6

A STRATIGRAPHIC APPROACH TO THE EVOLUTION OF THE LUNAR CRUST[1]

Farouk El-Baz

National Air and Space Museum
Smithsonian Institution, Washington, D.C.

The original lunar crust was physically and chemically modified by meteorite bombardment and the subsequent transport and redistribution of its materials. The exposed relics of this crust form the lunar highlands, which are predominantly sculptured by over 30 large basins that range in diameter between 300 and 2000 km. These basins are equally distributed on the near and far lunar hemispheres. The largest, the South Pole/Aitken basin on the far side, is among the oldest and is recognized by a subdued, discontinuous mountain chain surrounding a depression about 6 km deep. The youngest, the Orientale basin on the western limb, displays distinct mountain rings, a continuous lineated ejecta blanket surrounding the outer ring (930 km), and smooth plains and secondary craters farther out. Lunar basins display a continuous array of morphologies, from extremely subdued to fairly crisp features. This negates the possibility of sculpting the crust by meteorite impacts in one catastrophic event. Lunar crustal materials most likely were bombarded continuously by large objects throughout the early lunar history, or between 4.6 and about 3.9 billion years ago. In addition to impact products, some highland units may be volcanic in origin, including light plains on the lunar far side and spectrally distinct domes on the near side.

Although stratigraphically very significant, mare materials cover less than 20% of the lunar surface and compose only 1% of the crust. Mare basalts were deposited within the lunar basins and surrounding troughs during three or four major episodes,

---

[1] *This work was performed under NASA grant NSG-7188.*

ISBN 0-12-561340-7

between 3.85 and about 2.5 billion years ago. Basaltic volcanism indicates not only the chemistry of the crust, but also the amount and length of time of internal planetary differentiation.

INTRODUCTION

Stratigraphy is the study of the formation, composition, and correlation of surface rocks in space and time. Application of the principles of stratigraphy unravels the sequence of events that constitute the geologic history of a region or a planetary body. These principles grew from observation of terrestrial processes, but many are applicable to the Moon as well.

Two laws are basic to both lunar and terrestrial stratigraphy: (1) the law of superposition: when one rock unit is superposed on another, the uppermost is younger than the one it overlies. This law holds true if the rock sequence has not been disturbed or overturned since its formation. (2) The law of cross-cutting relationships: a geologic feature is younger than the unit it cuts across.

The Moon displays other features, unavailable on Earth, for deciphering stratigraphic relationships. One of these is the nature and frequency of craters on a given surface area. The older the surface, the longer it has been exposed to meteorite bombardment. Therefore, an older surface will generally display a greater number of craters, and/or a degraded and subdued appearance. Relative ages of different mare units can be established by analysis of crater diameter/frequency relations. In crater analysis, however, care must always be exercised to avoid confusing primary craters with secondary impact or volcanic craters.

Distinction between impact and volcanic craters on the Moon has long been a matter of controversy. Earth-based photographs provided the basis for the opposing theories of lunar crater formation by meteorite impact (e.g., Gilbert, 1893, 1896; Shoemaker, 1962; Baldwin, 1963) and by volcanic processes (e.g., Dana, 1846; Spurr, 1944, 1945; Green, 1962). Although the controversy is still with us, it is now feasible to photogeologically distinguish between features that are the product of meteorite impacts and those created through internal lunar processes. Close-up Lunar Orbiter photographs and those taken later by sophisticated cameras aboard Apollo missions 15 through 17 are used to distinguish characteristics of products of both processes (McCauley, 1968; Mutch, 1972; El-Baz, 1974). The fact that most lunar craters were formed by meteorite impacts was supported by studies of terrestrial meteorite impact craters

(Shoemaker, 1962; Fielder, 1965), underground explosions (Short, 1965; and Dence, 1972), and laboratory simulations (Gault *et al.*, 1968; and Gault, 1970). The impact theory was confirmed by results of the Apollo lunar missions (see reviews by El-Baz, 1975; Taylor, 1975; Short, 1975; King, 1976; and Lindsay, 1976).

Another stratigraphic tool that dominates the lunar panorama, but is lacking on Earth, is the presence of large multiringed basins of impact origin. Because these basins and their deposits cover large areas, they provide a widespread reference for correlating relative ages of surface units. Basins typically exhibit concentric rings of prebasin material disturbed by the impact, a hummocky ejecta blanket that thins with distance from the basin, and smooth plains and secondary craters beyond that blanket. The number of rings present depends on the basin size. Not all basins have mare fill; farside basins have little or none. There are over 30 basins on the Moon ranging in size between 300 and 2000 km in diameter. They vary in appearance from sharp and fresh to degraded and barely discernible.

On the basis of these morphologic characteristics the basins have been ranked according to relative age (Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971). The superposition and cross-cutting relationships of basins to other lunar features and units can therefore help define a lunar wide sequence of events. For example, it is clearly recognized that the Orientale basin is younger than the Imbrium basin, and that the Imbrium basin is in turn younger than the Nectaris basin.

THE LUNAR STRATIGRAPHIC COLUMN

Most of the Earth-facing lunar hemisphere was geologically mapped by the U.S. Geological Survey during the 1960s using telescopic photographs. This mapping was based on the premise that the lunar crust displayed material units that could be defined by physical properties and ranked in order of decreasing age.

Although lunar stratigraphy is still a relatively new field, several attempts have been made to classify features by relative age according to topographic and morphologic characteristics. The basic lunar stratigraphic sequence was first developed by Showmaker and Hackman (1962) in an area that includes the southern part of the Imbrium basin. This sequence was later modified and applied to most of the near side (McCauley, 1967; Wilhelms, 1970; Wilhelms and McCauley, 1971; Mutch, 1972).

An example of deducing lunar surface stratigraphy is in Fig. 1. Depicted in this sterogram are remnants of the rims of the craters Fra Mauro, Bonpland, and Parry. In the upper left corner of the area there is a thick deposit with radial segments, which is believed to be ejecta from the Imbrium basin to the north of the area of the sterogram. This deposit is superposed on the high rim of the crater Fra Mauro and therefore is younger than that rim. This lineated deposit has been named the Fra Mauro Formation (Eggleton, 1964). Crater interiors, as well as a region to the lower right, are occupied by a relatively flat, light-colored unit. This unit has also been interpreted as ejecta from the Imbrium basin and has been named the Cayley Formation (Wilhelms, 1965). It displays a well-developed system of straight rilles. Since the Parry Rilles cut across both the crater rims and the light-colored fill, these grabens are younger than both. A crater in the center of the photograph to the right obliterates a rille, and its ejecta overlies the light-colored (Cayley) unit. This relationship indicates that material of that particular crater is younger than the episode that resulted in the deposition of the Cayley unit as well as the tectonic movements that caused the rilles. The lower left part of the area is occupied by a dark, relatively smooth unit that displays fewer small craters than on the Cayley fill. This dark mare material shows flow fronts and wrinkly ridges. It overlaps and embays the Cayley unit and truncates and covers one rille in the center of the photograph on the left; it is therefore younger than both.

Hence the following sequence of events may be constructed. First to have formed are the three large craters, probably in the following sequence: Fra Mauro, Bonpland, and Parry. These craters probably predate the formation of the Imbrium basin to the north, because they are covered by the lineated unit that is believed to be ejecta from Imbrium (the Fra Mauro Formation). The craters were filled by finer ejecta from Imbrium and other impact events as well as locally generated debris, which formed the light-colored fill (Cayley Formation). This filling started prior to the formation of the Imbrium basin was nearly completed during that event, but continued after it. Tectonic movements caused the formation of Parry Rilles by the collapse of rock between two parallel faults. At a later time, lava flooded troughs southwest of the region and the flows covered the lowland, including terminal portions of some rilles. Finally, after the emplacement of the mare material, impact events created numerous craters in the region; some of these, showing very crisp features, are younger than others.

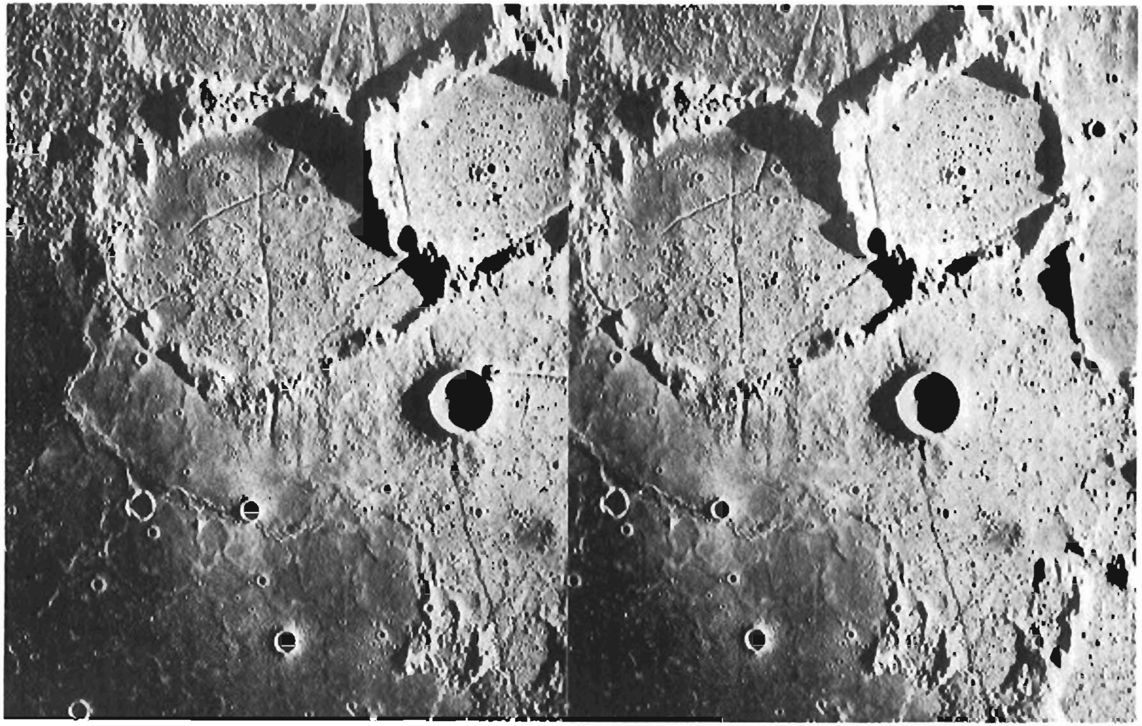


FIGURE 1. Stereopair showing remnants of the rim of the crater Fra Mauro (upper edge) and below it the craters Bonpland (left) and Parry (right). The lineated unit in the upper left corner is part of the Fra Mauro Formation, an ejecta deposit radial to the Imbrium basin. The crater rims and their light-colored fill are crossed by Parry Rilles, a system of forked linear depressions. The dark mare unit in the lower left area is superposed on, and therefore younger than, the three craters, the Fra Mauro Formation, the light plains, and the graben rilles. (Apollo 16 metric photographs 1980 and 1981.)

FIGURE 2. Three faces of the Moon showing the major stages of evolution of the near side: first, the formation of the Imbrium basin whose materials are superposed on earlier features; second, the flooding of the basins and nearby lowlands by mare materials; and third, the formation of postmare craters (after Wilhelms and Davis, 1971).

Sequences such as this can be worked out for many parts of the lunar surface. They are particularly clear where mare units abound. Within the older lunar highlands, however, there are many more complications that cloud regional as well as local stratigraphic sequences. However, it is possible to generalize the stratigraphic sequences on the near side of the Moon based on the Imbrium basin formation (Fig. 2). Also, it was recently realized that the nearside lunar stratigraphy could be extended, with modifications, to the far side as well (Stuart-Alexander and Wilhelms, 1974; El-Baz, 1975; El-Baz and Wilhelms, 1975).

