CHAPTER 4

Stratigraphy and Chronology of the Moon's Crust

Lunar Topography

Even when viewed from earth, the moon's surface is easily divided into mare and terra (or highland) areas on the basis of albedo. Upon closer scrutiny we find that highland areas are considerably rougher and more intensely cratered than the mare suggesting a considerable difference in age. This two-fold division of the lunar surface, first suggested by Galileo in 1610, is very basic in the understanding of the nature of the moon.

Laser altimetry data collected from orbit by the Apollo 15, 16 and 17 spacecraft has shown that the mare areas are, for the most part, topographic lows although not all mare surfaces are at the same altitude (Kaula, 1972, 1973, 1974) (Fig. 4.1). For example, Mare Crisium and Mare Smythii are extremely low (-5 km) whereas Oceanus Procellarum is not much lower than the surrounding highlands (-3 km vs -2 km). Overall the mare are 3–4 km lower than the terra. In Figure 4.2 a hypsometric curve for the moon based on the altimeter data is compared with the earth. A direct comparison of the two curves is difficult because the lunar curve is based on topographic deviations about a mean sphere centered at the center of the lunar mass. This center of mass is not coincident with the geometric center of the moon but is displaced 2–3 km towards the lunar near side at about 25°E. Terrestrial data are related to a complex mean geoid (i.e. mean sea level) rather than a simple sphere. However, the curves are grossly similar, except that the lunar curve is flatter, indicating that the topographic distinction between highland and mare areas is less clear than the division between ocean and continent on earth. It is tempting to suggest that the similarity of the two curves indicates that something similar to ocean floor spreading occurred during the early formation of the lunar crust but it is probably more realistic to suggest that the shape of the lunar curve resulted from the excavation of the mare by impact and a resultant redistribution of the crustal materials.

As a result of the extensive reworking of the lunar surface the moon's crust is structurally and stratigraphically complex and much of the early record of crustal evolution has been obliterated.

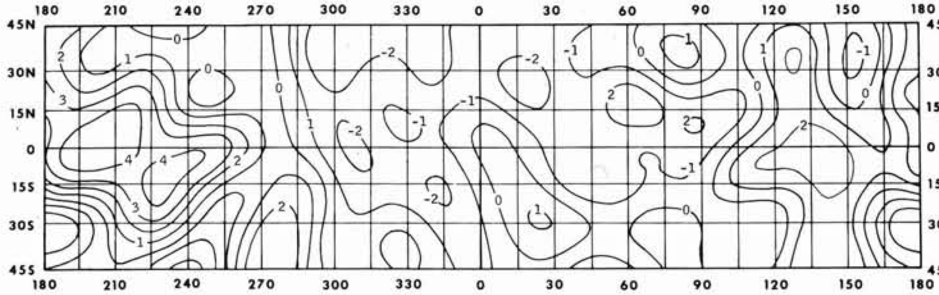


Fig. 4.1. Laser altimetry of the lunar surface. The mare are generally lower than the terra.

Early History of the Moon

The moon may be as old as ≈4.65 aeons (Tatsumoto, 1970; Nunes *et al.*, 1973). This age has been derived from U-Th-Pb systematics of lunar soils and soil breccias. However, while soils and soil breccias offer representative samples of large areas of the lunar crust, they can not be regarded as representative of the moon as a whole. Tera and Wasserburg (1974), while not suggesting that 4.65 aeons is an unreasonable figure for the age of the moon, suggest that the data are too limited at present to be certain. The approximate age of the solar system and the planets is however, reasonably well defined at ≈4.5 aeons with an uncertainty of ≈200 m.y. in the precise age of the planets. Presumably the moon originated within this time period.

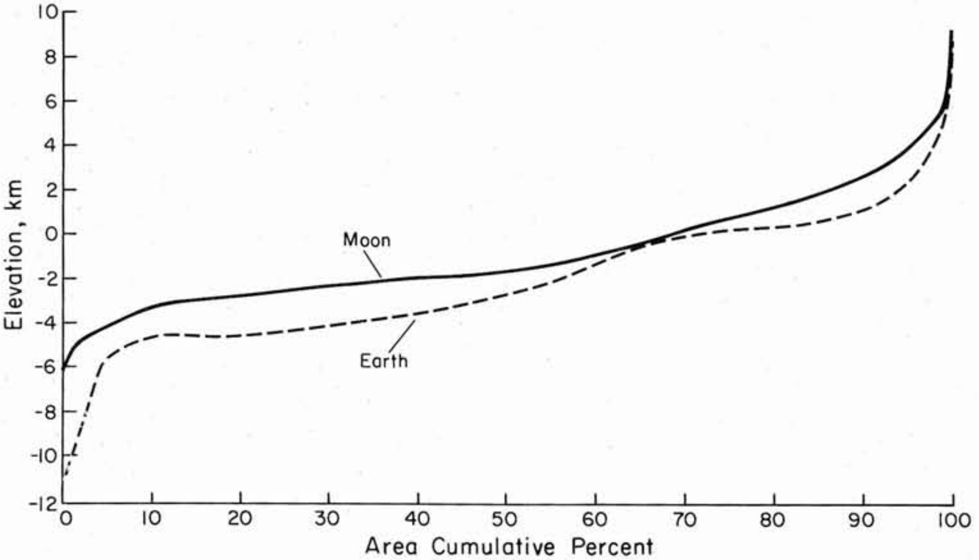


Fig. 4.2. Distribution of the surface of the moon and earth in terms of percentage of surface below a given altitude. Note the similarity between the two curves and the fact that the lunar curve is flatter (Lunar data courtesy of L. Srnka and W. Wollenhaupt).

There is little radiometric data concerning the early events in the formation of the moon prior to 4.0 aeons. Some consistencies in U-Pb evolution suggest an event at 4.42 aeons which may represent the age of crustal formation and large scale lunar differentiation (Tera and Wasserburg, 1974).

Tera and Wasserburg (1974) discuss two alternative models for the rate of formation of the lunar crust (Fig. 4.3). In the upper diagrams of Figure 4.3 the rate of formation is shown as a function of time while the lower figures show the percentage of the final crust as a function of time. In the first model the crust evolves rapidly such that within 150 m.y. 80 per cent of the final crustal mass is formed. Subsequent to 3.9 aeons only a small addition is made to the crust as the mare basalts are extruded. Two cases are shown in the second model, both involving a uniform rate of crustal growth. In one case the mare basalts are considered a major contributor to the crust, in the other they play a minor part. The second view, in which the basalts are a minor contributor, is more realistic in view of the seismic data presented in Chapter 1.

No conclusive evidence is available to support either model largely because of the lack of quantitative data concerning events in the first 500 m.y. of lunar history. Tera and Wasserburg (1974) prefer, from a schematic viewpoint in the light of the U-Th-Pb systematics, a model in which crust is formed rapidly at first. That is, about 60 per cent of the crust is formed in the first 200 m.y. This fast growth phase would be followed by less intense growth such that about 30 per cent more crust is added in about 3.9 aeons.

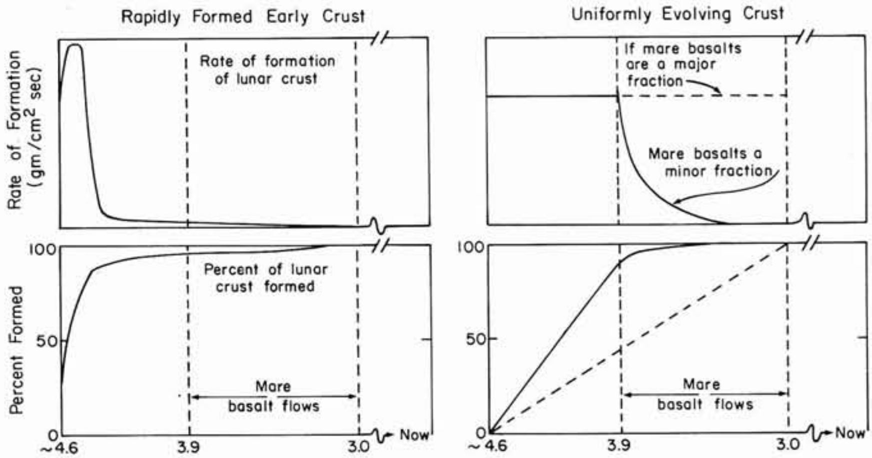


Fig. 4.3. The rate of formation and the percentage of crust formed as a function of time. On the left the crust is assumed to have formed rapidly and early in the moon's history whereas the diagram on the right depicts a situation where the crust evolved at a uniform rate up to 3.9 aeons ago. Mare basalts are assumed to be a minor contribution to the crust (from Tera and Wasserburg, 1974; *Proc. 5th Lunar Sci. Conf., Suppl. 5, Vol. 2,* Pergamon).

The suggestions put forward by Tera and Wasserburg (1974) on the basis of their isotopic data are also consistent with gravity data (Fig. 4.4)

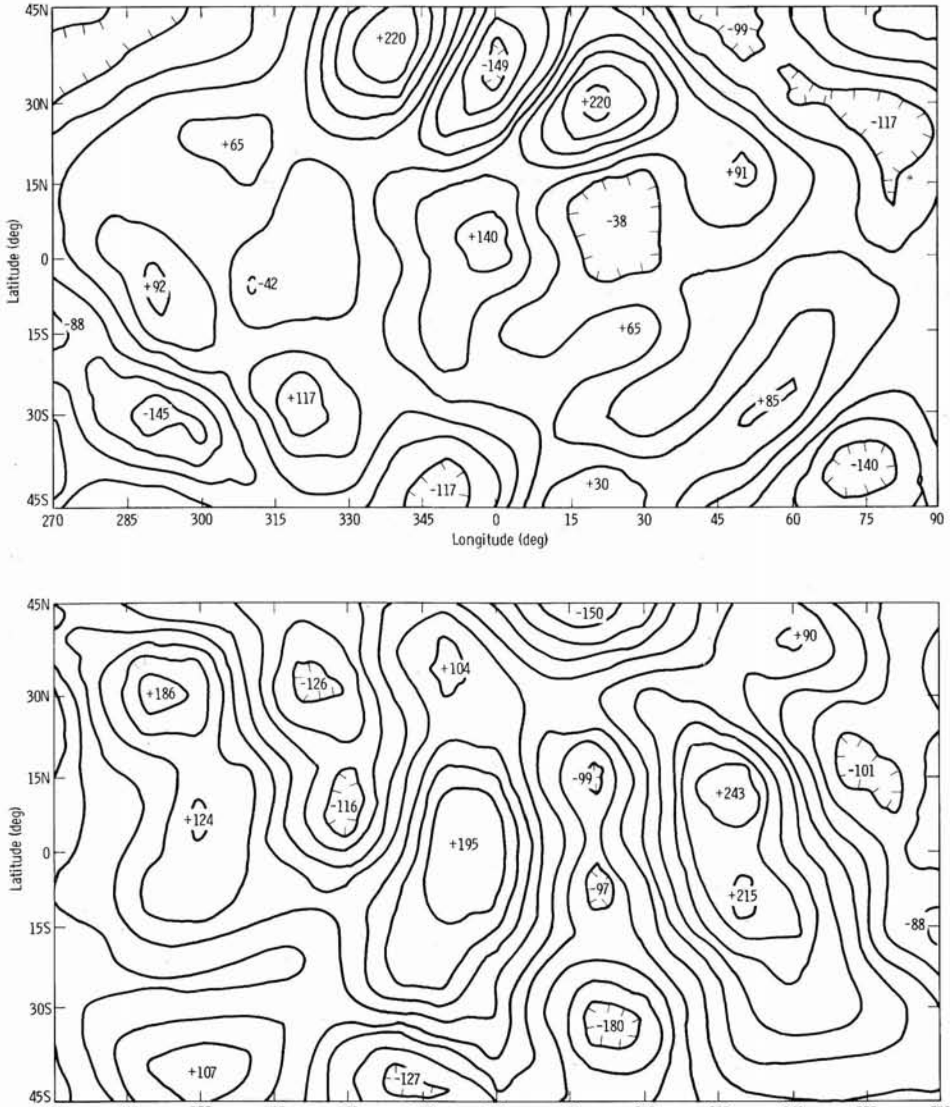


Fig. 4.4. Lunar gravity field; nearside at top, farside at bottom (from Ferrari, 1975; Copyright 1975 by the American Association for the Advancement of Science).

(Muller and Sjögren, 1968; Ferrari, 1975). The lunar highlands and the large mountain ranges surrounding the circular mare are all close to, or at, isostatic equilibrium. For example the Apennine Mountains on the southeastern edge of Mare Imbrium stand 7 km above the mare basalt surface but have a positive anomaly of only +85 mgal. This implies that the crust of the moon was still hot and mobile through the period of mare excavation up to at least 3.85 aeons when Mare Orientale the youngest circular mare, was excavated (Schaeffer and Husain, 1974).

The mare on the other hand show almost no evidence of isostatic compensation such that beneath Mare Imbrium there is an anomaly of +220 mgal. There are similar but somewhat smaller anomalies, or "mascons" as they have been frequently called, beneath most of the mare surfaces (Muller and Sjögren, 1968). The mascons appear to be near surface features and most likely relate to the mare basalt fill (Phillips *et al.,* 1974; Brown *et al.*, 1974). This implies that some time between the excavation of the mare and their flooding by basalt the lunar crust became cold and rigid enough to support the uncompensated mass of mare basalt. The crust must therefore have been essentially in its present state shortly after 3.85 aeons when the last circular mare was excavated and at least sometime between 3.96 and 3.16 aeons when the mare were flooded.

Lunar Stratigraphy

Craters are ubiquitous on the lunar surface (Fig. 4.5). From pits as small as microns on the surface of lunar soil particles they range upward in size to giant craters the size of the Imbrium Basin (Fig. 4.6). The recognition that the large craters are of impact origin and are surrounded by a radially disposed and sculptured ejecta blanket is basic to lunar stratigraphy.

Gilbert (1893) was the first to realize that a circular mare basin, the Imbrium Basin, was impact generated and surrounded by ejecta and that this event might be used to construct a geologic history of the moon. Similarly, Barrell (1927) discussed superposition on the moon as a means of establishing a stratigraphy. Later Spurr (1944-1949) and Khabakov (1960) proposed a series of lunar time divisions. Spurr's divisions were based on structural, igneous and depositional events while Khabakov chose to use topographic differences.

The basis for the present lunar stratigraphy was established in 1962 by Shoemaker and Hackmann although many changes have been made since. Shoemaker and Hackmann based their study on an area to the south of Mare Imbrium in the vicinity of the crater Copernicus where stratigraphic relations

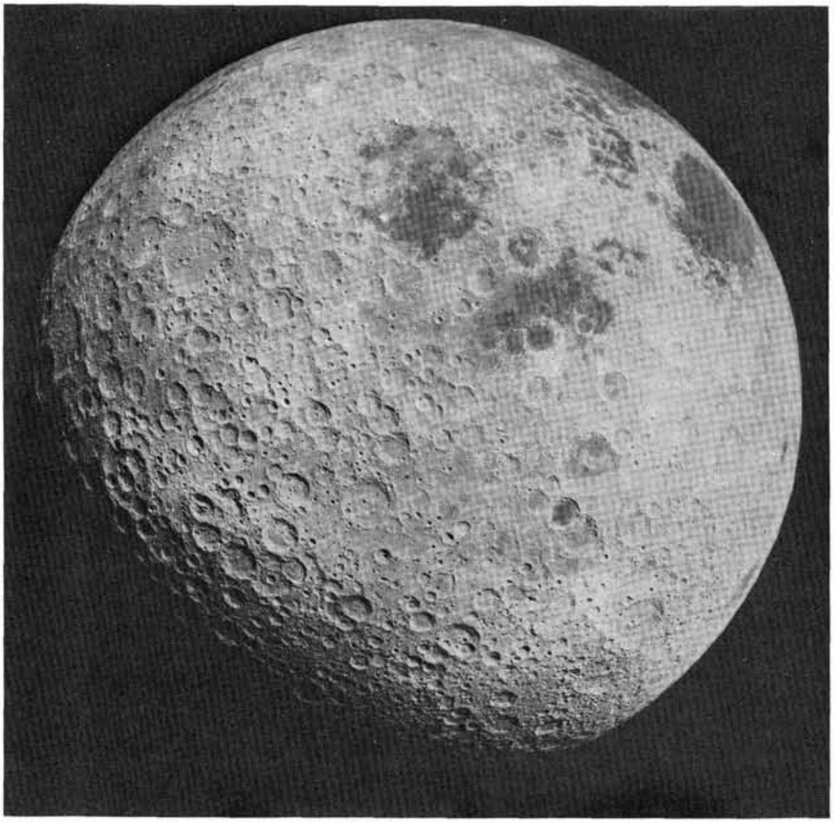


Fig. 4.5. The intensely cratered lunar farside and a portion of the nearside including Mare Crisium (NASA photo AS16-3028)

among the various ejecta blankets are clear (Fig. 4.7). They were able to show that the crater Copernicus was surrounded by an ejecta blanket which consisted of three "facies": a hummocky facies closest to the crater then a radial facies, and finally ray streaks with secondary craters. These three facies were seen to overlie craters such as Eratosthenes and Reinhold which in turn were imposed on the surface of Mare Procellarum. Finally, mare materials were seen to have flooded the Imbrium Basin and to overlie areas of Imbrium ejecta. In all Shoemaker and Hackmann identified five stratigraphic units, four of which they call systems. In order of decreasing age these are (1) pre-Imbrian, (2) Imbrian, (3) Procellarian, (4) Eratosthenian and (5) Copernican. This basic system has been maintained to the present although changes have been made due to a redefinition of some units. Most of the changes are concerned with the definition of rock and time units and their recognition beyond type areas.

