostly, or entirely, covered by these units. The regional blanket deposit around Mare Imbrium is draped as a relatively thin layer over pre-Imbrian materials and the morphology of the covered units shows through this layer in subdued forms. Younger, dark mare material underlies an approximately hydrostatic surface which almost completely hides underlying geology.

Crater rim and crater floor materials of the craters listed in table 6.1 make up a major part of the directly inferrable pre-Imbrian materials in the quadrangle. Pre-Imbrian mare-like material is inferred to underlie the regional blanket surrounding Mare Imbrium in areas such as the floors of Fra Mauro, Bonpland, Parry, and Guericke, and the

Table 6.1. Principal conspicuous pre-Imbrian craters in the Riphaeus Quadrangle.

Name	Diameter* of rim crest (km)	Center* Latitude (south)	Center* Longitude (west)
--	230	9°50'	24°20'
Fra Mauro	95	6°05'	17°00'
--	70	4°35'	27°35'
--	65	6°10'	26°20'
Bonpland	60	8°25'	17°20'
Guericke	60	11°35'	14°10'
Opelt**	50	16°20'	17°35'
Parry	45	7°50'	15°45'
--**	40	16°40'	27°15'
--	35	2°15'	24°25'
--**	30	16°25'	25°35'
--	30	4°15'	16°00'
Parry M	30	8°50'	14°30'
Guericke F	20	14°15'	15°15'

* Diameters rounded to nearest 5 km and latitude and longitude to nearest 5 minutes of arc. Diameters, latitudes and longitudes determined by fitting an average circle to the feature on the ACIC base map, except where noted.

** Diameter, latitude and longitude determined from Whitaker et al., 1963, plate 18-a.

similar, relatively flat, low uplands such as between Bonpland and Parry on the northwest and Guericke on the southeast (Eggleton and Marshall, 1962, p. 135-137, fig. 47). Pre-Imbrian materials below and between the identified pre-Imbrian units are expected to be mostly additional crater materials of mainly older craters like the dense array of craters in the southern lunar highlands.

It is problematic whether or not pre-Imbrian materials are exposed in the Riphaeus Quadrangle, but areas of relatively steep slopes are the most likely places for such exposures. Pre-Imbrian features such as the rims of Fra Mauro, Bonpland, Parry and Guericke are cut by conspicuous linear structures--probably fault and fracture zones--which result in local relief of the order of as much as 100 to 1000 meters in the present-day lunar surface. These structures produce numerous ridges, valleys, and scarps in the surface of the pre-Imbrian materials. Examples of places where such features are present are: a ridge northeast of Fra Mauro from 3°03'S., 15°22'W. to 3°53'S., 15°13'W (Kuiper, 1960; plates D5-a, Mt. Wilson 124; and D5-c, Yerkes 160); a valley cutting Riphaeus Boreus from 5°14'S., 27°08'W. to 5°43'S., 27°07'W. (Kuiper, 1960; plates E5-c, Mt. Wilson 124, and E5-a, McDonald 191); and a west facing scarp south of Fra Mauro C from 7°00'S., 21°26'W. to 7°23'S., 21°27'W. (Kuiper, 1960; plate E5-c, Mt. Wilson 124). The sharpness of these and similar forms show that the balnket deposit around Mare Imbrium is thin in these places and may be locally absent, so that pre-Imbrian materials may be exposed on such features at least locally and especially on the steeper slopes. Other steep slopes such as parts of the inner walls of Fra Mauro, Bonpland, Parry, and Guericke and parts of the east face of the Riphaeus Mountains may similarly have exposures of pre-Imbrian rocks.

Imbrian System

The Imbrian System as now defined includes at its base the blanket deposit around Mare Imbrium which is classified as the Apenninian Series. Overlying this are numerous younger individual deposits of crater materials which are nevertheless older than the youngest of the dark mare materials. These crater materials, together with the probably partly contemporanous dark mare materials, are now classified as the Archimedian Series. The mare material and associated dome material have been reclassified from their former status of Procellarian System to the Procellarum Group, at the top of the Archimedian Series of the Imbrian System.

Apenninian Series

The oldest extensively exposed materials in the Riphaeus Quadrangle of the Moon belong to the great sheet-like deposit around Mare-Imbrium, the Apenninian Series of the Imbrian System. The exposures occupy about one-third of the quadrangle, and the Apenninian is presumably present in the subsurface in the rest of the quadrangle. In this report, these oldest widely exposed materials of the quadrangle are named the Fra Mauro Formation. Another formation of the Apenninian Series, the Apennine Bench Formation, is named and defined by Hackman (1964) and discussed below under the heading of age relations of the Fra Mauro Formation.

Fra Mauro Formation. The regional blanket around Mare Imbrium consists of 1) a band, discontinuous in outcrop but probably connected through the subsurface and characterized by hummocky topographic texture, 2) its probable outward extension in a surrounding band characterized by much fairly smooth local topographic texture with generally rounded, but sometimes angular, intervening forms, and 3) fairly smoothly topographically textured, local patches filling low areas in the surface of the hummocky unit close to Mare Imbrium. Units (1) and (2) are here named the Fra Mauro Formation, from the large crater of that name in the east-central part of the Riphaeus Quadrangle. These materials fall into two facies based on the texture of the surface morphology--a hummocky facies and a smooth facies (Eggleton and Marshall, 1962, p. 132-134). The type area[1/] of the hummocky facies is here defined as those exposures shown on the map as the Fra Mauro Formation in the area extending from 0° S. to 2° S. and from 16° W. to 18° W. The hummocky facies lies in the northern one-half to one-fourth of the region (Eggleton and Marshall, 1962, p. 133, fig. 46). The smooth facies of the Fra Mauro is typically exposed in the areas extending

---

1/ In telescopically deciphered lunar stratigraphy various units can be recognized and their superposition can be detected and mapped, but vertical type sections cannot be studied. Therefore, in defining formations in telescopic lunar stratigraphy, a type area displaying the typical characteristics of the unit must be substituded for the type section of terrestrial stratigraphy.

from 6° S. to 7° S. and from 16° W. to 17° W. In the Riphaeus Quadrangle the boundary between the hummocky and smooth facies is gradational and has not yet been mapped in detail.

In its type area the hummocky facies of the Fra Mauro Formation is characterized by a range of moderate values of normal albedo (Minnaert, 1961) in an irregularly patchy areal distribution and by abundant close-spaced, low, rounded, subequidimensional hills and intervening depressions generally 2 to 4 kilometers across (Kuiper, 1960; plate D5-a, Mt. Wilson 124). The hills and depressions are believed to be mostly or entirely intrinsic to the Fra Mauro Formation, that is, they would be developed even if the Fra Mauro were deposited on a smooth surface. The hills and depressions are the principal characteristic of the hummocky facies of the Fra Mauro. In the type area there are also fairly common elongate, gently sloping, scarps (Kuiper, 1960; plate D5-b, Mt. Wilson 192). The scarps are typically 1½ or 2 kilometers wide, but up to 6 kilometers in width. The lengths are debatable due to uncertainties as to continuity, but elements 15 to 25 kilometers long are obvious. The scarps appear to be selectively oriented, concentrating crudely around the north-south direction, but this appearance may be affected by lighting effects. The scarps probably indicate more pronounced similar forms on the surface underlying the Fra Mauro at least in part, but part or all of the scarps may be intrinsic to the Fra Mauro layer. Two craters in the type area have subdued topography and are inferred to reflect the existence of Hortensius-type craters (Shoemaker, 1962, compare pp. 301-303 and pp. 345, 347) of pre-Imbrian age on the underlying surface. These are identified as follows:

Diameter	Center	
8.2 km	$1^{\circ}16'$ S.	$16^{\circ}26'$ W.
9.5 km	$0^{\circ}46'$ S.	$16^{\circ}08'$ W.

The hummocky facies of the Fra Mauro Formation locally has very low normal albedo, as in two small areas in the northeastern part of the quadrangle around 2° S., 10° W. and $0^{\circ}40'$ S., $11^{\circ}30'$ W. Much more extensive exposures of this dark material lie in patches southeast of Copernicus, south and east of Sinus Aestuum, and beyond to the east. The smooth facies in its type area has the same reflectivity characteristics as the moderately bright part of the hummocky facies and has very gently rolling topography.

Discrimination of the Fra Mauro Formation from other units in the area and placement of the contacts between them is accomplished with varying degrees of difficulty. The Fra Mauro formation rests on a complex surface including abundant craters of all sizes; numerous ridges, valleys, and scarps; and plains underlain by pre-Imbrian mare-like material (Eggleton and Marshall, 1962; Eggleton, 1963). Due to the previously discussed difficulties of identifying outcrops of pre-Imbrian materials, none have been mapped.

The present criteria for distinction between the hummocky and smooth facies of the Apenninian are entirely topographic and are described briefly in the names, and more extensively in the preceding paragraphs. Another part of the Apenninian Series, the Apennine Bench Formation, closely resembles the smooth facies of the Fra Mauro Formation. Discrimination of, and relations with, this unit will be treated below under the topic of age relations.

The Fra Mauro Formation is extensively overlapped by mare material of the Procellarum Group. Both the hummocky and smooth facies of the Fra Mauro are distinguished from the mare material by having greater densities of superposed and detectable underlying craters. The nearly ubiquitous hummocks of the hummocky facies of the Fra Mauro contrast sharply with the dominantly flat surface with numerous ridges and scarps characterizing the maria. The very gently rolling relief with a few scattered hills characteristic of much of the smooth facies of the Fra Mauro is not as distinct from mare topography, especially in small areas. However, values of normal albedo clearly set apart the mare material from all of the smooth facies of the Fra Mauro and from the part of the hummocky facies having moderate values of normal albedo. The part of the hummocky Fra Mauro which has very low values of normal albedo is darker than most mare material. Mare material with bright ray cover, especially in patches too small for determination of crater density, may resemble the smooth facies of the Fra Mauro. The pattern of the rays is the best clue to the truth. Features with shapes like domes of the Procellarum Group, but with normal albedo characteristics of the Fra Mauro, have not been recognized.

Commonly the mare material gradually thins to a feather edge over the Fra Mauro yielding sinuous contact traces on the smooth facies of the Fra Mauro as between Bonpland and Guericke F; and complex, disconnected contact traces with the hummocky Fra Mauro as in the north-central part of the quadrangle.

The deposits of craters superimposed on the Fra Mauro Formation stand out clearly due to the distinctive topography of the crater interiors and rim flanks (Shoemaker, 1962, p. 344-345). Around large craters the hummocks of the rim material are generally smaller than those of the Fra Mauro Formation, and the ridges of rim material subradial to the crater and associated secondary impact craters help to enhance the pattern of overlap. Rim materials of small craters stand out by the addition of the material of the raised rim. The rim materials of the craters superimposed on the Fra Mauro Formation grade to a feather edge so that placing of the contact trace is only approximate.

