# STRATIGRAPHY AND STRUCTURE OF THE 

 CLEOMEDES QUADRANGLE OF THE MOON
## by

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I hereby recommend that this dissertation prepared under my direction by Alan Bruce Binder entitled Stratigraphy and Structure of the Cleomedes Quadrangle of the Moon be accepted as fulfilling the dissertation requirement of the degree of $\qquad$


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#### Abstract

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Studies of the structure of the Crisium basin indicate that most or all of the structural elements of the basin consist of prebasin, Lunar Grid faults which were reactivated by the forces associated with: the formation of the Crisium basin. Similar studies of the Imbrian, Nectaris, and Humorum basins indicate similar, but less extensive development of the basin structural elements along earlier faults.

The stratigraphy of the Cleomedes quadrangle is discussed in Chapter IV. Evidence is given which indicates that deposition of the mare units is not limited to the Imbrian Period. Several types of small craters (diameters 10 km ) whose morphology and geological setting indicate that they may be volcanic in origin are discussed.

Infrared colorimetric observations of several units were made to determine if this type of observation could be used as a mapping aid. Though the infrared observations are presently limited in usefulness by instrumental limitations, colorimetric observations can be used to help differentiate among, and correlate seperate units which have been mapped visually.

An estimate of the lunar time scale is given based on the stratigraphic mapping and crater counts obtained from several stratigraphic maps. It is concluded that most of the units which have been mapped lack well defined time boundaries and should be classified as rock-


stratigraphic units rather than time-stratigraphic units: However, present mapping can be used to define local stratigraphic columns which may be dated by physical methods after manned exploration of the Moon begins.

## CHAPTER I

INTRODUCTION

The stratigraphic and structural mapping of the cleomedes quadrangle was undertaken as part of the lunar geologic mapping program being carried out by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration. The object of this program is to produce geological maps of the visible side of the moon at a scale of $1: 1,000,000$ in support of Project Apollo, the U.S. manned Iunar landing program. The maps are being made not only to serve as basic geological maps to aid future lunar exploration, but to determine the developmental history and the structure of the Iunar surface from ground-based observations.

The purpose of the study of the Cleomedes quadrangle and Mare Crisium was twofold: it was carried out as part of the mapping program and, further, was conducted in order to determine structural and stratigraphic relationships which would be useful for the understanding and interpretation of other areas on the moon. This last. objective is of particular significance since Mare Crisium may he one of the less complex maria.

## The Cleomedes Quadrangle

The Cleomedes quadrangle is located near the east limb of the Moon and includes the area between latitudes $16^{\circ} \mathrm{N}$ and $32^{\circ} \mathrm{N}$ and longitudes $50^{\circ} \mathrm{E}$ and $70^{\circ}$ E. Figure 1 shows the crescent Moon with the outlines of the quadrangle indicated. As can be.seen on Figure 1, the quadrangle is sufficiently close to the limb that the features are greatly foreshortened. Thus, the visibility of fine detail is generally inferior to that of areas more centrally located on the Moon, and there is a progressive loss of detail as the east side of the quadrangle is approached.

The uplands around Mare Crisium are: largely isolated from the rest of the lunar uplands on the visible side of the Moon by several maria and less-flooded areas. Except for the uplands in the vicinity of the Taurus Mountains and those north of latitude $35^{\circ} \mathrm{N}$, the uplands around Mare Crisium are dominated by the Mare Crisium basin structure. In the area around Crisium the effects of the Mare Tmbrium basin event are obscure. Thus, it is not possible to accurately corre1ate stratigraphic units in the Mare Crisium area with those units of the Mare Imbrium area, the region where the basic stratigraphic boundaries are defined. Therefore, the age assignments in the following chapters should not be considered fina1.

Figure 1. The location of the Cleomedes quadrangle on the Moon.
The outlines of the Cleomedes quadrangle are indicated on the morning crescent lunar photograph.

North is at the top. Approximate scale: 18.3 km per mm


Figure 1. The location of the Cleomedes quadrangle on the Moon.

## Lunar Stratigraphic Mapping

The original concept of lunar stratigraphic mapping was developed by Shoemaker (1962) and Shoemaker and Hackman (1962). Their basic time-rock units were defined in the following ways: (in order of in-: creasing age):
(1) Materials of the rayed craters and bright slopes are assigned to the Copernican System. These craters and slopes are so young that their rays and surface materials have not become darkened (this is based on the premise that these materials darkened with time)"
(2). Materials of craters without rays, but which are younger than the extensive mare surfaces are assigned to the Eratosthenian System. These materials are old enough to have become darkened.
(3). The materials which form the maria: are assigned to the Procellarian System。
(4) Materials which were deposited during and after the Imbrium basinforming event, but prior to the deposition of the mare units; form the Imbrian System.
(5) Materials deposited before the Imbrium basin event are members of the pre-Imbrian System.

It was thought that each of these systems belonged to a more or less well-defined period of lunar history. As mapping experience was gained, it was soon found that the deposition of the mare materials was not limited to a distinct phase of lunar history; therefore, these materials were given a Group status and were considered to be part of
the Imbrian Period. To be precise; the end of the Imbrian was defined by the deposition of the last mare unit.: At present, many mappers such as Carr (1965a), Pohn (1965), and the author (present study) have found mare units which are interpreted to be Eratosthenian or younger in age. This age assignment and others, to be discussed below, indicate that the units being mapped are really rock-stratigraphic units.

Genera1. Background

There are numerous books and articles on the Moon; most of these discuss the Crisium area in a general way or give special attention to some specific feature. Thus, the general morphology of the area, the polygonal shape of the Mare Crisium, the prominent structural rim of the basin, and/or the radial structure around the basin have been described by. such authors as Spurr (1949), Kuiper (1959), Firsoff (1961), and Fielder (1963). In fact, it is difficult, if not impossible, to find a major structural or morphological feature in the Crisium area or on the Moon in general which has not been mentioned in some earlier work. However, such references are either descriptive or made in connection with a general lunar study.

## CHAPTER II

METHODS OF INVESTIGATION

The methods which were used to investigate the Cleomedes quadrangle, the Mare Crisium area, and the other lunar basins included. telescopic observations, the study of high resolution lunar photographs, infrared colorimetric measurements, and statistical investigations of crater frequencies. The visual observations were made with the University of Arizona's Steward Observatory 21-inch telescope and the Lunar and Planetary 61-inch telescope.. The former instrument was used in the early phase of the program, and the maximum resolution obtained was on the order of 0.5 km . When the 61-inch telescope became available in the fall of 1965 , high resolution observations ( 0.1 km ) were made of many problem areas where the lower resolution studies proved inadequate,

Most of the photographs used in the program were taken from the collection of the Lunar and Planetary Laboratory. Of these photographs, those taken with the 61-inch telescope were most valuable. These photographs are of high quality and show detail as small as 0.15 km in dimension. In addition, the original photographs which were used in the production of the Photographic Lunar Atlas (Kuiper, 1960) and the Rectified Lunar Atlas (Whitaker et al.; 1963) were made available to me by Dr. G. P. Kuiper. Although these photographs haye inferior. resolution to those taken with the 61-inch telescope, the selection of lighting conditions is greater.

In addition to the LPL (Lunar and Planetary Laboratory) photographs, a small number of ACIC (Aeronautical Chart and Information Center) lunar photographs were used. These photographs were taken with the Lowell Observatory 24 -inch telescope at Flagstaff, Arizona. The infrared colorimetric observations were made with the LPL 61-inch telescope and the single channe1, infrared spectrometer described by Kuiper et al. (1962). The general observational technique and method of data reduction have been described in detail elsewhere (Binder and Cruikshank, 1966).

Statistical studies of crater frequencies were carried out to determine the relative ages of the major basins and of the mare surfaces. The details of the statistical methods used are given in Chapter VI. This information, and estimates of the cratering rates, was used to set up a tentative time scale for the pre-mare era. In all cases the crater statistics were obtained from diameter measurements made either on Rectified Lunar Atlas sheets or from USGS Iunar geological maps.

## CHAPTER III

THE STRUCTURE OF"THE CLEOMEDES QUADRANGLE

In order to avoid repetitious references to the stratigraphic and structural map of the dissertation and the ACIC map of the Cleomedes quadrangle throughout this and the following chapters, all the features discussed are displayed on one or the other of the maps (Figures 2 and 3) 。

## The Grid System

Strom (1964) has mapped the Iunar lineament system, which is called the Lunar Grid System. : He finds that the major lineament trends are $N-S, N E-S W, N W-S E$, with a subordinate trend of NNE-SSW: this system is similar to the major lineament system which many geologists :have found on the Earth and a lineament system found on Mars (Katterfel? ${ }^{\text {d }}$ 1959; Binder, 1965). Most of the faults and lineaments that occur in the Cleomedes quadrangle belong to the grid system; see Figure 40 . Also, the major structural elements of the Clemedes basin are related to the grid system.

Excluding those Iineaments which are associated with the Crisium basin, the effects of the grid system are most prominent in the Imbrian and pre-Imbrian units. It is generally accepted that tectonic activity was limited mainly to the early part of lunar history, i.e.,


Figure 4. Rose diagram of the lineaments and faults in the Cleomedes quadrangle.
the pre-Imbrian. However, many Eratosthenian and Copernican craters have polygonal shapes, which probably are the result of the formation of the craters in faulted or jointed material and of post-formation modifications along these lines of weakness: This view is supported by the square shape of the Arizona meteor crater which was formed in material cut by a set of orthogonal joints: (Shoemaker, 1959),

The Crisium Basin Structure

The general mega-structure of the Crisium Basin has been discussed in a series of papers on the concentric and radial structural elements of the mare basins (Hartmann and Kuiper, 1962; Hartmann, 1963, 1964a). These investigators found that the mare basins and some rather large craters have a series of concentric, nearly circular scarps surrounding the inner basin or crater and discuss the systems of radial fractures called the sculpture systems: Hartmann and Kuiper have described three concentric elements for the Crisium basin (see Figure 5). Upon closer inspection it is found that the outer Mare:Crisium scarp is somewhat irregular and consists of short faults which strike: nearly at right angles to one another. The orientation of these faults indicates that they are part of the Iunar grid system. This orientation of the faults implies that faults existed" before the Crisium impact occurred and that the faults were reactivated during or shortly after the impact event to form, the scarp. The outer scarp is we 11 developed to the NE and NW of Mare Crisium, in the areas where the radial sculpture is best developed. Unfortunately, if the scarp was formed to the


Figure 5. Concentric structural elements of the Crisium basin according to Hartmann and Kuiper.