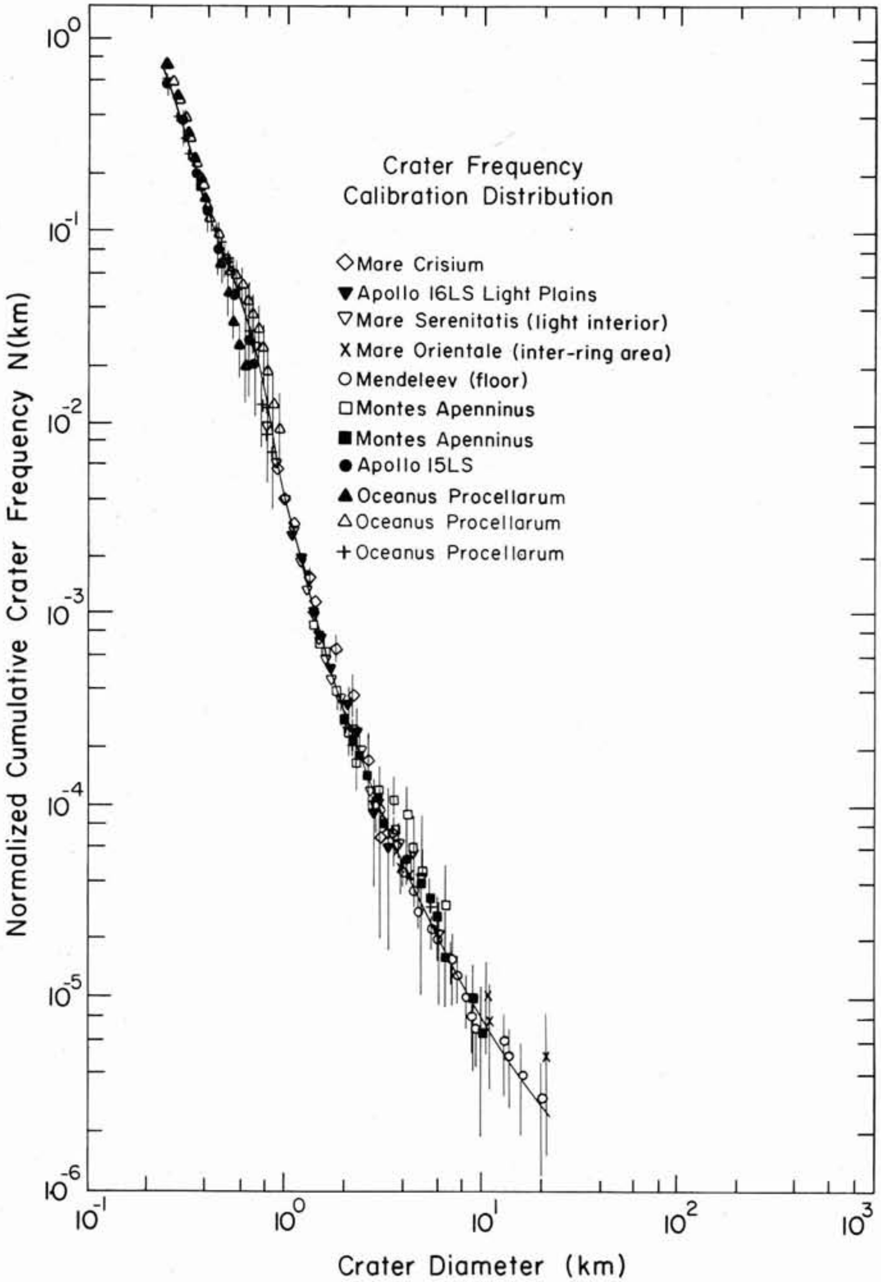


Fig. 4.6. Cumulative size-frequency distributions of all investigated crater populations normalized to the frequency of Mare Serenitatis Light Interior. The solid line represents the polynomial approximation of the calibration size-distribution (after Neukum and König, 1975).

Fig. 4.7. The classic area used by Shoemaker and Hackmann (1962) in establishing the first lunar stratigraphy. The area lies on the southern margin of Mare Imbrium. The arcuate mountain chain at top right forms the margin of the Imbrium Basin. The large rayed crater to the left is Copernicus, the smaller unrayed crater is Eratosthenes. Copernicus is approximately 90 km in diameter (NASA Photo Lunar Orbiter IV-M121).

Stratigraphic Units

A lunar stratigraphy, by necessity, must be based on remotely observable properties of the lunar surface. The units are mapped by outlining areas of similar topographic morphology or albedo or combinations of such properties that can be studied remotely. The stratigraphic significance of such units is a matter of judgment based on an understanding of geologic processes on the moon. In the terrestrial situation the most meaningful stratigraphic units have a three-dimensional form. When dealing with lunar units properties are sought that indicate layers of finite thickness or reflect lithology rather than post-depositional processes (Wilhelms, 1970). Topography is by far the most meaningful property that can be used as an indicator of the three-dimensional properties of the underlying rock body. Simple overall geometric form and lateral uniformity or regular gradation of texture offer best indications of lithologic uniformity, although there is a risk that they reflect a common structural or erosional history instead. Stratigraphic units can be confidently identified if their topographic texture appears similar to primary depositional patterns (Wilhelms, 1970). This points out one of the main weaknesses in lunar geologic mapping, which is that it is necessary to make some assumptions about the genesis of the deposits. It also points out the need for understanding cratering mechanics and the associated depositional mechanisms. Flow lobes, flow lineations and hummocky texture coarsening towards the assumed crater source all help determine the continuity and extent of stratigraphic units. Further confirmation can also be obtained where depositional units bury craters and valleys and thickness determinations are possible (Marshall, 1961; Eggleton, 1963).

It is also possible to use secondary age criteria to supplement superposition and transection relations. Particularly useful is the density of superposed craters and the apparent freshness of units (Wilhelms, 1970). In general crater density increases with age and the rims of older craters become more subdued.

The *lunar material unit* has been established as a parallel to the rock-stratigraphic unit on earth. The lunar material unit has been defined as "a subdivision of the materials in the moon's crust exposed or expressed at the lunar surface and distinguished and delimited on the basis of physical characteristics" (Wilhelms, 1970, p. F-11). Lunar material units have similarities with their terrestrial equivalents but are defined separately because they are observed remotely. That is, features such as the third dimension of the material unit and its lithology may not be known. Further it may be determined to some extent upon inferences based upon our understanding of its genesis.

Local lunar material units may be correlated by their relationship to more widespread units such as ejecta blankets surrounding the large circular mare or by using more subjective criteria such as crater density. Such methods have been employed to establish a stratigraphic column of lunar material units which, like its terrestrial equivalent, has been divided into time-stratigraphic units for use in summarizing geologic history (Shoemaker, 1962; Shoemaker and Hackmann, 1962; Wilhelms, 1970). The major time-stratigraphic units have been called "systems" and their subdivisions "series" as is the terrestrial convention. Similarly the corresponding geologic time units are periods and epochs respectively. The most recent comprehensive assessment of lunar stratigraphic nomenclature is that of Wilhelms (1970). According to his evaluation three systems are presently recognized, which are from oldest to youngest Imbrian, Eratosthenian and Copernican (Table 4.1). Materials older than Imbrian have not yet been assigned a system and are simply called pre-Imbrian. The use of these terms is in some ways unfortunate as much of the stratigraphy outside the Imbrian area is in fact older than Imbrian and eventually will require a more detailed subdivision. It may in fact have been better to avoid the old terrestrial time stratigraphic concepts and treat each major basin as a separate entity with regional correlations. The system names currently used are the same proposed by Shoemaker and Hackmann (1962) except that the Procellarian System has been dropped and the mare materials included in the Imbrian System.

Type areas have been established for each system in the regions where lunar stratigraphy was first studied near the craters Copernicus, Eratosthenes and Archimedes (Fig 4.7). Type areas are used out of necessity on the moon to replace terrestrial type sections. The base of the Imbrian System has been defined as the base of the Fra Mauro Formation, the Imbrium Basin ejecta unit exposed at the surface on much of the Apennine Mountains, Carpathian Mountains and the highlands between the craters Copernicus and Fra Mauro (Wilhelms, 1970). Schaeffer and Husain (1974) place the age of the Fra Mauro Formation at the beginning of the Imbrian at 3.95 ± 0.05 aeons. The top of the Imbrian System is the mare materials. As discussed in a following section, basalt samples returned by the Apollo missions range in age from 3.16 to 3.96 aeons. Presumably the younger limit can be used as a reasonable age for the upper boundary of the Imbrian System. A type mare area has not been designated; however, Wilhelms (1970) has suggested the area between the craters Eratosthenes and Archimedes as such.

Larger rayless craters such as Eratosthenes which are superimposed on the mare surface have been assigned to the Eratosthenian System. The ejecta blankets associated with rayed craters and many dark-halo craters have been assigned to the Copernican System because the rays of the crater Copernicus overlie the rayless craters (Wilhelms, 1970). Lunar time-stratigraphic units express only approximate correlations, because although most rayless craters are older than rayed craters there are exceptions (Wilhelms, 1970). Clearly this is a problem related to the relative albedo of the excavated materials and the surface onto which they are ejected as well as to the age of the craters. The moon's crust is obviously inhomogenous even on a relatively small scale. The absolute age of the Eratosthenian System has not yet been established, but, Eberhardt *et al.* (1973) have suggested that certain unique glass particles found in the lunar soil are Copernican in origin. These glass particles suggest an age of 900 m.y. for the base of the Copernican System.

Major Basin Stratigraphy

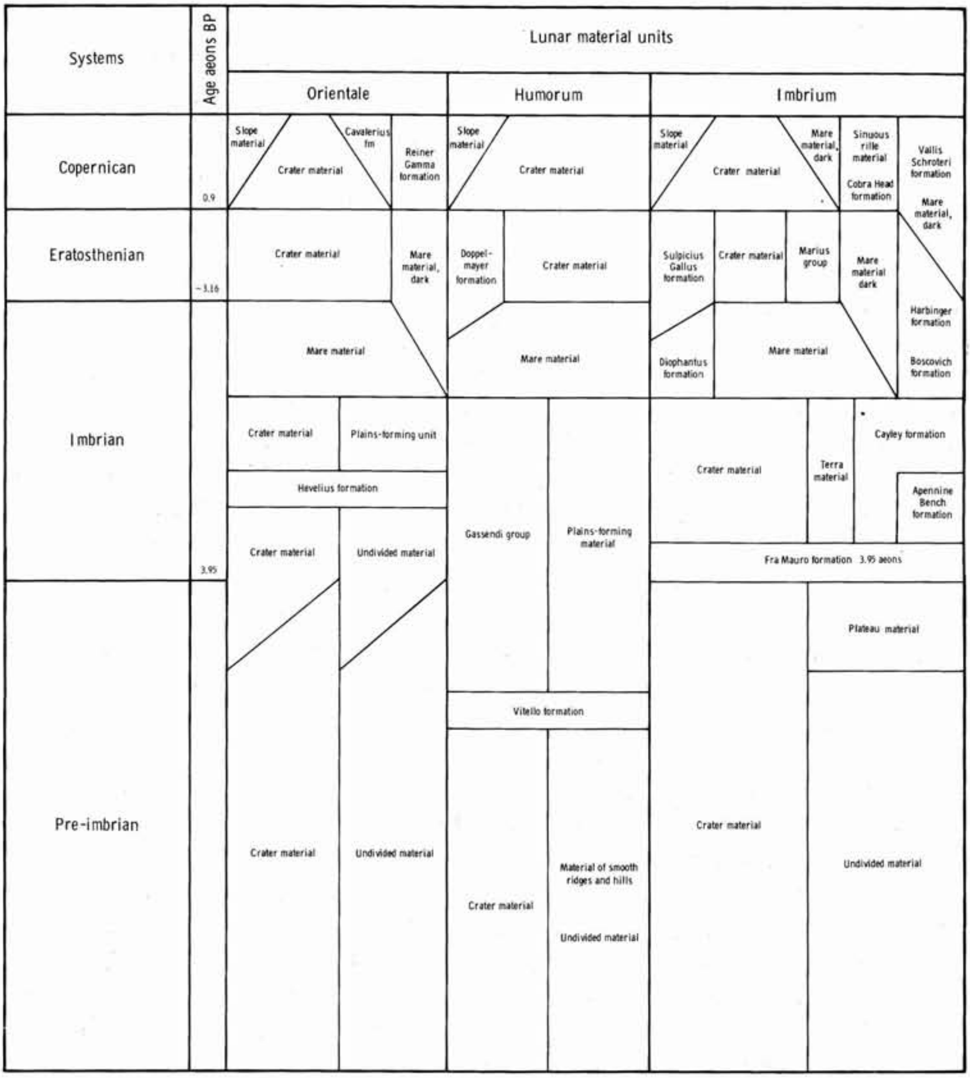
A number of large complex circular structures which have been flooded by mare basalts are readily apparent on the lunar nearside. They generally consist of an inner basin and several outer concentric troughs separated by raised, sometimes mountainous, rings (Hartmann and Kuiper, 1962; Baldwin, 1963; Wilhelms, 1970; Howard *et al.*, 1974). These large ringed basins are not confined to the lunar nearside, but are simply more obvious on the nearside due to the basaltic flooding. At least 43 basins larger than 220 km diameter occur on the lunar surface (Fig. 4.8) (Stuart-Alexander and Howard, 1970). These basins appear to be uniformly distributed over the lunar surface (Howard *et al.*, 1974). Many of the farsided basins appear to be extremely old; some of them eroded to the point where they are barely recognisable (El-Baz, 1973).

The circular multiringed basins are by far the largest structures on the moon and tend to dominate both its stratigraphy and structure. The excavation of a ringed basin is a major event and results in the destruction of much of the previous stratigraphic record. Features such as freshness of structures surrounding the basin and crater density on the ejecta blanket have been used to establish the relative times of formation of several of the major nearside basins (Hartmann and Wood, 1971; Hartmann, 1972; Stuart-Alexander and Howard, 1970; Wilhelms, 1970). The relative ages of some of these basins is shown in Table 4.2.

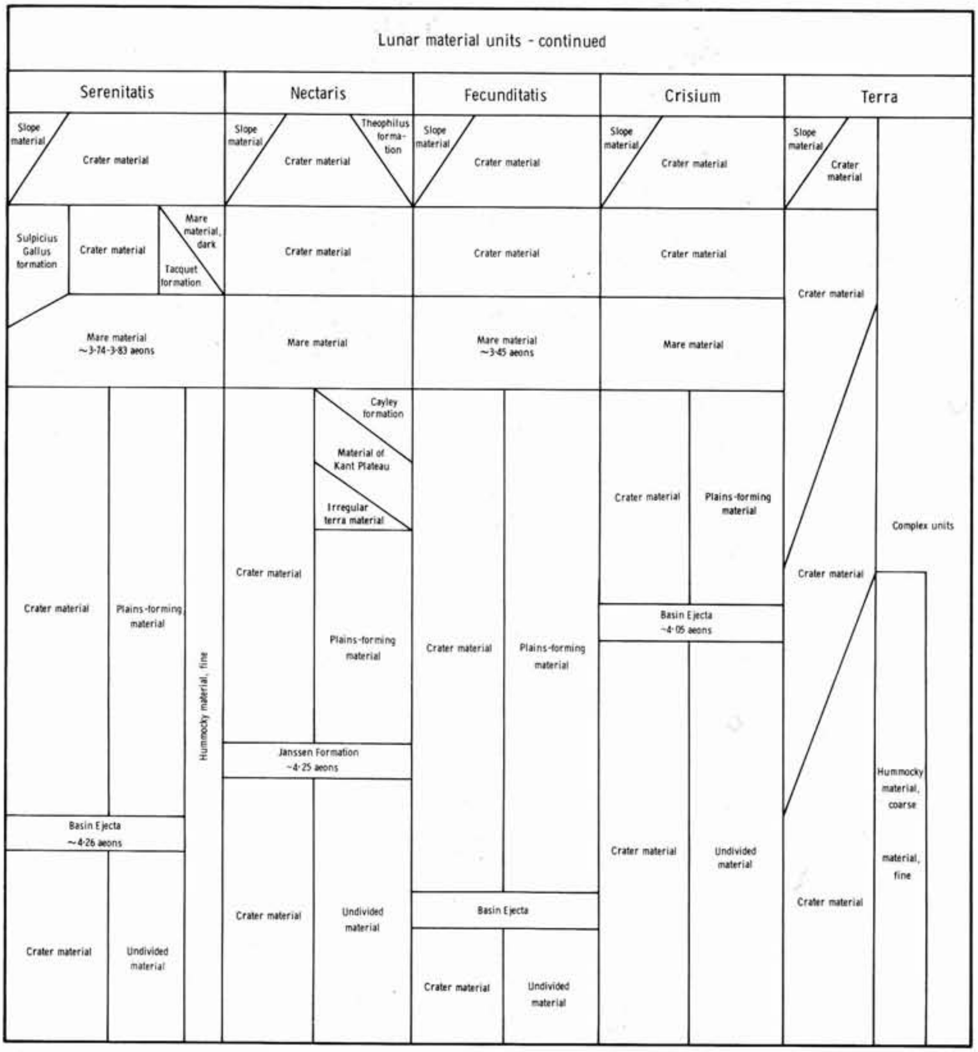
There has recently been considerable debate as to the distribution of these major events in time. The formation of large multiringed basins was clearly terminated prior to the major flooding of the lunar nearside by the mare basalts. The question then is, were these events unique in some way

TABLE 4.1

Composite lunar stratigraphy for seven lunar nearside basins. The columns are arranged in order from east to west across the lunar nearside. Where available, suggested radiometric ages are included beside each stratigraphic unit. The stratigraphy of each basin is initiated by the ejected material from that basin. Not all basin-contemporaneous units have formal stratigraphic names (after Wilhelms, 1970).



that they occurred in a relatively short period of time, or are the events for which we see a stratigraphic record simply the last of many events which obliterated the earlier record?



Tera *et al.* (1973, 1974a, 1974b, 1974c) have investigated the first hypothesis and have argued that there was a terminal lunar cataclysm at approximately 3.95 aeons ago. The cataclysm is suggested to have extended

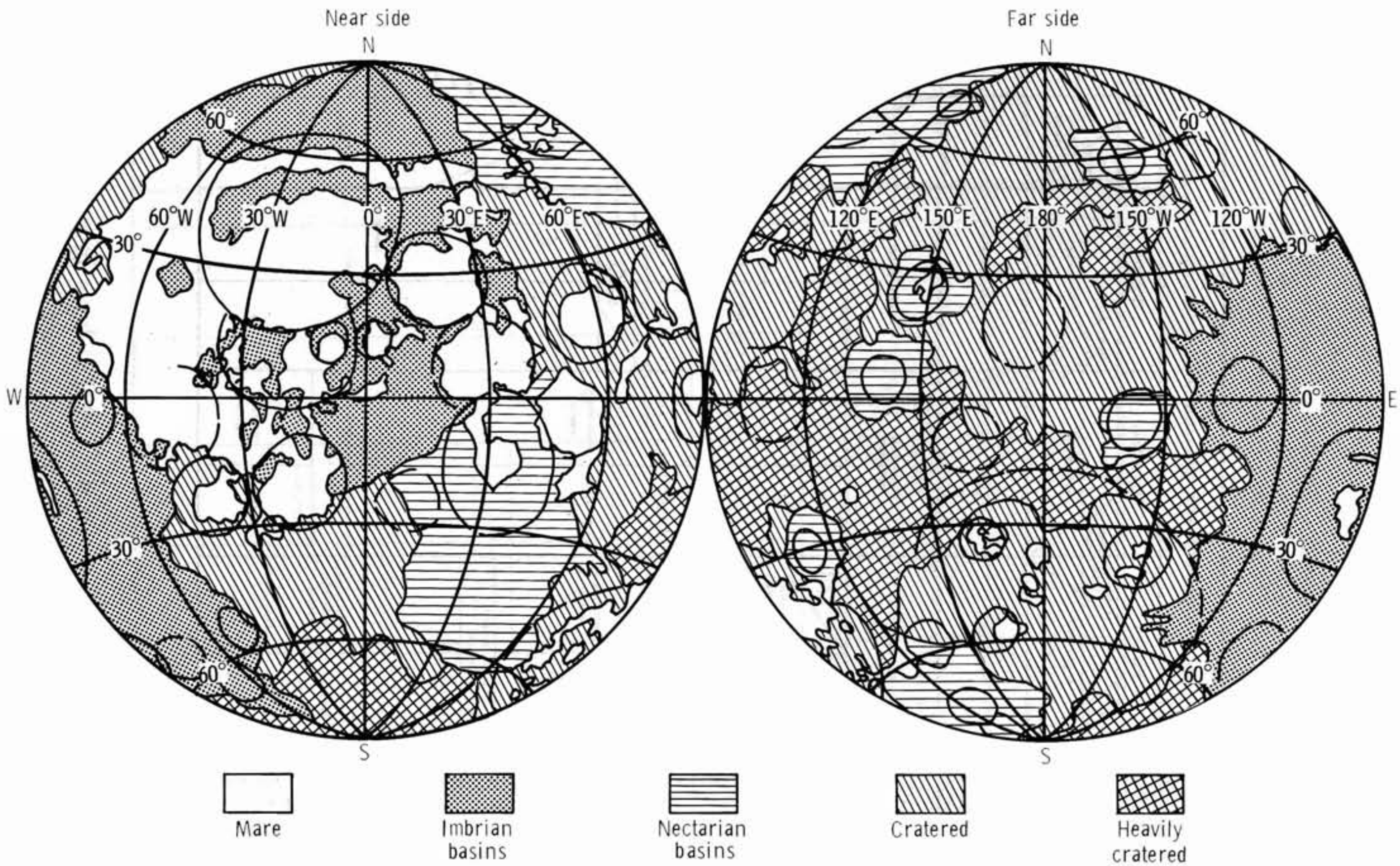


Fig. 4.8. Map showing the location of 43 multiringed basins in relation to the lunar highlands and mare. Imbrian topography is distinguished from older Nectaris basins. Highland areas beyond identified major basin ejecta blankets are subdivided in terms of crater density (from Howard, K.A., Wilhelms, D. and Scott, D.H., *Rev. Geophys. Space Phys.*, *12*, 309-327, 1974; copyrighted by American Geophysical Union).