An order-of-magnitude estimate of the thickness of the Apenninian Series has been made assuming the thickness to be of the order of the original depth of underlying craters just large enough to be detected as craters of very subdued form in the surface of the covering mantle of the Apenninian. In the Lansberg Quadrangle (16° N. to 16° S., 10° W. to 30° W.) the average thickness thus estimated is 600 meters, and in the eastern half of that Quadrangle the estimated thickness shows a general southward thinning from about 900 meters at the edge of Mare Imbrium at the northern edge of the quadrangle to roughly 550 meters in the southern two-thirds (Eggleton, 1963). Similarly estimated values in the rest of the belt surrounding Mare Imbrium would probably be within a factor of three of these. The thickness values include the Apennine Bench

Formation, where present, in addition to the Fra Mauro Formation, but only the Fra Mauro is present in the Riphaeus Quadrangle. Estimates of the partition of thickness between the two formations has not been made. The extent of the Apenninian, and hence of the Fra Mauro as now recognized, has been discussed by Eggleton and Marshall (1962).

The Fra Mauro Formation is the basal unit of the Apenninian Series, and as such, of the Imbrian System also. The Apennine Bench Formation has similar reflectivity and topography to the smooth facies of the Fra Mauro, but it fills in low areas in the surface of the Fra Mauro Formation, within and outside, but near the rim of the Mare Imbrium Basin. The Apennine Bench Formation is thus seen to overlie, and to be younger than, the Fra Mauro Formation. Because the hummocky facies of the Fra Mauro grades outward into the smooth facies, the two have been interpreted as being of essentially the same age. However, due to the similarity of the surface characteristics of the Apennine Bench Formation and the smooth Fra Mauro, it is possible that they are parts of the same unit. It is also possible that the Apennine Bench Formation forms a thin continuous surficial blanket across the whole extent of the hummocky Fra Mauro connecting recognized Apennine Bench and the smooth Fra Mauro into a single unit younger than the hummocky Fra Mauro.

Archimedian Series

The Archimedian Series forms the remainder of the Imbrian System above the Apennine Series. It includes 1) numerous individual deposits of crater rim and crater floor materials and 2) extensive mare material and local dome materials of the Procellarum Group.

Archimedian Crater Materials. Several craters were formed after the Fra Mauro Formation and before the youngest mare material. These are of Archimedian age and might all be older than the mare material, or all contemporaneous with some part of it, or partly both. The floors and outer parts of the flanks of Lansberg G and Lansberg C are both covered by mare material. The outer flanks of Guericke B and the floor of Parry A are likewise covered. Lansberg was previously mapped by Shoemaker (1962, p. 306, fig. 6) as a post-mare material crater, but repeated telescopic observations, during which craters at least as small as one kilometer in diameter were resolved, have indicated that smooth mare material extends far into the rim area where hummocky material and secondary impact craters would normally be expected. The mare material thus appears to have overlapped the flanks of Lansberg without invading the interior, the floor of which has been measured as 1900 meters below the level of the surrounding mare.

Procellarum Group. The youngest extensively exposed unit in the Riphaeus Quadrangle is the Procellarum Group of the Archimedian Series of the Imbrian System. The Procellarum Group includes widespread, generally flat mare material and local dome material. The mare material exhibits numerous narrow ridges 2 to 4 kilometers wide; some flat-topped ridges 5 to 18 kilometers wide; and some isolated, rounded, monoclinal scarps typically 1 to 2 kilometers wide. These all have gentle slopes and are probably due to folding of a surficial layer consisting of part or all of the mare material. However, some of the isolated scarps may be fronts of lava flows, and some broad ridges which are lobate in plan may be lava flows. Associated with the above gentle slopes are some steeper slopes which may result from thrust faults.

Some of the ridges are grouped into long, linear complexes, such as the one extending at least 220 kilometers southeast and 75 kilometers northwest from the edges of the central part of the Riphaeus Mountains. This linear trend suggests the existence of a major high-angle planar structure in the lunar crust underlying the mare material and Fra Mauro Formation. Its total length would be at least 370 kilometers, including a segment about 75 kilometers long in the Riphaeus Mountains and adjacent low uplands.

Dome material, as mapped in this quadrangle, includes, in addition to typical domes a few tens of kilometers across, dark hills $2\frac{1}{2}$ to 5 kilometers in diameter, occuring in four places singly or in aggregates. These appear to have steeper slopes than typical domes, and may be cinder cones. The low, dark mare-like material surrounding the hill at $10^{\circ}28'$ S., $15^{\circ}17'$ W., may be associated lava flows.

Eratosthenian and Copernican Systems

Numerous craters of the Hortensius type (Shoemaker, 1962, compare pp. 345-347 with pp. 301-303), 15 kilometers in diameter or less, and younger than the Imbrian System, are present in the quadrangle. Crater rim and crater floor deposits of those lacking bright rays are placed in the Eratosthenian System and crater rim, crater floor, and ray deposits of the ones with bright rays are classed in the Copernican System.

Craters of the Hortensius type are typically very symmetrical, conical pits, mostly 15 kilometers or less in diameter, with flat floors in the larger ones and symmetrical low rims rising ever more steeply near the crest. However, in the case of Darney C in the southwestern part of the quadrangle, the rim material, ray material, and slope material are asymmetrically distributed mainly to the southeast, indicating a low-angle impact from the northwest (elevation angle of trajectory probably considerably less than 45° at impact) with resulting asymmetrical ejection of debris and formation of interior slopes steeper on the southeast than on the northwest. Although the floors of many Hortensius-type craters appear flat, Mount Wilson lunar plates 123 and 124 (Kuiper, 1960, plates E6-c and E6-f) suggest that the floors of Darney C and Darney are slightly domed. This is not surprising in view of the very common occurance of central elevations in larger craters of all sizes up to that of Clavius (235 kilometers in diameter).

There are numerous secondary impact craters in the quadrangle measuring more than 1 kilometer across. Those in the southern part are probably mainly related to the Eratosthenian crater Bullialdus, to the south. Those in the northern part of the quadrangle are mainly from the Copernican craters Lalande, to the east, and Copernicus, to the north.

Crater materials with wide possible age range

Craters of the Hortensius type formed on the Apenninian Series may be of Archimedian, Eratosthenian, or Copernican age. In the Riphaeus

Quadrangle, craters in the area west of 22° W. longitude and some of the larger craters east of this point have been classed as Copernican if they have associated bright ray materials (map symbol C) or as Eratosthenian or Archimedian if they do not (map symbol EI). The remaining, supra-Apenninian, Hortensius-type craters have not yet been checked for the presence of bright ray material and are classed as undifferentiated Copernican, Eratosthenian, or Archimedian in age (map symbol Ec). In the same way, all post-Procellarum Group, Hortensius-type craters west of 22° W. and some of the larger such craters to the east have been classed as Copernican or Eratosthenian, but the remaining post-Procellarum Group, Hortensius-type craters are classified as undifferentiated Copernican or Eratosthenian in age (map symbol CE).

Possible volcanic materials

A number of lunar materials are probably of volcanic origin. Pre-Imbrian mare-like material and mare material of the Procellarum Group are probably volcanic lava flows or ash flows. Some of the more local possible volcanic features such as domes and possible cinder cones discussed above are probably associated in origin with the mare material of the Procellarum Group. Other possible volcanic features of limited extent have probably been developed sporadically throughout lunar history. Since the latter are rarely closely bracketed in age by dating critera, they have not been dated in the map explanation. The purpose of this section is to mention these poorly dated features.

In the maria within the Riphaeus Quadrangle eight circular to irregular, apparently rimless craters with diameters of 1 to 6 kilometers were identified. These may be volcanic collapse features related in origin to the mare material. Some of the circular ones may be volcanoes of the maar type with undetected low rims, of Procellarum or later age. The nature and extent of deposits directly associated with these features is uncertain. No distinctive topographic texture was detected inside or outside of them. The material adjacent to the depressions has the same normal albedo as surrounding mare material and is included in that unit. The interiors of most are bright at full moon and are mapped as slope material of Copernican age. Those interiors with the same values of normal albedo as adjacent mare material are mapped as mare material. Other probable volcanoes of the maar type are two low-rimmed craters near 8° S., 15° W. and 14° S., 24° W., surrounded by deposits forming dark haloes with diffuse edges and two similar dark patches near 7° S., 17° W. and 11° S., 14° W. in which craters have not been seen. One sinuous rille possibly containing deposits of and formed by a nueé ardente, as suggested by Cameron (1963), lies near 3° S., 16° W. Three patches of fairly smooth and flat material, in and north of Fra Mauro, may be a post-Apenninian volcanic unit. One patch in the northeastern part of Fra Mauro is mapped as questioned mare material of the Procellarum Group. The other two patches have not yet been mapped. One occupies a fairly smooth, roughly circular plateau about 20 kilometers in diameter, largely bordered by higher ground, lying between the Fra Mauro and Fra Mauro H. This occurance resembles the well-known filling of the crater Wargentin. The third patch occupies low ground a little further north.

References

Cameron, W. S., 1963, A possible interpretation of Schroter's Valley and other lunar sinuous rilles (abstract): Papers for the 113th Meeting of the American Astronomical Society, p. 40.

Eggleton, R. E., 1963, Thickness of the Apenninian Series in the Lansberg Region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A., p. 19.

Eggleton, R. E., and Marshall, C. H., 1962a, Notes on the Apenninian Series and pre-Imbrian stratigraphy in the vicinity of Mare Imbrium and Mare Numbium: U. S. Geol. Survey, Astrogeologic Studies semi-annual progress report, Feb. 25, 1961 to Aug. 24, 1961, p. 132-137.

Eggleton, R. E. and Marshall, C. H., 1962b, Pre-Imbrian history of the lunar surface (abstract): Am. Geophys. Union Trans., v. 43, no. 4, p. 464.

Hackman, R. J., 1962, Geologic map and sections of the Kepler region of the Moon: U. S. Geol. Survey Misc. Geol. Invest. Map I-355.

Hackman, R. J., Stratigraphy and structure of the Apennine region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A., p. 2.

Hackman, R. J., 1963, Stratigraphy and structure of the Montes Apenninus Quadrangle of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A, p. 1.

Kuiper, G. P., 1960, Photographic lunar atlas: Chicago, University of Chicago Press.

References--Continued

Marshall, C. H., 1963, Geologic map and sections of the Letronne region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A, p. 11.

Minnaert, M., 1961, Photometry of the Moon, <u>in</u> Kuiper, G. P. and Middlehurst, B. M., eds., Planets and satellites: Chicago, Univ. of Chicago Press, p. 217.

Shoemaker, E. M., 1962, Interpretation of lunar craters, <u>in</u> Kopal, Zdenek, ed., Physics and Astronomy of the Moon: London, Academic Press, p. 283-359.

Shoemaker, E. M., and Hackman, R. J., 1961, Stratigraphic basis for a lunar time scale: U. S. Geol. Survey, Astrogeologic Studies semiannual progress report, Aug. 25, 1960 to Feb. 25, 1961, p. 9-33; also <u>in</u> Kopal, Zdenek, ed., The Moon--Proceedings of the International Astronomical Union Symposium 14, Leningrad, 1960: London, Academic Press, p. 289-300.

Shoemaker, E. M., Hackman, R. J., Eggleton, R. E., and Marshall, C. H., 1962, Lunar stratigraphic nomenclatures: U. S. Geol. Survey, Astrogeologic Studies semiannual progress report, Feb. 26, 1961 to to Aug. 24, 1961, p. 114-116.

Whitaker, E. A., Kuiper, G. P., Hartmann, W. K., and Spradley, L. H., 1963, Rectified lunar atlas: Tucson, Univ. of Arizona Press.

