No. 12 CONCENTRIC STRUCTURES SURROUNDING LUNAR BASINS

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1. *Introduction*

STUDENTS of the moon have been familiar with the magnificent Altai Mountains, arching for about one quadrant around Mare Nectaris; and the continuation of this arc, as a broken series of ridges spanning about another quadrant, with roughly the same radius of curvature. Well known also are the several mountain arcs and depressions surrounding Mare Imbrium, though the outward resemblance between the Imbrium system and the Nectaris arcs is not close.

The systematic study of lunar photographs projected on a large white globe, with the resulting "rectification" of geometrical relationships, has brought to light several additional structures of the Nectaris class. This *Communication* contains a first report on these features, and gives a comparison with their prototype, Mare Nectaris, which itself is found to have a greater degree of complexity than appears to have been noted before. A selection of rectified photographs is reproduced with this report. They are shown with north up to make them readily comparable with topographic maps now in production, and with east and west used in accordance with the conventions adopted by the International Astronomical Union (1962) at Berkeley, in August, 1961. Supplementary direct photographs (not rectified) with north up also, are added to show specific detail. The present report discusses certain gross features of the ring structures. More detailed tectonic studies of each ring system are to follow.

2. *Well-Known Structural Features of Lunar Basins*

The discussion of the basins may start with a brief description of Mare Crisium, which well shows the features normally attributed to lunar basins. A rectified photograph of this mare is found in Plate 12.1. It is apparent that the mare and its surrounding mountain wall resemble a giant crater, such as Cleomedes just north of the mare. The shape of the mare's ring wall is not strictly circular but somewhat elliptical, with the major axis E-W, or more accurately, hexagonal, with rounded corners. But the mare shelf shown in Plate 12.1, presumably outlining the deep basin formed by the impact, is almost a perfect circle. The breach in the mountain wall to the east is apparently caused by local subsidence and melting, while a smaller similar disturbance occurs at the center of the west wall.

As Plate 12.1 shows, some narrow lava basins north of the mare are roughly parallel to (and concentric with) the mountain wall; several radial structures are also seen. This relationship is not unlike that shown by the Apennines bordering on Mare Imbrium (Plates 12.18ff). These peripheral basins seem to be due to subsidence and melting or flooding, possibly resulting from the overburden of the wall and the availability of lavas at moderate depths after the Crisium impact. The walls surrounding Mare Crisium show no signs of lava splashes, even by visual observation with large telescopes. Apparently the impact was a "dry" one, with the flooding having occurred later.

This classical concept of a crater-type mare may now be contrasted with the prototype of the structures here described, Mare Nectaris (Plates 12.2-11).

3. *Mare Nectaris*

Plates 12.2 and 12.3 are a matching pair, one morning and one afternoon illumination, both rectified, showing Mare Nectaris and surrounding structures. Of these structures, the Altai Scarp (SW quadrant) is the most prominent. It continues northward in broken fashion and is interrupted by the gate to Mare Tranquillitatis, in the upper-left corner of the plates. Vestiges of the scarp reappear due north of the mare basin, above the line continuing the double ray from crater Messier, seen in the upper-right corner. It should be noted that folded mountains (apart from low ridges in the maria) do not exist on the moon, and that therefore any mountains that are not obviously crater walls require an explanation. Seen in that light, the mountains near the upper margin of Plates 12.2 and 12.3 are noteworthy and clearly related to the Altai Ring. This is shown more clearly in Plate 12.4, which shows three concentric circles roughly outlining the remnants of three concentric walls.

In the NE quadrant, near Messier, the Altai Ring is again interrupted, here by Mare Fecunditatis. Beginning at the shore line, near the E. edge of Plates 12.2 and 12.3, the Altai Ring can be traced again, southward and to the west, meeting the Altai Scarp proper at the crater Piccolomini. The Altai Ring is therefore complete except for the two connecting maria, and therefore it antedates the surfaces of these maria in their frozen state. As Plate 12.4 shows, the Altai Ring is not strictly circular but slightly elliptical. Its detailed structure reveals many adjacent scallops, familiar from major geological structures, and similar to those in the scarps facing Mare Orientale (see below).

Outside the Altai Ring, in the SE corner of Plates 12.2 and 12.3, numerous linear grooves, valleys, and small ridges are just visible. The more prominent of these are noted on Plate 12.4. Although many of these features cross the rings of the concentric system, few of them are strictly radial to Mare Nectaris. In fact, the predominant direction is aligned toward Mare Imbrium, and these structural lines may be associated with the well-known Imbrium radial family. No Imbrium scars or ridges are seen in Mare Nectaris itself, however. The large number of grooves near Theophilus clearly radiate from that crater, and not from Imbrium. On the basis of these relationships, it appears that the lava of Mare Nectaris is post-Imbrium but that the concentric ring system is pre-Imbrium.

As Plates 12.6 and 12.7 show, the rim of the inner Nectaris basin is essentially a shelf (with a ridge system superposed on part) on the E. side, while on the W. side the shelf is separated from the inner basin by a broad ridge. This ridge is seen more clearly on Plates 12.10 and 12.11. If the basin were formed as a bowl-shaped impact crater later filled with lava, the subsequent solidification and cooling would indeed have caused the surface of the central area to be the lowest. The faults along which subsidence took place could then have become the seats of new lava upwellings and the formation of ridges.

The complex ridge system between Daguerre and Bohnenberger resembles the "braided" appearance of the ridge in Sinus Aestuum (*Photographic Lunar Atlas,* field D4, sheet S 20) or the en échelon structure of the Serenitatis ridges (sheet S 10).

The impact that caused the crater Fracastorius (right center in Plates 12.8 and 12.9) appears to have occurred *after* the formation of the Nectaris basin but *before* its flooding. No scars of the Fracastorius impact are seen on the mare floor, unlike the Theophilus impact, which left many (see Plates 12.10 and 12.11). Thus, Theophilus is clearly post-flooding, while Fracastorius is pre-flooding. The break in the crater rim on the side of the mare agrees with this relative age. However, if the crater were pre-basin, it could not have survived with most of its walls undamaged. Thus, Fracastorius must be post-basin. The north wall of the crater was probably initially lower than the rest, because of the basin's profile. A distinct difference in tonality is noted between the two halves of the crater floor, corresponding to the areas of the mare basin and the rim, respectively (see Plates 12.6 and 12.9).

The lavas that filled the mare basin appear to have covered most of low north wall of Fracastorius; but when solidification and further shrinking by cooling occurred, this submerged wall apparently became visible again, consistent with the smaller depth of the overlying lava. The low dark hills among those now outlining the north wall (see Plates 12.6, 12.8 and 12.9) are thus accounted for. Other initially submerged walls, now seen as low dark ridges, are found near the north shore of the mare. One is called Daguerre; the other, somewhat larger, toward Mädler, is nameless (Plates 12.6 and 12.7).

Examination of the reproduced plates will show that a wall surrounds Mare Nectaris proper, though this wall is broken and not as high as, e.g., the Apennines of Mare Imbrium. Around Mädler and between Rosse and Santbech the wall has been interrupted by melting. Melting and subsidence unmistakably have altered the appearance of the outer basin, in a broad ring from Goclenius past Colombo and Santbech to Weinek. Another zone of melting appears to have occurred further out, along the inner scarp of the Altai Ring, near Cook and Monge. The continuation of the ridge between these two zones of subsidence and flooding, most prominent south of

Colombo, can be traced south of Santbech, between Fracastorius and Piccolomini, and on to Catharina. This intermediate arc, some 150° long, has been outlined in Plate 12.4. Plates 12.5, 12.8 and 12.9 show parts of this arc quite well.

Plate 12.5 shows the Altai Scarp to full advantage. It illustrates, incidentally, that the losses during the rectification process can be made insignificant in spite of the four steps of copying and the long projection paths used. The northern extremity of the Altai Scarp is well shown on Plates 12.10 and 12.11, which includes the "swirling sound" connecting Mare Nectaris with Mare Tranquillitatis. The highlands are deeply cut by ravines and graben that appear to be part of the Imbrium system. This dates the Nectaris impact as pre-Imbrium, in agreement with the discussion of Plate 12.4. There is one other arcuate structural feature accompanying Mare Nectaris: The system of about five roughly-concentric rilles shown on Plates 12.2 and 12.7 between Gutenberg and Torricelli. It is a counterpart to a better-developed system around Mare Humorum (see below). The rilles do not occur on the shore line of the inner basin, but inside the outer (or Altai) ring. This also is analogous to Mare Humorum.

4. *Mare Humorum*

Plates 12.12 and 12.13 are a pair of rectified photographs of Mare Humorum comparable to Plates 12.2 and 12.3 for Mare Nectaris. The symmetry of the ridge systems of these maria shows that the basins are single dynamical units (contrary to Oceanus Procellarum or Mare Tranquillitatis). A shelf is present on the W. side, and beyond it a nearly continuous mountainous ring wall, which is broken only by impact craters and local subsidence (SW sector). On the E. side of the mare this wall is more fragmented, with several major breaks filled with lava. The role of the crater Fracastorius of Mare Nectaris is played here by several craters: Gassendi, Doppelmayer, Lee, Loewy, and Hippalus. This suggests a longer interval than for Mare Nectaris between impact and flooding. This in turn would probably imply a greater age for the Humorum impact, consistent with the more highly damaged appearance of its basin and walls. Crater Puiseux corresponds to crater Daguerre of Mare Nectaris.

The outer ring consists of a broken system of mountains clearly traceable through a semi-circle (see Plate 12.14) but probably represented also by additional mountain masses in the SE quadrant in Plate 12.14. There are vestiges of an intermediate arc just N. of the line connecting Gassendi and Mersenius, and in the triangle Fourier-Palmieri-DeGasparis, with lava basins found on either side of the second mass.

Rilles occur between the inner and outer rings, in two sectors, roughly diametrically opposite each other (Plates 12.13, 12.15, 12.16 and 12.17). The system between Hippalus and Campanus has three main concentric branches, though locally as many as five (comparable to the Nectaris system). A further rille occurs between Campanus and Mercator. The rilles on the opposite shore are best seen on Plates 12.15 and 12.16. The numerous white specks on the mare floor on Plate 12.16 are small impact craters, probably meteoritic (i.e. asteroidal) in origin. Several rilles are noted in Gassendi, not related to the Humorum system.

The inner ridge system and the floor profile are best observed under very low illuminations. Plates 12.16 and 12.17 give illustrations. A central depression may be seen to be approximately bounded on the east by the second of the four ridges; the slope is dark on Plate 12.17. It is noteworthy that one structural line, marked by the northward continuation of the first ridge, protrudes through the mare wall. The absence of ghost rings or flooded craters near the centers of Maria Nectaris and Humorum implies very considerable depths of these lava basins.

While there are close parallels between Mare Humorum and Mare Nectaris, as comparison of Plates 12.14 and 12.4 shows, there is a difference in that Mare Humorum shows more extensive subsidence and melting in its outer zones. Mare Imbrium, discussed below, shows an even more fully-developed subsidence and melting, while in Mare Orientale the subsidence is extensive, but the melting only sporadic.

5. *Mare Imbrium*

The structure of the Imbrium basin and related mountain arcs, ridges, rilles, and graben, as shown on photographs, has been reviewed before by one of us (Kuiper, 1959). Reference is made to Figures 12-18 of that publication for lunar photographs showing relevent structural features, and to one of them, Figure 15, for a synthesis of the principal data used at that time.

The present paper reiterates those conclusions that are relevant to the discussion of the multiple-ring structures. The discussion is mostly based on additional photography, presented here in Plates 12.18-28.

Plates 12.18 and 12.19 show, respectively, the Imbrium basin in early-morning and in late-afternoon illuminations, both rectified. The Inner Basin is bounded roughly by the quadrangle Archimedes, Plato, Sinus Iridum, and the mountain peak Lahire. More precisely, the boundary is thought of as being just *out*side the ridges shown particularly well on Plates 12.22 and 12.23. They are marked as curved lines on the overlay of Plate 12.24. Within the Inner Basin there are no mountains, only minor ridges and rises that are invisible except close to the terminator. There, the initial crust appears to have been completely destroyed.

Outside this ridge system there is a series of white mountains that visually in large telescopes are impressive by their clean-cut surfaces, resembling the large white blocks that form the main mountains of the lunar Alps. The mountain ring starts with Prom. Laplace, and continues with the Straight Range, the Teneriffe Mts., Pico, Spitzbergen and smaller mountains near Archimedes (Plates 12.18, 12.19, 12.21, 12.23, 12.26 and 12.27); Lambert γ (a cuneiform white mountain between Lambert and Timocharis); Lahire and its companion, α; and a small, darker mountain (ζ) near Caroline Herschel (the last members all shown on Plates 12.20 and 12.22).

This ring of mountains is nearly circular in outline (cf. Plate 12.24) and it is difficult to escape the conclusion that these isolated peaks are the remnants of an inner ring that originally surrounded the Inner Basin somewhat in a manner still found, e.g., in Mare Orientale (see below); and that the present separation from the outer walls by flooded zones resulted from subsidence. Such subsidence was noted on a more local scale in both Mare Nectaris and Mare Humorum. Subsidence is apparent also from the structure of the outer walls of Mare Imbrium and certain other features, mentioned below.

There are two such outer walls, as with Mare Nectaris, one called the Apennine Arc and the other the Alpine Arc. The first is formed by the Caucasus, the Apennines, and the Carpathians, which together span an arc of about 165°, designated by CC' in Plate 12.24. The extremity at C may be verified on Plate 12.18; the extremity at C' on Plates 12.19 and 12.24. The degree of circularity of the Apennine Arc is truly remarkable (see Plate 12.24). The Apennines themselves, particularly, form a prominent fault scarp, facing inward with the steep side, as is true for the Altai Mts. of Mare Nectaris. It is noted that the Apennine Arc contains the Harbinger Mts. (Plate 12.24 at H, and Plate 12.20). In the northern sector the arc approximately follows Mare Frigoris and its extension, Sinus Roris.

The second or intermediate wall is formed by the Alps and the Jura Mts. The arc has a well-defined face on either side of the Alpine Valley (Plates 12.24 and 12.21), but it broadens near Sinus Iridum, and ends in two isolated mountain groups at point A' on Plate 12.24, near Delisle. The structure is best seen on Plate 12.20.

The arc AA' is about 180° long. Its continuation cuts Archimedes Island at its highest point, so that the arc may initially have been more nearly a complete circle. Archimedes Island is best seen on Plates 12.26 and 12.27. The radial and transverse patterns are clearly marked, both in the mountains and the valleys, and the areas where subsidence and melting has taken place also conform to this pattern. The Apennines, with their steep and arcuate inner face and the parallel narrow ridges in front, have a typical fault-scarp appearance. The entire area enclosed by the arc has the unmistakable appearance of subsidence.

The outward extension of the Apennine pattern is seen on Plate 12.25, a rectified photograph viewed from above southern Mare Imbrium, looking outward toward Hyginus, near the center. Several of the major radial structural features are recognized by their vertical direction. A still wider view of the moon from above Imbrium is reproduced in Plate 12.28; the original was taken at full moon.

Returning to Plate 12.24, the ratios of the radii of the three circles drawn closely resemble those of the three circles drawn for Mare Nectaris, in Plate 12.4. In absolute scale they differ, with the Imbrium dimensions about 1.6 times larger, as is seen from Table 1.

Apart from the scale there is an outward resemblance between Fracastorius in the shore line of Mare Nectaris and Sinus Iridum in the shore line of Mare Imbrium. From Plate 12.20 one finds that Sinus Iridum is a nearly circular arc spanning 230°, with most of the missing 130° outlined by a ridge that intersects the Imbrium ridge such that a lens-shaped enclosure is formed. From the relative prominence of the two ridge systems it may be surmised that the Sinus Iridum impact occurred after the Imbrium impact but before either basin was flooded. The same chronology follows more directly from the fact that Sinus Iridum is carved out of the wall of Mare Imbrium, and not vice versa; and the fact that the Jura Mts. are seen by telescopic observation to be cut by hundreds of gouges, clearly issuing from Sinus Iridum. The complexity of the floor of the

Sinus Iridum basin may be surmised from the several parallel ridges and faults shown best on Plate 12.22. Their direction appears to relate them to the Imbrium Basin.

Plate 12.24 also marks some radial structures, such as the Alpine Valley and various graben, seen repeatedly in the photographs of Plates 12.18-27. Plate 12.28 well shows the ring of minor maria surrounding Imbrium, noted by Baldwin (1949), and also the alignment of the Aristarchus Uplift (Kuiper, 1959).

The ring of maria includes the dark areas around Manilius (incl. Mare Vaporum), Sinus Aestuum, the seas N. of Schroeter and N. of Gambart (both of which need to have names); and, on the north, Lacus Somniorum and the east end of Mare Frigoris (S. of Gärtner). Plate 12.28 also suggests that sectors of the highlands may be concentric. This is confirmed by inspection of other photographic material, not reproduced here; but the comments based on this inspection are given below.

First, there is the possibility that there is an Imbrium arc from Römer to Vitruvius to Jansen to Arago, which includes the ruins on the floor of Mare Tranquillitatis. However, it may also be that these ruins are older. Further study is needed to decide this.

Another band of interest extends from Ritter and Sabine to Herschel. This arc is crossed by many radial grooves or graben that are clearly related to the Imbrium impact; but the highland has subsided in many sectors. Higher ground lies to the north, in the arc from near Plinius and Menelaus to Agrippa to Herschel. These ridges are not impressive; they seem to be high areas left in a region of subsidence.

Finally, there is some evidence for a low concentric wall from Hypatia on the shore of Mare Tranquillitatis to the shore of Mare Nubium near the Straight Wall. The continuation of this arc runs through the islands separating Mare Nubium from Mare Humorum and Oceanus Procellarum (near Agatharchides), and then becomes the high shore line of Oceanus Procellarum from between Gassendi and Letronne past Hansteen and Hevelius, ending near O. Struve (25°N). More detailed studies will be required to clarify the relationships involved. The concentricity of this arc, which spans about 150°, may be seen from Plate 12.28, though a full-moon photograph cannot, of course, show elevations. The radius of this arc is about 57° selenocentric.

The Imbrium system of radial grooves and graben will not be discussed here. It is rich and complex, and will be reviewed in a separate study. A few radial features have been marked in Plate 12.24 to serve as a general comparison for Plates 12.4 and 12.14; others are seen in the various plates of this Section.

6. *Mare Orientale*

Mare Orientale is so named because it occurs on the east limb of the moon as seen in the sky (west according to selenocentric coordinates). It has associated with it a multiple system of mountain arcs which is quite unique on the moon.

Plate 12.29 shows the east limb of the moon near maximum libration, with a point about 20° S. and 10° beyond the mean limb as the center of projection. Grimaldi, usually seen quite near the limb, appears as a dark round spot above the center of the bright crescent, with Riccioli above it and to the left. The ray crater Byrgius stands out just below the center of Plate 12.29. Above Byrgius, at the center, is the dark crater Crüger; well below it, equidistant from Grimaldi, is Schickard, with the two lava patches on its floor. Near the lower cusp of the crescent is the giant crater Bailly, often hidden behind the south limb. Mare Humorum is on the right limb, as are the ray craters Kepler and Aristarchus above it — quite the reverse of the usual aspect.

At the center of the terminator a peculiar feature is present that is the object of this section. A closer view of the central portion of Plate 12.29 is shown in Plate 12.30. Two roughly parallel bands of dark lava are present in the left-central part, associated with an arc of bright mountains shown better in later photographs. In the right margin, the ray crater Byrgius is seen; Grimaldi and Riccioli show as dark patches in the upper margin, while the crater Schickard is found in the lower right-hand corner. The small, dark, oval basin between Byrgius and Grimaldi is the crater Crüger. Two broad parallel valleys are seen in the lower-left corner of the plate; these appear to be approximately radial with respect to the center of Mare Orientale. The various features shown on Plate 12.30 and their relation to the Orientale system are indicated on the overlay of Plate 12.42.

The relief in the area of Plate 12.30 is shown better in Plate 12.31. Its original was taken a fraction of a day before full moon, causing the mountains near the terminator to cast shadows. Three concentric scarps are now visible, with the outer one having the crater Eichstadt approximately at the center. The radial valleys in the lower or southern part of Plate 12.31 are now more prominent. It is also seen that to the right (east) of the Eichstadt scarp several more ridges occur, approximately concentric with it. These additional ridges are more pronounced on the subsequent plates which were taken with the terminator at greater distances from the limb.

Comparison of Plates 12.30 and 12.31 shows that the two narrow sequences of arcuate lava patches are situated just inside, i.e. at the foot of, the two prominent concentric scarps. The IAU names of these strips are Mare Autumni and Mare Veris (*Photographic Lunar Atlas,* charts 10 and 11, 1960). The double-lobed dark feature, some 2 inches above the crater Eichstadt, is seen to be located in a depressed region bounded on the right by a scarp of moderate elevation which is roughly parallel to the Eichstadt Scarp. This interpretation is confirmed by stereoscopic viewing (See Plate 12.43).

Some of the outer parts of the Mare Orientale system are shown more clearly on Plate 12.32, with the sequence continued in Plates 12.34 and 12.36. Plate 12.33 amplifies certain aspects of Plate 12.32. It was obtained from the same original but from a different globe photograph showing the area between the Eichstadt Scarp and the next inner one somewhat more clearly. Plates 12.34, 12.32, and 12.31 have the same scale and may be combined stereoscopically, bringing out mountain ridges and other relief more clearly than the individual photographs do. Plate 12.35 covers the same region as the central portion of Plate 12.34, based on the same original but a different globe photograph. It shows the region around Byrgius and Crüger more clearly, including the Sirsalis Rille and the vicinity of Grimaldi. Plates 12.34 to 12.36 show, incidentally, that the crater wall of Grimaldi is surrounded by an outer ring of approximately twice the diameter. This structure is described more fully in Section 12.

Plate 12.35 and stereo-comparison of Plates 12.32 and 12.34 show that between Byrgius and Crüger there are three prominent features running approximately north-south, appearing to be part of an outer ridge system surrounding Mare Orientale. It is true that these features coincide in part with walls of old craters; but their prominence and continuity show them to be of more than local nature. These structural features have been included in Plate 12.42.

The relief of the outermost structures surrounding Mare Orientale may be observed in Plate 12.36. The region just north of Byrgius is of special interest. The Sirsalis Rille between Byrgius and Crüger becomes a fault, with the right-hand or eastern portion being elevated above the left-hand or western portion, as is shown by the shadow. This interpretation has been confirmed visually. Several minor ridges and valleys north and east of Crüger are found to be oriented parallel to the ridge system surrounding Mare Orientale. The right-hand photograph of Plate 12.36 shows, in the lower portion, a complex sculptured terrain, somewhat resembling the Haemus Mts., with many of the structural lines running concentric with Mare Orientale. Among these features is a fault just visible on Plate 12.36 about one inch above Schickard. The extremities are marked by *F*. On March 19, 1962, this fault was quite prominent visually with the 82-inch telescope and was also photographed. Previously, photographs had been obtained with the Yerkes 40-inch refractor, such as Y467 and 468 (used in Plate 12.36).

The innermost basin of Mare Orientale is so close to the moon's limb, even at favorable librations, that rectified photographs give a distorted view owing to the very uneven terrain in this region. The discussion is therefore continued with unrectified photographs. Plate 12.37, taken with the 82-inch telescope, shows not only the main basin of the mare but, with stereoscopic viewing, two rows of mountains beyond its far shore. A photograph with even greater libration was obtained very recently (March 27, 1962), also with the 82-inch telescope, and is shown in Plate 12.38*a*. Stereoscopic comparison between Plates 12.37 and 12.38*a* clarifies the basin structure and the surrounding mountain chains, particularly those on the far side. The d'Alembert Mts. north of the basin are found to be mountain walls surrounding the mare seen in profile. The Cordilleras south of Mare Orientale are other portions of the peripheral chains. A mountain still more distant than the left-hand member of the d'Alembert Mts. is visible on Plate 12.38*a*, about one-half inch further to the left. Plates 12.38*b* and *c* show the limb area of Mare Orientale with successively less libration than Plate 12.37.

Plates 12.37 and 12.38 were taken somewhat after full moon, and show no shadows or relief except by stereoscopic comparison. Plates 12.39*a, b,* and *c* show a beginning of shadows which, especially with stereoscopic viewing, aid in the interpretation of the surface structure. In view of the importance of stereoscopic comparisons, an extra set of the plates, Nos. 12.30 through 12.39 (except 12.33 and 12.35) is provided with this publication. It will be found that some pairs should be viewed when displaced nearly parallel to the limb (e.g. 12.37 left, 12.38*b* right;

or 12.39*c* left, 12.39*b* right); while other pairs should be viewed when displaced nearly normal to the limb (e.g. 12.38*a* left, 12.37 right; or 12.37 left, 12.39*c* right); and still others in both directions — (12.39*a* left, 12.39*b* right; 12.39*c* left, 12.39*a* right). The latter pairs show the scarps well and were used in the preparation of Plates 12.42 and 12.43.

As has been stated, a synthesis of the main concentric and radial features of the Mare Orientale system is shown in Plate 12.42. At least four major concentric mountain rings have been noted, some of them associated with lava strips just inside major scarps. Fragments of three or more additional rings are also present. Segments of two mountain rings can be identified beyond the mare basin itself.

Mare Orientale, with its multiple structure, is one of the most fascinating lunar features. Some of the surrounding mountain chains, such as the d'Alembert Mts. (20,000 feet elevation), are among the most massive on the moon. In addition, several major radial valleys appear and also numerous minor grooves and valleys, many of which are just visible on Plate 12.32. It will be of great interest to photograph the missing sectors beyond the limb by means of spacecraft.

One of the most significant aspects of the Mare Orientale system is that the lava patches tend to occur on the valley floors, adjacent to the steep inner faces of the arcuate scarps. This may mean that the lava has welled up along fault planes associated with these scarps.

In conclusion, Plate 12.43 is a direct (not rectified) drawing by Mr. Hartmann, synthesizing a number of unrectified photographs viewed stereoscopically, and showing the various structural lines and mountain chains which he could recognize. The overlay may be compared with that of Plate 12.42 by Mr. Kuiper.

7. *New Basin on SE Limb*

During the study of the Mare Orientale system a new basin-like feature was noted in Plate 12.29, midway between Mare Orientale itself and the south polar cusp. A new rectified photograph centered over this feature was made from the same original, Y1614, and is shown in Plate 12.44. The new feature exhibits the concentric properties of a basin, surrounded by mountain walls or scarps.

An enlarged view of the basin is shown in Plate 12.45. Its interpretation is assisted by using unrectified photographs, four of which are shown in Plates 12.46 and 12.47. Plate 12.46*a* is from the same original as Plates 12.44 and 12.45 (and Plate 12.39*a* of Mare Orientale); Plate 12.47*a* matches Plate 12.38*a* and Plate 12.47*b* matches Plate 12.37 of Mare Orientale. Stereoscopic examination of Plates 12.46 and 12.47 shows the presence of a basin having a small, off-center patch of dark lava. Plate 12.46*a* indicates that what appears to be the floor of an inner basin in Plates 12.44 and 12.45 is in reality the far shore line.

The inner-basin diameter parallel to the limb is indicated by dots in Plates 12.45, 12.46*a* and 12.47*a*. Plates 12.45 and 12.46*a* also show the diameter of one of the principal outer rings. The far wall of the basin is double just behind the lava patch and extending to the right. This is seen especially in Plate 12.46*a*. In front of the basin, four main parallel ridges are seen which appear as the roughly-concentric arcs in Plates 12.44 and 12.45. However, neither the far ridges nor the frontal arcs are as regular and continuous as those surrounding Mare Orientale; nor is any of these arcs accompanied by arcuate lava strips, a difference clearly marked even on the small scale of Plate 12.44. The dark inner arc shown there is not the central lava patch, as comparison with Plate 12.46*a* (from the same original) will show. The patch is here hidden in the shadow and visible only with the increased libration and higher illumination of Plates 12.47*a* and *b*.

Plates 12.44 and 12.45 further show that the frontal arcs merge into the two major radial valleys emanating from Mare Orientale. These valleys, by their position, direction, and greater prominence toward Mare Orientale appear to be part of the Mare Orientale system. Yet, their exceptional strength and their merging into the SE basin system of frontal arcs suggest that these structures derived part of their prominence from the formation of the SE basin itself. The prominence of these two Mare Orientale valleys near the SE basin suggests that the latter was present at the time of the formation of the former. This sequence is consistent with the "fresher" appearance of the Mare Orientale scarps. The widespread presence of lavas suggests for Mare Orientale a late pre-mare age. We are thus led to an earlier pre-mare age for the SE basin, consistent with the near absence of lavas in this system.