TABLE 4.2

The size and location of some of the more prominent lunar basins (modified after Stuart-Alexander and Howard, 1970). The basins are listed in approximate order of increasing age.

Name		Location		Diameter	Age
		Longitude	Latitude	(km)	(aeons)
1.	Orientale	−95	−20	900	3.85 ± .05
2.	––	130	−70	300	
3.	Imbrium	−19	37	1250	3.95 ± .05
4.	Crisium	59	17	450	4.05 ± 4.20
5.	––	−129	3	490	
6.	––	−158	−3	450	
7.	Moscoviense	145	25	460	
8.	Bailly	−69	−67	310	
9.	––	141	5	330	
10.	Humorum	−39	−24	430	
11.	Nectaris	34	−16	840	4.25 ± .05
12.	––	160	−53	300	
13.	––	165	−35	370	
14.	near Schiller	−45	−34	350	
15.	––	−148	58	300	
16.	Grimaldi	−68	−5	430	
17.	Serenitatis	19	26	680	4.26 ± .02
18.	––	−153	−35	480	
19.	––	−98	35	320	
20.	Humboltanium	81	58	640	
21.	Pingre	−79	−56	300	
22.	Smythii	84	−3	370	
23.	Fecunditatis	51	−3	480	
24.	––	130	−78	370	
25.	W. Tranquillitatis	27	9	550	
26.	E. Tranquillitatis	38	11	500	
27.	Nubium	−17	−19	750	
28.	––	162	−11	480	
29.	Australe	90	−45	900	

for approximately 200 m.y. from about 3.8 to 4.0 aeons and resulted in global impact metamorphism. The reason for this suggestion is readily apparent from Figure 4.9 where it can be see that radiometric ages are concentrated at between 3.95 and 4.0 aeons. Husain and Schaeffer (1975)

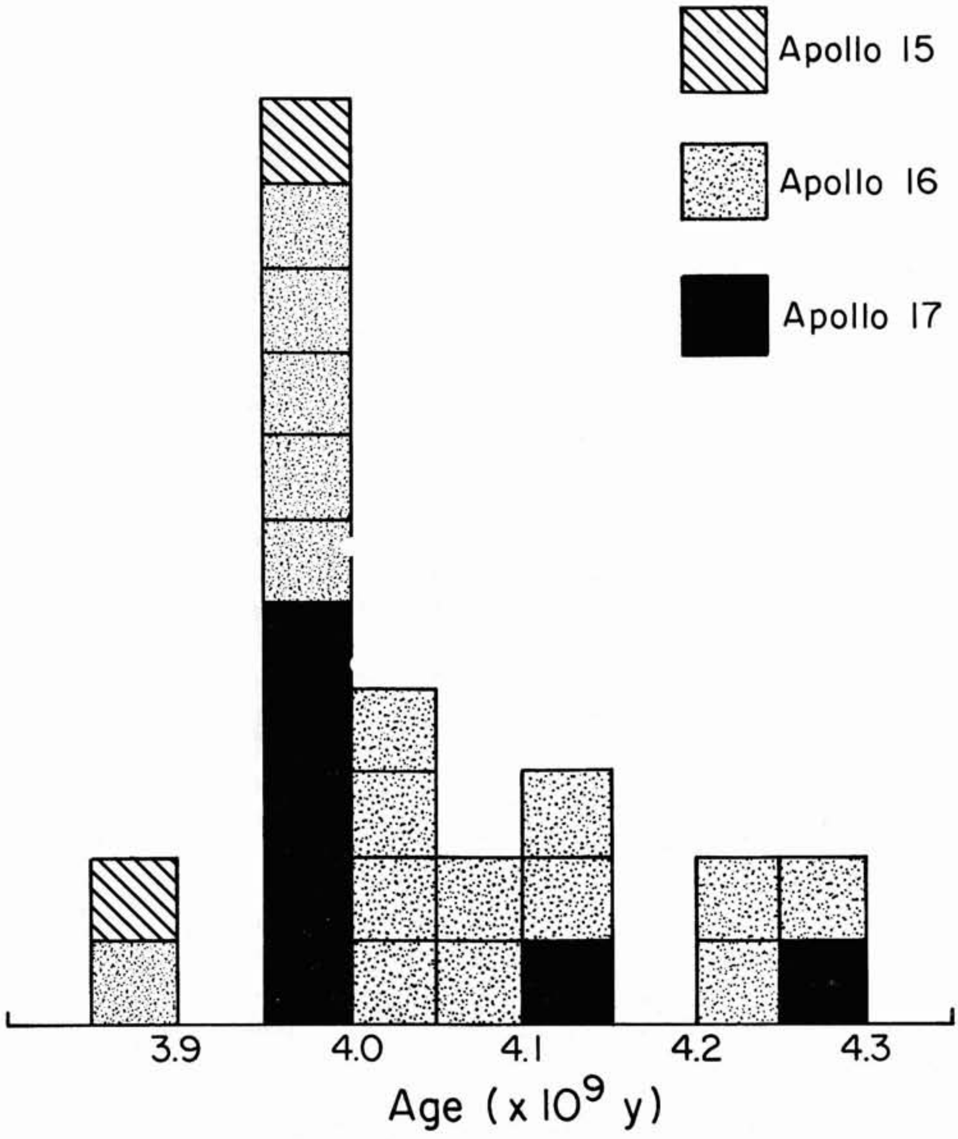


Fig. 4.9. A histogram of the ages of Apollo 15, 16 and 17 breccia samples (from Husain and Schaffer, 1975).

and Schaeffer and Husain (1974) have taken the second view of the origin of the large multiringed basins. They have carefully evaluated the lithology of the breccia samples used in the radiometric analyses and the relative importance of each major basin ejecta blanket at the Apollo landing sites. They have found that ejecta from the Imbrium Basin event, that is, the Fra Mauro Formation for the most part, dominates at all of the Apollo landing sites (Fig. 4.10). Consequently they have concluded that the dominant ages in the 3.95 to 4.0 aeon range simply date the Imbrium event. The Imbrium ejecta blanket is thinnest at the Apollo 16 and 17 sites and it is at these two sites that a number of radiometric ages exceeding 4.0 aeons have been found. As a result of this stratigraphic and radiometric age analysis they have been able to associate absolute ages with several of the major basin forming events (Table 4.2 and Fig. 4.10). They conclude that the era of basin formation extended over many hundreds of millions of years of lunar time up to the excavation of the Orientale Basin. This is consistent with the identification of very old and poorly defined basins on the lunar farside (Stuart-Alexander and Howard, 1970; El-Baz, 1973; Howard *et al.,* 1974). Some of these basins are so badly eroded that they only appear as depressions in the lunar crust and are only recognisable in laser altimeter data. They are undoubtably older than any of the basins listed with radiometric ages in Table 4.2.

Pre-Imbrian Stratigraphy

The pre-Imbrian includes, by definition, all units older than the Imbrium Basin ejecta blanket, that is the Fra Mauro Formation. In terms of geologic time the deposition of the Fra Mauro Formation was essentially instantaneous and it, or at least its lower contact, can be regarded as a time plane. As previously discussed the excavation of the Imbrium Basin occurred approximately 3.95 aeons ago. The use of the Fra Mauro Formation as a time plane and the separation of the Imbrian System from pre-Imbrian units is in many ways an accident both of man and nature. The Imbrium Basin was next to the last of the multiringed basins to be excavated. Consequently, its general features are still clearly discernable in the topography. The Imbrium Basin is also clearly visible from the earth, in contrast to the younger Orientale Basin, only half of which is visible on the lunar nearside. Because almost all of the original stratigraphic studies were made using earth based telescopic photographs the Imbrium area with its clearly defined stratigraphic relations was a prime candidate for study. If the original stratigraphic studies had not been made until after the moon had been photographed from orbit the definition of many time stratigraphic terms may have been

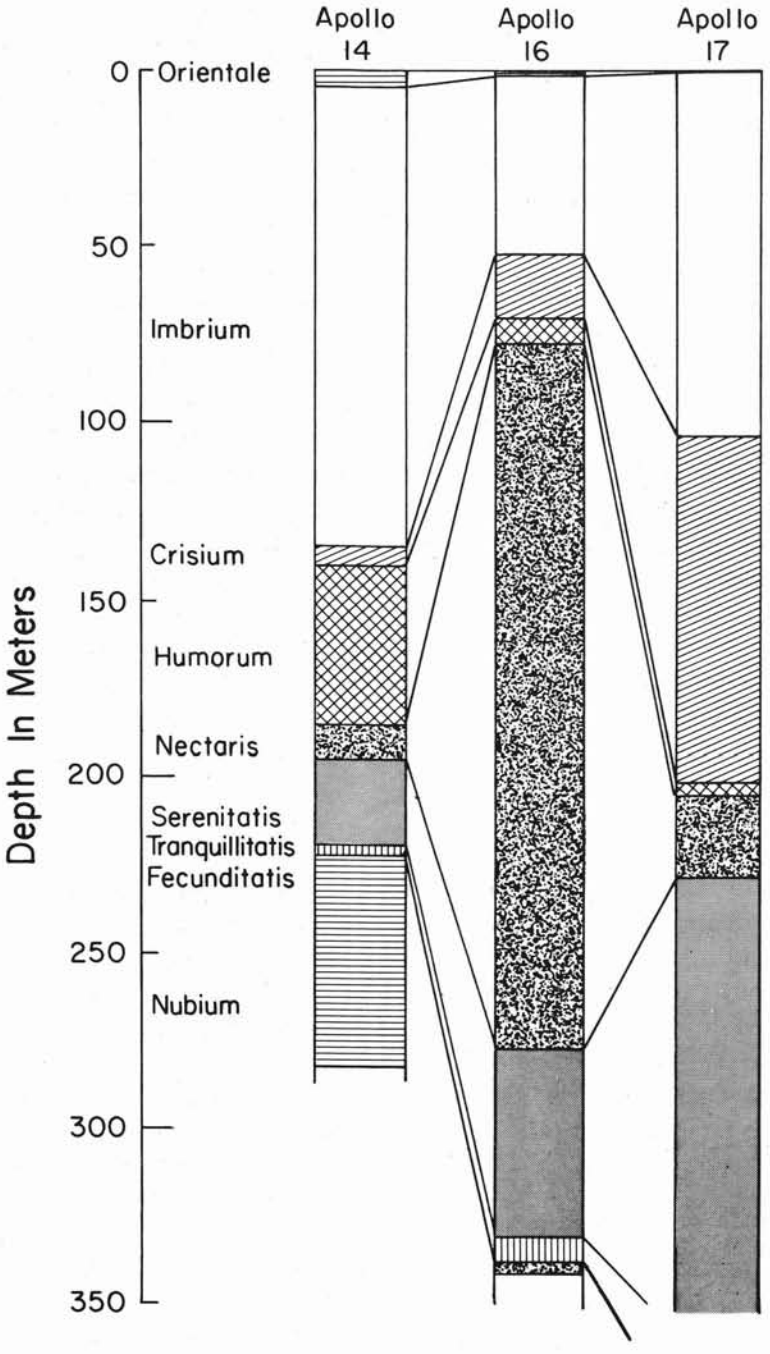


Fig. 4.10. Depth of ejecta, from large basin forming events, at the Apollo 14, 16 and 17 sites (from Schaffer and Husain, 1974).

entirely different.

Most of the pre-Imbrian stratigraphy mapped on the lunar nearside is associated with the older multiringed basins and is of the same age as or younger than the basins but older than the mare material filling the basins. There are thus a large number of stratigraphies, some of which are illustrated in Table 4.1, which are similar to the relationship of the Imbrian units to the Imbrium Basin. Clearly pre-Imbrian stratigraphy will ultimately be divided into many more time-stratigraphic units as the moon's stratigraphy is studied in more detail. The ejecta blanket associated with multiringed basin could be used in the same way as the Fra Mauro Formation to define the time planes subdividing pre-Imbrian time.

Beyond the limits of the Fra Mauro Formation and the Imbrian sculpture the age of material units can not be determined confidently relative to the base of the Imbrian System (Wilhelms, 1970). The top of the Imbrian System is clearly defined in many areas because the mare basalts are wide spread. Frequently material units can be dated in relation to the mare material, either by superposition or by crater density. Consequently some units can not be confidently dated except to say that they are at least Imbrian and possibly pre-Imbrian.

The lower portion of all of the major basin stratigraphies in Table 4.1 are shown as crater material. This broad designation has been established to distinguish very old subdued and degrading craters from the younger Eratosthenian craters. These old crater materials are overlain by the basin-contemporaneous ejecta units which are genetically equivalent and probably lithologically similar to the Fra Mauro Formation. The relative age for some of these units is shown diagramatically in Table 4.1 as are their possible radiometric ages. It should perhaps be pointed out that while the ages given in both Tables 4.1 and 4.2 are absolute their association with a particular multiringed basin is based on, and limited by, stratigraphic interpretations. The only event dated with any real confidence is the Imbrium event due to the fact that Apollo 14 sampled the Fra Mauro Formation directly.

Another series of unnamed pre-Imbrian (and Imbrian) units common to each major basin stratigraphy are the so-called plains forming materials (Wilhelms, 1970). The material units form smooth horizontal surfaces with a high albedo that resemble the Apennine Bench and Cayley Formations of Imbrian age. The last two units are discussed in the following section and in Chapter 5. These units occur over most of the lunar surface generally in the depressions or troughs around each multiringed basin and on the shelf between the inner basin and the first high mountain ring. The light plains units embay the rugged terrain of the basin-contemporaneous units and generally are not cut by the same faults which transect the circum-basin materials. The implication is that the light-plains material units are younger than the ejecta of the associated multiringed basins. The genesis of the plains materials is not well understood and because the stratigraphic relations with the morphologically similar Imbrian units is not known they are generally regarded as either pre-Imbrian or Imbrian in age. Further crater materials occur superimposed on the basin-contemporaneous units. These crater materials are clearly younger than the basin ejecta but older than the mare fillings. The craters range in age across the Imbrian–pre-Imbrian boundary.

The pre-Imbrian, despite its lack of subdivision, is in fact a relatively short time period (≈550 m.y.) compared to the Imbrian and Eratosthenian and is comparable in time available to the post-Cambrian period on the earth. When seen from the point of view of the potential for subdividing the pre-Imbrian time period we quickly realize that ultimately this very early period of the moon's history will be better understood than either Proterozoic or Archaean on the earth. In fact, in some ways, the ancient lunar stratigraphy is likely to be better understood ultimately than the post-Imbrian period simply because most of the post-Imbrian history of the moon is only recorded in the very thin lunar soil where the time resolution may not be good.

The Imbrian System

The Imbrian System has not been formally defined. However, Wilhelms (1970) who produced the most complete summary of lunar stratigraphy, has stated that the base of the Imbrian System is the Fra Mauro Formation and the top is mare material. It thus includes all of the time between the excavation of the Imbrium Basin and the ultimate filling of the basin by basalt flows. The term "Imbrian System" was originally applied to the hummocky blanket surrounding Mare Imbrium (the present Fra Mauro Formation) by Shoemaker and Hackmann (1962). Since this time the Imbrium System has gone through a large number of modifications mostly on a relatively informal basis (Wilhelms, 1970; Shoemaker *et al.*, 1962; Hackmann, 1962; Marshall, 1963). Material units included within the Imbrian System are listed in stratigraphic order in Table 4.1.