N66-86928

A SUMMARY OF THE GEOLOGY OF THE MARE HUMORUM QUADRANGLE OF THE MOON

by S. R. Titley

Introduction

The Mare Humorum Quadrangle lies in the southwest quadrant of the Moon between latitudes 16°S and 32°S, and between longitudes 30°W and 50°W. The most imposing feature of this region is Mare Humorum. Stratigraphic relationships about the mare are complex owing to the presence of regional units that are related to both Mare Humorum and possibly to Mare Orientale (McCauley, 1963). Materials of the Copernican and Eratosthenian Systems and the upper part of the Imbrian System are readily recognized in the Humorum region, but the stratigraphic relationships of group materials have not been completely worked out. Three new stratigraphic units have been mapped which may range in age from pre-Imbrian to late Imbrian. These units are: Humorum Rim material (Hr), Humorum Bench material (Hb), and the Gassendi Group.

Description of the Humorum Basin

Much of the topography about the southern, southwestern, and western periphery of the Humorum Basin resembles the topography of the northern and western border of Mare Imbrium. The central part of the basin is nearly circular, some 350 km in diameter, and is surrounded by a raised rim of irregular width that averages approximately 100 km across. The Procellarum unit obliterates the northeastern quadrant of the rim. Two units, distinguishable on the basis of morphology and albedo, comprise the present rim. These units are Humorum Bench material and Humorum Rim material, and together they constitute the Humorum Group.

Inasmuch as the stratigraphy of the Eratosthenian and Copernican Systems is similar to that in the Copernicus region (Shoemaker and Hackman, 1962), only pre-Imbrian features and features of possible Imbrian age will be elaborated upon in the following discussion.

Humorum stratigraphy

Humorum Bench material

Material of this type is extensively exposed about the northwest, west, and southwest edges of the basin where the unit adjoins the Procellarum Group. The line of demarcation is clearly visible and forms a scarp, coindicent with the Liebig I Rille, on which the craters Liebig G and Liebig F are superimposed. Similar scarp development has taken place along the bench-mare contact southwest of Gassendi, although here no rille is present. In the best exposures of typical Humorum Bench in the northwest quadrant, the surface is tilted both toward the center of the mare and toward the northwest. The Mersenius II Rille approximates the crest of this doubly-sloping surface.

The nature of the Humorum Bench surface is unique with respect to other portions of the lunar surface. Eggleton and Marshall (1961) have suggested that the exposures on the west side of the Mare Humorum (the Humorum Bench of this study) represent pre-Imbrian mare-like surfaces that have been covered with a thin veneer of Apenninian blanket. The interpretation presented here, based upon the lack of uniformity of albedo of the Bench surface, is that the unusually old, flat surface represents exposures of pre-Procellarum mare-like material. The surface of the Bench is smooth with some roughness apparently only at the limit of resolution. It has an obviously greater density of small craters, has a somewhat brighter albedo, and is broken and dissected to a considerably greater degree by linear structures than is typical Procellarum material.

Humorum Rim material

Outcrops of Humorum Rim material are scattered about approximately two-thirds of the basin circumference. These exposures have extreme to moderate relief. In the southern part of the quadrangle, the linear mountain range extending from Cape Kelvin southwestward toward Vitello is typical of this unit. The Rim material which is interpreted as a mixture of ejecta and thrust blocks, shows different degrees of deformation by cratering, ranging from negligible crater modification southwest of Lee to extensive modification in the vicinity of Doppelmayer G.

The distribution of the Rim unit strongly suggests that it represents, particularly at the outer edge of the rim, great ejecta blocks from the Humorum Basin. Near the inner edge of the rim the steep inward facing slopes and the more gentle outward slopes suggest that the topography may have resulted from faulting which occurred contemporaneously with or subsequently to formation of the basin. The scarp southwest of Cape Kelvin is typical of this type of feature.

Relationships of Rim and Bench units

Although precise relationships are lacking, the apparent greater density of craters in those areas interpreted as Rim material indicates that the Humorum Rim unit is the older of the two. This suggests that the Humorum Bench material may be an old mare unit that post-dates the development of the Humorum Basin and yet pre-dates the Imbrian Procellarum filling of the basin.

Post-Humorum stratigraphy

Gassendi material

Rocks of pre-Procellarum, post-Humorum age are exposed in the crater Gassendi. These rocks, called the Gassendi Group, have been subdivided into rim, slope, and floor material. Materials associated with craters of Archimedian-aspect have also been included in the Gassendi Group. Eggleton and Marshall (1961) suggested that the northern part of the Humorum region may be at the southern limit of exposures of Imbrian regional material. This possibility is recognized but in the present study, no Imbrian regional material was definitely recognized in the Humorum Quadrangle. For that reason, only the Procellarum Group is considered as positively Imbrian.

Procellarum Group

Although not mapped, moderate differences exist in albedo of the Procellarum filling the Humorum Basin. The filling of the center is typical dark Procellarum mare material, but about the southeast, south, and southwest edges a somewhat lighter albedo prevails which, coupled with an indication of variation of elevation, suggests at least a different composition, perhaps a different age, for units comprising the Procellarum. Typical dark Procellarum has apparently been faulted against lighter Procellarum and exhibits major scarps in parts of the west edge of Mare Humorum.

Unclassified regional material

Parts of the western border of the quadrangle are covered by units of uncertain origin which have been mapped as regional material, unclassified (rmu). The albedo is high and the topography is relatively less rugged. This material may be related to Mare Orientale (McCauley, 1963). Evidence for the stratigraphic relationships of this material has not been worked out. Hartmann and Kuiper (1962) and Hartmann (in press) have argued for a post-Humorum age for development of the system of Orientale features.

Structure

A variety of concentric and radial structures is associated with the Humorum Basin. Aside from the arcuate scarps enclosing the Procellarum on all but the northeast quadrant, the most striking structural features are the linear rilles (rimae), three of which make up the Hippalus system of rilles. The Hippalus Rilles are circumferential to the south and southeast side of the basin and extend into parts of Mare Nubium beyond the map area.

A second prominent rille system, the Mersenium Rilles, whose relationship to the basin is less clear than that of the Hippalus Rilles, is a northeast-striking system that crosses the Humorum Rim in the northwest quadrant. This rille system is associated with scarps and ridges of similar trend on the rim.

A level of the Procellarum filling of the basin suggests a pre-Procellarum subsiding or tilting of the east rim along a north-south diameter. This has resulted in burial of much of the eastern semicircumference by the Procellarum units. Two parts of this side of the rim may have been completely buried along depressions of nearly constant width suggesting development of graben-like structures. One of these Procellarum-filled depressions, some 15 km in width, lies just northeast of Cape Kelvin and persists toward the southeast out of the mapped area; the other, of similar width, lies just east of Gassendi and has a north trend.

Basinward tilting of pre-Procellarum craters on the periphery of the basin is evident on the south rim of Gassendi and the north rims of Puiseux, Doppelmayer, and Lee M. On the east side of the basin incomplete rims on the basin side of both Hippalus and Loewy suggest similar tilting, but it should be noted that there is no clear evidence that west rims existed on these craters. Tilting is less obvious than general subsidence.

A pronounced system of mare ridges lies several tens of kilometers west of exposures of the present east rim. The ridges group themselves into three crudely concentric arcs on the east half of the mare. The concentricity is obvious and the ridges may reflect the position of an original rim, now buried by Procellarum units. All of the ridge systems on the mare, except for those close to and directly south of Gassendi, have a general circumferential trend suggesting a relationship to underlying topography or structure.

History of the Humorum region

No relationships were observed that permit definition of pre-Humorum stratigraphic units. Some pre-Humorum rocks may, however, be exposed locally in areas mapped as Humorum Rim material. Thus, the chronology begins with the development of the basin.

Mare Humorum is about one-third the size of Mare Imbrium. The Humorum event developed, at reduced scale, the same fringing mountain ranges and regional ejecta blanket that accompanied the Imbrium Event. Following formation of the basin, the rim was subjected to impact with development of the craters Gassendi, Doppelmayer, Puiseux, Lee, and Lee M. All are of typical Archimedian aspect, that is, their floors are wholly or partially flooded by Procellarum mare material. Other craters developed in this interval and coeval with Gassendi are the irregular craters Mersenius and Agatharchides.

Present morphology and relationships along the Procellarum-Humorum Bench contact suggest that there may have been an early stage of flooding and that either this early flooding occurred at high levels along the edge of the Humorum basin or that faulting has taken place about the basin preserving an uplifted, older surface now exposed. At any rate, units of the Procellarum were deposited in the basin and are now in contact with the older unit. The Procellarum has partially inundated the basinward walls of some of the peripheral pre-Procellarum craters. Preceding or concomitant with deposition of the Procellarum, there may have been subsidence of the eastern half of the rim.

Mare ridges suggest the presence of an inner basin smaller than the basin outlined by the present rim. The arcuate form of the mare ridges on the east side of Mare Humorum is suggestive of slump blocks on and within the rim of the smaller basin.

The rille (rima) systems are of Procellarum or post-Procellarum age. The fact that they are circumferential on the east side of the basin, yet are developed on the Procellarum, suggests that deposition of the Procellarum may have been a multiple process of recurring nature rather than a single event. If there has been subsidence, as suggested above, and if the circumferential rilles (rimae) are related to the inner basin in some way, as seems possible, then, there may be at least some post-Procellarum adjustment of the lunar crust. A possible explanation may lie in multiple events of Procellarum age, perhaps rim flooding or partial flooding of the central basin followed by structural adjustments influencing both the deposited Procellarum and the pre-Procellarum units. While present explanations must be considered as speculative, the relationships require a complex sequence of events to explain them.

In summary, it can be stated that whereas a considerable amount of detailed work remains to be done in the region, some extensions of the lunar stratigraphic column can be made. The significant relationships are as follows:

1. There exists in the Mare Humorum region a separate stratigraphy that is generally analogous to that of the Imbrium Basin.

2. There are well-defined areas of pre-Procellarum and possibly pre-Imbrian mare-like units.

3. Deposition of the Procellarum in the Mare Humorum region was a complex sequence of events whose details may be more closely defined with further study.

References

Eggleton, R. E., and Marshall, C. H., 1961, Notes on the Apenninian series and pre-Imbrian stratigraphy in the vicinity of Mare Humorum and Mare Nubium: U. S. Geol. Survey, Astrogeologic Studies, semiannual progress report, Feb. 26, 1961 to Aug. 24, 1961, p. 132-137.

Hartmann, W. K., in press, Radial structures surrounding lunar basins, II, Orientale and other systems--Conclusions: Arizona Univ. Lunar and Planetary Lab. Comm.

Hartmann, W. K., and Kuiper, G. P., 1962, Concentric structures surrounding lunar basins: Arizona Univ. Lunar and Planetary Lab. Comm., v. 1, no. 12, p. 51-66.

McCauley, J. F., 1963, Stratigraphy of the Mare Orientale Region of the Moon: U. S. Geol. Survey, Astrogeologic Studies, annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A.

Shoemaker, E. M., and Hackman, R. J., 1962, Stratigraphic basis for a lunar time scale, _in_ Kopal, Zdenek, and Mikhailov, Z. K., eds., The Moon--Symposium no. 14 of the International Astronomical Union: London, Academic Press, p. 289-300.