North is at the top. Approximate scale: 8.3 km per mm
north of Mare Crisium, it has been obliterated by Cleomedes; Burckhardt, and other craters. Also, if there was a scarp segment extending from the $S$ to the $W$ of Mare Crisium, it is now buried under the lavas of Mare Tranquillitatis and Mare Foecunditatis. A very small segment of the scarp is located NNW of Trantius, so there is evidence that the scarp did form to the SWW of Mare Crisium and there are a fewe small segments of the scarp to the $S$ and $S E$ of Mare Crisium, The remaining segments of the circle which join these segments of the scarp show no evidence that the scarp ever formed in those places. Figure 6 shows the faults which form the concentric scarp segments: It is apparent from Figure 6 that the scarp is developed in areas whose directions from Mare Crisium are those of the major lineament trends. The intermediate concentric circle indicated in Figure 5 : connects a few high peaks which lie just beyond the rim of the Crisium Basin. The major structural feature at that approximate: distance from Crisium is a system of graben and not the isolated peaks. The locus of points through these graben is approximately elliptical, In the western part of the Undarum quadrangle (south of the Cleomedes quadrangle)'these graben are joined at nearly right angles and form a saw-toothed pattern of flooded low areas. In the eastern part of that quadrangle the graben are more nearly parallel to the shore line of Crisium. In the Cleomedes quadrangle the graben lie behind the horsts which form the rim of the basin in that area, As can be seen in Figure 6, the faults of these graben are probably largely grid-system faults which were utilized to form this nearly circular depressed zone around Crisium.


Figure 6. Structural elements of the Crisium basin.
The major linear structural elements which make up the radial and concentric structural features of the Crisium basin are indicated on the photograph. Due to a loss of detail in the photograph to the east of the mare, the elements of the radial sculpture and the scarp are not well shown in that area.

North is at the top. Approximate scale: 8.3 km per mm

Hartmann and Kuiper (1962) indicate one circular element within Mare Crisium, but there are two important structural members in the vicinity of their inner circle. The first is the rim of the basin. From $\mathrm{N} 20^{\circ} \mathrm{E}$ to $\mathrm{S} 55^{\circ} \mathrm{W}$ the rim consists of three well-defined horsts. From $N 70^{\circ} \mathrm{E}$ to $N 20^{\circ} \mathrm{E}$ the rim consists of a system of small faulted horsts: The southern rim, which extends from $555^{\circ} \mathrm{W}$ to $\mathrm{S} 40^{\circ} \mathrm{E}$, consists of high fault blocks arranged in such a way that the shore line has a saw-toothed appearance. At Mare Crisium's eastern side a $55^{\circ}$ segment of the rim arc is missing and the mare extends eastward into the graben zone:. These features are shown in Figure 6.

This, the shape of the Crisium Basin is controlled by a few large structural blocks which have resisted fracturing on the 10 km scale. The trends of the horsts or structural blocks are similar to the trends of the grid system. The places where the horsts meet, that is, where the rim changes its trend to maintain some degree of circu larity, occur in areas whose directions from the center of the mare are major grid directions. These areas are also those in which the radial sculpture is developed. The integrity of the blocks from which the horsts were formed is indicated by the extension of the $N 60^{\circ}{ }_{E}$ trending horst (south of Cleomedes) into the uplands beyond the graben zone (See Figure 6),

The basin which 1ies within these horsts and fault blocks. can be divided into two structural units, a bench and an inner basin, The bench extends inward from the rim scarps and its inner boundary is indicated by a system of mare ridges and mare scarps. This boundary is
the second structural unit associated with the inner concentric circle. The Procellarum fill is rather shallow on the bench, and many hills and Yerkes craters protrude through the surface of the mare: The level of the mare surface on the bench is several hundred meters higher than the surface of the mare in the inner basin. Since no preflooding topography is found in the inner basin (except Eimmart C which is located on the outer boundary of the inner basin), the inner basin must be quite deep and must be filled with a thick section of Procellarum material. Apparently the inner basin is the part of the lunar "crust" which was excavated by the impact. The bench consists of blocks which slumped into the basin along reactivated grid faults. The mare ridges and scarp system at the boundary of the bench and inner basin may be intrusive and/or extrusive units (Fielder, 1963) of igneous material which have worked their way up from depth along the edges of the bench; or they may be pressure ridges as suggested. by Cruikshank (1965),

Hartmann (1964a) has shown that there is a distinct radial sculpture system associated with the Crisium basin, and he notes that the sculpture faults tend to be parallel to one another rather than strictly radial from the center of Crisium. The tendency for the faults to be parallel (and orthogonal) to one another and the fact; that the areas where the sculpture is developed are in directions from Crisium which are grid system directions, indicate that these faults are also grid system faults which were reactivated by the Crisium basin event.

This detailed study of the Crisium basin structure has revealed that most or all the structural elements of the Crisium basin consist of faults or zones of weakness which were reactivated by the forces associated with the formation of the Crisium basin. It seems likely that the concentric.scarps, troughs, and horsts:may have formed as the lunar "crust" adjusted to the new1y formed excavation. Gravitational tectonics, such as centripetal faulting, may have been active in the formation of the basin structure; Figure 7 illustrates a suggested mechanism of movement sequence.

## Lunar Rilles

The only prominent rilles in the quadrangle are those in the floor of Cleomedes. This rille system is partially buried by ejecta from Cleomedes A and E, Copernican and Eratosthenian craters respectively. Since the rilles are formed in Imbrian materials; their age is Imbrian or Eratosthenian. Just to the SE of Clemedes.B there is a large, topographically high, triangular shaped mass of procellarum material, which is bounded on the west side by a mare scarp and on the SE side by the rille. The origin of this wedge of material and its relation to the rille is unknown. The only other rilles in the quadrangle are a small sinuous rille, latitude $22{ }^{\circ} 5 \mathrm{~N}$ and longitude $50 \% 7 \mathrm{~N}$; and a sma11 linear rille which is associated with a cratered cone

Crater Rim Separations.

On their eastern rim crests; the craters Tralles and Cleomedes have interesting structural features which may be the result of gravituational
$N$ S


| A | INNER BASIN | D | SOUTHERN RIM |
| :--- | :--- | :--- | :--- |
| B | BENCH | E | GRABEN ZONE |
| C | RIM HORST | F | OUTER SCARP |

Figure 7. Idealized cross section of the Crisium basin.
The upper diagram shows the basin and the associated faults as it would have appeared before movement on the fault occurred. The lower diagram shows the basin as it appears at present.
sliding. The features are shown on the map as irregular depressions which follow the rim crests for a considerable distance. For convenience only, these features are referred to as rim crest rilles. The Tralles rim crest rille is terminated at its north end by a 6 km Eratosthenian-Imbrian crater which may be of volcanic origin. Immediately to the east of the rille there is a large mass of Tralles rim material which has slumped down the wall of Clemedes: Cleomedes has two rim crest rilles, a very long one at the eastern crest and a short rille immediately to the west of the major rille. Both these rilles open into a large, irregular depression which is located at the southern end of the rilles. The floor of the irregular depression consists of undisturbed Cleomedes rim material; so this depression is almost certainly a subsidence feature.". The northern end of the major rim crest rille cuts through the rim material of Burckhardt, which is younger than Cleomedes. Thus, the major rille post-dates Cleomedes and is not the result of the crater formation process,

The lack of a definite floor in the rilles, their linear nature, and the definite slumping associated with the Tralles rim crest rille indicate that these features are scars which mark the head of large masses of brecciated rock that have moved down the wall of the crater. Figure 8 illustrates the mechanics in the formation of the rim crest rilles.


Figure 8. Idealized cross section of a rim crest rille.

Major crater wall slumping has occurred in Tralles; Burckhardt, Eimmart, and Delmotte: In the first three craters the slumping has occurred on the $S E$ segment of the crater wall, and in Delmotte the slumping has occurred on the NW part of the wall: The part of the crater walls just above the slump masses are generally Copernican slope material. The trends of these slump scars in Eimmart and Burckhardt are the same as one of the prominent lineament directions in their vicinities. The trend of the scars in Tralles and Delmotte is similar to the trend of the large horsit just south of Cleomedes. The coincidence of the slump scar trends with the major structural trends strongly suggests that the slumping has occurred along preexisting faults of the lunar grid system and/or the Crisiumsculpture system.

In Tralles, Burckhardt, and Delmotte; the slump masses traveled far onto the floors of the craters. These units are thus considered to be a hilly floor unit and it is possible that other hilly floor units: have a similar origin,

The age of the craters discussed in this section range from Imbrian-pre-Imbrian to Eratosthenian. The slumping observed in these craters is a good example of crater modification with age and this process represents one of the methods of crater obliteration,

# STRATTGRAPHY: OF THE CLEOMEDES QUADRANGLE 

## The Copernican System

As originally defined, the materials which form the Copernican System are those which are inits of the bright ray craters and other high albedo units: This definition was based on the premise that lunar rocks darkened with time; evidence supporting this concept has since been given by Hapke (1964), Binder et a1. (1965), and Cruikshank (private communications): These investigators have shown that rocks and rock powders become dark and change color when they are bombarded with low-energy protons. The protons were used to simulate the effects of the solar wind on the Iunar surface.

There are no prominent Copernican craters (Cc) in the quadn rangle; the largest; Eimmart $G$, is only 15 km in diameter, Howeyer, the ray systems of Eimmart $G$ and $A$ are sufficiently prominent to make the interpretation of other stratigraphic units in their vicinity difficult.: In addition, ray material from within and from outside the quadrangle have greatly modified the albedo characteristics of large portions of Mare Crisium, As is shown on Figure 9, the surface of Mare Crisium is covered with a complex system of linear rays, many of which originate from Proclus,


Figure 9. Ray systems on Mare Crisium.
The rectified, full Moon photograph shows the prominent ray systems which cover parts of the surface of Mare Crisium. The most prominent rays originate from the crater Proclus, the bright crater just west of the mare.