The Fra Mauro Formation

The Fra Mauro Formation forms the basal unit of the Imbrian System (Fig. 4.11.). The term was first used by Eggleton (1964, 1965) although the formation was not formally defined until much later (Wilhelms, 1970). The type area lies between latitudes 0° and 2°S and longitudes 16° and 17°30'W to

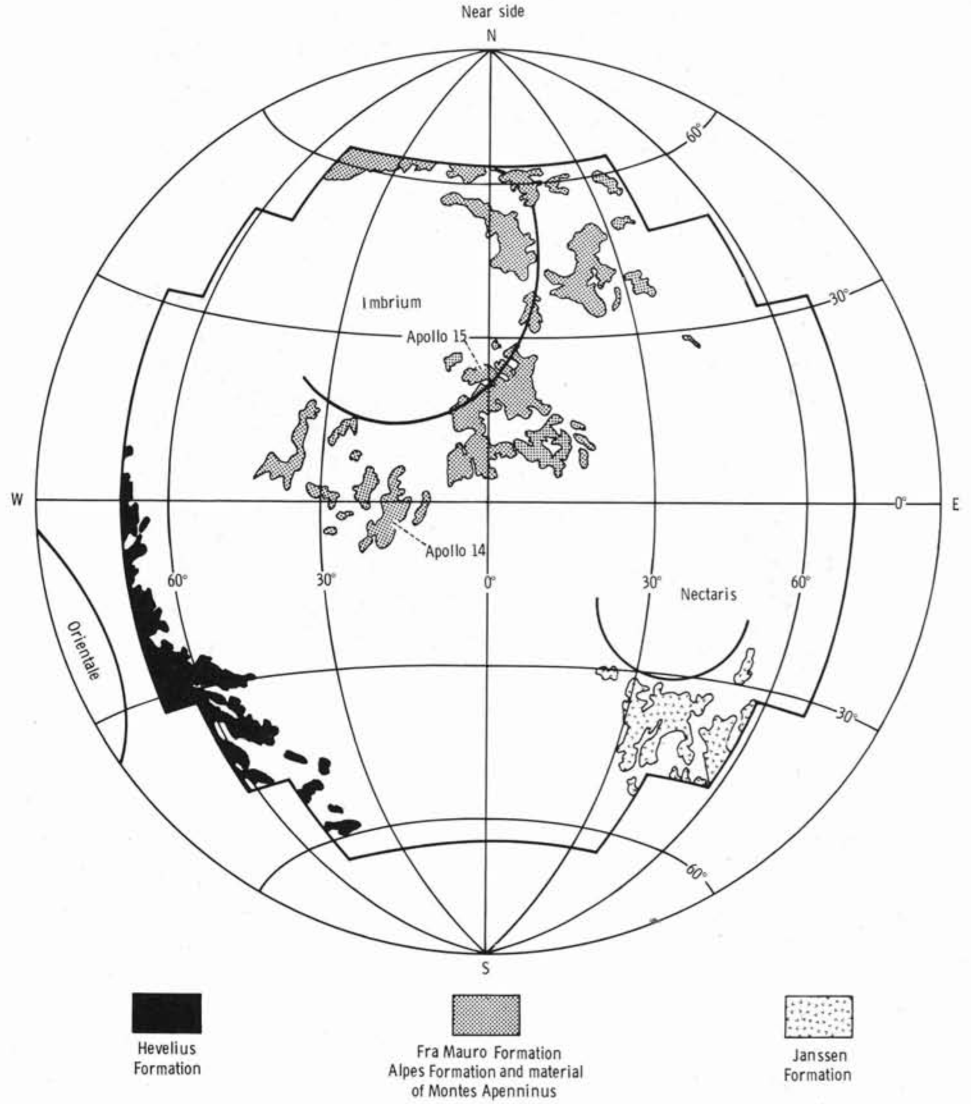


Fig. 4.11. Nearside of the moon showing textured basin ejecta (from Howard, K. A., Wilhelms, D. E. and Scott, D. H., *Rev. Geophys. Space Phys., 12:* 309-327, copyrighted American Geophysical Union).

the north of the pre-Imbrian crater Fra Mauro after which it is named. Eggleton isolated two members (facies) on the basis of topography, one with a hummocky surface, the other smooth. The type area is in the hummocky facies where the surface consists of abundant closely-spaced hummocks (Fig. 4.12). The hummocks are low rounded hills 2-4 km across and are approximately subequidimensional although there is a tendency towards a

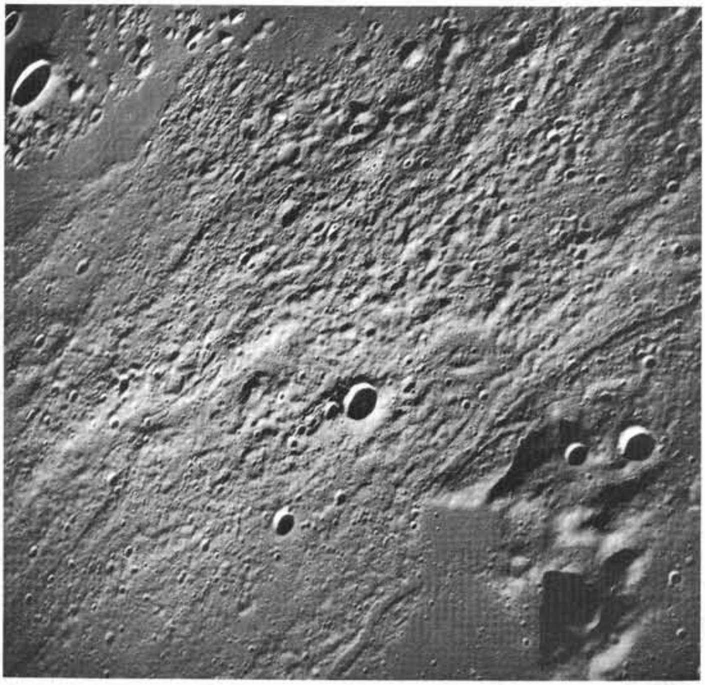


Fig. 4.12. The Fra Mauro Formation close to its type area south of Mare Imbrium. Note the hummocky nature of the formation in the north and the gradual increase in smoothness further south (NASA Photo AS12-52-7597).

north-south elongation. The regular nature of the topography suggests that it is a single depositional unit which probably consists of ejecta resulting from the excavation of the Imbrium Basin. Samples of the Fra Mauro Formation returned by the Apollo 14 mission support this view. They consist of poorly-sorted breccias which are metamorphosed to varying degrees. Chapter 5 is devoted largely to a discussion of these lithologies.

In the vicinity of the type area the formation averages 550 m in thickness although lateral variations in thickness are considerable due to the variable relief of the pre-Imbrian terrain (Eggleton, 1963). Other local estimates of the thickness of the Fra Mauro Formation have been made by McCauley (1964) and Eggleton and Offield (1970) who, like Eggleton (1963) used the degree of burial of pre-Imbrian craters in relation to crater size to make the estimates. Kovach *et al.* (1971) used active seismic data to determine the thickness of the Fra Mauro Formation at the Apollo 14 site and concluded that it is between 46.5 and 84.5 m thick. McGetchin *et al.* (1973) made estimates of the thickness of the Fra Mauro Formation using empirically derived formulae based on cratering models. Their estimates of the radial thickness variations are shown in Figure 4.13. In general this empirical model agrees well with all other available estimates and is

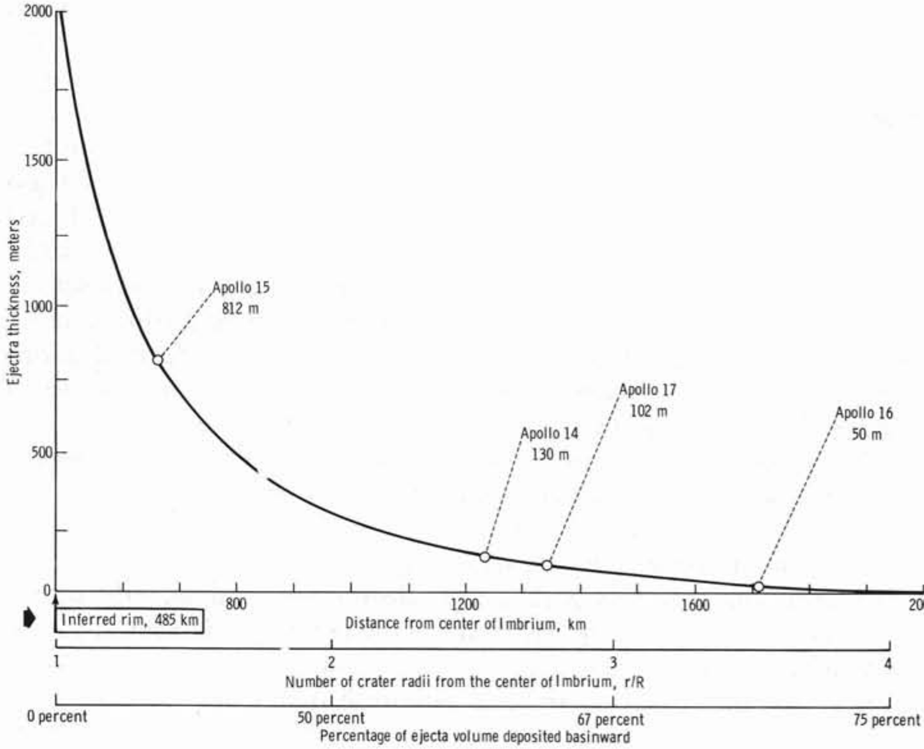


Fig. 4.13. Radial thickness variation of the Fra Mauro Formation (from McGetchin *et al.*, 1974).

consistent with a base surge depositional model (see Chapter 3). From Figure 4.13 it can be seen that the formation thins dramatically away from the basin and that 50 per cent of the ejected material lies within one crater (basin) radius of the inferred rim of the Imbrium Basin.

Exposures of the Fra Mauro Formation are relatively limited in extent beyond the type area by mare basalt flooding and light-plains units which may be Cayley Formation (see following section). Correlations beyond the type area are difficult but the formation is believed to extend all around the Imbrium Basin (Wilhelms, 1970) which is again consistent with cratering models.

Beyond the type area of the Fra Mauro Formation away from Mare Imbrium the hummocks on the surface of the formation gradually disappear and it grades into the "smooth" member (Fig. 4.12). The surface of this member has very low ripple-like hummocks or sinuous ridges. In general this member occurs farther from the basin than the hummocky member. However, local occurrences of the smooth member are found on topographic highs closer to the basin. It is difficult to visualize the transportational mechanism involved in an event of the magnitude of the Imbrium event. However, the regular nature of the hummocky terrain and the fact that the hummocky terrain dies out farther from the basin suggests transport by a giant base surge, at first in supercritical flow and then becoming subcritical as the flow is decelerated by loss of momentum due to gas loss. This is also consistent with the occurrence of the smooth member on topographic highs which presumably caused a momentary local braking of the flow. If base surge was the primary mechanism of transport the regular hummocks may be related to antidune structures. The 2-4 km dimensions of the hummocks in the type area would imply flow velocities of the order to 23 to 32 m s^{-1} which is consistent with base surges of a much smaller scale formed during terrestrial volcanic eruptions and experimental explosions. Mean velocities of this order of magnitude would require about 20 hr to complete the deposition process. The textural evidence from the breccias that suggests base surge is discussed in more detail in the following chapter.

The Cayley and Apennine Bench Formations

Plains-forming materials with a high albedo occur abundantly on the lunar nearside. Stratigraphic relationships in the northern and central part of the lunar nearside suggest that these plains are younger than the Fra Mauro Formation and the associated Imbrian sculpture, but older than the local mare basalts (Wilhelms, 1970). The Apennine Bench Formation consists of light plains-forming materials near the crater Archimedes and was defined originally by Hackmann (1964, 1966). Similar high albedo plains occur in a circum-Imbrium trough in the vicinity of the crater Cayley (Wilhelms, 1965; Morris and Wilhelms, 1967). Morris and Wilhelms defined this material unit as the Cayley Formation (Fig. 4.14). The Cayley Formation appears independent of Imbrium sculpture, and is embayed by mare basalts from Mare Tranquillitatis. It occurs in topographic lows and generally has a smooth and horizontal surface. The contacts of the Cayley Formation with surrounding units are extremely variable ranging from sharp to gradational. Locally many occurrences of Cayley Formation merge into areas of subdued topography without a detectable change in albedo. Milton (1968) and Wilhelms (1968) refer to these material units as the "hilly" member of the Cayley Formation.

Prior to the Apollo landings the Cayley Formation was generally believed to be volcanic in origin, and to consist either of flows or pyroclastic materials (Wilhelms, 1970). The Apollo 16 landing site (Fig. 4.14) was selected in part to determine the nature of the Cayley Formation; it would have been particularly important if it had in fact been the result of late stage volcanism. As a result of this mission it can be concluded that the Cayley

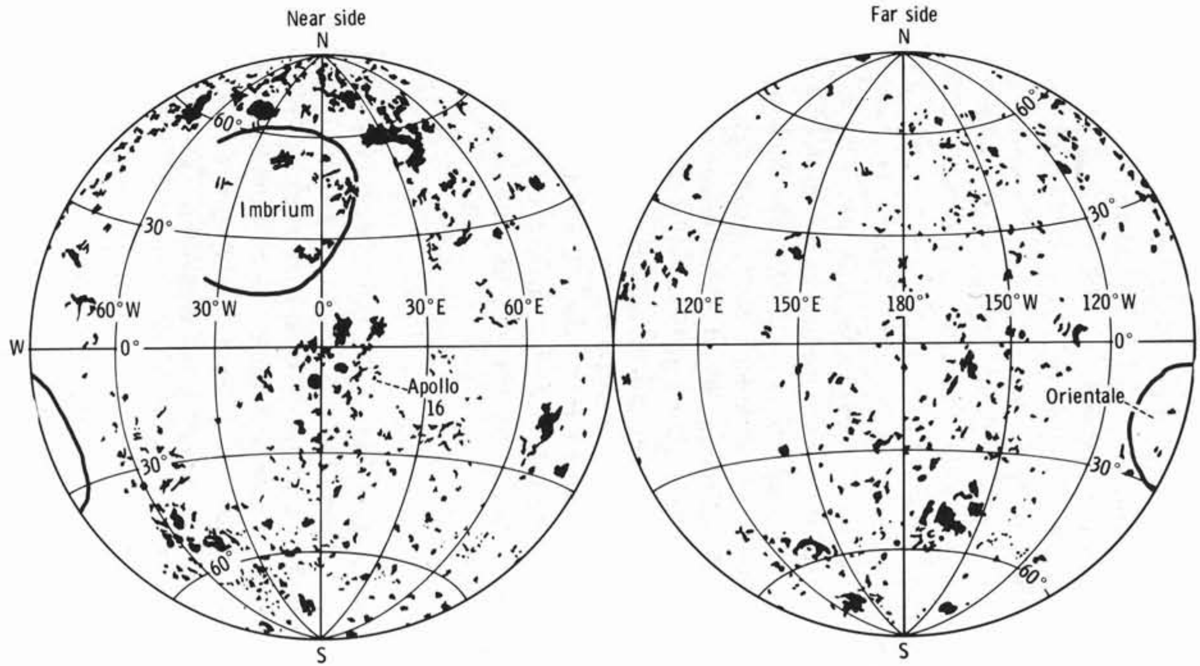


Fig. 4.14. Distribution of Imbrian age plains (Cayley Formation). The Apollo 16 landing site is indicated. Plains tend to be concentrated outside the ejecta blankets of the Orientale and Imbrium basins (from Howard, K. A., Wilhelms, D. E. and Scott, D. H., *Rev. Geophys. Space Res., 12:* 309-327, copyrighted American Geophysical Union).

Formation is not volcanic in origin but consists of impact generated clastic rocks (Warner *et al.,* 1973; Wilshire *et al.,* 1973; Walker *et al.,* 1973; Bence *et al.,* 1973). The problem is which event or events to associate the formation with. There are essentially three theories of its origin (1) it is ejecta from a large basin-forming event possibly Orientale, (2) it is secondary ejecta from a large scale event such as Orientale, or (3) it is locally derived material moving down slope, filling depressions by slumping or possibly as secondary ejecta. Several authors (Hodge *et al.,* 1973; Eggleton and Schaber, 1972; Chao *et al.,* 1973) have argued that the Cayley Formation is extremely widespread (Fig. 4.14) and occurs in areas well beyond the potential source event at Orientale. If McGetchin *et al.*'s (1973) empirical relationship is correct the Orientale ejecta deposits would be extremely thin at many Cayley Formation occurrences, particularly at the Apollo 16 site, and the volumetric requirements for such an extensive unit would be unrealistic in terms of this one event. This last problem is more easily resolved if we appeal to the mechanism proposed by Oberbeck *et al.* (1974) which suggests that the Cayley Formation consists of secondary ejecta produced by Orientale ejecta. This cascade effect could potentially double the volume of available materials. Possibly the strongest evidence in favor of a local origin for the Cayley Formation comes from orbital geochemical data (Hörz *et al.,* 1974). There is no systematic relationship between either Al/Si values determined by the X-ray fluorescence experiment or the Th values determined by gamma ray counting and the mapped distribution of the Cayley Formation (Fig. 4.14). In general the Cayley Formation is similar in composition to the surrounding surficial deposits.

The Orientale Basin

The Orientale Basin (Fig. 4.15) is the only large multiringed basin younger than the Imbrium Basin. The material units surrounding this basin are very similar in their texture and distribution to the Fra Mauro Formation (McCauley, 1964). The inner hummocky facies which extends for about 900 km has not been formally named but is undoubtably genetically equivalent to the hummocky facies of the Fra Mauro Formation. The name Hevelius Formation has been applied to the smooth outer facies.

McCauley (1969) described some very distinctive topography on the hummocky material units surrounding the Orientale Basin. Dune-like structures and braided surfaces appear intermixed on the surface of the unit (Fig. 4.16). The dunes are often more pronounced in front of major topographic obstacles whereas the braids are best developed on level upland surfaces. These features are again very suggestive of bedforms produced during super-critical flow and probably relate to a very large base surge

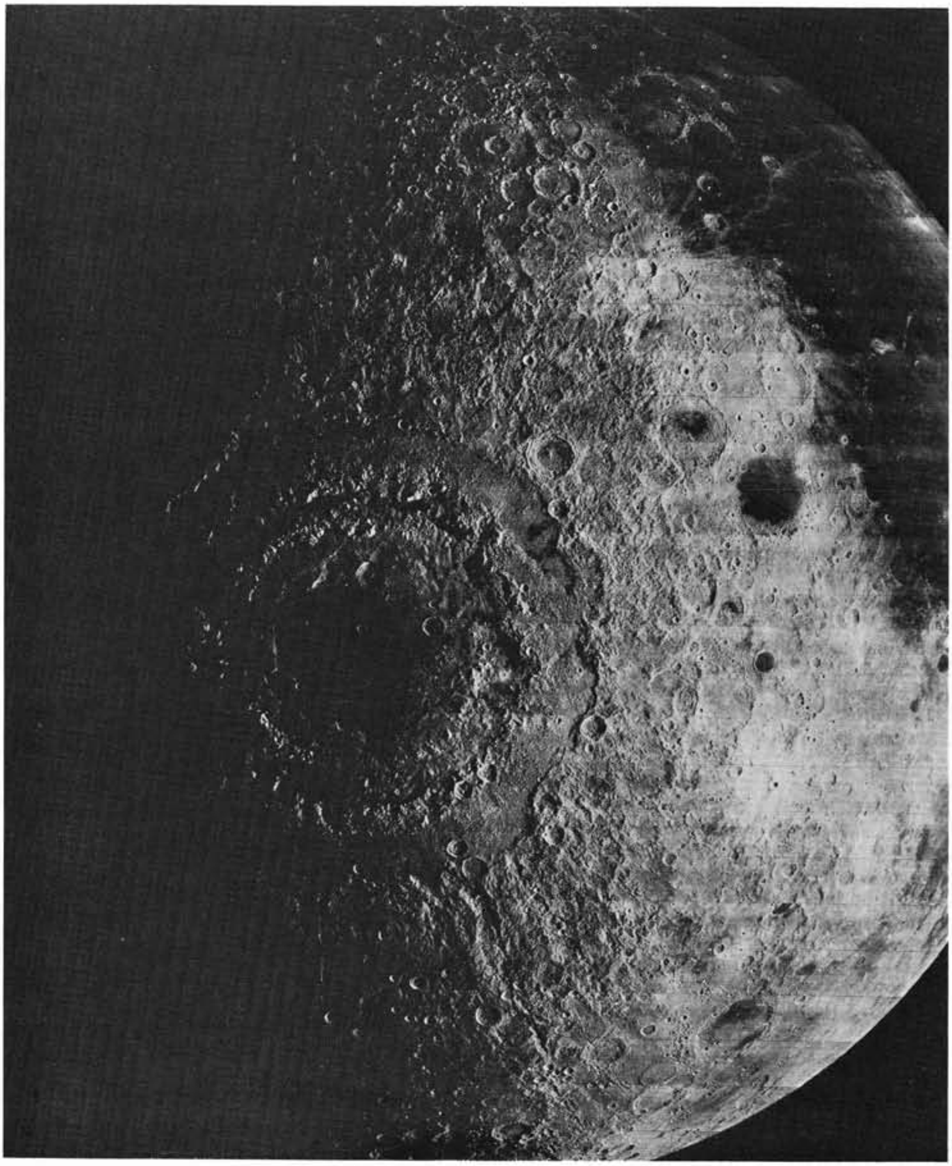


Fig. 4.15. An orbital view of the Orientale Basin surrounded by its braided and hummocky ejecta blanket. The annular mountain ranges are clearly visible. Mare Orientale is approximately 900 km in diameter (NASA Photo Lunar Orbiter IV-M 187).

flowing outward from the Orientale Basin immediately following its excavation. The topographic relationships suggest that the braided bedforms may develop on flat surfaces at higher velocities, while the dune-like structures occur where local topography has reduced the velocity of the

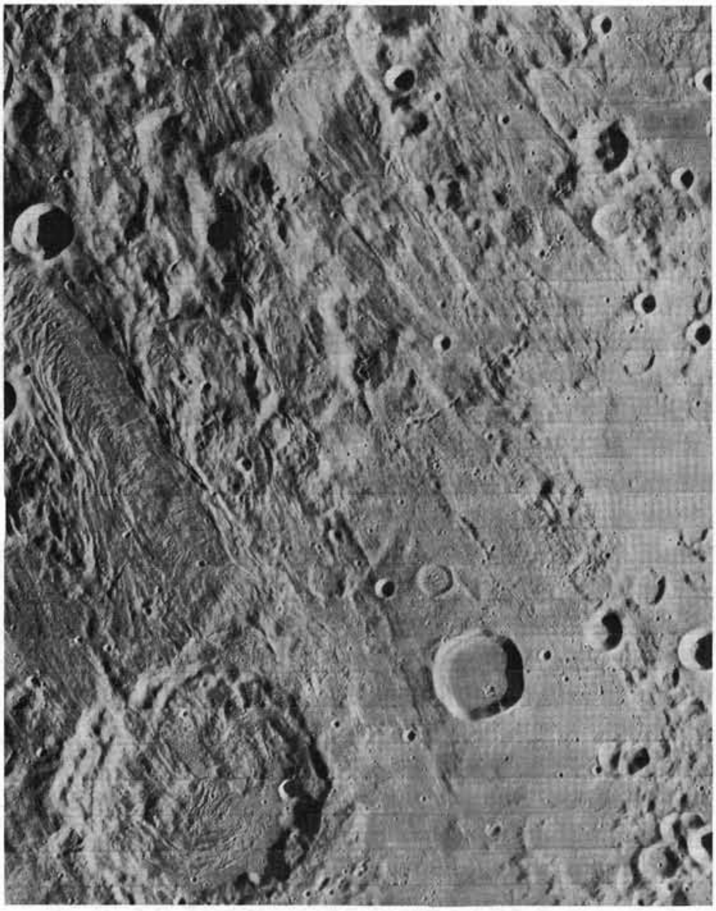


Fig. 4.16. Braided ejecta materials surrounding Mare Orientale. This area lies about 1100 km southeast of Mare Orientale. The crater Inghirami is about 90 km across and is only partly covered by the swirling braided ejecta (NASA Photo Lunar Orbiter IV-H172).

flow.

