NO. 24. RADIAL STRUCTURES SURROUNDING LUNAR BASINS, I: THE IMBRIUM SYSTEM

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ABSTRACT

The system of radial structures in the uplands surrounding Mare Imbrium contains a variety of objects and has modified certain pre-mare features. Many of the structures cannot be the result of gouging by flying fragments. They may have formed along radial fractures associated with an Imbrium impact. The morphological evidence for crustal breakup suggests that this impact occurred during a high-temperature stage in the outer layers of the moon when the surface was in tension and the subsurface plastic.

1. Introduction

As long ago as the 1890's it was recognized that at least one of the lunar maria is accompanied by a family of radiating surface structures. Gilbert (1893) described the Imbrium system in a paper which discusses the "Imbrium sculpture." Most of the discussion of such radial structures has concentrated on the array in the region from the Haemus Mountains to Ptolemaeus, radiating from Mare Imbrium (see Pls. 24.1-24.3).

The program of rectified lunar photography at this Laboratory permitted a survey of the regions around the mare basins without the complications caused by foreshortening. The results on concentric-ring structures surrounding several of these basins were reported in *Communications No. 12,* Volume *1,* "Concentric Structures Surrounding Lunar Basins" (Hartmann and Kuiper, 1962), to which the present paper is a companion.

In accord with previous *Communications,* astronautical directions adopted by the International Astronomical Union (1962) are used. Most of the photographs are oriented with the basin center downward, so that radial features fan upward. References to plates in earlier *Communications* are by plate number (e.g., Pl. 12.1). Several lightings of most regions (Pls. 24.4-24.39) are given to allow optimum interpretation. Original plate number, scale, and the sun's selenographic colongitude accompany each plate.

2. Review of Literature

Because of the extensive literature on the Imbrium radial pattern and the conflicting views expressed, a somewhat more extensive review of the literature is given here than is customary in a research paper. This review will emphasize the need of additional studies based on the best available rectified photographs.

Many of the roughly-parallel structures were noted by the early selenographers. For example, Beer and Mädler (1837, p. 250) described (translated) a "[SE-NW] direction of mountain ridges of the most decided prominence" between Mare Tranquillitatis and Mare Vaporum. However, the early observers usually discussed individual formations, not wider patterns.

In his classic paper "The Moon's Face," Gilbert (1893) wrote (pp. 275-276):

> "The rims of certain craters are traversed by grooves or furrows, which arrest attention as exceptions to the general configuration. In the same neighborhood such furrows exhibit parallelism of direction. Similar furrows appear on tracts between craters, and are there associated with ridges of the same trend, some of which seem to have been added to the surface. Elsewhere groups of hills have oval forms with smooth contours and parallel axes, closely resembling the glacial deposits known as drumlins, but on a much larger scale. Tracing out these sculptured areas and platting the trend lines on a chart of the moon, I was soon able to recognize a system in their arrangement, and this led to the detection of fainter evidences of sculpture in yet other tracts. The trend lines converge toward a point near the middle of the plain called Mare Imbrium, although none of them enter that plain. Associated with the sculpture lines is a peculiar softening of the minute surface configura-

> tion, as though a layer of semi-liquid matter had been overspread, and such I believe to be the fact; the deposit has obliterated the smaller craters and partially filled some of the larger. These and allied facts, taken together, indicate that a collision of exceptional importance occurred in the Mare Imbrium, and that one of its results was the violent dispersion in all directions of a deluge of material — solid, pasty, and liquid...."

In addition to the "sculpture," Gilbert described (pp. 279-280):

> "... a series of gigantic furrows. In general direction they are remarkably straight, but their sides and bottoms, with a single exception, are jagged, abounding in acute salients and reëntrants.
>
> ....
>
> It was my first idea that the furrows are the tracks left by solid moonlets whose orbits at the instant of collision were nearly tangent to the surface of the moon, and for some of them I have still no better explanation to suggest; but when they came to be platted on a chart of the moon's face it was found that more than half of them accord in direction with the trend lines of the Imbrian outrush...."

Figure 1 is taken directly from Gilbert's paper and is his map of the system of "sculpture" and "furrows." These terms are not used here because they are regarded as oversimplified. The Alpine Valley and the Rheita Valley, though classed together as "furrows," show differences as great as those between the Alpine Valley and some "sculpture" structures.

It appears that Gilbert may be credited with the discovery of the Imbrium radial system (cf. also Shoemaker, 1962, and Urey, 1962*a*) and with the most complete study of it until the last two decades.

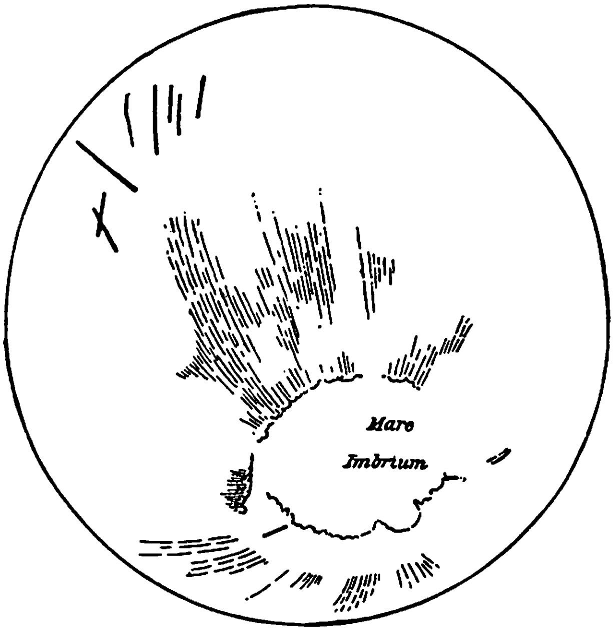

Fig. 1.—Diagram of "lunar sculpture" by G. K. Gilbert (1893). "Great furrows" are shown by heavy lines. Thinner lines do not show individual structures, but rather show "the general distribution of the sculpture comprising the districts in which it is faintly exhibited as well as those in which it is conspicuous."

Edward Suess (1895) supposed that during the solidification of a molten surface a crust was subjected to considerable fracturing, creating linear structures. He discussed the Alpine Valley as follows (p. 39, translated):

> "One might first think it to be a graben structure between two linear faults; it is not that.... The steepness of the linear walls, the even floor, the regular decrease in width, and the sudden offset allow the supposition that the whole solidified crust, similar to a huge cake of ice, has been cracked diagonally from the [W] and that both blocks are displaced horizontally from one another."

In 1919 Steavenson, apparently independently, proposed two categories of "linear depressions." The "clefts" were irregular, and common in the low-lying districts and maria. Steavenson implied that in some cases they are causally associated with nearby craters. The "furrows" were broad (usually 2-6 miles wide), shallow, and "confined, with very few exceptions, to one region," from the Haemus Mountains to Ptolemaeus. His "clefts," usually referred to now as *rilles,* are indeed distinct from the radial structures discussed in the present paper. His "furrows" are part of Gilbert's "sculpture" and make up a portion of the radial system discussed here. While they are most prominent in the region noted, other examples will be shown below. Steavenson made no mention of a convergence of his "furrows" toward Imbrium. He stated,

> "... it may fairly be taken that that origin, whatever it be, is a common one, for their great similarity in breadth and general appearance and their close parallelism seem to demand this. The only question is whether they were produced by internal (*i.e.* volcanic or seismic) forces or by external agencies, such as the grazing impact of meteoric bodies."

Steavenson here juxtaposed the two basic mechanisms which have subsequently been considered for the origin of the radial structures. He was inclined to favor a meteoritic origin for his "furrows," though he was "not an advocate of the meteoric theory as accounting for the craters."

Fielder (1961*a*) and Urey (1962*a*) refer to additional papers of the early 1900's describing the Imbrium radial structures.

Spurr (1945*a, b,* 1948) wrote at length on the Imbrium system. He proposed an igneous origin for all the major lunar features, and his work has been somewhat neglected in recent studies, which emphasize meteoritic processes. Nonetheless, Spurr pointed out many interesting structures and discussed both the Imbrium radial pattern (and included a map) and the "grids" (a term he introduced) which have recently aroused wide interest. He wrote (1945*b*, p. 15):

> "The 'transverse' faults of the Imbrian system, radiating from the interior of the Mare Imbrium, are extended and identifiable for a long distance away from the mare. They do not appear on the various mares which lie beyond the Mare Imbrium, and are therefore older than the crust of all of these, as they are than that of the Mare Imbrium itself. This indicates that all the mares are (but only approximately) of the same age and period. But the faults do appear in the older uplands in which these mares lie, far to the south, beyond the equator of the visible moon: abundantly as far as the Mare Nectaris, . . . and more sparingly as far as . . . the south end of the Mare Nubium. . . . This amounts to an extent of a thousand miles, or more than the diameter of the Mare Imbrium itself. . . . In all this field they are plainly marked by scarps, ridges, or grooves. . . . if the tectonic influence of the Mare Imbrium uplift and subsidence extends as far in all directions as it does southerly, it must affect a circle with a diameter of nearly 3,000 miles [160° selenocentric] . . . ."

Spurr throughout advocates tectonic mechanisms to explain the radial system, a proposal for which the writer finds considerable support (though he questions Spurr's "uplift and subsidence" origin for Mare Imbrium). The observations here and in *Communications No. 12* concur with Spurr's relatively uniform ages for the mare surfaces, but indicate more varied ages for the basin systems themselves.

Baldwin has given considerable attention to the Imbrium radial system. Considering the elongated structures in the Haemus Mountains, he wrote (1942, p. 366):

> "Thus their nature, location, and orientation mark them as a unique type and are overpowering evidence of a common origin. Formations like these certainly are not volcanic in nature. They could only have been formed by the almost tangential impacts of tremendous masses of material. . . ."

He listed four types of radial structure (1943, p. 117):

> "[1] In Mare Vaporum . . . at least a dozen elongated craters, from thirty to fifty miles in length and perhaps ten miles broad. They are nearly, but not exactly parallel and their major axes projected in the convergent direction all pass close to the center of Mare Imbrium. . . . [2] the strange appearance of the southern and [southwestern] rim of Mare Serenitatis. . . . Apparently . . . mutilated by flying material . . . from . . . Imbrium. . . . [3] [near Ptolemaeus] grooves approximately three miles broad and from twenty to seventy miles long. . . . which may be regarded as more elongated versions of the Mare Vaporum splash craters, . . . [4] [in the Carpathian district] a group of ridges . . . roughly twenty miles long and three miles wide."

These four types are all parts of Gilbert's "sculpture." Clearly, the various classification schemes proposed show considerable differences; but Baldwin's description establishes the nonhomogeneity among the radial features. In his book *The Face of the Moon* (1949, p. 208) Baldwin concluded:

> "This system of valleys is simply an exaggeration of the structure surrounding so many of the newer-appearing craters such as Aristillus and must have been produced in the same way."

