E. LUNAR TECTONICS

LUNAR MARE RIDGES, RINGS AND VOLCANIC RING COMPLEXES

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Abstract. Mare ridges often consist of two separate but related features: (1) a broad gentle arch overlain by (2) a sharper, more contorted ridge. Often these sharper, secondary ridges have flowed into craters in the adjacent terrain indicating they are extrusions. Major flows in Mare Imbrium appear to have issued from several prominent mare ridges. These flows show color differences which may be related to their abundance of titanium. The association of flows with mare ridges, the broad arching linked with many ridges and the coincidence of linear ridges with the directions of major fracture patterns in the highlands indicates that arched mare ridges are dike, sill or laccolithic-type intrusions along major fractures. In many cases these intrusions appear to have broken through the surface to form short flows and bulbous lava extrusions. Mare ridges unassociated with arching are probably lava extrusions only.

Mare ridges often take the form of rings indicating that they developed along ring fractures. Several linear mare ridges and mare ridge rings have bright hills situated along them and are considered to be post-mare volcanic hills of more siliceous composition than the maria. Evidence suggests that many of the ring structures are post-mare volcanic ring complexes formed over large igneous masses.

1. Introduction

Mare ridges are ubiquitous features of the maria and their origin has a strong bearing on the nature of the processes that have shaped the maria. Both a tectonic and magmatic origin has been suggested for the formation of these ridges, but the evidence for either origin has been inconclusive until the recent acquisition of the Lunar Orbiter photography. New evidence from this photography strongly implies that both tectonism and magmatism have played a role in their formation, but magmatic activity seems to have been the principal process in forming the ridges as they appear today.

Mare rings (sometimes referred to as 'Ghost Rings') are nearly circular structures which occur exclusively in the maria and consist of mare ridges or intermittent groups of relatively low, bright hills situated along the ridges. These structures have been interpreted as the rims of craters which were almost completely buried by mare lavas and, therefore, of pre-mare age. This interpretation was challenged by Fielder (1965) who suggested that many of these features (which he termed elementary rings) are young, post-mare extrusions of volcanic material along ring fractures. Recently, Fulmer and Roberts (1967) and Guest and Fielder (1968) have found evidence on the Lunar Orbiter photography which supports this theory. The evidence consists primarily of fine, preferentially oriented lineaments on the hills, and the general structure and geological relations of the ring structures.

The present paper is primarily concerned with the origin of mare ridges and their association with certain ring structures. There appears to be a complete transition from linear mare ridges, through mare ridge rings, to rings made up almost entirely of

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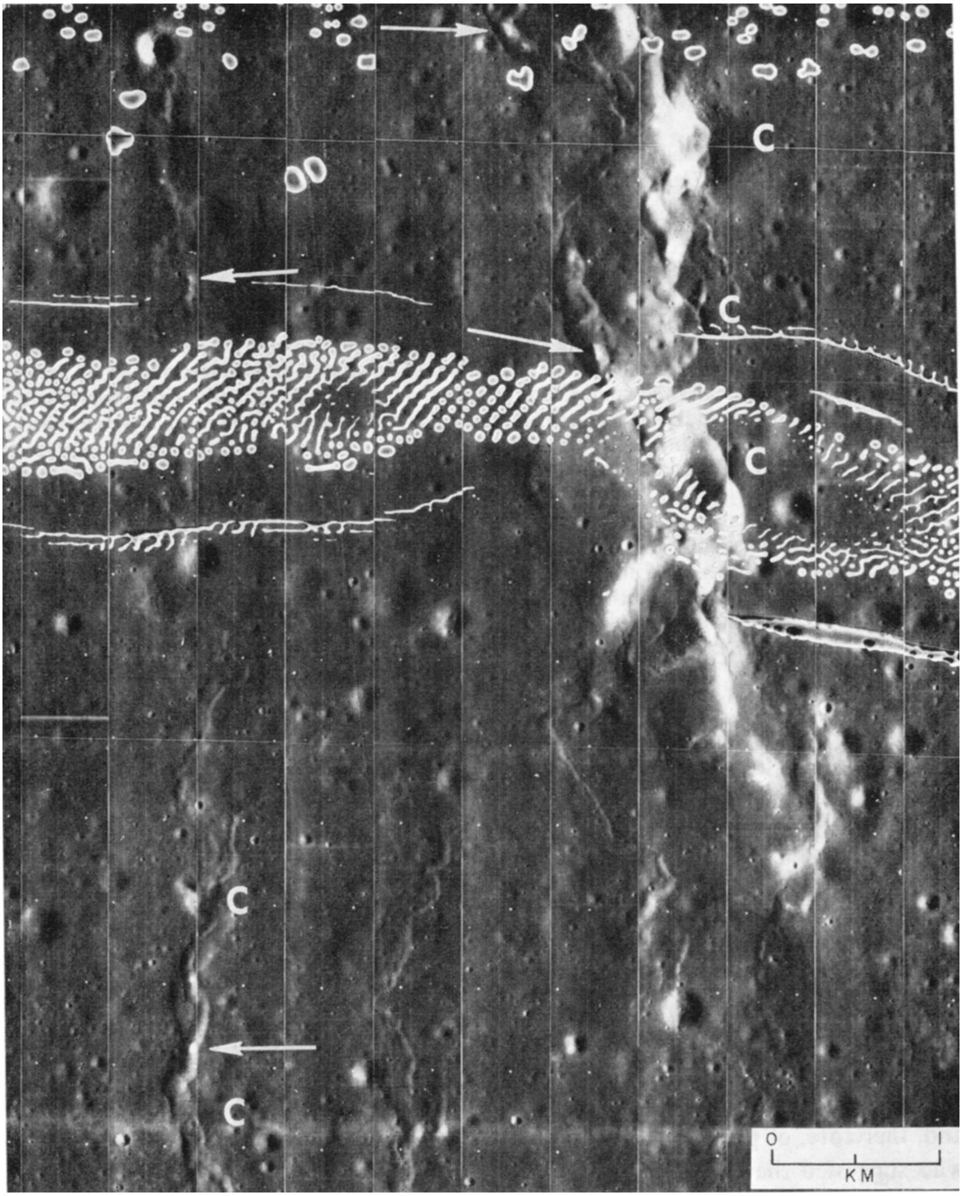

Fig. 1. Mare ridges in Mare Serenitatis near the Littrow Rilles. The ridges have flowed into and partially filled craters located at *c*. Small bright incipient hills similar to those in Figure 15 and discussed in the text are indicated by arrows. The horizontal white patterns are bimatt processing defects. (*NASA Lunar Orbiter 5*)

bright hills situated on mare ridges. These associations indicate that certain ring structures are post-mare volcanic ring complexes. Several bright hills seem to be superimposed on mare ridges which indicates they are post-mare volcanic hills rather than flooded portions of the highlands.

2. Mare Ridges

Mare or 'wrinkle' ridges are long, low ridges which are concentrated in, but not limited to, the maria. They range from less than 1 km to over 20 km wide and may reach lengths of several hundred kilometres. Their height varies from a few metres to about 200 or 300 metres. Many of the ridges consist of a broad arch capped by a sharper, more irregular secondary ridge. The mare ridges seen on the Lunar Orbiter photography are generally the sharper portions of the structures. These photographs primarily were taken at a Sun angle of about 20° but the broad arching is generally visible only at Sun angles less than 15°. Sometimes these gentle arches are asymmetrical and, if a secondary ridge occurs on them, it is usually situated on the crest of the arch.

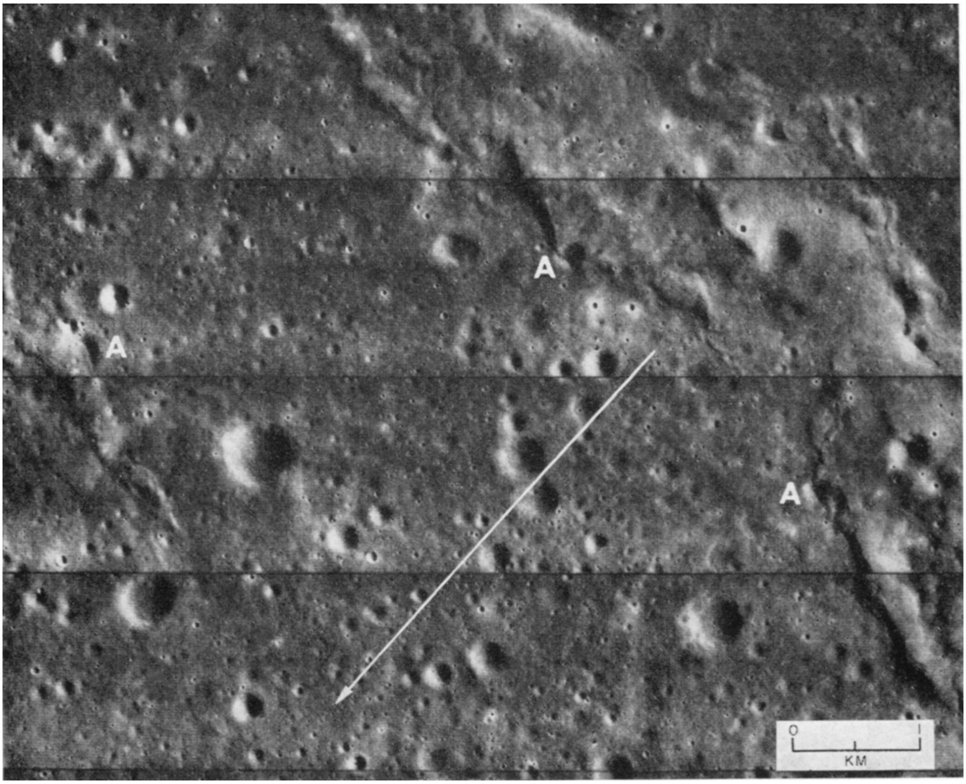

Fig. 2. **Mare ridges in Mare Tranquillitatis that have flowed into craters located at *A*. The arrow represents the direction and extent of slope of the arch upon which the righthand ridge lies. For the location of this area see Figure 3.** ***(NASA Lunar Orbiter 1)***

Usually the secondary ridges comprise about 25–60% of the total width of the structures. Although the association of sharp ridges with broad arches is relatively frequent, there are numerous examples of sharp ridges unaccompanied by arching.

The general geometric arrangement of the ridges may be sinuous, linear or concentrically oriented with respect to the borders of the circular maria. However, the Orbiter photography has shown that even the sinuous and arcuate ridges often consist of short, linear segments. These linear segments, as well as the linear mare ridges, often coincide with the directions of the major lineament systems (grid system) found in the lunar highlands (Fielder and Kiang, 1962; Strom, 1964). Recently Fryer (personal communication) has found a striking agreement in orientation between the mare ridges in the western part of Oceanus Procellarum and the lineaments in the adjacent highlands. This coincidence in direction of linear mare ridges and the fracture pattern in the highlands strongly suggests that these ridges are situated along major fractures in the lunar crust.