The Moon-wide, time-stratigraphic sequence in order of decreasing relative ages is as follows:

1. *Pre-Nectarian* All materials formed before the Nectaris basin and as long ago as the formation of the Moon are classed as pre-Nectarian. Most pre-Nectarian units are present on the lunar far side. These include materials of very old and subdued basins, and mantled and subdued craters.
2. *Nectarian System* This system includes all materials stratigraphically above and including Nectaris basin materials, and up to but not including Imbrium basin strata. However, in much of the area surrounding the Imbrium basin. Nectarian basin materials cannot be recognized and the pre-Nectarian and Nectarian can be combined as pre-Imbrian materials. Ejecta of the Nectaris basin that can be traced near the east limb region allow recognition of these materials as an important stratigraphic datum for the farside highlands. Some light-colored plains units, particularly on the far side, are believed to be Nectarian in age.
3. *Imbrian System* A large part of the lunar surface is occupied by ejecta surrounding both the Imbrium and Orientale basins. These form the lower and middle parts of the Imbrian System, respectively. They include the Fra Mauro Formation and several patches of light-colored plains. Two-thirds of the mare materials belong to the Imbrian System, particularly in the eastern maria of Crisium, Fecunditatis, Tranquillitatis, Nectaris, and the dark annulus of Serenitatis, as well as most mare occurrences on the lunar far side.
4. *Eratosthenian System* This system includes materials of rayless craters such as Eratosthenes. Most of these are believed to have once displayed rays that are no longer visible because of mixing due to prolonged micrometeoroid bombardment and solar irradiation. The system also includes about one-third of the mare materials on the lunar near side. These are generally concentrated in Oceanus Procellarum, in western Mare Imbrium, and possibly in the central region of Mare Serenitatis.
5. *Copernican System* This is stratigraphically the highest and, hence, the youngest lunar time-scale unit. It includes materials of fresh-appearing, intermediate to high albedo,

bright-rayed craters. The system also includes exposures of very high albedo material on the inner walls of craters and scarps. Brightness in these cases is believed to result from fresh exposure by mass wasting and downslope movement along relatively steep slopes. The Copernican System also includes isolated occurrences of relatively small, dark-halo craters. Although some of these are probably impact craters, others may be volcanic in origin.

THE HIGHLANDS

When Galileo Galilei observed the Moon through a telescope for the first time, he noticed a dichotomy between highlands and maria. This dichotomy was confirmed by both photogeologic interpretations and the study of returned lunar samples.

Highland materials cover nearly 83% of the lunar surface, including most of the lunar far side. They are composed mainly of light-colored, low-density, feldspar-rich impact breccias.

Basins and large craters dominate the highland physiography. In many cases overlap relationships between basins and large craters are clear, and in some cases superposition relationships are not easy to decipher. As an example of decreasing numbers of craters with age, in the central far side region of the Moon (between 50^0 north and south and 140^0 east and west), Stuart-Alexander (1976, p. 9) recognized the following sequence of craters 100 km or more across: 47 pre-Nectarian craters, 38 Nectarian age craters, and 14 Imbrian age craters.

Large, multiringed lunar basins vary greatly in the degree of preservation. Many are indicated only by a few subdued and discontinuous mountain rings. The Orientale basin on the west limb of the Moon (Fig. 3) is the youngest of lunar basins. Its fresh appearance and its sparse mare fill make it the best preserved example of lunar basins. Knowledge gained from study of Orientale can therefore be extrapolated to the other less distinct structures.

The Orientale Basin

Photographs of the Orientale basin, which is centered at 96^{0}W, 21^{0}S, have been most convincing in deducing theories of origin of lunar basins. Although the first photographs were provided by Zond 3, the Lunar Orbiter IV images have revealed the critical information that this basin is probably the youngest of all the large lunar depressions (Fig. 3). Its features are crisp and sharp, and resulted in numerous interpretations.

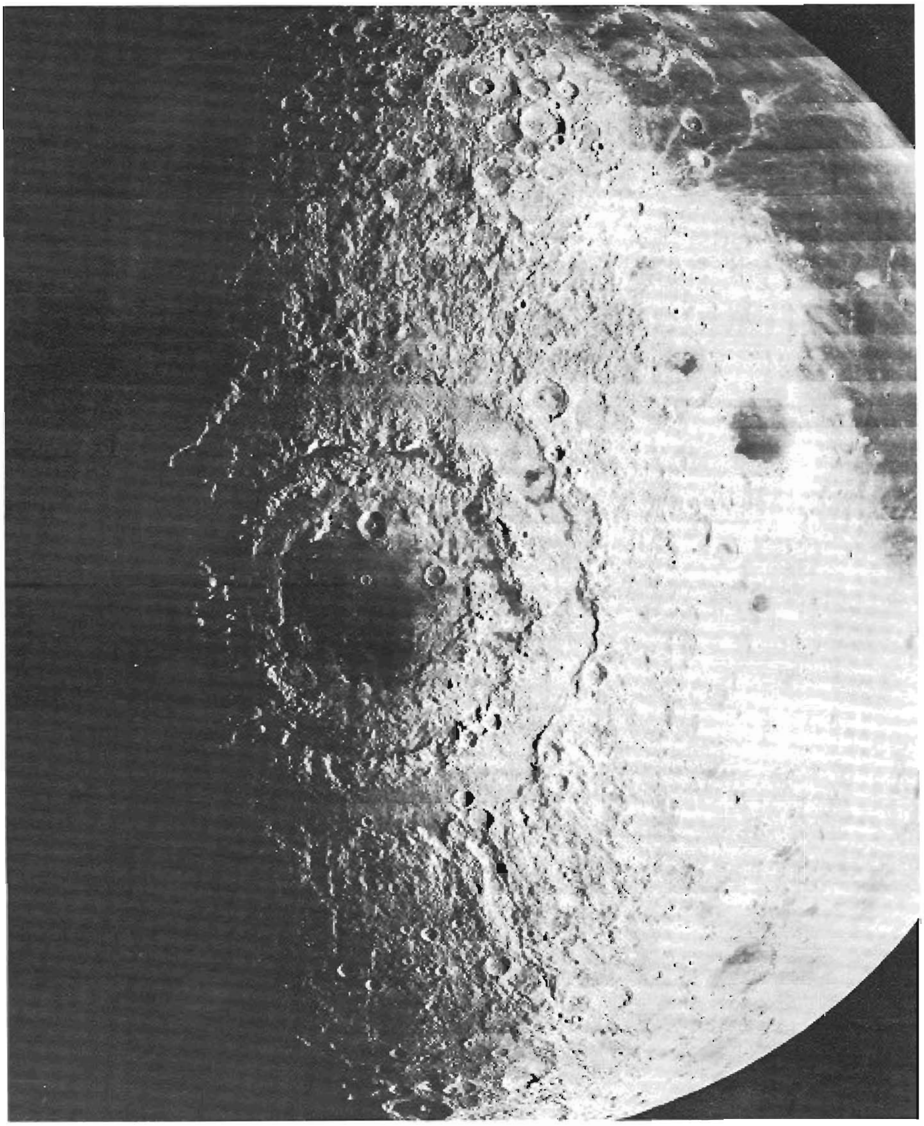
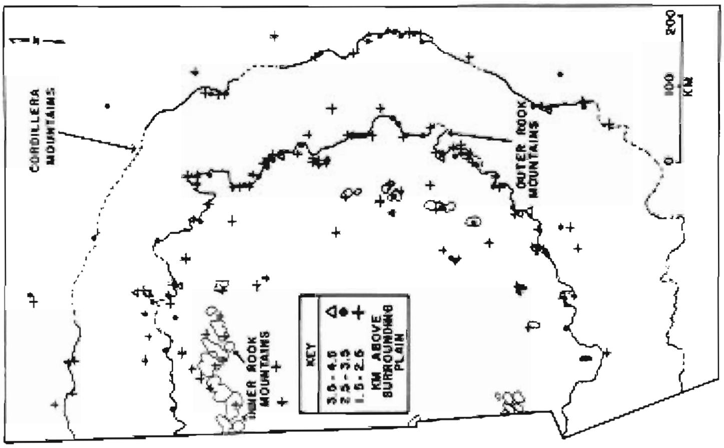
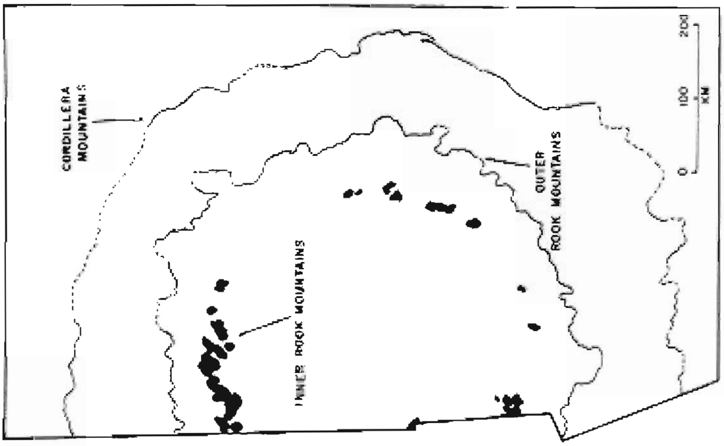
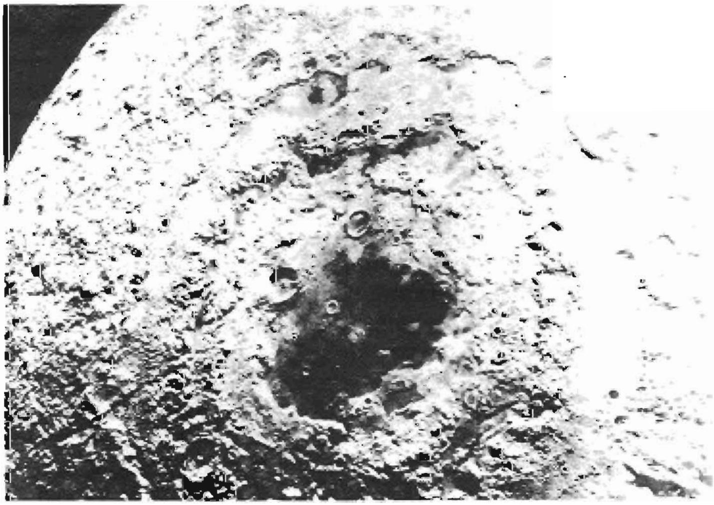


FIGURE 3. The multiple rings of the Orientale basin. Four major circular rings are displayed; the innermost is 320 km in diameter and the outermost is 930 km in diameter. Note the radial ejecta blanket surrounding the outer ring. (Lunar Orbiter IV frame M-187.)