Baldwin thus supported his argument that the craters and the mare basins are both products of explosive impacts. His impact hypothesis of basin formation appears to provide the best explanation of the basins. However, our comparisons between the radial patterns around craters and those of the mare basins indicate that the quoted statement is oversimplified. Baldwin in his recent book *The Measure of the Moon* (1963) appears to have maintained his views.

Urey (1952) supported the impact hypothesis for basin formation and the flying fragment hypothesis for the origin of the radial features. He wrote (p. 40):

> ". . . I wish to suggest that a large object striking near Sinus Iridum at a low angle partially rebounded from the surface, spreading its substance through approximately 180° between the [western] Carpathians and the [eastern] border of Plato. Immediately beyond the point of contact it dropped materials into Mare Imbrium, whose lavas were still to cover its floor. Just beyond the shores of the mare it dropped the Alps, Caucasus, Apennines, and Carpathian Mountains in radiating ridges, and in the region of the Haemus Mountains, Mare Vaporum, and Mare Nubium further long and short ridges. It also supplied the objects which ploughed out the grooves at still greater distances.
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> "These radial patterns are of two distinct kinds and must have been made by materials of different physical properties. The straight narrow grooves suggest materials of high density and tensile strength such as iron-nickel alloy plowing through the surface, while the ridges suggest silicates of low tensile strength. The Alpine Valley also indicates that part of the meteoric body contained a high-density body embedded in the silicate, which because of its greater momentum and energy per unit volume moved on through the region in which the silicates spread themselves into Mare Frigoris, sinking in its lavas or being subsequently covered by them. . . ."

Concerning the mare materials, he concluded (1962*a*, p. 482) that ". . . lavas resulted from high-energy collisions . . . and are not the result of subsurface melting as is true for the Earth."

Urey has maintained these views (1961, 1962*a*, *b*). They are similar to those expressed here and in *Communications No. 12* as regards the origin of the Imbrium basin (as opposed to Spurr, Firsoff, and von Bülow; see below), but differ in the role of Sinus Iridum, the origin of the mare material, and the nature of the radial structures.

Kuiper has discussed the Imbrium system at length. In 1954 (p. 1104) he wrote of isolated ridges W of Copernicus and others near the center of the disk:

> ". . . both groups look like jets of lava or rather lava-covered bits of old crust (or planetesimal) which have been shot from the same splashing center in Mare Imbrium. Related, but in a different category, are the many *grooves* cut in the lunar surface, particularly in high regions like

> old crater walls, and radiating also from Mare Imbrium. They are U-shaped in cross-section and are rarely more than five diameters long; the only exceptions I have observed are extremely shallow grooves, where the ratio may approach ten. It is natural to assume that they also have been caused by flying fragments. . . ."

For the Alpine Valley Kuiper suggested the explanation (p. 1105):

> ". . . that the crust surrounding the impact area in Mare Imbrium split open where the valley is now, that the interior lava rose to the level of the present floor, and that the entrance was filled with large *solid* blocks of crust tossed out of Mare Imbrium, covered with some lava. . . ."

In 1959 he attributed to Mare Imbrium (p. 310) "a global system of faults and graben" in which were included such features as

> ". . . the radial and orthogonal fracture system in the north polar area, north and [E] of Mare Frigoris, several of which became fault planes (and others produced extrusions); . . . the Aristarchus Uplift, . . . many graben in the Ptolemaeus area, near the center of the lunar disk (which have sometimes been classified erroneously as grooves, cut by flying fragments; some genuine grooves occur there as well); . . . the Rheita Valley, a beautiful example of a graben; . . . the Straight wall. . . ."

The difficulties of identifying many of these individual features with the Imbrium system are discussed below. With respect to their shapes and the tendency for craters to lie along them, the structures called "graben" show some differences from the features on earth to which this term is applied. In the sense that the term implies some tectonic origin, it is compatible with the conclusions reached here. The 1962 paper by Kuiper and the writer summarizes their views on the nature of the basins themselves.

Within the last eight years several discussions of radial structures have appeared in the *Journal of the British Astronomical Association.* Fielder (1955, 1956, 1957) published a series of papers which are summarized in his book (Fielder, 1961*a*). He discussed the grooves near Ptolemaeus and concluded that blocklike masses along many of them may be the original projectiles which carved them, mentioning a "clearly defined association between blocks and grooves." Many of Fielder's "blocks" are described here as ridges, and no unique origin is ascribed to them. In an examination of the mechanics involved in penetration of the flying fragments through the crust, Fielder concluded that this mechanism is "wholly plausible." Fielder's writings properly stress the difficulties in any final interpretation of the radial structures.

Firsoff (1956*a, b*) rejects the meteoritic hypothesis for basin formation, preferring a subsidence origin. He thus rejects not only the flying-fragment theory, but also the existence of radial systems altogether. Summarizing his views, Firsoff (1961) writes (p. 45):

> ". . . the Apennine valleys are not radial to the supposed focus of explosion in Sinus Iridum [Urey's hypothesis]. In fact they have no common radiant . . . and consist of several roughly parallel swarms which belong to the grid systems."

Firsoff thus related the linear structures discussed here to a more general grid system of the lunar globe and discussed their origin in terms of shear stresses resulting from compression of the surface. However, while it is true that lineaments exist independent of basins, there are also genuine radial systems structurally related to various basins. Some of Firsoff's deductions may be criticized. For example, in his (1956*b* and 1961) chart of the "Apennine valleys," the extrapolation of the long Ariadaeus Rille is misplaced (its extrapolation passes near the S edge of Eratosthenes, as seen on Pls. 24.3 and 24.12, while Firsoff shows it well to the N). An approximate convergence of a great number of structural features may definitely be established by inspection of lunar photographs such as those given below.

Von Bülow (1957) also advocated an internal origin for the basins. What we consider to be a radial system around Imbrium he describes as part of a more general grid system. He believes that the basins lie in subsidence zones: a longitudinal zone N of the equator, and meridional zones of basins and uplands extending S from it. He writes (p. 606, in translation):

> ". . . The uplands are dominated by two grid lattices, which stretch across the meridional zones at sharp angles NE-SW and NW-SE. Departures appear especially in the central upland spur. . . ."

A third N-S pattern is also proposed. Von Bülow attributes the linear grid structures to extensive lunar tectonic activity, e.g., faulting, fracturing of the uplands, and production of graben, domes, crater chains, etc., which accompanied the production of the maria. The present writer agrees that extensive tectonic activity probably occurred, but does not concur with the suggestion of a significant alignment of the basins into zones.

Shoemaker (1962), who examined the ballistics of crater formation, also reviewed the Imbrium system. He wrote (p. 349):

> ". . . Trenches, ridges, and scarps in this pattern tend to be approximately aligned along a series of great circles that intersect in the northern part of the Mare Imbrium. The ridges and troughs of the Carpathians are layered over by rocks of the Imbrian system and plunge beneath the Procellarian [a division in his stratigraphic sequence] along the northern margin of Mare Imbrium. Individual ridges that rise above the level of the surrounding Imbrian ejecta are the prominent features of the Carpathians. It is possible that

> some displacement has occurred along some of these ridges since the Imbrian system was deposited, but there is no apparent displacement of the Procellarian where it overlaps the ridges and valleys along a series of promontories and bays that constitute the mountain front. . . . Aside from the fact that the trajectories and strength of the ejecta required for the plowing of such furrows are improbable, offsets in the walls of the troughs and ridges show that they are more likely to be fault scarps. It appears highly probable that the Imbrian sculpture is the topographic expression of a radiating set of normal faults that were formed during dilation of the lunar crust by divergent flow behind the shock front generated by the impact that produced the Imbrian ejecta. The ridges of the Carpathians are thus interpreted as horsts; probably they were scarcely formed before they were partially buried by ejecta."

The present writer believes that the set of radiating faults postulated by Shoemaker is a prime influence in the production of the radial system. The convergent point, described as being in the northern part of the mare, can be considered the center of the structural basin, as discussed below and in *Communications No. 12.*

The divergent opinions quoted here suggest that a final solution may have to await surface exploration, though obviously considerable progress is still possible from earth-based studies. Such studies at the same time will prepare for surface exploration.

3. *Morphology of the Imbrium Radial System*

Associated with the Imbrium basin is a ring of isolated peaks on the mare surface, forming a circle approximately 670 km in diameter. A surrounding arc of mountains is nearly continuous for 165°, concentric with the inner ring, and approximately 1340 km in diameter. Several upland areas between these rings define a subsidiary ring about 970 km across. All of these features find analogues in other basin systems (Hartmann and Kuiper, 1962, pp. 64-65).

The inner ring is often described as being off-center. It is true that it does not lie in the center of the mare surface. However, Kuiper (1959) and Hartmann and Kuiper (1962) have suggested that because of its concentricity with the Caucasus-Apennine-Carpathian arc and in view of the presence of numerous other concentric ring systems, the inner ring in Mare Imbrium may be regarded as defining the center of a vast, structural basin system with concentric mountainous arcs and radial features. The mare itself is considered as a surface phenomenon; it is the mare material which is off-center in the Imbrium system rather than the ring structure.

Baldwin (1942), Arthur (private communication), and others have pointed out that although the observed radial features do not converge to a point, their projections do intersect within the inner mountain ring of the Imbrium basin. This is further evidence that the mountain arcs, not the mare material, reveal the fundamental basin structure. Rectified photographs from above the Imbrium Inner Basin assist in defining the center of the radial system. Plates 24.1 and 24.2 are examples, and show especially well the region from the Haemus Mountains to Ptolemaeus, which contains the most prominent radial pattern observable from the earth (cf. also Pls. 12.24 and 12.25). Plate 24.3 adds a more nearly vertical view. Just beyond Hipparchus (see Pl. 24.2) are two valleys whose projections pass on opposite sides of the center of the Imbrium ring system, but within the Inner Basin. These projections intersect in Sinus Medii (see Pl. 12.25). Similarly, the Straight Wall, seen in the upper right of Plate 24.2, is somewhat out of alignment with the center of the Imbrium Inner Basin. One might thus ask: How far out of alignment may a linear feature be and yet be considered part of a radial family?