It has been suggested that the mare ridges are anticlinal or fault ridges formed by compression, or ridges resulting from the intrusion and/or extrusion of magma along

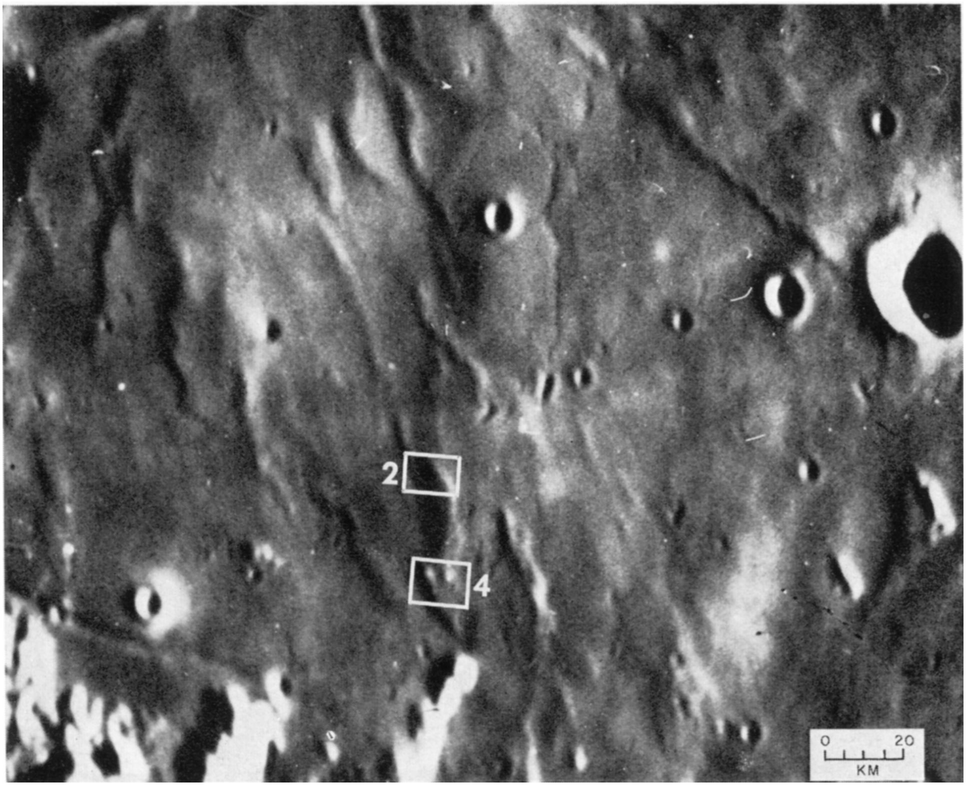

Fig. 3. Earth-based photograph of the mare ridges shown in Figures 2 and 4. Notice the extent of the arch in this low-illumination (7°) photograph which is not readily discernible in Figure 2 taken at a Sun angle of 20°. *(LPL Catalina Obs. photo)*

fractures. The Orbiter photography shows rather conclusively that the second explanation is basically correct. Figure 1 is a portion of a mare ridge at the eastern border of Mare Serenitatis near the Littrow rilles. The ridge has a very ropy texture and has flowed into and partially filled three craters. The texture and lobate character of the flow front where it overlaps the most northerly crater is characteristic of a relatively viscous lava flow. A smaller ridge to the west also has been extruded into several shallow craters. Figure 2 shows similar extrusions which form ridges in Mare Tranquillitatis and also partially fill or overlap several craters (A). The larger structure to the east is a secondary ridge that caps a gentle asymmetrical arch visible on low-illumination Earth-based photographs (Figure 3). This secondary ridge is located at the crest of the arch. The arrow in Figure 2 represents the slope direction and western extent of the arch. The eastern extent of the arch coincides with the position of the sharp ridge. Figure 4 shows a short, hummocky flow (F) about 1.8 km long which forms part of a ridge in the same vicinity (see Figure 3). This flow is clearly superimposed on the adjacent terrain showing the extrusive origin of this ridge. Notice the

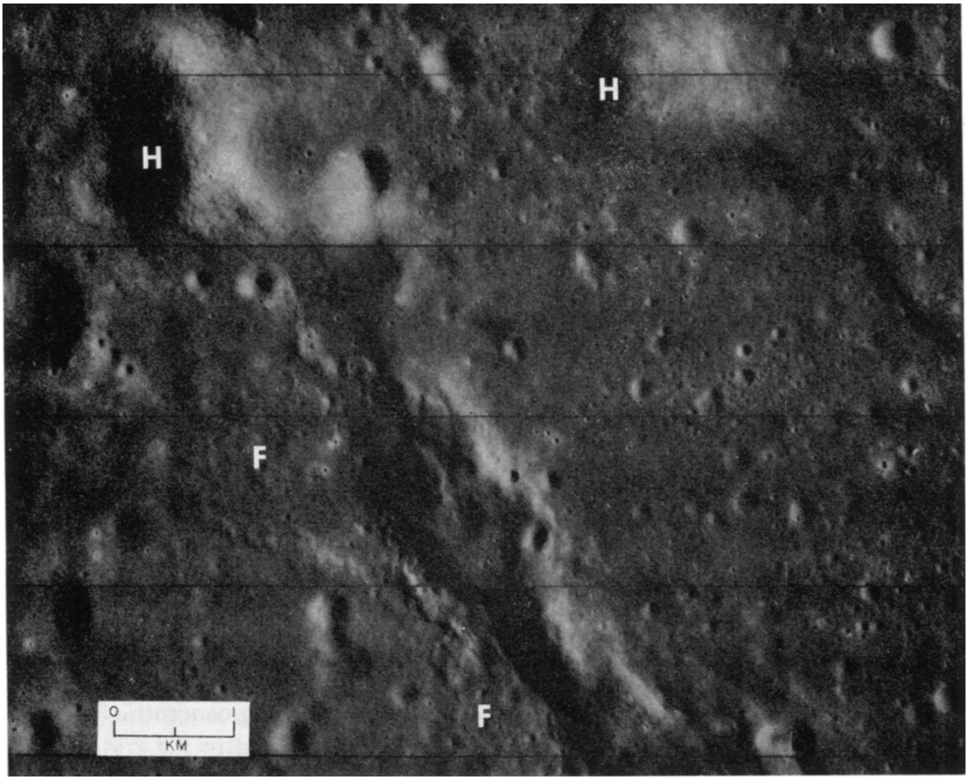

Fig. 4. A mare ridge in Mare Tranquillitatis (see Figure 3) showing an associated short hummocky flow (*F*). Two bright hills (*H*), discussed in the text, are situated along the ridges. *(NASA Lunar Orbiter 1)*

small bright hills (H) which appear to be integral parts of the ridges and are similar to the bright hills discussed later.

In several instances mare ridges traverse portions of the highlands where they also form short flows with well-defined fronts which have flowed into craters. This indicates that mare ridges are deep-seated structures which follow zones of weakness not necessarily restricted to the maria.

The examples mentioned above are only several of many ridges which show similar phenomena. The broad, gentle arching associated with many ridge systems implies that uplift has been a major factor in shaping these ridges. The fact that many of the sharper ridges which cap broad arches have partially filled pre-existing craters strongly indicates that the secondary ridges are extrusions of post-mare age. Their positions on the uplifted arches suggests that this uplifting was the result of magmatic intrusions, which may have migrated up major fractures and been injected between planes of lava flows in the form of sills or laccoliths. The position of many extrusive ridges on the crests of the arches – the area of maximum curvature – indicates that in these areas the surface was fractured by the uplift allowing the magma to reach the surface in the form of short flows and bulbous lava extrusions. The proposed relationships are shown diagrammatically in Figure 5.

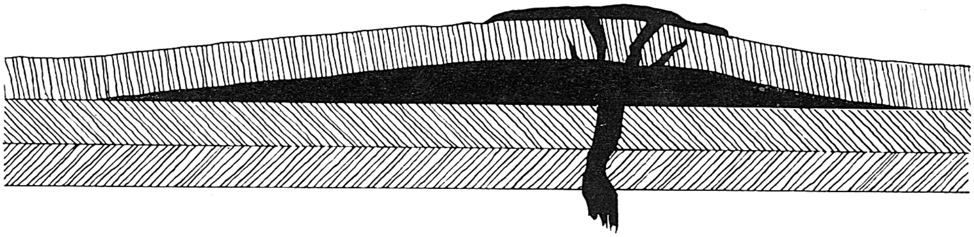

Fig. 5. Diagrammatic representation of the proposed intrusive/extrusive relationship of mare ridges exhibiting uparching and extrusions. See text for explanation.

Mare ridges are very complicated structures, and the explanation of their origin expressed here should be considered a generalization applying to the broad arches with associated sharp secondary ridges. There are numerous ridges unassociated with arches which are probably extrusions along fractures or faults. Rarely, on the other hand, ridges consist of a broad gentle arch only, and may represent intrusive action unaccompanied by extrusion. However, the basic premise that the ridges are tectonically controlled features of intrusive and/or extrusive origin seems well supported by the evidence at hand.

The mare ridges concentrically oriented with respect to the borders of the circular maria probably have a similar origin but have been formed along concentric fractures related to the circular basins rather than linear fractures related to the grid system.

Near the central and west central portion of Mare Imbrium occur an extensive series of flows, several of which are associated with, and appear to have issued from, prominent mare ridges. Figure 6 is a detailed map of the flows based on Lunar Orbiter

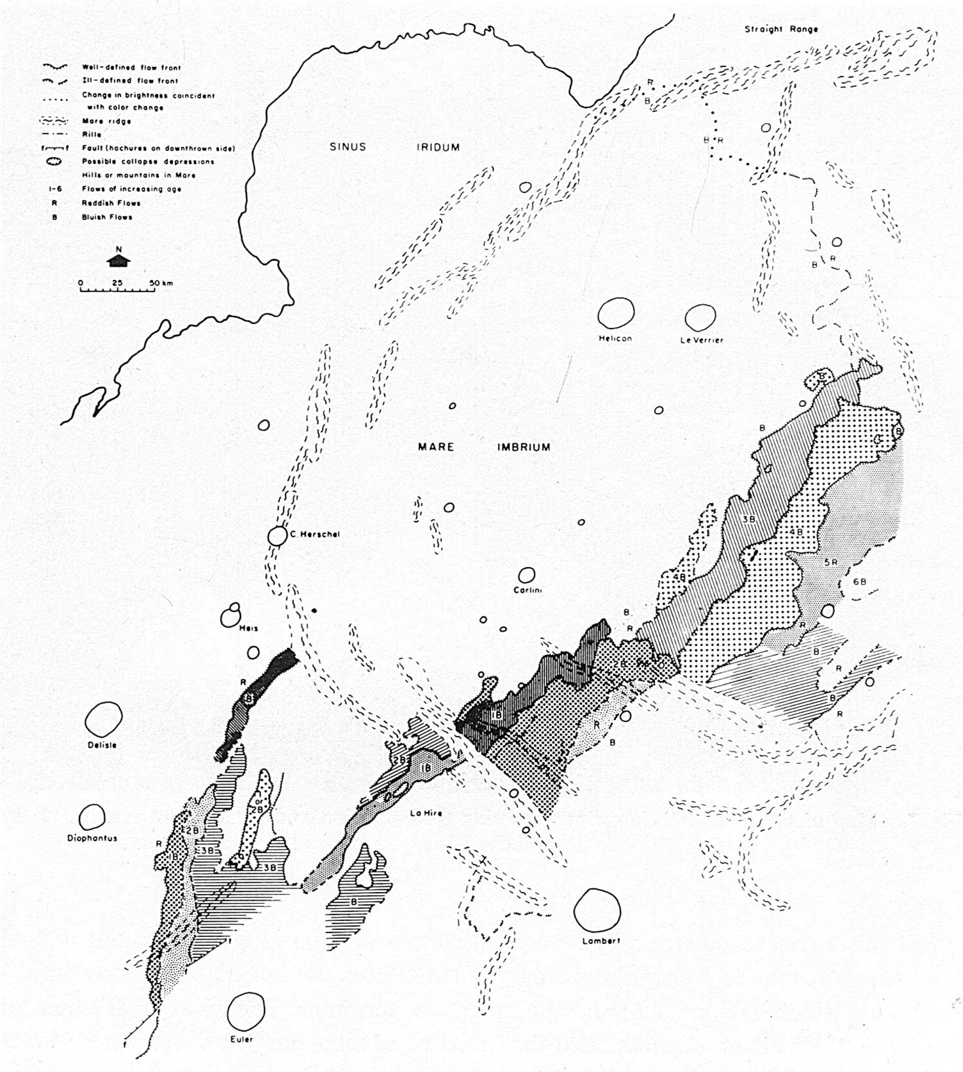

Fig. 6. Map of the flows in Mare Imbrium.

and low sun angle Earth-based photography, whereas Figure 7 is a map of the main flows superposed on a photograph of Mare Imbrium in order to show the position and areal extent of the flows relative to the Imbrium basin. Near the center of the mare the flows trend in a northeasterly direction, but in the west central portion their trend is in a more north-south direction. The flows are long plateau-like features which range from 65–235 km in length to 10–60 km in width, averaging about 130 km long and 28 km wide. Shadow measurements indicate they vary in thickness from about 10–40 m. The main flows cover a minimum area of 3×10^4 km^2. Their total volume may exceed 1000 km^3.

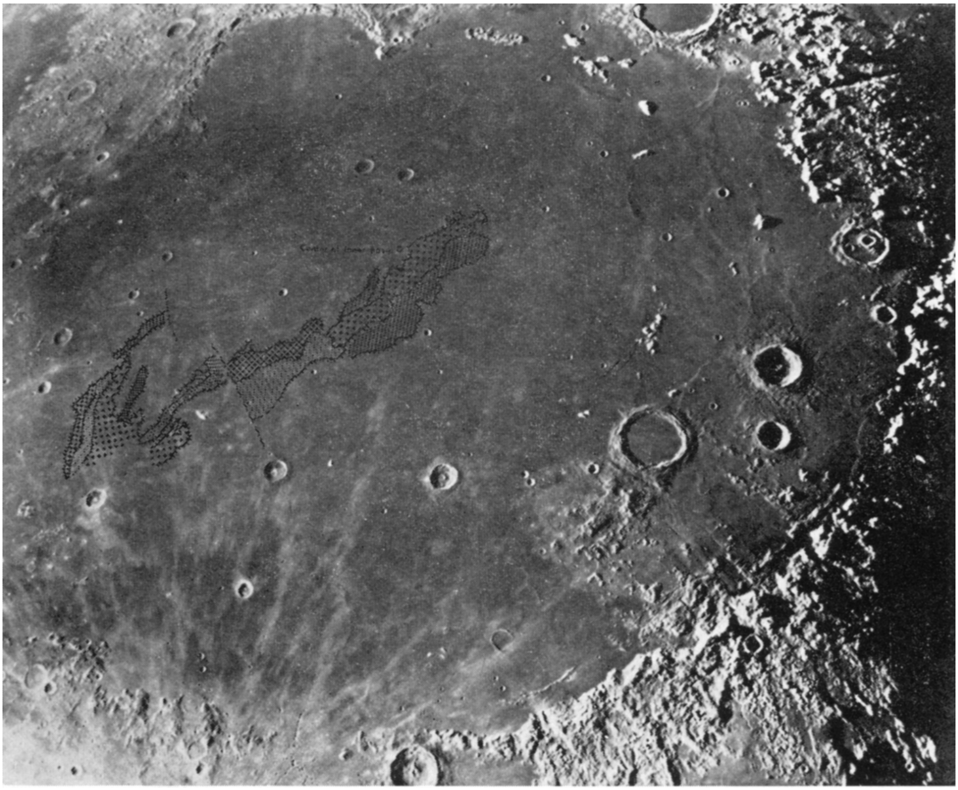

Fig. 7. Map of the main Imbrium flows showing their position and areal extent relative to the Imbrium basin.