8. *Mare Humboldtianum*

This mare is an excellent example of a multiple-ring system surrounding an inner basin. Plates 12.48-51 show rectified photographs illustrating the principal features. The outer ring is seen to be a prominent scarp in Plate 12.48 not unlike the Altai Scarp of Mare Nectaris or the Eichstadt Scarp of Mare Orientale. The bifurcation in the scarp northeast of the dark-floored crater Endymion (left-center in Plate 12.48) is very similar to several such satellite scarps present in Plates 12.31-33 and 12.42. Comparison of Plates 12.48 and 12.49 shows its inner face to be the steeper, as was found to be true in the other systems discussed. Some radial structural lines are also visible.

Plates 12.50 and 12.51 show that the inner basin of Mare Humboldtianum is double, not single. The dark lavas do not cover the entire double floor but only approximately half the area of the larger of the two basins. The Russian far-side records discussed in *Communication* No. 13 show no evidence of additional lava outside this one patch nor do our own plates, which have a larger scale but cover only the visible side of the moon.

9. *Mare Crisium*

In Sec. 2, reference was made to Mare Crisium as an example of a typical circular mare. After concentric features had been found to be typical of lunar mare basins, a closer scrutiny of Mare Crisium was made, and it was seen that the Crisium Basin, too, exhibits this structure.

Plates 12.52 and 12.56 supplement Plate 12.1. On all three of these, the peripheral basins discussed in Sec. 2 are prominent. But further to the north, and near the edge of Plate 12.1, a typical concentric scarp or mountain ring can be traced through an arc of at least 130° (*AA′* in Plate 12.53). The ring is rather broken, but its similarity to other such features described in this paper is unmistakable, and its elevated nature is proven by the rows of peaks extending beyond the terminator in both Plates 12.1 and 12.52. The extension of the arc contains the high peninsula between Cauchy and Taruntius, shown especially well on Plate 12.56. On the east, in the complex peripheral structure associated with Mare Marginus (Plates 12.58 and 12.59), the ring cannot be traced; and on the west and south the continuation of the ring would pass through Mare Tranquillitatus and Mare Fecunditatis.

The degree of circularity of Mare Crisium has often been discussed. In Plate 12.53, taken from above the mare, circles have been superimposed on both the inner and outer walls. The discussion of Sec. 2 is thus clarified and the concentricity of the outer wall is seen to be quite remarkable. A dashed line is added to indicate the position of a possible intermediate low arc analogous to the intermediate arcs of Mare Nectaris and Mare Humorum.

The regions north of Mare Crisium may be studied in greater detail in the large-scale Plates 12.54 and 12.55. They show particularly well the peripheral wall, with its locally quite flattened top, some 50 km wide; and the shelf inside the shore line, also some 50 km wide. Various ridges follow approximately the inner boundary of the shelf. Just outside the flattened main wall a broad low channel is seen, interrupted by the wall of the crater Cleomedes, clearly of later origin. Additional peripheral and radial valleys are seen to cover a broad zone, over 200 km wide, outside the north wall of Crisium. These valleys and channels are usually of the dark lava tone; melting appears to have been extensive in this region. The north edge of the zone is marked by the outer concentric scarp or mountain ring.

10. *Mare Smythii and Mare Marginus*

On the extreme east limb there are two maria, Smythii and Marginus. These maria are studied with some difficulty from earth-based photography. The Russian Lunik III records supplement this information in a most desirable way and Mr. Whitaker in *Communication* No. 13 assembles and analyzes this material. We are indebted to him for allowing us to reproduce in Plate 12.57 his synthesis of the Russian records of this region, together with a reprojected earth-based photograph having a similar aspect.

Both photographs are essentially "full moon" views, showing no shadows. The Marginus basin to the north is a somewhat irregular dark patch, while Mare Smythii is more nearly circular. (A supplementary high lighting view has been included in Plate 12.76.) Under low-oblique lighting, however, both maria are found to possess nearly circular walls of rather similar radii. This is seen from Plates 12.58 and 12.59, with the Marginus wall showing especially well on Plate 12.58. The two mare basins resemble the inner basin of Mare Humboldtianum, in that all three are partially covered with light-colored material, explaining in part the irregular outlines as seen under high illumination.

The recognition of the circular design of these two mare basins suggests examination of the surrounding terrain for concentric structures. Plate 12.58 shows several arcuate ridges near Mare Marginus but they do not appear to be concentric with the mare wall noted above. One major ridge meets the mare wall almost tangentially near the large crater Neper, lying between the two maria; this unusual geometry may exclude a causal relationship between the two systems. However, Mare Smythii, which has the more prominent circular wall (Plate 12.59) appears to possess some associated concentric walls, the most prominent of which is cut by the crater Lapeyrouse, indicated by *L* on Plate 12.58. Possibly the Mare Crisium flood has erased some of these earlier structures. Also, only half the surrounding terrain can be observed from the earth with the necessary low illumination, and the relief beyond the limb is not known.

11. Basin Near Schiller

Southeast of the crater Schiller a curious double ring exists, first noticed in 1959 by Mr. Paul Kuiper in the course of the globe photography program. This system is smaller than those discussed above, the inner ring having a diameter of some 180 km and the outer one 350 km, i.e., very nearly double in size. Thus, the diameter of the inner basin is comparable to that of the larger craters. The region is shown in Plates 12.60-63.

A comparison of the inner and outer rings reveals interesting structural differences. The inner ring is composed of mountainous masses, while the outer ring is at least locally a scarp having an outside slope with only a slight drop in elevation. The structure is thus comparable to that of the Nectaris Basin with its inner ring of hills and outer Altai Scarp; or of Imbrium with its inner ring of peaks and outer Apennine cliffs.

The Schiller Basin gives the impression of being very old. Its walls are interrupted by many craters, and Schiller itself falls at the position of the expected northeast part of the outer ring. The region has undergone some flooding. Under high lighting the area is darker in tone than the surrounding uplands, although the tone is not quite as dark as that of the major maria. The low-lighting views included here reveal "ghost ring" patterns, especially in the inner basin and just north of it, where the dark tone is most pronounced (Plates 12.62 and 12.63). These observations suggest extensive melting. Several craters on the inner wall and parts of the northern sector of the wall itself appear to have been affected by this melting. This includes one large crater and at least two smaller ones, resembling Fracastorius and Doppelmayer, with the wall facing the inner basin partly destroyed. The presence of these craters is taken to indicate a finite interval between basin formation and flooding. Furthermore, the large number of craters in this area indicates that the flooded surface itself is old. We conclude that this basin formed during the earliest history of the lunar surface, that melting and flooding occurred thereafter, but that the melting occurred so early that much damage has since been done to the surface.

12. Grimaldi

Plates 12.64-66 are rectified views of Grimaldi. This formation, long thought of as a typical flooded crater, is clearly shown to be a double-ring basin, with ring diameters of about 220 km and 410 km, respectively. The first two plates, under low morning illumination, reveal the usual structure: an inner ring, the wall of Grimaldi proper, composed of mountain masses and peaks, and an outer ring which is more scarp-like with the steeper drop inward. This outer ring may be traced through almost a full circle; it is lost only where it would cross Oceanus Procellarum. It is most prominent on the south side where it runs south from Damoiseau on the east and curves back to the north, intersecting Riccioli on the west.

In Plates 12.65 and 12.66, the dark floor of Grimaldi appears to be displaced toward the southeast. Some of this displacement is probably real, but it should be noted that the effect is increased by the distortion from the rectification process near the limb, caused by the elevation difference between the mountain ring and the floor of the basin.

The crater Damoiseau A, just inside the outer ring, tangent to Damoiseau, and about 2 inches north of Sirsalis A, provides a good example of a phenomenon which can be found in many of the concentric ring walls. In all three plates, but especially in Plate 12.65, it can be seen that the outer scarp curves very smoothly outward and along the east wall of Damoiseau A. The northern junction between the outer Grimaldi ring and the rim of Damoiseau A may be affected by Damoiseau itself, but the southern junction gives the impression that it is the Grimaldi ring which interrupts the Damoiseau A rim, rather than vice versa. In other words, Damoiseau A appears older than the ring. If this be accepted, it follows that the zone between the Grimaldi rings was not grossly disturbed by the formation of Grimaldi; and that the outer ring was locally displaced by a pre-existing structure, presumably in response to a local zone of weakness. It is inferred that the outer ring is in the nature of a fault scarp.

13. Janssen

Plates 12.67-69 show the crater Janssen under both low and high lighting. The name Janssen applies to the large elongated crater-like object filling the central one third by one third of Plate 12.68. The object is an example of an unusual class of double craters where the larger (southern) overlaps the smaller, so that the larger member is the younger of the two. Even this larger member has a very old appearance, as it has been disturbed by many more-recent craters. The still greater age of the northern member is compatible with its unusually battered appearance.

A low outer ring, making an arc of nearly 90°, is found on Plate 12.67 one inch NW of the northern component, and is concentric with it. The ring itself has a rounded and "eroded" appearance. This impression of old age is strengthened by the presence of many nearly linear features, some radial to Mare Nectaris, cutting through the ring. There is a fragment of a third ring, an arc some 40°-50° long, in the nature of a scarp about one inch further out, between Stiborius and Wöhler (cf. Plate 12.67). The great age of these rings is consistent with the great age of the northern Janssen component, cited above. Plates 12.68 and 12.69, taken at high sun, do not show any dark lavas nearby. Thus, the Janssen concentric ring system may be thought of as a very old pre-mare structure which has subsequently been heavily damaged by tectonic events, but has not been seriously affected by later flooding.

No clear evidence has been found that the larger, southern component of Janssen has a ring system of its own, a fact that raises interesting questions.

Attention is called to the many structural ("grid") lines including the Rheita Valley, shown on the Janssen photographs. These and similar lines elsewhere will be considered in a separate study in these Communications.

14. The Leibnitz Mountains

The south polar area is known for its rugged Leibnitz Mountains. They have a tendency to be aligned in major ridges or scarps as is seen from Plates 12.70 and 12.71. These plates reveal that while the ridges or scarps tend to follow crater walls, they are more continuous than the crater walls themselves. There is thus a resemblance with the outer scarp of Grimaldi and its relation to Damoiseau A (cf. Sec. 12). This supports the view that the ridges or scarps were formed by local faulting, the course of which was affected by pre-existing craters in certain regions.

On the plates shown, the Leibnitz Mountains exhibit an arcuate pattern. An outer arc stretches from the limb near Bailly, at the top of Plate 12.71, about an inch right of the terminator near the center, and back to the limb at the bottom. A second arc, more conspicuous due to its long shadows, lies inside this. On the basis of the general pattern for basins which has emerged from this paper, one is led to conclude that these mountain arcs indicate the presence of a large basin beyond the limb. This statement merely amplifies and makes more precise the well-known fact that all major mountain arcs on the visible lunar surface are associated with mare basins. Because the Leibnitz Mountains are very high, the highest (8-9km) of any mountains on the moon, the basin might be presumed to be quite large.

A determination of a position of the center of the arcs from the plates shown leads to approximately 65°S and 160°-180°W longitude, i.e., well beyond the lunar limb between Bailly and South Pole. Because elevated points near the limb will project too far out on rectified photographs, the recorded arcs will be somewhat distorted in the sense that their curvature is too high. Their true center will therefore be somewhat farther out, i.e., at a latitude lower than 65°S.

The Russian photographs show this region very near the limb, and therefore not well, but indicate the presence there of a large mare, named Mare Desiderii on the Russian Atlas (Barabashev et al, 1961) and officially named Mare Ingenii at the Eleventh General Assembly of the International Astronomical Union (1962), in 1961. In the Russian Atlas, the center of this mare is about 50°S at roughly 170°W longitude, close enough to the center of the Leibnitz arcs found above to suggest that the Leibnitz Mountains are a major peripheral system to Mare Ingenii.

On the two plates of the far side of the moon shown in *Communication* No. 13 a faint whitish arc is seen between Tsiolkovskiy and the South Pole. This arc somewhat resembles the bright Apennine arc seen at full moon. However, its center appears to coincide approximately with the large dark-floored crater Jules Verne, and not with the center of Mare Ingenii.

15. Other Lunar Basins

The discussion so far has covered all cases of lunar basins which were found to have well-defined concentric structures. Most of these basins are the sites of extensive flooding and are known as maria. For two maria on the east limb, Smythii and Marginus, a fragmentary concentric structure was found for the former only, but as pointed out, for more than half of the surrounding terrain the relief is unknown.

The remaining maria fall into several groups. Mare Serenitatis and Mare Nubium are found to have broken circular outlines marked in part by mountain walls, and are almost certainly the site of typical lunar basins, probably of great age. Particularly for Mare Nubium the pre-mare history is apparently long and very complex. No outer concentric structures are evident for either mare. Mare Tranquillitatis has a two-lobed or double appearance and Mare Fecunditatis has a roughly-circular outline, but no prominent surrounding walls are present. They may be the sites of very old basins. Oceanus Procellarum shows no basin-like features. In the last three maria there seems to have been so much flooding that the outlines of any pre-existing circular basins must have been largely destroyed. Maria Frigoris, Vaporum, Veris, Autumni, and the like, are probably to be classed as peripheral flooding zones related to their larger neighbors. Mare Australe appears to be a site where local melting was considerable, but where no large basin provided a center for symmetry. A number of scattered craters were thus flooded.

Only a preliminary search has been made for smaller double-ring structures of the basin type. Such structures should not be confused with another type of double-ring craters that has been previously recognized. It is exemplified by the craters Taruntius, Fabricius (cf. Plate 12.69), and Doppelmayer (Plates 12.12-15). This second type shows an inner ring of mountains on the crater floor, lower than the main crater walls and with a diameter of about half that of the main wall. This type is probably related to craters exhibiting near-circular rilles on the crater floor, such as Vitello (Plates 12.12-13), in the sense that the Taruntius-type structure may have been generated from the Vitello type by upwelling of lavas from the fissure. The relationship between the circular-type rille and the inner mountain ring has a parallel. There appears to be a similar relationship between the radial crater-floor rille (exemplified by Petavius) and the radial crater floor mountain chain (exemplified by Arago). The best known cases of upwellings from crater floors are the central mountains themselves (e.g. Kuiper, 1954, p. 1107).

Returning to the basin-type structure of sub-mare dimension, we shall be concerned with low concentric walls or scarps *outside* the main crater wall. Two such cases, Grimaldi and Janssen, have already been described. Several more have been noted or suspected and they are mentioned here only provisionally, pending further study.

Plate 12.72 shows a rectified photograph of Bailly and its large neighbor, Pingré, craters that are not well known to lunar observers owing to their position on the lunar limb.

An outer wall is faintly but definitely indicated for Bailly and is outlined by black dots. Its extension toward the limb is interrupted by the Leibnitz mountains, as may be observed from Plates 12.44, 12.70 and 12.71. Apparently Bailly is older than these mountain arcs.

Plate 12.72 indicates also the presence of a low outer wall for Pingré (indicated by white dots). For both Bailly and Pingré the ratio between inner and outer wall is close to 2.0, in agreement with the ratios found for Grimaldi, Janssen and the Schiller Basin, all of similar size.

A low, heavily damaged wall may surround Clavius, running from Scheiner (midway on the N. wall) to just south of Longomontanus to Maginus, and continuing through Deluc southward. Other craters in this class, with even more fragmentary data, are Vieta, Neper (Plate 12.59) Gauss, Petavius and Furnerius. Further work is contemplated on these more doubtful cases.

16. Terrestrial Analogies

A very interesting photograph of what is almost certainly a large terrestrial impact crater with a *double-ring structure* is reproduced in Plate 12.73. It was kindly made available by Dr. C. S. Beals, Dominion Astronomer of Canada. The lake shown is Clearwater Lake, 56°10'N, 74°20'W, and its diameter is about 20 miles (32km). The ring of islands has a diameter equal to half this amount. The lake was first included in a list of possible fossil meteorite craters by Beals, Ferguson and Landau (1956) and is described more fully by Beals, Rottenberg and Innes (1962). The islands and the shore line have been greatly damaged by glaciation which, according to Dr. Beals, has proceeded from right to left on the photograph. The nature of the rock of the inner ring has not yet been investigated, but this is scheduled to be done. This structure may be analogous to the Taruntius type of lunar crater, not with the Grimaldi-Janssen type. Taruntius has a diameter of about 35 miles (55km).

We have discussed, particularly in connection with Maria Crisium, Nectaris, Humorum, and Imbrium, the occasional presence of *shelves* and *rilles* inside the shore lines of the lava basins. Reference is made also to an earlier study (Kuiper, 1959, p. 303 ff). Two terrestrial examples of shelves and tension rilles observed on the floor of a Hawaiian volcano, may therefore be instructive. They are reproduced in Plates 12.74 and 12.75. The originals were taken in color by Mr. Fred Greer, January, 1962, and kindly made available for reproduction. It is noted that the peripheral cracks are the most prominent, as is true on the moon; that an échelon pattern among these "rilles" is common, as on the moon; but that numerous smaller cracks occur all over the lava surface. We should therefore be prepared to find numerous finer rilles on the lunar maria as the resolving power of lunar photographs increases.

The shelf shown on Plate 12.74, with its hummocky fine structure and numerous fine fissures, is also suggestive of lunar applications. Plates 12.74 and 12.75 show no "ridges," but none would be expected since the interior of the lava basin had not cooled.

Plate 12.76 shows a small terrestrial *fault* produced by a subterranean explosion (Stephens, 1962). Comparison with Plates 12.5 and 12.31 shows remarkable similarity of topography, including the "scalloped" appearance of the fault itself. Also, the transition of a fault to "hills" is suggestive.

Finally, in Plate 12.76, a supplementary rectified photograph of Mare Smythii is included, showing somewhat more detail than Plate 12.57.

17. Summary: The problem of Lunar Basins

A primary conclusion of this paper is that multiple-ring structures are typical of the large circular depressions to which we have referred as *basins*. The positions of the principal of these multiple-ring structures are shown in Plate 12.77, and Table 1 summarizes the data on their diameters. The main structural features of the basins are listed in Table 2. In the present earth-based exploration of the moon, the emphasis is of necessity on morphology; and we have kept the discussion almost entirely descriptive. The main conclusions of this paper are therefore empirical and factual, and are independent of any preferred theory of basin or crater formation. The authors hold that the impact hypothesis accounts best for the origin of the basins and the concepts of melting and flooding by darker lavas have been freely used. These attempts at understanding the observed structures are of course separate from the existence and recognition of the structures themselves. Certain ideas on the origin and relative ages of the basins and ring walls emerge rather readily from the observations. These are found in the text and included in Table 2.

We believe that none of the observations presented is inconsistent with the hypothesis of an impact origin for the basins; tectonic processes may be called upon to explain many of the surrounding structures.

A plausible outline of the history of these systems is as follows. Major impacts formed basins in a manner analogous to the crater-formation processes discussed by Baldwin (1949). Around these larger impact sites, stresses were set up which resulted in faulting at some distance outside the inner basin or crater rim. The faulting may have occurred shortly after the impact, or in some cases with a greater delay, as a result of gravitational settling. Subsequent crater impacts, which tended to grow less frequent as time passed, damaged both the inner basins and outer ring systems. Some of the outer ring systems became lost in the rough terrain produced by these later crater-forming events. Meanwhile, the internal temperature of the moon was rising due to radioactivity (Kuiper, 1954). This heating and resulting expansion of the moon could have aided the faulting processes at the surface, releasing strains set up by the original impacts. Since lines of weakness probably also existed along crater walls, the slippages, which on a large scale were concentric with the basins, tended to be diverted locally along crater rims. Finally, toward the end of the internal melting process, lavas reached the surface and partial flooding or melting of the crust occurred. Lavas tended to well up at two typical positions, (1) at the site of an impact, i.e., in the inner basin where the crust was shattered to great depth and where there was a local mass deficiency; and (2) along the fault planes of the outer rings. The schematic and partly hypothetical profile of a fully-developed system such as Mare Orientale showing fault scarps and lava crescents is shown in the left half of Figure 1.

This arrangement extends, however, in no known case, over the full 360° around the mare basin. An average upper limit is between 90° and 180°. For this arrangement to be valid over all azimuths would require the entire surroundings of the mare to have developed tensional forces (as opposed to compressional forces); only then could a series of normal slip faults occur around the entire mare. Impacts, on the contrary would be expected to cause predom-

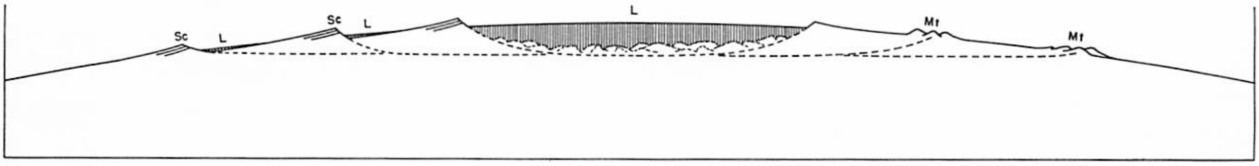

Fig. 1. Schematic cross-sections of well-developed basin system,
left: Showing fault scarps and lava crescents. *right:* Showing compressive and extrusive mountain chains.

inantly crustal compression just outside the impact crater.

The best-known case of an outer scarp, the Altai Scarp, extends over about one quadrant. Beyond this the arc is continued as a ring of mountains. Other mountain rings, not scarps, have been found in wide sectors around several other basins. A second type of arc profile therefore exists, typified by the right half of Figure 1. Such a profile could indeed arise from compressional forces, to which local lava upwellings, along bowl-shaped fault planes caused by the impact, could have made further contributions. The presence of both fault scarps and mountain arcs around the basins seems to indicate the simultaneous presence of tensional (scarp-forming) and compressional (hill-forming) forces, in different quadrants around the same impact center. This in turn suggests the presence of a horizontal stress radiating from the impact center. This stress may be attributed to the horizontal component of the impacting momentum. If this analysis is correct, it follows that the *direction of impact* may be derived from the structure of the surrounding walls. Such a deduction had already been made for Mare Imbrium (Kuiper, 1959), though from a different set of data.

It may be presumed that the horizontal stress would be most effective in moving the crust during the interval that the subcrustal layers had become plastic or at least weakened by partial melting. The best developed ring systems would be expected to have been generated during that interval. It probably follows that such ring systems could no longer develop once the moon had finally solidified. In fact, no post-mare ring systems have been found.

This outline appears to account in a general way for the shapes and surrounding wall structures of the maria and larger craters.

The working hypothesis presented for the basins and their rings requires testing and elaboration in several directions. The prominence of the ring system should be correlated first with age and the melting cycle. Then, did some near-vertical impacts occur and do they fail to show outer walls? Are the various rings around one basin strictly equal in age or was there a sequence of events that can be reconstructed? Can one account for the details of the distribution of scarps and hills on the basis of a stress field attributable to a single impact? What is the relation of the various outer walls to the so-called grid system so widely observed? These matters will be considered in later Communications as will the construction of accurate traverses through the different ring systems observed. Among the more interesting *moon-based measures* would be (a) the gravity anomalies across the basins and their fault systems and (b) the seismic activity along the faults. A close comparison with terrestrial arc tectonics will be of great interest though the origins of the two classes of structures are probably very different.

Acknowledgments. — This paper could not have been written but for the plate collections on which it is based. The Yerkes collection has been taken during the past 3 years entirely by Mr. Elliott Moore and the many excellent plates obtained attest to the quality of his work. Mr. Harold Spradley has conducted the globe-photography program of the Rectified Lunar Atlas during the past year and many of the rectified photographs shown here were reproduced from his globe negatives. Mr. Ewen Whitaker, in selecting the best plate material for the globe-projection program, also assisted us in finding the best available views of the topography discussed. We are further indebted to these men and to others at the Laboratory for discussion and recognition of various aspects of the multi-ring structures here described, and we wish to express to them our sincere thanks. Mrs. Alice Fabe assisted us ably in preparing the plates for publication.

The continued use of the Yerkes and McDonald telescopes, as will be clear from this paper, has been of the greatest value to the development of the lunar program of the Laboratory; and we wish to thank Director Morgan and his staff for making this possible. The studies here described were supported by the National Aeronautics and Space Administration through Grants NsG37-60 and 161-61; the basic globe photography was also supported by AF 19(604) 8064.