North is at the top. Approximate scale: 7.9 km per mm

Copernican slope material (Cs) is found throughout the uplands and on the walls of many craters. This material is thought to be fresh talus and freshly exposed bedrock: This interpretation is supported by the fact that slump scars on crater walls are frequently very bright. Further, Cs is found most frequently in areas of high relief.

The Eratosthenian System

Eratosthenian craters (Ec) are those craters which occur on the surfaces of the maria, but do not have rays: It has been found that many Ec's and Cc's are bright spots on the infrared images of the eclipsed Moon by Saari et al. (1966). Thus; any upland crater which is not a Cc, but has the above characteristic has been identified as Ec. The materials of these craters, and other materials, whose age can be demonstrated to be Eratosthenian; make up the Eratosthenian System,

Delmotte and Pierce are the largest definite Eratosthenian craters in the quadrangle; Cleomedes $E$ is almost certainly Eratos-: thenian in age, but the ray pattern of Cleomedes A, which is situated on the east wall of Cleomedes $E$, reduces the certainty of the class ification. Under excellent observing conditions, these three craters exhibit very well-defined, rough rim units: with large mounds, whose dimensions are on the order of a few hundreds of meters. Figures 10 and 12 show some of these rim units fairly well.


Figure 10. The western half of Mare Crisium.
The rough texture of the rim unit of the Eratosthenian crater Picard (Pi) is shown in this photograph. The crater Peirce (Pe) has a similar rim unit, also an Ec, but the fine details in the rim are too small to be we11 photographed. The pre-Imbrium hills (b) of the structural bench which inclosed the inner basin of Crisium are well shown in this photograph. The mare scarp (s) marks the inner boundary of the bench. The crater Yerkes, the type crater for the Yerkes Group, is the large flooded crater on the bench to the west of Picard.

North is at the top. Approximate scale: 2.3 km per mm

It is noted that three of the five largest Eratosthenian craters on Crisium are located on exposures of dark mare material. Owing to the limits of telescopic resolution, it has been impossible to determine if the rim material of these three craters is superimposed on the mare. Therefore, it is possible that the dark mare materìal was deposited after the craters were formed. Thus, the dark mare material may be Eratosthenian in age; such is also indicated by other observations which are discussed in the section on the Imbrian System below: If the dark material, which is almost certainly lava or ash; post - : dates the craters, it is possible that eruption of the lava or ash occurred through deep fissures formed by the cratering impact. If lunar craters are the result of volcanic activity (Fielder; 1965 and others); then the ash or lava would probably be contemporaneous with: or slightly younger than the crater.

The major part of Mare Angius has been mapped as Eratosthenian mare material (End) because of its low albedo and stratigraphic reIation to other units: Carr (1965a) has discussed similar dark:mare units and has concluded that they are Eratosthentan or eyen early Copernican in age. By analogy, other dark mare units may be of postm: Imbrian age. A further indication of the Eratosthentan age of the surface of Mare Angius is that all the upland crater fims that are on the edge of the mare are overlapped by the dark material. The most prominent craters of this type are Eimmart DA and B (both are identified as Ec) and Eimmart $D$ and $K$ (both mapped as EratosthenianImbrian EI craters): If the surface of Angius was of Imbrian age;
all the craters on Mare Angius' edge would be Imbrian and preImbrian in age. This circumstance would require that there would have been no cratering in the immediate: vicinity of Mare Angius from the end of the Imbrian to the beginning of the Copernican, or later. Because this is statistically unlikely, it is fairly certain that the age of this dark mare material is at least Eratosthenian. It is possible that this material is even early Copernican in age, because there are very few rays on the surface of Angius except at its northern end. However, the presence of these few rays, all from Eimmart A, indicate that the present classification is probably correct.

The NW limit of the dark mare material has been tentatively placed to the NW of the crater Eimmart because the dark mare material of Mare Angius and the mare material north of Eimmart overlap the rim unit of Eimmart. This crater has a fresh appearance, a large amount of Cs on its walls, its rim unit has a higher albedo than the surrounding upland materials, and it is a bright spot on the infrared image of the eclipsed Moon. Therefore, Eimmart is most probably an Ec. However; the ray systems of Eimmart $A$ and $G$ may have contributed to the brightness of the walls of Eimmart, and its rim unit does not have the rough topography of most Eratosthenian craters. This, the age is somewhat questionable. Assuming that the Eratosthenian age. of Eimmart is correct, the mare material north of Eimmart would also be of Eratosthenian age even though it has a higher albedo than the dark mare material. The difference in the albedo between these mare
surfaces is probably due to the extensive ray systems (the rays of Eimmart $A$ and $G$ ) which cover the mare north of Eimmart. There is no evidence to indicate how far the dark mare material extends NW of Eimmart, so a tentative limit for the dark mare material has been placed a few tens of km NW of Eimmart.

## Eratosthenian-Imbrian Materials

Upland craters which are relatively fresh looking, i; e, not greatly distorted by faulting and slumping of the walls; and have small to large amounts of Cs on their walls, are classified as Eratos-thenian-Imbrian craters, This is a very broad classification, but there are no really satisfactory criteria for identifying Imbrian and Eratosthenian craters in the uplands. Similarly, smooth material, which occurs on steep slopes, but which has an albedo inferior to that of Cs, is designated as Eratosthenian-Imbrian slope material (EIS): This material is similar to Cs, but it is sufficiently stable to have become darkened. EIs is prominent on the steep scarps of the horsts which form the rim of the Crisium basin.

## The Imbrian System

The only Imbrian materials which can be identified in the Cleomedes quadrangle are materials of the Procellarum Group, Tpm1, Ipm2; Ipm3; and Ipm3?, The major characteristic wich is used to distinguish these units is relative albedo. Ipml has the highest albedo and each successive unit is somewhat darker A major factor
in the variations of albedo of the mare units appears to be the number of faint rays which have been superimposed on their surfaces. Because an older surface would have more ray material deposited on it, it is considered. that Ipm1 is the oldest and the Ipm3 the youngest of the Procellarum materials: The very low albedo of Emd is consistent with this hypothesis,

Most of the surface of Mare Crisium is covered with Ipm2: However, the north-central part of the mare is we11-covered with rays and approaches the albedo of Ipm1: The IpmI is limited to areas which are peripheral to Ipm2 and in low areas outside of the basin. The third and fourth Procellarum units, Ipm3 and Ipm3?, seem to be genetically related andmay even be the same material, Ipm3? is a dark unit found in upland areas and seems to consist of dark mare material (Ipm3), which is insufficiently thick to cover small hills and ridges of the pre-deposition topography.

There are three fields of Ipm3? in the quadrangle, one east of Tisserand $K$, asecond $S E$ of Eimmart, and the third around Clemedes G.: Each of these exposures of Ipm3? is located adjacent to, or near Ipm3: Telescopic observations indicate that the dark material of the Ipm3? has flowed down from the uplands onto the mare surface and formed the Ipm3 exposures,

The easternmost part of Mare Crisium consists mainly of Tpm 3 : There are only two craters on the boarder between the uplands and the Ipm3; both of these craters are less than 5 km . in diameter and are. classified as EIc. :The rims of these two craters are overlapped. by".
the Ipm3, This allows an argument, though weak, (due to the lack of a sufficient number of similarly situated craters) for the age of the Ipm3 to be Eratosthenian. However, this argument is backed up by the proximity of the Ipm3 to the Emd, the low albedo of the Ipm3, and the lack of rays on its surface: It is concluded that the Ipm3 and its genetically related Ipm3? may be Eratosthenian in age; by analogy, all the Ipm3 of Crisium may be Eratosthenian.

The Imbrian-pre-Imbrian Materials and the Yerkes Group

There is a second class of materials in the uplands whose stratigraphic position can not be uniquely determined, namely the Imbrian-pre-Imbrian materials. The craters of this class are divided into two groups. The first, designated IpIc, are general upland craters which are somewhat destroyed or deformed, but not so much so that they would be classified as pre-Imbrium craters; see below. The second type consists of cratexs belonging to the distinct Yerkes Group, which is analogous to the Archimedian Group of craters in the Imbrium area: Yerkes materials (Masursky, 1965) are those which" were deposited after the Crisium basin formed, but before the final Procellarum units:were deposited. Because the Crisium Basin formed before the Imbrium basin (Chapter VII), the different Kerkes materials may be either pre-Imbrian ( pI ) or Imbrian (I) in age, Archimedian type craters are usually positively identifiable only in the maria; however, in the Cleomedes quadrangle there are anmar of large craters which can be readily classified as members of the rerkes Group,

Cleomedes is a Yerkes crater (IpIy) and its extensive rim unit covers a large part of the NW quadrant of the quadrangle, This rim unit may be one of the best preserved ejecta: blankets of IpI age on the Moon. The unit is characterized by smoothly rounded humocks of 1 to 3 km diameter. Figures 11 and 12 show this texture very well. Since the ejecta of younger craters is blocky and rough, the appearance of the Cleomedes ejecta suggests that its rolling topography is the result of lunar erosional processes and some mantling by other, thinner ejecta blankets.

Two other prominent Yerkes craters, Tralles and Burckhaidt; are located on the rim of Cleomedes, and the rim units of these two craters grade into: Cleomedes! rim unit.: The TpIy classification of these craters is based on the observations that they are stratio graphically higher than Clemedes, but they: are overlapped by IpI plains-farming units:

Several Yerkes craters are found on Mare Crisium near its edge. These craters were formed on a structural bench which surrounds the deep inner basin. The Procellarum fill is sufficiently shallow on this bench that these craters are not covered. The crater Yerkes; the type crater for the Yerkes Group, is located on this Bench in the southern half of Mare Crisium.

Many upland craters which have been classified as Imbrian-preImbrian craters may be Yerkes craters, but there is no definite proof that they are post-Crisium craters. Howeyer, for statistical purposes, all IpIc's are considered to be members of the Yerkes: Group.