The flows are characterized by lobate outlines as shown in Figures 8, 9 and 10, and the distal end of the flow photographed by Lunar Orbiter 5 (Figure 10) shows secondary flow units which have issued from the main flow terminus. The great areal extent of the flows, their lobate outlines, and the presence of secondary flow units are characteristic of basaltic lava flows. This interpretation if supported by the basaltic composition and extrusive nature of the rocks returned from Mare Tranquillitatis and Oceanus Procellarum by the Apollo 11 and 12 astronauts, and the Surveyor 5 and 6 chemical analyses in Mare Tranquillitatis and Sinus Medii.

Furthermore, the boundaries of the flows often coincide with color boundaries in the mare. Figure 11 is a photograph showing color boundaries in Mare Imbrium, Mare Frigoris and the northern part of Oceanus Procellarum. The darker the tone, the redder the lunar surface. This photograph was prepared by Ewen Whitaker from a composite consisting of an original negative ultraviolet plate and a positive copy of an original negative infrared plate. The color differences were verified by photoelectric calibration by T. Gehrels. The color and relative age of the individual Imbrium flows are indicated on the map (Figure 6). The younger uppermost flows are usually the

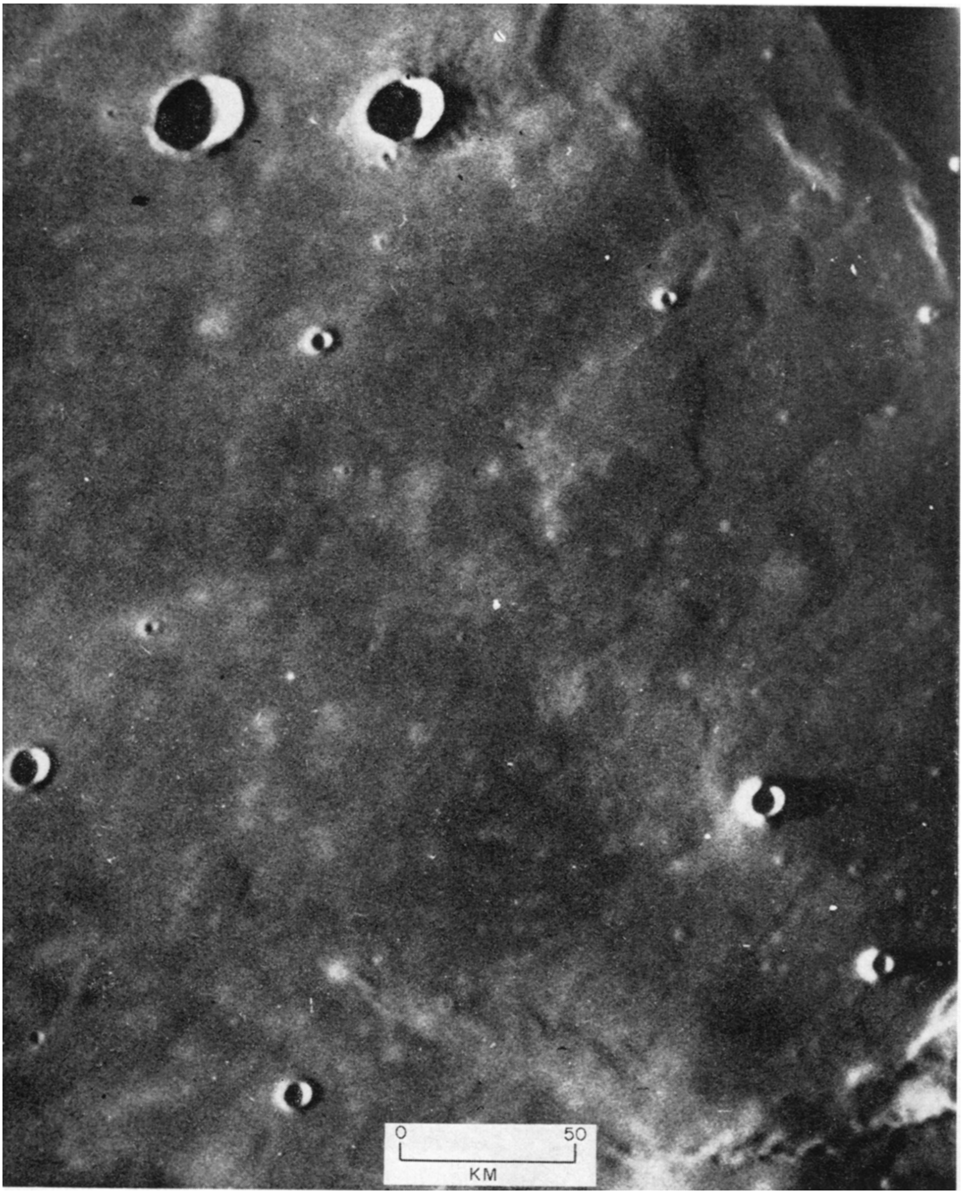

Fig. 8. Earth-based sunset photograph of several Imbrium flows. *(Mt. Wilson Obs. photograph)*

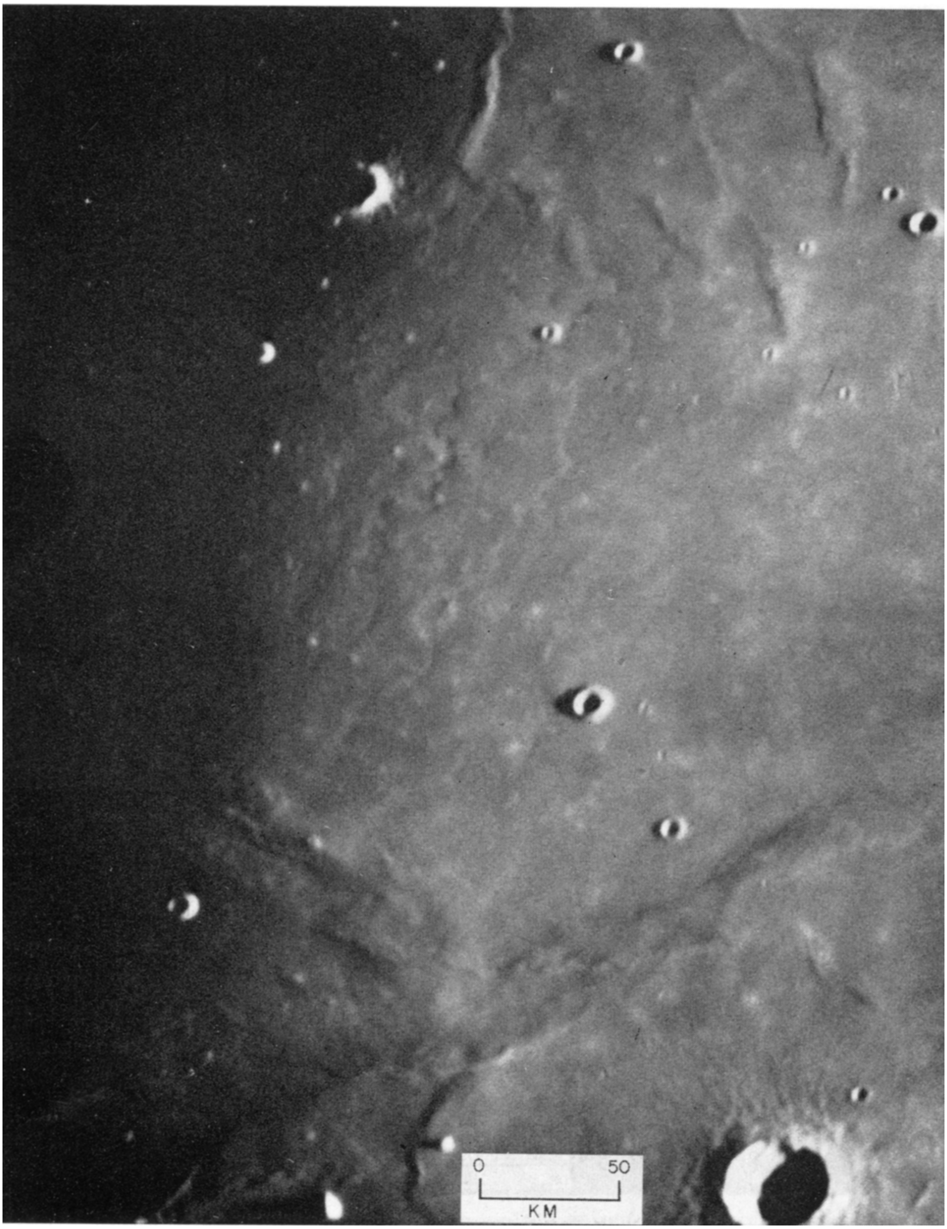

Fig. 9. Earth-based sunrise photograph of the flows shown in Figure 8.
(LPL Catalina Obs. photograph)

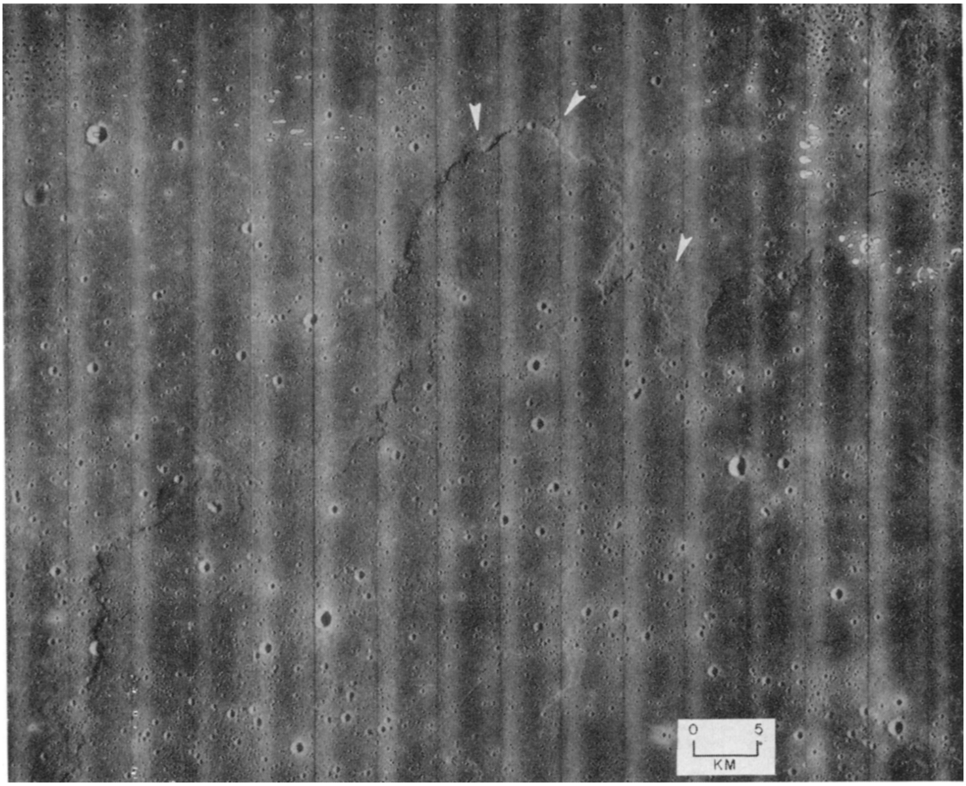

Fig. 10. Lunar Orbiter 5 photograph of one of the Imbrium flows. The arrows point to secondary flow units which have issued from the terminus of the main flow.