Clearly, a radial system cannot be defined solely by the directional properties of its members. Sometimes a *parallelism* of the features, rather than strict radialism, is seen in localized areas. This also applies to the rays of Tycho (see front cover or Pl. 1.2), though no one has questioned their association with the crater. A system is made apparent by the presence of an unexpectedly large number of individual structures aligned with the center of a basin system. These components range in dimension from at least tens of kilometers to the limit of resolution (hundreds of meters). Observers with large instruments have noted that under the best conditions the surface in the midst of these systems is marked by innumerable, fine linear structures. Further, it is shown below that a variety of structural forms composes these systems and that similar forms are found in association with more than one basin. Thus, alignment, number of features, and structural form are all criteria in defining these systems; and while the projections of the members do not meet at one point, they typically intersect within the innermost rings of the basin systems. Thus, as Urey (1961) states, "It is not clear whether some of the individual ridges and grooves belong to the system or not, but the overall pattern is entirely convincing."

An example of such an individual structure is the Straight Wall. The evidence that the Straight Wall belongs to the Imbrium system includes not only the near-alignment of this linear structure, but also the presence of a similar formation nearly aligned. The Straight Wall and this second feature, the Cauchy scarp, are shown in Plates 24.4 and 24.5 to the same scale. Their probable association with the Imbrium system was first pointed out by Kuiper (1959, p. 293). The similarity in form and size (length 100+ km) is enhanced by the presence of a parallel rille in each case. Further, each scarp lies near the edge of a mare surface; the foot of each is on the mare side; each has domes nearby; they are nearly equidistant from Imbrium. Arthur (1962*a*) has called attention to a rille running along the foot of the Cauchy scarp; a similar, but less prominent, rille has been reported along the Straight Wall by some observers, although the evidence for the latter is less certain (Whitaker, private communication). Subsidiary graben along the bases of many terrestrial normal fault scarps are undoubtedly analogous. The Cauchy fault also shows *en échelon* structure and forking, characteristic of many terrestrial normal faults (de Sitter, 1956, p. 151).

The Straight Wall lies nearly on a diameter of an ancient, 200-km ring. This ring has been flooded, and its W wall is now shown only as an arc of wrinkle ridges in the mare. An arc of mountains to the SE and wrinkle ridges to the W suggest a similar ring for the Cauchy scarp. These faults most probably are post-mare, originating not long after the mare surface was laid down, while there was still considerable tectonic activity. We might suppose that they formed along stress lines set up in the sub-mare surface by the Imbrium impact. Hence the association of these faults with the Imbrium radial family would be consistent with their apparent age and would explain their direction. If this be accepted we have a case where *faulting,* not grooving by projectiles, is part of a radial system.

The remainder of this section describes the Imbrium structures, starting with the Haemus Mountains and following around the basin in a clockwise direction. Reference may be made to Plates 24.1, 24.2, and 24.40 for orientation purposes.

Plates 24.6 and 24.7 show the Haemus Mountains in detail. They form the southern wall of Mare Serenitatis (to the left), but their linear structure shows no symmetric relationship to the Serenitatis basin. Rather, each linear component is radial to the inner Imbrium basin. Because of this and because of the difficulty of tracing mountain walls on the other side of the Serenitatis basin, we conclude that the Serenitatis basin is older than the Imbrium system.

The two plates illustrate several characteristics of the radial systems:

(*a*) The crater Auwers and several others W (lower right) of Menelaus have remarkably rectangular outlines. Often the wall which would lie on the side toward the parent basin is missing. A sequence exists from normal, round craters to these box-like objects, indicating various stages of modification.

(*b*) There is a tendency for individual mountain masses to show a central cleavage. Some such cases are marked *R* in Plate 24.6. They have at times been considered gashes left by flying fragments, but a faulting mechanism is considered here. The well-known dome N of Menelaus on the Serenitatis plain shows a similar cleavage (see Pls. 24.6 and 24.7) not attributable to a flying fragment. Urey (e.g., 1962*a*) has argued that had there ever been extensive melting in subsurface layers, the mountains would have been unstable and subsidence would have occurred. It is suggested that the Haemus Mountains are to be interpreted in just this way. There is strong evidence (Hartmann and Kuiper, 1962) that most of the basin structures were created well before the formation of the maria, and we may assume that the Haemus Mountains pre-date the melting in this area. Therefore, the fissuring of these mountains may have been caused by subsidence, with the direction of the faults attributed to fractures generated by the Imbrium impact.

(*c*) Individual ridges roughly 8 km by 3 km are also present. They share in the alignment of the Imbrium radial family, but are difficult to explain by either gouging or tectonic mechanisms. However, we see much evidence that by some process, probably involving melting in subsurface layers, mountain masses in flooded regions are broken up. Near major basins the fragmentation is along radial lines. These ridges are therefore likely to be the remains of more imposing pre-mare structures. Alternatively, the ridges could be extrusions along radial fractures.

Baldwin (1963, p. 323) states that the Haemus Mountains "have been almost obliterated [by] Countless valleys, great and small, [which] have been ripped through this range. . . . It can only mean that the valleys were dug by missiles from the collision zone." The writer believes that the term "valleys" is inadequate to describe all the radial structure in the Haemus Mountains, and questions this general interpretation.

It has been stated that the grooves cut the higher areas and skip the lower areas, indicating that projectiles carved them (e.g., Steavenson, 1919, and Baldwin, 1963, p. 323). However, examination of, e.g., Plates 24.6 and 24.7 shows that, instead, the

Imbrium radial structure in the "upland" regions is present at *all* levels. The smoother areas are avoided, and while it is true that these tend to be at lower levels, it seems clear that the distinction between areas with and without radial structure is not one of elevation, *but of surface type*. Not all of these smooth areas are the dark mare material. Radial grooves of the Imbrium system are never found in the maria, although a few radial ridges protrude above their surfaces. The maria must be the result of flooding, and their surfaces must have formed after the radial system itself. However, there are relationships between the mare surfaces and the radial structures that suggest that both are the product of a high-temperature stage of lunar surface history.

These concepts will be used and verified in the discussion of the remaining plates.

Plates 24.8-24.10 show the Apennine region. Some ridges in these mountains exhibit radial structure. The pattern is most prominent along the shores of Mare Vaporum where the uplands have been most affected by flooding. The plates show extensive flooding in the Haemus Mountains and reveal several unusual upland areas which are darker than even the maria. Some radial features are seen inside the Apennine ring (bottom). An example is the rectangular depression flooded with dark material N of Conon. Plates 12.24-12.27 also show the radial pattern in this area.

Plates 24.11 and 24.12 cover the upward adjacent region. Various classes of radial features are represented here. Nearly half the floor of Julius Caesar (left-center on Pl. 24.11) is dark, flooded, and smooth; the other half is light, higher, and grooved parallel to the Imbrium family. Elongated, flooded depressions, similar to those N of Conon, are found S of Manilius (left-bottom on Pl. 24.12); especially remarkable is the rectangular end of the depression nearest Manilius. In the central region of the Haemus Mountains is an elongated trough roughly 30 km by 110 km (lower left-hand corner of Pls. 24.11 and 24.12; Pls. 24.6 and 24.7), and along the NE (left) side of Julius Caesar lies a similar formation roughly 17 km by 85 km.

Troughs of this sort usually contain craterform segments. The NW branch of the Hyginus Rille (lower-right, Pl. 24.12) illustrates that crater chains can develop along rilles. Also, visual observation of the Ariadaeus Rille (above center), similar in form to the SE part of the Hyginus Rille, establishes that it is a graben (Kuiper, 1959; Fielder, 1960). Therefore, we have evidence that craterlike objects up to 5 km (or 11 km if one includes Hyginus itself) can form in chains along graben-producing faults. Shoemaker (1962, pp. 290, 301-303) suggests that these craters are analogous to terrestrial maars, "opened by piecemeal spalling and slumping of the walls of a volcanic vent," and that they reach diameters of 15 km in lunar chains. The larger, trough-like features with their craterform segments may be related to these crater chains. Discussing the Stadius chain, Baldwin (1963, p. 378) states, "These craters were formed along an existing crack, and the eruptions which formed them probably were primarily gas venting or gas explosions." While this seems the best explanation of the craterform segments, the scarcity of crater chains in the radial systems remains puzzling, as does the appearance, instead, of large troughs. The crater chain in the NW part of the Hyginus Rille is exceptional in sharing with the Imbrium alignment.

High-resolution photographs with low lighting (e.g., Mt. Wilson 124) show that the rille on the E side of Hyginus is continued nearly to the highlands in the SW part of these plates as a fine *en échelon* series. The Ariadaeus and Hyginus Rilles define a direction which is different from the Imbrium system and is not radial to any nearby basin. The cause of alignment in this direction is unknown.

Fielder (1961*b*) has measured the distortion (one minus the ratio of the axes parallel and normal to the "grid system" axis) of craters in this region. He finds (p. 3) that "the craters are distorted preferentially, with their longer axes in the direction of the most prominent [i.e., Imbrium] family of the grid system," and that "Segregation of the craters . . . in accordance with their age shows, that . . . the mean percentage distortion of the old craters is considerably greater than that of the young craters." No dependence of distortion on size was found. The two age groups were defined by ". . . characteristics such as ease of recognition of a crater and the height, or degree of erosion, of its walls; but *not* by considering the degree of distortion of its walls." Fielder believes (pp. 6-7) ". . . that the oldest craters have been deformed so greatly from the circular shape that the deviations from radial symmetry cannot be explained by tensions alone. It is suggested that the deformations arose as a consequence of thrust faulting." However, characteristics of certain recent craters and "the rilles — recent graben features —" lead him to suggest a more recent tension. He concludes, "All the observations may be explained by supposing that the crust of the Moon was in compression when the oldest visible craters were formed and that, more recently, the stresses reversed in sign, to become tensions."

In the writer's opinion these mechanisms are improbable. Most of the linearity in this area Fielder takes to be the result of an early compression. This implies that either (*a*) the radial structure of this area is independent of Imbrium, or (*b*) Imbrium formed before the expansion began and is a very old feature. Either of these alternatives is difficult to accept. Fielder's distortion measures may be criticized. For example, a chart of his 134 craters shows that the most prominent elongated depression S of Manilius and the trough along the NE of Julius Caesar (already discussed) were divided into three craters each. We have noted the craterform segments here, but it is difficult to accept the inclusion of such "craters." Fielder's statistics may be interpreted as semi-quantitative proof that the pre-Imbrium, premare features have been deformed along lines radial to Imbrium while the post-Imbrium features are seen in approximately their initial state. The evidence for compression is considered inconclusive.

Returning to Plate 24.12, we note that partially-destroyed craters show a relationship to the radial system (e.g., just NW of Julius Caesar). The front and rear walls, with respect to Imbrium, have vanished, leaving the sides standing as radial ridges. Although Beer and Mädler clearly described this phenomenon in 1837, there has been little comment on it recently. In their words (Beer and Mädler, 1837, p. 250), the craters in the area between the Haemus Mountains and the Ariadaeus Rille are "bordered by walls only on the particular sides which coincide with the general lineation."