N 66-86929

A PRELIMINARY REPORT ON THE GEOLOGY OF THE HEVELIUS QUADRANGLE

by J. F. McCauley

Introduction

The Hevelius Quadrangle is bounded by latitudes 0° and 16°N and longitudes 50° to 70°W, and lies along the west central margin of Oceanus Procellarum, approximately 100 kilometers from the center of the Imbrium Basin. It exhibits three topographic divisions, the first of which, in the northeast, consists of smooth, dark, hummocky terrain with an albedo similar to that of the surrounding maria but which is topographically higher and has considerably more local relief.

The second division is the relatively flat mare material of Oceanus Procellarum which occupies the central, southeastern, and northwestern parts of the quadrangle. Numerous north to north-northwesterly trending ridges are present in the central part of the map area, midway between the dark hummocky upland near the crater Marius and the brighter upland near Hevelius. Numerous bright rays are superimposed on this surface, the most conspicuous of which radiate from the crater Olbers, located to the northwest outside the quadrangle. The center of the mare exhibits a very bright, irregular patch identified as Reiner G. Also superimposed on its surface are a number of rayless craters of fresh appearance, such as Reiner and Galilaei.

The third topographic division is the highland area along the western margin of Oceanus Procellarum that contains the two largest craters, Hevelius and Cavalerius, along with numerous small craters. This surface is predominately of light albedo and has a distinctive north-northeast trending structural grain which is essentially radial to Mare Orientale. Except for the younger craters such as Cavalerius, this surface is covered with relatively fine regional material related to Mare Orientale (Kuiper and Hartmann, 1962; McCauley, 1964a).

Stratigraphy

Pre-Imbrian rocks

The oldest rocks in the area are steptoes of rim material of light albedo that occur in the southern part of Reiner R and north of the crater Hevelius D. A rough cratered area lies just north of the equator on longitude 64°W which may also be pre-Imbrian in age. It has a higher crater incidence rate than the highland to the west and may be an older surface, although it is well within the outer limits of the Orientale regional blanket. It may represent an area of nondeposition of the regional material derived from the Orientale Basin (McCauley, 1964a).

Imbrian System

The stratigraphy of the Hevelius Quadrangle is complicated because of its position between the tapering edges of two regional blankets, i.e., the Imbrian to the northeast and the Orientale to the southwest. No unambiguous evidence has been found that establishes the relationship between the two units, but that which is now available favors a younger age for the Orientale rocks. The materials surrounding the Orientale Basin are, therefore, tentatively assigned to the Archimedian Series pending additional work.

Apenninian Series

North and west of the crater Marius is a hummocky highland area of dark albedo in which a well developed set of north trending lineaments is present. Outlines of buried craters can be recognized, suggesting that the surface material obscuring this older terrain is relatively thin. Its albedo differs only slightly from that of the adjacent maria and contacts between the two can be drawn only on the basis of topography. Numerous small outliers of similar material are common as typified by the area to the south of Marius F.

The dark material in the Marius area lies at approximately the same distance from the center of the Imbrium Basin as the dark Apenninian of the Copernicus Quadrangle (Shoemaker, 1961), and is adjacent to material mapped as Apenninian in the Kepler Quadrangle (Hackman, 1961). It, therefore, has tentatively been assigned an Apenninian age. However, the coincidence in albedo between this material and the maria leads to the possibility that Apenninian rocks are actually absent here, or that they are covered by a thin layer of ash of the same composition and albedo as the maria. Several possible volcanic features, to be described later, are present, lending support to the latter alternative.

Archimedian Series

The crater Marius (40 kilometers) appears to be of Archimedian age. It lies across the contact between the mare material of the Procellarum Group to the east and the dark hummocky material tentatively assigned an Apenninian age, to the west. The crater rim on the east is clearly flooded by mare material, as is the floor of the crater. The relationships on the north and western side of the crater are less clear. This area has been carefully examined under low illumination with the 36-inch Lick refractor and no secondary or satellitic craters could be detected, although Marius is sufficiently large to permit the telescope to resolve such features. This hummocky surface to the west may then be post-Archimedian as is the mare material to the east.

<u>The Cordillera Group</u>: The Cordillera Group forms an extensive continuous blanket around Mare Orientale which is recognizable at least 800 kilometers from the center of the basin. It is first described in another paper in this report (McCauley, 1964a). The group is present in the southwestern part of the Hevelius Quadrangle, where it overlies an older, extensively cratered surface, which is probably pre-Imbrian in age.

The largest crater within the quadrangle, Hevelius, is covered by a thin sheet of Cordillera Group rocks which only partially obscure the topographic details of the rim. The Cordillera Group is, in turn, overlapped along the western margin of Oceanus Procellarum by mare material of the Procellarum Group. It, therefore, probably lies within the Archimedian Series, if the Orientale Basin is indeed younger than the Imbrium Basin.

The Cruger Group: Also first described elsewhere in this report, and apparently a part of the Archimedian Series, is the Cruger Group (McCauley, 1964a), named after the large crater about 400 kilometers to the south of Hevelius. The rim deposits of the craters in the Cruger Group overlie rocks of the Cordillera Group but are inturn older than the mare material of the Procellarum Group. The upper boundary of this unit is the same as that of the Archimedian Series as originally defined by Shoemaker, Hackman, Eggleton and Marshall (1961), but its lower boundary is apparently younger than the Apenninian.

The most significant crater of this unit in the quadrangle lies just to the northeast of Cavalerius but does not have a formal name. It consists of a semi-circular ruined crater wall, the northeastern part of which is buried by Oceanus Procellarum. Near what would be the center of the crater is an island of lighter colored rock which appears to be the remnant of a central tumescence in the crater. The rim material is predominantly dark and appears to overlap the Cordillera Group to the northwest. It is in turn overlapped to the south by the rim of Calaverius, which is of Eratosthenian age. Smaller but better preserved craters of the group are Galilaei B, Cavalerius U, Cavalerius E and Cavalerius K.

Procellarum Group: The Procellarum Group is the most extensive rock unit within the map area. It appears to be relatively thin in the southern and western part of the quadrangle, where the ramparts of several buried craters project to the surface (Reiner R, Reiner P). It thickens to the northwest, i.e., toward Galilaei, where steptoes and crater ramparts are absent.

The albedo of the mare surface varies considerably, but individual units have not yet been mapped. The albedo differences are in part the result of the extensive Kepler ray pattern which overlaps the area from the northeast and the Olbers ray pattern radiating from the northwest. However, the albedo differences which exist over broad diffuse areas, such as the dark zones north and west of Reiner G, and northeast of Cavalerius D, are probably inherent to the maria. These albedo gradations may represent differences in the rock composition or may be the result of differences in the degree of saturation by unresolvable small craters. The latter alternative suggests that major age differences exist at the surface of the maria and that its upper boundary may not be contemporaneous, as originally suggested by Shoemaker and Hackman (1961).

Eratosthenian System

Rayless, post-mare craters assigned to Eratosthenian System are relatively common in the Hevelius Quadrangle (Reiner, Galilaei, Galilaei A, Hevelius D, and Reiner A). The largest Eratosthenian crater, Cavalerius, is located on the border between the western highlands and Oceanus Procellarum. Superficial examination suggests that its eastern flank is inundated by mare material. However, numerous small secondary craters, present on the maria surface to the east, indicate a post-Procellarum Group age.

The crater Reiner also appears to be Eratosthenian, but exhibits an unusual northwest and southeast distribution of rim material. A mare dome is located just to the northwest of the crater in a relatively smooth area that would normally be covered by rim material if the rim were symmetrical, and an extensive mare ridge system is present south of the crater. Reiner lies at the southern end of a broad mare plateau on which there are several craters of possible volcanic origin. The possibility, therefore, exists that Reiner rim material may have been modified by volcanic processes which may have taken place in Eratosthenian time.

Preliminary statistical studies, to be more fully described in a later report, indicate that the density per unit of area of craters aligned on ridges and rilles is greater than those on the flat parts of the maria by at least a factor of two. This distribution suggests that a substantial number of these structurally aligned craters may be volcanic rather than the result of random impact.

Three aligned rayless craters of somewhat irregular shape, and surrounded by rims which appear to have steeper slopes than those recognized around Eratosthenian craters, are located on the broad mare plateau north of Reiner. Reiner H is the best example. Its crater is elliptical, is surrounded by lobate rim projections, and is flanked on the north side by smaller steep-sided cones. The evidence to date, both statistical and morphological, suggests that these three large craters may be of volcanic origin. Their relationship with Reiner, particularly that of Reiner L, suggests a post-Reiner age indicating that they may have formed during or after the Eratosthenian Period. The upper age limit cannot be established because similar dark halo craters also cut the rim of Copernicus, attesting to the presence of probable volcanic activity up through the Copernican Period. The difficulty of classifying craters of this type has been discussed by Carr (1963).

Copernican System

The Hevelius Quadrangle exhibits no medium to large Copernican craters, although a number of 3 to 5 kilometer craters of this type are present. Two large Copernican craters are present, however, in the western limb area beyond the limits of the Hevelius and Grimaldi Quadrangles. The more prominent of these is Olbers (about 60 km in diameter), the rays of which overlie the craters Cavalerius and Hevelius. Further to the south, the crater Byrgius is the center of a well developed ray system which overlies the upland surface in the southern part of the Grimaldi Quadrangle.

The most noteworthy feature of Copernican age in this part of the moon is the bright patch of material called Reiner G which lies on the maria between Reiner and Cavalerius. It has the same albedo as that of the brighter rays, but is apparently unrelated to any particular crater and exhibits no recognizable relief. It is unique in that no similar features are presently recognizable on the moon. The main part of the body is elliptical in shape with a dark "horseshoe"-shaped interior. Trending in a northeasterly direction away from the main body is a discontinuous "tail" approximately 120 kilometers in length. The origin of this feature is obscure but its geometry has the general form of a comet. It has been suggested (Shoemaker, personal communication) that many of the lunar craters originate from the impact of cometary material. However, the great majority of these are specifically unrecognizable because the relatively high impact velocity offsets their low mass resulting in a crater of the same form as that caused by denser, slower moving meteorites. The impacting body in this case, however, must have been either very tenuous or of relatively low velocity, or both, not to have formed a discrete crater. In addition, the trajectory must have been very oblique in order for the tail to have affected the surface.

Structural geology

The northeastern part of the quadrangle appears to be a positive area within Oceanus Procellarum, analogous to similar positive areas around Aristarchus and Copernicus. The smooth, dark material at the surface, however, is of insufficient thickness to obscure the form of subjacent older craters as is the case closer to the center of the Imbrium Basin. The area exhibits numerous north-northeast trending, rounded scarps, the steep faces of which dip westward. These scarps may be monoclines or may represent older thinly covered faults. They are responsible for what appears to be a subdued "basin and range" topography.

Oceanus Procellarum deepens progressively to the west, and in the central part of the quadrangle exhibits no ghost craters. This deep central area coincides with the zone of maximum development of mare ridges near the crater Galilaei. From the central part of this quadrangle, Oceanus Procellarum thins westward to where it finally overlaps the older cratered terrain covered by regional material of the Cordillera Group.

The upland area is characterized by northeast trending structures which are radial to Mare Orientale, and along which considerable lateral and vertical movement has taken place. Westward from the Hevelius Quadrangle, numerous craters still visible beneath the Cordillera Group show considerable departure from a circular shape because of lateral movement along these fractures. Vertical movement is evidenced by numerous linear "bays" of mare material which have invaded structural troughs along the western margin of Oceanus Procellarum. Rimless chain craters, probably of the maar type, oriented parallel to this fracture system, are common both in the Hevelius and Grimaldi Quadrangles.