Figure 11. The Northwestern quadrant of the Cleomedes quadrangle: A.
Large blocks of the rim material of Cleomedes $E$ ( $E$ ) are visible to the south and southeast of the crater. In this area the rim unit of Cleomedes E partially buries the northwestern end of the rille ( $r$ ) in the floor of Cleomedes. Though the lighting is somewhat unfavorable, mantling of a scarp (west of s) by ejecta from Cleomedes can be seen. Ejecta from Cleomedes is well shown in the bottoms of Debes (d) and Debes A (A).

North is at the top. Approximate scale: 1.9 km per mm


Figure 12. The Northwestern quadrant of the Cleomedes quadrangle: B.
A view of the region around Cleomedes (c) is shown in this photograph which was taken about 3 hours earlier than the one shown in Figure 11. Because of the slightly greater angle of illumination, the characteristic topography of the Cleomedes ejecta, south of Cleomedes, is better shown than in Figure 11. Similarly, the mantling of the scarps south of Cleomedes is well shown. The three scarps are to the east of each letter s. Rim material of Delmotte (D) is visible to the southwest of the crater.

North is at the top. Approximate scale: 1.9 km per mm

The remaining IpI units are the upland plains-forming units (IpIp). This material has smooth to spomewhat hilly surfaces of small lateral extent. The relative albedo of the $\operatorname{Ip} I_{p}$ is slightly higher than that of the Ipml , and in many places; where $\operatorname{IpIp}$ and Ipm1 are in contact; their mutual boundary is not very distinct.: IpIp is limited to low areas and troughs in the uplands. A unit of the $\operatorname{Ip} I p$ whose surface is somewhat hilly is designated as Ip Tpt, thin plainsforming unit, and the hills are thought to be remnants of pre-existing topography.

Because the plains-forming units are relatively smooth and usually fill in low areas, these units are interpreted as volcanic units, perhaps ignimbrite; ash or basalt deposits. : Thus, the IpIp is similar to the Procellarum units and may represent old mare fill units. However, some $E$ and $C$ craters have light, smooth floors (Copernicus itself) and it seems possible that this material is related to the IpIp. It seems likely that plains-forming units have been deposited throughout Iunar history, and the IpI age estimate: is too restricted.

## The pre-Imbrian System

Units classified as pre-Imbrian ( p I) are those which show extensive faulting by the lunar grid system and the basin sculpture systems. . The craters assigned this age are generally deformed and their walls are frequently partially destroyed by faulting, later impacts. Undifferentiated units (pIu) which are found on the uplands;
also show evidence of large scale faulting by the grid and sculpture systems. The pIu units probably consist of old crater materials, ejecta from basin formation events, and volcanic units; which are indistinguishable from one another because of their great age and degree of destruction.

The most important pI units in the quadrangle are the two associated with the Crisium basin. The first is the Crisium bench unit ( pIkb ) which consists of hills that project through the Procellarum units in Mare Crisium (Figure 10), These hills are high blocks of the materials which form the structural bench under the outer part of the mare. It is possible that some of these hills are partially covered with or consist of fall-back.

The second unit is the Crisium rim unit ( pIkr ), Materials of this unit form the high structural rim of the Crisium basin and are found at the surface mainly on the NE side of the mare. The horsts which form this rim are cut by many faults; and the topography resembles that of a tilted fault block area. The blocks are on the order of 10 km in dimensions and the local relief is quite great, though the sides of the iblocks are rather smooth. The smoothness may be due to mantling by Crisium ejecta, but there is no evidence for this interpretation. A more likely explanation for the smooth slopes is that the $p I$ rocks are covered with a thick veneer of talus on the lower slopes and the upper part of the slopes consist of fresh bed rock. Thus, the surface would consist of EI slope material with
some patches of Cs on the steepest places. Figure 13 illustrates this concept. Volcanic units and some crater debris may contribute to the filling of the valleys.

## Special Volcanic. Features

Morphological characteristics have been used to tentatively identify small volcanic features in the quadrangle. Craters which are aligned in chains, such as the crater chain north of Cleomedes $G$, are in this category. This chain extends from Cleomedes G northward to the normal fault scarp which forms the southern wall of cleomedes: A series of ehain craters on the floor of Cleomedes; just south of Cleomedes $B$, probably is an extension of the main crater chain. The line which these craters define is sub-radial to the center of the Crisium basin and nearly perpendicular to the trend of the horst on which some of the craters are situated. Four of the eight craters of the main chain are located on three faults which form a series of steps leading down to the floor of Cleomedes. At the northernmost fault the chain begins to swing to the west in order to follow the fault. Finally, the part of the chain on the floor of cleomedes is just west of and nearly parallel to a relatively prominent mare scarp. The geometrical arrangement of these craters and their placement with respect to major faults and structural trends strongly indicates that these craters are volcanic in origin. Since the craters are broad, but show only a low rim, they are probably diatremes,


Figure 13. Idealized cross section of the Crisium rim (pIkr).

Another type of feature that is possibly of volcanic origin occurs in an area that is NW of Mare Crisium and is well-cut by the Crisium sculpture. These features are called crater cones by the USGS (private communication) and consist of relatively steep-sided cones, each with a small summit crater. Just west of Crisium there are two little hills with craterlets on them. The westernmost hill is identified as a cratered cone since the craterlet is situated on the summit. Also, there is a relatively large mass of material extending from the NW side of the cone onto the surface of the mare. So, the feature resembles a large volcano with a lava flow. The craterlet on the eastern hill occurs on the flank of the hill. Although this hill may be a cratered cone, its morphology is not sufficiently convincing to give it that classification。

A second cratered cone with: a "lava flow" is found at latitude 23.4 N and longitude 50.5 E . This cratered cone is located at the end of a small graben. Two other cratered cones are located at about latitude $26^{\circ} \mathrm{N}$ and between longitudes $50^{\circ} \mathrm{E}$ and $51^{\circ} \mathrm{E}$, these cones do not have associated "lava flows." These features are all located on or near faults and in an area which has been highly faulted. Thus, their structural setting and morphology suggest that they are volcanoes. There is a small crater located at the junction of a secondary rille with the main rille in the floor of Cleomedes: This situation is similar to those found in the floor of Alphonsus (see Figure 14). In the Alphonsus examples the craters have dark rims and are considered.


Figure 14. Ranger 9 photograph of two of the dark halo craters in Alphonsus.

The dark halo craters are the somewhat elliptical, smooth craters located on the rilles. At the contrast level of the Ranger photograph, the halos around the craters are not well shown.

North is at the top. Approximate scale: 150 meters per mm
to be diatremes, which are genetically related to the formation of the rilles. By analogy, it is possible that the Cleomedes rille crater is also a diatreme.

Owing to the peculiar morphology of a group of craters with diameters of 10 km or less, it is suspected that the members of this group are volcanic in nature and that they may be sources of Procellarum materials and/or upland plains forming materials. Craters in this category are Eimmart B, Eimmart TB, Cleomedes DA, Cleomedes DB, a crater at latitude $25^{\circ} \mathrm{N}$ and longitude $68^{\circ} \mathrm{E}$, and possibly a small crater on the NE part of the rim crest of Tralles. Figure 15 shows the morphology of these craters. With the exception of the Tralles craterlet and possibly Eimmart B, the troughs which extend from breached sides of the craters in this group lead directly to mare or IpIp. In the case of Eimmart B, the trough leads to a valley which is filled with Ipm3?, but there is an obstruction between the end of the trough and the beginning of the valley. It is not known whether or not the trough and the valley were once connected, allowing volcanic material to pass into the valley, or if they have always been separated. It is also possible that the crater was a source of Emd for Mare Angius. However, owing to the location of the crater and the western shore of the mare, it is impossible to observe if the mare materîal has flowed down the escarpment into the mare.

Figure 15. Diagram of a type of possible volcanic craters.

## CHAPTER V

## INFRARED STUDIES OF THE CLEOMEDES QUADRANGLE

To date, the methods used for stratigraphic mapping have been limited mainly to visual observation and inspection of lunar photographs. It is desirable to determine whether or not the various stratigraphic units as mapped have uniform physical properties other than texture and visual labedo. For this purpose, infrared colorimetric measurements were made of several units in the Cleomedes quadrangle and of Ipm units in the Serenitatis quadrangle for comparison. The equipment, general observational technique, and basic data reduction method have been described elsewhere (Binder and Cruikshank, 1966). Briefly, the observations were made by scanning the lunar infrared spectrum from $1 \mu$ to $2.5 \mu$ at an effective resolution of $\lambda / \Delta \lambda=50$. Because of the strong terrestrial water vapor bands in this part of the spectrum, the reflectivity profile is divided into four segments. The centers of these segments occur at $1.05 \mu, 1.30 \mu, 1.55 \mu$, and $2.1 \mu$, and the intensity at these four points for the areas observed are plotted to give a color curve. Because the spectrometer used to make the observations is not designed to make accurate absolute intensity measurements, but rather accurate relative intensity measurements, the data were reduced first to the relative color of the points observed. The weighted mean of these curves was then adjusted to fit the very accurately calibrated geometrical albedo measurements of the full lunar disk made from the

Gemini 7 spacecraft (Condron et al., 1966). The results obtained indicate only the color differences in the observed points, not the albedo differences; i.e. the curves are normalized so that the sum of the intensities at the four points is a constant.

The lunar observations were made with a circular entrance diaphragm. Because of foreshortening effects; the regions observed in the Crisium area were elliptical in shape with a 5 km minor axis and a 10 to 15 km major axis. The areas observed in the Mare Serenitatis area were nearly circular, the major axis being less than 6 km long and the minor axis remaining 5 km . In order to get a series of reliable colorimetric scans, it was found that the area which was being studied had to have a rather uniform visual albedo over an area whose linear dimensions were about three times those given above, This restriction is due to normal guiding errors, and severely limits the number of areas and, therefore, the number of units that can be studied by this method. It follows that fewer upland areas can be studied than mare areas.

The results of the colorimetric observations are listed in Table 1. . The areas observed are plotted on Figure 16 using their number designations from Table. 1. The size of the circle around each number corresponds to the area observed.