bluest; the older deeper-lying flows, which are partly covered, are usually (but not always) the reddest. These color differences may be due to slight compositional differences in the basalts. Figure 12 is a preliminary generalized map of the color differences in the lunar maria compiled from Figure 11 and similar color photographs constructed by Ewen Whitaker. Also shown are the locations of the Surveyor and Apollo sites where chemical data or rock samples have been obtained. Both Apollo 11 and Surveyor 5 are located in Mare Tranquillitatis which is a bluish mare; Surveyor 6 and Apollo 12 landed in Sinus Medii and Oceanus Procellarum respectively at sites which are intermediate in color but toward the reddish side. Table I lists the chemical composition at the Surveyor and Apollo 11 and 12 sites. A comparison of the abundance of the various major rock forming elements at the sites in the bluish mare (Mare Tranquillitatis) and the intermediate reddish maria (Sinus Medii and Oceanus Procellarum) indicates that the abundance of titanium may be responsible for the color differences. Both sites in the bluish mare have from 2–3 times more titanium than those in the intermediate reddish areas. Furthermore, the highlands are redder than the most reddish mare areas, and the Surveyor 7 site in the highlands north of

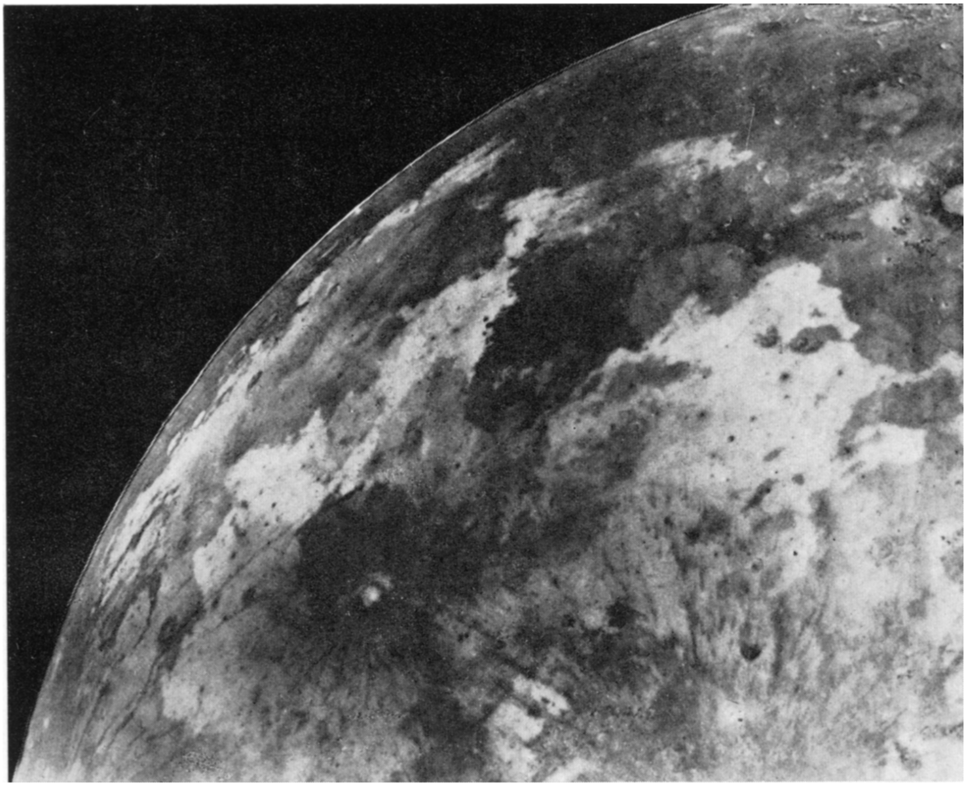

Fig. 11. Earth-based composite of UV and IR photographs prepared by E. Whitaker showing color differences in the maria. See text for explanation.

TABLE I

Chemical composition (% by weight) of Apollo and Surveyor sites

Oxide	Surveyor 5	Apollo 11 basalts (aver.)	Surveyor 6	Apollo 12 basalts (aver.)	Surveyor 7	Apollo 11 anorthosites	Apollo 12 sample 12013
SiO_2	46.4	40.8	49.1	40.0	46.1	45.7	61.0
TiO_2	7.6	10.5	3.5	3.7	–	0.3	1.2
Al_2O_3	14.4	10.0	14.7	11.2	22.3	30.5	12.0
FeO	12.1	18.8	12.4	21.3	5.5	4.5	10.0
MgO	4.4	7.5	6.6	11.7	7.0	4.8	6.0
CaO	14.6	10.9	12.9	10.7	18.3	15.8	6.3
Na_2O	0.6	0.48	0.8	0.45	0.7	0.35	0.69
K_2O		0.21		0.06		–	2.0
MnO		0.22		0.26		0.1	0.12
H_2O		0.005					

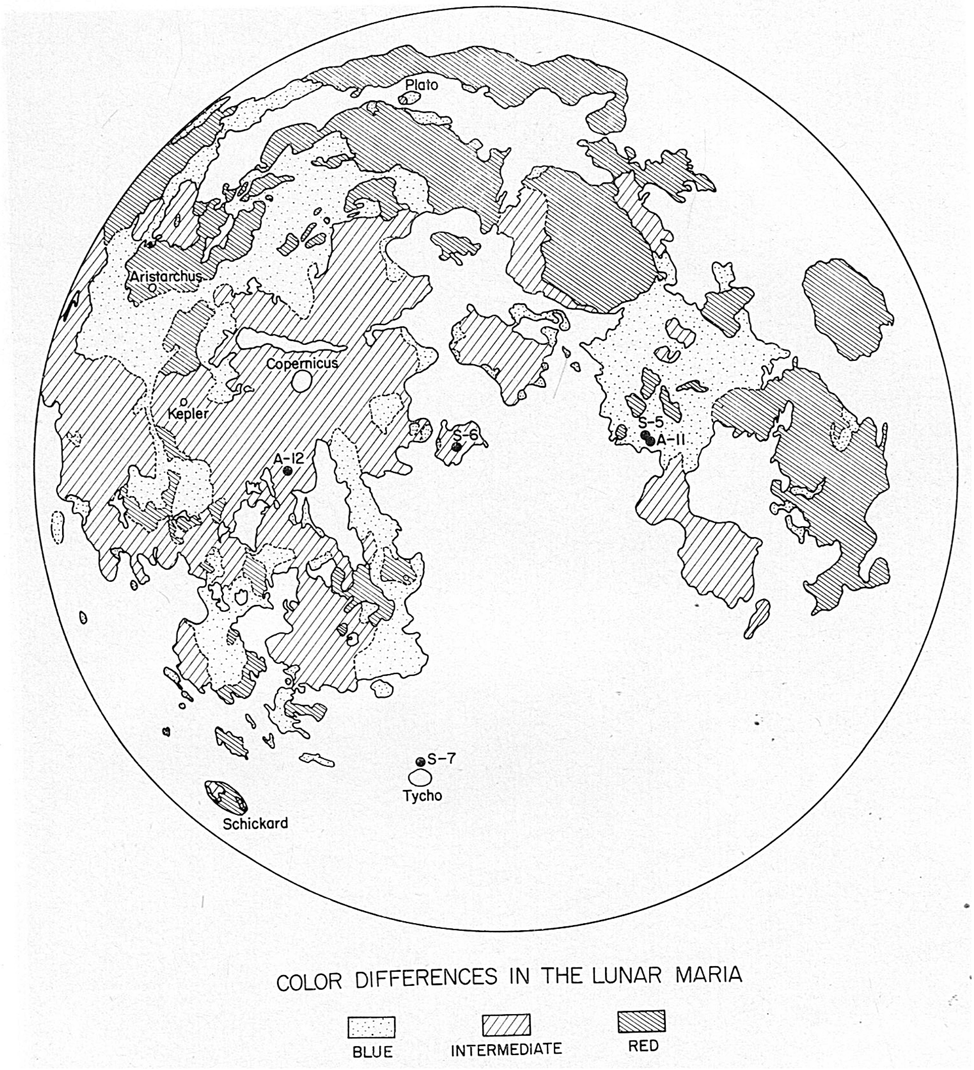

Fig. 12. Preliminary generalized map of the color differences in the lunar maria.

Tycho and the Apollo 11 and 12 anorthosite fragments thought to originate in the highlands have very low titanium abundances. Therefore, the color differences in the mare basaltic lavas may represent differences in the titanium content; the bluer the mare, the higher the titanium abundance.

3. Bright Hills Associated with Mare Ridges

Numerous bright hills in the maria are intimately associated with mare ridges. The hills have a higher albedo than the maria (confirmed on Earth-based full Moon

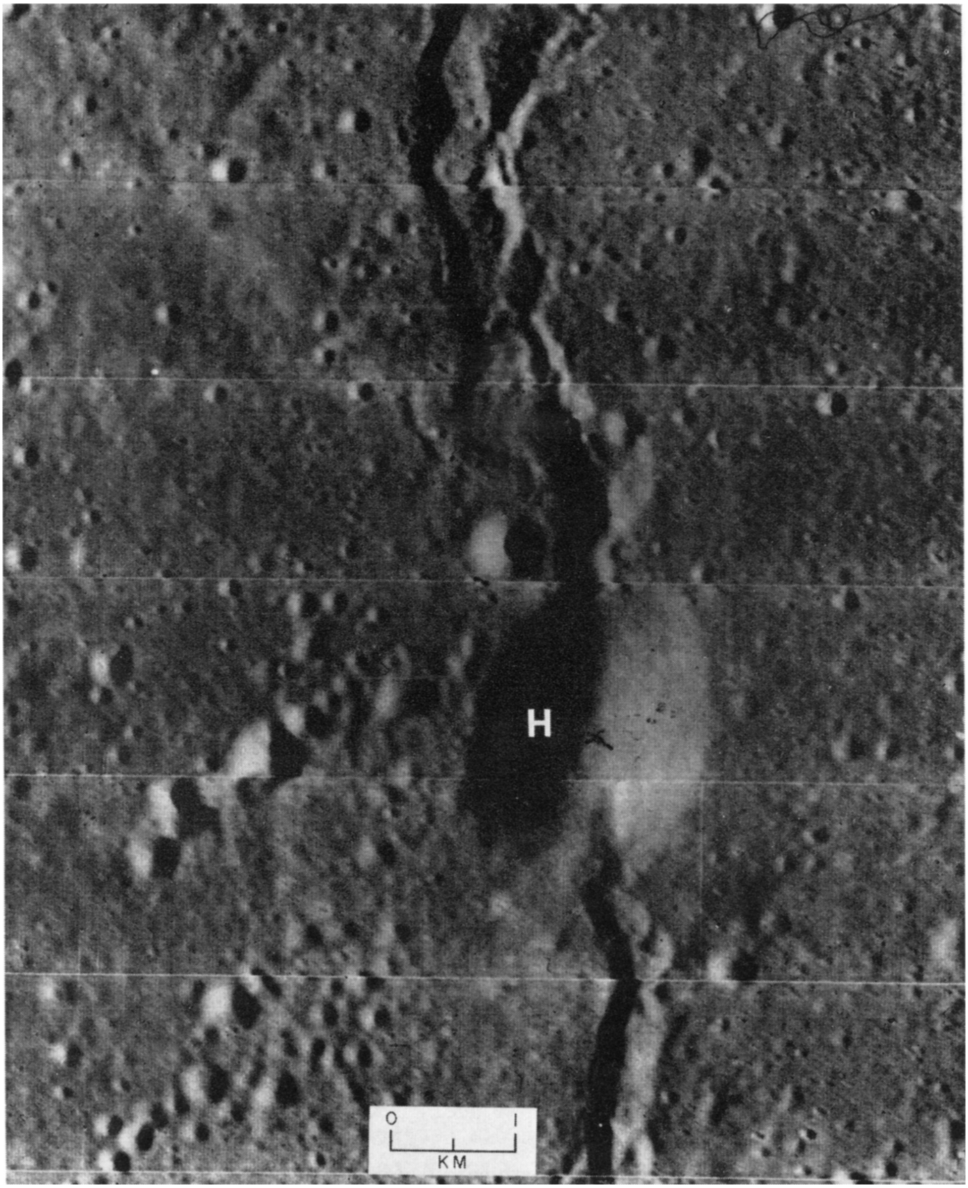

Fig. 13. Conical bright hill (*H*) overlying mare ridge in Oceanus Procellarum. (*NASA Lunar Orbiter 1*)

photographs), and exhibit similar morphological and reflectivity characteristics as the highlands. They range in height from a few tens of metres to over 0.5 km.