Further light on the relation between crater walls and radial systems is shed by Plates 24.13-24.15, showing the area around Ptolemaeus. (An overlay outlining the radial structures is added in Pl. 24.21.) The walls of nearly all of the craters bordering the S edge of Sinus Medii are broken up into linear ridges aligned with the Imbrium system. Réaumur and Oppolzer present the best examples. One must assume that these were once ordinary craters, pre-dating both the mare flooding and the formation of the Imbrium radial system. All that remains of the wall of Oppolzer, which lies on the mare surface, are a few ridges, predominantly aligned with Imbrium. The N wall of Réaumur, also lying toward the mare, though not in a completely-flooded area (see Pl. 24.14), is similarly broken into ridges roughly 9 km by 4 km, each aligned toward Imbrium. The S wall of Réaumur, on the uplands, is relatively undamaged. Similar structure is found in other craters, e.g., the large ring W (right) of Ptolemaeus. Further, the E and W walls of Ptolemaeus show linearities aligned with the radial pattern. It is not just the crests of these walls which are damaged; they have been cut clear down to the level of the mare.

In summary, the walls of pre-mare craters lying on or near mare surfaces tend to be broken up into linear segments which are aligned with structures in nearby radial systems. The amount of fracturing is correlated with the degree of local flooding, whereas the alignment of the fractures relates to the nearby large basin. These correlations would be unexpected and are unexplained by the hypothesis of flying fragments.

Incidentally, Plate 24.13 shows W of Rhaeticus a groove-like structure not radial to Imbrium. It is marked by a dotted line on Plate 24.21, where it is seen to parallel a local, non-Imbrium grid pattern. It is so similar to certain Imbrium grooves (e.g., the one which joins it at its S end) that one may ascribe a similar origin to it. However, one can not attribute it to a flying fragment unless one assumes that the fragment came from Serenitatis. This and other parallel structures in this region form part of a "grid" system marked by dotted lines on Plates 24.20 and 24.21. The relation of this system to Mare Serenitatis will be further investigated.

The southern extension of the area just discussed is shown in Plates 24.16-24.19; Plate 24.20 adds an overlay map of the region. The areas of Plates 24.13-24.19 are known for a large number of grooves or trough-like features, similar to those pointed out near Julius Caesar. These are probably the most discussed of the radial structures and have been considered the strongest evidence for the grooving action of flying fragments. Fielder (1961*a*) not only suggested "a clearly defined association between blocks and grooves," but concluded that "... there is a marked tendency for the blocks to be elongated and to be so oriented that their major axes are generally roughly coincident with the axes of their associated grooves." We have already noted the tendency for the pre-mare structure to be broken into radial ridges, and the elongated blocks may be of such origin. It may be noted on Plates 24.13-24.15 that the often-discussed groove near Herschel, as well as some others, has more than one ridge on its floor. The sculpture of such ridges from existing terrain would require multiple impacts of flying fragments along the same groove. Similarly, the groove running for some 230 km from near Lalande to Alphonsus is resolved into nearly parallel segments and would seem to require multiple impacts along a very narrow azimuth interval radial to Imbrium. Baldwin (1963, p. 325) in fact assumes this: "It is the result of at least ten. . . impacts by missiles . . . which were ejected on almost identical paths." The high-lighting views of Plates 24.14 and 24.18 reveal that the walls of these grooves are frequently bright, but the floors are generally darker. If the valleys were carved by flying fragments, we might expect the walls and floors to be covered by bright, pulverized material, as is true of recent craters on the maria, although it could be argued that these valleys are analogous to many pre-mare craters in being dark floored. On the other hand, many valleys have raised rims, ruling out a simple subsidence origin. A comparison of photographs at varying illumination (cf. Pls. 24.16 and 24.17) confirms the earlier statement that the radial structures occur at all levels in the rough uplands, but that other surface types lack them.

Urey (1962*b*, p. 134) believes that the Imbrium collision should have produced many "narrow and closely spaced" fissures in this area, and Shoemaker (1962, p. 349) speaks of radiating faults. The writer suggests that much of the radial structure has been produced by subsidence and/or volcanic action along such fissures. However, the impact hypothesis presupposes that material was hurled from the Imbrium basin center, and consequently, secondary impact structures must exist. The question is not whether flying fragments existed, but whether they are responsible for the varying types of radial structures with widths from a few to tens of kilometers. The secondary impact craters around recent craters such as Copernicus are typically slightly oval pits, not grooves. Perhaps the most likely candidates to be the secondary impacts of Imbrium are small pits about 1 km across with grooves trailing out of them, away from Imbrium. These are not seen on the plates here reproduced, but are shown in the USAF-NASA lunar charts (1963; e.g., LAC-77, near Albategnius).

Plates 24.13-24.19 show the ridge structure in Alphonsus to be aligned with the Imbrium system. This is another case where alignment alone does not prove a simple or direct causal relationship. Nonetheless, this deformation of the floor of Alphonsus may be related to the stress field surrounding Imbrium.

Comparison of the high- and low-lighting views of the region around Ptolemaeus points out that the customary division of the lunar surface into bright uplands and dark maria is incomplete. Great expanses of the surface, e.g., the area of Hipparchus, the floor of Ptolemaeus, and the region of Flammarion and N of it, are smooth with a slightly higher density of crater pits than the mare surfaces. They are usually depressed with respect to the rough uplands and have many "ghost craters." They are bright under high illumination and form an intermediate-type surface between the rough, bright uplands and the smooth, dark maria. Existing theories do not clearly explain the form and distribution of these areas. One might suggest that during some stage of lunar history parts of the crust melted to various degrees, causing a leveling of relief, and that later many of these areas were flooded by the dark material. This suggestion, of extensive melting as a separate process from flooding, differs from a concept equating melting with an immediate inundation by dark lavas. Alternatively, these smooth areas may be covered by ignimbrites resulting from ash flows, as discussed by O'Keefe and Cameron (1962). The area from the Haemus Mountains to Ptolemaeus contains much surface area of this intermediate type. The suggestion that much of the radial structure in this area was produced by subsidence and breakup of a wide area of stressed crust with associated volcanism during a high-temperature stage is consistent with the above observations. This also would account for the distribution of the dark mare material in the circular basins. The darker material was probably produced at greater depth and reached the surface only in areas where the surface layers had been severely damaged, namely, in the large impact basins and their concentric subsidence zones.

In the northern Mare Nubium, to the W of Ptolemaeus, lies a region containing some of the most interesting examples of ridges and deformed craters as parts of a radial system. Plates 24.22-24.25 show this region, continuing the scale of the preceding plates. The low-lighting views in the first two plates reveal a great amount of low relief, even in the mare. The relatively smooth but bright surfaces near Fra Mauro (cf. Pls. 24.23 and 24.24) are examples of the surface type noted above. A study of the relief near the apparently isolated ridges E and NE of Fra Mauro is instructive. For example, one ridge complex in the mare, Lalande η (Pl. 24.23), is continued by a curved wrinkle ridge, giving the appearance of a crater whose E wall has been almost completely destroyed. This is a further case of a partially destroyed crater whose walls are broken down preferentially with respect to the radial system. Another clear example is Parry M. Here the front wall (facing Imbrium) is missing, the back wall is broken, but the side walls are intact despite the fact that the mare abuts closely on the E (Pl. 24.24). There can be little doubt that this was once an ordinary crater; the fact that its N wall cannot now be traced testifies to the presence of some agent remarkably effective in reducing relief in localized areas. Again, Fra Mauro has suffered damage mostly on the E side, which is nearest to the mare surface. Many craters in the Sinus Medii area (Flammarion, Sömmering, etc.) show similar structure. Similar evidence was cited by Fielder (1961*a*, p. 183) as evidence against modification by flying fragments. The resemblance between some of these disturbed crater walls and the isolated ridges suggests that these ridges are the remains of more complex mountain or crater structures which have been almost completely destroyed. They are thus further evidence that a process of crustal breakup has left individual blocks aligned with nearby radial systems. The northern walls of Hipparchus, Réaumur, Oppolzer, Flammarion, and Parry M may show this breakup in sequence. The lower lighting views (Pls. 24.23 and 24.25) reveal that the floors of Fra Mauro and its southern neighbor Bonpland are lined by both rilles and ridges which are aligned with the radial system. The structure resembles the floor of Julius Caesar (cf. Pls. 24.11 and 24.12). The same plates show that the mountains N of Fra Mauro are scored by numerous valleys with similar alignment.

Plates 24.26 and 24.27 show the Carpathian Mountains, with the scale remaining the same (cf. also Pl. 12.19). These mountains extend the Apennine arc, but differ from it in being less massive and in showing more pronounced radial ridges. This is evident from a comparison of Plates 24.10 and 24.27. Baldwin (1949, p. 212) writes of this area:

> "... [W] of Mare Imbrium the crust sank considerably. It is even possible that the [magma] load caused so great an adjustment to occur relatively quickly that the [western] mountain border disappeared beneath the surface except for the scattered Harbinger peaks. The steady [westward] dip of the Carpathians and the mountains on the [NW] of Mare Imbrium support this view...."

The pronounced appearance of the radial ridges in the western Carpathians, coupled with our association of such ridges in the Haemus Mountains with crustal breakup, supports in a general way Baldwin's view. Urey's suggestion that these ridges are masses thrown out from the impact site does not explain the very similar aligned ridges forming the walls of Oppolzer, Réaumur, Parry M, and other craters. A tectonic process of crustal breakup and/or extrusion is more suitable. It is significant that the part of the Imbrium outer arc which shows this ridge structure most plainly is that very part where the mountain arc dwindles out into flooded maria, a correlation already noted above concerning the Haemus Mountains.

Farther out from this region, near the SW shore of Oceanus Procellarum, are additional structures which appear to be aligned with the Imbrium system. These are shown in Plates 24.28 and 24.29. Several ridges are seen NW (right) of the crater Hansteen (central on Pl. 24.28), including two which form a box-like valley typical of other radial structures discussed earlier. The larger, flooded crater to the NW shows the characteristic pattern of a missing front wall (downward) and aligned side walls. As was pointed out by Kuiper (1959), the Sirsalis Rille, lying on the opposite side of the basin from the Alpine Valley (see Pl. 24.40), is aligned with the Imbrium system. Kuiper has suggested (p. 304) that the rille "... is therefore a major structural feature of the Imbrium impact....," and that both features were generated during a non-vertical Imbrium impact by a horizontal thrust component toward the Apennines. He points out, however, that this puts the Sirsalis Rille "in a class by itself."

Features similar to those of the Hansteen area can be found in a similar region further to the N, on the W shore of Oceanus Procellarum. The region near O. Struve is shown in Plate 24.30. A linear ridge forming the S wall of O. Struve and a linear valley in the N wall are seen to be aligned with the Imbrium basin. Similar ridges and valleys are found in the uplands SW of here, where the peak marked *P* displays a split appearance similar to examples noted in the Haemus Mountains. These shoreline regions of Hansteen and O. Struve are further examples of radial structures lying close to mare surfaces.