The Orientale Basin itself has several concentrically arranged scarps which form two mountain ranges (Fig. 4.15). The inner range is called the Rook Mountains and the outer-most range the Cordillera Mountains. The origin of these regularly arranged concentric scarps has been much debated (Hartmann and Yale, 1968; Dence, 1974; van Dorn, 1968; Baldwin, 1972). The scarps may be related either to shock waves produced during cratering or to tectonic subsidence following cratering. The center of the basin inside the Rook Mountains is flooded by mare basalts. The material unit between the Rook and Cordillera Mountains has been informally called the Montes Rook Formation. It is distinguished by a relatively irregular topography of small, smooth and closely spaced hills. On the insides of the Montes Rook Formation a second material unit with a higher albedo can be distinguished.

These units may be either fall back or slump fractured rim deposits (McCauley, 1968). Due either to great age or mare basalt flooding similar deposits are not readily apparent in other multiringed basins.

The Orientale material units are clearly older than the mare basalts. The lower density of craters on the Hevelius Formation and its hummocky correlative strongly suggest that they are younger than the Fra Mauro Formation. This is supported further by the sharpness and freshness of the basin scarps. If Schaeffer and Husain (1974) are correct in their analysis the Orientale Basin was formed 3.85 aeons ago (Tables 4.1 and 4.2) which places it early in Imbrian time.

The Mare

The dark smooth surfaces with low albedo which form the lunar nearside mare (Fig. 4.17). are obvious even to the casual observer standing on the earth's surface. Perhaps the first important contribution by Apollo to our knowledge of the moon was to verify early suggestions that the mare consisted of basalt flows (Baldwin, 1949; Kuiper, 1954; Fielder, 1963).

Because, when studying the stratigraphy of the moon, we are dealing mainly with material units, Wilhelms (1970) defines mare material as being "dark flat and smooth" and locally having "characteristic ridges and domes." The only other units which could be confused with mare materials are the smooth flat materials similar to the Cayley Formation. The main differences between these units and the mare are related to the interdependent variables of crater density and albedo. These variables simply reflect age – the mare material being much younger.

Baldwin (1963) and Mutch (1972) both recognized the presence of old lava flow fronts on the mare surface (Fig. 4.18), particularly in southwestern Mare Imbrium. It thus became clear that the mare were similar to terrestrial flood basalts such as the Deccan Traps and that the mare were probably underlain by an extensive stratigraphy. When Apollo 15 landed beside Hadley Rille in southern Mare Imbrium this view was further supported by observations of massive layering in the opposite rille wall (Fig. 4.19).

The sequence of well-defined flow fronts visible under low-angle lighting conditions in southwestern Mare Imbrium has received detailed attention (Schaber, 1973), and has provided considerable insight into the mare filling process. These late stage basalt flows are believed to be Eratosthenian in age. The age is based on crater counts and in light of past problems should be treated with caution until the validity of the method is more firmly established.

The eruption of the flows occurred in at least three phases (Fig. 4.20). The source of the youngest lava appears to be a 20 km long fissure close to

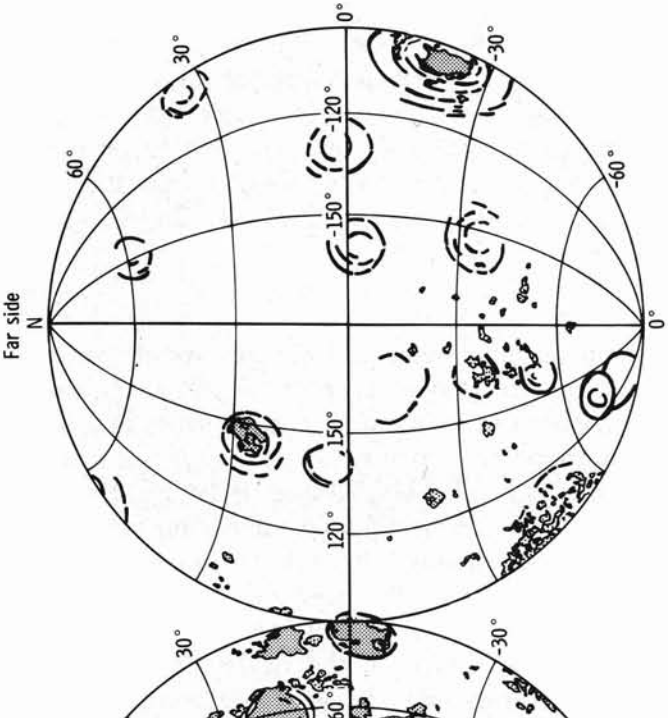


Fig. 4.17. Distribution of mare (shaded) and large circular basins. The highest mountain ring of each is shown by a heavy line; secondary mountain rings are shown by the light lines (after Stuart-Alexander and Howard, 1970).

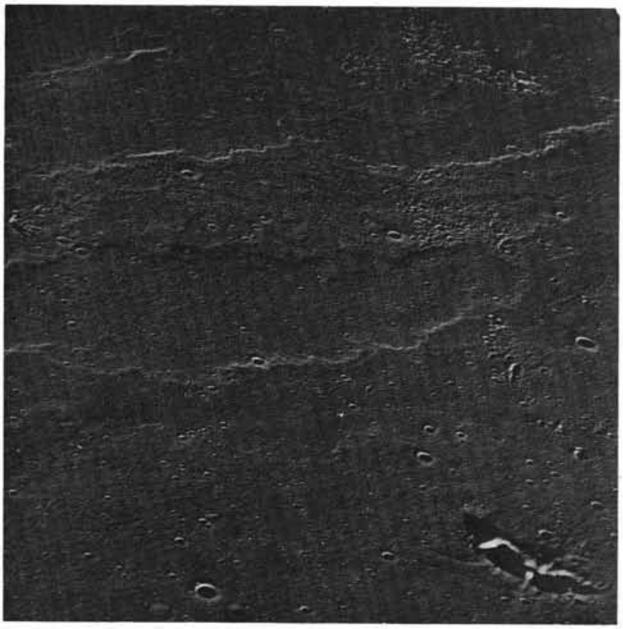


Fig. 4.18. A well-defined lava flow front on the surface of Mare Imbrium (NASA Photo AS15-96-13023).

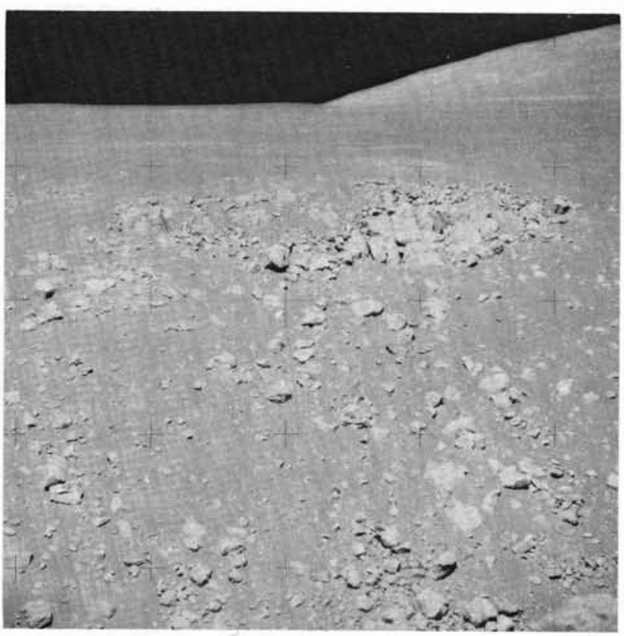


Fig. 4.19. Massive horizontally bedded units in the wall of Hadley Rille (NASA Photo AS15-89-12100).

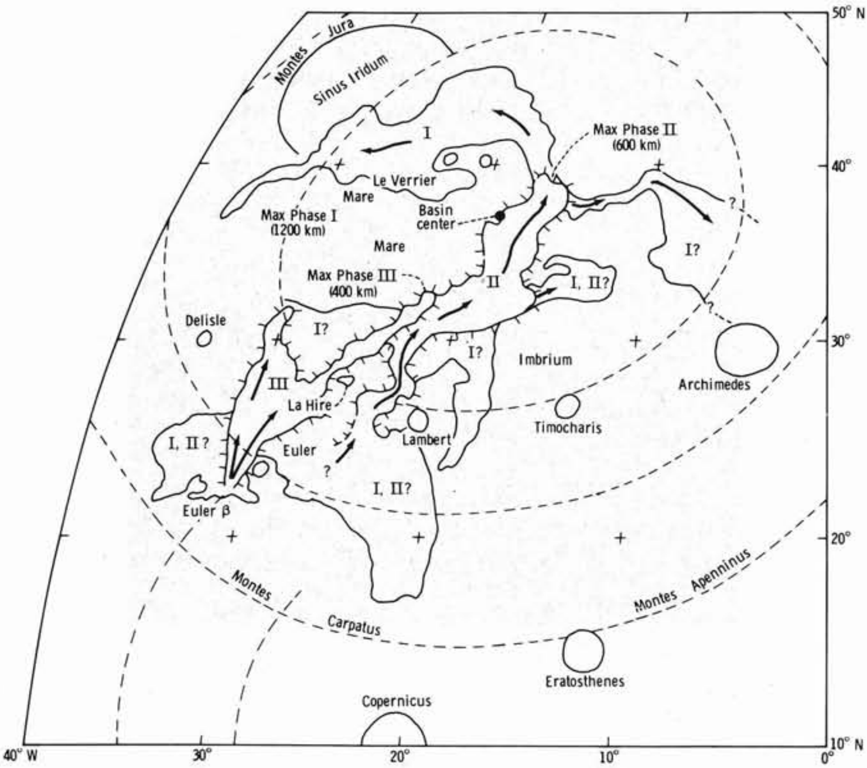


Fig. 4.20. Distribution of late-stage mare basalt flows in the Imbrium Basin (from Schaber, 1974; *Proc. 4th Lunar Sci. Conf., Suppl. 4, Vol. 1,* Pergamon).

the crater Euler at 22°50' N and 31°20' W near the southwestern edge of Mare Imbrium. Possibly significant is the fact that this source lies close to a seismically active region (Latham *et al.,* 1974) and in an area where the Imbrium Basin appears to intersect an older poorly-defined basin. This suggests that the migration of lava to the surface may be controlled by faults associated with the major multiringed basins. The lavas from the three eruptive phases extended 1200, 600, and 400 km respectively indicating a gradual decrease in magma volume with time. These flows accounted for a volume of at least 4×10^4 km^3 over an area of 2×10^5 km^2. The figures are of a similar order of magnitude as terrestrial flood basalts.

Individual lava flows range from 10 to 63 m in thickness and flowed down slopes with a gradient between 1:100 and 1:1000. The flows surmounted local uphill slopes of at least 0.5° but locally were ponded behind mare ridge crests. Leveed channels developed at the ridge as the lava overflowed some ridges. Deep leveed channels are also present along the center of some flows and braided channels have been seen near source vents (Schaber, 1973). Lava channels are common on the earth but the lunar lava channels are several orders of magnitude larger. The extreme distances to which the flows travelled on the lunar surface probably related to a rapid rate of extrusion of the lava with low melt viscosity playing a secondary role. It could thus be construed that the mare are underlain by a well-stratified complex sequence of basaltic flows.

Mare Surface Features. The extreme smoothness of most of the mare surfaces make the few topographic features all the more pronounced. While many minor topographic features have been described there are two large scale features apparent in most mare; rilles and wrinkle ridges.

The use of the term "rille," which was originally helpful in terms of classifying lunar topographic features, is perhaps, in the long term, unfortunate. There are three general types of rille which relate to at least two different mechanisms; straight, arcuate and sinuous (Schubert *et al.*, 1970; Schumm, 1970; Howard *et al.*, 1972; Oberbeck *et al.*, 1972). Straight and arcuate rilles appear to be genetically related (Figs. 4.21 and 4.22). They may be many kilometers long and several kilometers across. Typically these features transect both mare and highland surfaces and there appears little

Fig. 4.21. Graben-like straight rilles transecting mare and highland surfaces (NASA Photo AS14-73-10115).

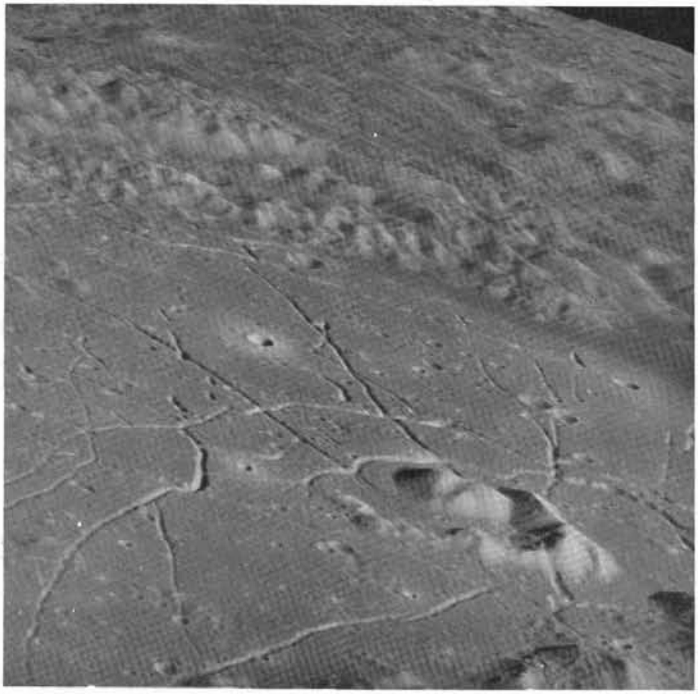


Fig. 4.22. Straight and arcuate rilles in combination (NASA Photo AS15-93-12642).

reason to suggest that they are anything but fault controlled graben-like structures (McGill, 1971; Mutch, 1970; Young *et al.,* 1973).

Sinuous rilles, as the name suggests, look like meandering river channels (Fig. 4.23) which, in the past, led some authors to suggest that they were eroded by water (Lingerfelter *et al.,* 1968; Schubert *et al.,* 1970). The majority of sinuous rilles occur along the edge of the mare, sometimes running along the highland front but never crossing into the highlands (Fig. 4.24). In cross section the rilles may be V-shaped but generally their profiles are more U-shaped and give the impression of having been smoothed or subdued by subsequent erosional processes (Fig. 4.25 and 4.26). In some cases rilles have flat floors and inner sinuous channels (Fig. 4.27). Longitudinal profiles of sinuous rilles generally slope in the same direction as the regional slope (Gornitz, 1973) (Fig. 4.28). However, there are some unexplained anomalies which are inconsistent with open-channel fluid flow. For example, the source of Prinz I Rille is deeper than its termination, perhaps suggesting that the crater was drained by an alternate channel. Marius Hills Rille displays a rise where it crosses a wrinkle idge. The gradient

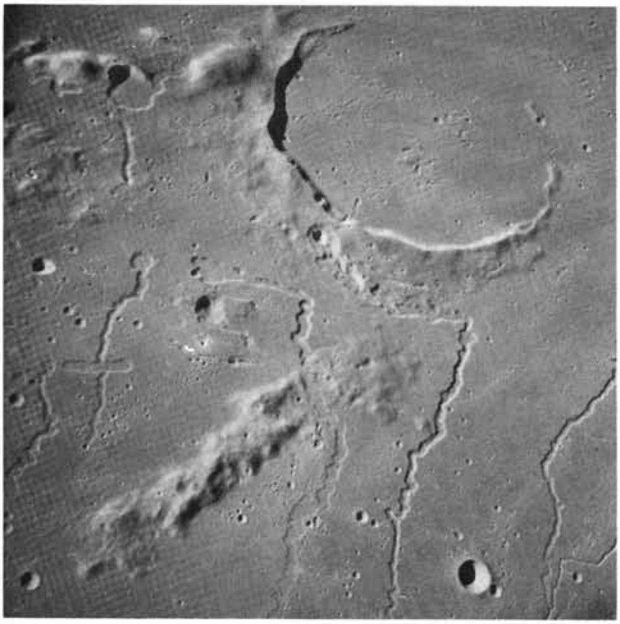


Fig. 4.23. Sinuous rilles on the Aristarchus Plateau. Most are flat bottomed and some have inner sinuous channels. The large partially flooded crater (Prinz) at top right is ≈40 km in diameter (NASA Photo AS15-93-12608).

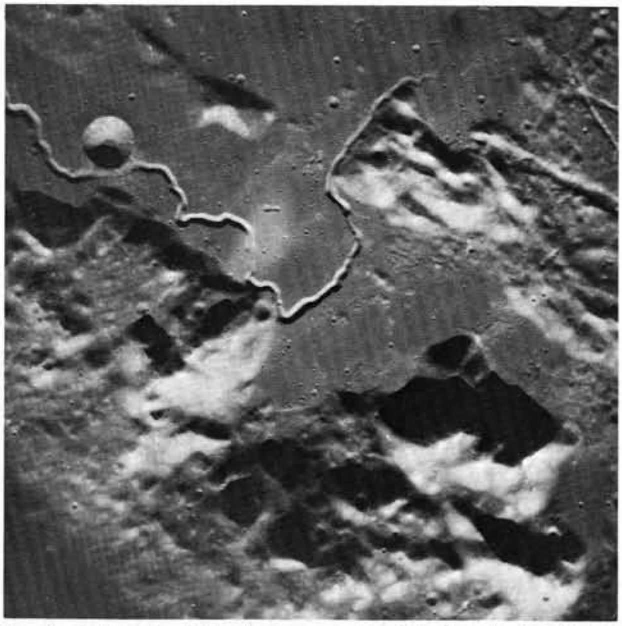


Fig. 4.24. An orbital view of Hadley Rille the sinuous rille visited by the Apollo 15 mission. Note that the rille follows the mare-highland boundary for short intervals but never crosses into the highlands; thus implying a genetic association with the mare filling (NASA Photo AS15-94-12813).