TABLE 1

DIAMETERS OF LUNAR BASIN SYSTEMS

BASIN	RINGS	DIAMETER (km)	RATIO WITH INNER RING	RATIO WITH PREC. RING
M. NECTARIS	Inner Ring	400	1	
	Catharina Ring (weak)	600	1.5	1.5
	Altai Ring	840	2.1	1.4
M. HUMORUM	Inner Ring	410	1	
	Mersenius Ring (weak)	560	1.35	1.35
	Cavendish Ring	700	1.7	1.25
M. IMBRIUM	Inner Ring	670	1	
	Alpine Ring	970	1.45	1.45
	Apennine Ring	1340	2.0	1.4
M. ORIENTALE	Inner Ring	320	1	
	2nd Ring	480	1.5	1.5
	3rd Ring	620	1.9	1.3
	Eichstadt Ring	930	2.9	1.5
	Rocca Ring	1300	4.1	1.4
SE LIMB	Inner Ring	290	1	
	Intermediate Rings Ill-Defined			
	Outer Ring	620	2.1	2.1
M. HUMBOLDTIANUM	Inner Ring	300	1	
	Outer Ring	620	2.1	2.1
M. CRISIUM	Inner Ring	450	1	
	Middle Ring (weak)	670	1.5	1.5
	Outer Ring	1060	2.4	1.6
NEAR SCHILLER	Inner Ring	180	1	
	Outer Ring	350	1.9	1.9
GRIMALDI	Inner Ring	220	1	
	Outer Ring	410	1.9	1.9
JANSSEN	Inner Ring	160	1	
	1st Outer Ring	350	2.2	2.2
	2nd Outer Ring (part)	540	3.4	1.5
BAILLY	Inner Ring	320	1	
	Outer Ring	660	2.1	2.1
PINGRE	Inner Ring	300	1	
	Outer Ring	660	2.2	2.2

TABLE 2

CHARACTERISTICS OF LUNAR BASINS

ITEM	EXAMPLES	EXCEPTIONS
1. The large circular maria are the sites of depressions called basins.	All Cases	
2. The basins tend to be surrounded by more than one concentric ring of mountains which set them apart from ordinary craters. For the larger basins each ring tends to be about 1½ times larger than the ring interior to it. For the smaller basins two rings are observed and the ratio of the radii tends to be 1.9-2.2; the difference may be due to the invisibility here of the weaker intermediate ring shown by the larger basins (cf. Table 1).	cf. Table 1	Serenitatis Nubium
3. Basins with concentric rings tend to be larger than ordinary craters.	All but the smallest examples mentioned in text	
4. The slopes of the inner faces of the concentric rings tend to be steeper than those of the outer faces.	Nectaris (Altai scarp) Imbrium (Apennines) Orientale (outer rings)	
5. Flooding by dark material, apparently lava, is most probable within the inner-most ring and decreases outward.	All cases	
6. In the outer parts flooding is favored in the low-lying zones between the mountain rings, especially at the foot of the inner face of scarp-like rings, making small, arc- like, satellite maria.	Orientale — Aestatis; Imbrium — Frigoris Nectaris	
7. Flooded surfaces tend to have systems of "wrinkle ridges," roughly concentric with the ring systems.	Imbrium Humorum Nectaris	
8. The basins tend to have concentric rille systems.	Humorum Nectaris Imbrium	
9. The basins tend to be surrounded by radial-valley, ridge, and fault systems.	Imbrium Nectaris Orientale Humboldtianum	
10. The inner rings tend to be made up of more isolated peaks as opposed to the outer rings which appear locally as fault scarps.	Imbrium Orientale Grimaldi	
11. The concentric rings tend to detour along the lines of crater walls, rather than cut through them. As in the discussion of Grimaldi, points 10 and 11 are taken to indicate that the outer rings are primarily the result of local faulting.	Orientale Grimaldi Object near Schiller Leibnitz scarps	
12. There are many cases where craters have damaged the basin walls, and have themselves been damaged by flooding. Therefore, the formation of basins tends to precede the time of their flooding by considerable intervals. The evidence is strong that the flooding did not accompany the basin-forming process. There is no evidence for post-mare basins.	Nectaris (Fracastorius, etc.) Humorum (Gassendi, etc.)	
13. The basins with the best-developed concentric-ring systems appear to be the youngest. Basins which seem to be very old tend to have only traces of outer rings. These older basins must have formed in the early stages of the crater-forming process, as they are heavily damaged by later craters.	Imbrium (young) Orientale (younger than next) SE Limb Basin (old) Basin near Schiller (old) Janssen (old)	

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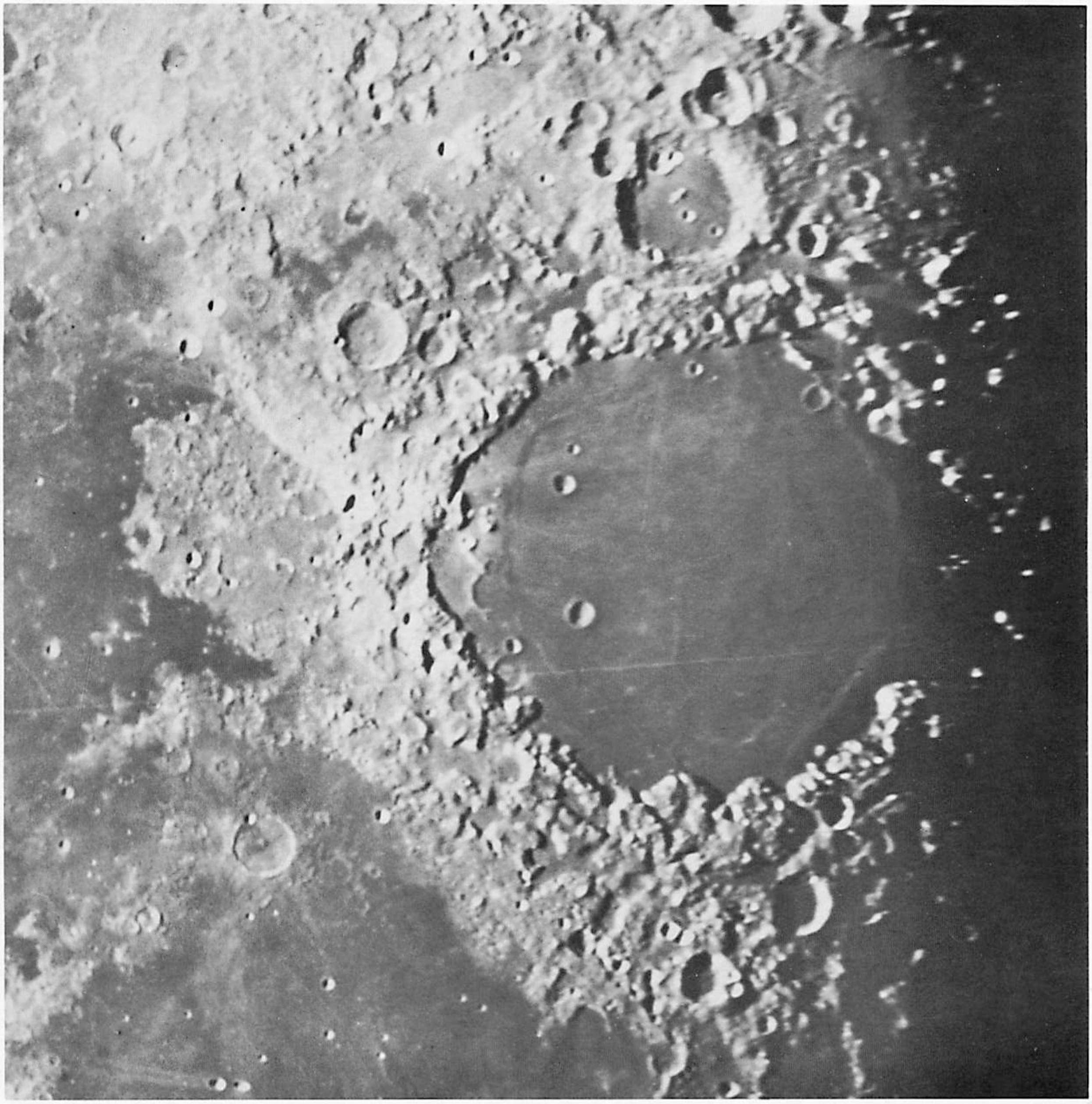


Plate 12.1. Mare Crisium, rectified photograph. The white east-west line is a star trail (added for selenodetic purposes). North up in all plates, unless otherwise indicated. Y369.

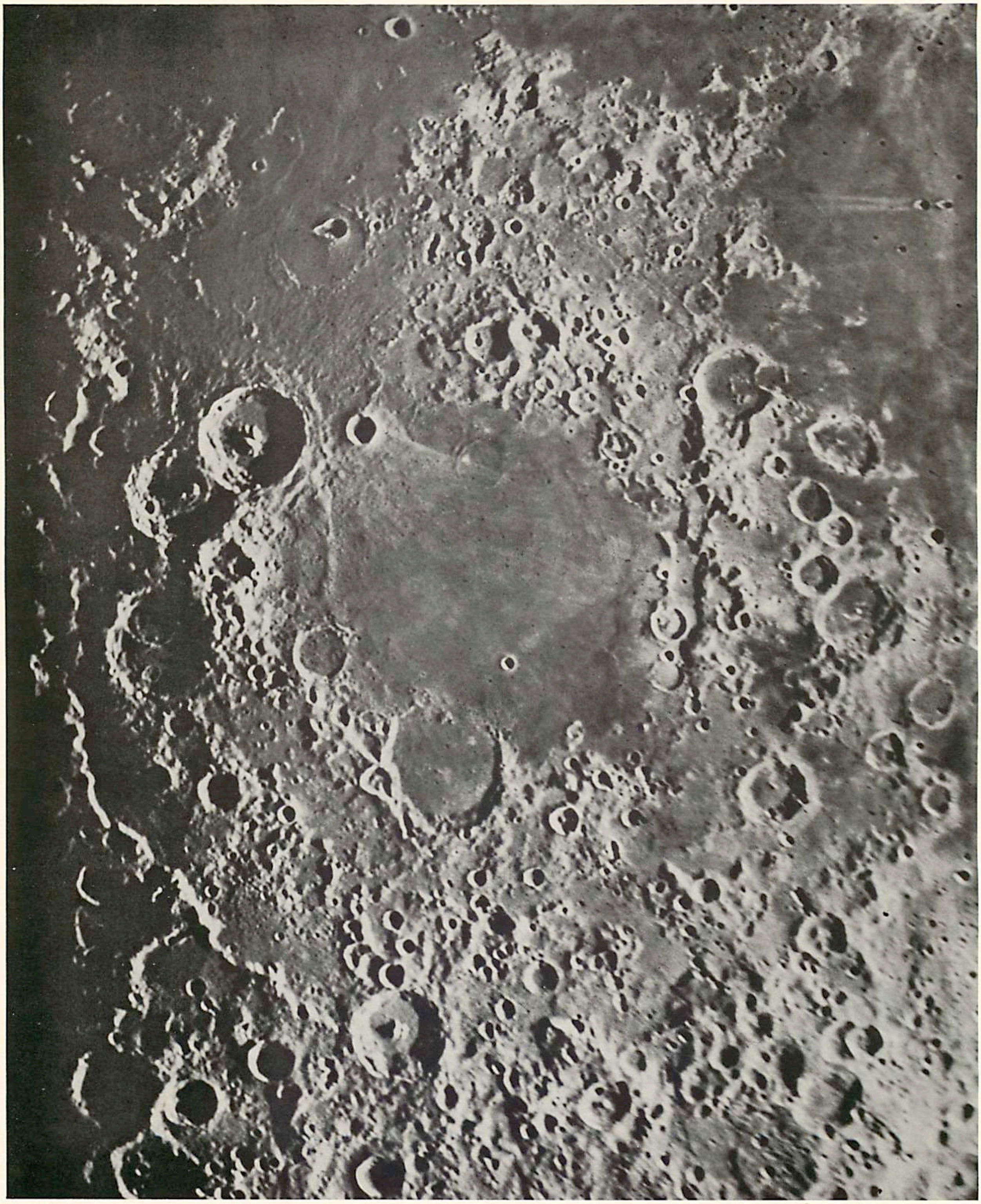


Plate 12.2. Mare Nectaris, sunrise, rectified, Y65.

Plate 12.3. Mare Nectaris, sunset, rectified, Y1200.

Plate 12.4. Mare Nectaris, as Plate 12.2, with three concentric circles outlining walls and scarps, and nomenclature: 1, Theophilus; 2, Cyrillus; 3, Catharina; 4, Kant; 5, Beaumont; 6, Fracastorius; 7, Zagut; 8, Rabbi Levi; 9, Lindenau; 10, Rothmann; 11, Stiborius; 12, Piccolomini; 13, Neander; 14, Weinek; 15, Reichenbach; 16, Borda; 17, Santbech; 18, Monge; 19, Cook; 20, Colombo; 21, Magelhaens; 22, Bellot; 23, Goclenius; 24, Messier; 25, Secchi; 26, Gutenberg; 27, Gaudibert; 28, Capella; 29, Isidorus; 30, Daguerre; 31, Mädler; 32, Torricelli; 33, Maskelyne; 34, Hypatia.

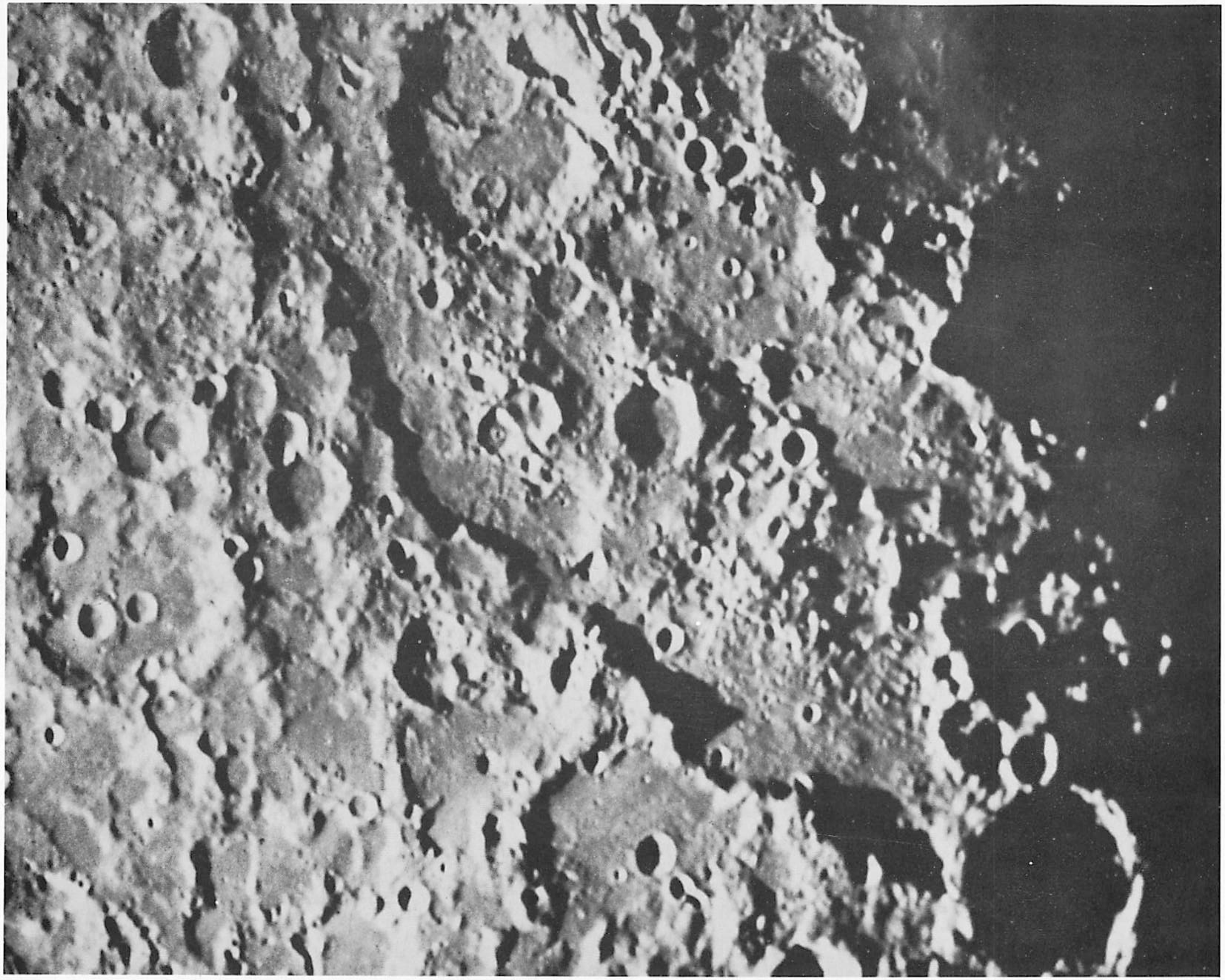


Plate 12.5. Mare Nectaris, southwest quadrant, three outer walls including Altai scarp. Rectified from W97.

Plate 12.6. Mare Nectaris, inner basin, sunset, rectified, Y1334.

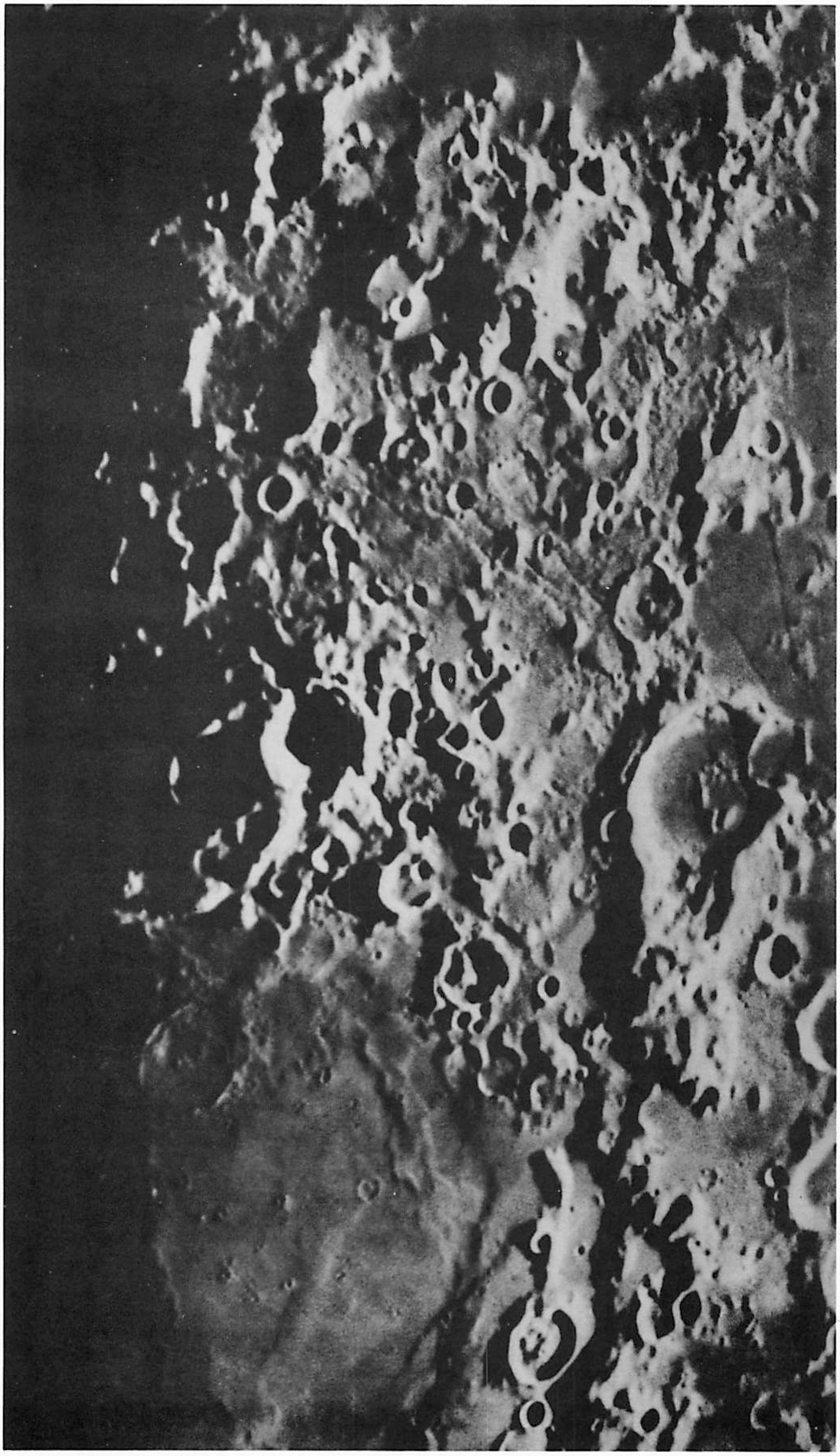


Plate 12.7. Mare Nectaris, inner basin and system of rilles to north, sunrise. Not rectified, Lick 17b.

Plate 12.8. Mare Nectaris, three outer walls, west side, sunrise, rectified, Y65.

Plate 12.9. Mare Nectaris, same region as 12.8, sunset, rectified, Y1335.

Plate 12.10. Theophilus region of Mare Nectaris, sunrise, not rectified, Lick 7.

Plate 12.11. Same region as 12.10, sunset, not rectified, W97.

Plate 12.12. Mare Humorum, sunrise, rectified, M694.

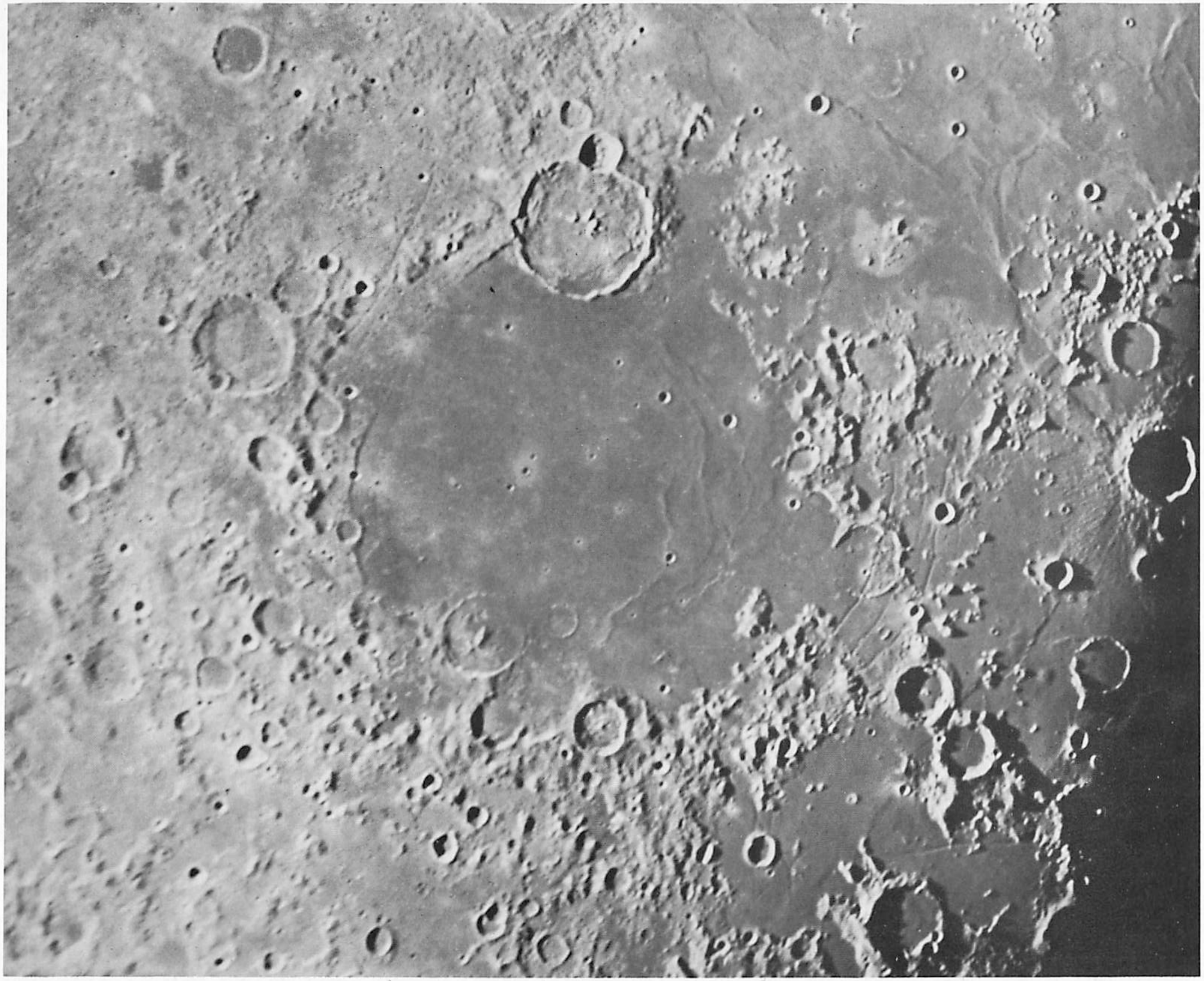


Plate 12.13. Mare Humorum, sunset, rectified, M191.

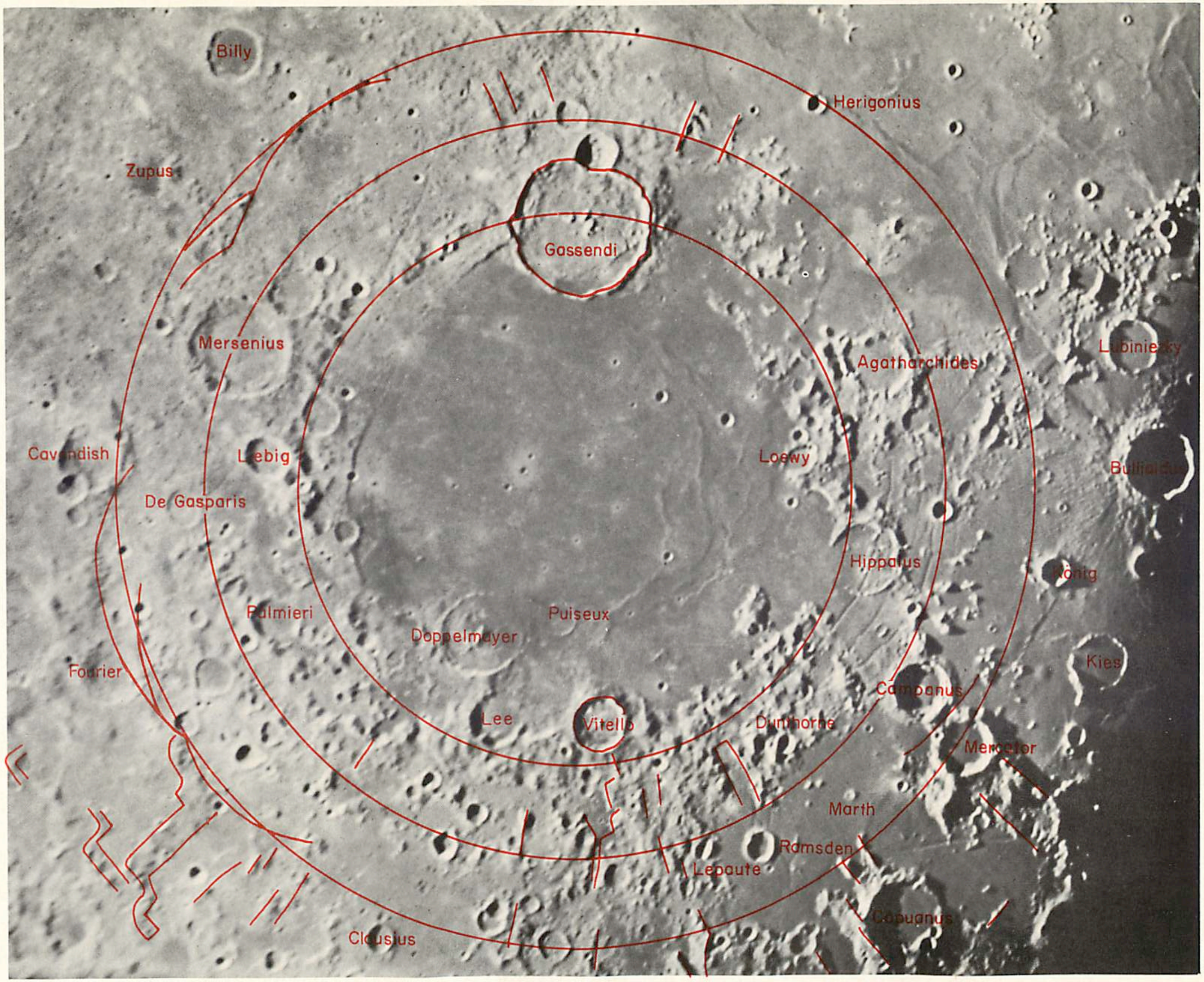


Plate 12.14. Mare Humorum, as Plate 12.13, with three concentric circles outlining walls, and some radial features.

Plate 12.15. Mare Humorum, as 12.12, showing shelf, rilles, and concentric walls at increased scale.

Plate 12.16. Mare Humorum, inner basin, with outer ring on terminator at NW, sunrise, not rectified, M630.

Plate 12.17. Mare Humorum, ridges and rilles on E. shore, not rectified, M611.

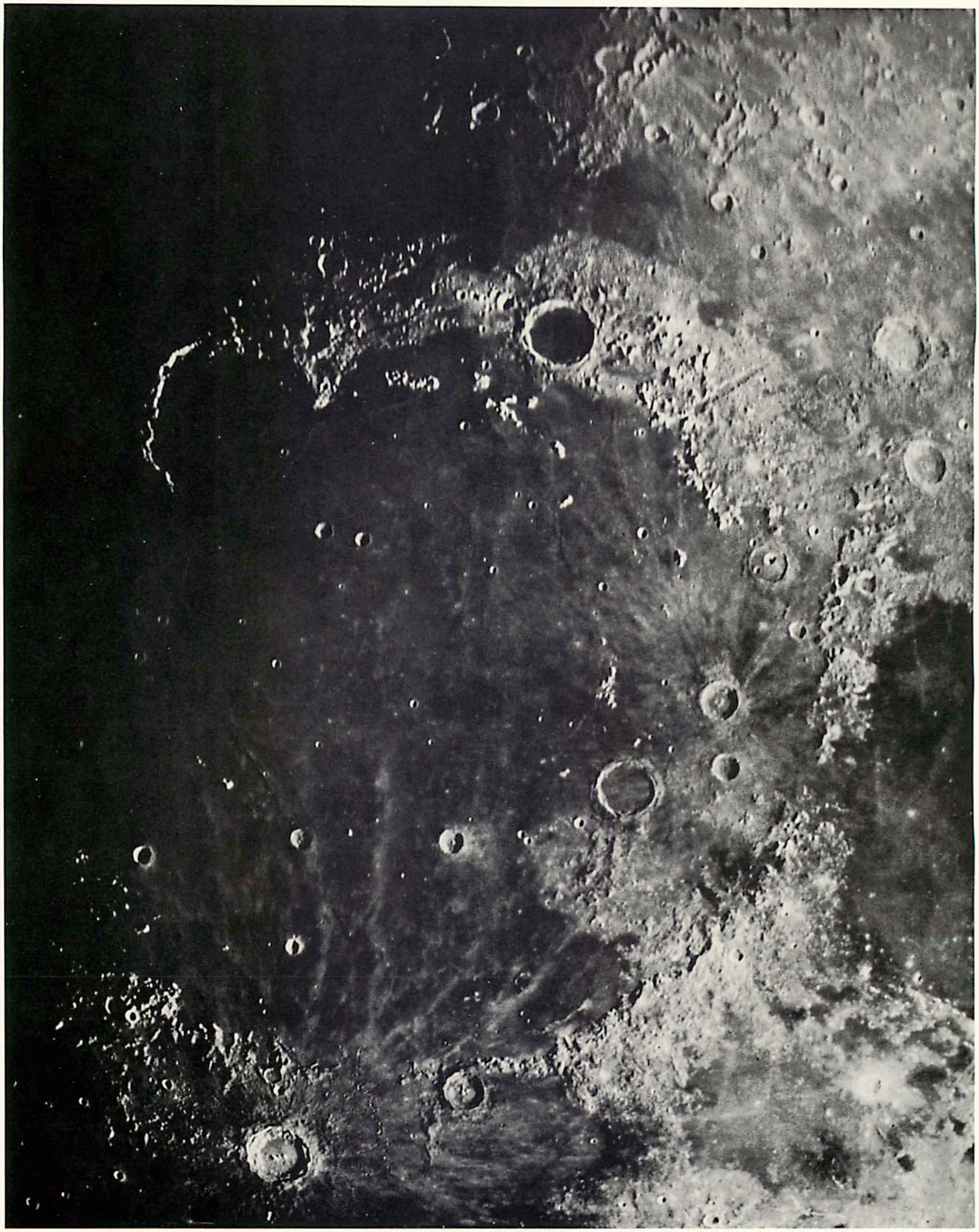


Plate 12.18. Mare Imbrium, sunrise, rectified, Y160.