Two distinct types of rilles are present within the area. The first is the linear type best seen in the floor of the crater Hevelius. These are either straight, or gently curving, and some are associated with small craters. The floor of Hevelius is broadly arched, and the numerous rilles present are interpreted to be the result of fracturing associated with this deformation. This arching must have taken place after the deposition of the Cordillera Group because the rilles appear very fresh and cut the surface of the Cordillera Group. The second type of rille is sinuous in outline and commonly exhibits a meandering pattern similar to that of a graded stream. The Marius rille, just northeast of the map area, is the best example. The origin of these structures is less clear, but many observers have suggested that they are the product of fluid erosion (Cameron, 1963).

The crater Cavalerius exhibits several concentric shelves in its rim that appear to be shallow thrust sheets analogous to those described for the Ries Basin (Shoemaker and Chao, 1961). These may be buried by thin layers of "fallout" or may actually be exposed at the surface as suggested by their crisp topographic expression. Similar structures are also seen in the southeast part of the rim of Reiner.

References

Cameron, W. S., 1963, An interpretation of Schröter's Valley and other lunar sinuous rilles: Astron. Jour., v. 68, no. 5, p. 275.

Carr, Michael H., 1963, The geology of the Timocharis Quadrangle: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, part A: Lunar and Planetary Studies.

Hackman, R. J., 1961, Geological map and sections of the Kepler region of the Moon: U. S. Geol. Survey Map I-355.

Hartman, W. K., and Kuiper, G. P., 1962, Concentric structures surrounding lunar basins: Ariz. Univ. Lunar & Planetary Lab Comm., v. 1, no. 12, p. 51-72, 30 pls.

McCauley, J. F., 1963, The stratigraphy of the Orientale region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A: Lunar and Planetary Studies.

Shoemaker, E. M., and Chaeo, E. C. T., 1961, New evidence for the impact origin of the Ries Basin, Bavaria, Germany: Jour. Geophys. Research, v. 66, no. 10, p. 3371-3378.

Shoemaker, E. M., 1962, Interpretation of lunar craters, in Kopal, Zdenek, ed., Physics and astronomy of the moon: London, Academic Press, p. 283-359.

Shoemaker, E. M., Hackman, R. J., Eggleton, R. E., and Marshall, C. H., 1961, Lunar stratigraphic nomenclatures: U. S. Geol. Survey, Astrogeologic Studies semi-annual progress report, Feb. 26, 1961 to Aug. 24, 1961, p. 114.

THE STRATIGRAPHY OF THE MARE ORIENTALE REGION OF THE MOON

N66-86930

by John F. McCauley

Introduction

Geological mapping in the Hevelius (McCauley 1964b) and Grimaldi Quadrangles during 1963, revealed the presence of a major new Imbrian stratigraphic unit in the Western Highlands adjacent to Oceanus Procellarum (fig. 9.1). As originally described for the central part of the Moon (Shoemaker, 1961; Eggleton and Marshall, 1962; Eggleton, 1963), the lower most division of the Imbrian System, the Apenninian Series, consists primarily of a regional unit surrounding Mare Imbrium. The Apenninian Series, however, has not been recognized west of the northeastern part of the Hevelius Quadrangle, approximately 1500 kilometers from the center of the Imbrium Basin. A study of the extreme western limb area was, therefore, undertaken, with particular emphasis on the region around Mare Orientale. Hartmann and Kuiper (1962) had previously described the prominent concentric scarps surrounding Mare Orientale in a paper on the structures of the major lunar basins. The photographs accompanying their report suggested, that in addition to concentric scarps, Mare Orientale was surrounded by an extensive blanket of material resting stratigraphically in an older cratered surface. Additional rectified photographs of the Mare Orientale area were obtained through the courtesy of W. K. Hartmann

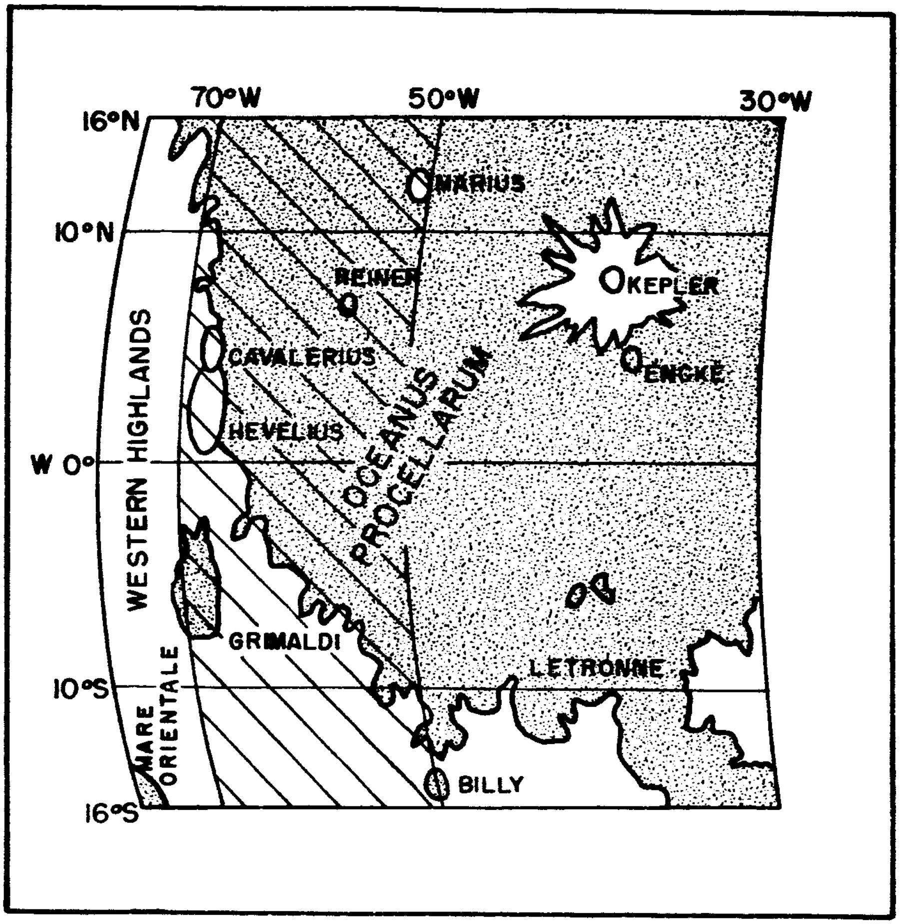


Figure 9.1. Location map showing the relations between the Hevelius and Grimaldi Quadrangles (lined area), Mare Orientale and the Western Highlands.

and G. P. Kuiper of the Lunar and Planetary Laboratory, University of Arizona. Study of the photographs along with visual telescopic work has led to the establishment of new stratigraphic units which have been employed in the map and text of the Hevelius Quadrangle (McCauley, 1963b).

General Description of Mare Orientale

Mare Orientale is a relatively flat, dark plain with a maximum diameter of about 320 kilometers. It lies on the extreme west central limb and is visible only under favorable libration. It is surrounded by three distinct concentric scarps with intervening flat benches and one indistinct outer scarp (fig. 9.2). According to Hartmann and Kuiper (1962) these rings are 480, 620, 930, and 1300 kilometers in diameter. The d'Alembert Mountains, rising almost 6500 meters above the level of the adjacent bench on the western flank of the basin and visible only during extreme libration, and the Cordillera mountains on the east (fig. 9.3) are the highest scarps.

Stratigraphy

Regional Relations

The material composing the surface of the Cordillera Mountains (Eichstadt Ring) and the regional blanket beyond is rough and hummocky both photographically and visually (fig. 9.2). Numerous subjacent older craters can be seen within the blanket such as Darwin and Rocca (fig. 9.3). The regional material obscures the rims and drapes over the floors of these craters, filling them either partially or completely.

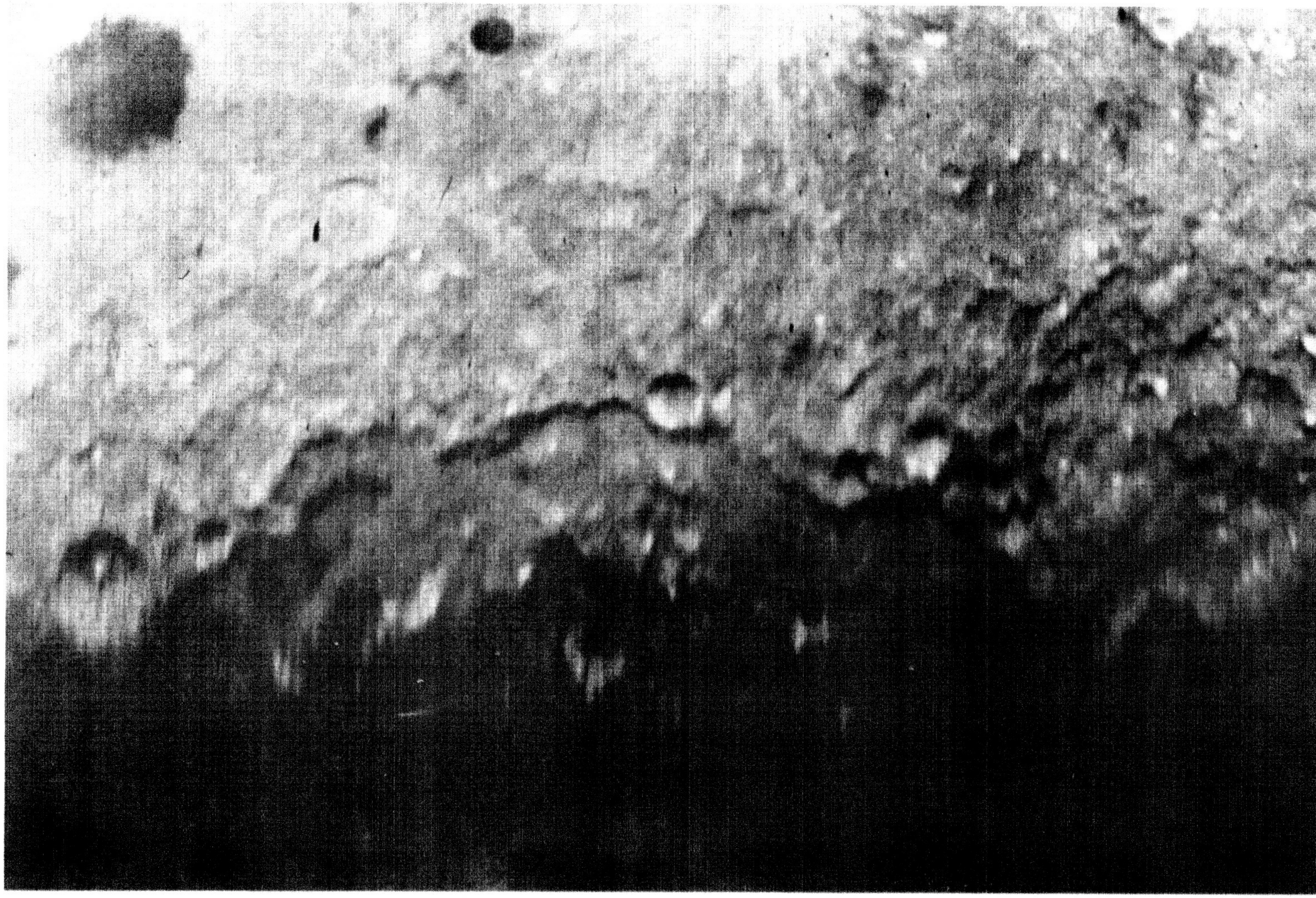


Figure 9.2. Mare Orientale scarp system and regional blanket (rectified limb photograph). Rayed crater is Gyrgius. Large circular mare area in the northeast is the crater Grimaldi.