The basin displays four well-defined rings and a possible fifth ring (Hartmann and Wood, 1971). The four main rings are as follows:


CORDILLERA MOUNTAINS
OUTER ROOK MOUNTAINS
INNER ROOK MOUNTAINS
KEY
3.6 - 4.6 Δ
2.5 - 3.5 ●
1.5 - 2.6 +
KM ABOVE SURROUNDING PLAIN
0
100
200
KM


CORDILLERA MOUNTAINS
OUTER ROOK MOUNTAINS
INNER ROOK MOUNTAINS
0
100
200
KM



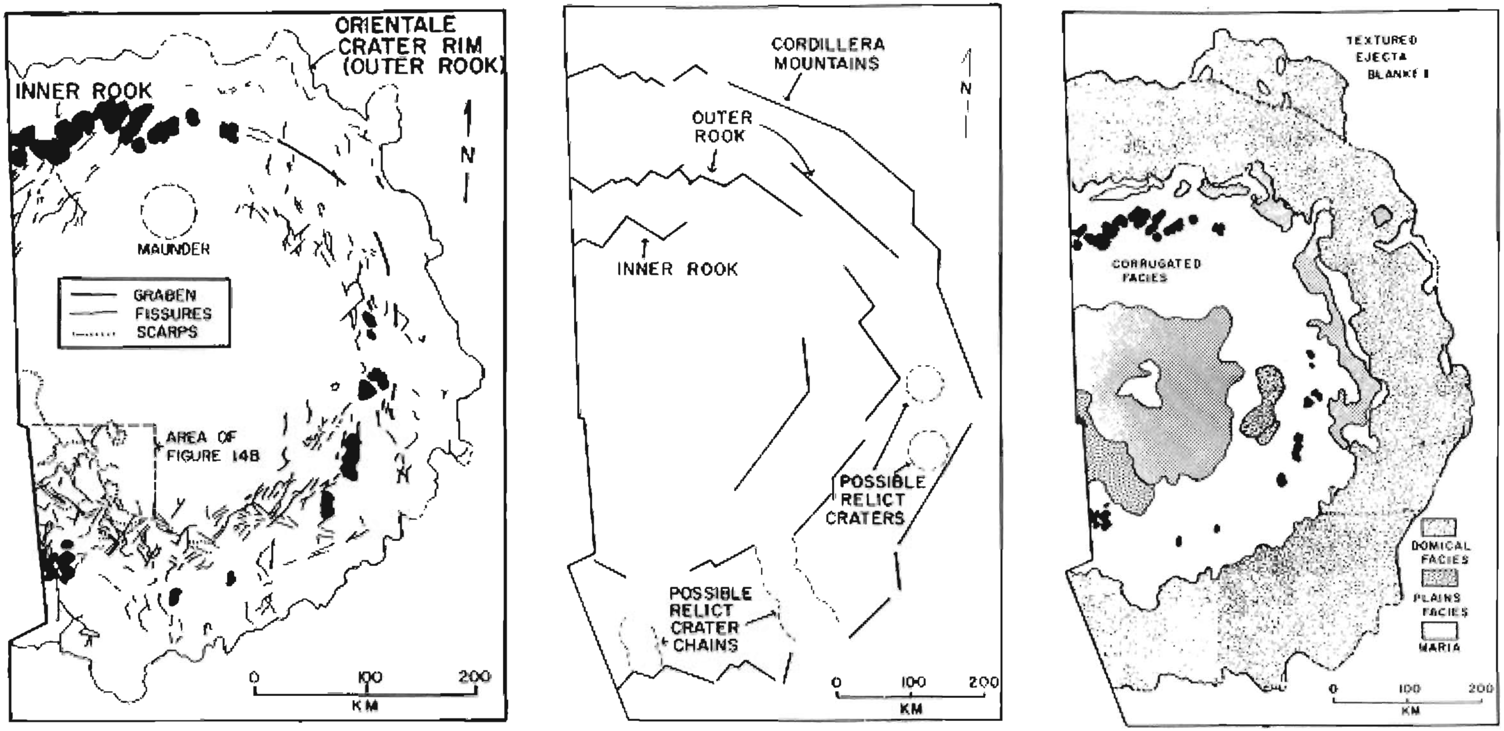


FIGURE 4. *Illustrations of the major textural units and structural features of the Orientale basin (after Head, 1976a).*

(1) An inner ring, 320 km in diameter, which encloses most of the dark, basaltic material of Mare Orientale. This ring is here called the "Maunder Ring" after a well-defined, superposed crater on the nothern part.

(2) The second ring, 480 km in diameter, which is marked by the inner Montes Rook, and is surrounded on the east side by mare materials of Lacus Veris.

(3) The third ring, 620 km in diameter, which is marked by outer Montes Rook.

(4) An outer ring, 930 km in diameter, which is bounded by Montes Cordillera.

The possible fifth ring (up to 1300 km in diameter) is only suggested by a few discontinuous and barely visible scarps.

Interpretation of basin stratigraphy and thickness of ejecta depends upon the mode of formation of basin rings. Although textural and structural characteristics of Orientale are easy to decipher (Fig. 4), there is no agreement as to how the rings formed, and consequently, how much ejecta was excavated by the impact event. Also, since Orientale is the best preserved example of the lunar basins, its deposits have been subject to many interpretations, resulting in an abundance of nomenclature (Table I).

The concentric rings of the Orientale basin are related one way or another to the impact of a large body at the center of the basin. The earliest interpretations of these rings ascribed them to collapse along concentric faults (Hartmann and Kuiper, 1962). McCauley (1968) proposed that during the early stages of shock wave propagation that followed the instant of impact there was compressive failure and uplift of large structural blocks. Some uplifts may have occurred along concentric inward-dipping thrust faults. The rings may therefore represent frozen shock waves, or "frozen tsunami-like waves" (Baldwin, 1972). Alternatively, these immense mountain chains may have resulted from later readjustment of the terrain by upward thrust along the circular faults created by the impact event.

Most investigators agree that the mare material within the Maunder ring was emplaced well after the basin event, and that the more hummocky and fractured material within the Rook Mountains was formed as a shock melt (Moore *et al.*, 1974) during the impact event. Similarly, most investigators agree that the basin deposits outside the Cordillera ring were formed as ejecta during the basin excavation. Well-developed radial lineations and alignment of secondary craters support this interpretation, and the outer fringes of Orientale may be subdivided into several textural units (Moore *et al.*, 1974; McCauley, 1976).

The interpretation of the region between Montes Rook and Cordillera, however, is not as simple (Fig. 5). The terrain

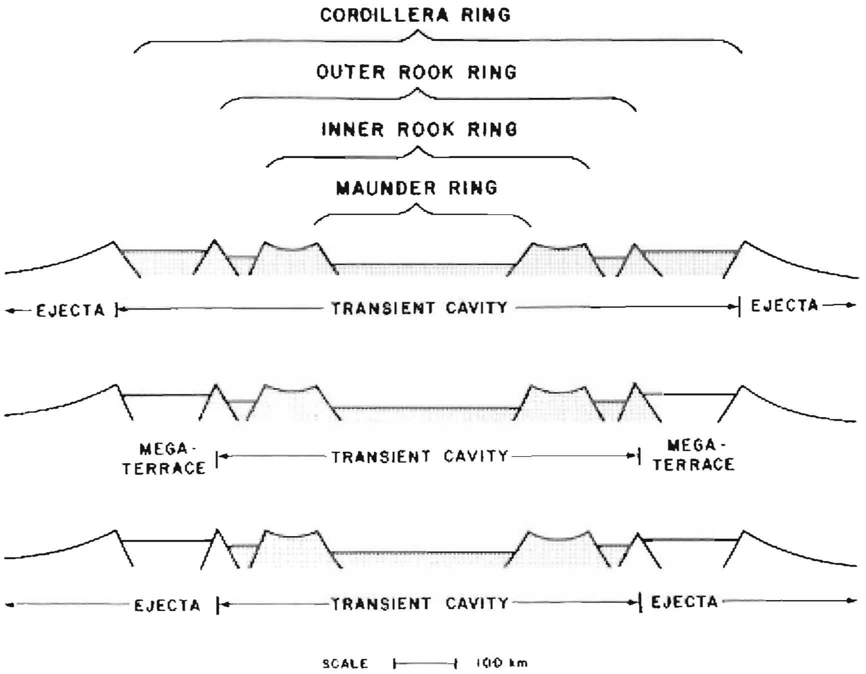


FIGURE 5. Schematic illustrations of three theories of origin of the Orientale basin rings. Top: according to Hodges and Wilhelms (1976a, b), the transient cavity is marked by the Cordillera ring where the multiple ring structure may be caused by uplift of discrete resistant layers; middle: according to Head (1976a) the outer Rook ring constitutes the crater rim where a megaterrace is assumed to form the Cordillera ring; bottom: according to McCauley (1976), the outer Rook mountains mark the transient cavity, since lineated ejecta can be traced inward to their rims.

TABLE I. Correlation of Nomenclature of the Orientale Basin and Related Materials.

Center of basin	*Maunder ring*	*Inner rook ring*	*Outer rook ring*	*Cordillera ring*	
radius in km ——→	*160*	*240*	*310*	*465*	*Source*
Central basin plains and mare material			*Montes rook formation*	*Cordillera formation*	*McCauley (Mutch, 1972)*
Corrugated facies; plains facies; mare			*Domical facies*	*Textured ejecta*	*Head (1974)*
Floor material			*Knobby material*	*Hevelius formation*	*Howard* et al. *(1974)*
Central basin material			*Knobby basin material*	*Concentric facies; radial facies; smooth plains; grooved facies*	*Moore* et al. *(1974)*

between these rings is made up of highly fractured, closely spaced, smooth hills. Inferences on both the depth of excavation and the volume of the basin ejecta are necessarily dependent on the interpretation of this region.

There are two dominant theories for the formation of the knobby or domical material (Table I). The origin has been ascribed to initial deposition of thick ejecta and later modification by seismic activity accompanying the formation of Montes Cordillera (Head, 1974a and 1976a), or the fallback of ejecta during the terminal stages of the cratering event (Howard *et al.*, 1974; Moore *et al.*, 1974). McCauley (1976) suggested that the material may represent coherent blocks excavated from beneath the 60 km seismic discontinuity at the base of the lunar crust. There is photogeologic support for both interpretations, and inferences depend on the mode of origin of the outer basin rings and the size of the transient cavity.

Calculation of the volume of material ejected from Orientale based on gravity data indicates a minimum of 5.3×10^6 km^3 of ejecta, based on the Cordillera ring as the original crater rim (Scott, 1974). As shown by Moore *et al.* (1974), this value agrees well with the amount of radial ejecta (4.5×10^6 km^3) estimated from the region outside the Cordillera ring; the transient cavity was assumed to be smaller than this ring and about the size of the outer Rook ring (Moore et al., 1974, p. 84).

Hodges and Wilhelms (1976) advocate an initial crater rim at the Cordillera ring by analogy with terrestrial impact craters. They believe that the inner rings may represent layering in the crust, structurally deformed by rebound of the crater floor. (This interpretation is supported in part by the mode of formation of central peaks in craters smaller than 100 km, and peaks and rings in large craters between 100 and 300 km in diameter, (Fig. 6). In contrast to this interpretation, Head *et al.* (1975) estimate an ejecta volume of only 1 - 3×10^6 km^3 using the outer Rook ring as the initial crater of excavation. Consequently, the Orientale event would not have ejected material from deeper than 20 km.

Recent mapping of the Orientale basin indicates that the Cordillera scarp is not as well developed on the western side of the basin, and that the region between the Rook and Cordillera mountain chains does have radial lineations suggestive of ejecta (McCauley, 1976). In addition, ratios of basin rings to central peak rings also imply that the outer Rook Mountains are the site of the original crater rim (Head, 1976a). Consequently, although Orientale is well preserved, details of its formation are not yet entirely understood.