Plate 24.31 is a rectified view of the outer western part of the Imbrium system. The radiating ridges of the Carpathians and similar ridges near Kepler are shown well, and the ring of peaks marking the Inner Basin is marked. It is interesting to note that several of the elongated blocks *of the ring* are oriented parallel to the ring, not radial to it. Among the peaks near Delisle, the uplands near Sinus Iridum, and the Harbinger Mountains, little radial structure is seen. The significance of this is not clear; it may be that any Imbrium stress pattern in the region of Sinus Iridum was altered by the formation of that bay. A significant problem is the reason for the differences in form between the Caucasus, Apennine, Carpathian, and Harbinger Mountains, which constitute what appears to be a single structural arc of the Imbrium system. Non-isotropic stresses from a nonvertical impact may be involved.

A prominent feature of Plate 24.31 is what Kuiper has called the "Aristarchus Uplift." In 1959 he wrote (pp. 296, 299):

> "... The Uplift is seen as a diamond-shaped area that is slightly yellowish in color — which is entirely exceptional on the Moon .... [This] area itself has clearly been uplifted and cracked into several large blocks, some of which have been left in a tilted position .... On the lower border one finds an isolated ridge (locally composed of three parallel ridges) ... the structural lines of the Aristarchus Uplift are radial and orthogonal to the Imbrium Center. It is therefore very probable that the Uplift occurred as a result of the Imbrium impact. ..."

Plates 24.31 and 24.32 confirm an approximate alignment of the plateau edges with the Imbrium system. Plates 24.33-24.35 show rectified views under various lightings. There is no doubt that the area is elevated relative to the mare. In view of the previous discussion it seems uncertain whether the area has been raised or the surrounding crust has subsided during a flooding which produced Oceanus Procellarum. Schröter's valley may be analogous to the large graben which frequently cut across major terrestrial uplifts. In either case it is likely that the rectangular outline is associated with the Imbrium fracture pattern. Evidence in support of this, besides alignment, is the ridge structure along the N edge. Examination of the plates reveals that this ridge forms the N side of a flooded trough about 34 km by 170 km, strikingly similar to others in the radial system, e.g., that through the central Haemus Mountains (about 30 km by 110 km) shown in Plate 24.12 at the same scale. Plate 24.35 also reveals that one of the ridges (marked *R* in Pl. 24.34) near the middle of this trough and a small mountain just W of Herodotus show a split appearance as found among the Haemus peaks, and that several parallel valleys about 3½ km wide cut the northern plateau surface. Some ridges on the southern half of the plateau, near Herodotus, appear to share the alignment. What appears to be an aligned, block-faulted region nearly 70 km wide just N of Aristarchus is also noteworthy. The Aristarchus plateau could be interpreted as an upland mass which, while not flooded, is bounded by subsided, flooded regions and shows signs of block faulting and other radial structure along stress lines created by the Imbrium impact. The peculiar surface color and the tone, darker than most upland regions, remain unexplained.

The similarity of many structures in Plates 24.28-24.35, considerably W of Imbrium, to those of earlier plates in the E and S is evidence of the structural unity of the radial system.

The northern reaches of the Imbrium system are shown in Plates 24.36 and 24.37. This region is marked by the curious upland arm containing the Alps, Plato, and Sinus Iridum (see also Pls. 24.1 and 24.40). The opening remarks of this section leave uncertain the nature of this upland arm, which is only roughly concentric with the Imbrium Inner Basin, and which lies in part in the expected position of an inter-mountain zone (see Pl. 12.24). One might consider the arm made up of three parts: the Alps, which are part of an intermediate, raised arc of the Imbrium structural system and analogous to those of other basin systems (Hartmann and Kuiper, 1962); a raised area around the post-Imbrium, pre-flooding Plato impact; and a raised area around the post-Imbrium, pre-flooding Sinus Iridum impact. We thus suppose that the Plato and Iridum impacts are principally responsible for the relief in their neighborhoods. They altered the stress fields set up by the Imbrium impact and therefore locally altered the symmetric pattern of subsidence around the Imbrium system. The relative lack of tectonically-produced Imbrium radial structure in the Plato and Iridum uplands is accounted for if these uplands were molded chiefly by post-Imbrium forces.

In addition to the unusual Plato-Iridum arm we note the absence of a mountainous scarp along the northern projection of the Carpathian-Apennine-Caucasus arc (see Pl. 12.24). The northern border of Mare Frigoris may correspond to this expected relief. At any rate, as the plates show, it is N of this border that the Imbrium radial system again assumes full prominence. These pictures take us close to the limb where a streakiness due to elevation differences is introduced by the rectification process; this must not be confused with true radial structure. One of the most interesting structures related to the Imbrium system is the large square formation, W. Bond, well shown in Plates 24.36 and 24.37. It gives perhaps the most striking demonstration of the alignment of walls of large craters, a situation already cited in Ptolemaeus. Further, it is bounded on E and W by two remarkable valleys, about 16 km by 90 km and 28 km by 140 km, respectively. The valleys themselves contribute to the rectangular appearance and show striking similarity to the large troughs bordering the Aristarchus Uplift, in the Haemus Mountains, and along the wall of Julius Caesar. Local curvature of the valley walls in several places produces strong resemblances to craters some 20 km across. A prominent example of the latter forms the N end of the valley E of Bond. The crooked shape, the highland mass closing the Imbrium end, the craterform segments, and symmetry with the valley on the other side of Bond indicate that this valley is not a groove carved by a flying fragment. The craterform segments may therefore indicate non-impact craters (maars?) of up to 20 km diameter on the moon.

The entire region of W. Bond is scored by Imbrium radial ridges and valleys. Several examples of craters with the "front" wall missing are found on the border between the mare and upland; one case on a promontory SW of Bond bears some resemblance to Oppolzer. Plates 24.36 and 24.37 show a tendency for the linear structure to exhibit a local *parallelism* while forming part of a larger radial system.

Plate 24.38 shows the region of J. Herschel, lying to the W of the preceding field. The crater South, identified on the plate, is another remarkable example of a large, damaged "crater" with linear, aligned walls. One may also note the angular outline of J. Herschel, showing alignment with Imbrium and resembling Ptolemaeus and the valleys in the surrounding uplands. The striking similarity of radial structures in these uplands to those near Ptolemaeus (cf. Pl. 24.13) testifies to the structural unity of the Imbrium radial system. The alignment of linear walls in Ptolemaeus, J. Herschel, South, W. Bond, and many smaller examples contradicts Baldwin's statement (1963, p. 427) that "The polygonalism of many lunar craters is a normal [i.e., intrinsic] aspect and is not a part of the lunar grid system."

Plate 24.39 shows aligned structures in and near Mare Tranquillitatis. Certain features in the uplands are aligned with the Imbrium system and are similar to those noted before. On the mare surface, however, we see a prominent family of parallel lineations, including the Cauchy fault and at least three major, and numerous smaller, wrinkle ridges. Rilles in the area exhibit a similar parallelism. This may be seen near Cauchy and Sabine and is clearly marked in the neighboring Mare Fecunditatis on the chart of rilles by Arthur (1962*a*). The ridges may be the surface expressions of flooded formations under the mare surface. (This is clearly the case with the flooded crater Lamont.) These structures should be classed either as a local parallel grouping of the Imbrium system or as part of an independent grid system.

Some other regions not shown here may be mentioned. High-resolution views of the Taurus Mountains show many linear features which are roughly aligned with Imbrium (Arthur, Whitaker, private communications; cf. also Mt. Wilson 80). Palus Somni shows similar fine features; some coarser ones can be seen on some plates accompanying the Crisium discussion (Pt. II). The Rheita Valley and neighboring linear structures, often considered to be associated with the Imbrium system, appear in later plates showing the Nectaris region.

A synthesis of the linear features described in this paper is given in Plate 24.40. The rectified photograph was taken at a distance equivalent to about 10,500 km above the center of the Imbrium basin. Each red line represents a structural feature and indicates the length and direction of each. This representation should provide a truer picture of the nature of the system than some earlier charts where lines were used that were much too long. Plate 24.40 is intended as a summary of the distribution and relative sizes of the Imbrium radial structures rather than a detailed map showing every known example.

4. *Conclusions*

There is unquestionably a major system of diverse linear structures radiating from the Imbrium basin. Several structural types may be listed. In the unflooded uplands, many valleys roughly 10 by 100 km define a prominent radial pattern (e.g., regions of Ptolemaeus and J. Herschel). Wider, aligned troughs roughly 30 by 120 km frequently show craterform segments (Haemus Mountains, N border of Aristarchus plateau). Walls of polygonal craters (Ptolemaeus, J. Herschel) and craterlike formations of remarkably rectangular outline (Auwers, W. Bond, South) are typically aligned with these systems. In areas characterized both by major mountain masses and extensive flooding, the mountain blocks typically take the form of radially-oriented ridges of lengths some 5 to 10 km (Haemus, Carpathian Mountains). Mountain blocks in such regions often show a split or grooved appearance (Haemus Mountains, N border of Aristarchus plateau). Crater walls lying in proximity to areas of extensive flooding are often made up of parallel, ridgelike segments aligned with radial systems (Réaumur, Oppolzer). In many craters, usually close to areas which show flooding, the wall toward the basin is missing or damaged; sometimes only side walls remain as ridges radial to the basin (Parry M, Lalande η).

The following observations are of special importance: (1) Some of the diverse structures, especially the ridges, cannot be the result of gouging. (2) There is some agent capable of drastically reducing surface relief, as noted in Parry M and Réaumur. (3) The dark regions described here as "flooded" appear to have a spatial relation to radial structure. (4) The elongated ridges in the mountain arcs around Imbrium, especially the Carpathians, are similar to those forming the walls of craters such as Réaumur. The conclusion that they are of similar origin contradicts the hypothesis that such ridges are masses thrown into place by an explosion. (5) Many valleys and troughs show craterform segments. (6) The Imbrium radial family overlies the majority of craters present and is therefore younger than they are, though older than the mare surfaces.

The above observations are consistent with the hypotheses that the processes which reduced relief and produced the flooding had a single cause, namely a heating and partial melting at depth after most of the craters and basins had been formed; and that a major impact at this time produced fractures along which crustal breakup, subsidence, volcanism, and possible extrusion caused most of the Imbrium radial system. In analogy with secondary pits near recent craters, there must be numerous secondary craterlets produced by Imbrium fragments among the field craters.