To facilitate comparison of the data, the average colors of the various units are given in Table 2. As can be noted, the mare type units in Mare Crisium consist of two colorimetric types. The IpIp and the Ipm1, both: of which are found only external to the mare proper, are of one type. Perhaps the Ipm1 is a facies of the IpIp

TABLE 1. RELATIVE ALBEDO OF VARIOUS POINTS IN THE CLEOMEDES QUADRANGLE AND THE SERENITATIS QUADRANGLE

| POINT | UNIT | AREA | RELATIVE ALBEDO AT |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | $1.05 \mu$ | $1.30 \mu$ | $1.55 \mu$ | 2.104 |
| 1 | Ipm2 | Mare Crisium | . 196 | . 232 | . 296 | . 307 |
| 2 | Ipm 3 | " | . 198 | . 229 | . 296 | . 313 |
| 3 | Ipm3 | " | . 194 | . 229 | . 299 | . 316 |
| 4 | Emd | Mare Anguis | . 195 | . 229 | . 298 | . 316 |
| 5 | Emd | " | . 197 | . 231 | . 294 | . 307 |
| 6 | Ipm2 | Mare Crisium | . 194 | . 227 | . 299 | . 322 |
| 7 | Ipm3 | " | . 194 | . 228 | . 298 | . 319 |
| 8 | Ipm1 | Uplands N of Crisium | . 203 | . 230 | . 288 | . 310 |
| 9 | Ipm1 | " | . 202 | . 232 | . 288 | . 304 |
| 10 | IpIp | " | . 203 | . 230 | . 288 | . 307 |
| 11* | Ipm4 | Mare Serenitatis | . 196 | . 229 | . 296 | . 319 |
| 12* | Ipm3 | " | . 196 | . 230 | . 294 | . 319 |
| 13* | Ipm4 | " | . 198 | . 229 | . 290 | . 325 |
| 14* | Emd | " | . 192 | . 223 | . 294 | . 370 |
| 15* | Ipm1 | " | . 197 | . 231 | . 292 | . 313 |
| 16* | Ipm2 | " | . 192 | . 227 | . 302 | . 328 |
| 17 | IpIyr | Uplands N of Crisium | . 201 | . 229 | . 278 | . 316 |
| 18 | IpIyr | " | . 204 | . 231 | . 275 | . 307 |
| 19 | IpIyr | " | . 203 | . 230 | . 277 | . 310 |
| 20 | Cc | " | . 211 | . 234 | . 272 | . 304 |
| 21 | Cc | " | . 206 | . 232 | . 290 | . 280 |

TABLE 1--Continued.

| POINT | UNIT | AREA | RELATIVE ALBEDO AT |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
| 22 | IpIkr | Uplands N of Crisium | . 200 | . 229 | . 289 | . 313 |
| 23 | EIs | " | . 203 | . 230 | . 277 | . 307 |
| 24 | pI u | " | . 205 | . 232 | . 286 | . 218 |
| 25* | Not Mapped | " | . 206 | . 232 | . 284 | . 301 |
| 26 | Ecf | " | . 202 | . 320 | . 286 | . 310 |
| Estima | es Average | Error | $\pm .001$ | $\pm .002$ | $\pm .002$ | $\pm .006$ |

A11 points are shown on Figure 16 except those marked by the star (*). These points are located as follows:

| POINT | LATITUDE | LONGITUDE |
| :---: | :---: | :---: |
| 11 | 30.3 N | 27.8 E |
| 12 | 18.5 N | 28.2 E |
| 13 | $16^{\circ} \mathrm{8N}$ | 29.2 E |
| 14 | $19^{\circ} 1 \mathrm{~N}$ | $29^{\circ} \mathrm{BE}$ |
| 15 | $16^{\circ} .4 \mathrm{~N}$ | $26^{\circ} \mathrm{8E}$ |
| 16 | 22.0 N | $15^{\circ} .1 \mathrm{E}$ |
| 25 | $\mathrm{N} 34{ }^{\circ} \mathrm{N}$ | N $57{ }^{\circ} \mathrm{E}$ |

TABLE 2. AVERAGE RELATIVE ALBEDO OF VARIOUS STRATIGRAPHIC UNITS

| UNIT | QUADRANGLE | $1.05 \mu$ | $\begin{gathered} \text { RELATIVE } \\ 1.30 \mu \end{gathered}$ | $\begin{array}{r} \text { ALBEDO AT } \\ 1.55 \mu \\ \hline \end{array}$ | 2. $10 \mu$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| IpIp | Cleomedes | . 203 | . 230 | . 288 | . 307 |
| Ipml | " | . 203 | . 231 | . 288 | . 307 |
| Ipm2 | " | . 195 | . 229 | . 298 | . 313 |
| Ipm 3 | " | . 196 | . 228 | . 298 | . 316 |
| Emd | " | . 196 | . 229 | . 296 | . 310 |
| Ipml | Serenitatis | . 197 | . 231 | . 292 | . 313 |
| Ipm2 | " | . 192 | . 227 | . 301 | . 328 |
| Ipm3 | " | . 196 | . 230 | . 294 | . 319 |
| Ipm4 | " | . 196 | . 229 | . 293 | . 322 |
| Emd | " | . 192 | . 223 | . 294 | . 370 |
| pIu | Cleomedes | . 205 | . 232 | . 286 | . 298 |
| IpIkr | " | . 200 | . 229 | . 289 | . 313 |
| IpIyr | " | . 202 | . 230 | . 277 | . 310 |
| Ecf | " | . 202 | . 230 | . 286 | . 310 |
| EIs | " | . 203 | . 230 | . 277 | . 307 |
| Cc | " | . 208 | . 233 | . 281 | . 292 |

materials rather than of the Ipm materials even though the visual albedo and occurence of the Ipml are similar to those of the other Ipm materials. Unfortunately, this problem can not be resolved until better techniques of colorimetric mapping can be evolved and carried out.

The remaining mare units in Crisium, $\operatorname{Ipm2;} \operatorname{Ipm} 3 ;$ and Emd; form the second colorimetric class of materials. If the visual albedo is an indication of age and if the colorimetric properties are an indication of composition, then Mare Crisium (in the Cleomedes quadrangle) and most of the small mare areas which are peripheral to the Mare seem to consist of the same type of material, though of different ages. This conclusion is tentative and again requires more detailed colorimetric mapping,

Though the number of observations is limited, in Mare Serenitatis there seem to be three types of mare materials based on their color. The first group consists of Ipm units (Ipm1, Ipm3, and Ipm4) which make up the wel1-known reddish, dark border of Mare Serenitatis. The second type of material makes up the blue, light center of the mare. The peripheral mare material, mapped as Emd, is the third colorimetric type of mare material in the Serenitatis area. Thus, those areas which show color differences in the visual also show color differences in the infrared. Based on visual albedo, Carr (1965b) has mapped both Ipm1 and Ipm2 in the central part of Serenitatis and Ipm1; Ipm2; Ipm3, and Ipm4 in the outer margin of the mare. Based on the colorimetric observations, the Ipm1 and Ipm2 units should be divided into blue and red Ipm1's and Ipm2's. It should be noted that for the
observed areas, those inits which are red in the visual are also red in the infrared; and similarly units which are blue in the visual are blue in the infrared.

Comparison of the colors of the different units in Mare Crisium and Mare Serenitatis which have similar visual albedo indicate that the units differ in what is assumed to be composition. This indicates that geologic correlation of units between these two maria is not necessarily valid.

Hapke (1964) and Binder et al. (1965) have given evidence which shows that under the influence of the solar wind, lunar materials become redder and more iniform in color with age. While this reddening does not seem to occur for mare units (based on the present mapping criteria and observed overlap relations); the data in Table 2 indicate: : that, if the pIu observation is neglected, the earlier conclusions are correct for the upland units. This difference might be explained if the uplands are compositionally uniform while the mare show distinct. compositional differences. This, the upland materials woizld probably. redden uniformly, while the mare units would probably redden at rates which would be a function of their compositional differences.

Although it is not too difficult to determine the extent of different units in the maria by normal mapping technìques; the problem, becomes quite difficult in the uplands, especially for ejecta blankets: The major criteria used to define an upland ejecta blanket is texture, and so it was desirable to determine if infrared colorimetry could:be: used as a second criterion. For this purpose three points (17, 18;
and 19) on the Cleomedes ejecta blanket (IpIyr) were observed. The color of these points is very uniform (Table 1). However, the color of most of the uplands is fairly uniform, so this is not completely satisfactory. In Table 1 it can be seen that the $1.55 \mu$ point shows wide variations for the different upland units, but that for the IpIyr areas the $1.55 \mu$ point is the same within the error of the observations. Thus, the uniformity of the Cleomedes blanket seems to be confirmed by the uniform color and uniformity of the intensity of the $1.55 \mu$ point for the areas observed on the IpIyr and it is concluded that infrared mapping at a higher resolution than presently attainable should be very useful in the upland areas.

With the present equipment and the above observational technique, the number of observational points required to define a stratigraphic boundary would be prohibitive. Therefore, an attempt was made to map such a boundary, which had been defined by visual mapping, by using the infrared albedo differences across the boundary. The wavelength used for the experiment was $1.55 \mu$, though any of the other points discussed in this chapter could have been used. The spectrometer was set at the desired wavelength and the Moon was slowly scanned in right ascension in a series of parallel strips. The parallel scan traces are shown on Figure 16. The boundary, across which the scans were made, is between Ipm2 and Ipm3 and is defined on the scans by a decrease in the recorded intensity. As can be seen on the illustration, the boundary as defined by the infrared scans (dashed) is not very accurate when compared to the boundary as defined by the
visual mapping (solid). This is due primarily to the very poor reso1ution ( 20 km ) of the infrared scans as compared with the high visual resolution ( $0.1-0.2 \mathrm{~km}$ ) ;

It is concluded that the infrared albedo scans of the resolution used cannot be used for mapping and that with the present equipment, infrared colorimetric obsexvations can only be used to differentiate between, and to correlate separated stratigraphic units. If the effective resolution can be increased by a factor of five or greater, then infrared colorimetric observations should be: an effective mapping tool, especially in the uplands.