Correct interpretation of the structural history of the Orientale basin is of great consequence both to highland stratigraphy of the western limb region, and to the extrapolation of data to older, less well-preserved lunar basins. Using an empirical relationship between ejecta thickness and crater radius from McGetchin *et al.* (1973), the thickness of Orientale ejecta at the western edge of Oceanus Procellarum would be about 90 m if the outer Rook ring represents the original crater, and 270 m if the Cordillera ring is the original rim. The difference becomes more pronounced closer to the basin, and at the Cordillera ring, thickness estimates range from 0.5 to 2.1 km, depending on which basin model is used. While the exact thickness and extent of the Orientale ejecta is a matter of controversy, the observation that ejecta of this and other lunar basins and craters overlie and subdue preexisting craters is undisputed.

Light Plains and Terra Domes

In addition to deposits of basins and craters of varying sizes, the lunar highlands display numerous other features. Two types of highland landforms have puzzled lunar photogeologists for a long time: (1) the light-colored, heavily cratered, but otherwise featureless, smooth plains that cover about 4% of the lunar surface (Howard *et al.*, 1974); and (2) rugged, highly textured domical structures with distinct multispectral signatures.

Prior to sampling the Cayley-type lunar light plains on Apollo mission 16 north of Descartes crater, they were considered as most likely volcanic. Although the plains were initially interpreted by Eggleton and Marshall (1962) as smooth facies of Imbrium basin ejecta, their distribution over the Moon and at varying topographic levels favored the volcanic theory. They were interpreted as possibly old marelike basalt or more silicic lavas and/or pyroclastic materials (e.g., Milton, 1968; Wilhelms and McCauley, 1971). Free-fall or ash-flow tuff was suggested by the similarity beyween plains and adjacent mantled terra units (Howard and Masursky, 1968).

As explained by Hodges *et al.* (1973) the volcanic interpretation appeared more plausible for the following reasons:

1. The Cayley plains are similar to mare plains in most aspects except for a higher albedo (different composition) and a higher crater density (longer exposure age).
2. The plains occupied unconnected topographic lows and therefore appear to be locally derived.
3. Within a few plains units (e.g., the floor of the crater Alphonsus), volcanic vents occur along linear depressions.
4. The plains fill in and truncate_sculpture of the Imvrium basin and thus are assumed to be younger.

The Apollo 16 samples indicated that the light plains are predominantly impact breccias (LSPET, 1973). Because of this, numerous theories have been advanced to explain the light plains as relatively fine-grained ejecta from multiringed basins and craters:

1. *Multiple Basin Ejecta*. This theory was advanced by Hodges *et al.* (1973, p. 1), who recognized that

> the Moon-wide occurrence of Cayley-like plains and the apparent impact origin of the returned samples suggest a possible relation of such plains deposits to multi-ringed impact basins. The apparent contemporaneity of all the Imbrium light plains units, including those around and genetically related to the Orientale basin, suggests further that at least the top layer of these deposits may be a product of the Orientale impact. It seems probable that the total thickness of plains material at Apollo 16 comprises a sequence of deposits from multi-ringed basins, including Nectaris and Imbrium as well as Orientale.

Hodges *et al.* (1973) carried this idea further to conclude that since the seemingly best example of viscous highland volcanism (the Descartes highlands) was discredited, it was unlikely that such a process did operate on the Moon. They believed that other areas previously mapped as possible products of highland volcanism may be interpreted as products of multiring basin impacts. However, this should not include terra domes that cannot be explained in that manner. This author, among others, believes that there are several structures that are probably the product of viscous terra volcanism, such as the Mons Hansteen and the Mons Gruithuisen domes (Fig. 7).

2. *Orientale Basin Ejecta*. Chao *et al.* (1975) further refined the multiringed basin ejecta theory and concluded that most Cayley-type, Imbrian-age plains may be composed mainly of Orientale basin ejecta. They based this on the fact that stratigraphic relations and crater size-frequency distributions, and dating by erosional morphology of superposed craters, they have established that the plains are younger than the Imbrium basin and older than the maria. Therefore, this hypothesis implies that the Orientale impact struck a highland area underlain by feldspathic material and spread it over much of the Moon.

3. *Secondary Impact Ejecta*. Oberbeck *et al.* (1975) disagreed with the two hypotheses concluding that light-plains cannot be solely basin ejecta. They based their new idea on the premise that ejecta thrown beyond the continuous deposits of basins and large craters produces secondary impact craters that excavate and deposit masses of local material equal to multiples of that of the primary crater ejecta deposited at the same place. They support this interpretation by the fact that

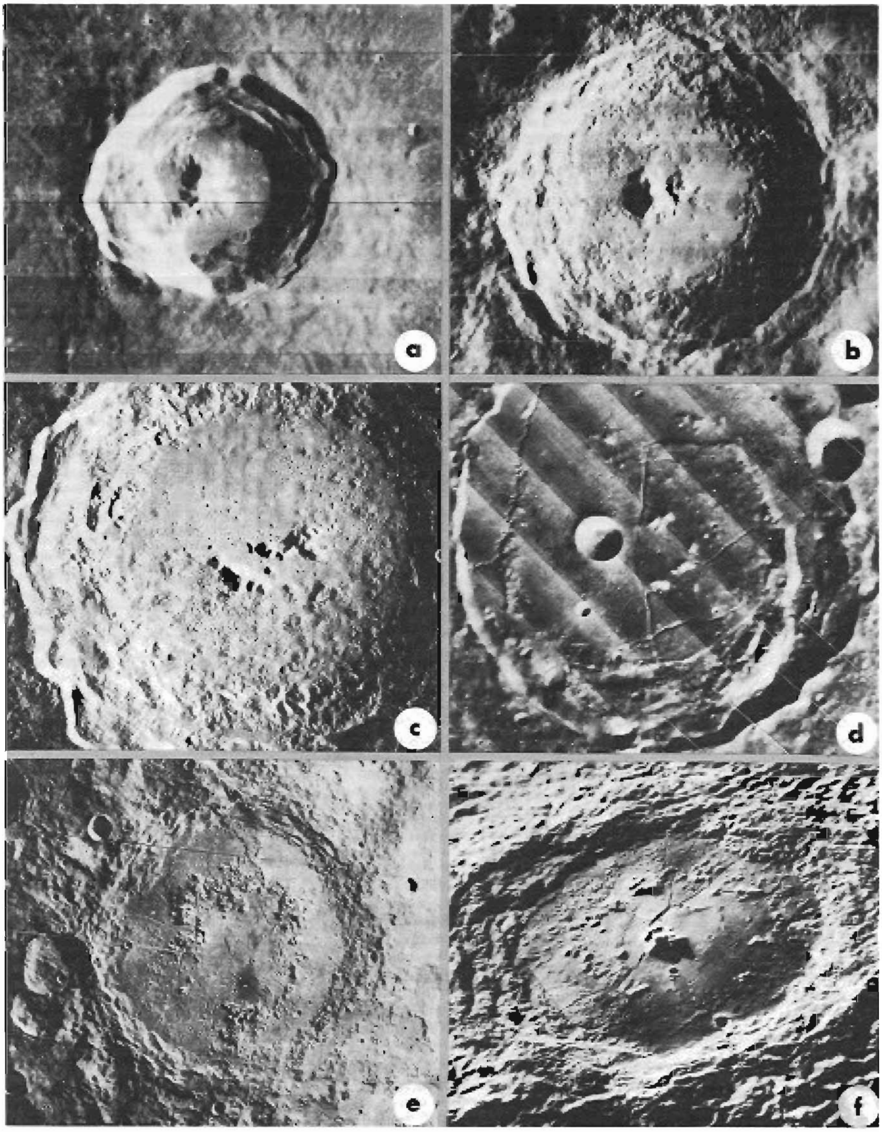


FIGURE 6.

FIGURE 6. This sequence of craters illustrates stages of central peak and inner ring development. Peak and ring morphology is in part size-dependent, and is probably affected by subsurface characteristics and impact velocity as well. (a) Crater Burg, 40 km in diameter, located in Lacus Mortis, north of Mare Serenitatis. It exhibits a simple, single peak representative of many craters of its size range (LO IV H-91); (b) Crater Tycho, 70 km in diameter, displaying a split or double peak (LO IV H-119). (c) Crater Copernicus, 90 km in diameter where the central peak is spread into large detached segments (LO IV M-151). (d) Isolated peaks within the crater Posidonius, 100 km in diameter, arranged in a small incipient ring (LO IV H-79 and H-86). (e) The basin Schrödinger, 320 km in diameter, displays a well-defined but discontinuous inner ring (LO M-8). (f) The crater Compton, 170 km in diameter, showing a central peak in addition to an inner ring (LO V M-181). This sequence may ultimately lead to multiringed basins like Orientale (see Fig. 3).

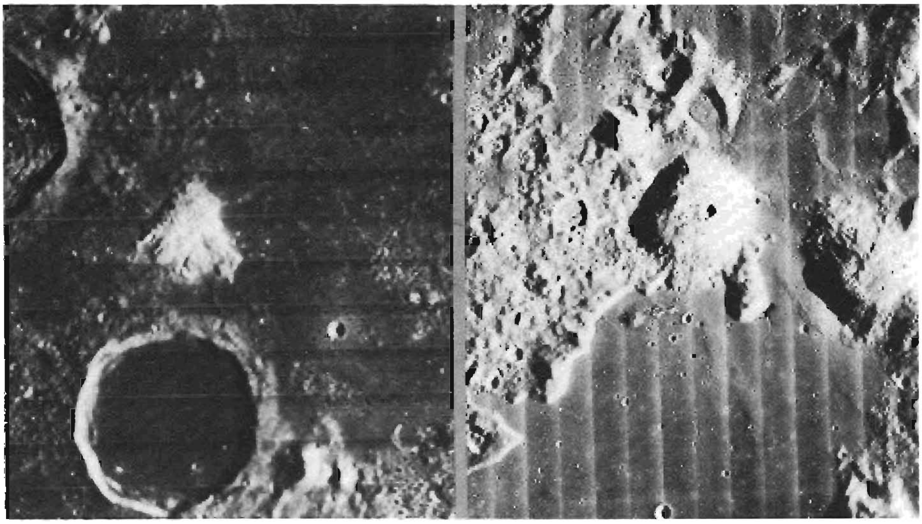


FIGURE 7. Two lunar orbiter images illustrating rugged, highly textured domes of probable (silicic) volcanic origin: left, the Mons Hansteen structure, 20 km in diameter, on the southern edge of Oceanus Procellarum (LO IV H-149); and right, Mons Gruithuisen Gamma (center, about 20 km across) and Mons Gruithuisen Delto- (right center) in northeastern Oceanus Procellarum (LO IV H-145).

several plains units have compositions similar to adjacent highlands, but different from other plains regions.

4. Local Impact Ejecta. Head (1974b) interpreted the stratigraphy of the Cayley-like plains in the Apollo 16 site region as a result of complex interaction of deposits of local and regional impact events. He proposed that large 60 - 150 km diameter craters have had a dramatic effect on the history and petrogenesis of that region. He concluded therefore that contributions from Imbrium are minor and those from Orientale are negligible.

Detailed geologic mapping of the Moon does not support the interpretation of lunar light-colored plains as the product of one or a few impact events. In the course of mapping the east side of the Moon (Wilhelms and El-Baz, 1977) different light-plains units were encountered. Some of these are most likely the products of local and regional impacts, others may be volcanic in origin. Figure 8 illustrates the geology of this region. As explained by El-Baz and Wilhelms (1975), the mapped geologic provinces (where a geologic unit or groups of units related in age and origin are concentrated) include the following (Fig. 8c):

1. *Cratered Terra.* This province is mostly on the far side and consists of densely packed craters. It contains little basin materials except for the ancient, subdued rings of the Al-Khwarizmi/King (El-Baz, 1973), Tsiolkovskij/Stark, and Lomonosov/Fleming basins (Fig. 8b), and a few additional short arcs of rings. The province owes its preservation to a lack of significant modification by relatively young basins, and its materials are the most primitive on the east side of the Moon.