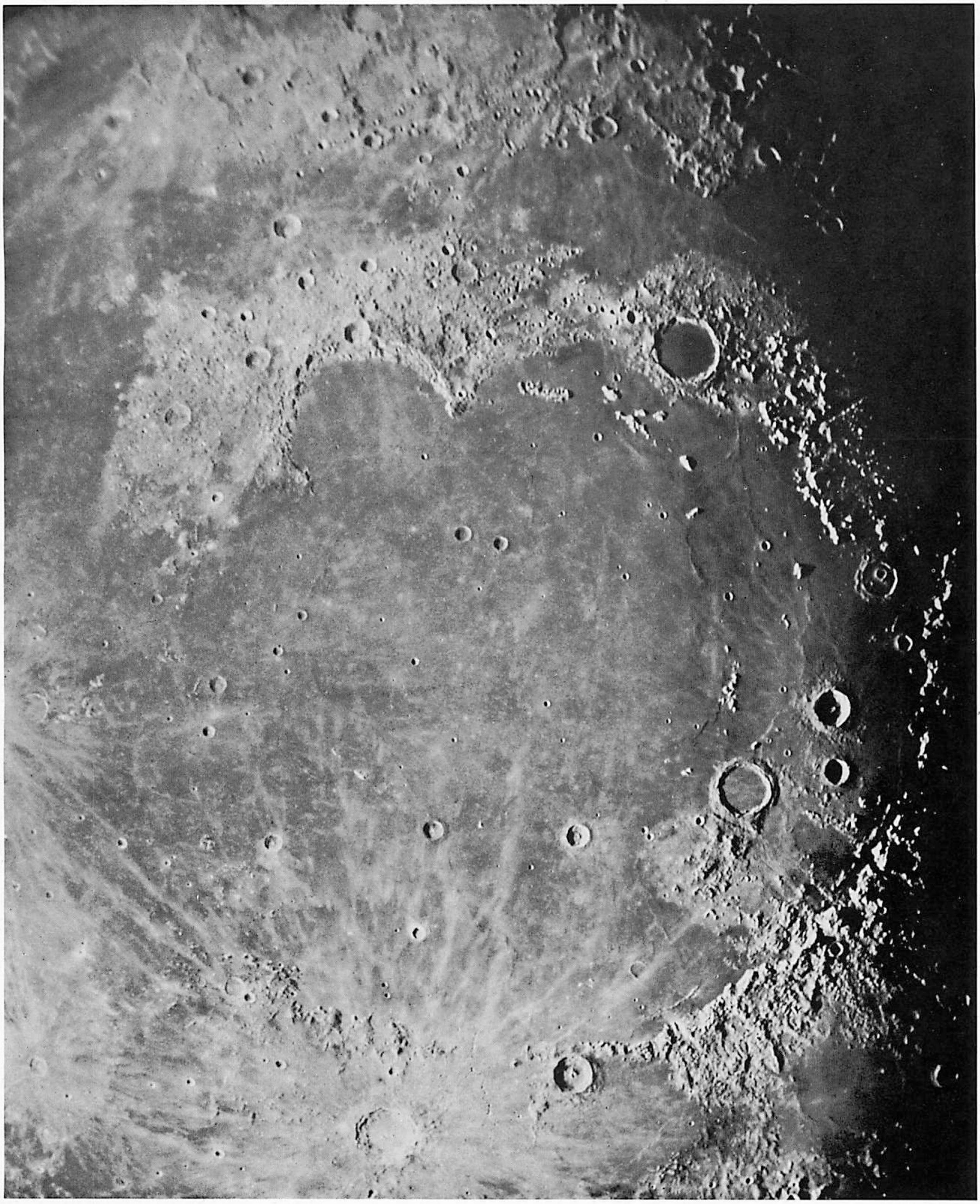


Plate 12.19. Mare Imbrium, sunset, rectified, W115.

Plate 12.20. Mare Imbrium, W. part, rectified, W252.

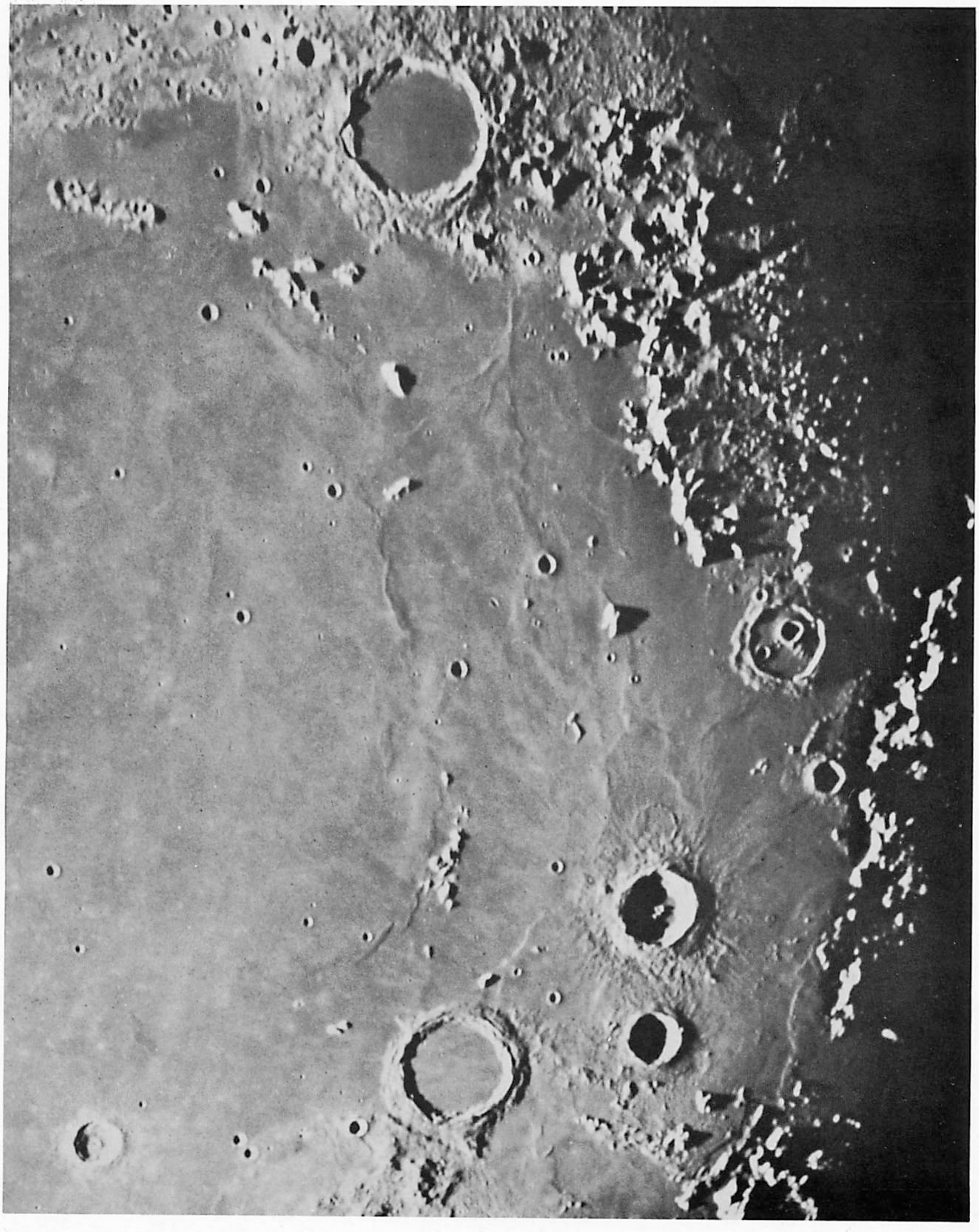


Plate 12.21. Mare Imbrium, E. part, rectified, W115.

Plate 12.22. Mare Imbrium, Inner Basin, W. half, not rectified, Y163.

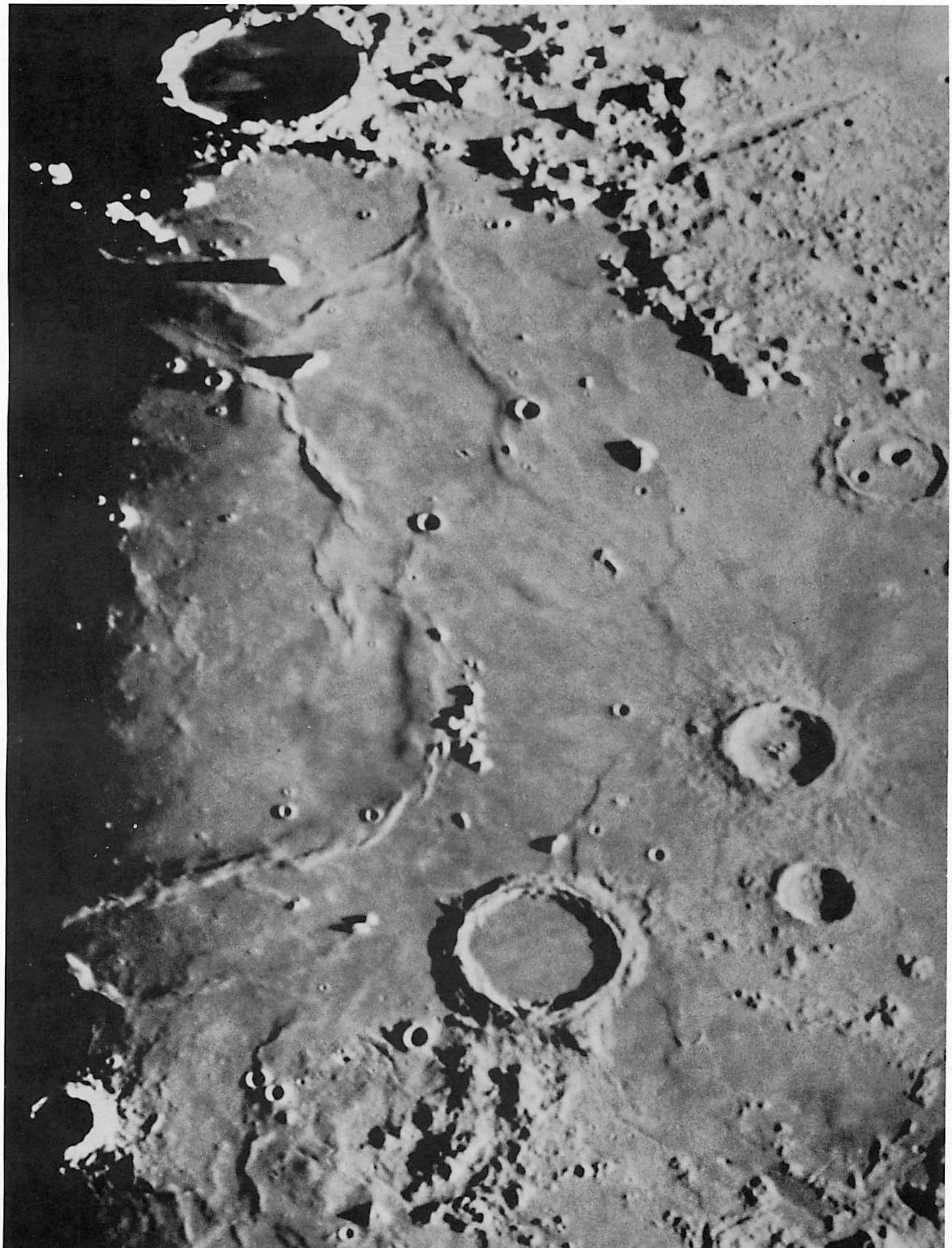


Plate 12.23. Mare Imbrium, Inner Basin, E. half, not rectified, Y1267.

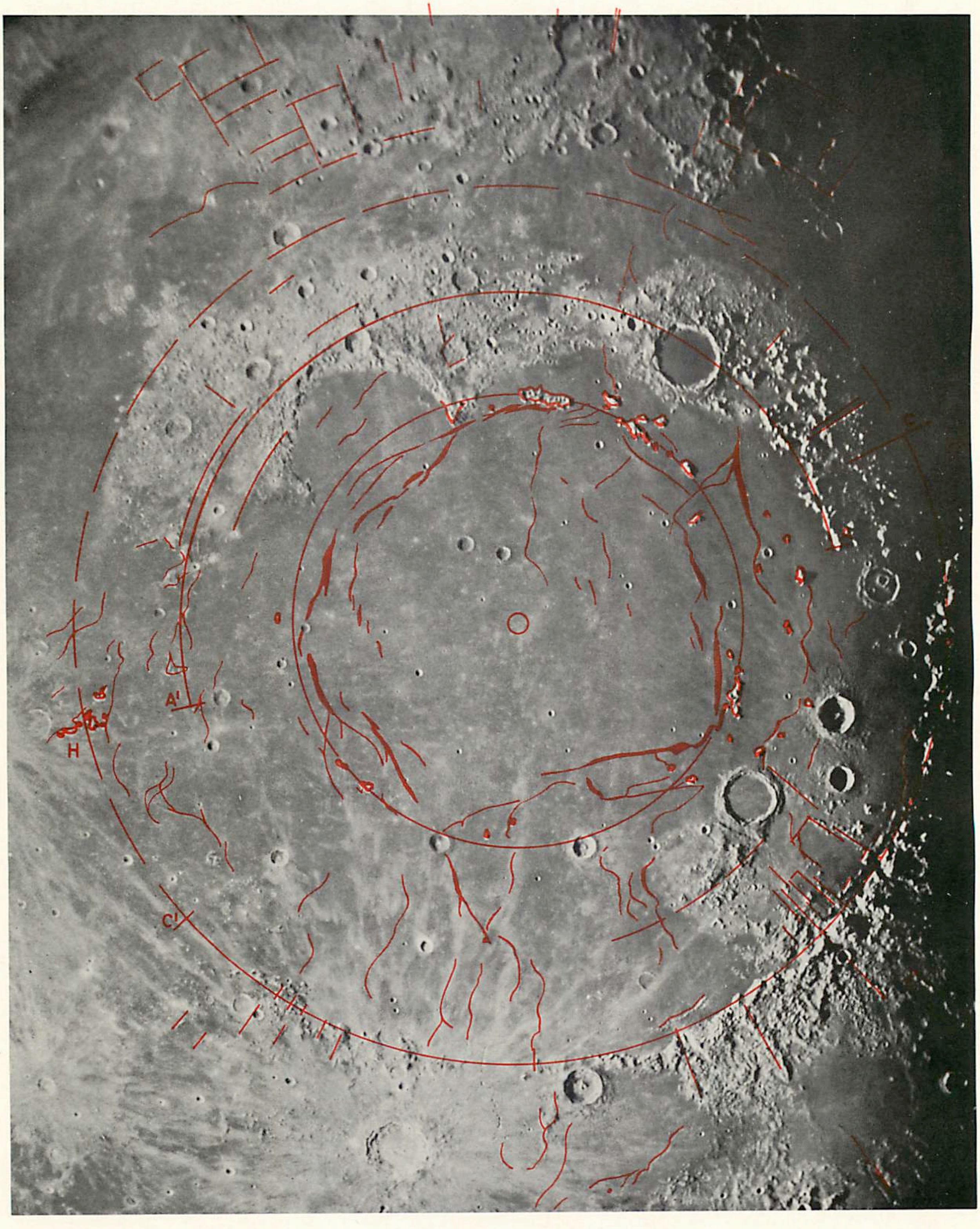


Plate 12.24. Mare Imbrium, as Plate 12.19, with overlay showing three concentric circles outlining walls, and some radial features. Ridges indicated by curving lines.

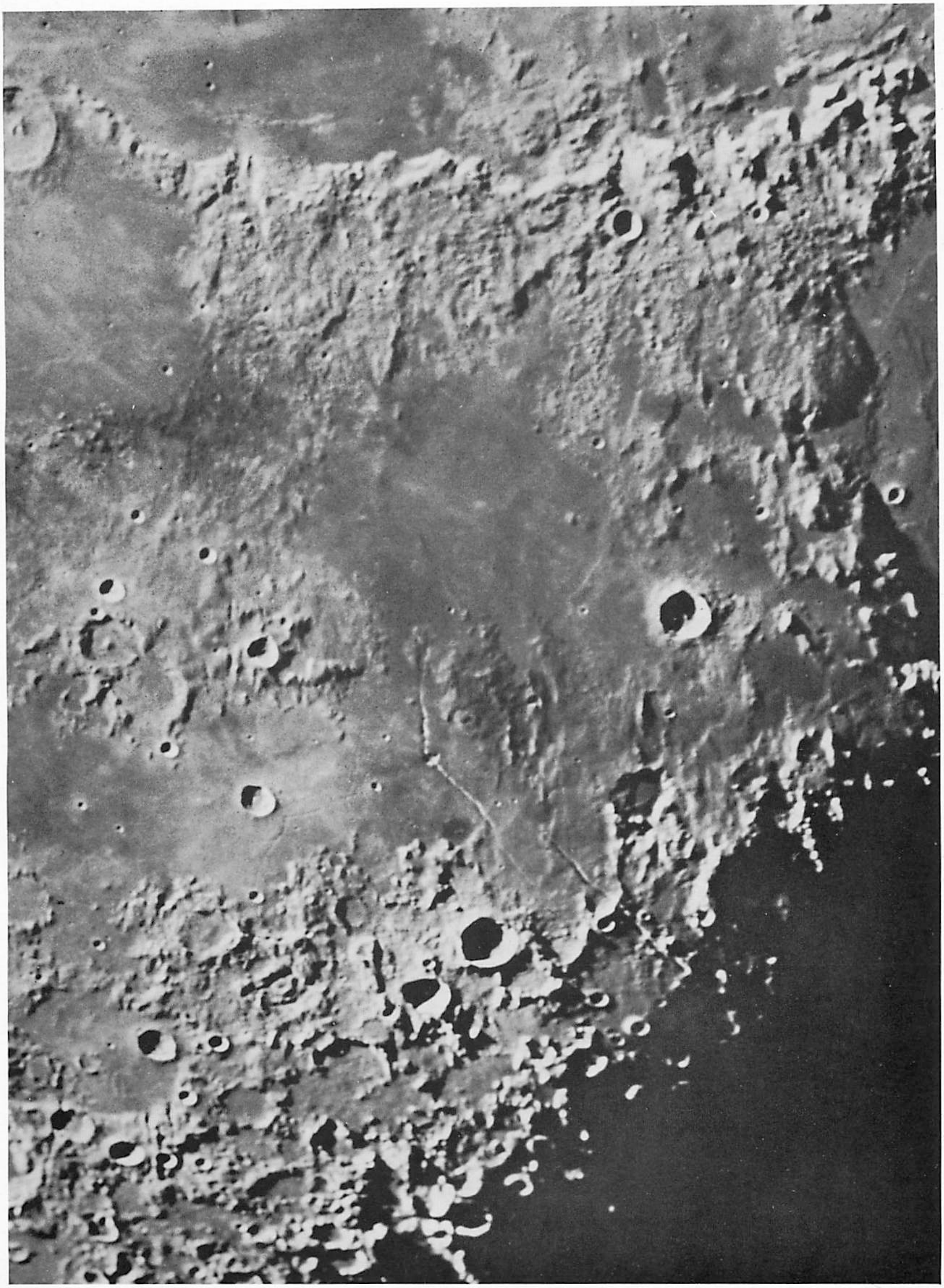


Plate 12.25. View of Apennines (top), Haemus Mts. (right), Hyginus and Hipparchus regions, seen from above southern Mare Imbrium. Fan-shaped Imbrium pattern best seen by turning south up, Y1350.

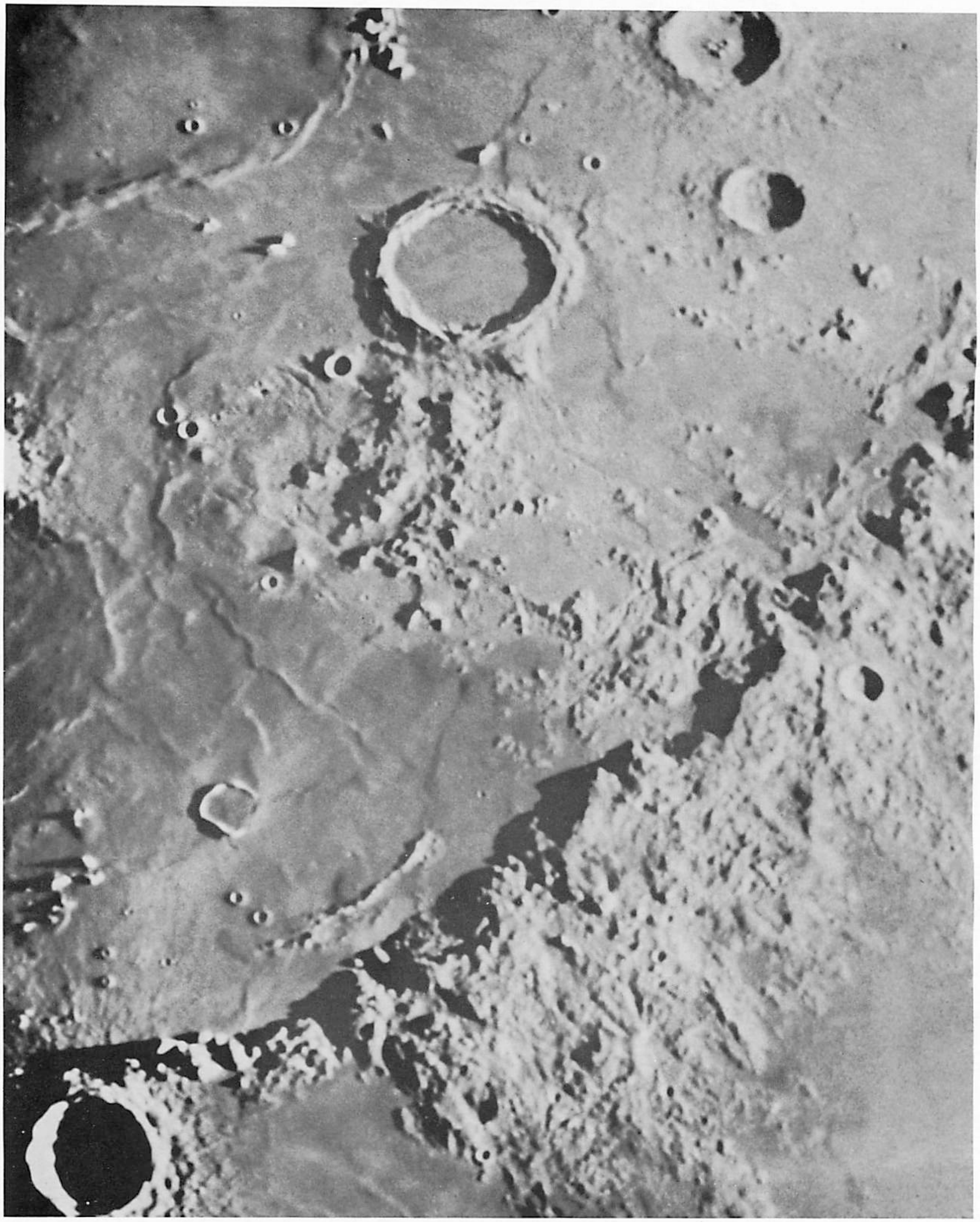


Plate 12.26. Apennines and Archimedes Island, after sunrise, showing ridge pattern, rilles, both in front of and behind the main fault scarp, and much related detail. Note orthogonal pattern in Archimedes Island. Not rectified, Y1269.

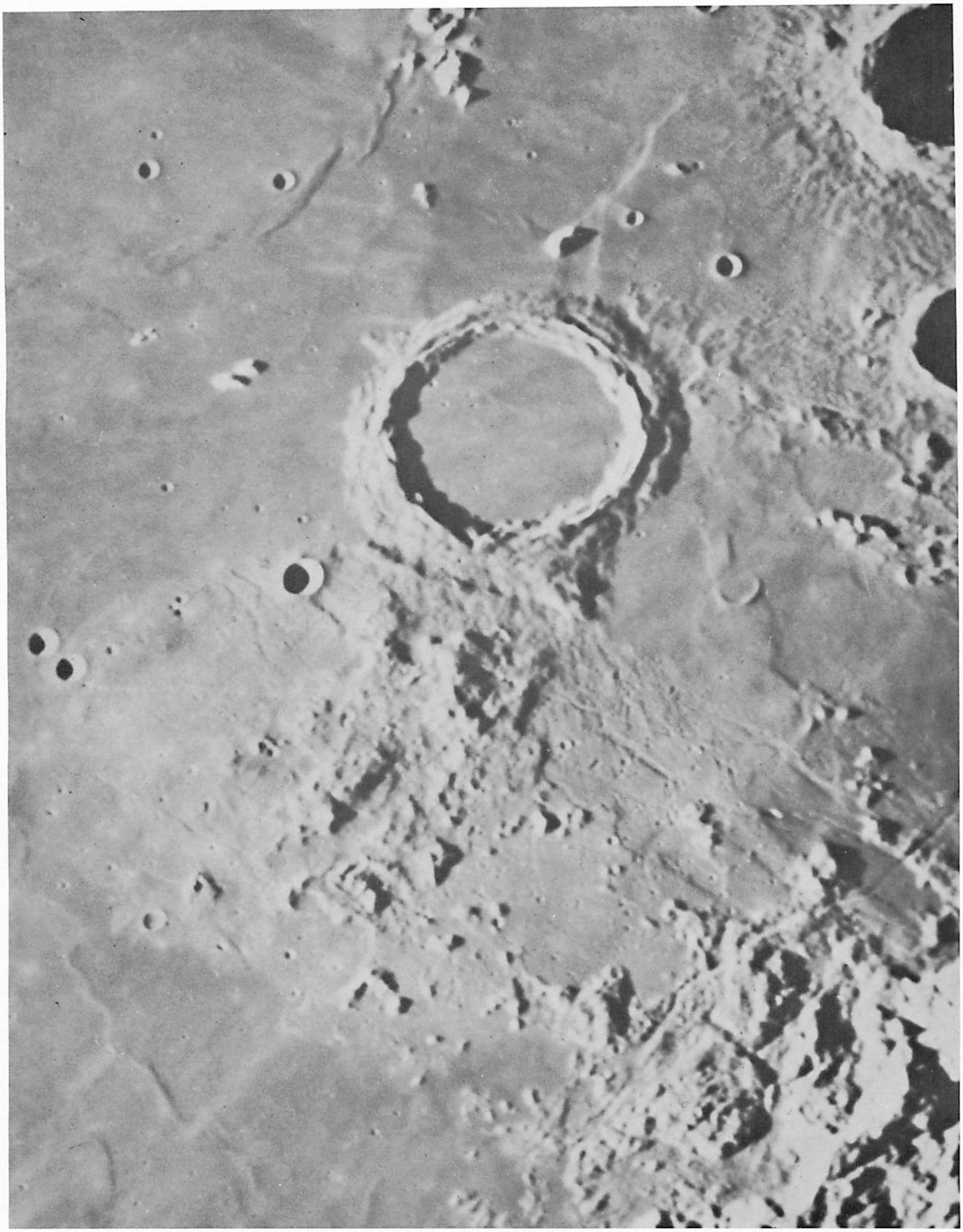


Plate 12.27. Apennines and Archimedes Island, before sunset, showing rilles and graben. Not rectified, W121.

Plate 12.28. View of the full moon as seen from above the Imbrium basin (15°W, 37°N), Y577.