Figure 13 shows a bright, conical hill about 2 km in diameter and 300 m high situated on a prominent mare ridge in Oceanus Procellarum. The ridge is very sharp and fresh appearing but has had no visible effect on the hill. If the hill were older than the ridge one would expect the hill to have been affected by the ridge, particularly since the hill is relatively small compared with the ridge. Since this is not the case, it seems clear that the hill overlies the ridge and is therefore younger than both the ridge and the surrounding mare. A previous reference was made to the bright hills situated on the ridge in Mare Tranquillitatis and shown in Figure 4. These hills are identical in

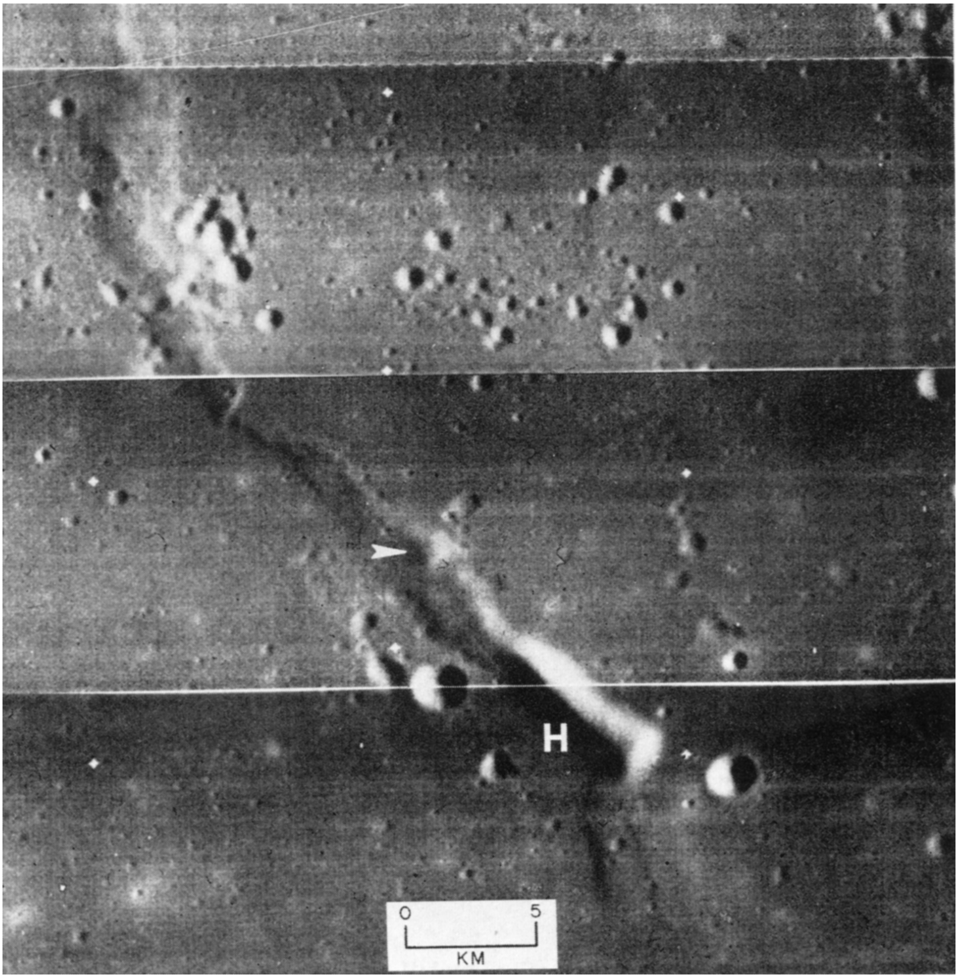

Fig. 14. Bright linear hill (*H*) forming the terminus of a mare ridge in Oceanus Procellarum. A small conical hill situated on the ridge is indicated by the arrow. *(NASA Lunar Orbiter 4)*

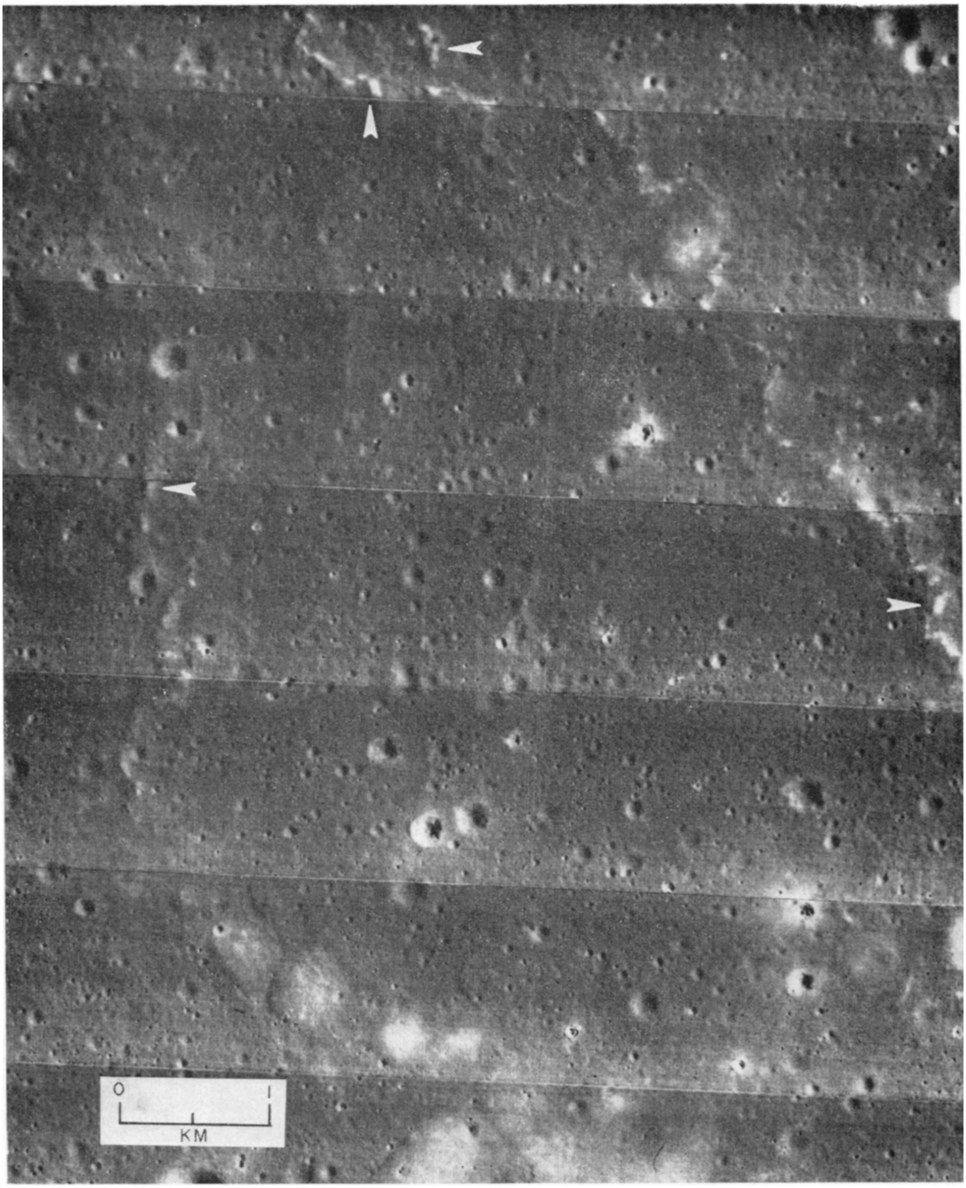

Fig. 15. Small bright incipient hills (arrows) located on mare ridges in Oceanus Procellarum northeast of Flamsteed P. See Figure 23 for location. *(NASA Lunar Orbiter 1)*

morphology and albedo to the hill shown in Figure 13 and are clearly related to the ridges on which they lie. Again the ridges have had no visible effect on the hills indicating the hills formed after the ridges.

Figure 14 shows a bright hill 7 km long, 1.7 km wide and about 400 m high which is located near the terminus of a mare ridge in Oceanus Procellarum. The long axis of the hill follows the direction of the ridge suggesting a genetic relation to the ridge. Since the axis of both the hill and ridge coincide with one of the main directions of the global grid system (NW-SE), they are probably controlled by a major fracture related to the system. About 4 km northwest of the elongated hill is another bright conical hill which lies on the ridge.

Occasionally ridges contain small, bright incipient hills or knobs which are similar to the above mentioned hills but appear not to have developed to the same extent as the other hills. Figure 15 shows a series of such hills located on two ridges northeast of Flamsteed P in Oceanus Procellarum (see Figure 23). On the examples shown, the hills are about 70 to 140 m in diameter and about 1–20 metres high. Other possible incipient hills occur on the ridges shown in Figure 1. These small hills may represent a transitional phase in the development of the larger, bright hills.

The association of mare ridges with bright hills clearly indicates a genetic relation between them. The examples mentioned above, and numerous others, are not chance occurrences on the ridges because they are isolated hills or groups of hills which are relatively distant from the highlands. Hills which are very near the highlands and appear to be flooded portions of the highlands usually do not occur on ridges although there are numerous mare ridges in the area. Furthermore, the hills show no visible effect from the ridges upon which they are situated and therefore, they probably are younger than the ridges. Certainly the small, incipient hills are post-mare since they usually occur only on, and are smaller than, the sharpest part of the ridge and clearly form an integral part of these ridges.

Since the ridges are most likely intrusive/extrusive phenomena located along fractures, it seems probable that the hills associated with these ridges are of volcanic origin, possibly consisting of pyroclastic and/or viscous extrusions. The fact that the hills have a higher albedo than the mare lavas and are of different morphology suggests they differ in composition. Although the extrusive portions of mare ridges have the same albedo as the adjacent mare terrain, they appear to have been more viscous than the lavas which flooded the basins; their texture is more ropy and they have flowed only a short distance. This higher viscosity may reflect a generally lower iron and higher silica content relative to the Apollo 11 and 12 basalts. The hills may consist of more highly differentiated material similar to the siliceous rock of intermediate composition (No. 12013) returned by the Apollo 12 astronauts (*Science*, 1970b) or, less likely, anorthosites (*Science*, 1970a).

4. Mare Ridges in the Form of Rings

Locally, mare ridges take the form of rings which vary in size from 1 to 2 km to over

80 km in diameter. Many of the rings are circular but a large number are elliptical to irregular in shape. The character of the ridges that form rings is identical in most instances to normal mare ridges. One exception is a peculiar ring, R, which appears to consist of flows arranged in a circular pattern (Figure 16). This ring is situated southwest of Flamsteed near a highly contorted mare ridge and is about 8 km in diameter. Figures 17 through 20 are Lunar Orbiter photographs of several rings ranging in size from 3 to 55 km in diameter. In most cases the rings are situated on linear ridges and these ridges may terminate at the ring boundary, deviate in an arcuate pattern to form one side of the ring (Figure 19) or bifurcate to form both sides of the ring. The centers of several rings appear to be slightly depressed with respect to the exterior plain, while

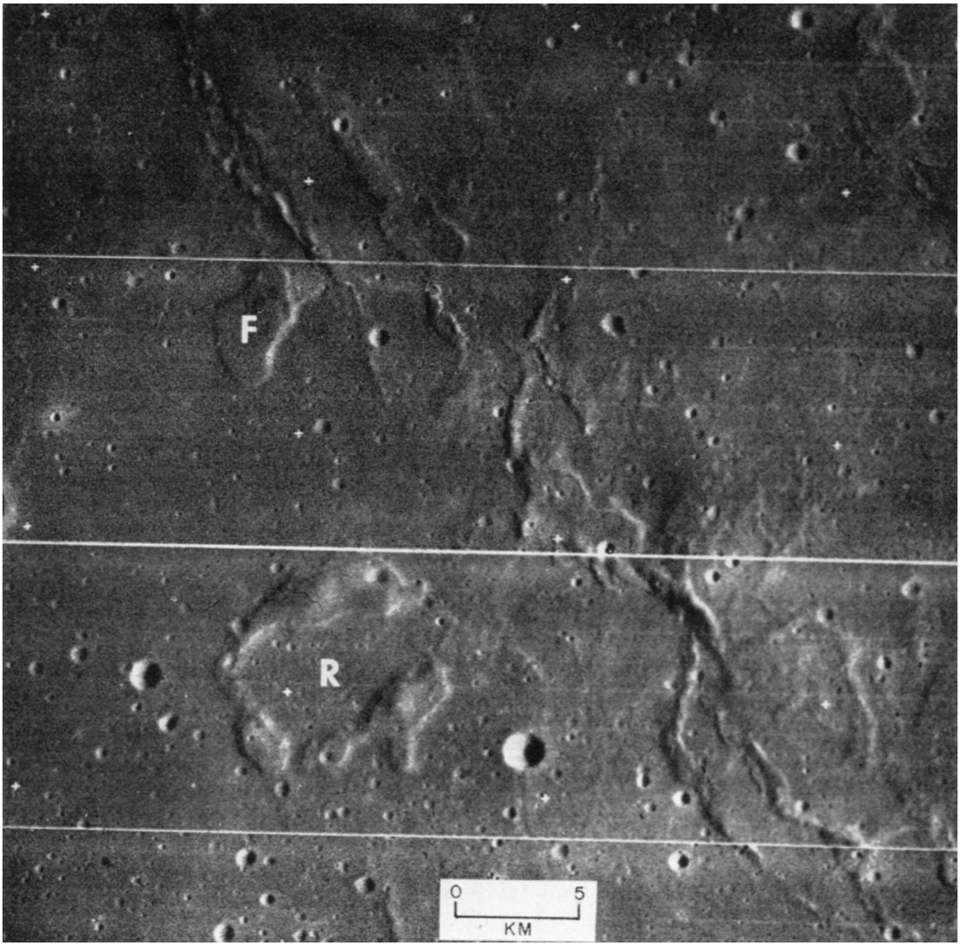

Fig. 16. A ring (*R*) in Oceanus Procellarum apparently composed, at least in part, of lava flows. Notice the flow (*F*) associated with a mare ridge, and of similar morphology as the ring. *(NASA Lunar Orbiter 4)*