## CHAPTER VI

STATISIICAL STUDIES OF CRATERS OF THE CLEOMEDES QUADRANGLE

In this chapter and some of the following chapters, the craters are separated into four age groups. The first two:groups are the Copernican and Eratosthenian craters. The third group consists of a11 craters formed after the Crisium basin formed; but before the Eratosthenian Period. This includes the Yerkes craters and IpI craters and will be referred to as Yerkes craters, The fourth group consists of those" craters formed before the Crisium basin formed and consists of only pI craters which will be referred to as preCrisium craters.

The total area of the quadrangle is about $2.6 \times 10^{5} \mathrm{~km}^{2}: 0 f$ this area about $43 \%$ is covered with mare material and the remaining $57 \%$ consists of upland units of various types and of various ages a Table 3 is a listing of the percent of the quadrangle which is covered by each of the major stratigraphic units: This information is important for the understanding of the effects of crater obliteration on crater counts;

As can be noted from Table 3, the area covered by Eratosthenian and Copernican craters is sufficiently small that almost all of the craters of these ages are preserved This is especially characteristic for craters with diameters greater than 4 km .

TABLE 3. AREA COVERED BY VARIOUS STRATIGRAPHIC UNITS IN THE CLEOMEDES QUADRANGLE

## UNITS

Copernican Craters
PERCENT OF TOTAL AREA

Eratosthenian Craters $\sim 2.5$
Eratosthenian-Imbrium Craters
$\sim 2.5$

Walls and Inner Rims of the Major
Imbrium-pre-Imbrian, Yerkes Craters $\sim 10$
Rims of IpIy Craters ~ 12
Eratosthenian Mare Material, dark ~ 2.5
Procellarum Material, dark 7
Procellarum Material, thin <1
Procellarum Material, light and intermediate 33
A11 Mare Material 43
Crisium Bench 13
Mare Crisium 36
Slope Materials $\quad \approx 10$
Uplands Plains-Forming Material $\approx 5$
pre-Imbrium Materials $\quad \approx 10$

Yerkes craters are preserved and identifiable on the Crisium bench ( $13 \%$ of the quadrangle area) and on Cleomedes crater rim materials (12\% of the area). Yerkes craters could be preserved on the remaining parts of the uplands ( $30 \%$ of the area), but they cannot be positively identified, so the total number of IpIy craters in this area can only be estimated from the number of EI craters found there. The total area on which Yerkes craters could be preserved is about $50 \%$ of the area of the quadrang1e.

The only areas where pre-Crisium craters are preseryed: are the pI regions and part of the IpIp formations: This area includes only $10 \%$ of the area of the quadrangle.

From the study of the areas covered by the different units; it is concluded that almost all of the Eratosthenian and Copernican craters which were formed in the quadrangle are preserved. Of the Yerkes craters about $50 \%$ have been destroyed, and some $90 \%$ of the pre-Crisium craters were destroyed。

Crater frequency counts were made for each of the four crater groups (Copernican $-\mathbb{C}$, Eratothenian $-E$ Yerkes $-\mathbb{I}$, and pre-Crisium $-\mathrm{pK})$. The craters were divided into $\log 2$ diameter intervals and counted, These counts are xepresented by a cumulative log log base 2 plot of the different types of craters. A cumulative plot was used because the number of craters in the $C$ and $p K$ groups was sma11; This type of representation tends to smooth over fluctiations in the data, whether real or statistical." In this case, where the number of
craters is small, the fluctuations are mainly statistical; so the use of cumulative plots is justified.

The crater frequency curves obtained are shown in Figure 17. Included in the E group are $40 \%$ of the EI craters, and the remaining $60 \%$ of the EI craters were added to the $Y$ group. These estimates are based on the relative area on which $Y$ and $E$ craters are preserved. From Figure 17 it is apparent that the ratio of the number of craters of the different groups to the number of Copernican craters is about 7:1 for the E craters, $20: 1$ for the Y craters, and $12: 1$ for the pK craters. When these figures are corrected for the areas involved, the ratios become $7: 1$ for $E$ craters, $40: 1$ for $Y$ craters, and $120: 1$ for the pK craters. These ratios represent the number of craters formed during each period relative to the number of craters formed during the Copernican period:

It has been reported earlier (Shoemaker et al。, 1961; and others) that the post-mare crater density on Mare Crisium is much 1ess than that of the other maria.. This result implies that the surface of Crisium is younger than any other extended mare surface. This result is not confirmed by crater counts made in this report. Figure 19 shows that the post-mare density of craters on Mare Crisium is about equal to those of Mare Imbrium and Mare Nectaris. Because Shoemaker et a1. (1961) indicate that the latter two maria have crater densities nearly equal to that of the average mare, it is concluded that the age of the surface of Mare Crisium is not very different . from the age of the average mare surface: An inspection of Shöemaker's

Figure 17: Crater Frequency distributions in the Cleomedes quadrangle.

In this crater frequency diagram the craters are divided into four relative age groups: Copernican (C), Eratosthenian (E), Yerkes ( $Y$ ), and pre-Crisium ( pK ) . These counts are not corrected for area.


Figure 17. Crater frequency distributions in the Cleomedes quadrangle.
counts indicates that the low crater density he found was the result of the partial absence of small craters (less than 10 km ) in the area, The absence of these small craters in his count was probably. the result of the lack of high resolution photographs of Mare Crisium when the work was done.

## CHAPTER VII

GENERAL BASIN STUDIES

## Relative Ages of the Major Basins

One of the important problems of lunar stratigraphy is to determine the relative ages of the major mare basins. On the basis of structural characteristics, Hartmann (1964a) has indicated that the Mare Orientale basin is younger than the Imbrium basin and that the remaining basins are older than Imbrium. Baldwin (1963) and others have determined the relative ages of the maria basins using crater counts made from Iunar photographs. At the present time there are a sufficient number of stratigraphic maps available, to determine the relative ages of the Imbrium, Crisium, Nectaris, and Humorum basins, using crater counts based on the stratigraphic mappingo The most direct approach to this problem is to compare the relative density of Archimedian type craters (post basin but premare) associated with each basin. If the surfaces of the mare are nearly equal in age, the number of Archimedian type craters is a function of the length of time from the formation of the basin until it was filled. The major source of error in this method is determining the area in and around the basins where the Archimedian craters are preserved and identifiable. To check the validity of the assumption
that the mare surfaces are about the same ages, postmare crater counts must be made, These counts are designated by M. The Archimedian type crater counts are designated by A. Because stratigraphic maps are not available, the $\underline{A}$ counts for Imbrium were made from photographs printed in the Rectified Lunar Atlas (Whitaker et al., 1963). The A counts may be somewhat low, as a large part of the area where Archimedian craters are identifiable occurs on the moderately flooded bench, and the Ipm cover may be deep enough to cover small and even medium craters. The $M$ counts.were based on the final map of the Timocharis quadrangle (Carr, 1965b) which covers a large portion of the interior of Mare Imbrium and the results should be reliable. The Cleomedes quadrangle and the preliminary map of the Undarum quadrang1e (Masursky, 1965) were used for both types of crater counts in the Mare Crisium area. A11 the counts are probably quite accurate owing to the good exposures of the counting areas,: especially the A counts (Yerkes group), as these craters are readily identifiable in the uplands in both quadrangles,

The preliminary maps of the Colombo and Fracastorius quad rangles (Elston, 1965a; 1965b) and the preliminary map of the Rupis Altai quadrangle (Rowan, 1965) were used to obtain the crater counts for the Nectaris basin. Unfortunately, the area flooded in Nectaris is rather small, so the statistical sample for the $\underline{M}$ counts is small. The small amount of flooding also makes the identification of the Archimedian type craters somewhạt uncertain.

Finally, the Humorum quadrangle (Titley et al., 1963), the Pitatus quadrangle (Titley, 1964), and the Byrgius quadrangle (Trask, 1965), all of which are preliminary maps, were used for the study of the Humorum basin crater distributions. As was the case for Crisium, the counts are probably reliable because of the well-exposed areas of interest.

To insure that the diameters measured on these maps were accurate, some of the measurements were compared with the crater diameters given in The System of Lunar Craters, Quadrant I (Arthur et al., 1963). It was found that for craters larger than 5 km the geologic maps (based on the ACIC charts) could be used without error. However, for craters smaller than 5 km there is a tendency for the craters to be somewhat large on the ACIC maps.

The results of the crater counts are given in Figures 18 and.19. The graphs represent the number of craters per $\mathrm{km}^{2}$ in each $\log 2$ diameter interval. The counts are not cumulative since the number of craters in each group is fairly large. In all cases, the greater the number of craters, the older the surface. As can be seen from the graph of A craters, the Imbrium basin is the youngest and the Crisium basin is older than Imbrium but definitely younger than the Humorum and Nectaris basins. According to the A counts Nectaris is younger than Humorum. However, the difference in the relative crater counts is small and the crater counts extend only over two diameter intervals. Thus, the difference between the counts may not be significant.

Figure 18...Frequency distributions of Archimedian type :craters.
The basins for which the counts were made are Imbrium (I), Crisium (C), Nectaris: (N), and Humorum (H).


Figure 18. Frequency distributions of Archimedian type craters.

Figure 19.: Frequency distributions of post-mare:craters.
The maria for which the counts were made are Imbrium (I), Crisium (C), Nectaris ( $N$ ), and Humorum ( $\mathbb{H}$ ). The counts indicate that the surfaces of Crisium, Imbrium, and Nectaris are about the same age, while the surface of Humorum is somewhat older than the other three.


Figure 19. Frequency distributions of post-mare craters.

From the M counts it appears that the surfaces of Nectaris, Crisium, and Imbrium are about the same age, while the surface of Humorum is older than the others. These results indicate that comparisons of the type counts are valid for Crisium, Nectaris, and Imbrium, but not for Humorum. Since the surface of Humorum is older than the other surfaces which are considered, the type $A$ counts are probably low, so the Humorum basin is most probably older than the Nectaris basin. Thus, it is concluded that the sequence of basin formation from the youngest to the oldest is: Orientale (after Hartmann), Imbrium, Crisium, Nectaris, and Humorum.