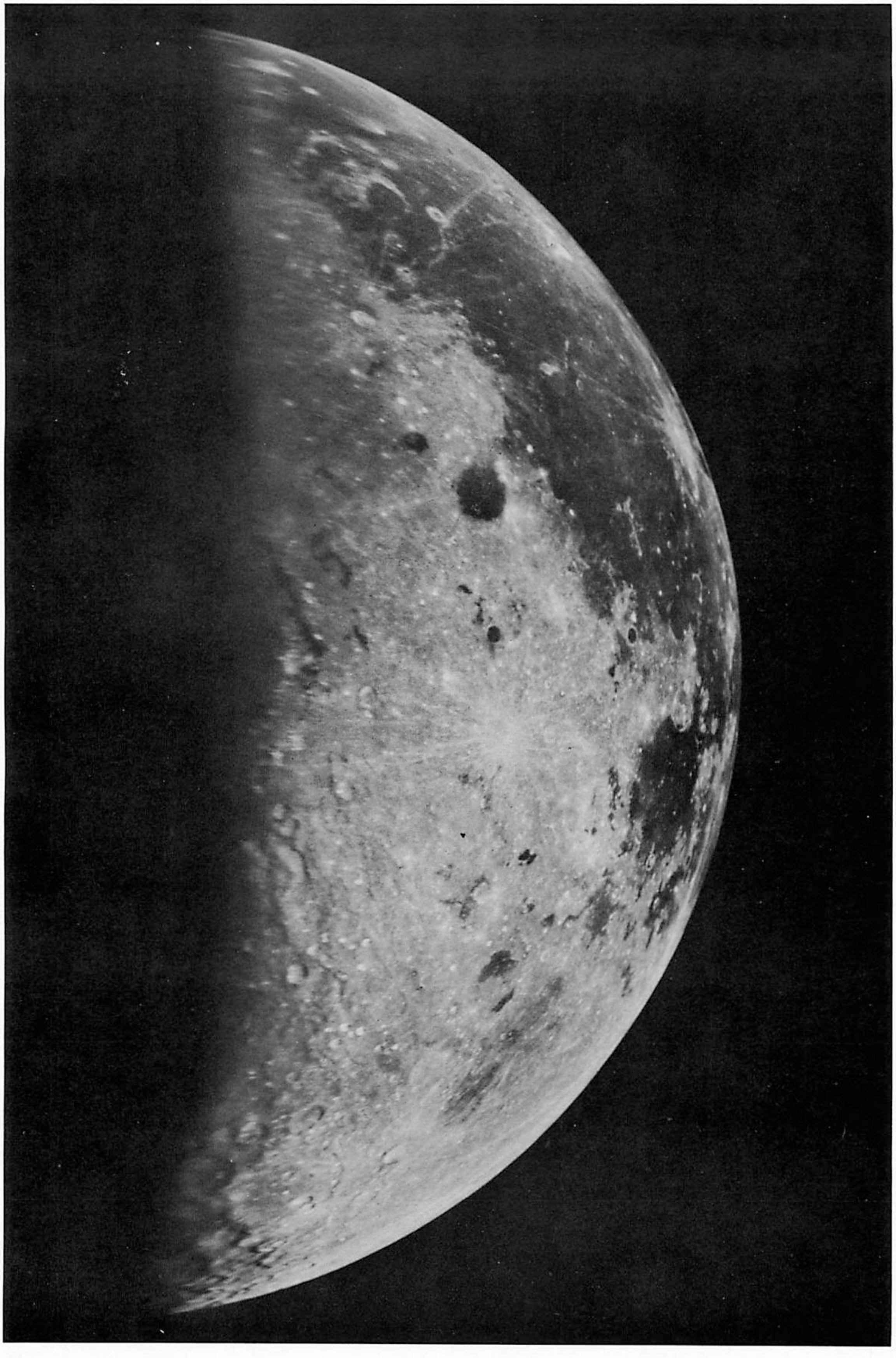


Plate 12.29. East limb of lunar disk, centered on Mare Orientale. Round dark patch is Grimaldi. Prominent ray crater is Byrgius. Kepler and Aristarchus on limb. Curved star trail crossing Kepler for astrometric purposes. Y1614.

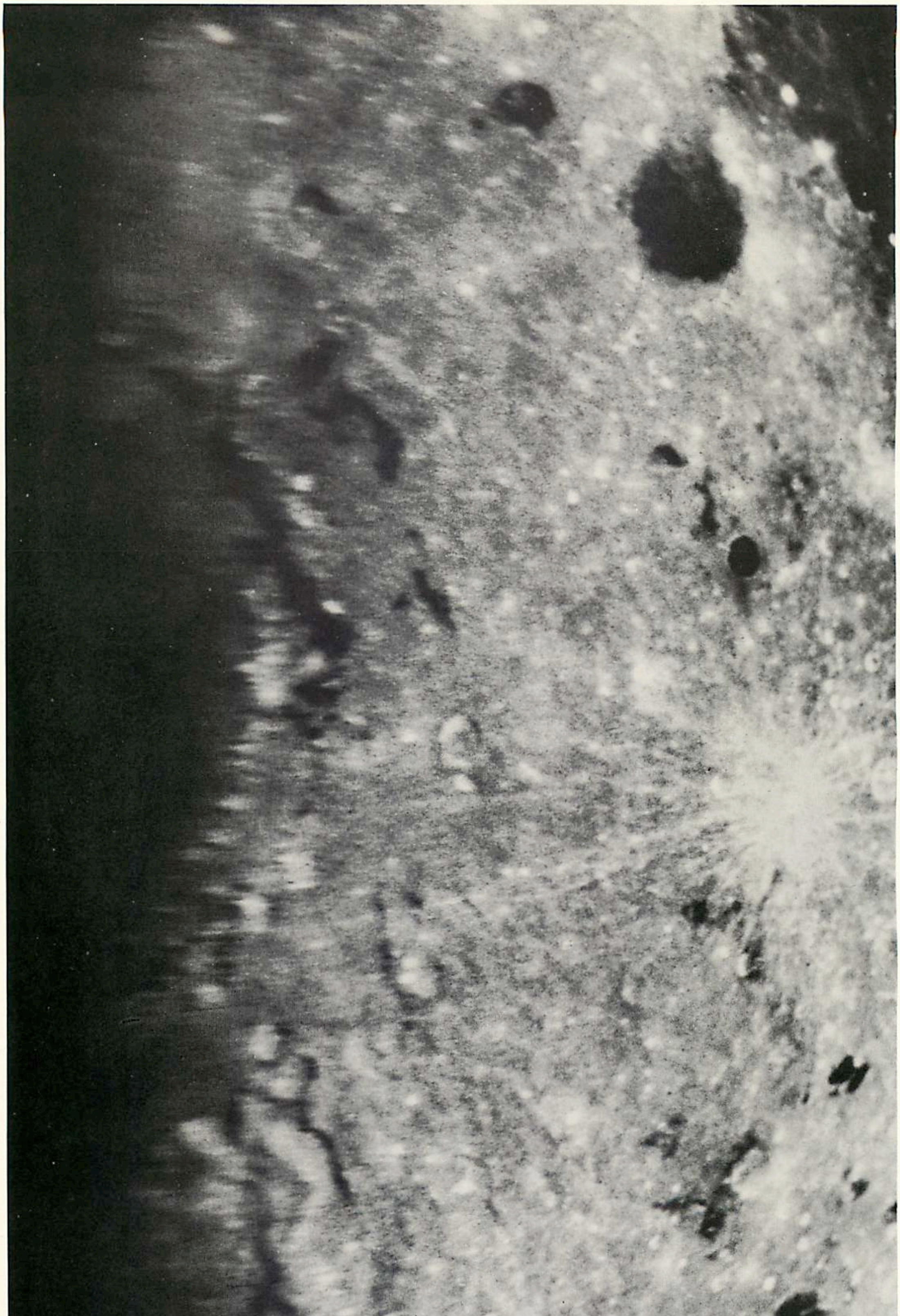


Plate 12.30. Mare Orientale system, rectified, Y1614.

Plate 12.31. Mare Orientale scarp system, rectified, M74.

Plate 12.32. Mare Orientale scarp system, rectified, M372.

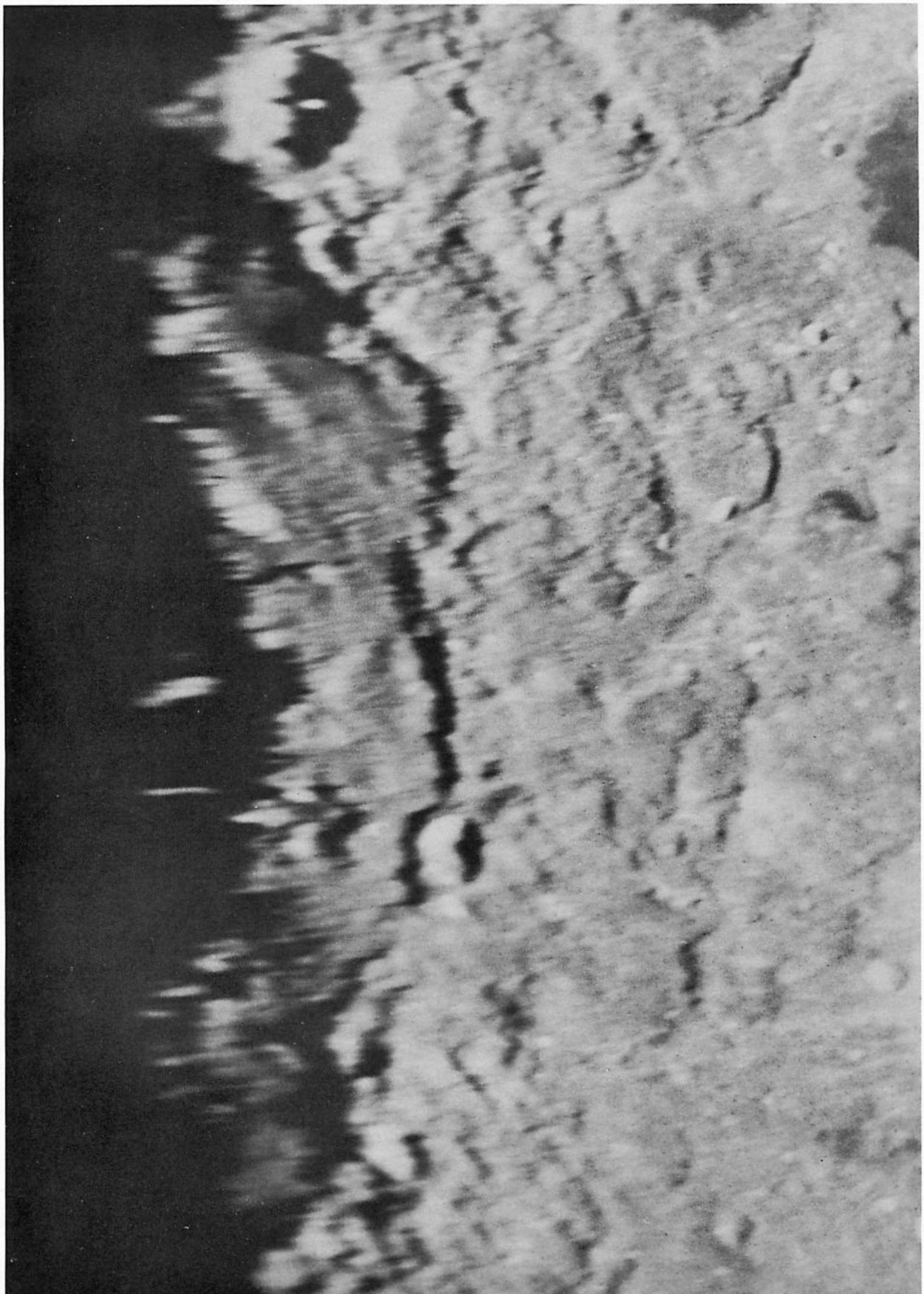


Plate 12.33. Mare Orientale system, region between scarps, rectified, M372.

Plate 12.34. Mare Orientale scarp system, rectified, Y108.

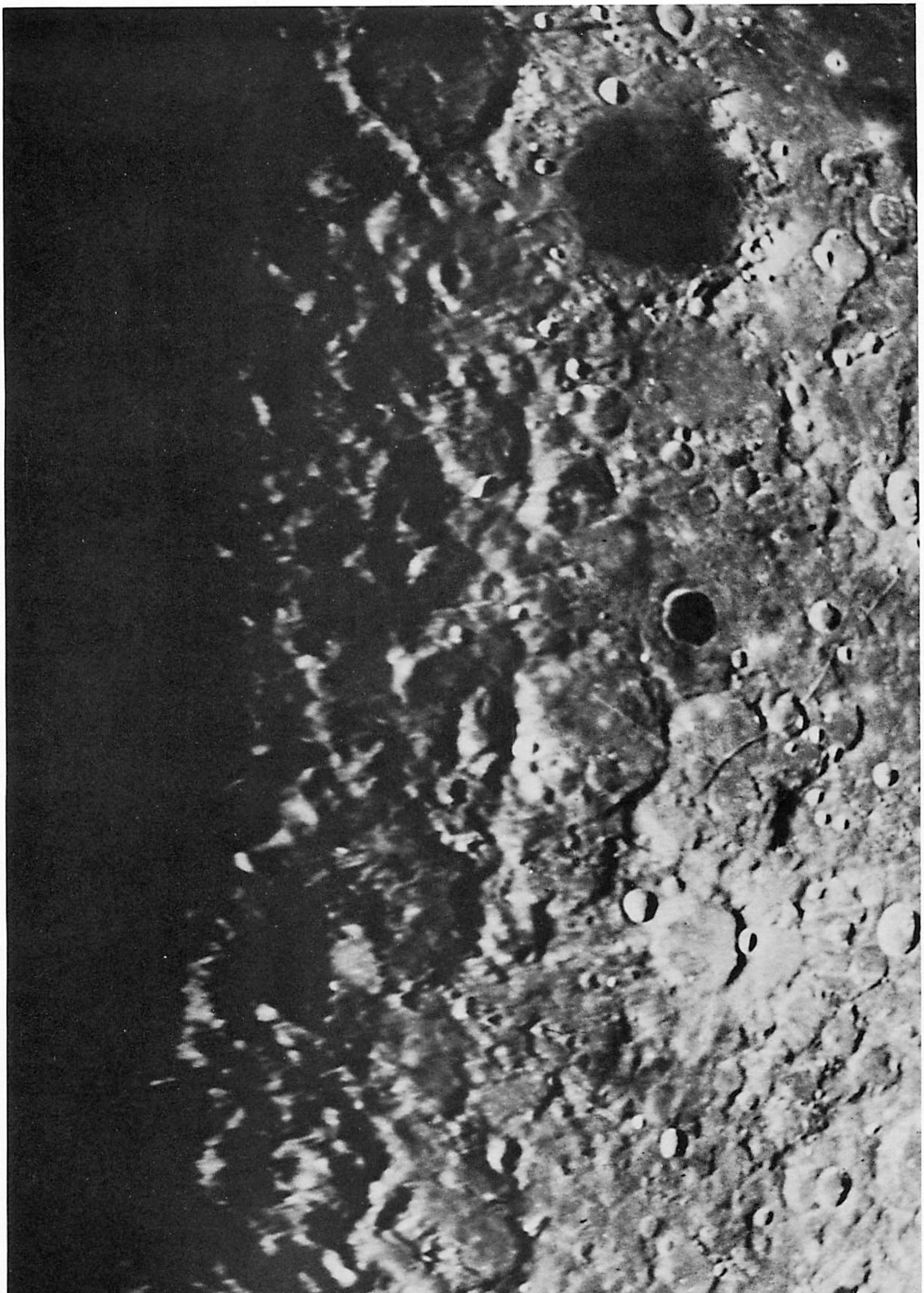


Plate 12.35. Mare Orientale system, region near Sirsalis Rille, Y108.

(*a*) (*b*)

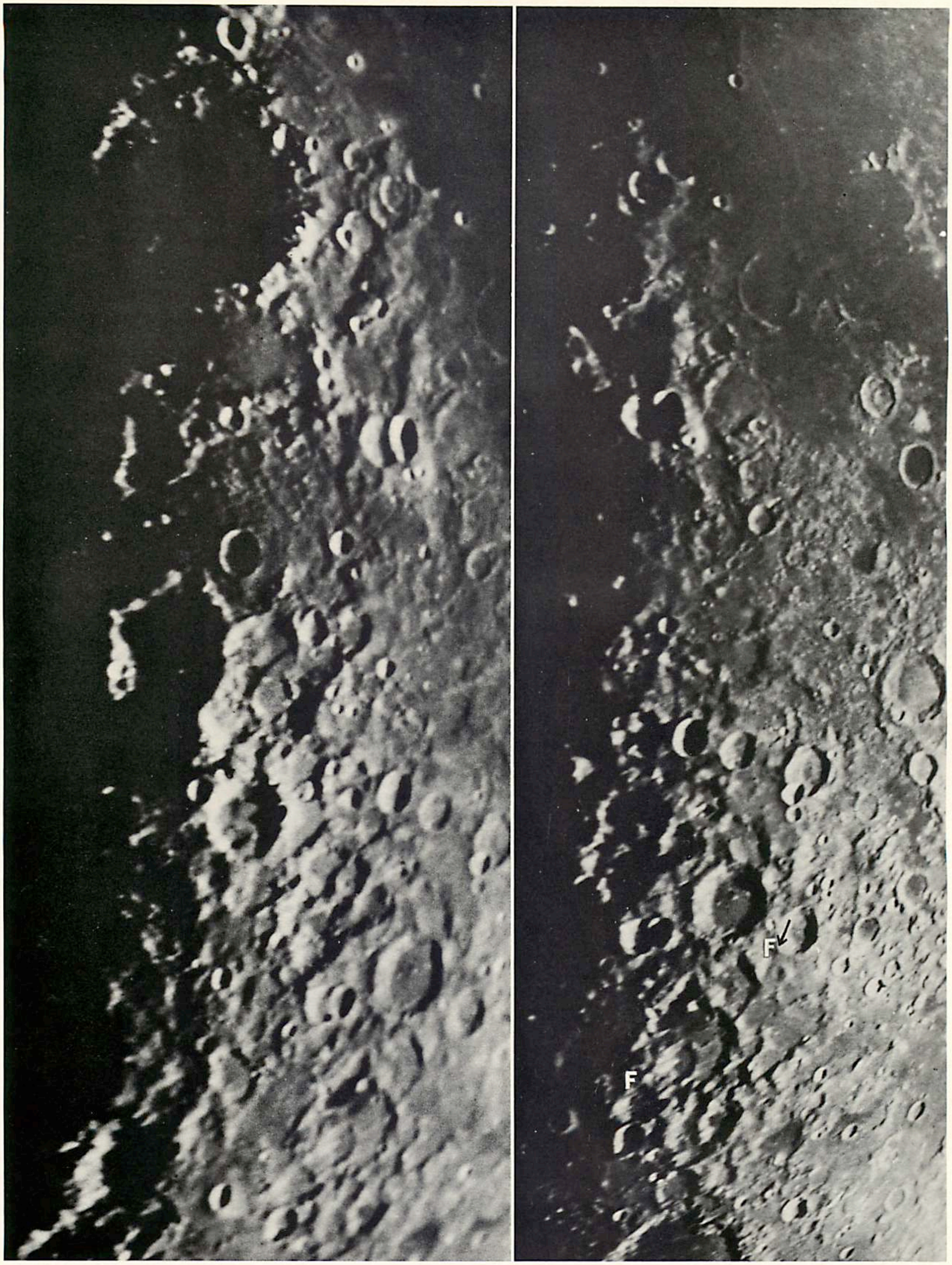
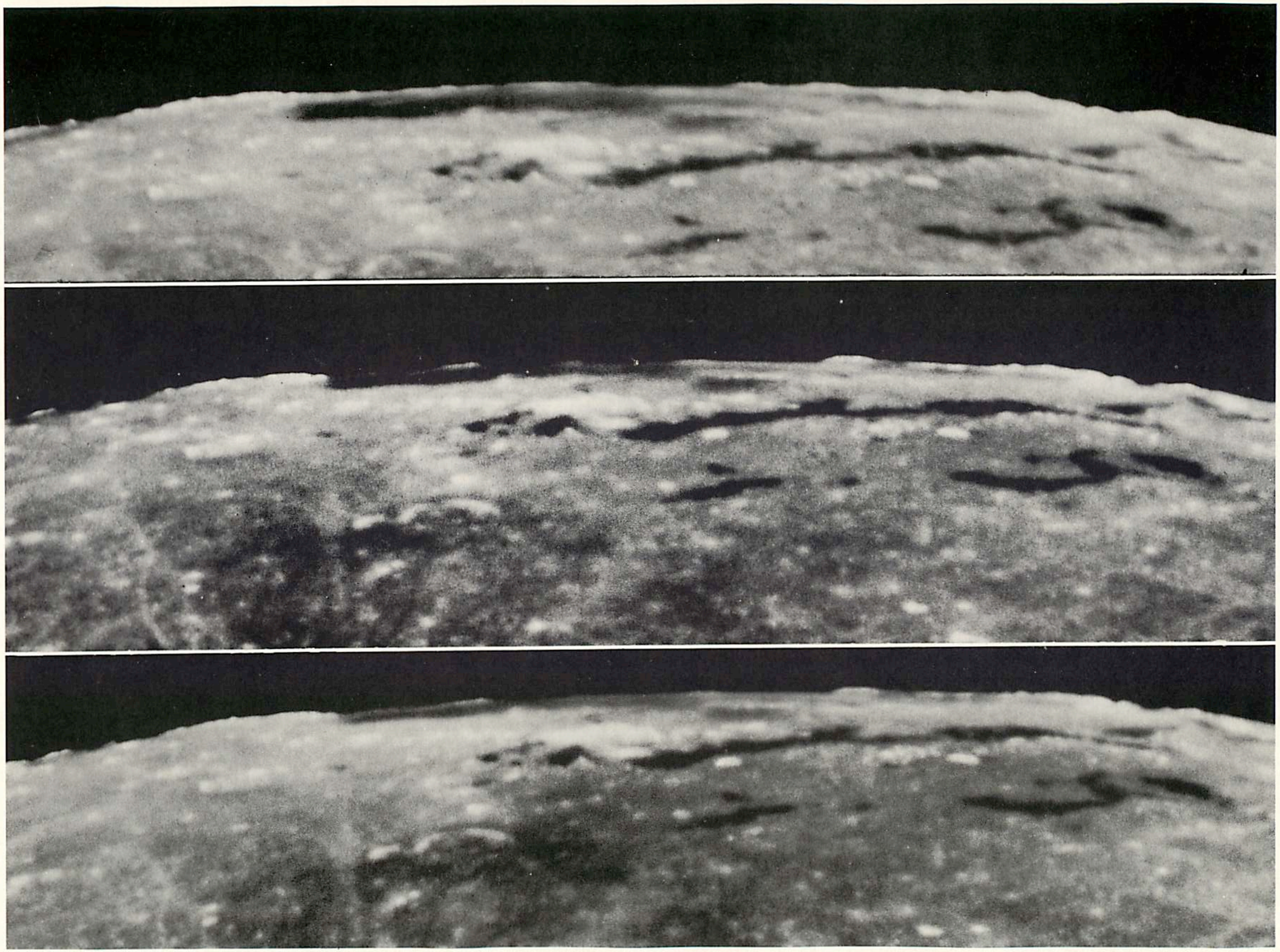


Plate 12.36. Region from Mersenius and Billy (right margin) to Crüger, Darwin, and Byrgius (left margin); rectified. Two concentric Grimaldi Rings in (*a*), top. FF in (*b*) marks fault. (*a*), Y1502, and (*b*), Y468.

Plate 12.37. Mare Orientale system, not rectified, M121.



(*a*)

(*b*)

(*c*)

Plate 12.38. Mare Orientale system, after full moon, (*a*) M831, (*b*) Y1589, (*c*) Y1578.

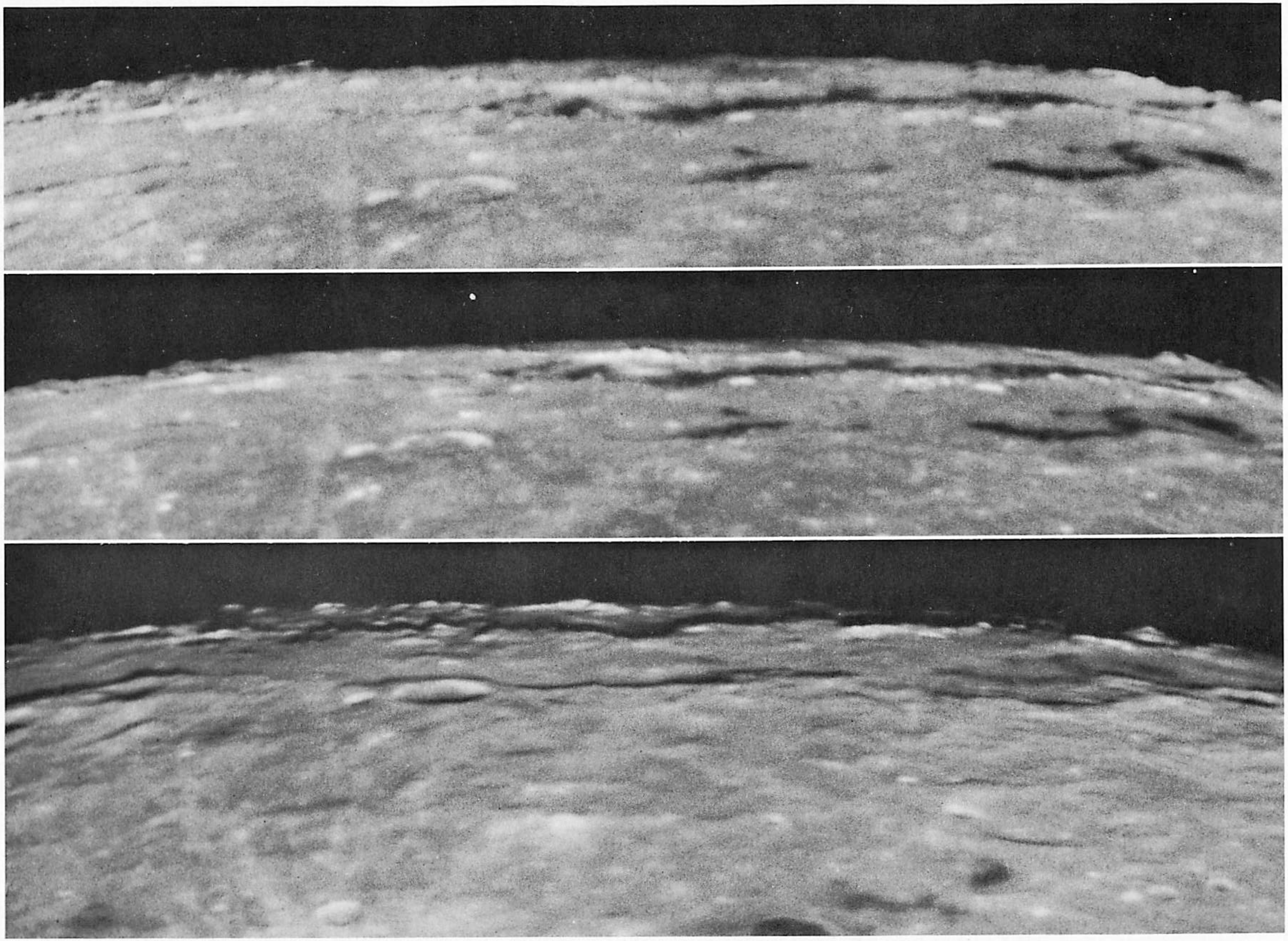


Plate 12.39. Mare Orientale system, just before full moon, (*a*) Y1614, (*b*) Y836, (*c*) M74.

Plate 12.40. Mare Orientale at full moon, rectified, Y1592.