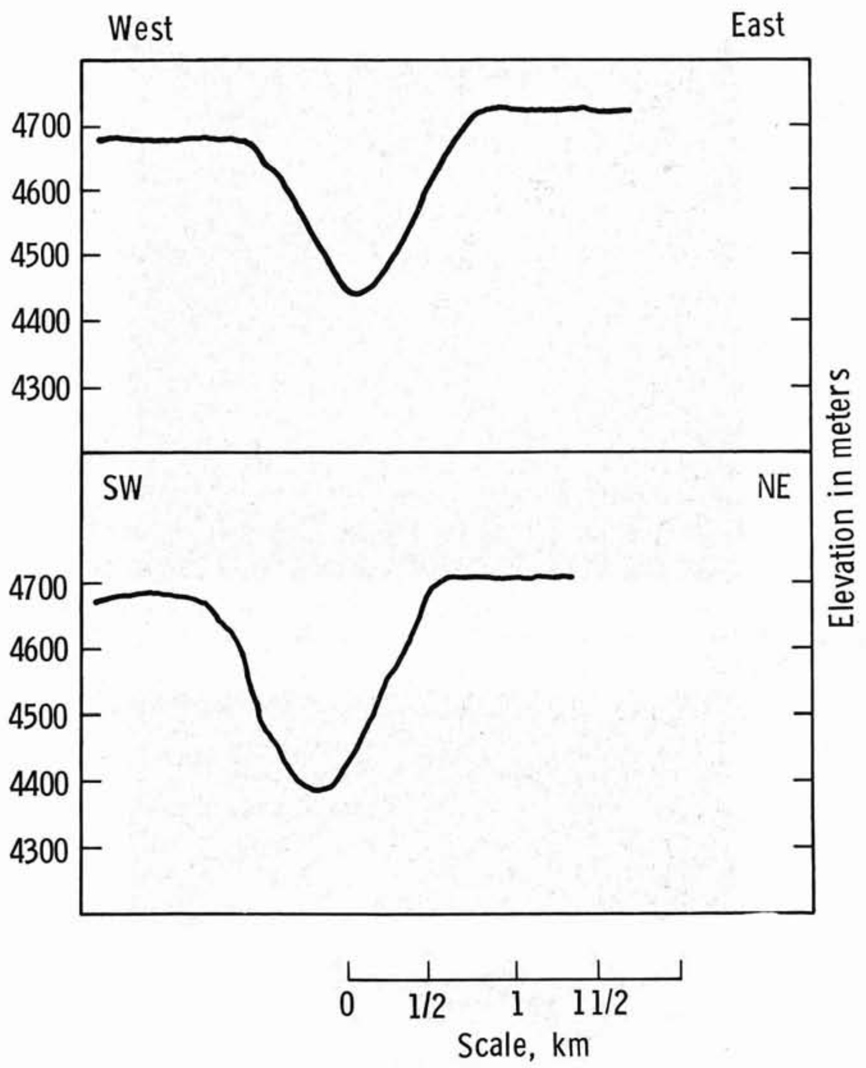


Fig. 4.25. Cross sections of Hadley Rille (from Gornitz, 1973).

of the rilles typically ranges from 0.0224 to 0.0026. These gradients are steeper than some terrestrial rivers crossing their flood plains. The dimensions of some sinuous rilles cover a considerable range but show some internal consistencies. The relationship between depth and width are roughly linear (Fig. 4.29). They have walls which slope between 10° and 23° with an average slope of 17° (Gornitz, 1973). The meander length of the rilles is approximately twice the channel width. The radius of curvature of the rille

Fig. 4.26. Hadley Rille viewed from the level of the mare surface. Notice the subdued appearance of the rille and the large numbers of boulders which have rolled to the rille floor (NASA Photo AS15-85-11451).

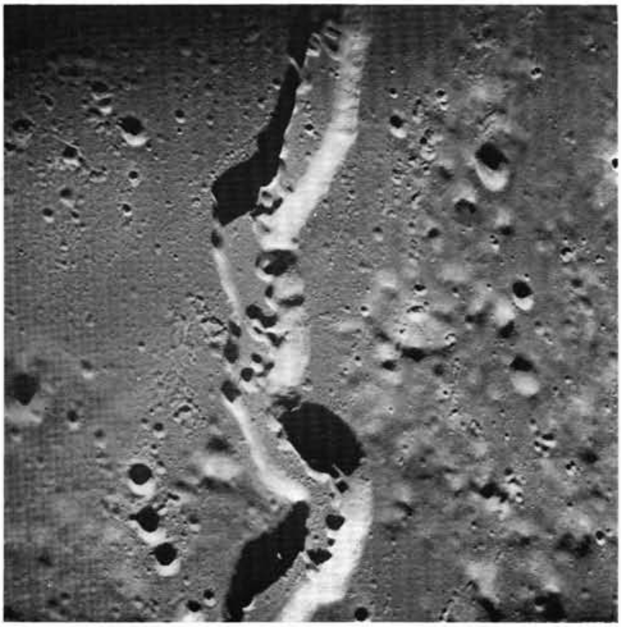


Fig. 4.27. Schroeters Valley, a broad flat-bottomed sinuous rille with an inner channel (NASA Photo AS15-97-13258).

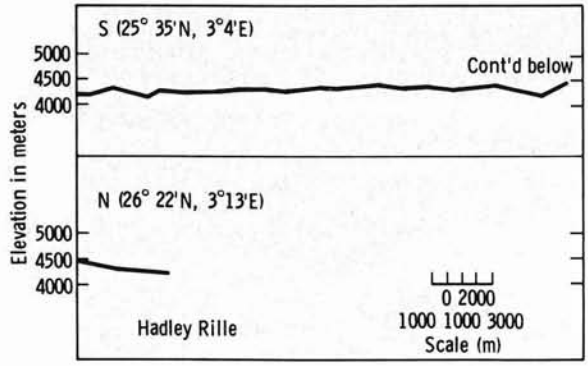


Fig. 4.28. Longitudinal bottom profile of Hadley Rille (from Gornitz, 1973).

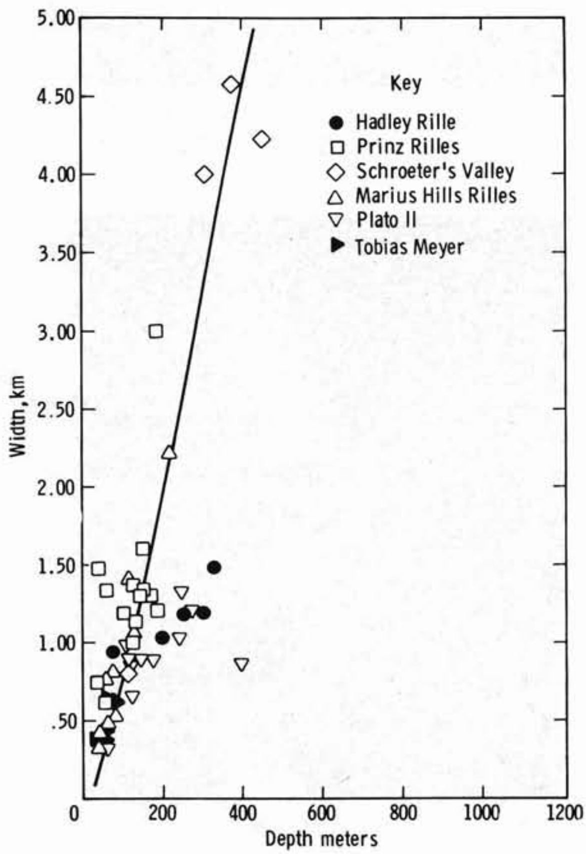


Fig. 4.29. Relation between width and depth of sinuous rilles (after Gornitz, 1973).

meanders is generally less than 1 (Fig. 4.30) in contrast to rivers where it may be as much as 4.3. No correlation exists between channel width, meander length or radius of curvature. This is in contrast to terrestrial rivers but much more in keeping with lava tubes and channels. Sinuous rilles are thus wide relative to meander length and the radius of curvature is small. The consensus at the present time is that most sinuous rilles are lava tubes, the roofs of which have collapsed presumably due to meteoroid bombardment (Howard *et al.*, 1972). Arcuate depressions are seen in places on the mare surface following sequentially in a sinuous path (Fig. 4.31). The depressions may in fact be the partially collapsed roof of a sinuous lava channel or due to later stage fissure eruptions. Young *et al.* (1973) have pointed out other evidence of partial bridging of sinuous rilles. The abrupt termination of many rilles in a downstream direction is also consistent with a lava tube origin as lava tubes may disappear upon entering lava lakes or pools. Finally the overall geometry is most similar to terrestrial lava tubes.

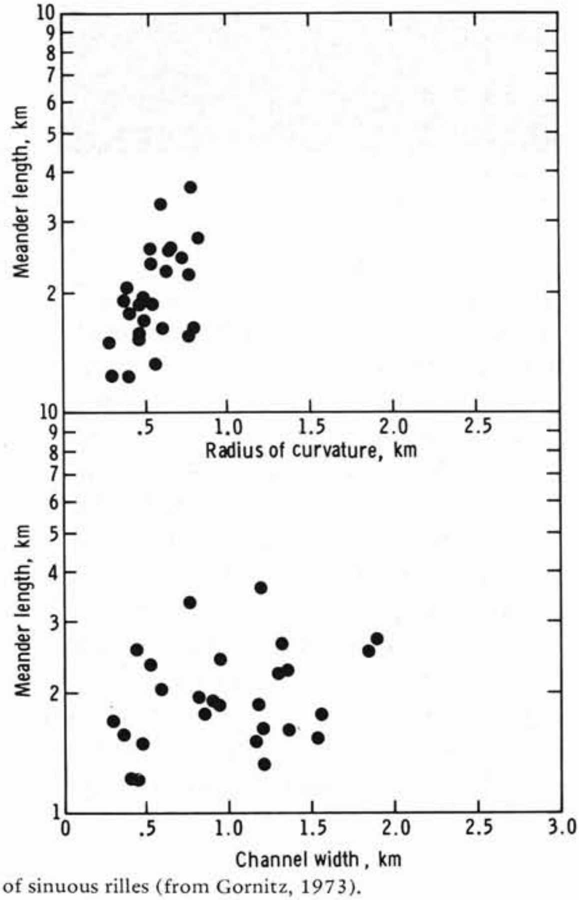


Fig. 4.30. Geometry of sinuous rilles (from Gornitz, 1973).

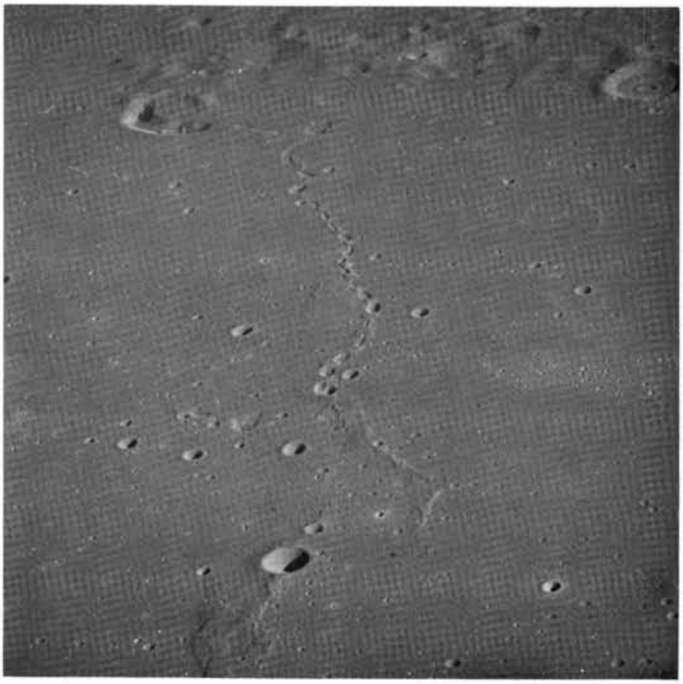


Fig. 4.31. This sinuous line of depressions may indicate the presence of a partially collapsed lava tube or a late stage fissure (NASA Photo AS15-93-12725).

Some rilles have conspicuous levees along their margins. They are generally less sinuous than other rilles and have been interpreted as being open channels on the surface of lava flows (Young *et al.*, 1973). The rilles are large by comparison with terrestrial equivalents and it has been difficult to accept a simple lava tube or channel hypothesis. However, Carr (1974) has carried out a series of simulation studies based on our present understanding of the conditions of the lava during extrusion, and he has shown that such channels may develop very rapidly (Fig. 4.32). The erosion rate is very sensitive to the difference between the lava temperature and the yield temperature. The results of Carr's work imply that large amounts of erosion are possible under conditions of sustained flow and that lava channels may deepen at rates in excess of 1 m per month on the lunar mare.

Sinuous rilles of volcanic origin are presumably of the same age as the surface flows in which they occur. The length of sinuous rilles thus give indications of the dimension of lava flows flooding the mare. Some rilles extend for between 300 and 400 km showing the extreme mobility of the lunar lavas.

Wrinkle ridges (Fig. 4.33) are intimately associated with mare materials. The ridges are generally concentric to the basin but radial ridges also occur.

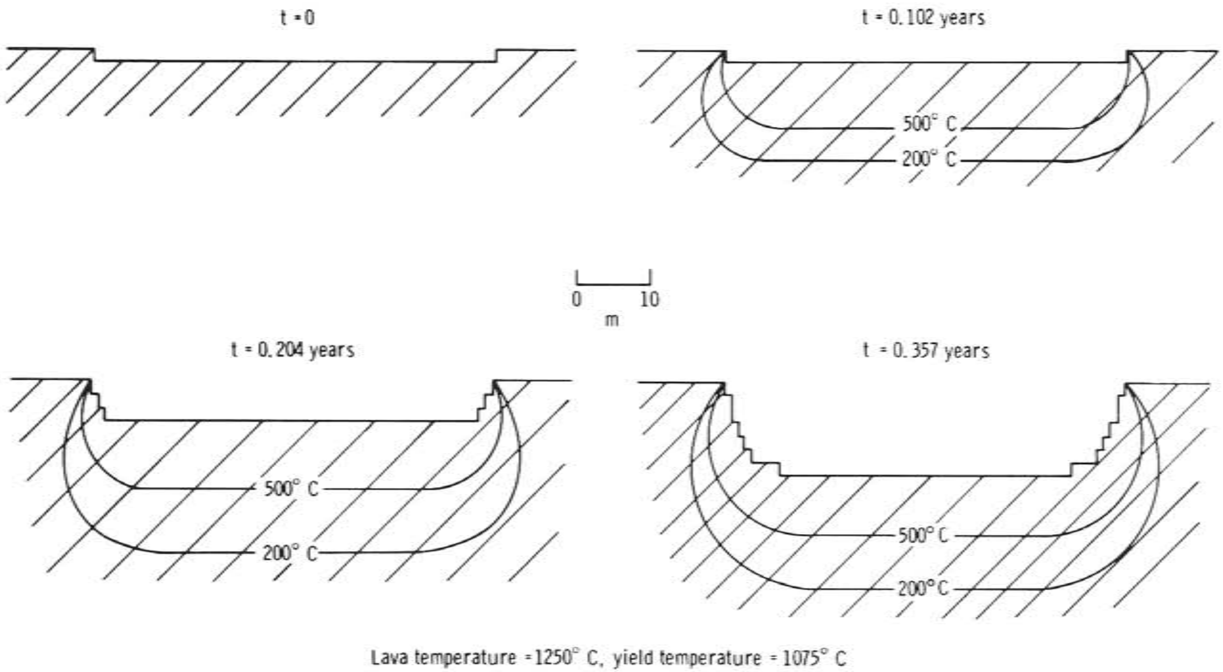


Fig. 4.32. Computer modelling of the growth of a lunar lava channel. Growth is rapid because of the high lava temperatures (after Carr, 1974).

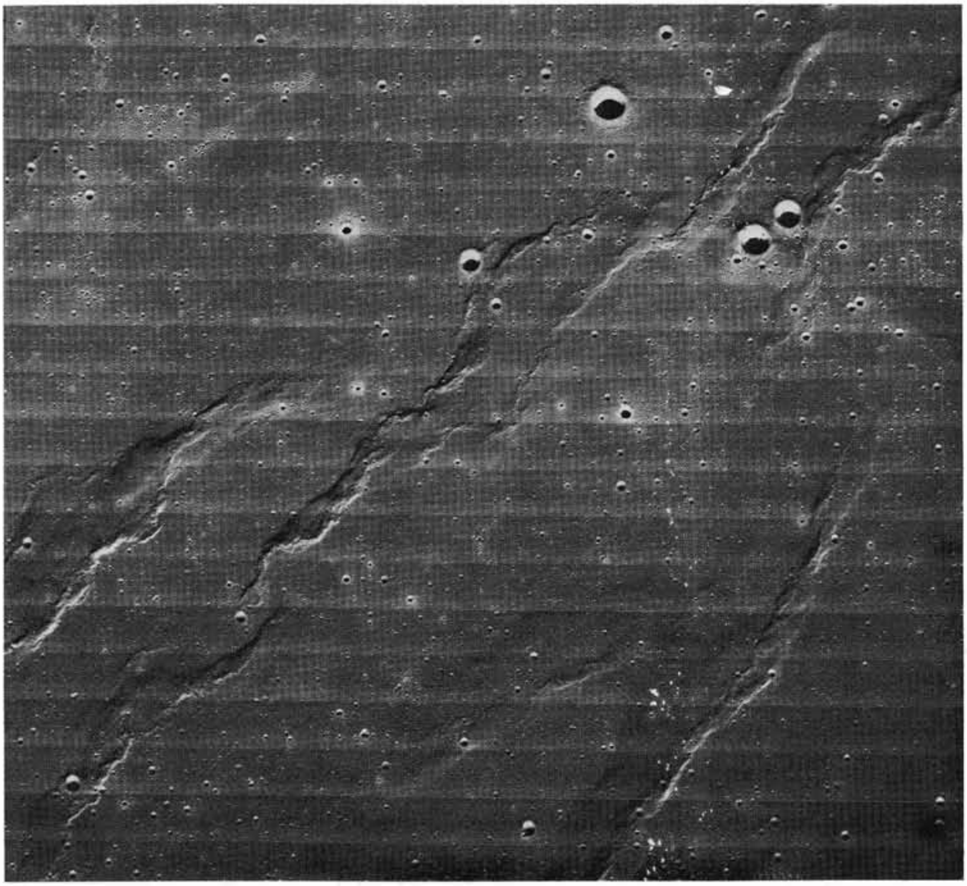


Fig. 4.33. Wrinkle ridges in Oceanus Procellarum (3°50' S, 36° W). The ridges in view are maximum 3 km wide (NASA Photo Lunar Orbiter V-M172).