The two largest craters within the blanket, Riccioli and Grimaldi, have had their partially filled floors flooded by later mare material. The degree of crater infilling clearly decreases to the east as the distance from the inner basin increases. In contrast to the faint "ghosts" in the Cordillera Mountains, the craters on the western margin of Oceanus Procellarum, such as Hevelius (about 1000 kilometers from the center of the basin) are covered by only a thin veneer of blanketing material.

The surface of this stratigraphic unit is cut by numerous faults radial to the central basin and which are responsible for a "horst and graben" type of topography. The shapes of many of the older buried craters have been modified by displacements along these fractures as evidenced along the southern border of the crater Grimaldi.

Two irregular but somewhat linear maria are present at the foot of the scarps surrounding the inner basin. The more easterly of these is Mare Autumni on the bench beneath the Cordillera Mountains and the other is Mare Veris lying on the shelf at the foot of the Rook Mountains (fig. 9.3). The non-mare material occupying the benches below the concentric scarps has not been observed visually. However, the available rectified photographs suggest that this material is considerably smoother and less hummocky than the material further from the center of the basin.

The surface texture, thickness relations, and the structure of the rocks surrounding Mare Orientale are analogous to those of the Apennine and Carpathian Mountain areas south of the Imbrium Basin, and it is believed that they have a similar origin and history (Shoemaker, 1961).

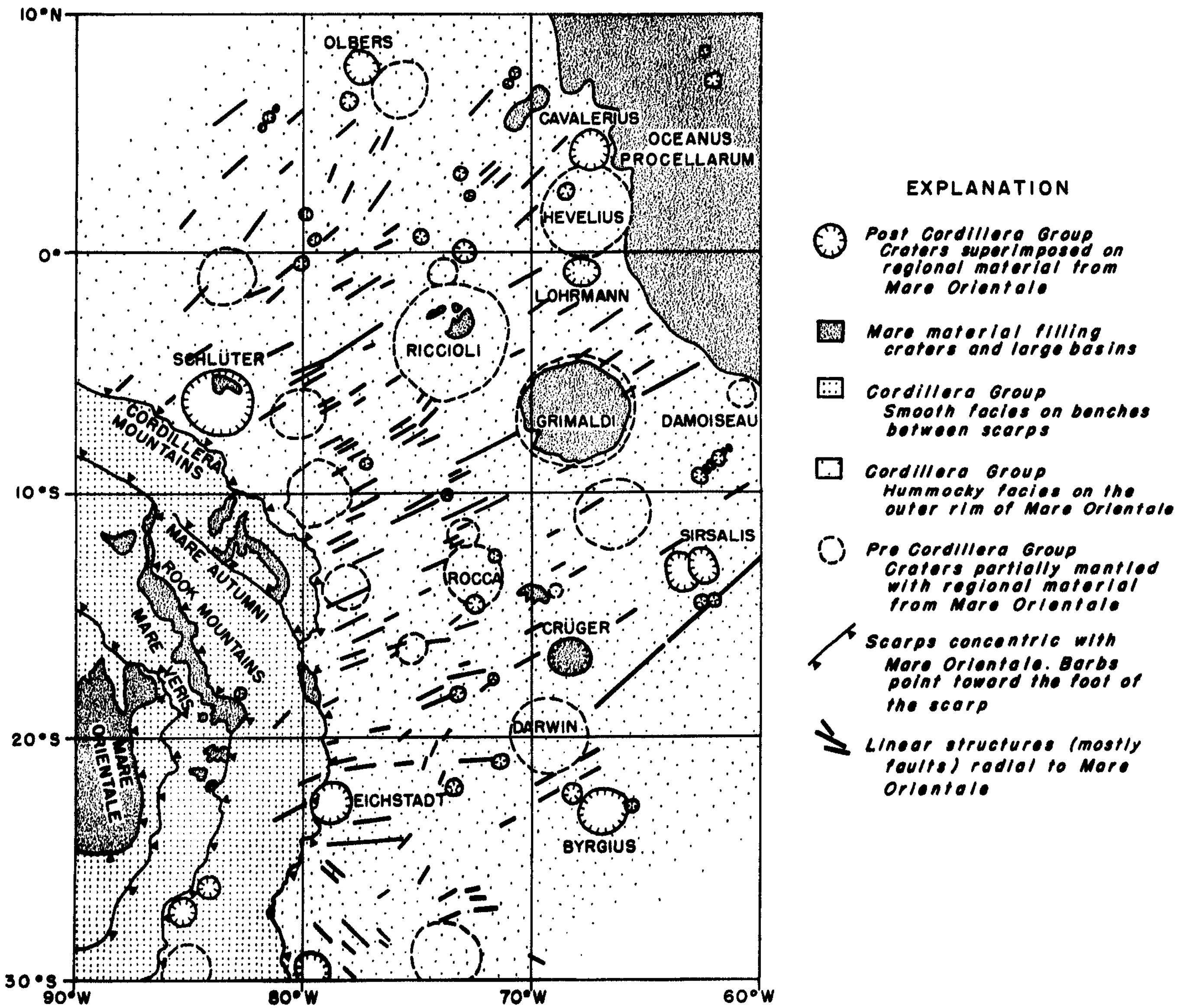


Figure 9 3. Generalized geological map of the Mare Orientale Region.

Cordillera Group

The regional material surrounding the Orientale Basin which is recognizable for distances up to 1000 kilometers from its center is designated as the Cordillera Group. Lithologically, the blanket is thought to consist of scattered large blocks along with finely crushed debris derived from the central part of Mare Orientale and deposited in a continuous layer which thins progressively away from the scarps surrounding the inner basin. It appears that this unit may be separable into a number of formations because the smooth material present on the benches beneath the scarps is quite distinct from the hummocky material on the rim. These refinements, however, will have to await more favorable libration of the western limb along with better rectified photographs. Pending formal subdivision, these two distinct rock units will be designated as the bench and rim facies. The bench facies is typically developed between the Cordillera-d'Alembert Mountains scarp and the inner basin (fig. 9.3). This facies appears relatively smooth at the present limit of photographic resolution and generally does not exhibit buried "ghost" craters. The rim facies consists of the hummocky material present outward from the Cordillera-d'Alembert scarp which ov erlies a highly cratered older terrain.

The type area for the Cordillera Group lies between the Rook Mountains along the scarp above Mare Veris, eastward for a distance of 600 kilometers to the crater Sirsalis in the Grimaldi Quadrangle. The unit is distinguished by its geometric relation to Mare Orientale, generally hummocky surface, radial structure and albedo. Preliminary photometric studies indicate that the average albedo is about the same as the lighterparts of the Apenninian, i.e., intermediate between dark maria and the very light terrae in the south central part of the visible disk.

The surface of the regional blanket appears relatively fresh and preliminary studies using rectified photographs indicate that the number of craters per square kilometer is less than that of the Apenninian by about a factor of three. Craters overlying the surface of the Cordillera Group include: Byrgius and Olbers, both of Copernican age, and the centers of extensive ray patterns; Cavalerius of Eratosthenian age; Eichstadt, a large, fresh, rayless crater on the edge of the Cordillera Mountains which is post-Cordillera Group but pre-Copernican in age; Crüger and Schlüter, which are also post-Cordillera Group but partially or completely flooded by mare material, presumably of the Imbrian Procellarum Group. These craters provide the basis for a separate rock-stratigraphic classification, discussed under the next heading. The base of the Cordillera Group overlies a complexly cratered, older surface containing numerous very large craters such as Darwin, Riccioli, Grimaldi and Hevelius. This subjacent surface, prior to burial, must have been very similar topographically to the extensively cratered pre-Imbrian terrain in the south central part of the Moon. The regional material on the western flank of the Humorum Basin, of Imbrian or pre-Imbrian age (Titely, 1964) is overlapped by the thin outer edge of Cordillera Group in the southeastern part of the Grimaldi Quadrangle, about 1000 kilometers from the center of Mare Orientale. It is not presently known whether the group actually extends into the Humorum

Quadrangle to the east. The newly discovered Southeast Basin, located directly to the south of Mare Orientale and comparable in size (Hartmann and Kuiper, 1962) is also overlapped by rocks of the Cordillera Group. The regional relationships surrounding the Southeast Basin will be the subject of future investigations.

The thickness of the Cordillera Group is known imprecisely, primarily because of the poor resolution of most available limb photographs. A first estimate, however, can be made using the technique first described by Eggleton (1963) for the Apenninian Series: A revised crater diameter to depth curve (Baldwin, 1959) was employed. Filled craters, recognized only by their faint outlines and located at increasing distances from Mare Orientale, were used to estimate the thickness variation of the Cordillera Group. The maximum observed thickness is about 4000 meters at approximately 300 kilometers from the center of the basin and this appears to decrease linearly to less than a thousand meters at a distance of about 800 kilometers; in the floor of Hevelius, about 1200 kilometers from the center, the thickness of the blanket is estimated to be less than 100 meters.

The exact stratigraphic position of the lower boundary of the Cordillera Group is uncertain because exposures of the two units are separated by a wide expanse of mare material. However, the albedo and the lower crater incidence rate strongly suggest that the unit is post-Apenninian. The upper limit for the age of the Cordillera Group is established by the mare fillings beneath the concentric scarps, such as Mare Veris and Mare Autumni, along with the filling of several large post blanket craters by mare material (Cruger, Schluter). In the lack of evidence to the contrary, these mare fillings are assigned to the Procellarum Group of the Archimedian Series. It appears that the Cordillera Group was formed in the Imbrian Period prior to the Procellarum Group. The Cordillera Group, therefore, is a local rock-stratigraphic unit within the Archimedian Series.

Crüger Group

A significant number of rayless craters later than the Cordillera Group are present around Mare Orientale. Those craters which are not flooded by later mare material are assigned a post-Cordillera Group of pre-Copernican age. However, those that have been flooded by mare material of the Procellarum Group have their upper limit fixed within the Imbrian System and can be restricted to a relatively narrow age span. They are analogous to the craters of the Archimedian Series as defined by Shoemaker, Hackman, Eggleton and Marshall, (1961). The upper boundary (Procellarum Group) is the same for both units, but these craters overlie rocks of the Cordillera Group which are younger than those of the Apenninian Series and the lower boundary is not correlative with that of the Archimedian Series. Therefore, these craters are designated as another local group which is post-Cordillera and pre-Procellarum Group in age. The type area is the mare filled crater Crüger (fig. 9.3) surrounded by a well defined rim that overlies the Cordillera Group. Another crater of the same type, also partially filled with mare material, is Schlüter in the Cordillera Mountains ring. Numerous smaller craters of the same group can be recognized over the entire surface of the Orientale blanket and several have been mapped in the Hevelius Quandrangle (McCauley, 1964b).