2. *Basin Rims.* Topographically the most rugged, this province includes the multiple rings and some peripheral terrain of several basins. It is most extensive around the Crisium, Marginis, and Smythii basins.

3. *Mantled Terra.* This province includes extensive tracts of terra that appear mantled near young and old basins. Although the distinctive lineated textures usually associated with basin ejecta have not been observed in this province, its proximity to basins suggests that it is composed mostly of degraded basin ejecta.

4. *Lineated Ejecta.* The five Nectarian basins in the area are surrounded by radially lineated ejecta and clusters of secondary impact craters. These features are diagnostic of the impact origin of the source basins, and are most extensive around the Humboldtianum and Nectaris basins.

5. *Old Plains.* This province includes densely cratered, light-colored plains in topographically low areas. Although most plains may be of impact origin, some may be volcanic.

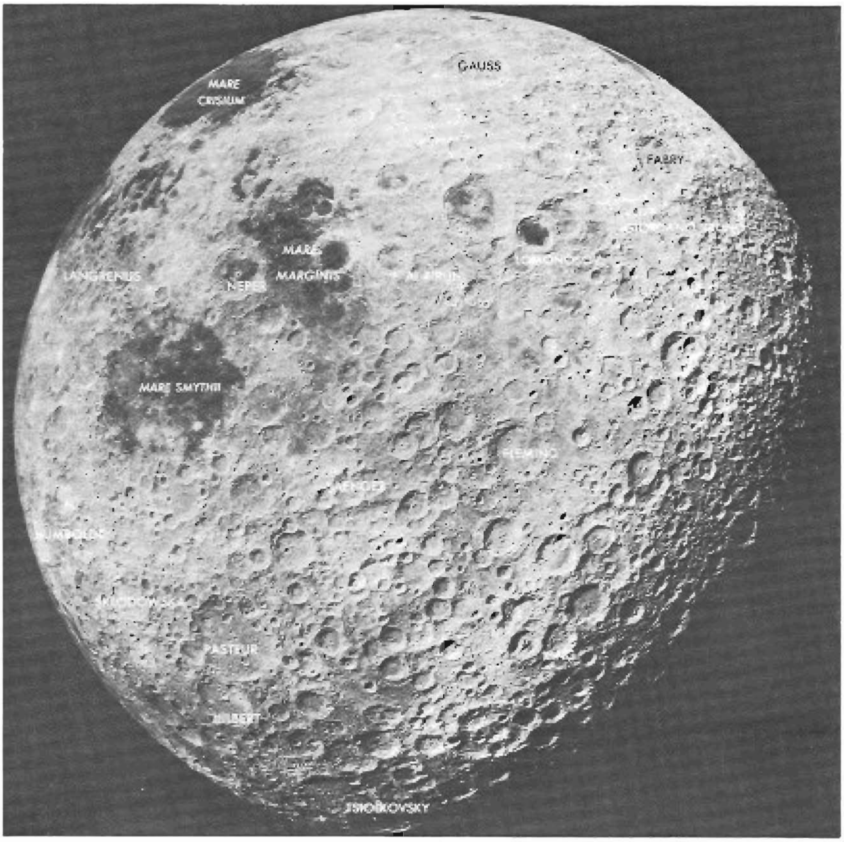


FIGURE 8a. Photograph of the east side of the Moon showing major surface features. Note the large area occupied by light-colored plains between the craters Lomonosov and Fleming. (Apollo 16 metric photograph 3023.)

6. *Young Plains.* The province includes light-colored plains that are less densely cratered than old plains, and fills low areas near basins and within large craters. Most occurrences are probably derived from impact melts; however, a volcanic origin cannot be excluded, particularly for the plains within the Lomonosov/Fleming basin (Fig. 8a,b).

7. *Old Mare.* The largest expanse of a relatively old mare province is in the Australe basin. In this locality the mare is overlapped by materials of the Imbrian-age craters Humboldt (27°S, 81°E) and Jenner (42°S, 96°E). This relation indicates that this province includes units that are older than most or all nearside mare materials.

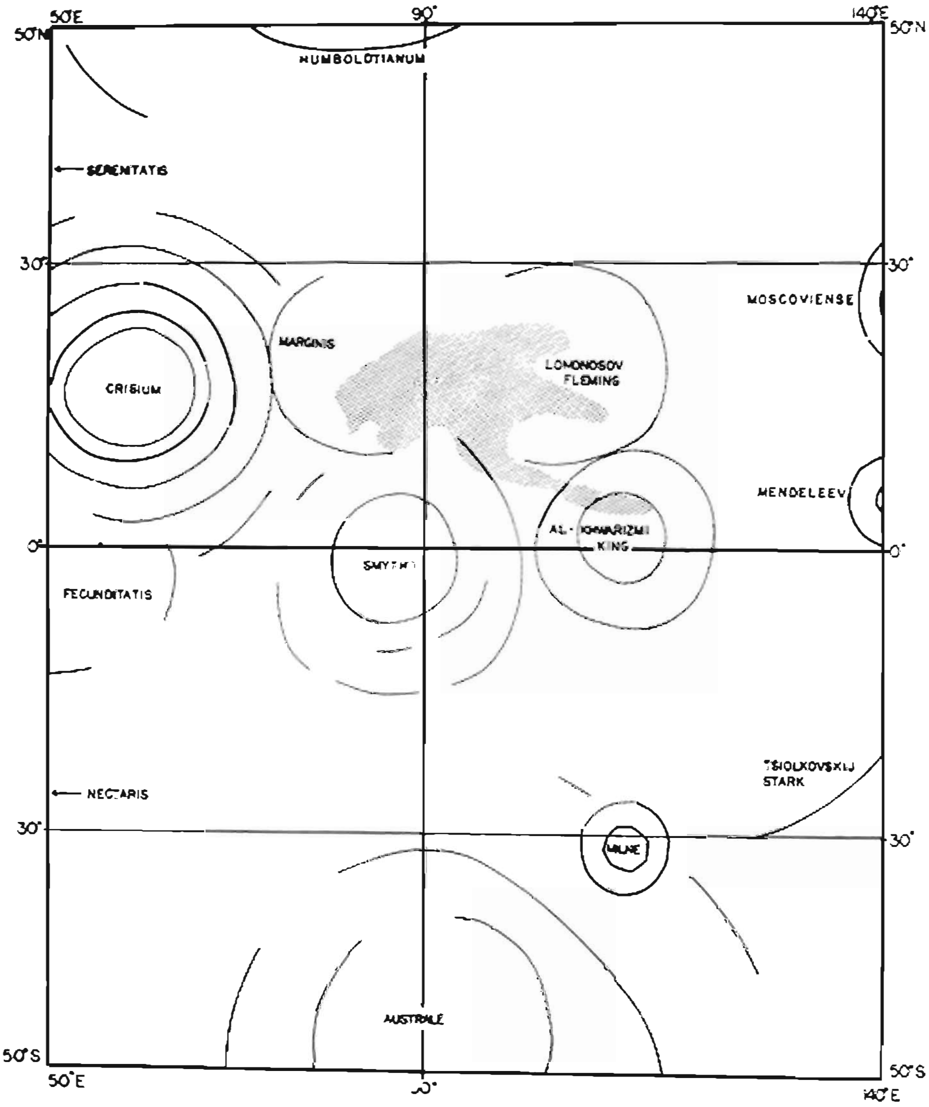


FIGURE 8b. Basin rings on the east side region of the Moon. Solid lines indicate conspicuous arcs and dotted lines indicate subdued rings. The stippled area centered at about 15°N, 19°E shows light-colored swirls in and northeast of Mare Marginis (after El-Baz and Wilhelms, 1975).

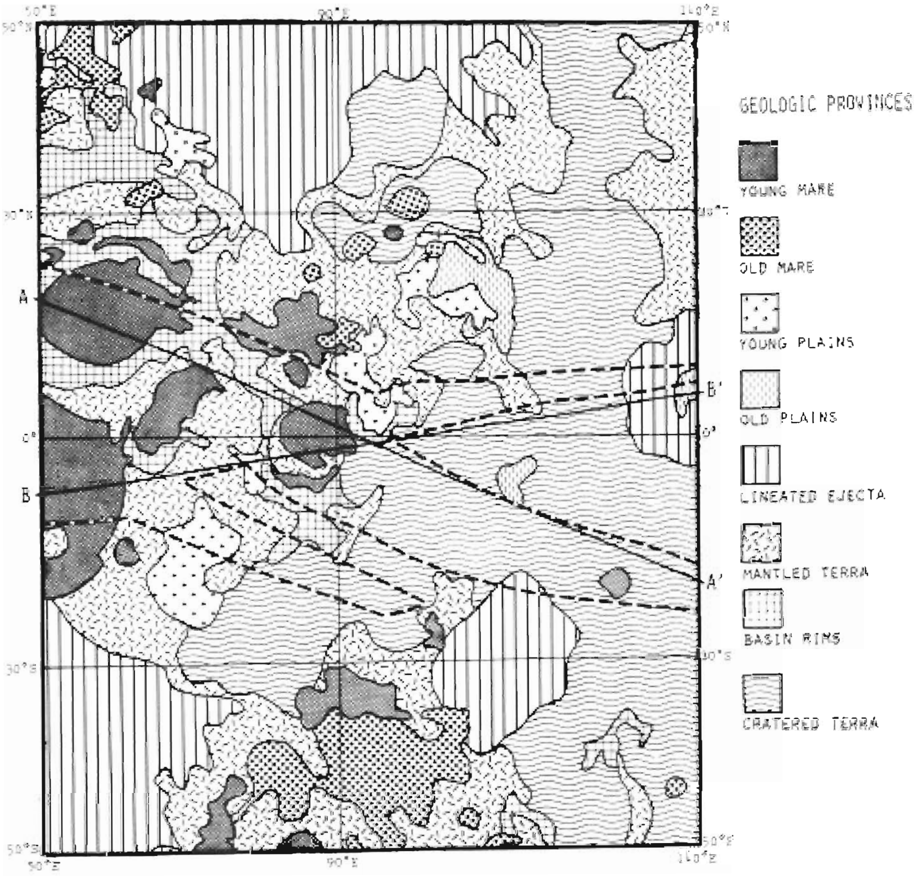


FIGURE 8c. Geologic provinces on the east side region of the Moon. Lines AA' and BB' represent tracks of laser altimeter measurements and dashed envelope represents the extent of geochemical remote-sensing on Apollo missions 15 and 16 (after El-Baz and Wilhelms, 1975).

8. *Young Mare.* The young mare units are concentrated mainly in the Crisium, Fecunditatis, and Smythii basins and the troughs between them. The crater Tsiolkovskij in the southeastern part of the region (20°S, 129°E) and a few other craters and depressions on the far side within larger basins contain maria. A conspicuous farside patch of young mare materials not near either a basin or a large crater is centered at 27°S, 130°E (see El-Baz, 1972, pp. 48-49).

THE MARIA

Prior to the Apollo lunar missions, most investigators interpreted the dark lunar plains as volcanic (probably basaltic) lava flows. This interpretation was confirmed by analyses of lunar samples returned by Apollo 11, 12, 15, and 17 and Luna 16 (0°42'S, 56°18'E) missions.

The maria are mostly confined within the multiringed basins and nearby troughs (Fig. 9). However, these basins are older than and not genetically related to, the basalts they contain. They only provide the depressions in which the basalts rest. (Fractures that may have been produced at the time of basin formation may have provided channel ways for the later upward movement of basaltic magmas.)