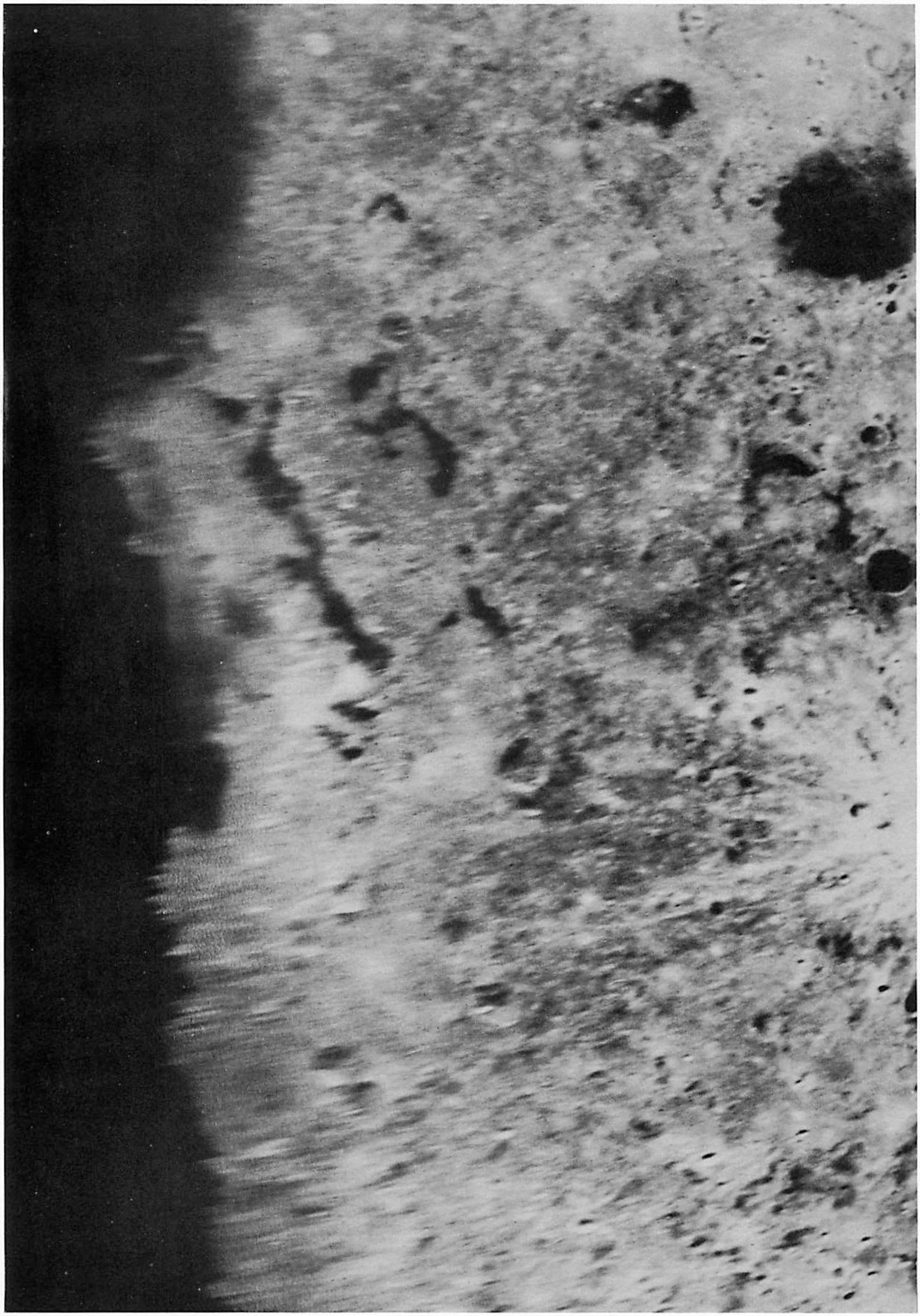


Plate 12.41. Mare Orientale system, last quarter, rectified, W172.

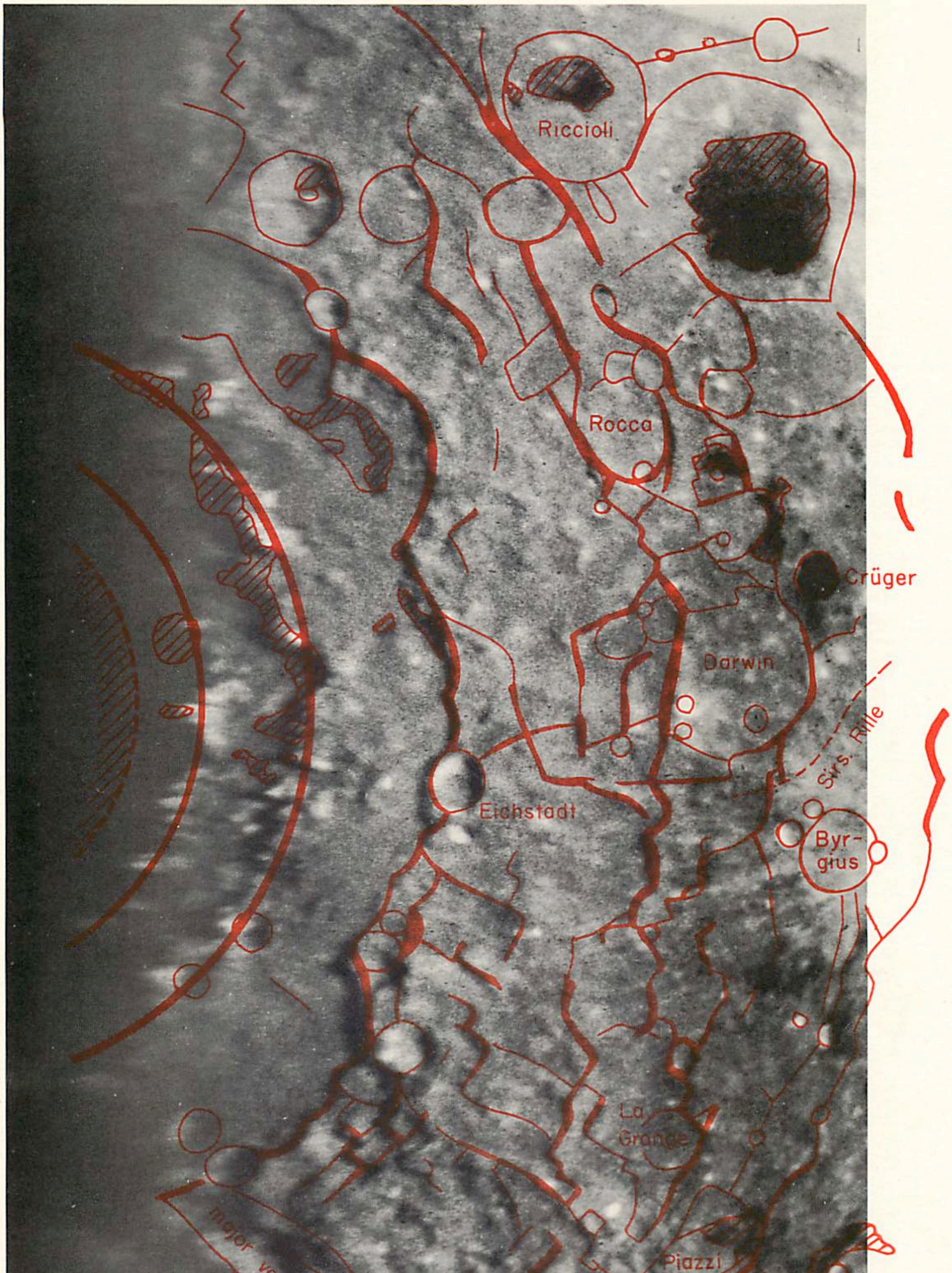
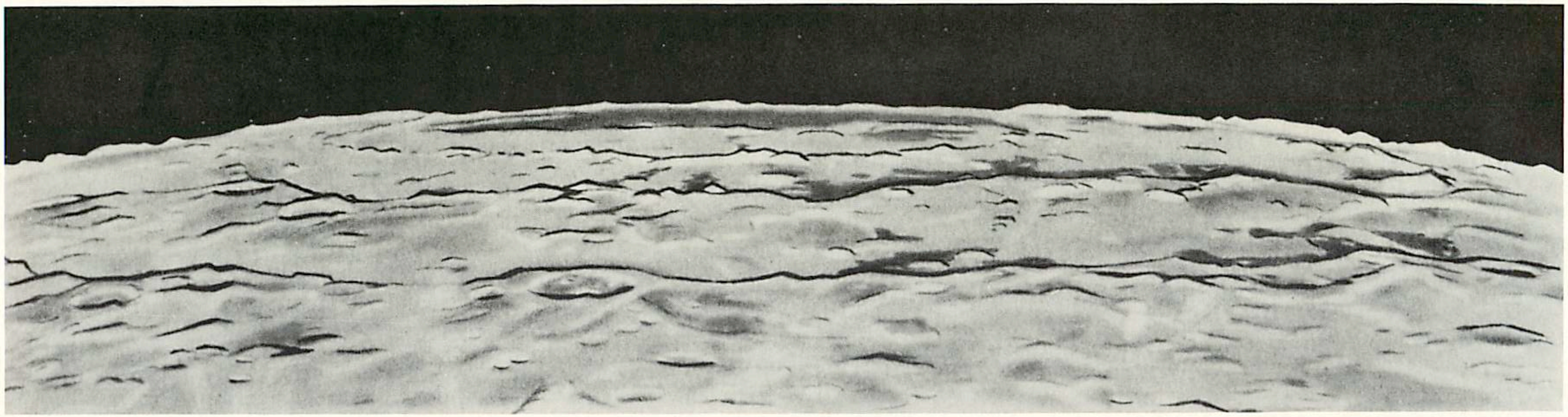


Plate 12.42. As Plate 12.31, with nomenclature and structural lines observed stereoscopically by Mr. Kuiper. Heavy lines are major scarps.

(*a*)



(*b*)

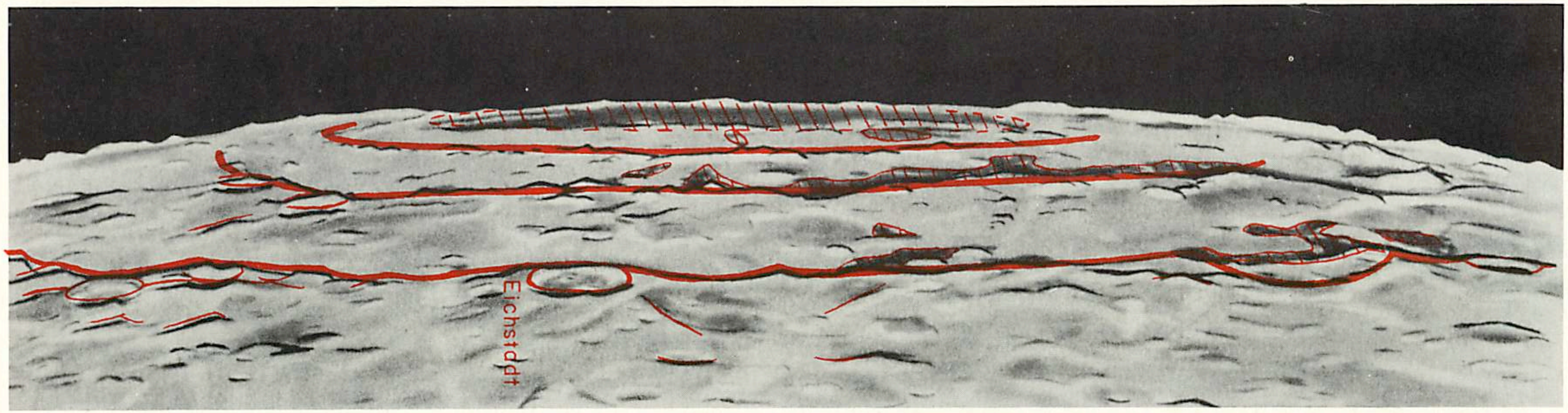


Plate 12.43. (*a*) Mare Orientale system, not rectified, synthesis by Mr. Hartmann. (*b*) As (*a*) with overlay corresponding to 12.42.

Plate 12.44. Southeast limb of lunar disk, centered on SE Basin, Y1614.

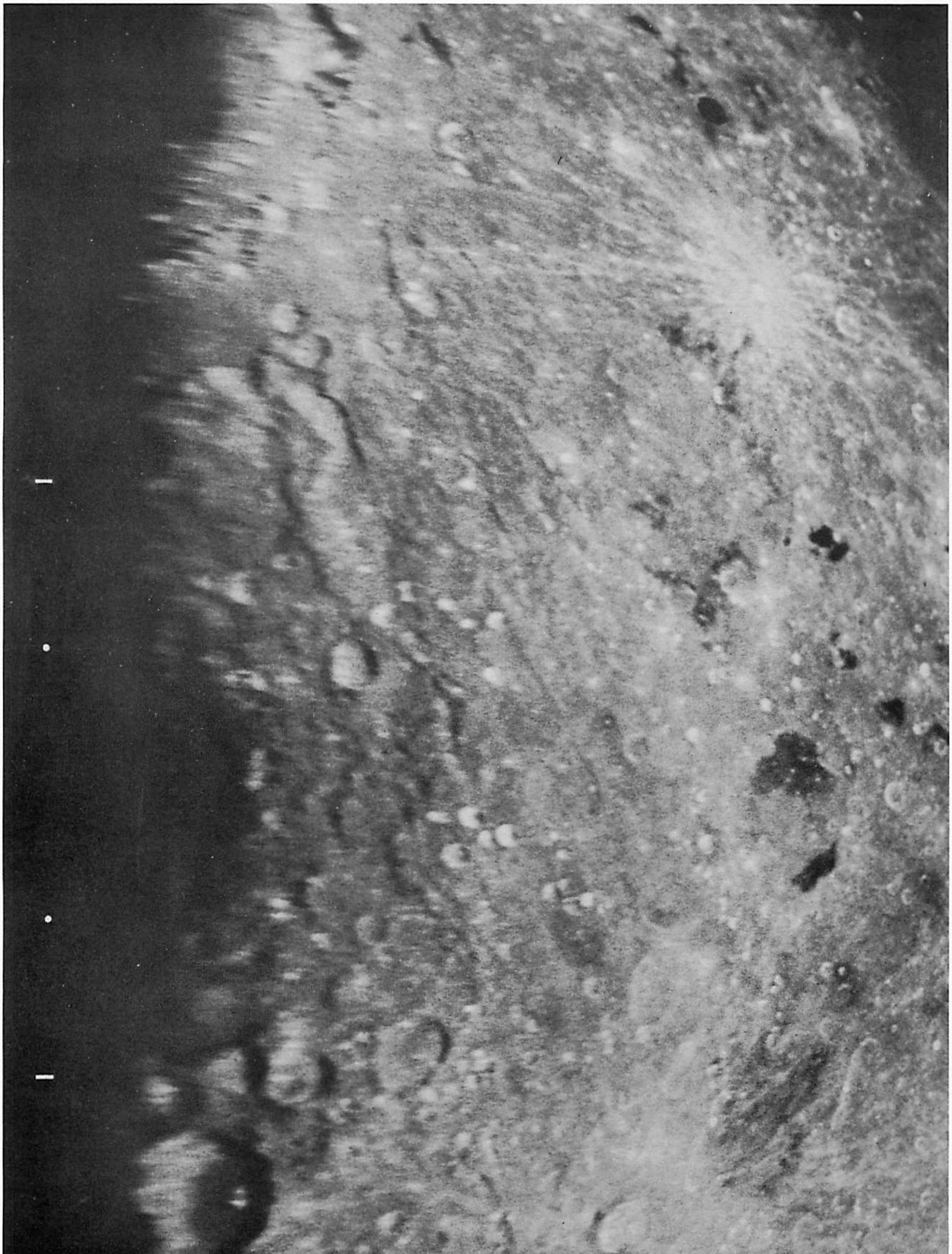
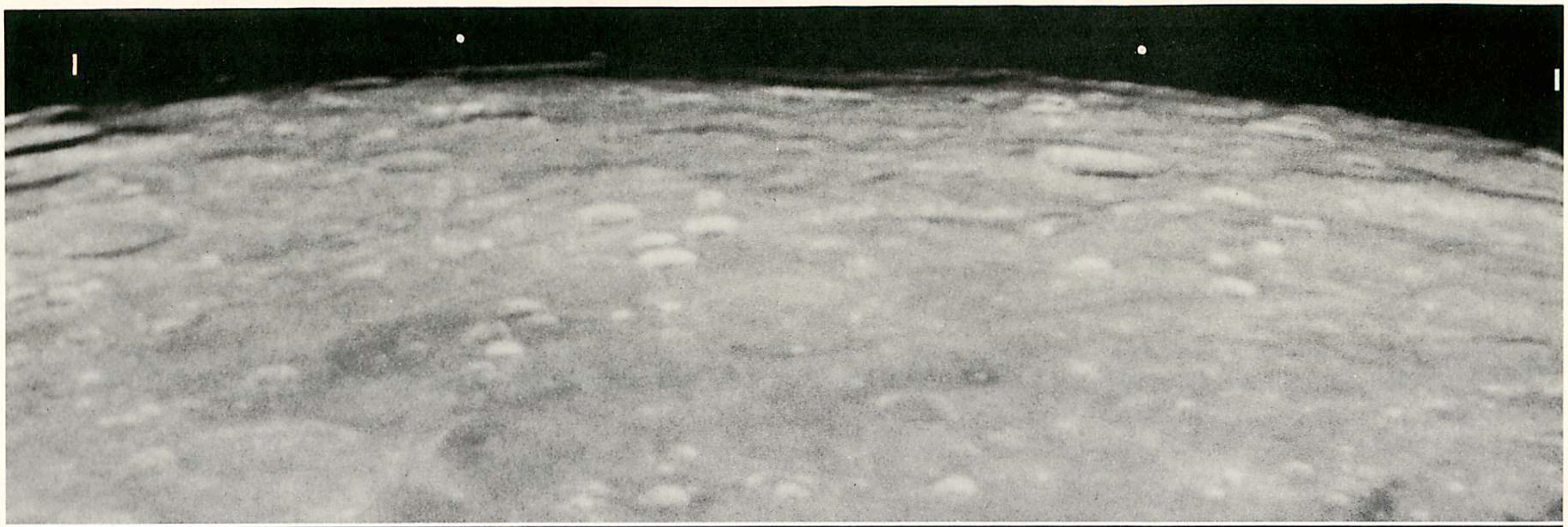
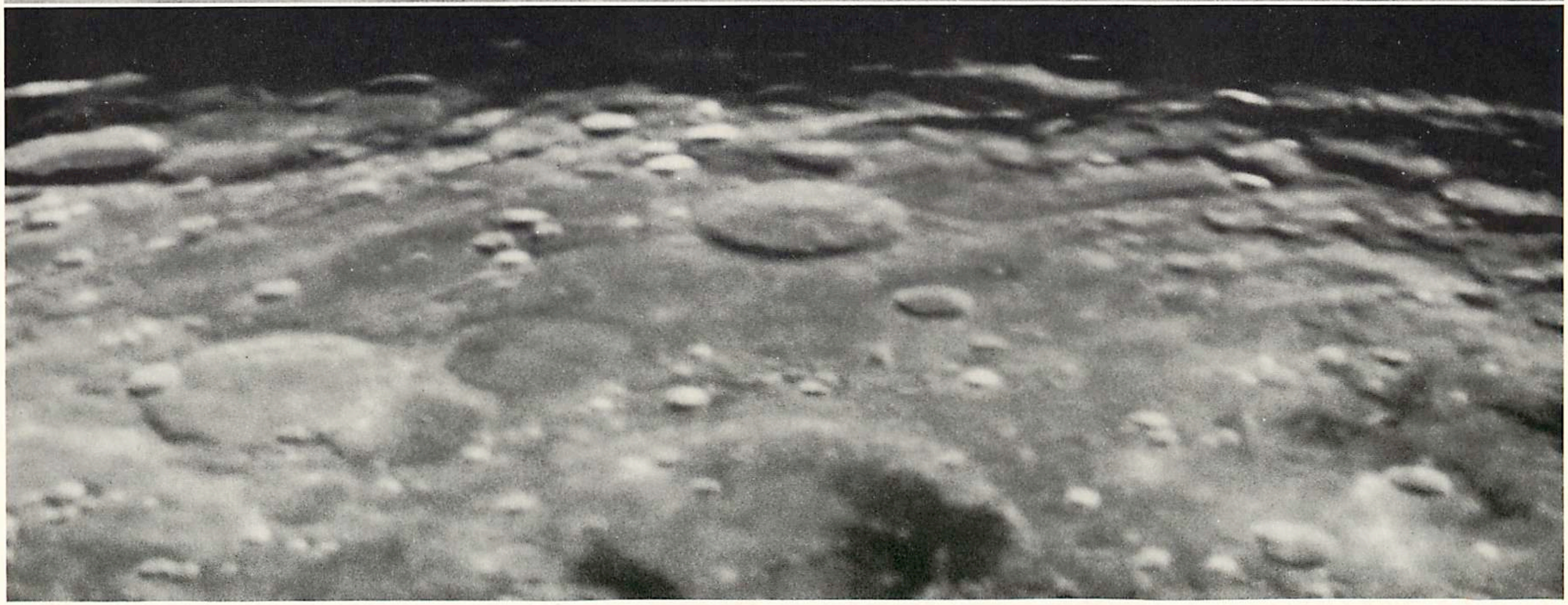


Plate 12.45. Southeast Basin, rectified, Y1614.

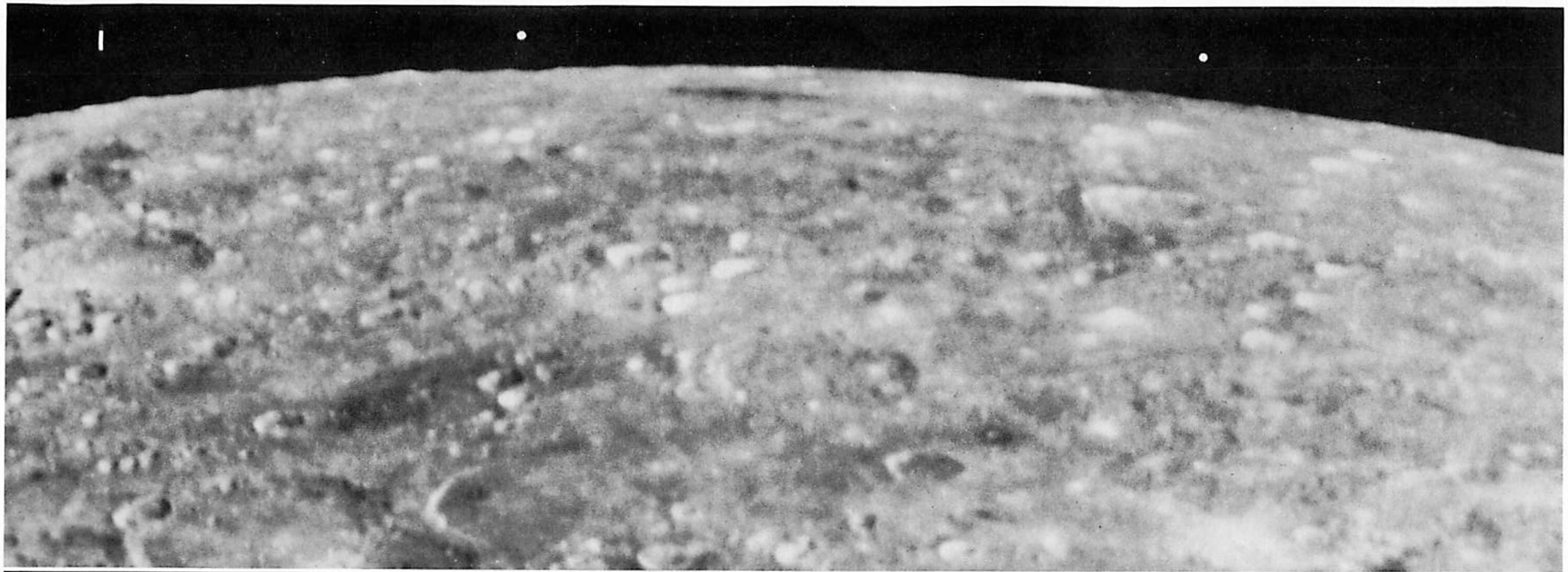


(a)

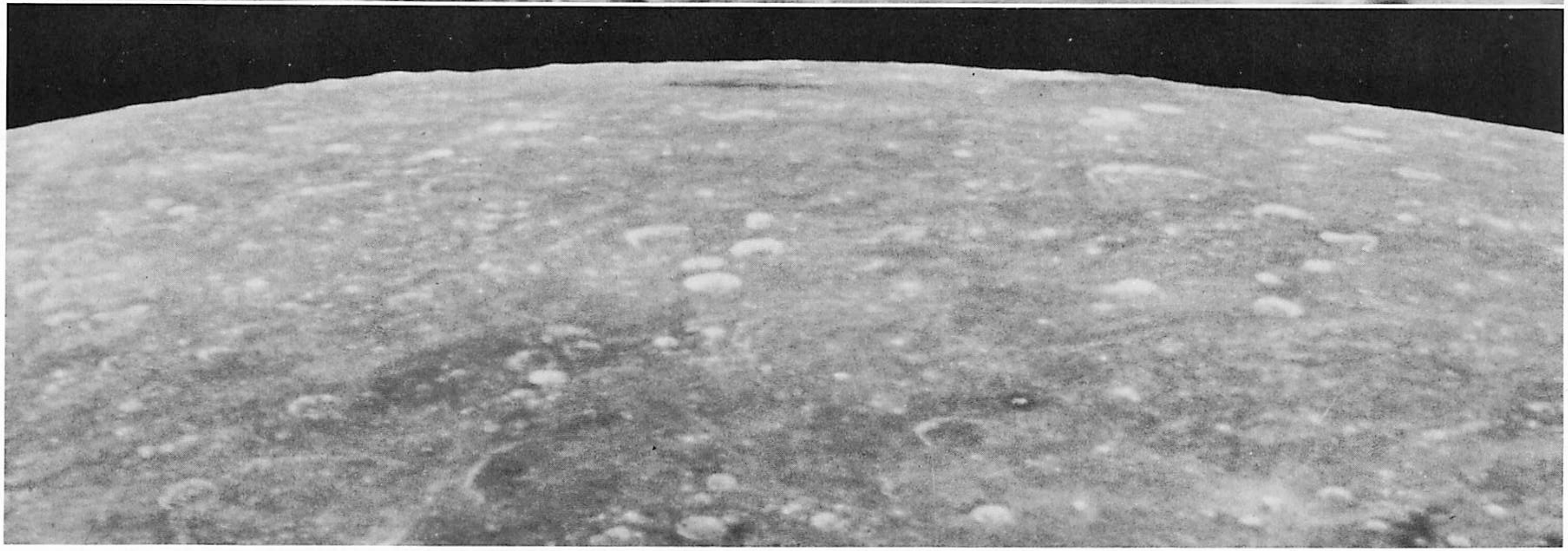


(b)

Plate 12.46. Southeast Basin, not rectified, (*a*) Y1614, (*b*) Y1654. This pair and 12.47 may be viewed stereoscopically.



(a)



(b)

Plate 12.47. Southeast Basin, not rectified, (a) M831, (b) M121. This pair and 12.46 may be viewed stereoscopically.

Plate 12.48. Mare Humboldtianum, rectified, evening illumination, showing inner wall and outer scarp, Y482.