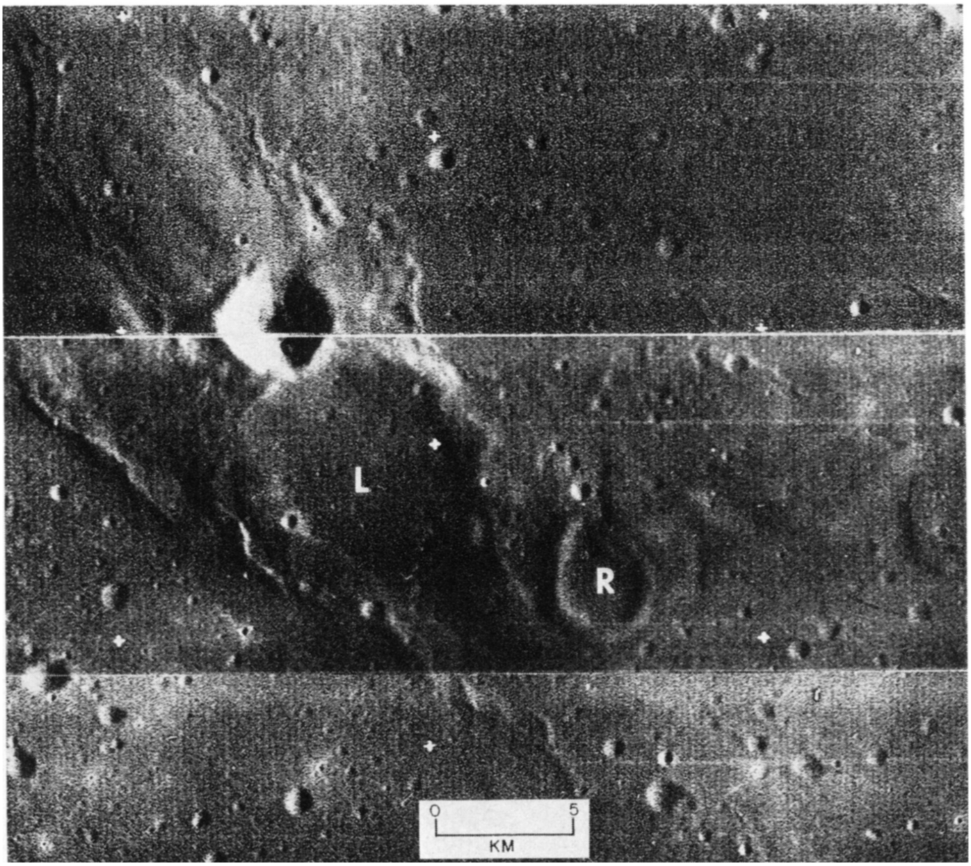

Fig. 17. Irregular ring structure (*R*) 3 km in diameter associated with a mare ridge in Oceanus Procellarum. To the left of this small ring is a larger ring (*L*) formed by the NW trending mare ridge. *(NASA Lunar Orbiter 4)*

in others the ring forms a plateau covering most of their centers (Figure 18). There appears to be gradational stages in the development of the rings; from partial semi-circular rings to completely formed rings.

The best example of a mare ridge ring is the Lamont structure in Mare Tranquillitatis (Figure 20). This structure is a double ring about 70 km in diameter with subradial ridges. The subradial ridges are equally as prominent as the ridges that comprise the rings. Lamont has been studied in detail by Guest and Fielder (1968) and, therefore it will be mentioned only briefly here. They conclude, from a study of the peripheral arcuate rilles associated with the margins of a broad depression which surrounds the western portion of the structure, that the formation of Lamont was accompanied by subsidence, and that the ridges are extrusions. The present author agrees with this interpretation. Evidence that the sharper parts of the Lamont ridges are extrusions is shown in Figure 21. This is an Apollo 10 photograph of part of the

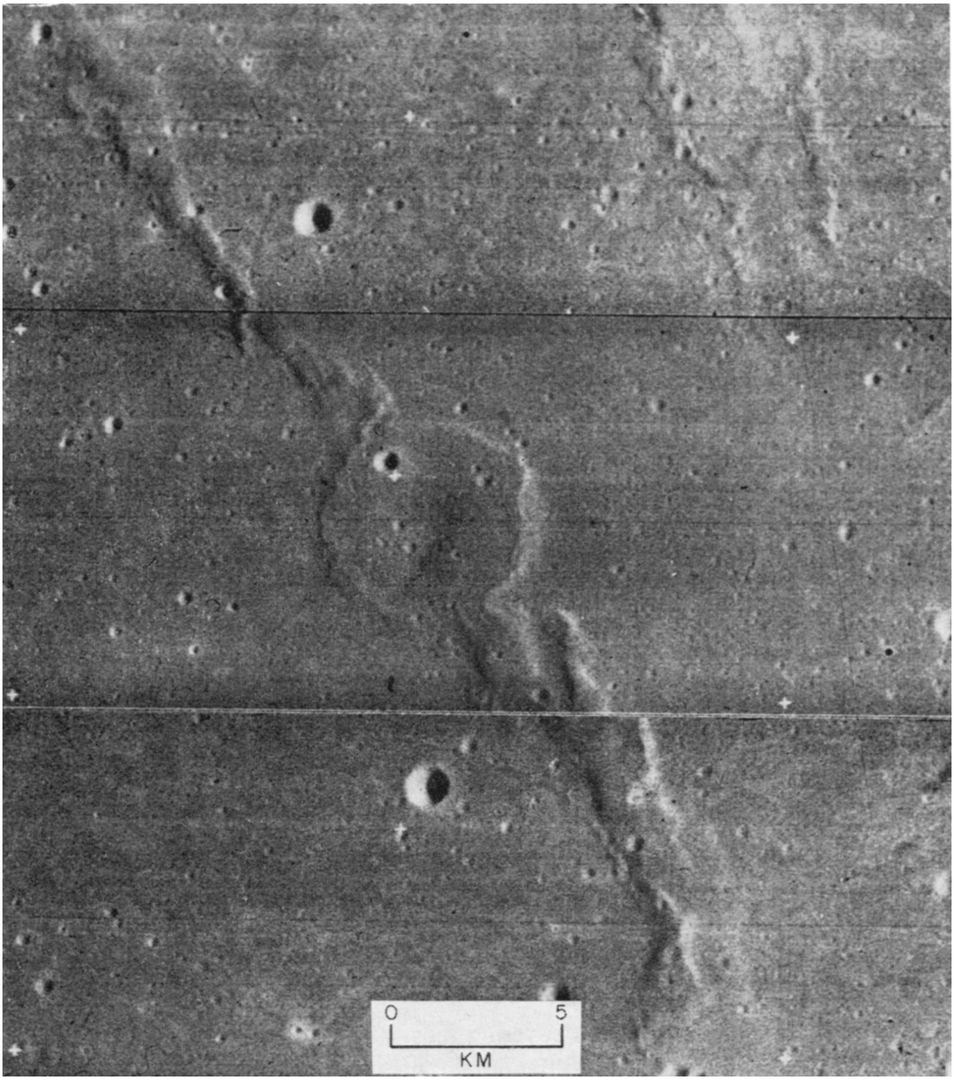

Fig. 18. Ring structure 5 km in diameter formed along a NW trending mare ridge. Note that most of the interior of the ring, except the extreme centre, is an elevated plateau, and that the linear portion of the mare ridge does not traverse the ring. *(NASA Lunar Orbiter 4)*

eastern outer ring clearly showing that the ridge has been extruded into a chain of craters indicated by the arrows in Figures 20 and 21. However, the ridge shown in Figure 21 is only the sharper part of a much broader gentle arch visible on the low-illumination Earth-based photographs (Figure 20). Therefore, at least this part of the Lamont ring appears to have formed by both intrusive and extrusive processes. The crater chain in question is radial to Theophilus, and, if it represents a secondary

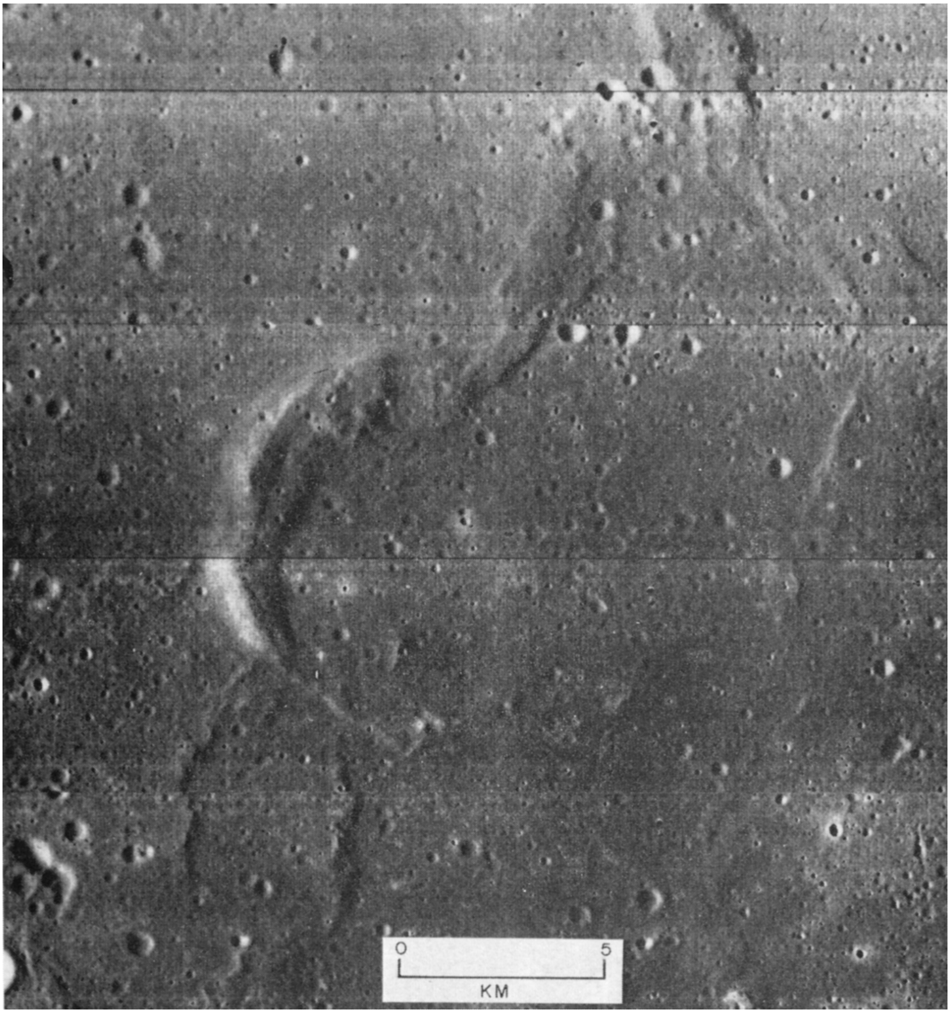

Fig. 19. Partial ring structure in Mare Fecunditatis. Notice that the mare ridge broadens where it forms the ring. *(NASA Lunar Orbiter 1)*

impact from Theophilus, then this ridge, and possibly the entire Lamont structure, is younger than Theophilus. This again indicates that mare ridges and mare ridge rings are relatively young features of post-mare age.

The mare ridges which comprise the rings are in almost every case identical to normal ridges found in linear or arcuate arrangements. Since the mare ridges are almost surely intrusion/extrusion phenomena, the ring structures must be of the same origin. The circular nature of these structures indicates they have formed along ring fractures somewhat similar to terrestrial ring dike complexes. The possible origins of these ring fractures will be discussed later.