As illustrated in Fig. 9, the maria constitute about 17% of the lunar crust. Head (1976b) calculates that volumetrically, the maria compose only 1% of the crustal materials. However, mare basalts (which are compositionally simpler than highland rocks), contain much information about the thermal history of the Moon and the nature of the lunar interior (Papike et al., 1976).

Because of the preponderance of flow fronts and other superposition relationships in the lunar maria (El-Baz, 1974), age relationships between mare units are relatively easy to decipher. Where superposition relationships are not distinct, three methods of dating based on crater density may be used:

(1) Assuming a known flux rate of impact, the absolute crater frequency will be proportional to the age of the surface (Showmaker and Hackman, 1962).

(2) Considering the morphologically oldest superposed crater on a mare surface, a sequence of lava flooding can be deduced (Pohn and Offield, 1970).

(3) Determining the maximum diameter of craters that have been eroded such that the interior slope is less than the Sun angle. The maximum crater diameter is then converted to an equivalent diameter (D_L) of a crater that would have been eroded

to an interior slope of 1° by the net accumulated flux. Therefore, values of D_L became proportional to the total number of craters on a given surface (Soderblom and Lebofsky, 1972).

Application of these methods has resulted in working out detailed stratigraphic sequences in Mare Imbrium (Boyce and Dial, 1975), in Oceanus Procellarum (Boyce, 1975), and in southeastern Mare Serenitatis (Maxwell, 1977). Data on relative ages in these studies are usually correlated with albedo and color-difference data of Whitaker (1972). For example, Boyce and Dial (1975) recognized the following units in Mare Imbrium and Sinus Iridum:

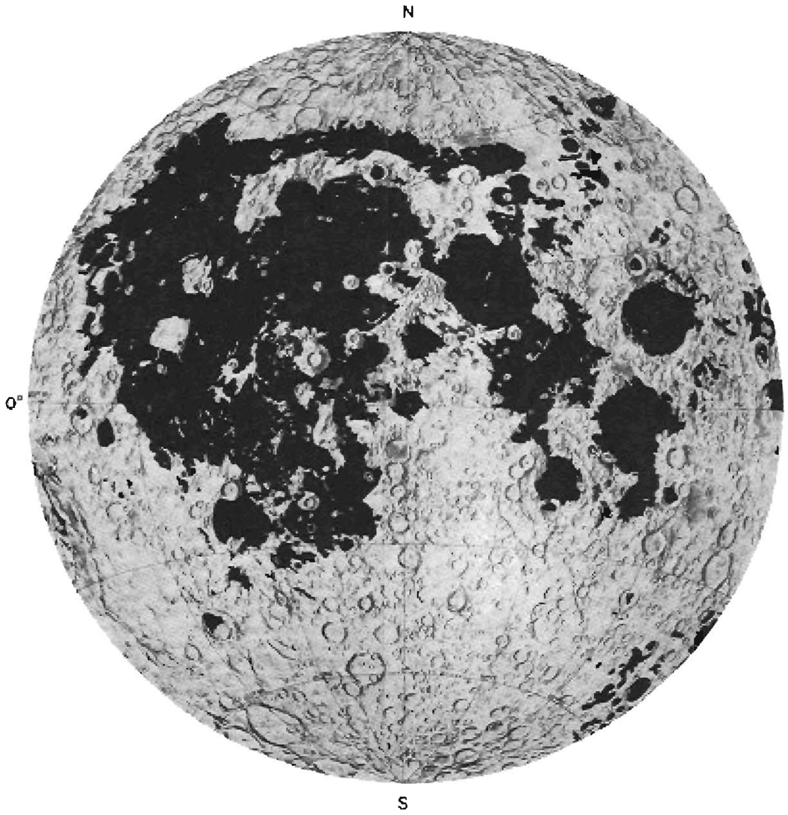
1. An old, low albedo unit in the southeastern corner of the Imbrium basin.
2. An old, intermediate red unit around the edge of the basin.
3. A young, intermediate red unit in Sinus Iridum, which is contemporaneous with a blue unit.
4. A young, blue unit in the southwest and central parts of the basin.

The relative age scheme of mare units can not be calibrated by the results of age dating of returned mare samples. These samples vary in age between 3.15 and 3.85 billion years (Tera *et al.*, 1974). However, the aforementioned relative age dating techniques indicate that basalts as young as 2.5 billion years exist in Oceanus Procellarum, within an area of the Moon that has not yet been sampled.

Chemically, the sampled lunar mare basalts can be divided into two groups: old (3.55 - 3.85 billion years), high-titanium basalts of Apollo 11 and 17; and relatively young (3.15 - 3.45 billion years), low-titanium basalts of Apollo 12 and 15 and Luna 16. According to Papike *et al.* (1976), these two groups were derived from mineralogically distinct source regions. The low-titanium basalts could have been derived from an olivine-pyroxene source rock at depths ranging from 200 to 500 km, while the high-titanium basalts could have been derived from olivine-pyroxene-ilmenite cumulates in the outer 150 km of the Moon.

LUNAR GEOLOGIC PROVINCES

After the completion of detailed geologic mapping of the Moon, it is now possible to divide the lunar materials into six distinct provinces (Howard *et al.*, 1974). As explained by Wilhelms (1974), to best compare these to geologic provinces on Mars, the maria are divided into young and old. The highlands or terrae are divided into four provinces according to



even

FIGURE 9a. Distribution of lunar mare materials (black areas) on the near side of the Moon. (Base map is an equal area projection by the National Geographic Society.)

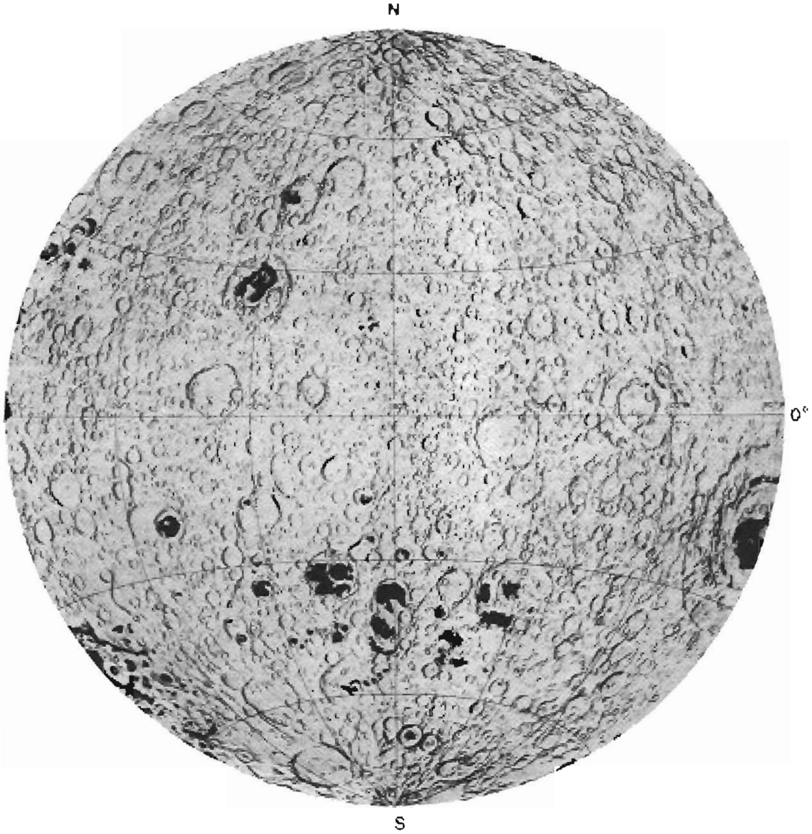


FIGURE 9b. Distribution of lunar mare materials (black areas) on the far side of the Moon. (Base map is an equal area projection by the National Geographic Society.)

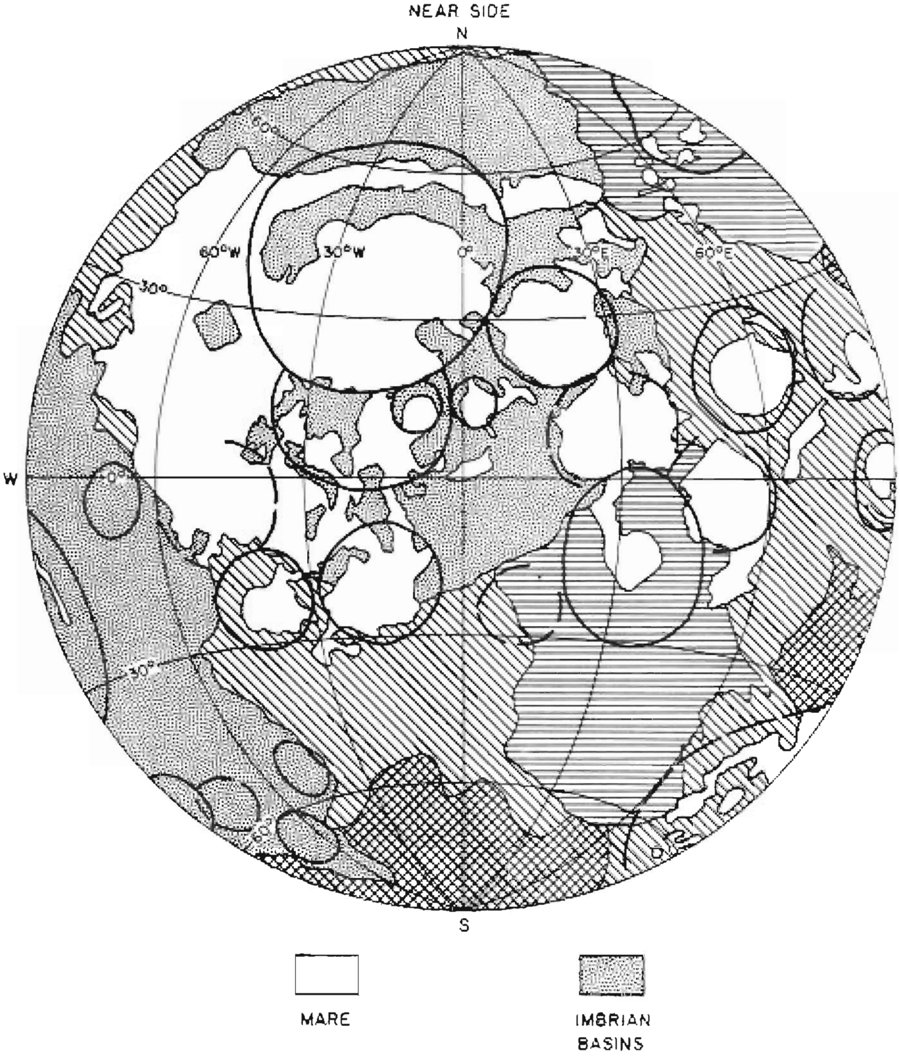


FIGURE 10a. Thematic map of major geologic provinces on the Moon. For explanation of provinces refer to text (after Howard et al., *1974).*