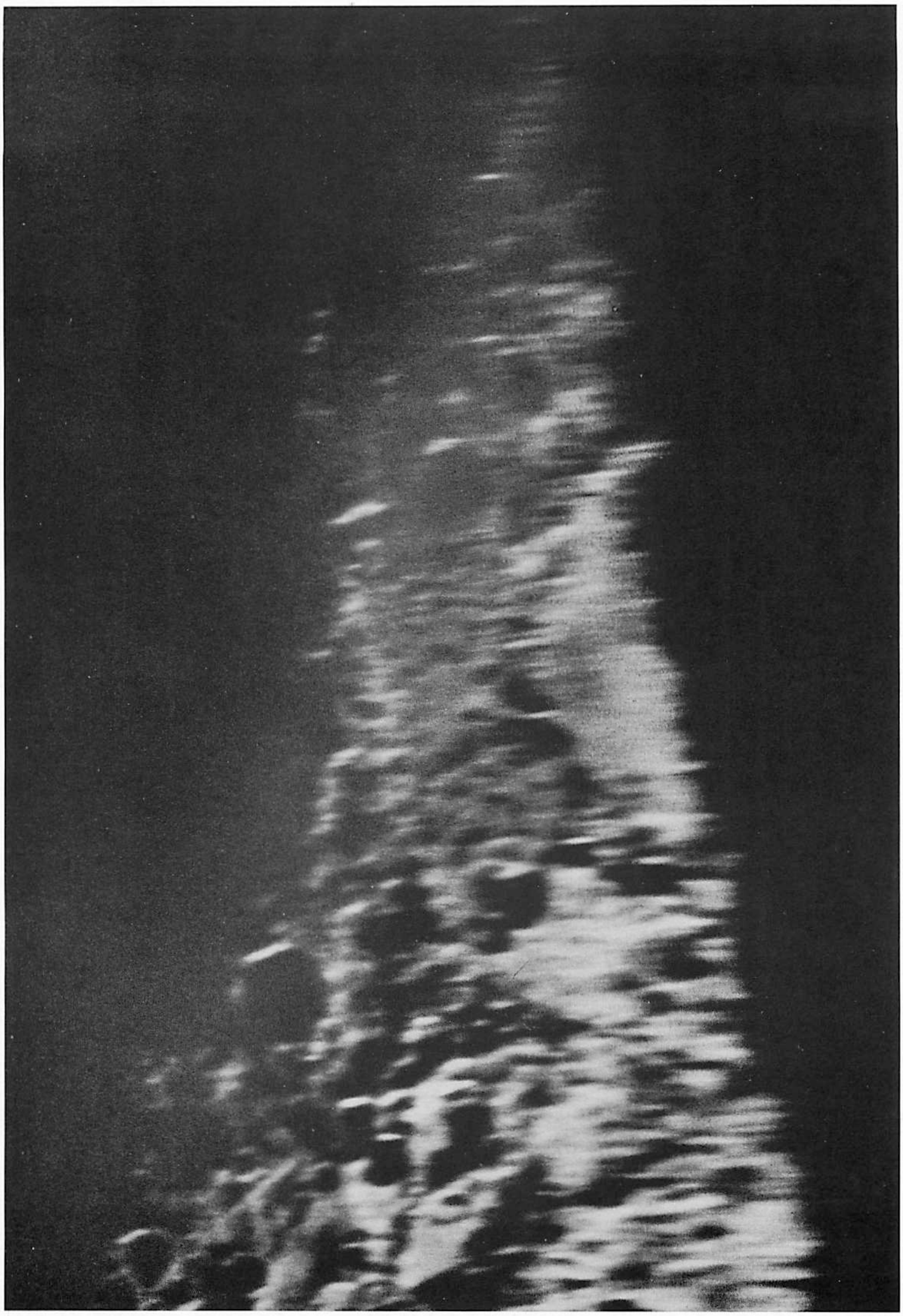


Plate 12.49. Mare Humboldtianum, rectified approximately, morning illumination, Y686.

Plate 12.50. Mare Humboldtianum, rectified approximately, morning, showing inner basin and outer scarp, Y781.

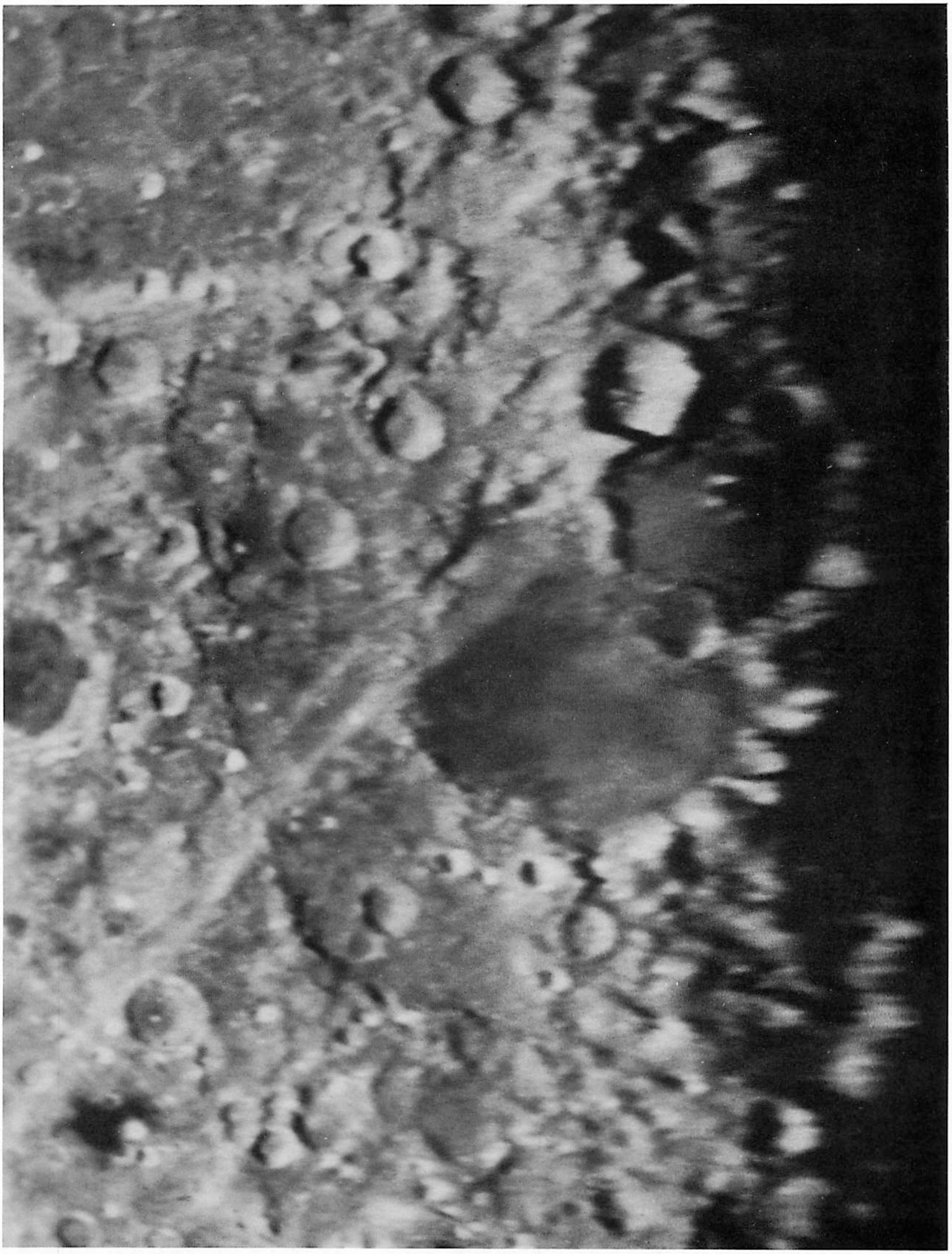


Plate 12.51. Mare Humboldtianum, rectified, evening, showing duplicity of inner basin and hexagonal outer scarp, M30.

Plate 12.52. Mare Crisium, rectified, morning, showing outer arc (cf. 12.54), Y784.

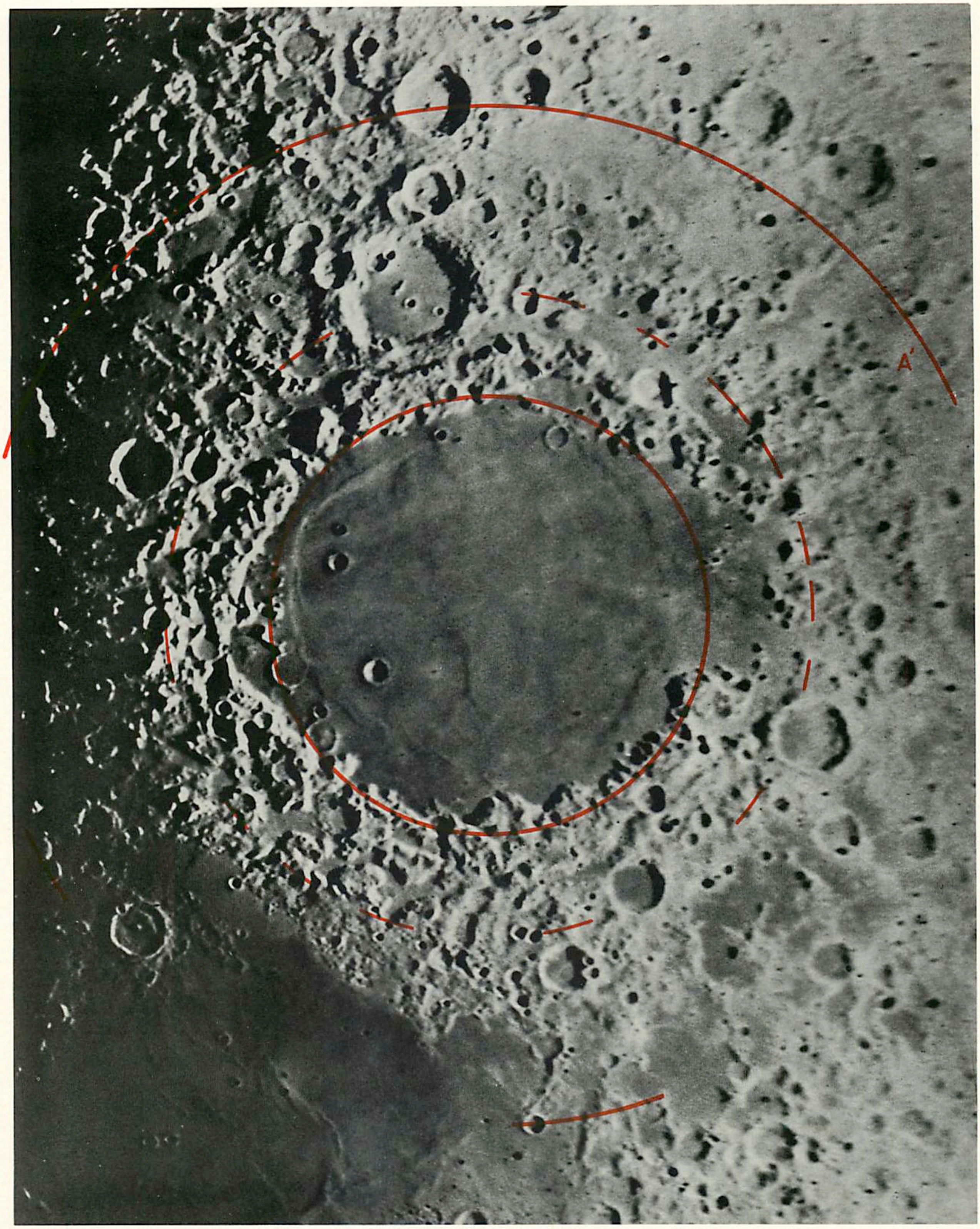


Plate 12.53. Mare Crisium, rectified, morning, as 12.52, with circular arcs shown. Intermediate arc, indicated by dashes, is similar to those in Mare Nectaris and Mare Humorum, marking hills surrounding prominent flooded channel.

Plate 12.54. Region of north shore of Mare Crisium, showing flat-topped north wall, radial and peripheral valleys; morning, Y784.

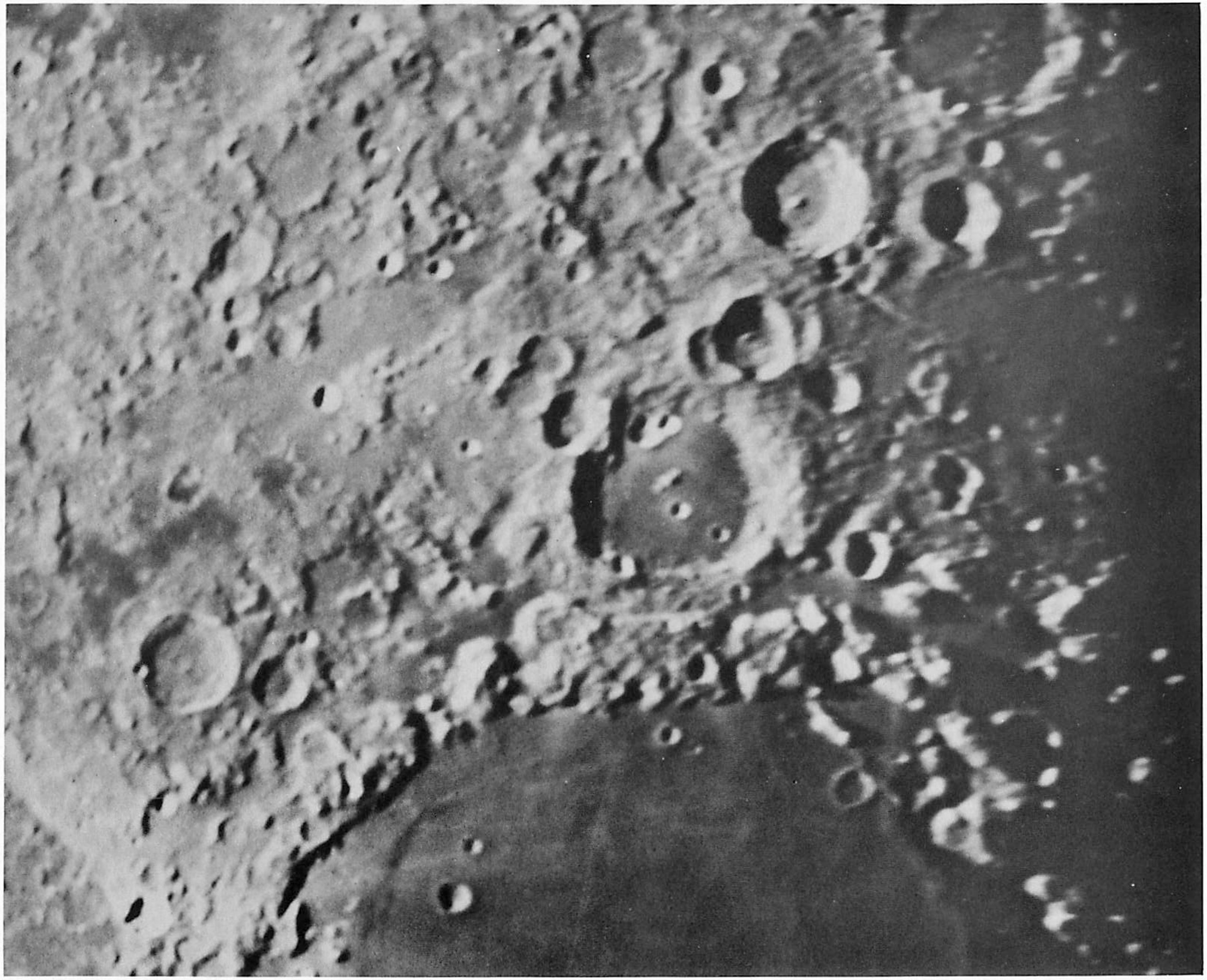


Plate 12.55. Region of north shore of Mare Crisium, evening view, matching Plate 12.54, Y369.

Plate 12.56. Mare Crisium, rectified, evening, showing west shore, peripheral valleys, and part of outer arc (NW), Y1315.

(*a*) (*b*)

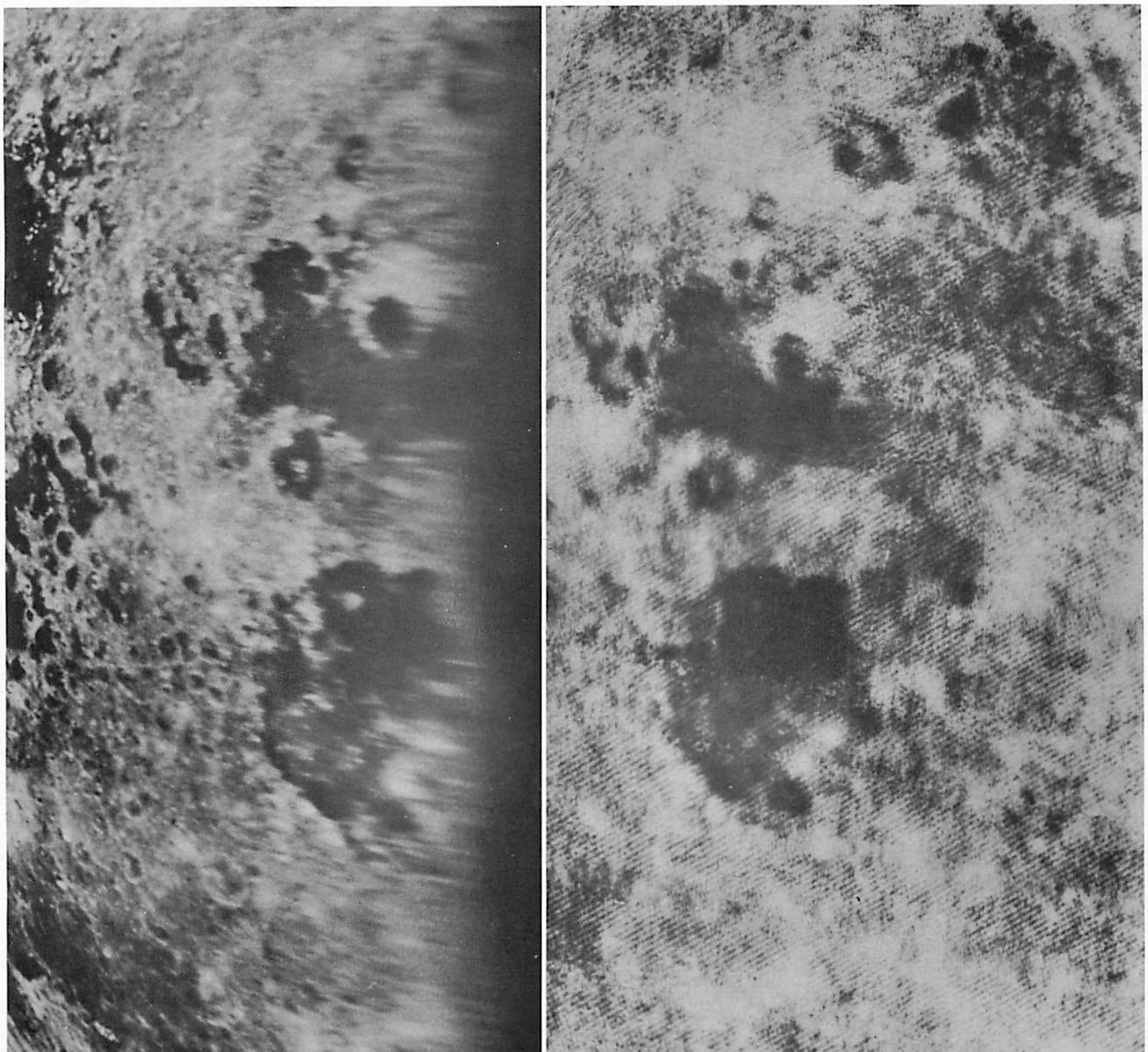


Plate 12.57. Region of Mare Marginus (above) and Mare Smythii (below), seen under high illumination to show distribution of lavas. (*a*) Earth-based photograph, reprojected to match (*b*); (*b*) Lunik III-based photograph reproduced from *Communication* No. 13 by Mr. Whitaker.

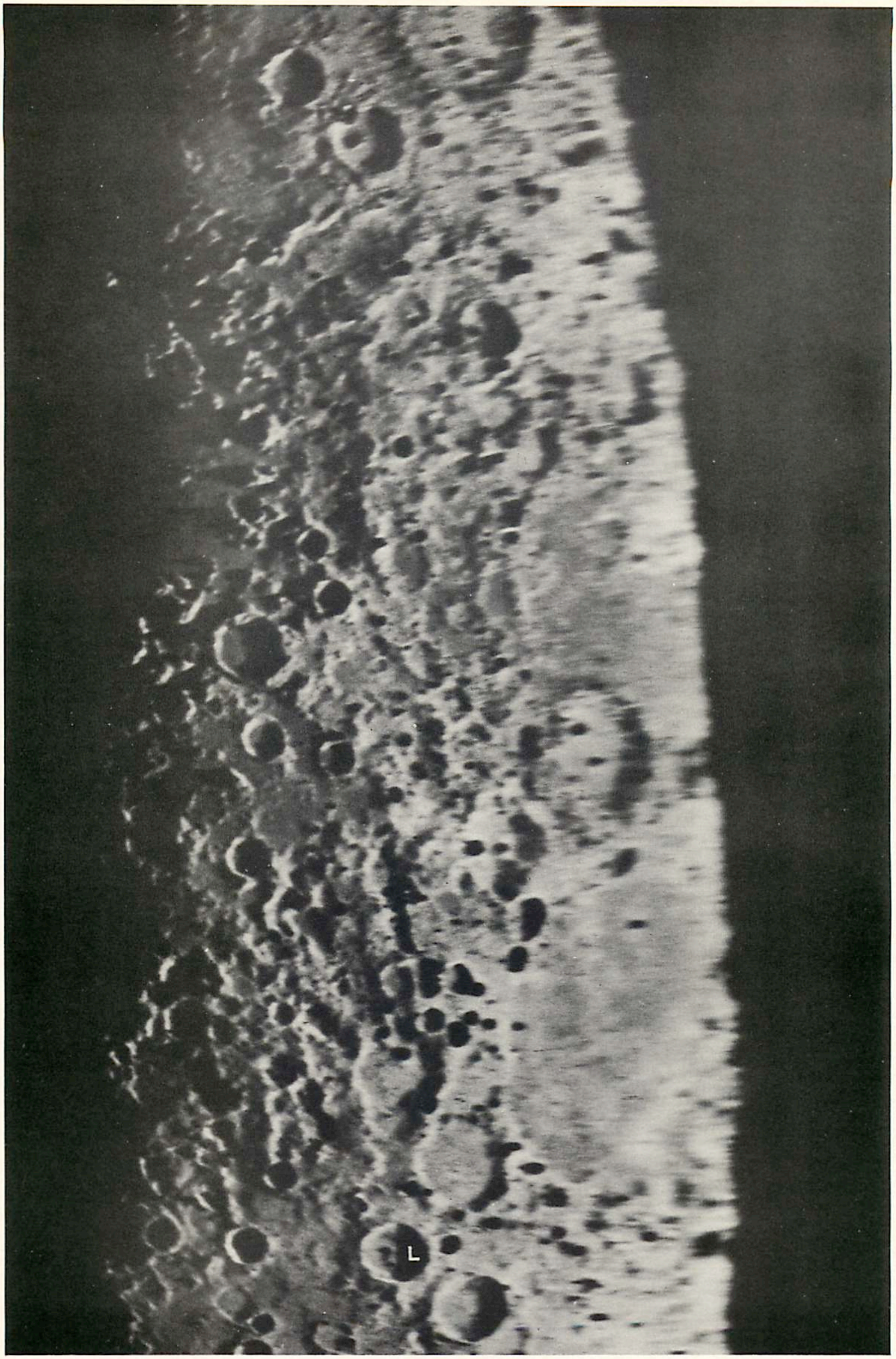


Plate 12.58. Mare Marginus and Mare Smythii, approximately rectified, morning, Y686.

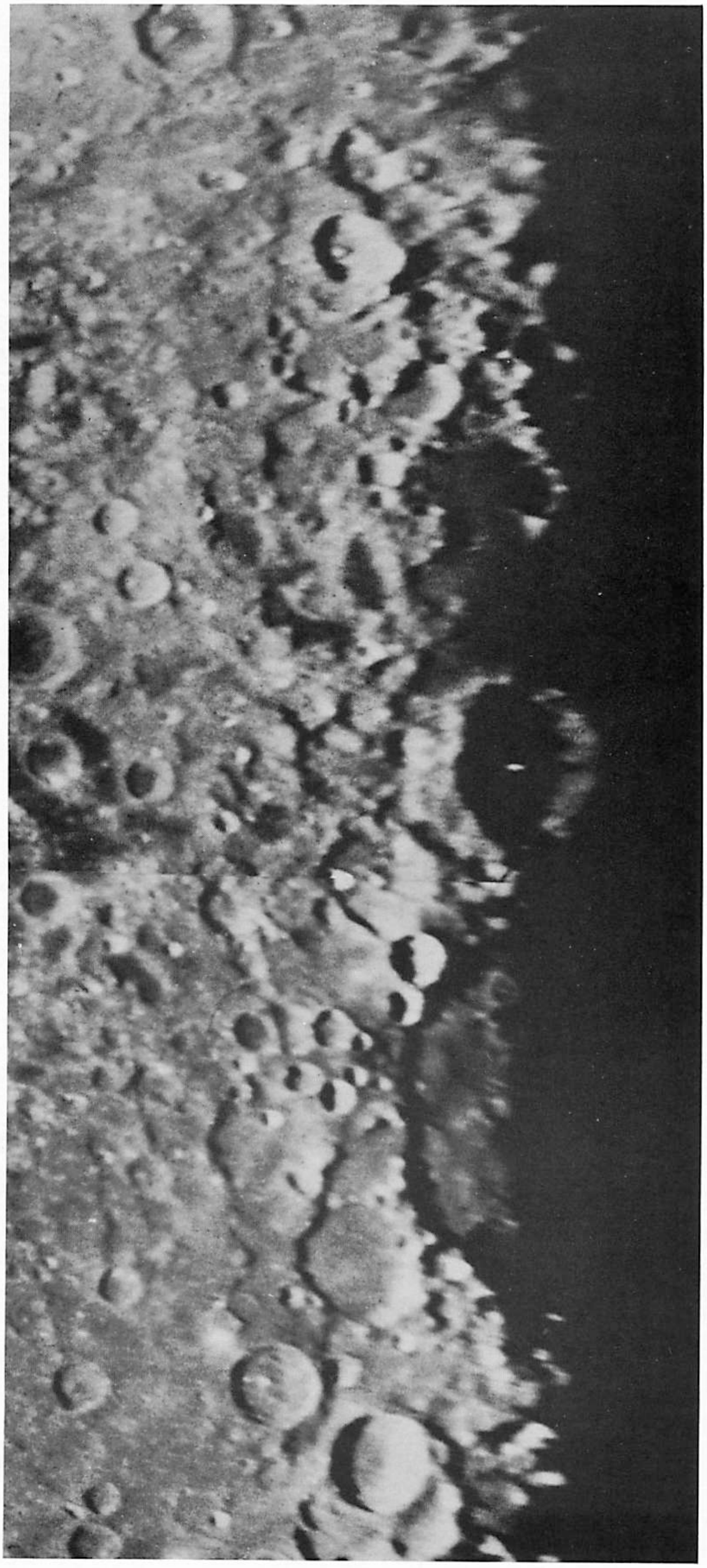


Plate 12.59. West shores of Mare Marginus and Mare Smythii, sunset. Composite of two photographs each approximately rectified, both M479.

Plate 12.60. Basin near Schiller, rectified, morning, Y1122.

Plate 12.61. Basin near Schiller, rectified, morning, Y1011.

Plate 12.62. Basin near Schiller, approximately rectified, morning, M694.

Plate 12.63. Basin near Schiller, approximately rectified, evening, W171.

Plate 12.64. Grimaldi, rectified, morning, Y1502.

Plate 12.65. Grimaldi, rectified, morning, Y108.

Plate 12.66. Grimaldi, rectified, evening, Y1395.

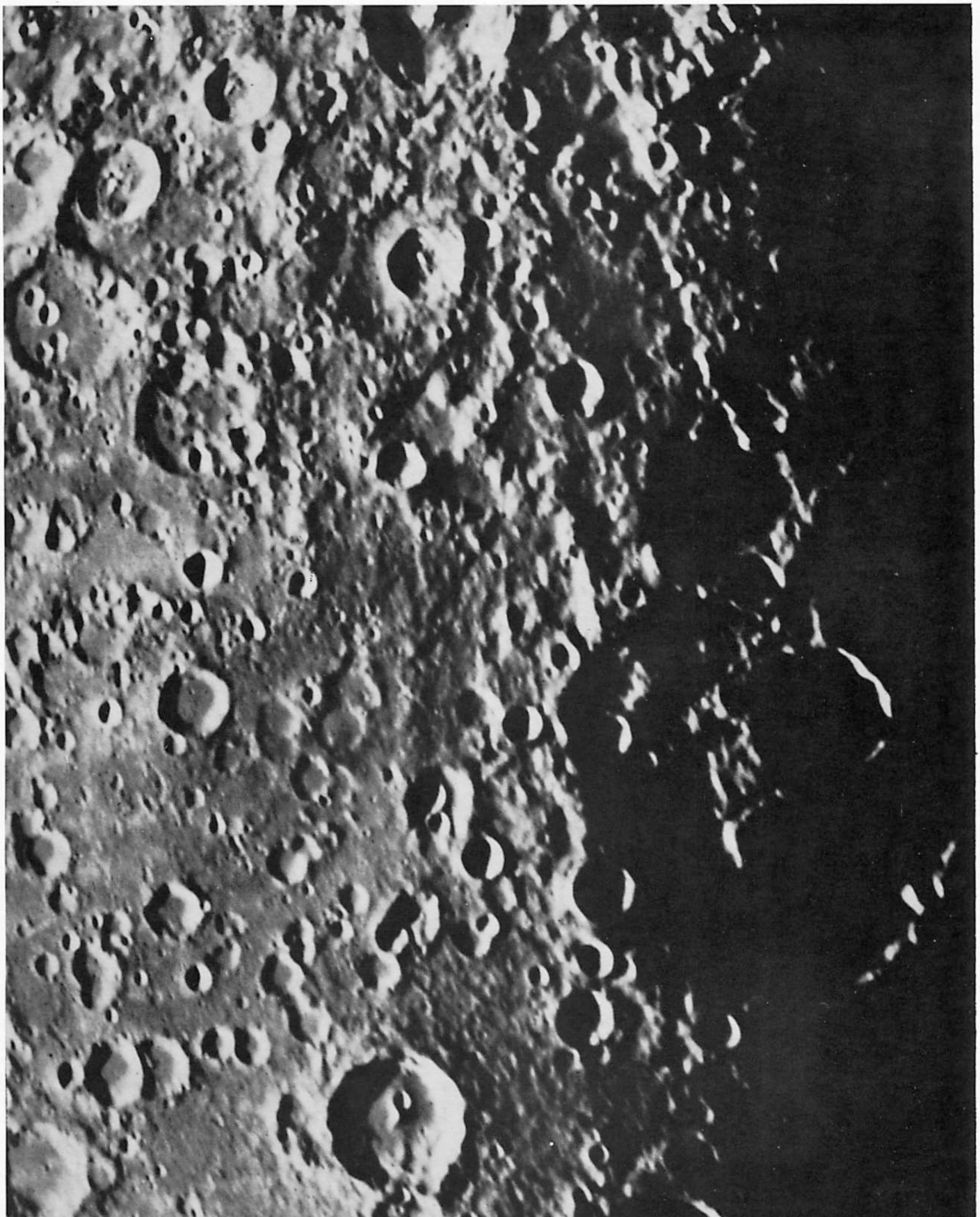


Plate 12.67. Janssen, rectified, evening, Y1335.