General Basin Structure

As was shown in Chapter III, the Crisium basin structure was developed along lines of weakness and old faults of the grid system. With the Crisium structure as an example, it is worthwhile to examine the other large basins to determine if they have utilized the grid system faults in the formation of their concentric and radial structural features, Figures 20-22 show Mare Imbrium, Mare Nectaris, and Mare Humorum with the linear elements of the concentric features indicated. The inner and intermediate rings of Nectaris, and the Inner ring of Humorum show strong evidence of grid system control in their development. The remaining concentric rings of each of these basins show little or no linear structure, and in fact; the outer rings, especially of Nectaris, haye a scolloped


Figure 20. Major linear elements of the Imbrium basin structure.
North is at the top. Approximate scale: 10 km per mm


Figure 21. Major linear elements of the Nectaris basin structure.
North is at the top. Approximate scale:
5.5 km per mm


Figure 22. Major linear elements of the Humorum basin structure.
North is at the top. Approximate scale: 6.2 km per mm
appearance as Haxtmann and Kuiper (1962) have shown. Tn the case of the Imbrium basin, which has a distinct hexagonal shape (Darney, 1950), the scarp of the A1ps, Apennine, and Carpathian Mountains show distinct linear elements, both on the large scale and the small scale.

Hartmann (1963, 1964a) has examined the sculpture system of the basins in detail and in all cases except Crisium and Humorum the sculpture is truly radial to the centers of the basins. As Hartmann (1964a) states, there is a"...tendency for local parallelism $\therefore$.." in the sculpture systems of Crisium and Humorum. In Chapter III it was concluded that the Crisium radial system of Iineaments consisted of reactivated grid faults. This also seems to be true in the case of the Humorum sculpture.

As was shown in the case of the Crisium sculpture, the sculpture systems of the other maria also tend to be developed to the $S W, S E$, NW, or NE of the basins, ioe, in one or more of the major grid trends. Hartmann's (1964a) plate no. 36.26 illustrates these sculpture trends very well. This, even though some of the sculpture systems do not seem to consist of reactivated grid system faults; it is clear that the radial lineaments formed only in those areas where their trends were close to those of the pre-existing grid fau1ts.

From the study of the structure of the major basins, it is concluded that the following features of the mare basins are the
result of reactivation of pre-existing grid system faults and/or the weakness of the lunar crust along the directions of the grid system faults: (I) the polygonal shapes of some of the maria, (2) the linear elements of some of the concentric structural rings, (3) the areas in which some of the arcs of the structural rings were formed, (4) the areas in which the sculpture systems were formed, and (5) the elements of some of the sculpture systems. It is probable that the above structure elements were all formed at the time that the basins formed or shortly thereafter. This conclusion may also apply to polygonal craters, i.e., their present shapes are primary and not due mainly to post-formation modifications along preexisting lines of weakness.

## CHAPTER VIII

## THE LUNAR TIME SCALE

The relative time scale of lunar history is fairly well established, even though some of the time boundaries may not be very well defined; see below.: However, there is relatively 1ittle known about the absolute time scale of lunar history except that the Moon was formed about $4.5 \times 10^{9}$ years ago. It is generally believed that the majority of the mare materials were deposited about $4 \times 10^{9}$ years ago, though this figure is certainly not well established. Until samples of the lunar surface are available for laboratory analysis, the only method for determining the absolute time scale is an analysis of crater statistics. If the relative crater densities of the different periods are known and if a realistic cratering rate as a function of time is available, then simple calculations would yield the absolite ages of the different periods.

As Kuiper (1954) and others have discussed, the Moon has undergone bombardment by bodies which can be divided into two timedependent groups. The first group of bodies is responsible for the intense cratering of the upland areas, i,e., most of the pre-mare craters. Because the pre-mare time was relatively short (as compared with post-mare time) and the number of these craters is large, the
rate of cratering was very great.: The second group of bodies formed the post-mare craters and the cratering rate was rather low. Evidence that these two groups are of different origin is given by Hartmann (1966).

For convenience, the lunar time scale is divided into preand post-mare eras for the following discussion. This division is based on the assumption that the overlap of the two cratering fluxes is of little consequence and that the period of the changeover from the first flux to the second occurred close to the time of the filling of the mare basins.

## Post-Maria Time

The beginning of the post-mare era is also the beginning of the Eratosthenian period, It was pointed out in the introduction and was shown in Chapter III that there are mare units which have been found to be much younger than the general Ipm units: Even though some very distinctive mare units can be given an Eratosthenian or even a Copernican age, it is impossible to determine the exact cutoff between Ipm and Emd units. Thus, the criterion used to determine the bottom of the Eratosthenian stratigraphic column is a time transgressive one. It is estimated that the "beginning" of the Eratothenian Period in different areas may vary in time by $5 \%$ of the total average length of the post-mare era (about $4 \times 10^{9}$ years).

Similar difficulties are found in the criterion used to define the Copernican Period. Since cratering is a random phenomenon and if there is a definite lower age for the ray material, then the ratio of Copernican to Eratosthenian craters would be constant all over the Moon. Several mare quadrangle maps were used to test the validity of the last assumption, and they are listed in Table 4 with the results obtained from them. As can be seen in Table 4, there are great differences in the results obtained from the different quadrangles. These differences are probably the result of personal factors involved in determining the cutoff point between craters with faint rays and craters without rays, especially in the case of small craters. Also, the general albedo of the background mare affects the detectability of ray systems of small craters. Neglecting the differences between: the quadrangles, the combined results are shown in Figure 23. For craters smaller than 16 km there are 2 E craters for every C crater, but for craters larger than 16 km there are more C craters than . The result that there are more large $C$ craters than $E$ craters on the maria is verified by an inspection of a full Moon photograph. There are two possible reasons for the results: (1) the mass-frequency distribution of the impacting bodies has changed with time, and (2) ray systems are more readily formed in the case of large craters than for small craters. Hartmann (1964b) has shown that the frequency distribution of pre- and post-mare craters is the same, thus (1) is

TABLE 4. COPERNICAN AND ERATOSTHENTAN CRATER COUNTS FOR SELECTED MARE : AREAS

*Carr, 1965
**Eggleton, 1965
***Hackmann, 1962
****Moore, 1965

Figure 23. Frequency distributions for post-mare craters.
The graphs indicate the relative frequency of Copernican (C) and Eratosthenian (E) craters.


Figure 23. Frequency distributions for post-mare craters.
unlikely. If the second possible cause is true, then there is no unique criterion by which to differentiate between the two periods; however, it is probably true that most $C$ craters are jounger than the E craters.

In addition to the differences in the frequency distribution of $C$ and $E$ craters with size in the mare, D. Wilhelms (private communications) has noted that there are differences in the relative density of $E$ and $C$ craters when the maria are compared to the uplands. Thus, it is concluded that there is no unique beginning of the Copernican Period and the post-mare era can not be divided into time units which are based on the present lunar stratigraphic systems.

## Pre-Mare Time

Since reasonably good crater counts were obtained for the determination of the sequence of the formation of the mare basins (Chapter VII), it should be possible to determine the ages of these basins relative to the age of the mare surfaces, providing an acceptable model can be found for the pre-mare cratering rate. Hartmann (1966) has discussed the origin of the bodies which formed the premare craters and he has concluded that the most likely source of the bodies is the debris which was left over from the formation of the Moon. Hartmann tentatively rejects the possibility that the early cratering is the result of the accretion process (assuming the Moon formed by accretion), since the uplands do not have a crater-on-
crater topography: However, the stratigraphic mapping has shown that an upland plains unit exists; the IpIp, and that this unit may have buried a large number of older craters. Thus, this unit may thave masked the crater-on-crater nature of the lunar surface if it ever existed. If the early cratering is the resilt of the accretion of the Moon; then the post-mare cratering rate may be approximated by a 1/e function of time.

A second source of the early cratering objects was suggested by Wise (1963), Wise has postulated that the Moon was formed by fission from the Earth . during the formation of the Earth?s core. Just prior to the separation of the two bodies, the Earth-Moon body had a Poincare figure with the proto moon at its: smaller end. During the separation, the neck of the Poincare figure broke into a number of small bodies: Just after fission, the system consisted of the Earth; the Moon; and a large number of small bodies which were concentrated close to the Earth and Moon: With time these bodies would be dispersed by Earth and Iunar perturbations. Thus; in the beginning of lunar history there would have been an abundant: supply of impacting bodies; and as the Moon moved away from the Earth (MacDonald, 1964; and others), there would have been fewer and fewer impacts. So, the cratering rate may be approximated by a 1/e function of time in the case of Wise's theory.