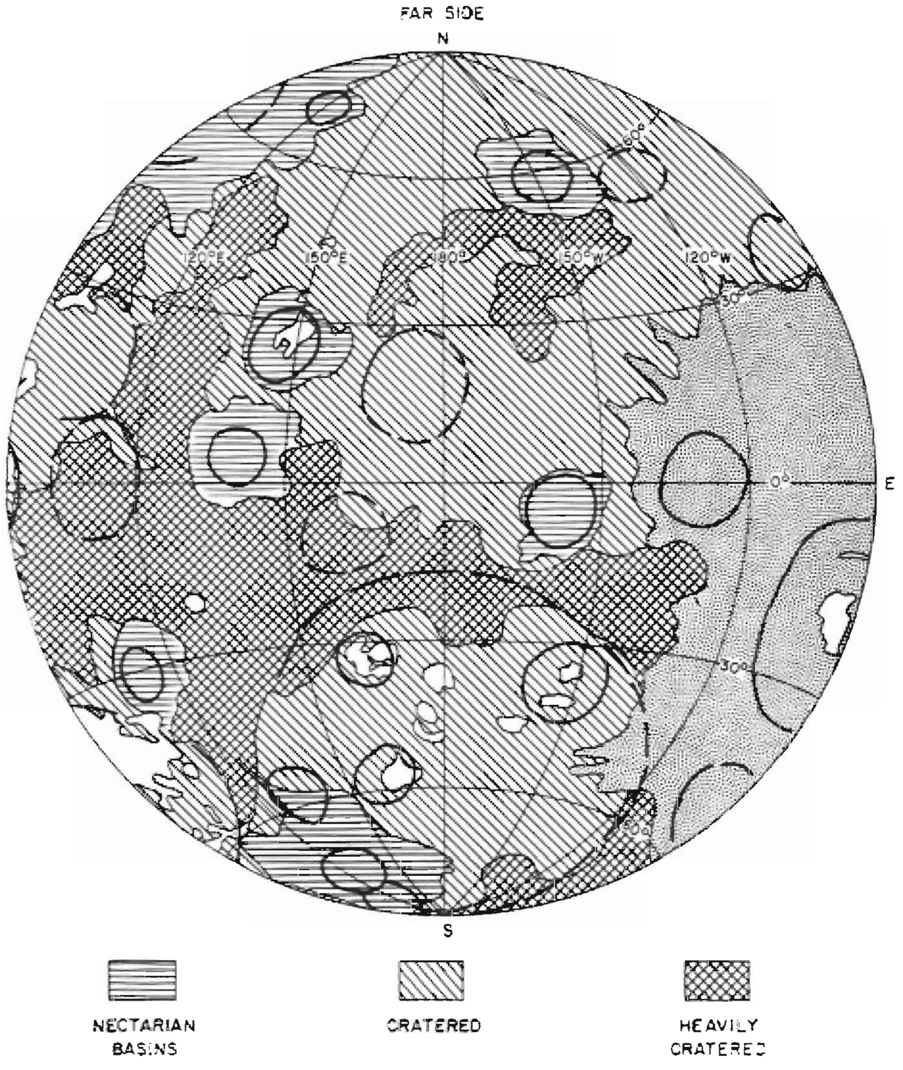


FIGURE 10b. Thematic map of major geologic provinces on the Moon. For explanation of provinces refer to text (after Howard et al., 1974).

the degree of development of multiringed circular basins (Fig. 10). Wilhelms (1974) defines these provinces as follows:

1. *Heavily Cratered Provinces.* Parts of the lunar highlands show no evidence of basin ejecta blankets, although they may contain some degraded basin rings. In this province there is a high density of overlapping craters, probably saturated to sizes of 200-300 km or even to the size range of basins (Howard *et al.*, 1974).

2. *Cratered Provinces.* This province, which has fewer old and degraded craters than the heavily cratered province, occurs near basins and contains degraded basin rings and much undulatory mantling material that is believed to be basin ejecta. The basins have apparently reduced the number of visible craters from that of the heavily cratered province.

3. *Nectarian Basin Province.* Basins of Nectarian age (that is, late pre-Imbrian) have distinct ejecta and secondary craters and rugged raised rings. The largest basins are Nectaris (the oldest) and Humboldtianum; the other smaller ones are more like craters but still have the multiple rings (usually two) that distinguish basins from craters (Hartmann and Kuiper, 1962; Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971) The basin materials have obliterated or obscured old craters and form surfaces on which there are fewer craters than in the first two provinces.

4. *Imbrian Basin Province.* Young lunar multiringed impact basins have obvious similarities to impact craters, including sharply lineated ejecta blankets and satellitic clusters of fresh-appearing secondary impact craters (summaries by Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971; Wilhelms and McCauley, 1971; Wilhelms, 1973; Howard *et al.*, 1974). Materials of the two basins of Imbrian age, Imbrium and Orientale, constitute the province that is most obviously of basin origin. The basin ejecta blankets have covered pre-Imbrian and early Imbrian craters and have thereby given rise to the lowest crater densities on the lunar terrae.

5. *Old Mare Province and Light Plains Material.* As stated above, in the Mare Australe region of the Moon (Fig. 8c), mare material is pitted by the secondary impacts of the craters Humboldt and Jenner, which themselves contain mare material (Stuart-Alexander and Howard, 1970, p. 451; see also El-Baz and Wilhelms, 1975; Wilhelms and El-Baz, 1977). These craters are of Imbrian age. Therefore the Australe mare material is older than the near side maria. A few other patches of the old mare material are also present elsewhere on the far side.

A similar but lighter-colored lunar plains unit was formed at about the same time as the old mare material. The two units have a similar crater density, but the light plains appear in places to be overlain by the dark. The light plains are no-where sufficiently concentrated to be considered a province at this scale. The greatest concentrations occur near the Orientale and Imbrium basins and are included in the Imbrian basin province, in accord with the interpretation that these plains are mostly basin ejecta (Howard *et al.*, 1974).

6. *Young Mare Province*. All of the maria on the lunar near side and some mare patches on the far side are assigned to this province. The range of ages is from Imbrian to Eratosthenian, or from 3.85 to 3.15 billion years ago as so far sampled and dated. This period is 15% of the Moon's history but about 50% of the part of the history that included major surface changes, for the subsequent impacts did not severely obscure the maria. The era represented by the maria was itself much less active in terms of impact events than the preceding 50%, for in the earlier epoch the terra materials were repeatedly reworked and redistributed by a rain of impacting objects.

SUMMARY

Utilization and testing of the concepts of stratigraphy results in a reasonable account of lunar surface history. The evolution of the lunar crust is schematically shown in Table II, in which correlations are made between the major geologic provinces, the relative-age scheme of lunar surface materials, and the absolute ages as deduced mostly from returned lunar samples.

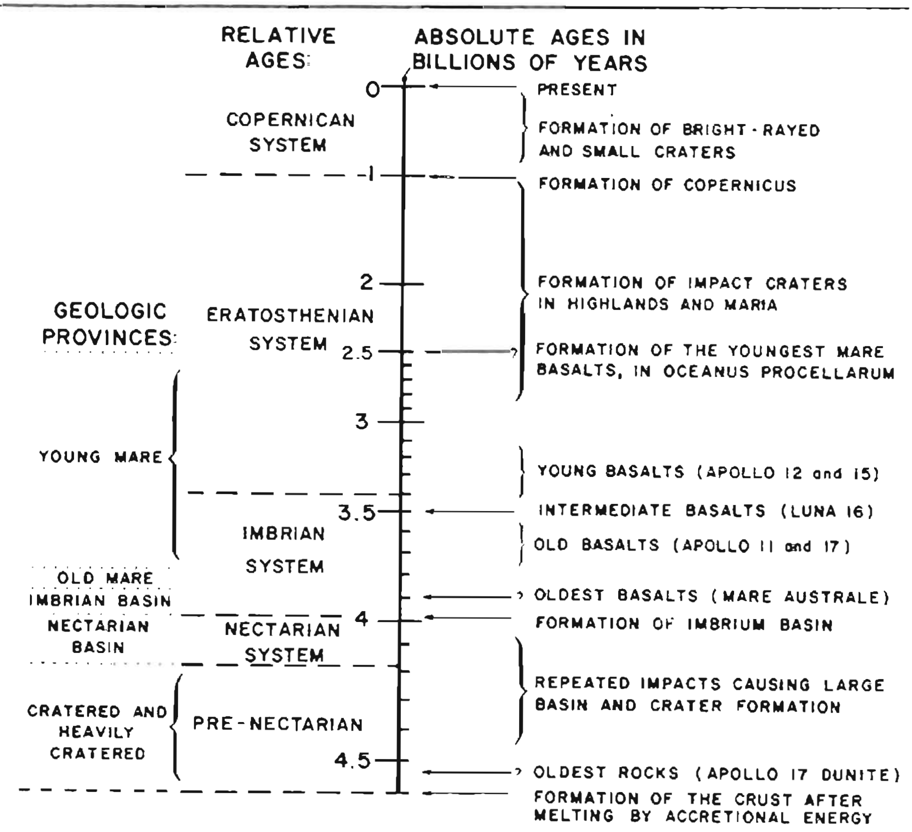
From this and preceding discussions, the evolution of the lunar crust can be divided into five major stages:

1. *Formation of the Original Crust*. Little is known about the early period of lunar crustal formation. Based on model ages of lunar soils, the Moon is assumed to have formed 4.6 billion years ago. This age is equal to that of meteorites and also to the one assumed for the solar system. Therefore, it is reasonable to assume that it represents the condensation age of the solar nebula. As the condensed material formed the Sun and the planets, some of it gathered to form the Moon. As the moonlet grew, it was repeatedly struck by a large amount of infalling debris. This probably resulted in melting the upper 100 - 300 km of the Moon by accretional energy. The melting resulted in a Moon-wide differentiation to form the feldspar-rich crustal rocks (anorthositic gabbros and gabbroic anorthosites).

2. *Heavy Cratering Episode*. As the amount of infalling objects decreased, the differentiated crust started cooling. When the crust solidified, it started preserving the scars of collisions with large and small planetesimals. Many basins and numerous craters pockmarked the surface over a long period of

time, where relatively new features obliterated or subdued older ones. This episode probably started as early as 4.55 billion years ago and continued to about 3.9 billion years ago. Remnants of the oldest impact scars are probably no longer visible.

TABLE II. Correlation of Nomenclature of the Orientale Basin and Related Materials.



The more recent impacts with discernible remains may be classed as early (including basins like Al-Khwarizmi/King, Australe, and South Pole/Aitken), middle (including Smythii, Nectaris, and Crisium), and late (including the youngest basins, Imbrium and Orientale, which probably formed at 3.95 and about 3.9 billion years ago, respectively).

3. *Formation of the Oldest Plains.* In many parts of the Moon, both light-colored (highlandlike) and dark-colored (marelike) plains formed contemporaneously with and after the formation of the youngest lunar multiringed basins. These plains probably span a period from 4.0 to 3.85 billion years ago. Most light-colored plains are genetically related to basin-forming impact events, although some of them may be volcanic in origin. The old dark-colored plains are probably composed of basalts.

4. *Major Basaltic Flooding.* Differentiated basaltic magmas were probably originated by melting due to heat generated by radioactive decay beneath the lunar crust. These magmas probably made their way to the surface via impact-induced fractures in the crust. Lavas flowed on the surface and accumulated in low areas, particularly within the multiringed basins. From the absolute age dating of returned lunar samples, this major episode of basaltic lava flooding may be divided into three distinct phases: (1) old, between 3.85 and 3.5 billion years ago (Apollo 11 and 17 rocks); (2) intermediate, between 3.5 and 3.4 billion years ago (Luna 16 rocks); and (3) young, between 3.4 and 3.15 billion years ago (Apollo 12 and 15 rocks). A fourth phase, as young as 2.5 billion years, is suggested by crater age dating in Oceanus Procellarum.