Differences in the types of radial structure in different regions may be attributed to differences in the effects of heating and to variations in pre-existing surface structure. Baldwin (1942) pointed out that

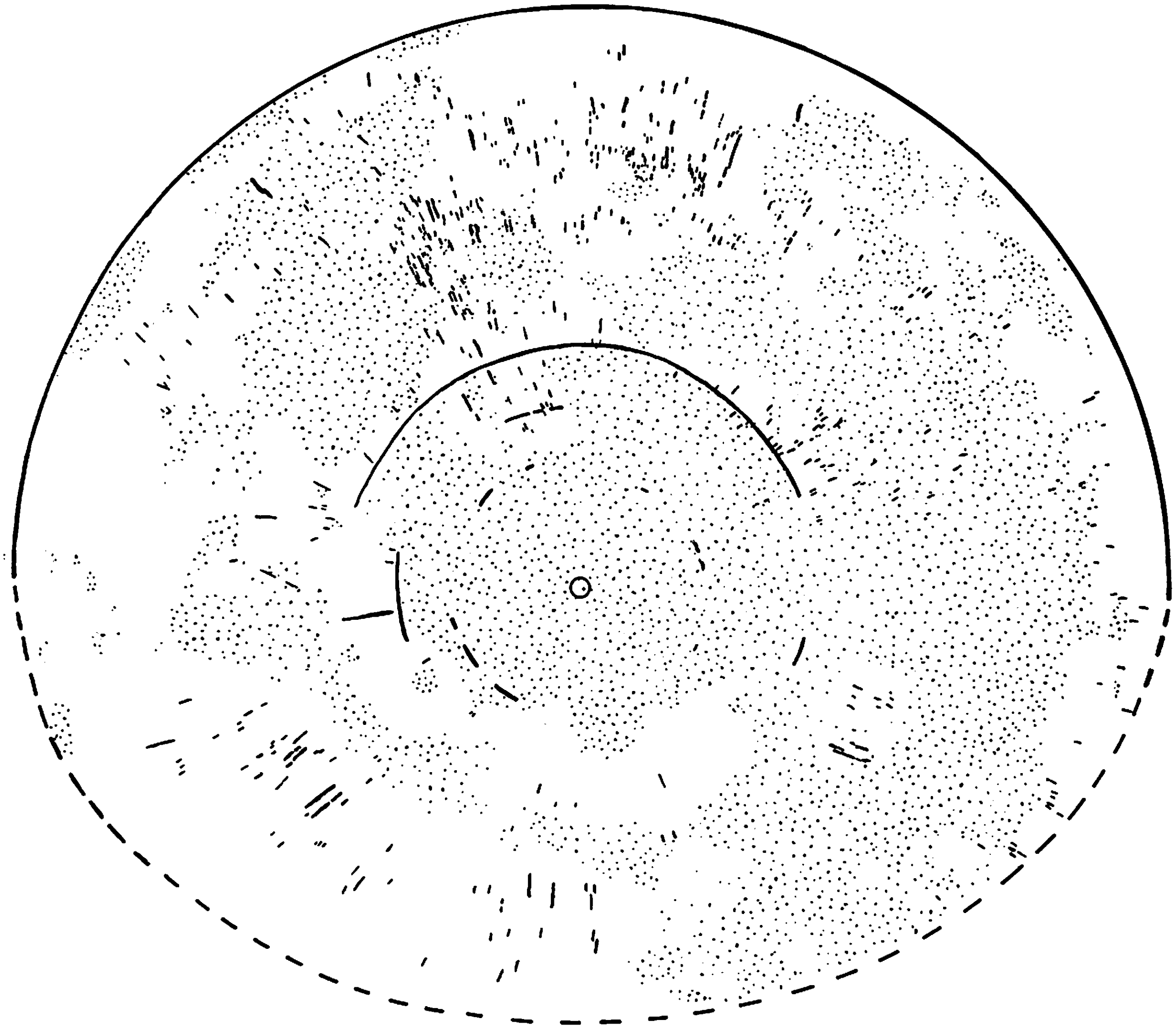

Fig. 2.—The Imbrium radial system, Imbrium concentric arcs, and distribution of the maria at the close of the "flooding" stage of lunar history. This diagram is based on the rectified photograph of Plate 24.40.

the ridges are on the average closer to the basin than the other structures. This follows at once if ridges were produced during the breakup of the mountainous arcs forming the boundaries of the basin.

In *Communications No. 12* an early lunar history involving impacts and radioactive heating was sketched. The observations presented here shed further light on this history. The heating of the moon was accompanied by an expansion, investigated by MacDonald (1960); this expansion set up crustal tension which may not have been generally relieved until partial subsurface melting allowed subsidence. Now consider the effect of a major impact somewhat prior to the maximum heating. By analogy with crater profiles, the impact must have tended to dome a vast area, creating additional tension. The shock front, as mentioned by Shoemaker (1962), probably caused radial fractures, also suggested by Urey (1962*b*). These fractures in a tensed, expanding crust, underlain at depth by partially-melted layers, would at once provide suitable conditions for the production of grabenlike features. Further heating and subsurface melting, with the release of volcanic products, primarily in the basins, could promote local faulting, subsidence, and extrusion along radial fractures in the regions of extensive flooding. Thus, tectonic effects during this period of maximum heating and flooding may explain in part the troughs, ridges, grabenlike valleys, the broken up mountain arcs, and the aligned fragmentation of crater walls. Subsidence along concentric arcs may have aided in producing such structures as the Apennine scarps. Most of these adjustments occurred when the heating and softening of subsurface layers first allowed such tectonic activity. Concurrently, or subsequently, flooding began. By the end of the flooding period vast expanses had been covered by smooth, dark deposits. The radial structures and concentric arcs of the Imbrium system, as well as the final distribution of the dark volcanic products at the end of the flooding period, are shown in Figure 2. (Post-mare features, such as Copernicus, are not shown.)

Just such a late pre-flooding impact has already been independently proposed as the origin of the Imbrium basin. The observations of the Imbrium radial structure serve to relate this proposed origin to the thermal history of the moon in a manner consistent with both the observed structure and the expected effects of the thermal processes.

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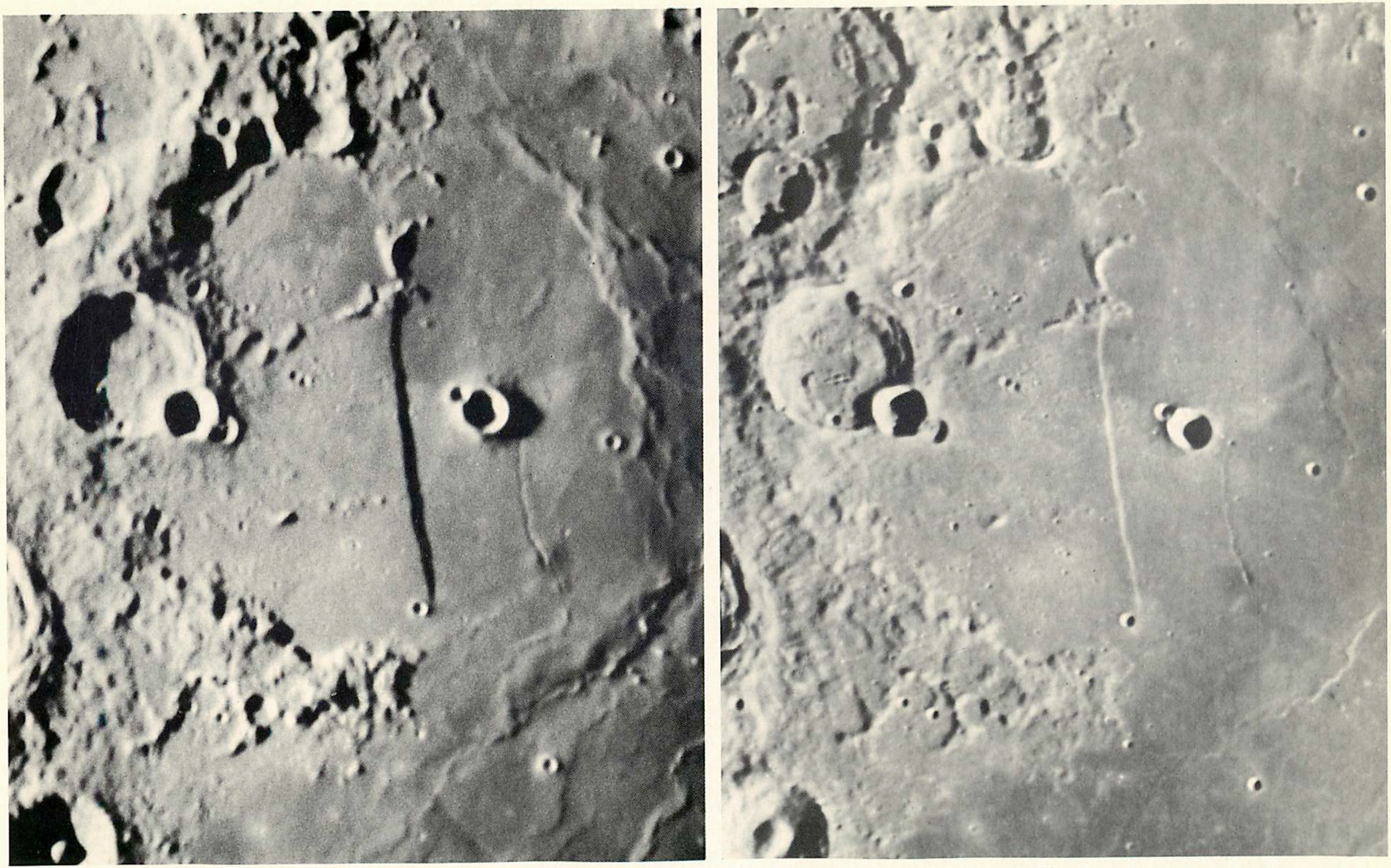
Plate 24.1.—View of the moon from above Mare Imbrium, showing mountain arcs and radial features. This plate serves to orient the later, larger-scale plates. Cf. Plate 24.40. Rectified; Y160; scale ca. 13 km/mm (1:13,000,000); col. 35°.1.