In comparison to the Crisium basin, the relative number of Archimedian type craters in the other basins are $\because$ Imbrium $=0.5$, and Nectaris $=1.8 ;$ see Chapter VII. From the data: given in Chapter VI,
there are about 3 pre-Crisium craters for every Yerkes (Archimedian type) crater. Thus, out of every 100 pre-mare craters, the number of post-basin craters is 12 for Imbrium, 25 for Crisium, and 45 for Nectaris. If $\mathrm{dn} / \mathrm{dt}$ is the cratering rate, as discussed above, $\mathrm{k}_{1}$ and $k_{2}$ are constants, and $t$ is the time, then

$$
\begin{equation*}
\mathrm{dn} / \mathrm{dt}=\mathrm{k}_{1} \mathrm{e}^{-\mathrm{k}_{2} t} \tag{1}
\end{equation*}
$$

Let $t=0$ at the beginning of lunar history and $t=1$ when the maria were formed. To evaluate $\mathrm{k}_{2}$ it is necessary to know or estimate the difference in $d n / d t$ at $t=0$ and $t=1$. If this difference is $\underline{m}$, then

$$
\begin{equation*}
\mathrm{dn} /\left.\mathrm{dt}\right|^{\mathrm{t}=0}=\left.\mathrm{mdn}\right|^{\mathrm{t}=1} \tag{2}
\end{equation*}
$$

Substituting equation (1) into equation (2) and evaluating, we have

$$
\begin{equation*}
\mathrm{K}_{2}=\ln (\mathrm{m}) \tag{3}
\end{equation*}
$$

For a unit area which contains 100 pre-mare craters, we have by equation (1)

$$
\begin{equation*}
100=\int_{0}^{1} k_{1} e^{-\ln (m) t} d t \tag{4}
\end{equation*}
$$

which reduces to

$$
\begin{equation*}
100 \ln (m) k_{1}^{-1}=1-1 / e^{\ln (m)}=1-1 / m \tag{5}
\end{equation*}
$$

If $m \mp 100$ (see below) then $1 / m$ is insignificant, and equation (4) reduces to

$$
\begin{equation*}
\mathrm{k}_{1}=100 \ln (\mathrm{~m}) \tag{6}
\end{equation*}
$$

From equations (1), (3), and (6) we have

$$
\begin{equation*}
\mathrm{dn} / \mathrm{dt}=100 \ln (\mathrm{~m}) \mathrm{e}^{-\ln (\mathrm{m}) \mathrm{t}} \tag{7}
\end{equation*}
$$

For a given value of $\underline{m}$, equation (7) can be integrated to determine the length of time needed for $n$ craters to have formed. For example, in the Imbrium basin since 88 out of 100 pre-mare craters formed before the basin formed,

$$
\begin{equation*}
88=100 \ln (m) \int_{0}^{t} e^{-\ln (m) t} d t \tag{8}
\end{equation*}
$$

If $m=10^{3}$, then by equation (8), $t=0.46$. Thus, the Imbrium basin formed after $46 \%$ of the time had elapsed between the beginning of Iunar history and the formation of the mare if $\mathrm{m}=10^{3}$.

Based on the relative densities of pre- and post-mare craters, reasonable values of may be in the range of $10^{2}$ to $10^{4}$. Values of the ages of three of the major basins relative to the age of the mare surfaces are given in Table 5 for three values of $m$. It is noted in Table 5 that regardless of the value of $\underline{m}$ the relative ages of the basins with respect to Imbrium is about the same. If the Imbrium

TABLE 5. AGES OF THE MAJOR BASINS RELATIVE TO THE AGE OF THE MARIA FOR VARTOUS VALUES OF ㅍ

| 10 | $10^{2}$ | $10^{3}$ | $10^{4}$ |
| :---: | :---: | :---: | :---: |
| Imbrium Basin | 0.46 | 0.31 | 0.23 |
| Crisium Basin | 0.30 | 0.20 | 0.15 |
| Nectaris Básin | $0.17:$ | 0.12 | 0.09 |

Age of the Maria is 1,00
basin formed at $t=t_{i}$, than the Crisium basin formed at $t=0.65 t_{i}$, and the Nectaris basin formed at $t=0.38 t_{i}$. It is also concluded that unless $\underline{m}$ was less than $10^{2}$, or greater than $10^{4}$, the pre-Imbrian period occurred between the first quarter and the first half of the pre-mare era. If this era lasted about $5 \times 10^{8}$ years, as is generally accepted, if $\underline{m}=10^{3}$, and if $t=0$ marks the beginning of the development of lunar surface detail, then at $t=6 \times 10^{7}$ years the Nectaris basins formed, at $t=10^{8}$ years the Crisium basin formed, at $t=1.6 \times 10^{8}$ years the Imbrium basin formed and the Imbrian period began, and at $t=5 \times 10^{8}$ years the major basin flooding occurred and the Imbrian period ended.

Figure 24 shows the lunar time scale based on the discussions in this chapter and in Figure 24 m is assumed to be $10^{3}$.

Figure 24. The Iunar timescale.
The time scale is not linear, and time equals 0 is considered to be the time when the Moon first had a surface which was capable of preserving structural detail,


[^0]
## CHAPTER IX

SUMMARY AND CONCLUSTONS

## Sumary

As a summary of the material presented in this paper and the information displayed on the Geologic Map of the Cleomedes Quadrangle, the history of the quadrangle and the entire Crisium area is reviewed. During the first 100 million or so years after the formation of the Moon, the Moon was undergoing a period of intense cratering and crustal fracturing. There is little evidence of this early phase of cratering in the Cleomedes quadrangle due to the destruction of these craters by later impacts (mainly those which formed Cleomedes and the Crisium basin), and burial of the craters by ejecta, mare material, and IpIp. In addition to these obliteration processes, the early crustal fracturing also aided in the destruction of the early craters. The lineaments and faults which formed in this period of Iunar history are still recognizable and have had a great influence on the development of later lunar features. The causes of this tectonic activity may include tidal deformations of the Moon, thermal expansion and/or contraction, and changes in the figure of the Moon due to changes in its rotational velocity. Finally, widespread igneous activity in this period is indicated by the upland plains-forming units; which are considered to be early maxe-like materials.

The second period in the development of the Crisium region began with the formation of the Crisium basin at $t=10^{8}$ years: This event may have occurred less than $10^{8}$ years before the beginning of the Imbrian Period, but after the other major basins on the visible side of the moon. As a consequence of the Crisium event, a system of radial and concentric structúral elements developed which were : centered on the Crisium basin. These structural features developed along the lines of "weakness and faults of the grid system. However, the lunar crust was not completely broken by the grid faults, since large structural blocks were strong enough to resist being broken and they formed horsts which make up part of the Crisium rim.

As indicated above; the Crisium basin event destroyed many craters, not only in the inner basin, but also outside the basin by: the fault activity which occurred during and after the event: Since there is no substantial stratigraphic evidence for great amounts of Crisium ejecta; loss of earlier craters by burial may not have been too widespread.

Following the formation of the basin, cratering continued: at a fairly high rate and craters of the Yerkes group were formed: Some time during this period, the crater Cleomedes was formed with its extensive and distinctive ejecta blanket. Also, during this period, IpIp was deposited in low areas and presumably in the Crisium basin.

The final filling of the basin with Ipm units occurred near the end of the Imbrian period, perhaps $4 \times 10^{8}$ years after the basin
formed: The filling did not stop abruptly, but slowly decreased in intensity. The last units seem to have originated in the uplands which are adjacent to the mare. Many of these last flows are probably Eratosthenian in age.

By the time that the majority of the mare surface had formed, the cratering rate: had decreased and relatively few craters formed during the $4 \times 10^{9}$ year postmare era. Thus, the majority of the features in the Crisium area and the rest of the Moon were formed in the first 20\% of Iunar history.

## Conc1usions

It has been found that most of the stratigraphic units are time transgressive and that the post-mare lunar periods, as defined in the early stages of the development of lunar stratigraphic mapping, lack definite time boundaries. This conclusion is in agreement with the recent work of Carr (1965a) and others, Though the beginning of the Imbrian Period is well defined by the Imbrium basin event, it is impossible to find stratigraphic evindence of this event in areas far removed from the Imbrium area and in a large percent of the uplands. Thus, the beginning of the Imbrian can not be defined in such areas. It is concluded that the units which are mapped as time-rock units: are in reality rock-stratigraptic units and there is no general lunar geological time scale which can be defined by terrestrial base stratigraphic mapping.

The rock-stratigraphic units which are being mapped now can be used to set up local stratigraphic colimns, especially around the major basins. It is probable that in the course of future manned. lunar exploration, these local colums can be..accurately dated by geochemical methods and then an accurate time-stratigraphic scale can be established for the Moon.

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FIGURE 2 CROSS SECTION OF THE CLEOMEDES QUADRANGLE




| Contact <br> Long dashed where approximately located queried where inferred. <br> pl <br> Concealed contact <br> Buried formation indicated by symbol in parentheses. $\qquad$ <br> Faults <br> Hachured where fault acarp buried by later materials; dotted where concealed downthrown side. $\qquad$ <br> Faults too close together to use bar a <br> ball symbol to show downthrown block. <br> Lineament <br> Trough or scarp of unknown nature Trough or scarp of unknown nature. Interpretation: single fault, graben, or buried graben. $\frac{7}{\text { Mare scarp }}$ <br> Line marks base of scarp, barb points downslope. fault scarp, or edge of aubsurface si |
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| :---: |
| Line maxts crest. Arrou indicates taperel |
| $\xrightarrow[\substack{\text { end } \\ \text { Interpretati ion: Press }}]{\text { en }}$ |
|  |
| Breccia lens |
| Sham on cross section beneath |
|  |
| $\bigcirc$ |
| slump block |
| Arrows shou direction of moverent. |
| Ireewher dereesten |
|  |
| Interpretation: Collapse feature movement scar. |
|  |
| Concealed crater |
| Symbol shaw rim crest |
| crater |
| Subunits indistingui shaibe and |


| $\mathrm{ch}_{1}^{c h}$ |
| :---: |
| A11.ed or over lapping craters. Rim, wall, Ind foor materials undifferentiated |
| $\bigoplus_{\text {Rimeses round crater }}^{\Theta}$ |
| Interpretation: Mar, caldera, or other volcanic crater or partly buried crater of any origin. |
| $\underset{\text { craterece cone }}{\text { © }}$ |
| Steef flanked cone with crater at summit Interpretation: Volcano. |
|  |
| Interpretation: Channel eroded by vol- <br> canic llow or leveled flow channel. $\left[\begin{array}{c\|c} \operatorname{cxr} & \operatorname{cxw} \\ \hline \end{array}\right.$ |
| Crater-complex material |
| Characteristics $\quad$ Material of a line of contiguous craters cxr, rim material. |
| Interpretation secondary craters |


| Ple $/$ Pler | plew $/$ plep |
| :---: | :---: | :---: |
| Crater naterials |  |




| plu | plkr | plkb | plc pler plew $^{\text {Plep }}$ |
| :---: | :---: | :---: | :---: |
| Undif ferent tatee material | itium rim material | eench material | Crater materials |
| Has diverse copography and albedo. Well faulted by lunar grid system and, in places by cris suiun scul purues system. <br> Interpretation |  |  | Characteristics <br> imilar in occurrence to corresponding younger unite but forw |
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FIGURE 2 GEOLOGICAL MAP OF THE CLEOMEDES QUADRANGLE



[^0]:    Figure 24. The lunar time scale.