5. *Stabilization of the Crust.* Near the end of the main basaltic flooding stage, the major features of the Moon's surface had been formed. Events of only local significance ensued. Among these are the impacts that created many of the prominent lunar craters that are smaller than 100 km in diameter, e.g., Eratosthenes (about 3.2 billion years ago), Copernicus (about 1.0 billion years ago), and Tycho (70 - 95 million years ago). Dating of returned lunar samples also provided data on the ages of craters in the Apollo landing sites. For example, Shorty Crater at the Apollo 17 site (20 - 30 million years ago), and South Ray crater at the Apollo 16 site (only 2 million years ago). Smaller meteoroid impacts continue to locally modify lunar surface stratigraphy to this day.

ACKNOWLEDGMENTS

The author is indebted to T. A. Maxwell, P. L. Strain, and R. W. Wolfe for reviewing this paper. Thanks are due to D. J. Hennen and J. E. Murphy for typing and proofing the manuscript, and to A. W. Gifford for preparing the illustrations.

REFERENCES

Baldwin, R. B. (1963). *"The Measure of the Moon."* Univ. of Chicago Press, Chicago, Illinois.

Baldwin, R. B. (1972). The tsunami model of the origin of ring structures concentric with large lunar craters, *Phys. Earth Plan. Interiors 6,* 327-339.

Boyce, J. M. (1975). Chronology of the major flow units in the western nearside maria, *in Conf. Origins of Mare Basalt,* LSI, Houston, Texas, pp. 11-14.

Boyce, J. M., and Dial, A. L. (1975). Relative ages of flow units in Mare Imbrium and Sinus Iridum, *Proc. Lunar Sci. Conf. 6th 3,* 2585-2595.

Chao, E. C. T., Hodges, C. A., Boyce, T. M., and Soderblom, L. A. (1975). Origin of lunar light plains, *J. Res. U. S. Geol. Survey 3,* 379-392.

Dence, M. R. (1972). The nature and significance of terrestrial impact structures, *Internat. Geol. Cong-. Rept. Sess. 24th,* pp. 77-89.

Eggleton, R. E. (1964). Preliminary geology of the Riphaeus quandrangle of the Moon and definition of the Fra Mauro Formation, *in Astrogeol. Stud. Ann. Prog. Rept. (1962-63),* *Pt. A,* pp. 43-46.

Eggleton, R. E., and Marshall, C. H. (1962). Notes on the Apenninian series and pre-Imbrian stratigraphy in the vicinity of Mare Humorum and Mare Nubium, *in Astrogeol. Studies Semiann. Prog. Rept., Pt. A,* pp. 99-109.

El-Baz, F. (1972). New geological findings in Apollo 15 lunar orbital photography, *Proc. Lunar Sci. Conf. 3rd 1,* 39-61.

El-Baz, F. (1973). Al-Khwarizimi: A new-found basin on the lunar far side, *Science 180,* 1173-1176.

El-Baz, F. (1974). Surface geology of the Moon, *Ann. Rev. Astron. Astrophys. 12,* 135-165.

El-Baz, F. (1975). The Moon after Apollo, *Icarus 25,* 495-537.

El-Baz, F., and Wilhelms, D. E. (1975). Photogeological, geophysical, and geochemical data on the east side of the moon, *Proc. Lunar Sci. Conf. 6th 3,* 2721-2738.

Fielder, G. (1965). *"Lunar Geology,"* Butterworth, London.

Gault, D. E. (1970). Saturation and equilibrium conditions for impact cratering on the lunar surface: criteria and implications, *Radio Sci. 5,* 273-291.

Gault, D. E., Quaide, W. L., and Oberbeck, V. R. (1968). Impact cratering mechanics and structures, *in* (B. M. French and N. M. Short, eds.), *"Shock Metamorphism of Natural Materials"* pp. 87-99.

Gilbert, G. K. (1893). The Moon's face, a study of the origin of its features, *Phil. Soc. Washington Bull. 12,* 241-292.

Gilbert, G. K. (1896). The origin of hypotheses, illustrated by the discussion of a topographic problem, *Science 3,* 1-12.

Green, J. (1962). The geosciences applied to lunar exploration, *in* (Z. Kopal and Z. K. Mikhailov, eds.), *"The Moon"*, pp. 160-257. Academic Press, London.

Hartmann, W. K., and Kuiper, G. P. (1962). Concentric structures surrounding lunar basins, *Comm. Lunar Planet. Lab. 1,* 51-66.

Hartmann, W. K., and Wood, C. A. (1971). Moon: Origin and evolution of multi-ring basins, *The Moon 3,* 3-78.

Head, J. W. (1974a). Orientale multi-ringed basin interior and implications for the petrogenesis of lunar highland samples, *The Moon 11,* 327-356.

Head, J. W. (1976a). Origin of rings in lunar multi-ringed basins. Abstracts from *Symp. Plan. Cratering Mechanics,* LSI, Houston, Texas, pp. 47-49.

Head, J. W. (1976b). Lunar volcanism in space and time, *Rev. Geophys. Space Phys. 14,* 265-300.

Head, J. W., Settle, M., and Stein, R. S. (1975). Volume of materials ejected from major lunar basins and implications for the depth of excavation of lunar samples, *Proc. Lunar Sci. Conf. 6th 3,* 2805-2829.

Hodges, C. A., Muehlberger, W. R., and Ulrich, G. E. (1973). Geologic setting of Apollo 16, *Proc. Lunar Sci. Conf. 4th 1,* 1-25.

Hodges, C. A., and Wilhelms, D. E. (1976a). Formation of concentric basin rings, Abstracts from *Symp. Plan. Cratering Mechanics,* LSI, Houston, Texas, pp. 53-55.

Hodges, C. A., and Wilhelms, D. E. (1976b). Formation of lunar basin rings, *25th Internat. Geol. Cong.*, Sydney, Australia.

Howard, K. A., and Masursky, H. (1968). Geologic map of the Ptolemaeus quadrangle of the Moon, *USGS Misc. Geol. Inv. Map I-566.*

Howard, K. A., Wilhelms, D. E., and Scott, D. H. (1974). Lunar basin formation and highland stratigraphy, *Rev. Geophys. Space Phys. 12,* 309-327.

King, E. A. (1976). *"Space geology, an introduction."* Wiley, New York.

Lindsay, J. F. (1976). Lunar stratigraphy and sedimentology, *in* (Z. Kopal and A. G. W. Cameron, eds.), *"Developments in Solar System and Space Science," Vol. 3* Elsevier, Amsterdam.

LSPET: Lunar Sample (Apollo 16) Preliminary Examination Team (1973). The Apollo 16 lunar samples: petrographic and chemical description, *Science 179,* 23-34.

Maxwell, T. A. (1977). Stratigraphy and tectonics of southeastern Serenitatis. PhD. Dissertation, Univ. of Utah.

McCauley, J. F. (1967). The nature of the lunar surface as determined by systematic geologic mapping, *in "Mantles of the Earth and Terrestrial Planets"* (S. K. Runcorn, ed.), pp. 431-460. Wiley, New York.

McCauley, J. F. (1968). Geologic results from the lunar percursor probes, *AIAA J. 6,* 1991-1996.

McCauley, J. F. (1976). Orientale and Caloris. Abstracts from the *Conf. Comparisons of Mercury and the Moon,* LSI, Houston, Texas, p. 24.

McGetchin, T. R., Settle, M., and Head, J. W. (1973). Radial thickness variation in impact crater ejecta: Implications from lunar basin deposits, *Earth Plan. Sci. Lett. 20,* 226. 236.

Milton, D. J. (1968). Geologic map of the Theophilus quadrangle of the Moon, *USGS Map I-546.*

Moore, H. J., Hodges, C. A., and Scott, D. H. (1974). Multiringed basins--illustrated by Orientale and associated features, *Proc. Lunar Sci. Conf. 5th 1,* 71-100.

Mutch, T. A. (1972). *"Geology of the Moon: a Stratigraphic View,"* revised ed. Princeton Univ. Press, Princeton, New Jersey.

Oberbeck V. R., Horz, F., Morrison, R. H., Quaide, W. L., and Gault, D. E. (1975). On the origin of the lunar smooth plains, *The Moon 12,* 19-54.

Papike, J. J., Hodges, F. N., Bence, A. E., Cameron, M., and Rhodes, J. M. (1976). Mare basalts: Crystal chemistry, mineralogy, and petrology, *Rev. Geophys. Space Phys. 14,* 475-540.

Pohn, H. A., and Offield, T. W. (1970). Lunar crater morphology and relative age determination of lunar geologic units--Part 1, *USGS Prof. pap. 700-C,* 153-162.

Scott, D. H. (1974). The geologic significance of some lunar gravity anomalies, *Proc. Lunar Sci. Conf. 5th 3,* 3025-3036.

Shoemaker, E. M. (1962). Interpretation of lunar craters, *in "Physics and Astronomy of the Moon"* (Z. Kopal, Ed.), pp. 283-359.

Shoemaker, E. M., and Hackman, R. J. (1962). Stratigraphic basis for a lunar time scale, *in The Moon--Symposium 14--IAU"* (Z. Kopal and Z. K. Mikhailov, eds.), pp. 289-300. Academic Press, New York.

Short, N. M. (1975). *"Planetary Geology."* Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Soderblom, L. A., and Lebofsky, L. A. (1972). Technique for rapid determination of relative ages of lunar areas from orbital photography, *JGR 77,* 279-296.

Spurr, J. E. (1944). The Imbrian plain region of the Moon, *in "Geology Applied to Selenology,"* Vol. I. Science Press, Lancaster, Pennsylvania.

Spurr, J. E. (1945). The features of the Moon, *"Geology Applied to Selenology,"* Vol. II. Science Press, Lancaster, Pennsylvania.

Stuart-Alexander, D. E. (1976). Geologic map of the central far side of the Moon, *USGS Interagency Rept.: Astrogeology 79.*

Stuart-Alexander, D. E., and Howard, K. A. (1970). Lunar maria and circular basins--a review, *Icarus 12,* 440-456.

Stuart-Alexander, D. E., and Wilhelms, D. E. (1974). Nectarian System, a new lunar stratigraphic name, *U.S. Geol. Surv. Jour. Res. 3,* 53-58.

Taylor, S. R. (1975). *"Lunar Science: A Post-Apollo View."* Pergamon, New York.

Tera, F., Papanastassiou, D. A., and Wasserburg, G. J. (1974). The lunar time scale and a summary of isotopic evidence for a terminal lunar cataclysm, *in "Lunar Science IV,* LSI, Houston, Texas, pp. 792-794.

Whitaker, E. A. (1972). Lunar color boundaries and their relationships to topographic features: A preliminary survey, *The Moon 4,* 348-355.

Wilhelms, D. E. (1965). Fra Mauro and Cayley Formations in Mare Vaporum and Julius Caesar quadrangles, *in Astrogeol. Stud. Ann. Rept., Pt. A,* pp. 13-28.

Wilhelms, D. E. (1970). Summary of lunar stratigraphy--Telescopic observations, *U. S. Geol. Surv. Prof. Pap. 599-F.*

Wilhelms, D. E. (1973). Comparison of martian and lunar multiringed circular basins, *JGR 78,* 4084-4095.

Wilhelms, D. E. (1974). Comparison of martian and lunar geologic provinces, *JGR 79,* 3934-3941.

Wilhelms, D. E., and Davis, D. E. (1971). Two former faces of the Moon, *Icarus 15,* 368-372.

Wilhelms, D. E., and El-Baz, (1977). Geologic map of the east side of the Moon, *U. S. Geol. Surv. Map I-948.* In press.

Wilhelms, D. E., and McCauley, J. F. (1971). Geologic map of the near side of the Moon, *U. S. Geol. Surv. Map I-703.*