The ridges may develop as low swells concurrently with the inpouring of the most recent lava flows (Bryan, 1973). At some localities, particularly in Mare Imbrium, lava flows can be seen breaching the ridges and ponding behind ridges (Fig.4.34). The ridges appear to be deformational structures caused by compression (Bryan, 1973). The surfaces of the mare apparently were subsiding at the same time as they were being flooded. The subsidence produced fault scarps and monoclinal folds which resulted in the ponding of the lavas. The lava flows were then followed by more compressions. The close genetic relationship between wrinkle ridges and mare fillings is shown by the fact that the ridges tend to occur at approximately half the distance from the center to the margin of the basin (Fig. 4.35).

Age and Duration of Mare Volcanism. Thermal activity within the moon appears to have ended, at least in large part, at the time the mare

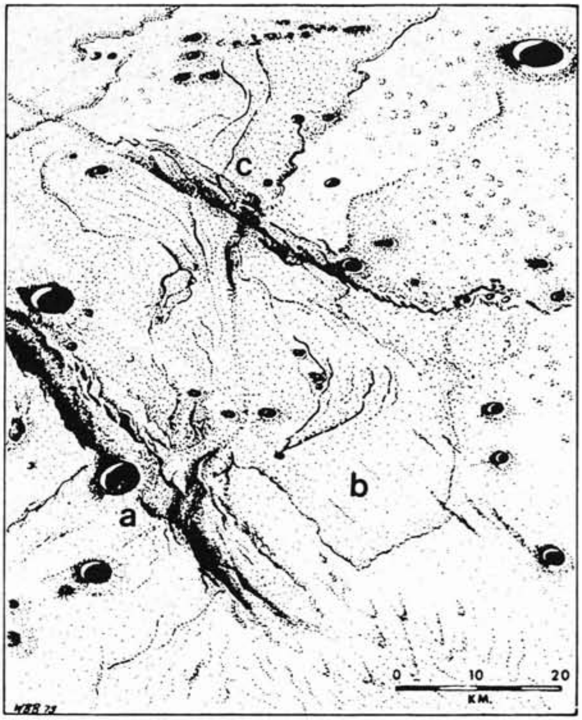


Fig. 4.34. Lava flows and wrinkle ridges on the south side of Mare Imbrium. A flow coming from the lower left crossed a ridge (a) and was ponded (b). The lava broke through the second ridge at (c) (from Bryan, 1973; *Proc. 4th Lunar Sci. Conf., Suppl. 4, Vol. 1,* Pergamon).

basalts were extruded. Tectonism continued into the post-mare filling period as evidenced by the straight and arcuate rilles but there is no evidence of either further volcanism or of any activity that could be interpreted as orogenesis or isostatic compensation. At this point in time the lunar crust appears to have become rigid and the moon became a "dead" planet.

Even though the mare filling was the most recent major activity on the moon, by terrestrial standards mare volcanism is extremely ancient. Radiometric ages provided by two main methods (Rb-Sr and ^{40}Ar-^{39}Ar) indicate a range of between 3.16 to 3.96 aeons for all available Apollo samples (Papanastassiou and Wasserburg, 1971, 1972; Wasserburg *et al.*, 1974). The time period is thus 800 m.y. which by terrestrial standards is longer than all of the time available from Cambrian to present. However, if we view the data on a basin by basin basis (Table 4.3) it is apparent that the continuity of mare volcanism is something of an illusion created by the morphologic continuity of the mare on the lunar surface. Keeping in mind the limited sampling, the mare flooding appears to have occurred for periods of 100 to 400 m.y. at different times and at different locations on the lunar

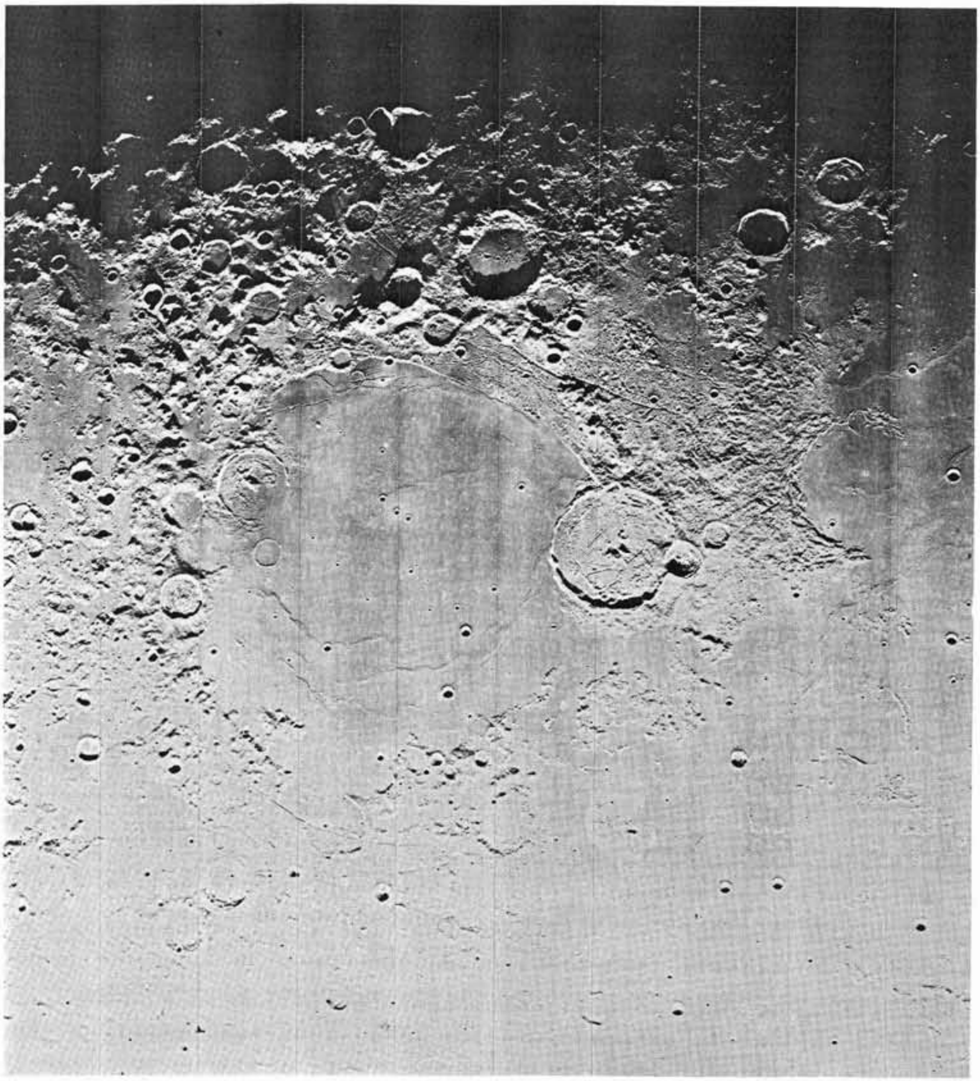


Fig. 4.35. Wrinkle ridges in Mare Humorum. Mare Humorum is about 350 km in diameter (NASA Photo Lunar Orbiter IV-M137).

surface. From the limited data it is apparent that there are large periods of time between the excavation of the multiringed basins and the flooding of the basins by mare basalt. For example, the Imbrium Basin was excavated 3.95 aeons ago but the oldest Imbrium basin sample is 3.44 aeons old; a time gap of 510 m.y. A similar time gap is apparent fof the Serenitatis Basin. This tends to suggest that the mare basalts were not the direct result of impact melting during basin excavation. Arakani-Hamed (1974) has proposed that the basin forming events did not trigger mare volcanism directly but the

TABLE 4.3

Age of mare basalts (data from many sources).

Mission	Mare	Age Range ($\times 10^9$ yr)	Time Period m.y.	Excavation of Mare Basin ($\times 10^9$ yr)
Apollo 14		3.95–3.96	100	
Apollo 17	Serenitatis	3.74–3.83	90	4.26
Apollo 11	Tranquillitatis	3.51–3.91	400	4.26
Luna 16	Fecunditatis	3.45		4.26
Apollo 15	Imbrium	3.26–3.44	180	3.95
Apollo 12	Procellarum	3.16–3.36	200	?

thermal balance of the moon was upset resulting in late magmatization and volcanism. This model poses further problems. In the first place it does not explain the absence of lava fillings in the lunar farside basins and second the time interval between basin excavation and filling does not appear to be regular. For example, Tranquillitatis and Fecunditatis are two of the oldest basins – both are older than Serenitatis – and yet they were flooded by basalt at about the same time or later. Overall, however, data are very limited. The density of rilles around the margins of the mare suggests that the most recent volcanic activity may have occurred around mare margins. By design the Apollo missions sampled the mare margins so that highland and mare could be sampled by a single mission. It is consequently difficult to make a definite statement concerning the relationship between basin excavation and flooding except that flooding appears to have occurred some time after excavation. This is also consistent with the pre-flooding cratering history of the mare basins (Baldwin, 1949).

The oldest dated mare basalts are clasts taken from Fra Mauro Formation breccias (Papanastassiou and Wasserburg, 1971). The greatest age found (3.96 aeons) is only slightly older than the Fra Mauro Formation (3.95 aeons) and suggests that mare volcanism began in late pre-Imbrian time. These basaltic fragments may have come from an older basin commonly referred to as "South Imbrium" which is now largely obliterated by Imbrian ejecta (Taylor, 1975). The youngest directly dated mare materials are those returned by Apollo 12 from Oceanus Procellarum. There are indications, however, that the youngest mare materials were not sampled by the Apollo missions. Structures of probable volcanic origin are superimposed on the mare surface in the Marius Hills area and may be younger than the Procellarum lavas (3.16 aeons). On the basis of crater counts, Schaber (1973) has suggested younger ages for the most recent lavas in southwestern Mare Imbrium. It thus seems that the upper and lower boundaries of the mare materials are considerably more complex than the generalized stratigraphy shown in Table 4.1 would suggest.

Composition of Mare Basalts. The lunar mare were flooded with high-iron basalts with a wide range in composition. Compositional variations are large both within and between sampling sites. In comparison with the earth the lunar basalts at each sampling site are texturally and compositionally much more varied. Mineralogically the most striking feature of the lunar basalts is their extreme freshness. Unlike the earth where water is abundant, there are virtually no secondary minerals due to weathering on the moon unless one regards impact produced glasses as the equivalent to terrestrial weathering products. As might be expected clinopyroxene and plagioclase dominate the basaltic mineralogy with olivine and ilmenite being important in some samples.

Pyroxene is the most abundant mineral in the lunar basalts and frequently forms more than 50 per cent of the rock (Table 4.4). Compositionally the pyroxenes are extremely complex. This complexity is determined largely by the chemistry of the host rock, paragenetic sequence, emplacement history and oxygen fugacity (Bence and Papike, 1972). Single pyroxene crystals frequently show extreme zoning (Fig. 4.36 a,b) and this combined with textural information suggests a definite sequence of pyroxene crystallization. magnesian pigeonite followed by magnesian augite and finally more iron-rich compositions (Dowty *et al.,* 1973). Possibly the best indication of the complexity and subtlety of compositional variations in the pyroxenes can be gained from the detailed study of the Apollo 15 basalt made by Dowty *et al.* (1974) (Fig. 4.36). Pyroxenes from feldspathic peridotite (Fig. 4.36c) contain more magnesium in the extreme range than other lithologies and few of the pyroxenes are iron rich. Olivine gabbros contain less magnesium again in the extreme range followed by olivine-phyric basalts which are lower still. Concurrent with the decreasing magnesium content in the extreme compositions is an iron enrichment.

The plagioclases have a relatively restricted compositional range with extremes of An_{60} and An_{98}. The crystals are frequently zoned although it

TABLE 4.4

Modal mineralogy of mare basalts (values in percentages) (after Taylor, 1975).

	Olivine basalt Apollo 12	Olivine basalt Apollo 15	Quartz basalt Apollo 15	Quartz basalt Apollo 12	High-K basalt Apollo 11	Low-K basalt Apollo 11	High-Ti basalt Apollo 17	Aluminous mare basalt Apollo 14	Luna 16
Olivine	10-20	6-10	–	–	0-5	0-5	5	–	–
Clinopyroxene	35-60	59-63	64-68	45-50	45-55	40-50	45-55	50	50
Plagioclase	10-25	21-27	24-32	30-35	20-40	30-40	25-30	40	40
Opaques	5-15	4-7	2-4	5-10	10-15	10-15	15-25	3	7
Silica*	0-2	1-2	2-6	3-7	1-5	1-5	–	2	–

*Tridymite, cristobalite

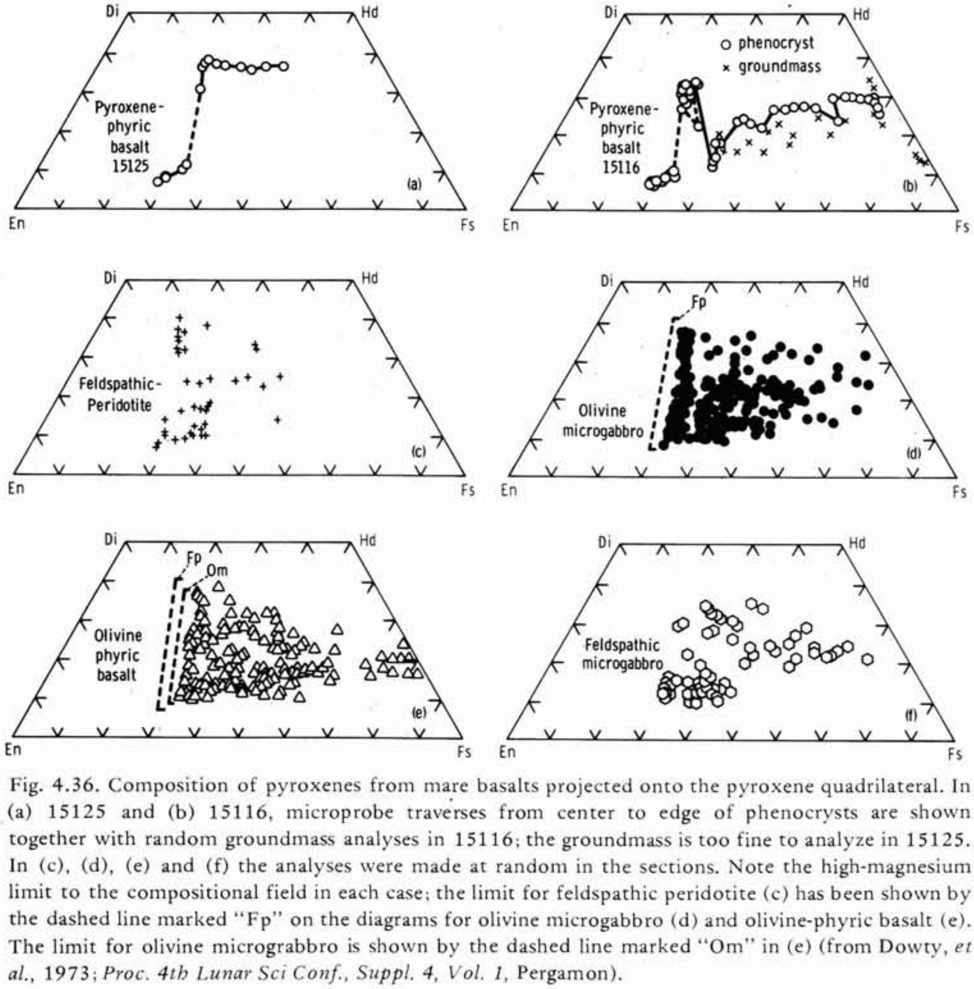


Fig. 4.36. Composition of pyroxenes from mare basalts projected onto the pyroxene quadrilateral. In (a) 15125 and (b) 15116, microprobe traverses from center to edge of phenocrysts are shown together with random groundmass analyses in 15116; the groundmass is too fine to analyze in 15125. In (c), (d), (e) and (f) the analyses were made at random in the sections. Note the high-magnesium limit to the compositional field in each case; the limit for feldspathic peridotite (c) has been shown by the dashed line marked "Fp" on the diagrams for olivine microgabbro (d) and olivine-phyric basalt (e). The limit for olivine micrograbbro is shown by the dashed line marked "Om" in (e) (from Dowty, *et al.*, 1973; *Proc. 4th Lunar Sci Conf., Suppl. 4, Vol. 1,* Pergamon).

is not always obvious optically. Zoning generally involves an increase in both Na and K adjacent to areas of late stage crystallization. The main body of the plagioclase grain is generally close to An_{90} whereas in the outer zones the composition drops below An_{80} (Dowty *et al.*, 1973). Nearly all of the feldspars are twinned with the majority having (010) of vicinal faces as composition planes (Wenk *et al.*, 1972). Simple or polysynthetic albite twins might predominate although other twin laws occur in small numbers. As might be expected, twinning of the lunar plagioclases is very similar to their terrestrial counterparts.

The olivine content of the mare basalts is variable – up to 34 per cent in some varieties and absent in others. The olivine grains are generally rich in magnesium with peaks in the range of Fo_{50} to Fo_{65} depending upon the individual lithology. In some lithologies a minor late-stage fayalitic olivine may be present (Dowty *et al.,* 1973). Zoning is common in some lithologies and in a few samples extremely skeletal olivine phenocrysts are present.

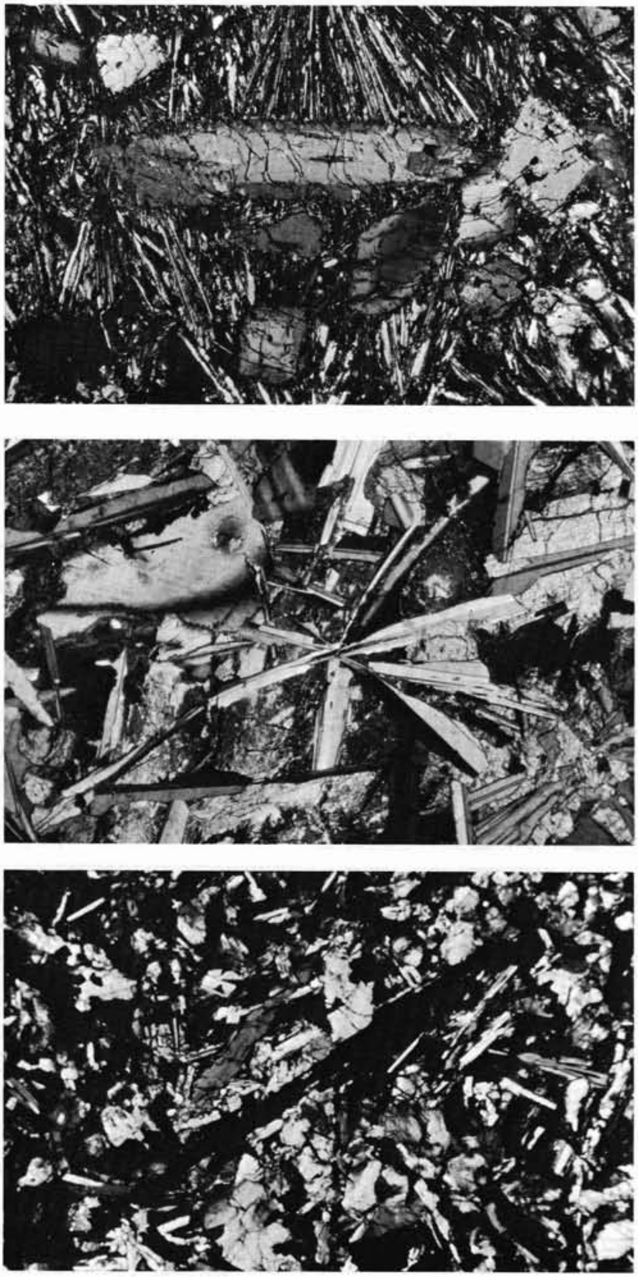
Ilmenite is the most common opaque mineral and is particularly conspicuous in rocks returned from Mare Tranquillitatis by Apollo 11. The other opaque phases are mostly metals or sulphides as a result of the extremely reducing conditions under which the basalts crystallized.