Geological history

The major stratigraphic features of the Mare Orientale region are interpreted to have formed by a combination of impact and volcanic processes which span the interval of time from the Imbrian to the Copernican. The Orientale Basin itself was probably formed by the impact of a very large meteorite which excavated a crater approximately 320 kilometers in diameter. The rock debris generated by impact was deposited within a very short interval of time over an area of at least 1000 kilometers in radius (Cordillera Group). This blanket covered the earlier highly cratered pre-Imbrian surface to a depth of several thousand meters near the center of the basin and to a hundred meters or less at a distance of approximately a thousand kilometers. The blanket overlapped the older regional material from the adjacent Southeast Basin and the more distant Humorum Basin. The stratigraphic relationship with the Apenninian Series of the Imbrian System are not clear since exposures of the two units are separated by a broad expanse of Oceanus Procellarum.

Contemporaneously with the deposition of the Cordillera Group, a very well defined set of concentric scarps were developed around the inner basin (Baldwin, 1963). An extensive, radial fracture system, clearly recognizable for at least 500 kilometers, also was developed in this short span of time. This structure is similar to that which surrounds the Imbrium Basin.

Subsequent to initial deposition of the Cordillera Group, three recognizable classes of craters formed on its surface. The earliest of these formed in Imbrian time and are characterized by craters of the Cruger Group. During Imbrian time, extensive lunar vulcanism caused the flooding of the major basins along with many of the larger craters. Mare Orientale, Mare Veris, and Mare Autumni were filled during this interval along with the floors of some of the craters which had formed earlier on the blanket. Another group of craters formed on the surface after lunar basin and crater filling were essentially complete at the end of the Imbrian time. The ray patterns around these craters are no longer visible because of darkening with progressive age. These craters are mostly Eratosthenian in age, but some may be older. The last class of craters to form in the area are generally lighter in color, have extensive ray systems, and are assigned a Copernican age.

References

Baldwin, R. B., 1963, The measure of the Moon: Chicago, Univ. Chicago Press, 488 p.

Hartmann, W. K., and Kuiper, G. P., 1962, Concentric structures surrounding lunar basins: Ariz. Univ. Lunar and Planetary Lab. Comm., v. 1, no. 12, p. 51-72, 30 pls.

Eggleton, R. E., and Marshall, C. H., 1962, Notes on the Apenninian Series and pre-Imbrian stratigraphy in the vicinity of Mare Imbrium and Mare Nubium: U. S. Geol. Survey, Astrogeologic Studies semiannual progress report, Feb. 26, 1961 to Aug. 24, 1961, p. 132-137.

Eggleton, R. E., 1963, Thickness of the Apenninian Series in the Lansberg region of the Moon: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1961 to Aug. 24, 1962, Part A--Lunar and planetary studies, p. 19-31.

McCauley, J. F., 1964, Preliminary report on the geology of the Hevelius Quadrangle: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A--Lunar and planetary studies.

Shoemaker, E. M., 1962, Interpretation of lunar craters, in Kopal, Zdenek, ed., Physics and astronomy of the Moon: London, Academic Press, p. 283-359.

Titley, S. R., 1964, A summary of the geology of the Mare Humorum Quadrangle of the Moon: U. S. Geol. Survey, Astrogeologic Studies, annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A--Lunar and planetary studies.

N66 86931

PRE-IMBRIAN STRATIGRAPHY OF THE COLOMBO QUADRANGLE

by Donald P. Elston

Introduction

The Colombo Quadrangle, which extends from 30°- 50°E longitude and 0° - 16°S latitude (fig. 10.1), encompasses an island-like highland area surrounded by maria. It is almost equidistant from the center of three major lunar basins--those of Mare Tranquillitatis, Nectaris, and Fecunditatis. Because these basins are now filled with mare material, evidence on their pre-mare history must be sought in the highland areas; the Colombo region, because of its stratigraphic location, is ideally suited for such study. Work carried out to date is far from complete, yet sufficient preliminary evidence has been obtained to present, in synopsis form, some of the salient stratigraphic and structural relations worked out to date. The most important units exposed in the Colombo Quadrangle are all apparently of pre-Imbrian age.

Physiography of the Colombo Quadrangle

Several diverse kinds of topography occur in the Colombo Quadrangle. In the northeast the quadrangle includes part of Mare Fecunditatis, and on the southwest, Mare Nectaris; the marginal parts of Mare Tranquillitatis extend into the northwest and north-central borders of the quadrangle. The maria have typically low relief, consisting mainly of low, elongate and circular ridges and scattered small craters. The margins of the maria are irregular and extend into embayments in a rugged highland

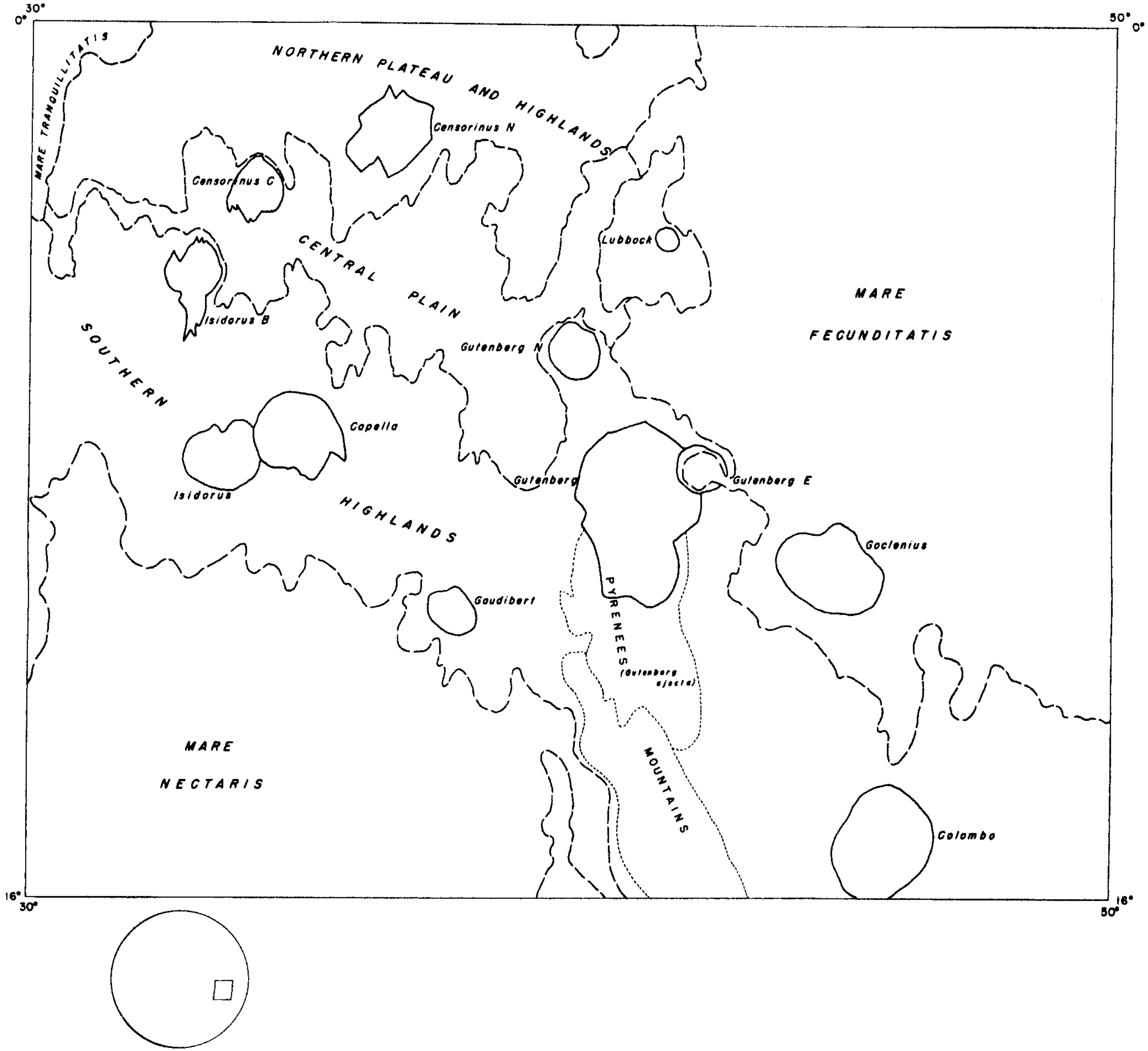


Figure 10.1. Index map of Colombo Quadrangle, showing location of principal physiographic and topographic features.

area. The highland area occupies nearly all of the northwest quarter of the Colombo Quadrangle and extends southeastward beyond the southern boundary of the quadrangle.

The highland area in the northwest part of the quadrangle is a plateau, the southern boundary of which is an irregular southward facing scarp. The upper surface of the plateau appears moderately smooth in part, and in part is gently hummocky. The surface of the plateau dips under the irregular margins of Mare Tranquillitatis to the north. South of the plateau is an area of lower elevation, here called the Central Plain, cut by prominent rilles and containing a morphologically distinctive class of craters. These craters are conspicuously polygonal in outline and their walls are cut by scarps along which lateral displacements appear to have taken place; the crater floors commonly are irregular. South of the Central Plain toward Mare Nectaris, the terrain rises, becomes more rugged and irregular, and, like the Central Plain, contains broken-walled craters of polygonal outline. This terrain, the Southern Highlands, forms part of an arc peripheral to the Mare Nectaris Basin.

General geology of the Colombo Quadrangle

Stratigraphic units correlative with those recognized and described for other parts of the Moon (Shoemaker, 1962), are found in the Colombo Quadrangle, but most of the materials exposed are older than the previously described strata.

Time-stratigraphic units discriminated regionally over the lunar surface fall into three systems which are, in order of increasing age, the Copernican System, the Eratosthenian System, and the Imbrian System.

The youngest materials recognized in the Colombo Quadrangle are crater deposits of Copernican age. These are characterized by high albedo and associated rays which are superimposed on all other materials. The next older materials are crater deposits assignable to the Eratosthenian System. Like Copernican deposits, the Eratosthenian materials are superimposed on older units both on the highland and on the mare areas, but are distinguishable by lower albedo and lack of associated rays. Crater deposits of Copernican and Eratosthenian age are not shown on the generalized geologic map that accompanies this report.

Material of low to very low albedo that occupies the maria and locally some isolated crater floors near the margins of the maria lies stratigraphically beneath the Eratosthenian. The relatively smooth mare material can be distinguished from other smooth materials present in the Colombo Quadrangle by its low albedo. Mare material in Mare Tranquillitatis, Fecunditatis, and Nectaris is tentatively assigned to the Procellarum Group of the Imbrian System, based upon its similarily in texture, structure, albedo, and crater density to material of the Procellarum Group of the western part of the Moon.

Rocks of pre-Procellarum age in the Colombo Quadrangle fall into at least three major units, all of which are believed to be pre-Imbrian in age. In the sections that follow, the topographic characteristics of these units are described briefly, the units are informally named, and their distribution, stratigraphic relations, and possible origin are discussed.

Pre-Imbrian Stratigraphy

Pyrenees Group. The oldest extensively exposed material in the Colombo region lies in the Pyrenees Mountains in the south-central part of the region, and also is present to the northwest where it occupies the region that also contains the rim deposits of the craters Capella, Isidorus, and Isidorus B (figs. 10.1 and 10.2). The exposures of the Pyrenees Group have subdued, irregular relief and occur in an arc that is peripheral to the north quadrant of Mare Nectaris. The material has intermediate to low albedo. It is here named the Pyrenees Group (informal usage) after the area of the Pyrenees Mountains in the vicinity of 41°E longitude, 14°S latitude (fig. 10.3).