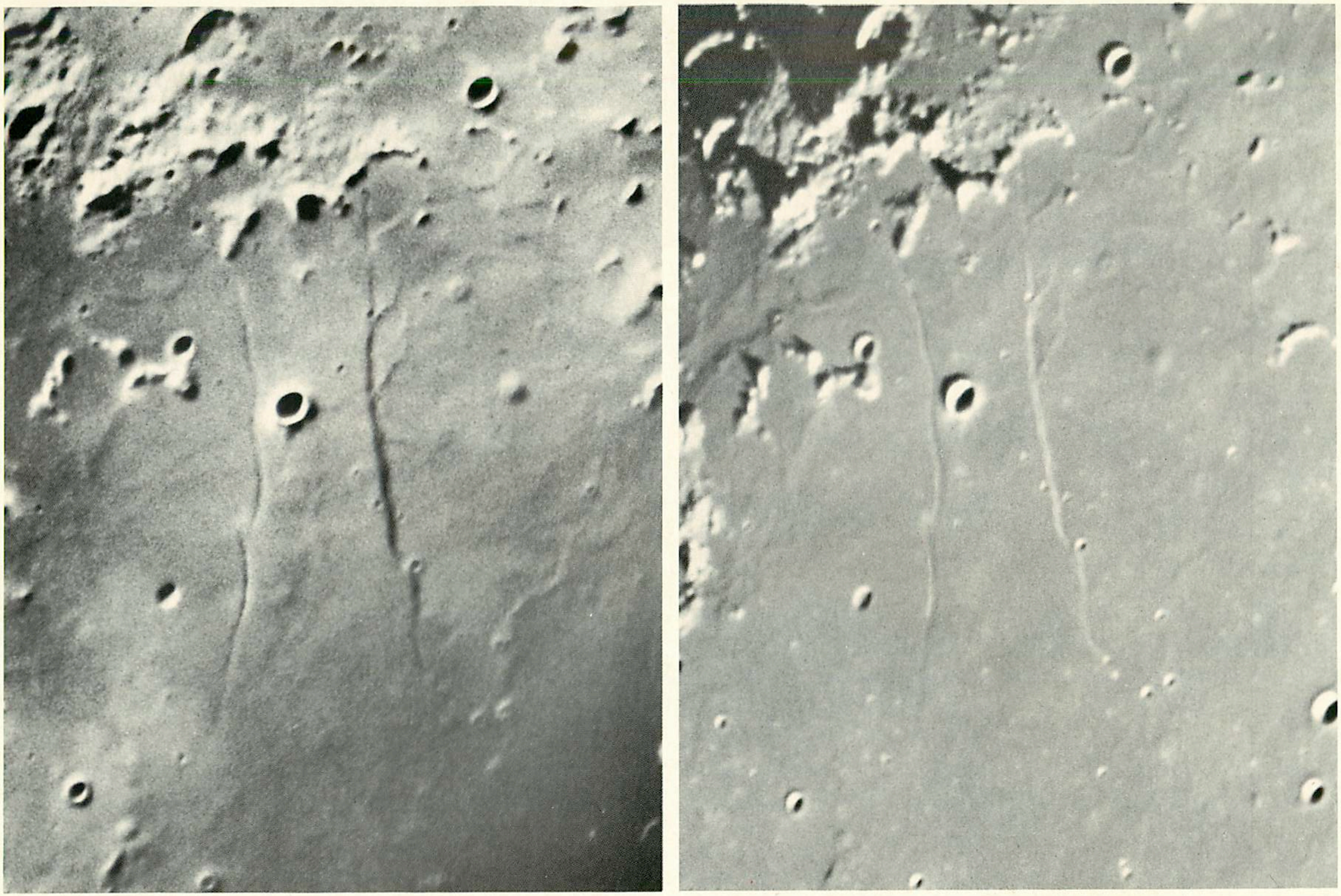
Plate 24.2.—Looking S from above center of Mare Imbrium. The radial pattern in the region from the Haemus Mountains to Fra Mauro may be verified. Rectified; Y1350; scale near center ca. 7 km/mm (1:7,000,000); col. 163°7.

Plate 24.3.—The Apennine Mountains and Mare Vaporum, showing radial structure throughout the upland surfaces. In this and other plates of selected regions, direction to Imbrium basin center is down. Rectified; Y1350; scale ca. 4.5 km/mm (1:4,500,000); col. 163°7.



(*a*) (*b*)

Plate 24.4.—The Straight Wall. (*a*) Not rectified; Y1271; scale ca. 2 km/mm (1:2,000,000); col. 13°.5. (*b*) Not rectified; W119; scale ca. 2 km/mm (1:2,000,000); col. 172°.0.



(*a*)

(*b*)

Plate 24.5.—The Cauchy scarp. (*a*) Not rectified; L17b; scale ca. 2 km/mm (1:2,000,000); col. 328°.7. (*b*) Not rectified; W80; scale ca. 2 km/mm (1:2,000,000); col. 134°.5.

Plate 24.6.—Haemus Mountains, with overlay marking some of the more prominent linear structures. *R*'s mark typical grooved ridges. Not rectified; Y1262; scale ca. 1.5 km/mm (1:1,500,000); col. 1°2.

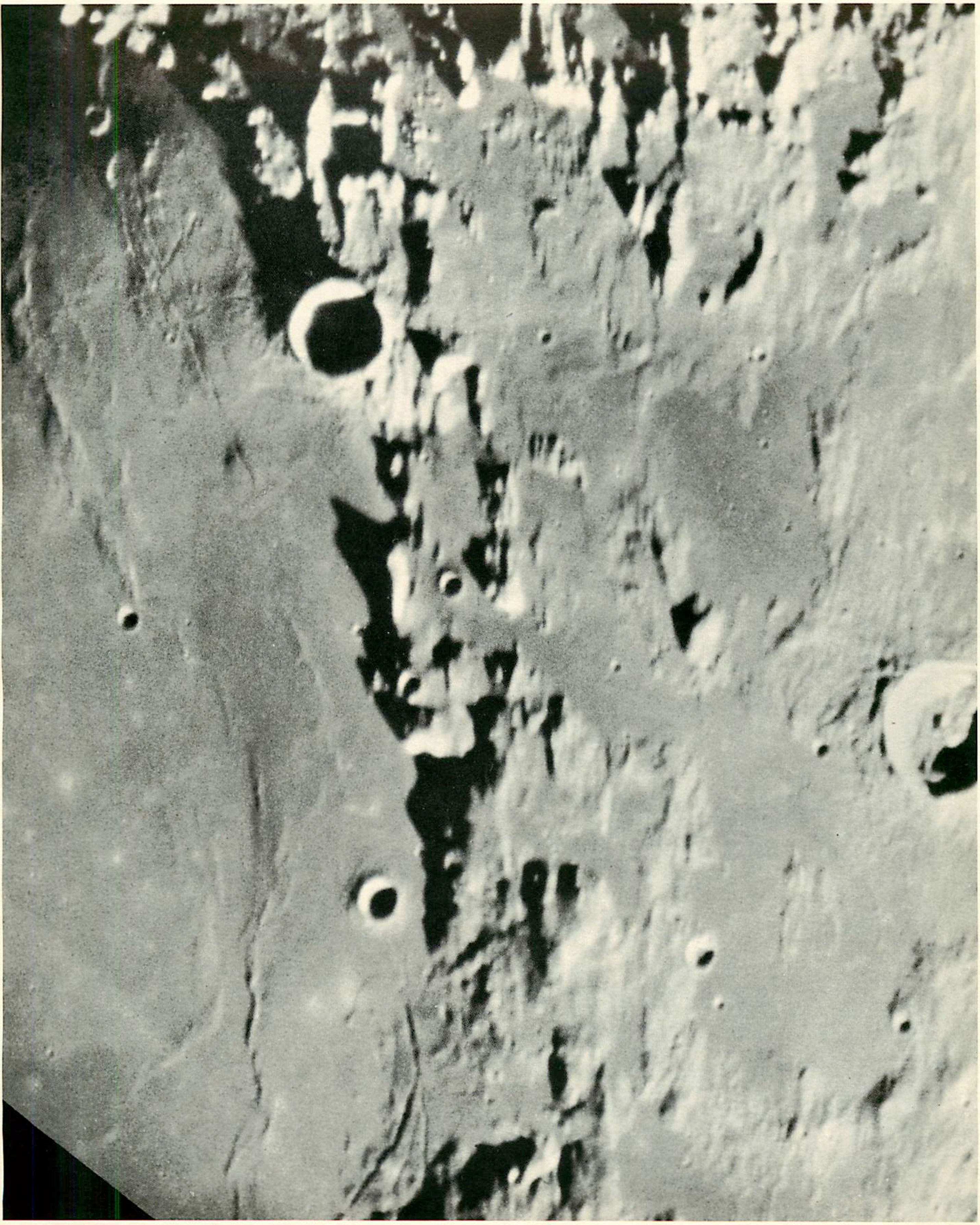


Plate 24.7.—Haemus Mountains. Rectangular outlines of some craters (e.g., Auwers) and large number of linear ridges are well seen. Not rectified; W111; scale ca. 1.5 km/mm (1:1,500,000); col. 159°.7.

Plate 24.8.—Apennine Mountains and Mare Vaporum. With Plate 24.10 this shows radial structure inside the Apennine arc as well as beyond it. Not rectified; Y150; scale ca. 3 km/mm (1:3,000,000); col. 10°.9.