Plate 12.68. Janssen, rectified, evening, Y369.

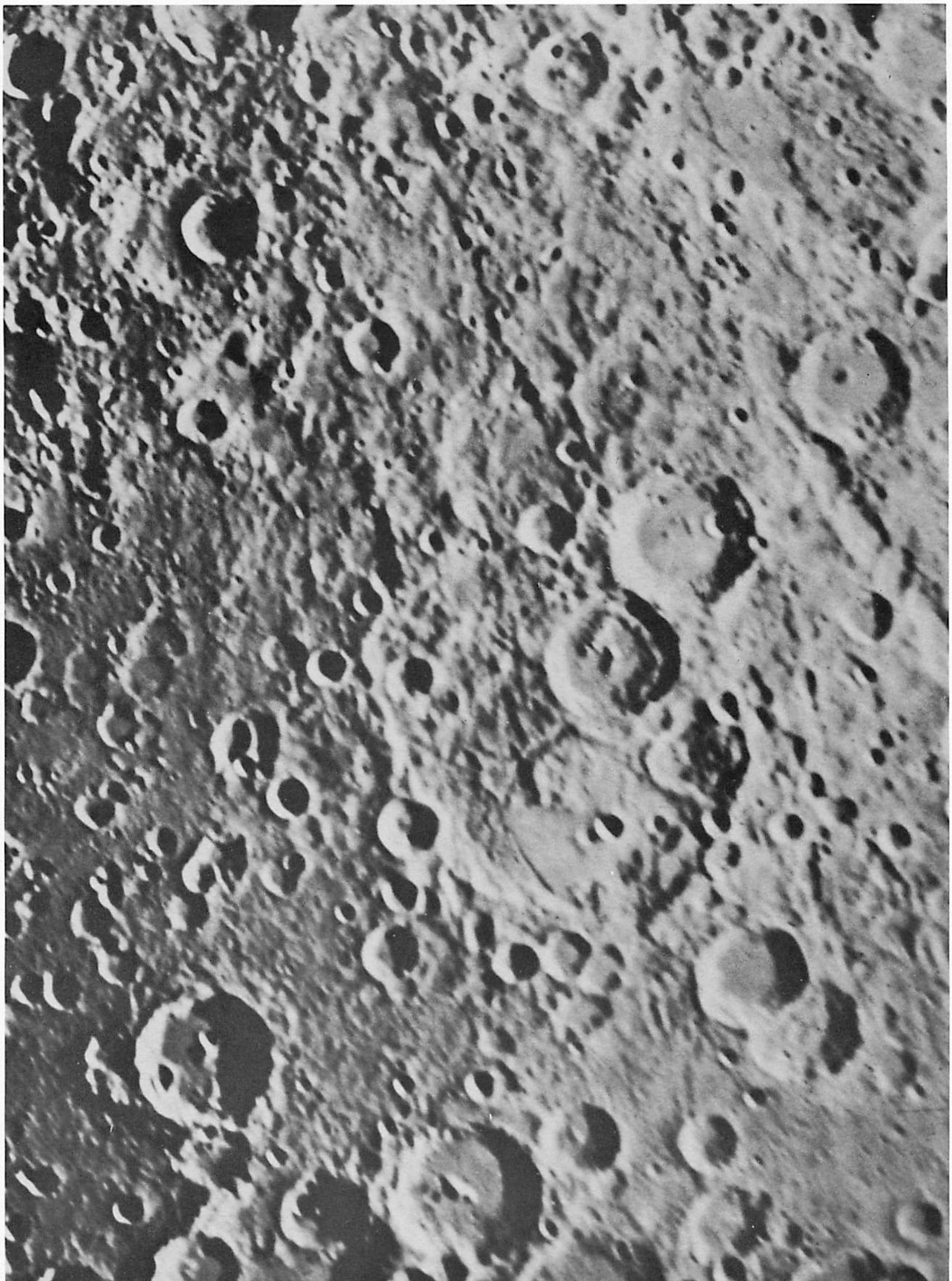


Plate 12.69. Janssen, rectified, morning, Y193.

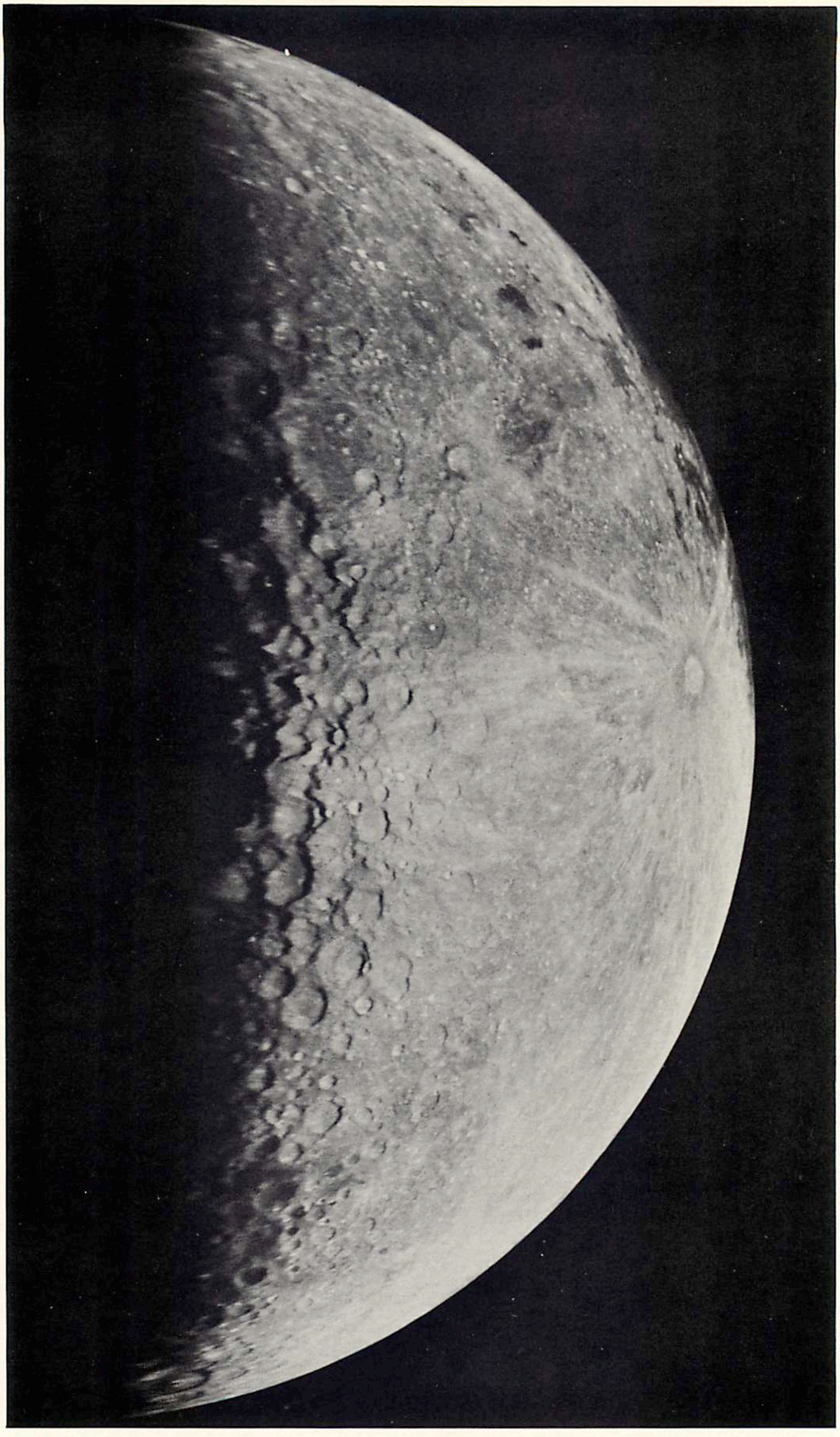


Plate 12.70. South Polar region, rectified, centered about 16° beyond the pole. Tycho near right-hand limb, Y1614.

Plate 12.71. Leibnitz Mountains near South Pole, rectified. Large crater at top is Bailly, Y1604.

Plate 12.72. Bailly and Pingré, rectified, Y1170. cf. Plates 12.44, 12.70, 12.71.

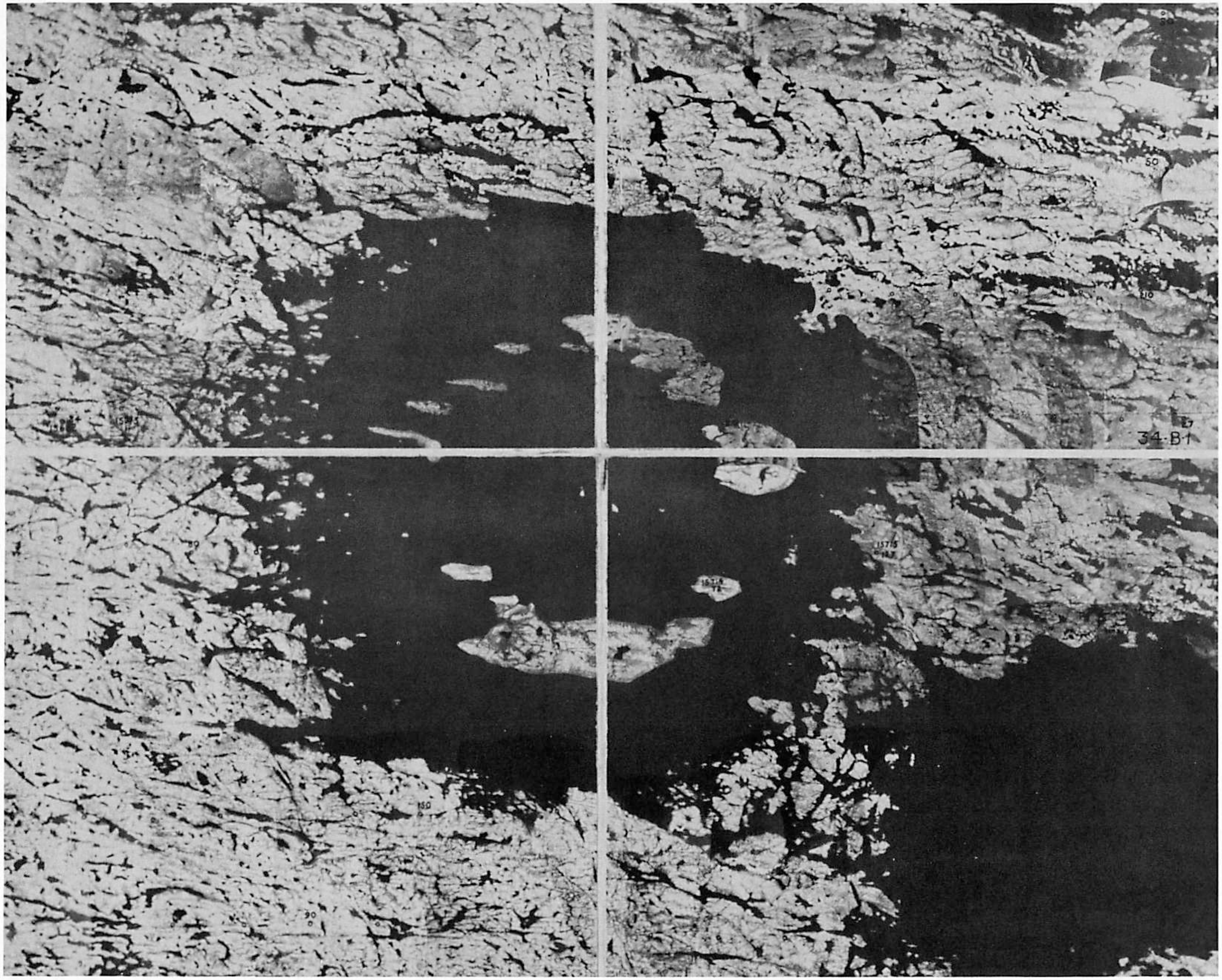


Plate 12.73. Clearwater Lake, Canada (56° 10′N, 74° 20′W), a fossil meteor crater with inner ring of islands. Courtesy, Dominion Astronomer.

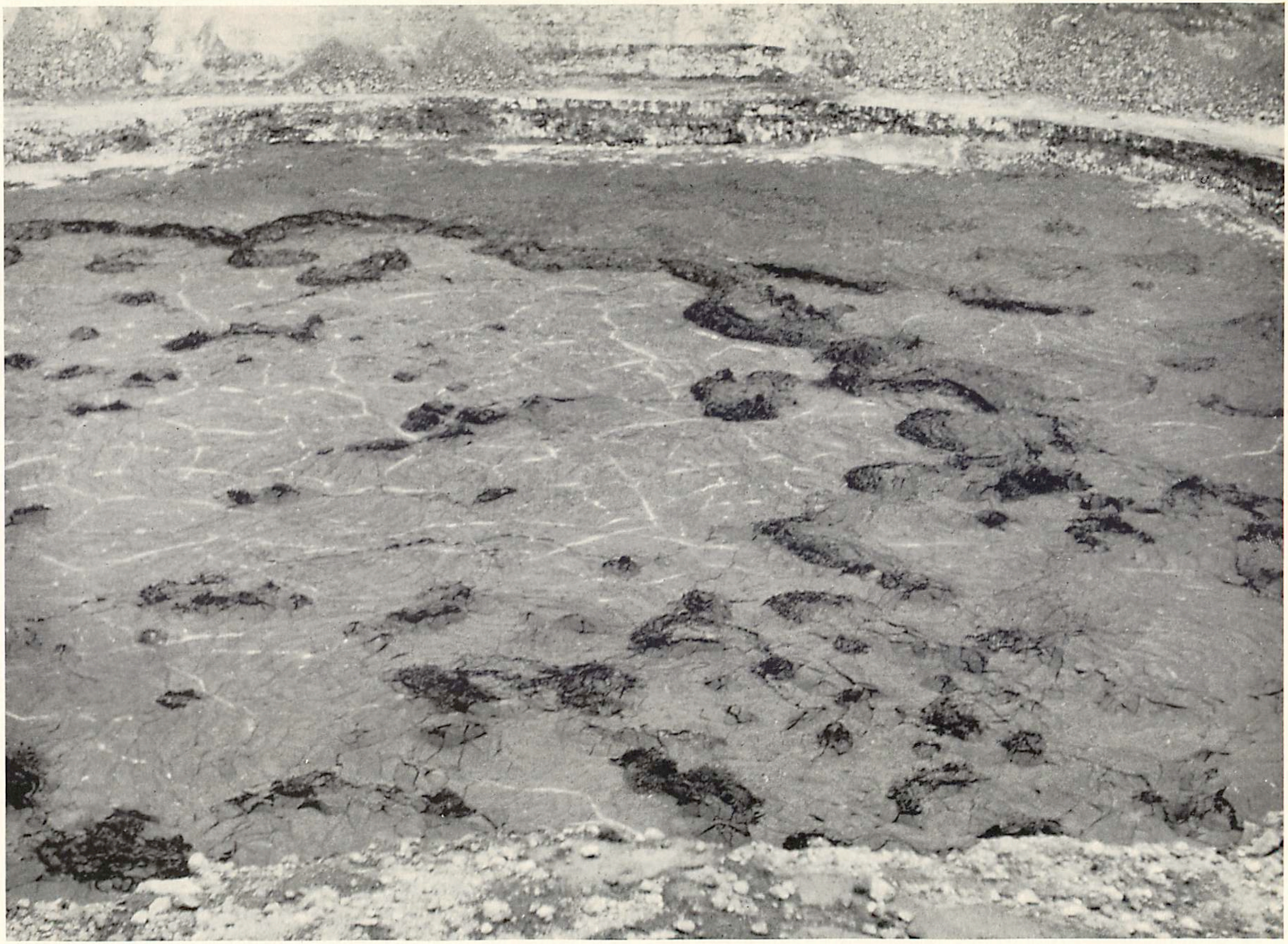


Plate 12.74. Floor of Halemaumau Crater, Island of Hawaii, Jan., 1962. Courtesy Mr. F. W. Greer.

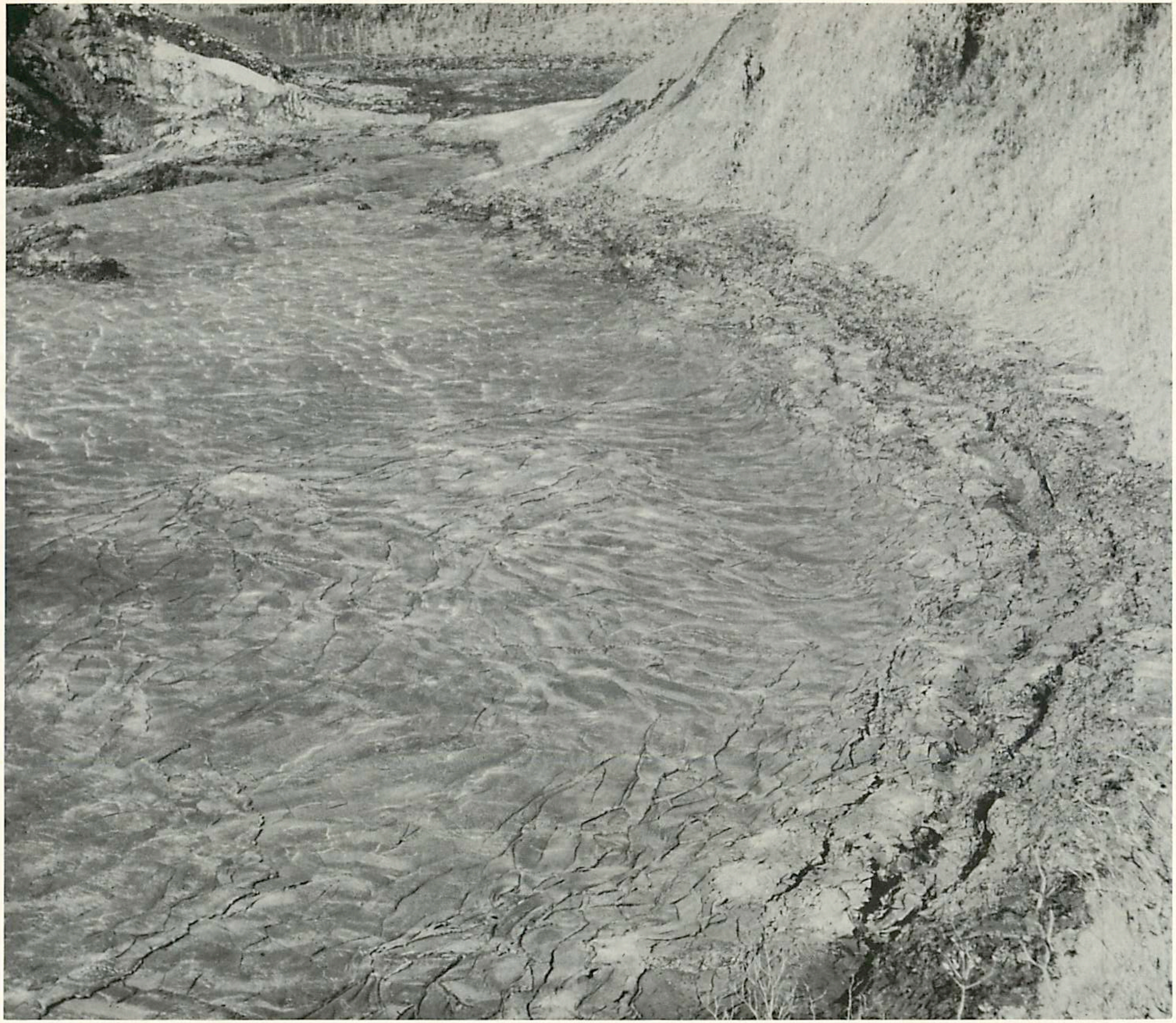


Plate 12.75. Floor of Kilauea Iki Crater, Island of Hawaii, Jan., 1962. Courtesy Mr. F. W. Greer.

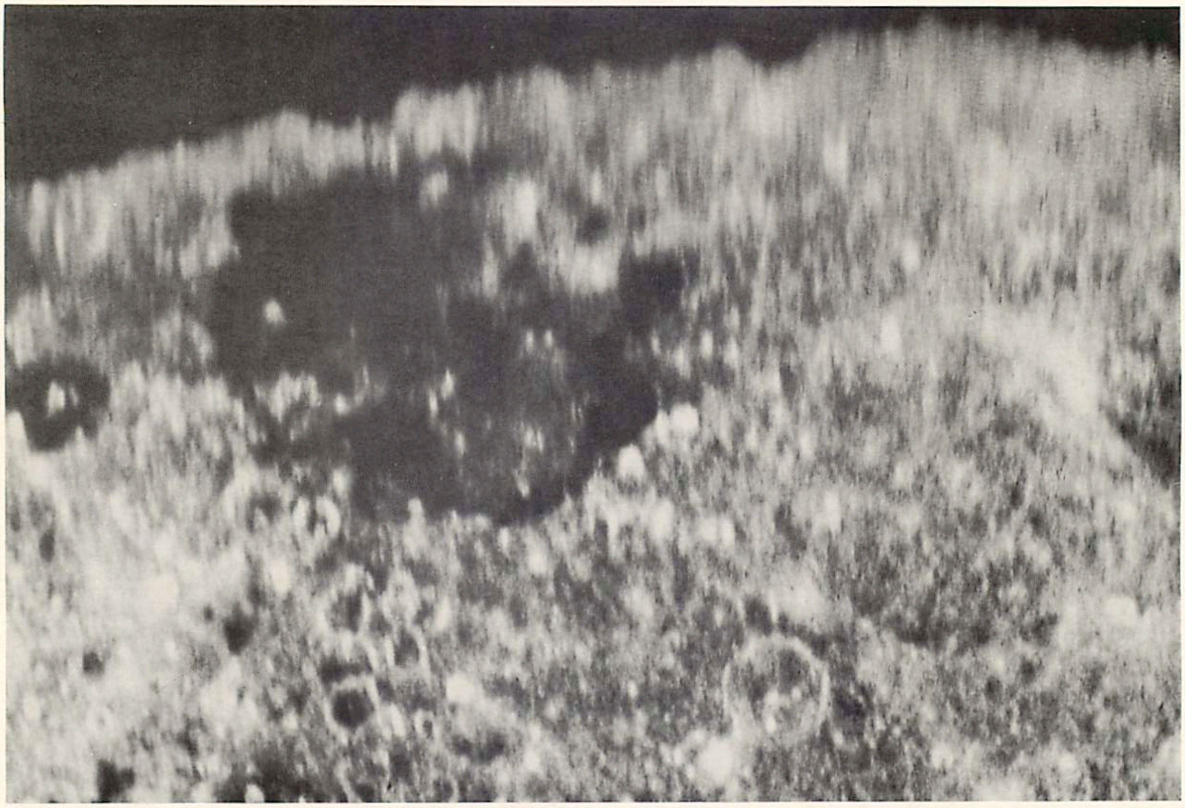


Plate 12.76. *Above*, Rectified photograph of Mare Smythii, Y204.
Below, Terrestrial Fault produced by subterranean explosion.

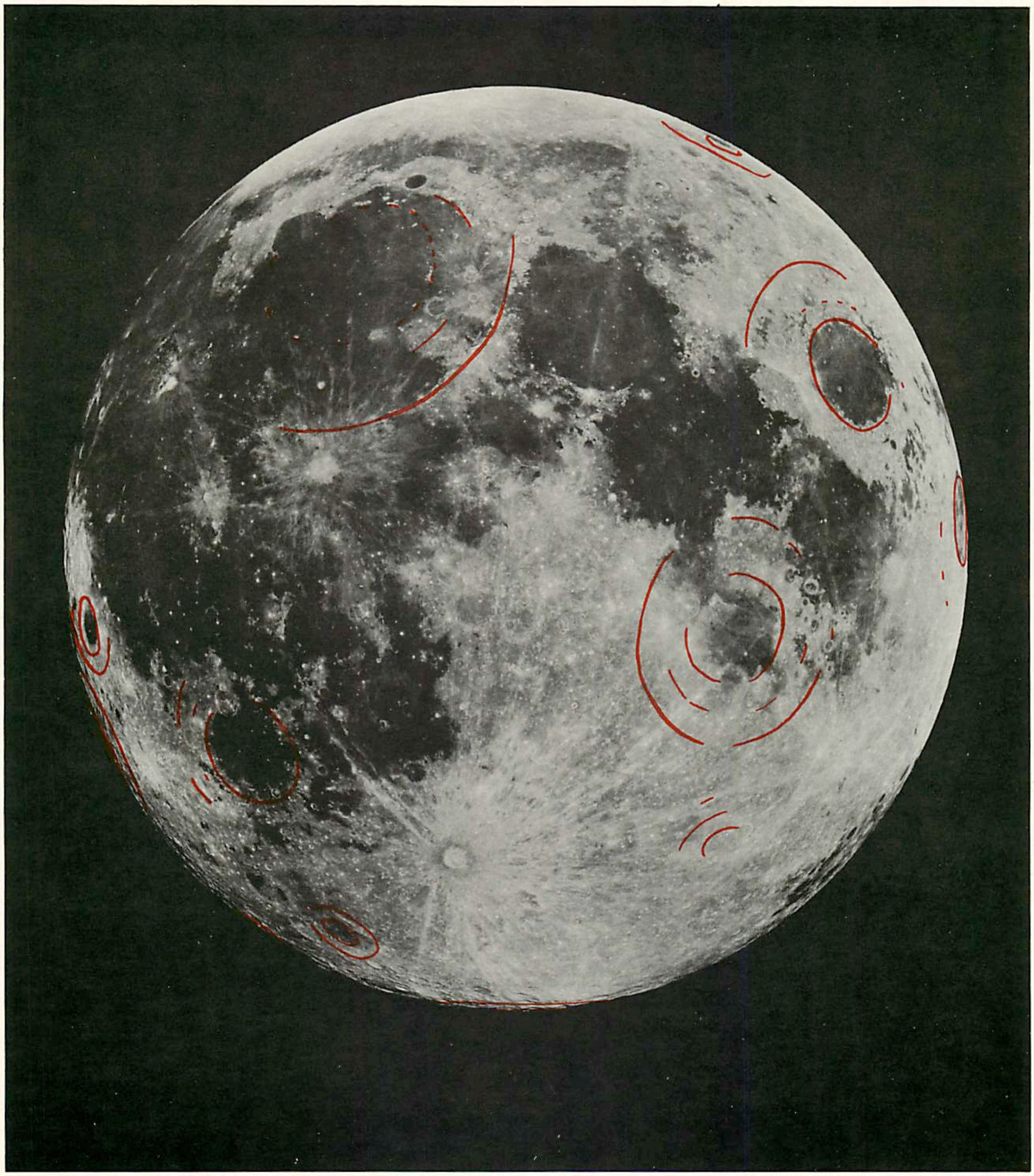


Plate 12.77. Full-moon photograph with schematic outlines of multi-ring basins, L18.