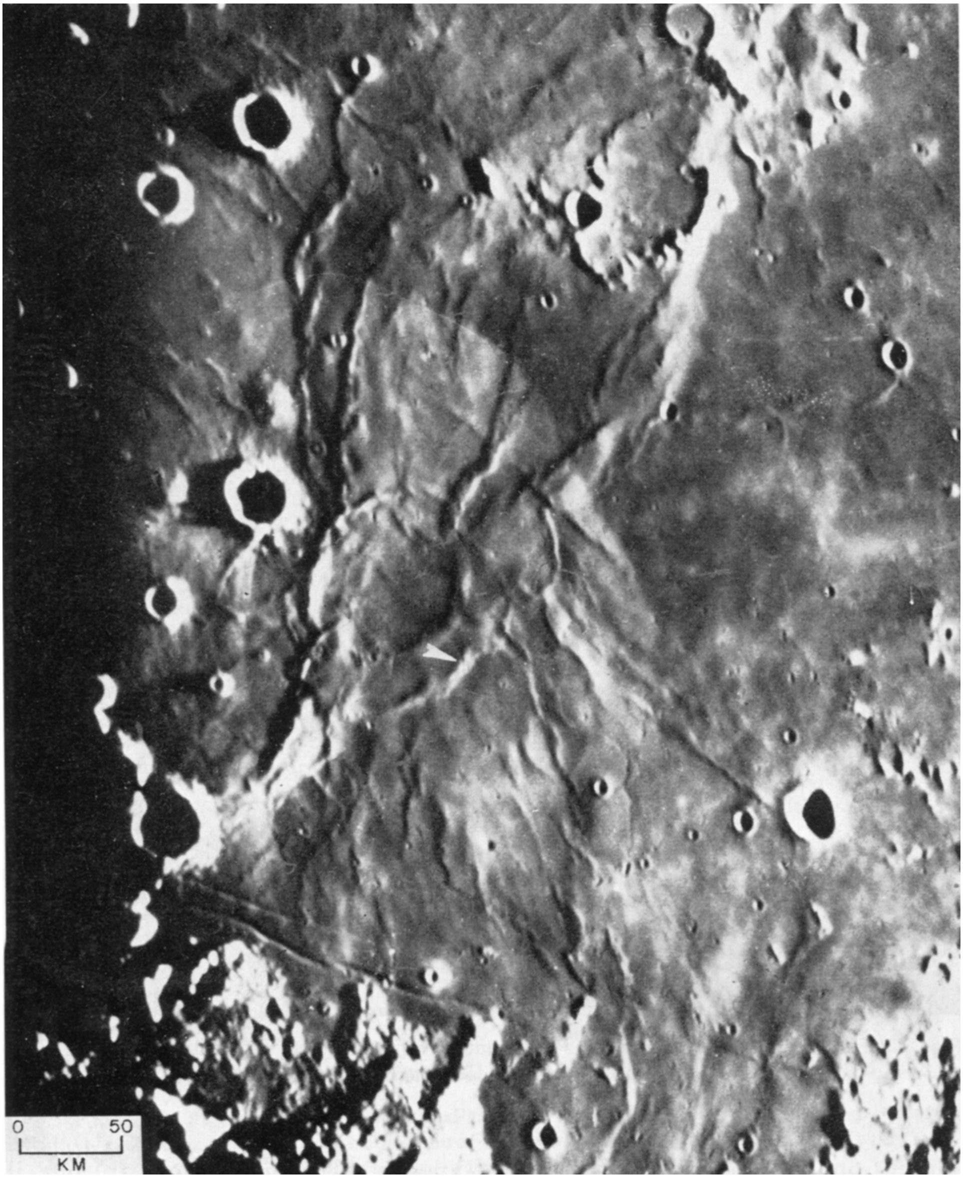

Fig. 20. The Lamont ring structure in Mare Tranquillitatis. The arrow indicates the location of the crater chain shown in Figure 21. *(LPL Catalina Obs. photo.)*

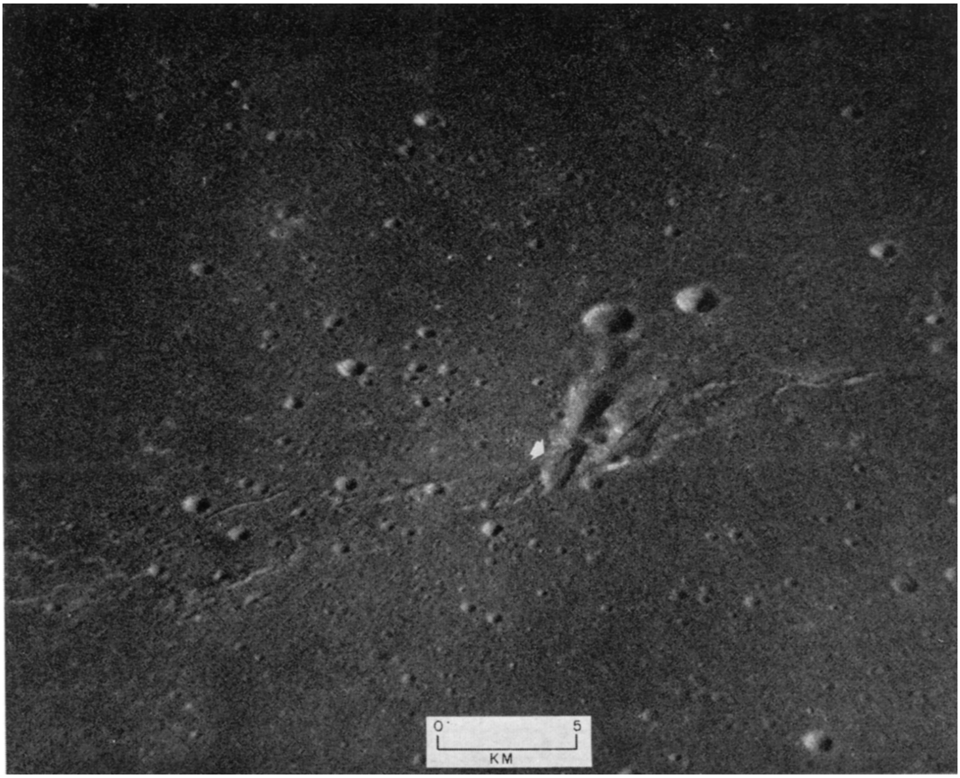

Fig. 21. Mare ridge, forming part of the outer ring of Lamont, which has been extruded into a crater chain. *(NASA Apollo 10 photo)*

5. Composite Ring Structures

Composite rings are circular mare ridges along which are situated bright hills. In almost no case do the hills form a continuous ring; they are usually discontinuous, their strongest development generally occurring along the east and west portions of the ring. Often the northern and southern portions of the ring are subdued or entirely missing. The hills comprising the rings have the same morphology and albedo as the previously mentioned bright hills on linear ridges and, therefore, may have a similar origin and composition.

Figures 22 and 23 are examples of mare ridge rings with associated bright hills. One of the most well-developed ring structures is Flamsteed P in the southern region of Oceanus Procellarum shown in Figure 23 and recently discussed by Guest and Fielder (1968). This structure, 100 km in diameter, is composed of a double ring, the outer ring consisting of a mare ridge or broad gentle arch with bright hills situated along it, and the inner ring consisting only of a mare ridge. It is somewhat similar to the Lamont structure, but contains bright hills and lacks subradial ridges. The mare ridge portions of the rings are related to a prominent linear ridge to the north which

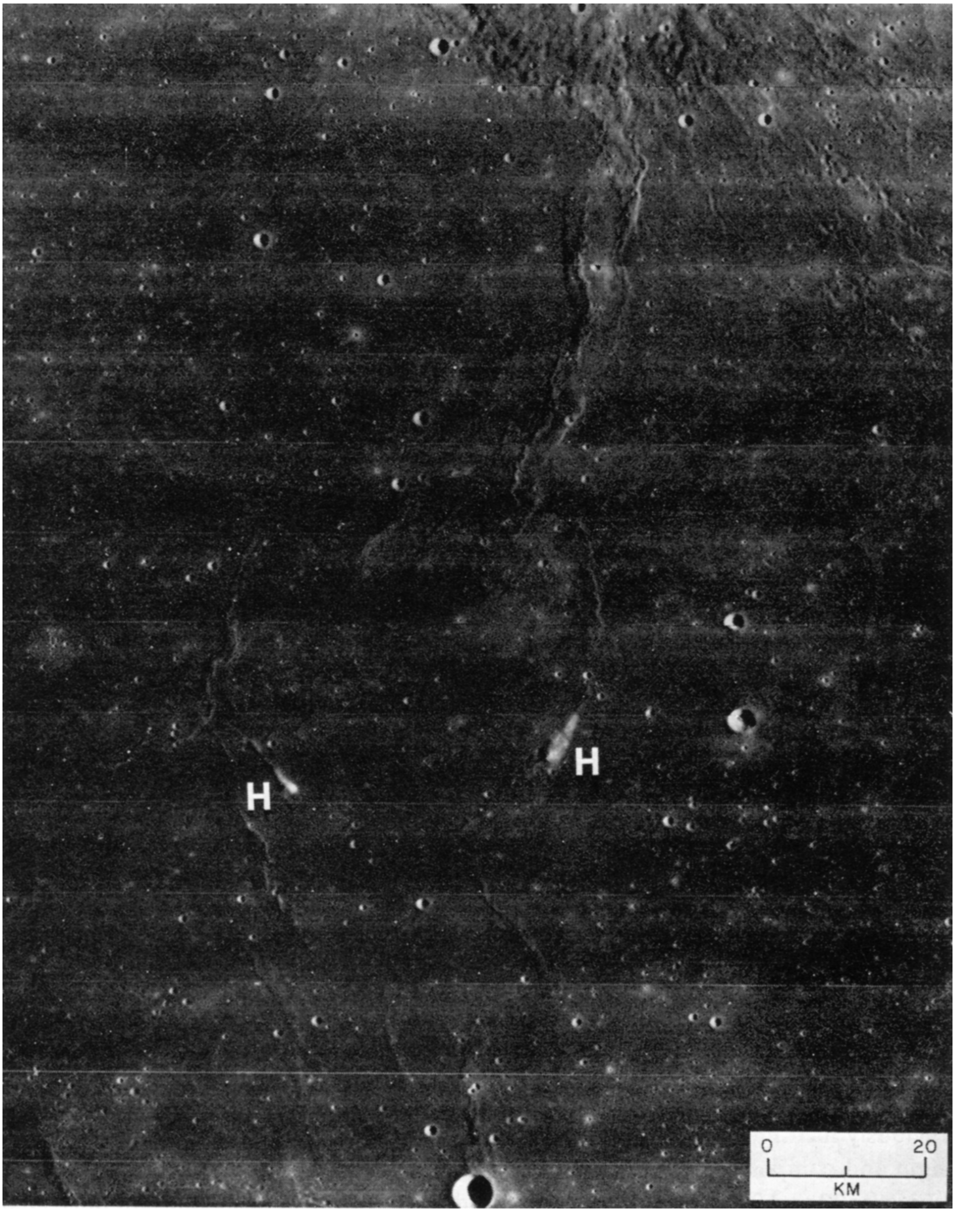

Fig. 22. Composite ring in Oceanus Procellarum south of Reiner. The southern portion of the ring is composed of two bright hills (*H*) situated along and elongated in the same direction as the mare ridges comprising the ring. *(NASA Lunar Orbiter 4)*