North and northwest of Capella is a fairly smooth plain, the Central Plain, which under conditions of excellent seeing displays a finely hummocky and pitted appearance. In a narrow sinus, at an elevation generally lower than that of the Central Plain, the finely hummocky material slopes northeastward toward Mare Fecunditatis. This material, as well as that throughout the Central Plain, is of intermediate albedo. Part of the smooth material in the sinus and in the Central Plain is interpreted to belong stratigraphically to the Pyrenees Group, and in part to a higher stratigraphic group. Additional detailed work will be required to separate the different stratigraphic units on the geologic map.

Figure 10.2a. Sunrise Terminator.
(Lunar atlas photograph B5-b)

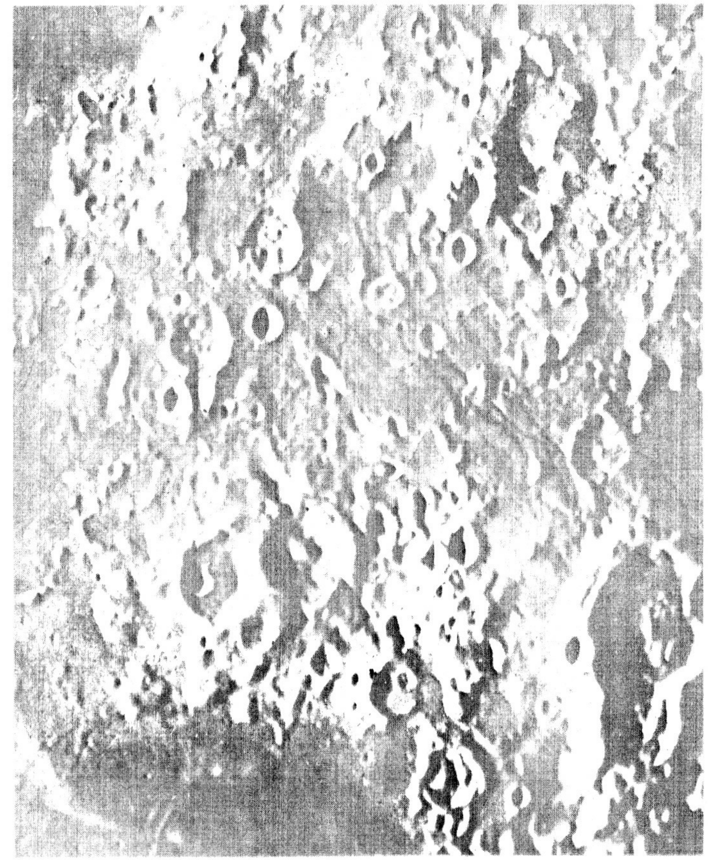


Figure 10.2b. Evening Terminator.
(Lunar atlas photograph B5-e)

Figure 10.2. Lunar atlas photographs of part of the Colombo Region of the Moon.

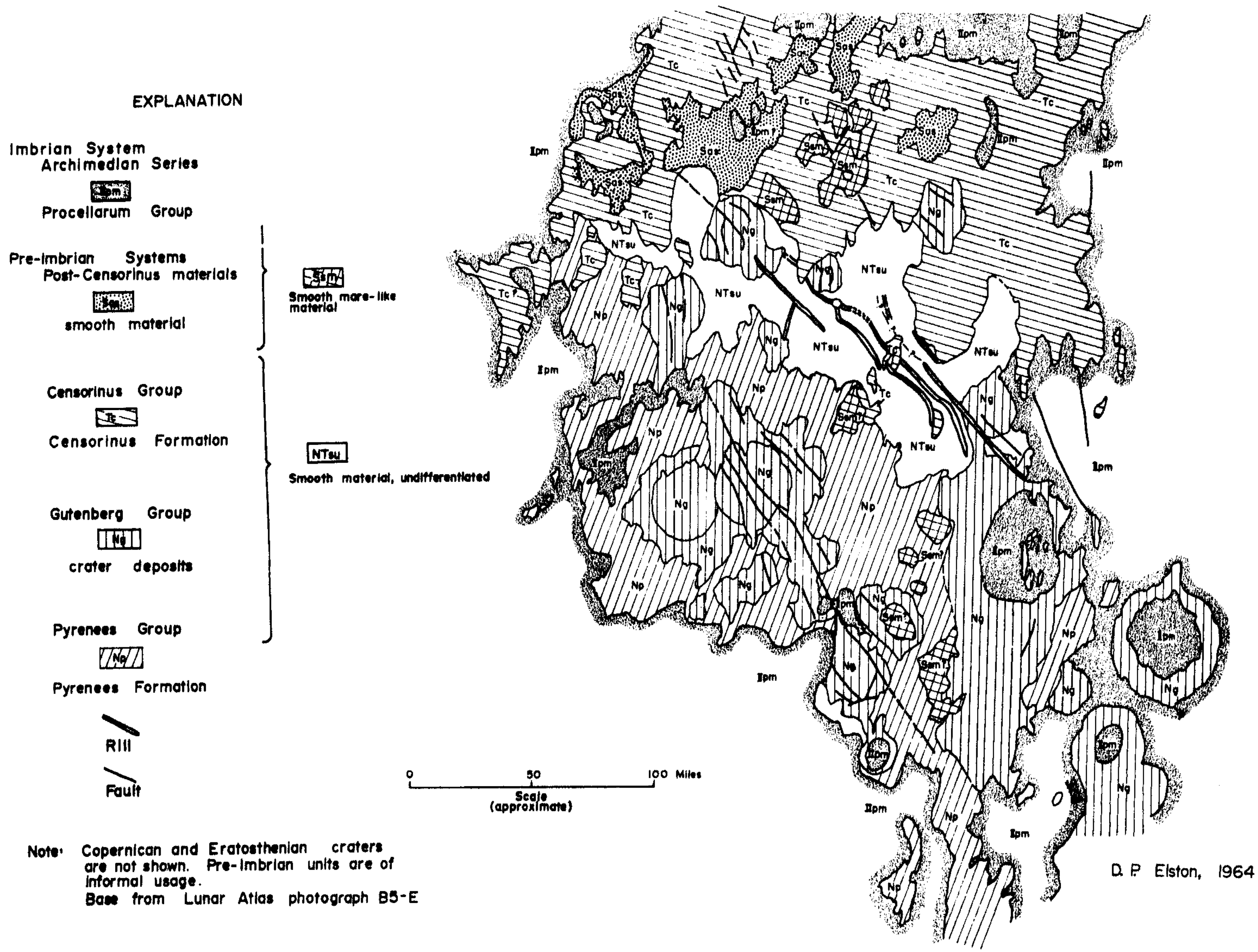


Figure 10.3. Generalized geologic map of part of the Colombo Region of the Moon.

The Pyrenees Group is interpreted to be a regional deposit consisting of both hummocky and smooth material emplaced during formation of the Nectaris Basin.

Gutenberg Group. The Gutenberg Group (informal usage) includes the deposits of a group of morphologically distinctive craters that rest stratigraphically on the Pyrenees Group, and certain rille material that transects these crater materials. The major craters associated with these deposits are irregular in plan and in some cases are sharply polygonal. The walls in many cases are cut by conspicuous scarps along which lateral offset appears to have taken place. The floors of most of these craters are irregular, consisting of rectangular and elongate hills, some of which appear to be bounded by extensions of the same scarps that cut the crater walls. At places, conspicuous rilles transect the crater rims and crater floors. The wall of the crater Gutenberg is not so markedly polygonal as other craters of the group, such as Capella and Gaudibert, but rim material of Gutenberg best displays the stratigraphic relationships of this class of craters. On the south flank of Gutenberg, its rim material lies stratigraphically on the Pyrenees Group. On the east flank, crater materials of Gutenberg E, a crater belonging to the same class, are superimposed on the rim material of Gutenberg. The albedo of Gutenberg Group crater materials is intermediate. The topographic detail of the crater floor and rim materials tends to be rounded and smooth or subdued. Similarly, the topographic detail of most of the rilles and chain craters of Gutenberg age in the Central Plain are rounded or subdued.

The period during which Gutenberg crater deposits were formed represents a significant interval of time that included a series of major cratering events. The crater floor and rim deposits were subsequently displaced, in some cases by apparent strike-slip faulting, prior to deposition of younger and locally superimposed regional material.

Regional material near Censorinus N. The youngest major pre-Imbrian stratigraphic unit in the Colombo Quadrangle is a regional deposit in the vicinity of Censorinus N which is exposed in the highlands and plateau area in the northern part of the quadrangle. This material forms a layer, the upper surface of which is gently irregular in the western and central part of the plateau, and hummocky in the eastern part. The material also crops out in south trending finger-like promontories that extend from the plateau, and along prominent south-facing scarps along parts of the plateau (fig. 10.2 and 10.3). For the most part the material has an intermediate albedo.

The Censorinus N regional material overlies Gutenberg crater deposits on the plateau; craters of Gutenberg age, such as Censorinus N, covered by this material, are distinguishable within the plateau area. At places along the southern margin of the plateau, Censorinus N material partly overlaps craters of Gutenberg age. A few rilles terminate abruptly against the margin of Censorinus N material, and, locally, outliers of Censorinus N material overlie rilles of Gutenberg age. Part of the materials with smooth topography exposed in the Central Plain may be correlative with the Censorinus N regional material, but information on this will have to await additional work.

A subdued series of north trending lineaments, some of which transect the walls of craters of Gutenberg age covered with Censorinus N regional material, can be traced through the exposures of Censorinus N material. These are part of a north trending lineament system which also is present but which is weakly developed to the south, in the region of Capella.

On the north, the Censorinus N regional material is overlapped by mare material in Mare Tranquillitatis. The regional material is tentatively interpreted to be derived from part of the area now occupied by Mare Tranquillitatis.

Smooth material of uncertain stratigraphic position. In the northern part of the Colombo Quadrangle in the vicinity of Maskelyne A, a thin layer of smooth material of intermediate albedo locally overlaps the Censorinus N regional material. This smooth material has a topography and albedo like that of smooth material in the Palus Somni, on the northeast border of Mare Tranquillitatis (Wilhelms, 1964). The equivalence of smooth material overlying the Censorinus N regional material in the Colombo region with smooth materials bordering Mare Tranquillitatis on the north is uncertain because of the lack of closely spaced exposures between the areas. They are tentatively correlated on the basis of topography, albedo, and stratigraphic position. This unit is here interpreted to be part of an extensive regional deposit associated with the Mare Serenitatis Basin.

Mare-like material. Smooth material of intermediate to moderately low albedo occupies the floor of Censorinus N and three step-like mesa areas to the north of this crater (fig. 10.3). The precise stratigraphic position of this material is not known. It may be of pre-Imbrian age. It differs from mare material of the Procellarum Group primarily in albedo, which is somewhat higher than that of the Procellarum Group.

References

Shoemaker, E. M., 1962, Interpretation of lunar craters, in Kopal, Zdenek, ed., Physics and Astronomy of the Moon: London, Academic Press, p. 283-359.

Wilhelms, D. E., 1964, Progress in mapping the Taruntius Quadrangle: U. S. Geol. Survey, Astrogeologic Studies annual progress report, Aug. 25, 1962 to Jul. 1, 1963, Part A.