Silica in the form of cristobalite and tridymite occurs in some basalt types but is never abundant. Tridymite laths are seen transecting the margins of pyroxene and plagioclase crystals whereas cristobalite occurs in the intergranular areas only. Tridymite thus crystallized earlier than cristobalite suggesting that the cristobalite must have been metastable (Mason, 1972).

Texturally, the lunar basalts are also extremely varied and at least at the Apollo 11 and 12 sites may be separated into three groups (1) Porphyritic basalts, (2) Ophitic basalts, and (3) Intersertal basalts (Warner, 1971). These three groups may be further subdivided into thirteen types on the basis of the nature of the matrix and phenocrysts in the porphyritic group, the plagioclase-pyroxene texture in the ophitic group and the grain size of the pyroxene-ilmenite network in the intersertal group.

The *porphyritic basalts* have pyroxene or plagioclase phenocrysts (sometimes both) in a glass matrix or in a matrix of fine-grained acicular crystals of augite plagioclase and opaques (Fig. 4.37 a). Modally these basalts are extremely variable. The *ophitic basalts* have a distinctive texture in which the mineral phases form a continuous size-graded series (Fig. 4.37b). The phases include subhedral to anhedral pyroxene, subhedral olivine, euhedral plagioclase laths or plate-like opaques and intersertal cristobalite (Warner, 1971; James and Jackson, 1970). This textural group shows little modal variation. The *intersertal basalts* are distinguished by a network of subhedral pyroxenes and skeletal or equant opaques of approximately equal size (Fig. 4.37c). Large and partially resorbed olivines are distributed throughout the network of pyroxenes and opaques. The interstitial areas are filled with euhedral plagioclase, anhedral cristobalite and glass.

Chemically the mare basalts are distinct from their terrestrial counterparts (Table 4.5). In general the iron and titanium content of the lunar lavas are higher and the sodium and potassium content is lower. Experimental data suggest that the lunar basalts were formed by local partial melting at depths of 200-400 km (Ringwood and Essene, 1970; Green *et al.,* 1971). The genesis of the mare basalts appears more complex than current models would suggest. Consequently, the models are presently under considerable revision and this makes further discussion difficult.



(a)

(b)

(c)

Fig. 4.37. Photomicrographs of typical lunar mare basalt textural varieties. (a) Porphyritic, (b) Ophitic and (c) Intersertal. The longest dimension of each photo is 3.1 mm (NASA Photos S-70-49563, S-70-49438, S-70-48984).

TABLE 4.5

Range in composition of mare basalts and the 10-90 per cent frequency range of terrestrial continental basalts (from Taylor, 1975).

	Moon	Earth
SiO_2	37–49	44–53
TiO_2	0.3–13	0.9–3.3
Al_2O_3	7–14	13–19
FeO	18–23	7–14
MnO	0.21–0.29	0.09–0.3
MgO	6–17	4–10
CaO	8–12	8–12
Na_2O	0.1–0.5	1.8–3.8
K_2O	0.02–0.3	0.3–2.0
P_2O_5	0.03–0.18	0.04–0.6
Cr_2O_3	0.12–0.70	0.005–0.04

Eratosthenian and Copernican Systems

Crater Materials

The Imbrian System is followed by the Eratosthenian System and finally by the youngest time-stratigraphic unit, the Copernican System. By definition these units are superimposed on the Imbrian; there are, however, many unresolved problems both in separating the Eratosthenian from the Copernican and separating both from the Imbrian. The main material units associated with the Eratosthenian and Copernican Systems are ejecta blankets surrounding craters. The Eratosthenian craters are generally fresh but rayless whereas the younger Copernican craters are surrounded by bright rays. The reason for using rays as a criterion is that they appear to be among the most recent materials on the moon and are superimposed on most other material units. Copernicus, the type-crater example, has a very extensive ray system which overlies the nearly rayless crater Eratosthenes. Secondary processes, such as micrometeoroid reworking, cause the rays to darken and disappear with time. The criterion is not entirely satisfactory. If, for example, rays fade due to mixing with darker materials, the rays surrounding small craters would fade faster than those surrounding large craters. Furthermore, there are craters with dark haloes clearly superimposed on the ray and rim materials of craters with light rays. Similar craters on surfaces with a low albedo would not be identifiable as Copernican in age.

The production of glass particles by micrometeoroid reworking and in particular the production of agglutinates (complex compound glass particles) causes a lowering of the albedo of lunar soil (Adams and McCord, 1974). Agglutinates are typically darker than the parent soil due to the presence of iron and titanium ions in solution in the glass and to finely disseminated materials in the glass. It has been argued that this is the principal darkening mechanism on the lunar surface (Adams and McCord, 1974). If so, it may well explain the fading of crater rays in which case fading would be directly time dependent.

Mantling Materials

Several types of mantling material have been observed on the moon. The oldest of these mantling materials are dark terra-mantling units which are generally darker than the mare and occur on the uplands near the mare margins (Fig. 4.38). These deposits may extend over as much as 500,000 km^2 (Head, 1974). Several of the areas shown in Figure 4.38 have been assigned formational names. The name Sulpicius Gallus Formation has been applied to dark mantling deposits on the southern edge of Mare Serenitatis and to similar deposits in areas adjacent to Mare Vaporum and Sinus Aesthuum and near Copernicus. Similar materials adjacent to Mare Humorum have been called the Doppelmayer Formation (Wilhelms, 1968, 1970;

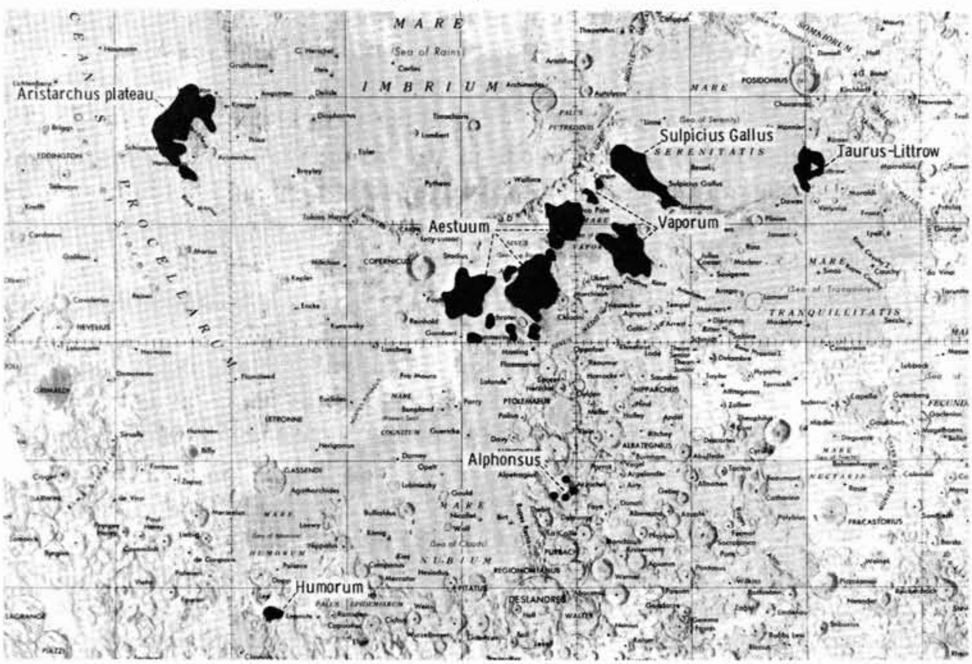


Fig. 4.38. Major lunar dark-mantle deposits. Location and extent (from Head, 1974; *Proc. 5th Lunar Sci. Conf., Suppl. 5, Vol. 1,* Pergamon).

Carr, 1966; Titley, 1967).

The surface of the dark mantle materials is generally smooth with no blocks or boulders visible. It appear to be draped over the antecedent topography and is thickest in topographic lows and may be absent entirely on some hilltops which appear as bright areas. The apparent rapid degradation of craters and the bare hilltops suggests that the dark mantle is unconsolidated.

The Sulpicius Gallus Formation has been found to be thickest along rilles, suggesting that this may be its source. The Apollo 17 mission landed in an area of dark mantling materials on the southeastern edge of Mare Serenitatis (Fig. 4.38). Initally there was confusion as to whether the dark mantle had been sampled until it was realized that orange and black glasses occuring in varying proportions in most of the soils were probably pyroclastic in origin. The black glass spheres which are relatively abundant in the soil appear to be the devitrified equivalent of the orange glasses; both probably originated in a volcanic fire fountain (Reid *et al.*, 1973; McKay and Heiken, 1973; Carter *et al.*, 1973). These spheres are spectrally the characteristic component of the dark mantle (Adams *et al.*, 1974). It therefore seems likely that the Sulpicius Gallus and Doppelmayer Formations consist of pyroclastic materials which have been reworked, at least closer to the surface, by the normal soil forming processes. Similar green glass spheres from Apollo 15 soils suggest that these pyroclastic deposits may be much more wide spread than even the distinctive dark mantle would suggest.

Orange and red materials occur in the Sulpicius Gallus Formation on the southeastern rim of the Serenitatis Basin (Lucchitta and Schmitt, 1974). The orange and red materials occur as patches, haloes or rays around small craters between 50 and 250 m in diameter. In larger craters the orange and red materials are exposed in layers underlying the dark mantle deposits to a depth of about 50 m.

The orange soil returned by Apollo 17 consists largely of dark-orange-brown glass particles with a mean size of 44 μm (4.51ϕ) (Lindsay, 1974) which is finer than the typical texturally-mature lunar soil (58 μm or 4.1ϕ). The glass particles are not particularly well sorted (σ = 1.39ϕ) and are comparable with normal texturally mature soils. The addition of pyroclastic materials to the lunar soil has minimal effect on its evolution unless they are added very early in soil development and in large volumes (Lindsay, 1974).

The dark orange-brown glass particles, which are the most abundant particle type, are generally non-vesicular, transparent, homogeneous, rounded forms such as beads, wafers and teardrops (Carter *et al.*, 1973). Two types of opaque particles are also present, one with a dust coated surface the other consisting of alternating layers of glass and olivine (Fo_{67-84}). The second glass type may also contain a feathery Ti-rich oxide phase (armalcolite) and a chromium-ulvöspinel. The average composition of these complex layered particles is the same as that of the homogeneous glasses (Table 4.6).

Compositionally the orange glasses are also very similar to the associated mare basalts from the Apollo 17 site suggesting a close genetic association. There are minor chemical differences, for example they are somewhat richer in MgO and volatile elements than the associated basalts (Table 4.6).

Carr (1966), who first defined the Sulpicius Gallus Formation, considered the unit to be of Imbrian and Eratosthenian age. It clearly overlies the Fra Mauro Formation and in some areas appears to overlie mare materials. In other areas the dark mantle appears to be embayed by mare basalts. Radiometric ages for the orange glasses range from 3.5 to 3.83 aeons (Schaeffer and Husain, 1973; Tatsumoto *et al.*, 1973). In comparison the mare basalts from the Apollo 17 site have ages ranging form 3.74 to 3.83 (Table 4.3). It is thus apparent that the dark mantle and the mare basalts are closely related and that their formation began in Imbrian time. How far the pyroclastic activity extended into Eratosthenian time is not certain. Head (1974) has suggested that the pyroclastic materials are associated with an early phase of basalt flooding in which case they may all be Imbrian in age. However, photogeologic information suggests that some dark-mantle materials are Eratosthenian and it seems more reasonable to suggest that the age of

TABLE 4.6

Chemical composition of glass particles from the Apollo 17 orange soil (from Carter *et al.*, 1973).

		"Barred" Particle			
Wt. %	Orange Glass	Glass	Olivine	Ulvöspinel	Dust Coated
SiO_2	38.0	39.6	35.8	0.7	45.2
TiO_2	8.87	11.8	1.4	29.4	0.49
Al_2O_3	5.51	7.58	0.3	3.3	23.4
Cr_2O_3	0.70	0.55	0.6	10.6	0.17
FeO	22.4	21.4	27.1	47.8	6.77
MgO	14.5	6.73	34.6	3.8	9.25
CaO	6.99	11.1	0.5	0.5	14.0
Na_2O	0.39	0.48	0.0	0.1	0.30
K_2O	0.06	0.06	0.0	0.0	0.06
TOTAL	97.42	99.27	100.3	96.2	99.71

the dark-mantle materials probably varies considerably from one locality to the next.

There are some extensive dark mantling units, similar to the Sulpicius Gallus and Dopplemayer Formations, that are assigned an Eratosthenian and Copernican age. The units appear thin and add little to the topography of the antecedent terrain. One of these units had been formerly defined as the Cavalerius Formation (McCauley, 1967). It is superimposed on the rim material of the post-mare crater Cavalerius, on the surrounding mare surface, and on Copernican rays. Consequently, the unit has been assigned a Copernican age.

The Reiner Gamma Formation (7° N, 59° W) is worthy of special mention in that it is a mantling unit that has a higher albedo than the underlying unit (McCauley, 1967a; Wilhelms, 1970). As with the dark mantling materials it is thought to be volcanic and has been assigned an Eratosthenian and Copernican age. Clearly volcanism continued in a small way at least for a considerable period of time on the lunar surface after completion of the mare filling.

Formations with Morphologic Expression

A number of units of probable constructional origin have been identified on the moon with ages ranging from Imbrian to Copernican. The Harbinger Formation, which occurs to the east of the Aristarchus Plateau (Fig. 4.23) appears to consist of volcanic domes, cones and craters although some of its relief may be antecedent Fra Mauro topography. This formation is transected by numerous sinuous rilles, the high ends of which begin in craters while the low ends terminate at the level of the mare. This adds further credence to the volcanic origin. The Harbinger Formation may interfinger with the mare materials locally although in other areas it appear to embay mare material. Consequently, it has been designated Imbrian or Eratosthenian in age. The activity of this volcanic complex appear to have moved westward at a later time and resulted in the development of at least part of the Aristarchus Plateau. The Vallis Schröteri Formation forms part of the Aristarchus Plateau (Fig. 4.23) and has been assigned an Eratosthenian or Copernican age. As well as thin blanketing materials this formation includes plains-forming materials, low rimmed craters and crater domes. Like the Harbinger Formation the Vallis Schröteri Formation is transected by sinuous rilles which terminate in the mare. These two formations probably represent continued volcanism the focal point of which simply change with time

A further complex of younger domes occurs in the northwest quadrant of the moon. The Marius Group has been assigned an Eratosthenian age (McCauley, 1967). The region consists of undulating plateau forming materials and two types of domes of possible volcanic origin (Fig. 4.39). One dome type is low and convex in profile, the other has steeper slopes with a concave profile.

Post-Imbrian Stratigraphy and the Lunar Soil

Since the lunar stratigraphy was initially established using earth based telescope photography and later orbital photography some of the subtlety of

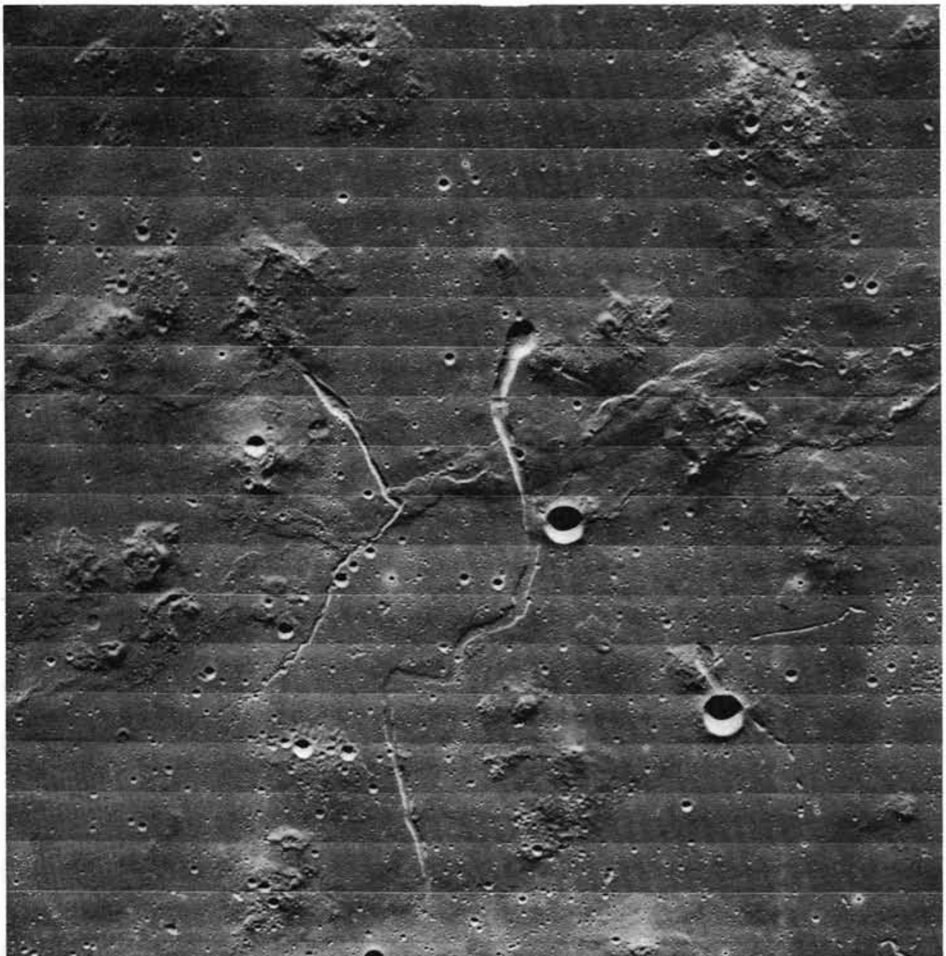


Fig. 4.39. The Marius Hills northwest of the crater Marius in Oceanus Procellarum at 14° N, 15° W. The numerous cones and domes are believed to be volcanic. There are two types of domes; gently rising smooth low domes and rugged heavily cratered steep-sided domes. Wrinkle ridges transect the area and are themselves transected by sinuous rilles. The two larger craters are 10 km in diameter (NASA Orbiter Photo V-M214).

the record must inevitably be lost. This is particularly true in the time period following the extrusion of the mare basalts. The ejecta blankets upon which the post-Imbrian stratigraphy was established are relatively small when compared to the multiringed basins. Consequently, it is difficult to establish an extensive stratigraphic history for this time period. However, all through the post-mare period a soil stratigraphy was evolving on the lunar surface. The Apollo missions allowed a detailed sampling of this thin but extensive sedimentary body which will ultimately allow a much more complete study of the late stage history of the moon. Because of the importance of the soil a separate chapter, Chapter 6 is devoted entirely to it.

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