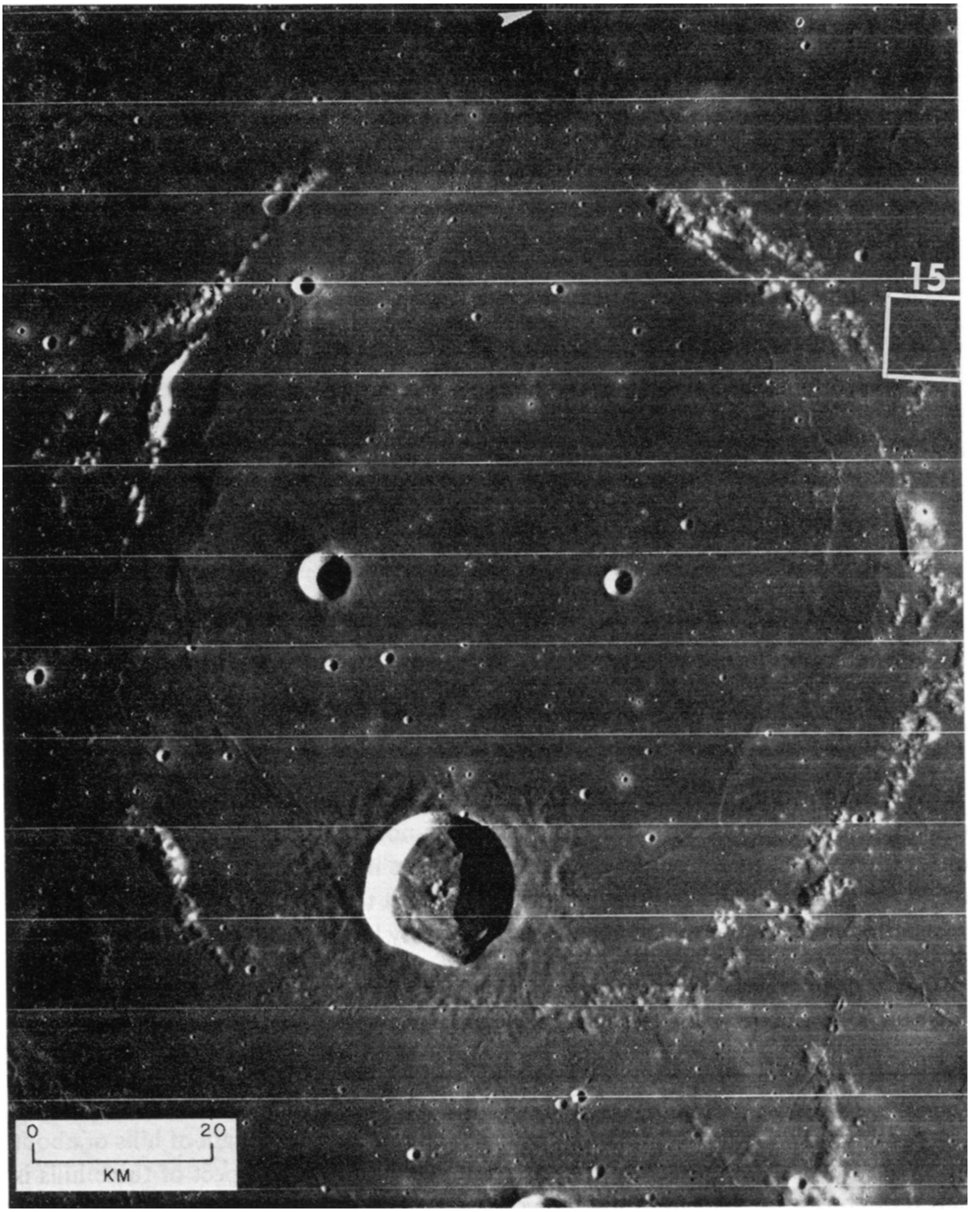

Fig. 23. The Flamsteed *P* composite ring structure in Oceanus Procellarum. The outlined area represents the location of Figure 15, while the arrowhead points to several small hills situated on the linear mare ridge which, further south, forms part of the eastern ring of Flamsteed *P*. Notice that the ejecta blanket of the Flamsteed crater is faintly visible on the outside of the ring but is completely missing from the inside. *(NASA Lunar Orbiter 4)*

has bifurcated to form the outer, and also possibly the inner, ring structure. On a portion of this linear ridge (arrowed in Figure 23) are three or four small, linear knobs which appear to be incipient hills. Both the northern and southern portions of the ring and about 32 km of the western outer ring lack bright hills. Mare ridges tend to connect individual hills on the ring.

The fact that the ejecta blanket surrounding the crater Flamsteed has been partly covered on the interior of the ring but is intact on the outside, as can be seen in Figure 23, shows that the interior is composed of more recent lavas which must be younger than the Flamsteed crater. This is substantiated by crater counts on the outside and inside of the ring by Fielder *et al.* (1968) and Fryer and Titulaer (1969) which show that the crater density on the interior is appreciably lower than on the exterior. The group of low hills forming the southern portion of the crater ring appears to have been partly covered by the ejecta blanket of Flamsteed indicating they are older than this crater. These facts strongly suggest that the Flamsteed ring has undergone a protracted development.

If the hills of the outer ring are extrusive, the sequence of events for the formation of Flamsteed P would be as follows:

(1) General flooding of the mare with highly fluid basaltic lava.

(2) Formation of the outer mare ridge ring and bright hills.

(3) Formation of Flamsteed crater.

(4) Flooding of the interior of Flamsteed P with highly fluid basaltic lava, possibly erupted from ring fractures later utilized in stage 5.

(5) Formation of the inner ring ridge.

If the bright hills are remnants of a buried crater rim it could be argued that the distribution of the ridges was controlled by the underlying crater. However, it is very difficult to explain the observation that none of the interconnecting ridges, so closely associated with the hills, cut the hills despite the fact that the ridge would be younger. No matter what the origin of the hills there is clearly late flooding and ridge formation within the ring indicating that this structure was the locus of igneous activity over a protracted period of time.

Figure 24 is a 36 km ring in the northern part of Mare Fecunditatis photographed by the Apollo 8 astronauts. The western side of the ring consists of a mare ridge with an associated short flow (F). This ridge continues to the north as a more-or-less linear mare ridge. The eastern side consists of a discontinous, arcuate chain of hills of about the same albedo as the adjacent mare terrain. The interesting aspect of these hills is that they consist of individual low conical or dome-shaped hills which resemble in many respects several of the volcanic cones and domes in the Marius Hills, and the chain of very dark volcanic hills in the southern part of Fra Mauro. On the summits of at least three hills there appear to be small pits which may be volcanic vents.

The association of bright hills with mare ridge rings and the similarity of these hills to those superimposed on the linear ridges suggests that the mare ridge rings with bright hills are post-mare volcanic ring complexes. The rings are no more than variations of the linear mare ridges which have apparently formed along ring fractures

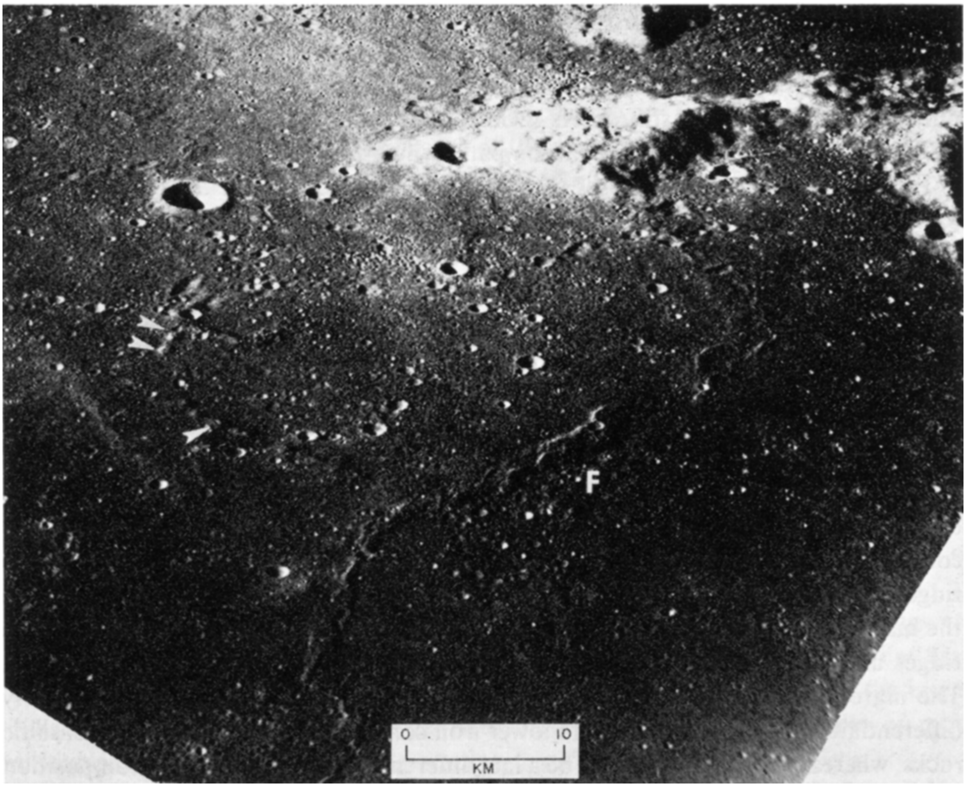

Fig. 24. Composite ring 38 km in diameter in Mare Fecunditatis. The righthand portion of the ring consists of a typical mare ridge with an associated flow (*F*), while the other side of the ring is composed of low hills or domes. Several of the hills may contain summit pits indicated by the arrows. *(NASA Apollo 8 photo.)*

The low cones or bright hills seem to be later eruptions which formed over the ridges. The high albedo and highland-type morphology of the hills suggest that they are of different composition from the mare ridges and may represent a late magmatic differentiate which evolved from igneous bodies associated with ridges.

6. Summary and Conclusions

It has been shown that mare ridges often consist of two separate but related features: (1) a broad gentle arch overlain by (2) a sharper more contorted ridge. The sharper, secondary ridge is usually situated on the crest of the arch and, in many instances, has clearly flowed into and partially filled pre-existing craters in the adjacent terrain. This relationship of broad arching with extrusive activity indicates that the mare ridges which show this relation consist of intrusions – probably in the form of sills or laccoliths intruded along planes between successive lava flows – that have uparched the surface and subsequently broken through the surface to form short flows or bulbous lava extrusions. The uparching apparently caused fracturing of the uplifted surfaces providing egress for the magma to reach the surface. Other ridges consist only of extrusions, while still others seem to represent gentle uplifts possibly caused by sill or laccolithic intrusions unaccompanied by an extrusive phase.

The fact that many mare ridges coincide with the directions of the global fracture pattern found in the highlands indicates that they are located along major fractures in the lunar crust. It is possible that the fractures along which the mare ridges formed were a major source of the low viscosity lavas that comprise the bulk of the maria. This view is strengthened by the fact that very extensive flows in Mare Imbrium seem to have issued from several prominent mare ridges. The ridges as they appear today probably represent the last intrusive/extrusive phase of this flooding.

There is at least one compelling and several probable examples of isolated bright hills overlying linear mare ridges. There is little doubt that these hills, at least, are post-mare volcanic cones or domes. The high albedo and highland-type morphology of these hills implies a composition different from that of the maria. Similarly, the contorted nature, ropy texture and short flow distances of the extrusive parts of the ridges suggest that they were more viscous than the bulk of the lavas which comprise the maria. Therefore, it seems possible that the igneous masses which gave rise to the ridges underwent magmatic differentiation prior to being extruded onto the surface. The mare ridge extrusions of the same albedo as the maria may represent an early differentiate with a higher silica and lower iron content relative to the Apollo basaltic rocks, whereas the bright hills may be a late differentiate of more siliceous composition similar to the siliceous rock of intermediate composition (No. 12013) returned by the Apollo 12 astronauts (*Science*, 1970b).

The fact that ordinary mare ridges take the form of rings must mean that they have formed along ring fractures in the same manner as the other ridges. This would be true for both mare ridge rings with and without bright hills. There are two possible explanations for the origin of the lunar ring fractures: (1) they are the result of very large cylindrical intrusions which have been intruded along major faults and fractured the surface in an annular pattern, or (2) they represent ring fractures or zones of weakness associated with the rims of buried craters which have been reactivated by later major fracturing. The former origin is somewhat similar to the formation of terrestrial ring dike complexes, whereas the latter has no known terrestrial counterpart. In several cases, such as Sinus Iridum and Respold R, linear mare ridges are diverted in an arcuate path around partially flooded highland craters. The arcuate part of the ridge is at the location where the crater rim is missing. This suggests that the formation of the mare ridges in these areas was influenced by pre-existing crater rims and were formed along reactivated ring fractures associated with the buried part of the rims, or that the major fractures were diverted around the buried crater rims because they represent a pre-existing zone of weakness. In either case the buried crater rims would be the indirect cause of the arcuate ridges. This may be the explanation for some of the rings in the maria. However, it is difficult to explain how the circular shape of the smaller rings, many of which are smaller than the ridge, could be so perfectly preserved by this mechanism. One would expect that the intrusive and extrusive activity along the fracture would completely obliterate such small, buried craters. Furthermore, many of the larger rings are quite irregular in shape, being very far from perfect circles. If pre-existing craters influenced the shapes of these ridges one would expect them to be more circular. The 8 km diameter ring comprised of flows near Flamsteed (Figure 16) is separated from, but possibly related to, the nearby mare ridge, and could only have been extruded along a separate ring fracture. This separate ring fracture is probably best explained by the intrusion of an independent igneous body rather than reactivation of fractures related to a buried crater. If the latter explanation applied there should be many other examples of this unique structure.

Also the Flamsteed P structure has undergone a late stage of flooding of its interior after the main period of mare deposition, indicating a protracted period of development. Although the bright hills comprising the Flamsteed ring may be remnants of a buried crater rim, it is difficult to understand the late flooding of its interior unless this structure was underlain by an independent magma source capable of expelling large volumes of lava. (The volume of lava necessary to fill Flamsteed P to a depth of 10 m is 80 km^3).

For these reasons I favour the hypothesis that many of the mare ridge rings are post-mare volcanic ring complexes associated with large, igneous bodies rather than reactivated fractures associated with buried crater rims; and that most of the bright hills associated with mare ridges are post-mare volcanic domes or cones of more siliceous composition.

It should be emphasized that I do not consider all incomplete rings in the maria to be of post-mare age. There are numerous examples of partially buried rims which are clearly pre-mare, flooded craters.

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