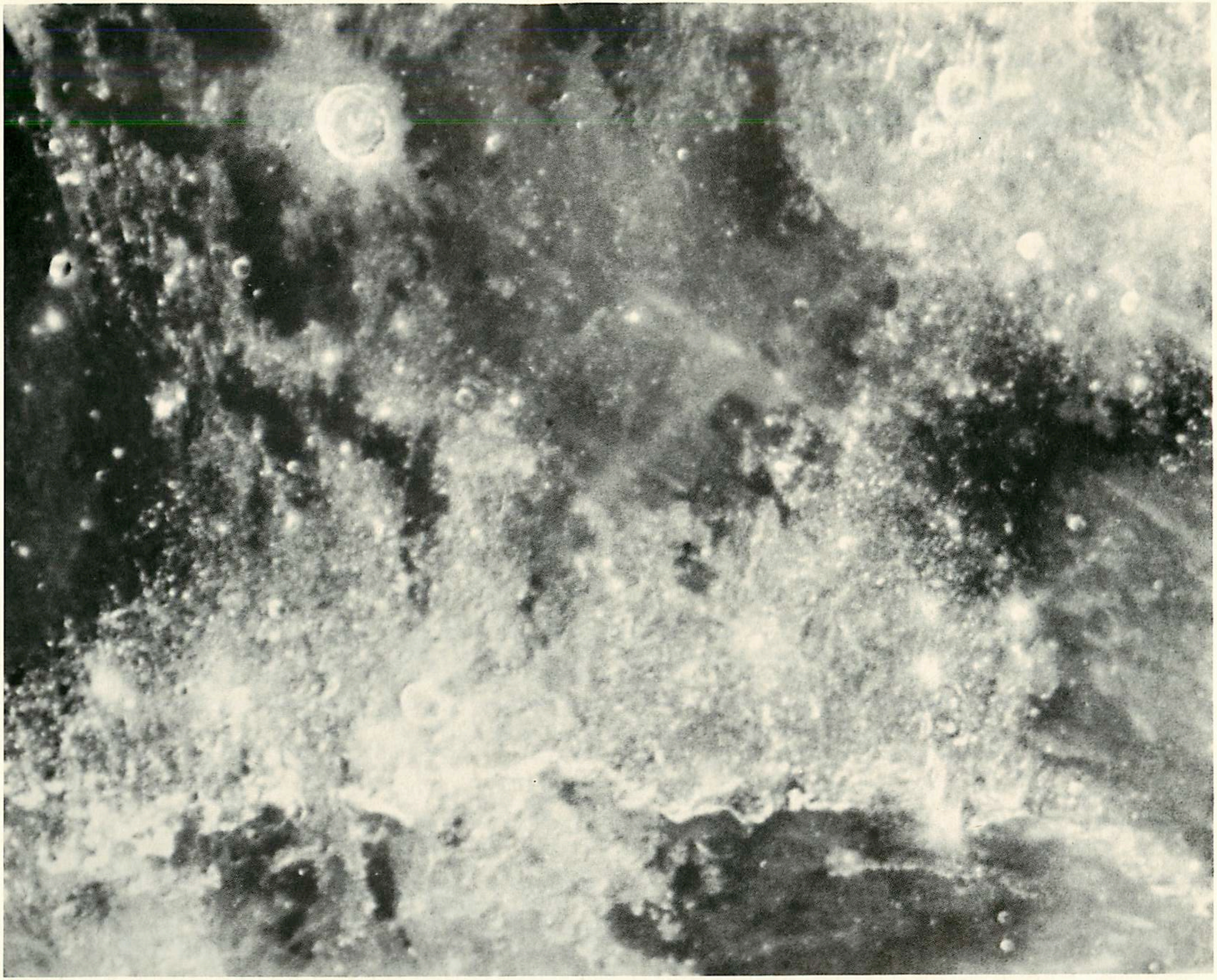


Plate 24.9.—Apennine Mountains and Mare Vaporum. This high-lighting view demonstrates the extensive "flooding" in the Haemus Mountains and parts of the Archimedes Island. Not rectified; Y1207; scale ca. 3 km/mm (1:3,000,000); col. 120°.5.

Plate 24.10.—Apennine Mountains and Mare Vaporum. Cf. Plates 24.8 and 24.9. Not rectified; W111; scale ca. 3 km/mm (1:3,000,000); col. 159°7.

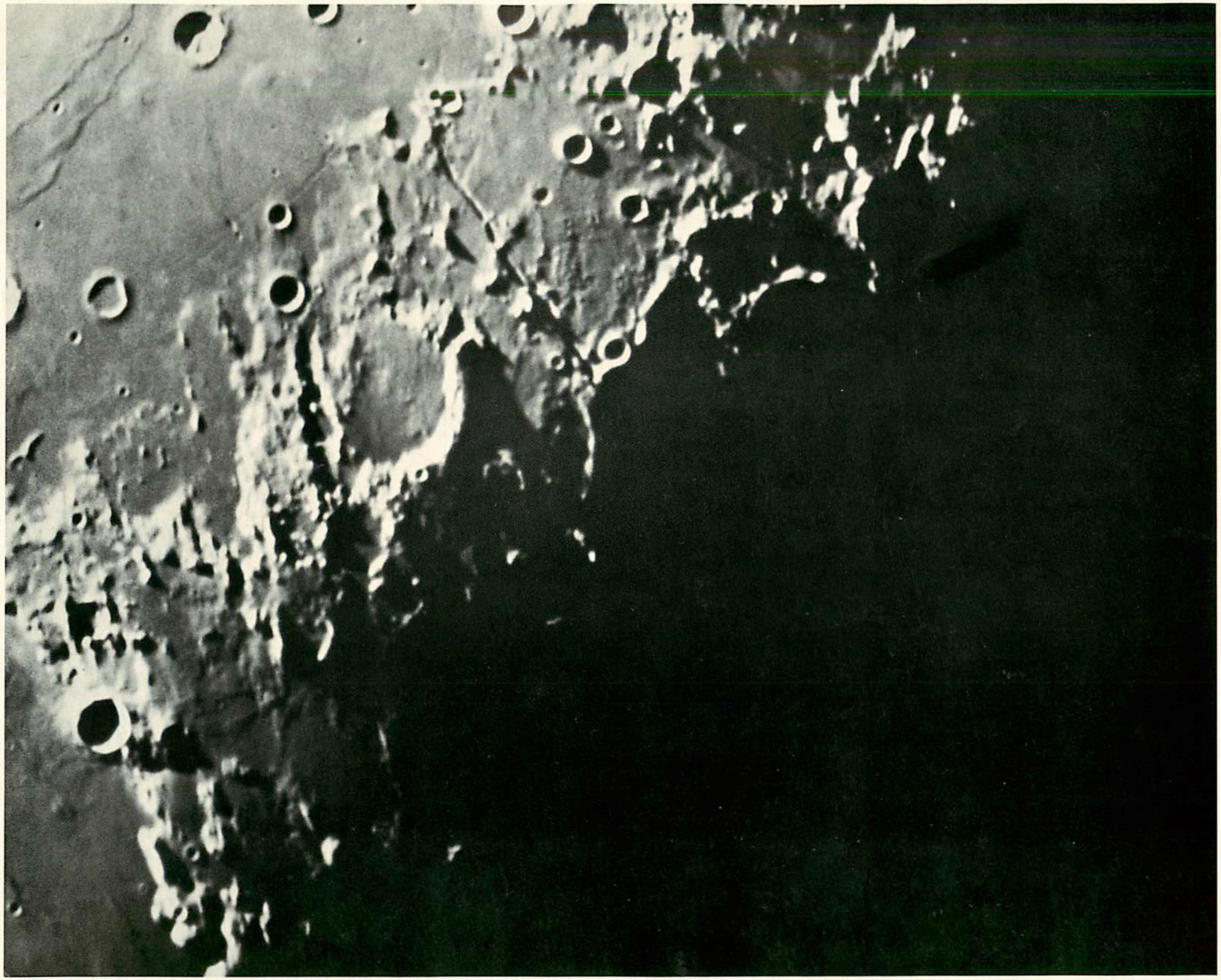


Plate 24.11.—Region of Julius Caesar. On Julius Caesar floor note distinction between raised, furrowed portion and "flooded," smooth portion. Cf. Plate 24.12. Not rectified; Y744; scale ca. 3 km/mm (1:3,000,000); col. 348°3.

Plate 24.12.—Region of Julius Caesar. Note rectilinear valleys, and similarity of troughs in Julius Caesar NE wall and in central Haemus Mountains. Not rectified; W111; scale ca. 3 km/mm (1:3,000,000); col. 159°.7.

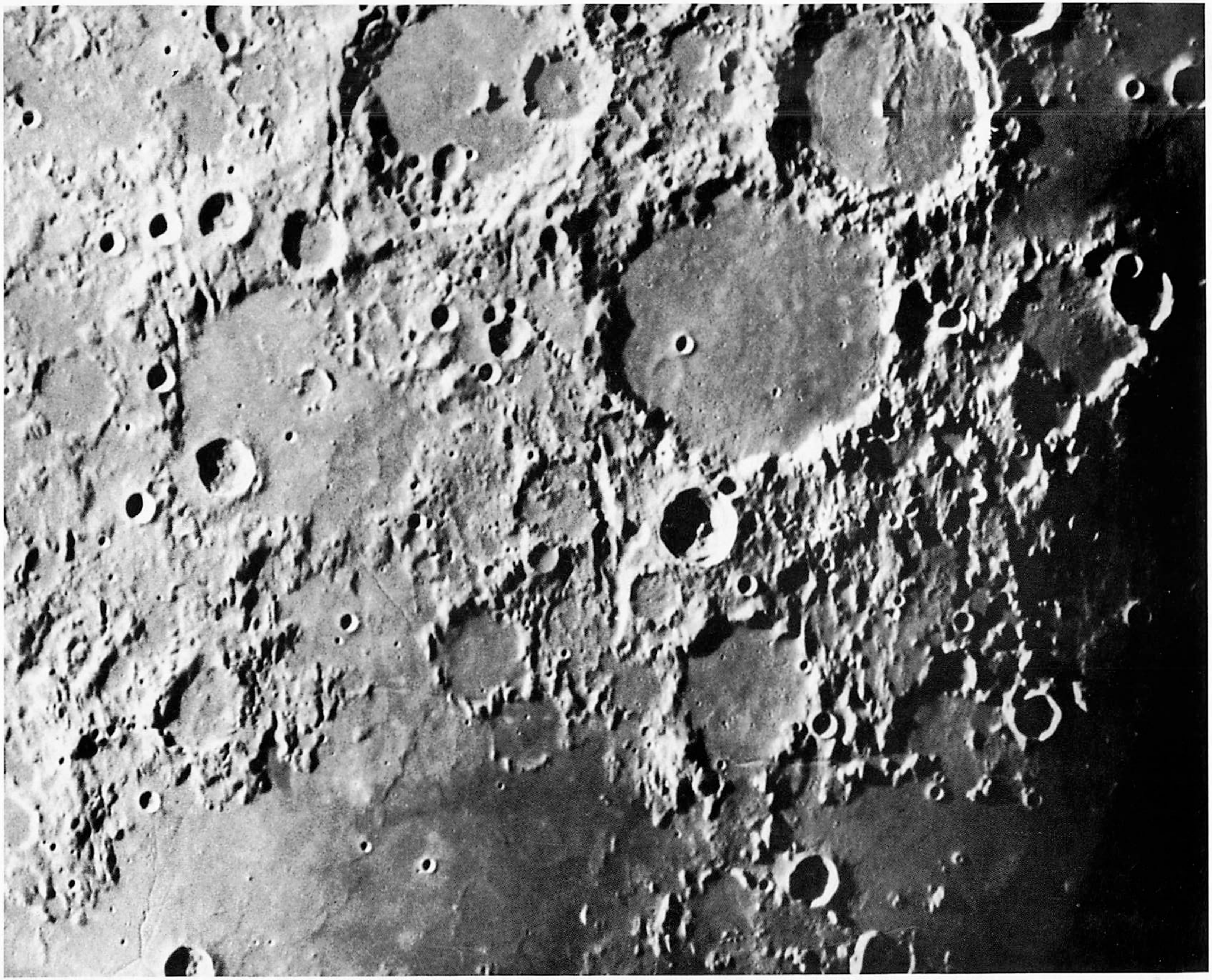


Plate 24.13.—Region of Ptolemaeus. Note that walls of Réaumur and Oppolzer have been broken into parallel, linear ridges. Cf. Plate 24.20 for overlay showing nomenclature and linear structures. Not rectified; Pic du Midi 34; scale ca. 3 km/mm (1:3,000,000); col. 10°5.

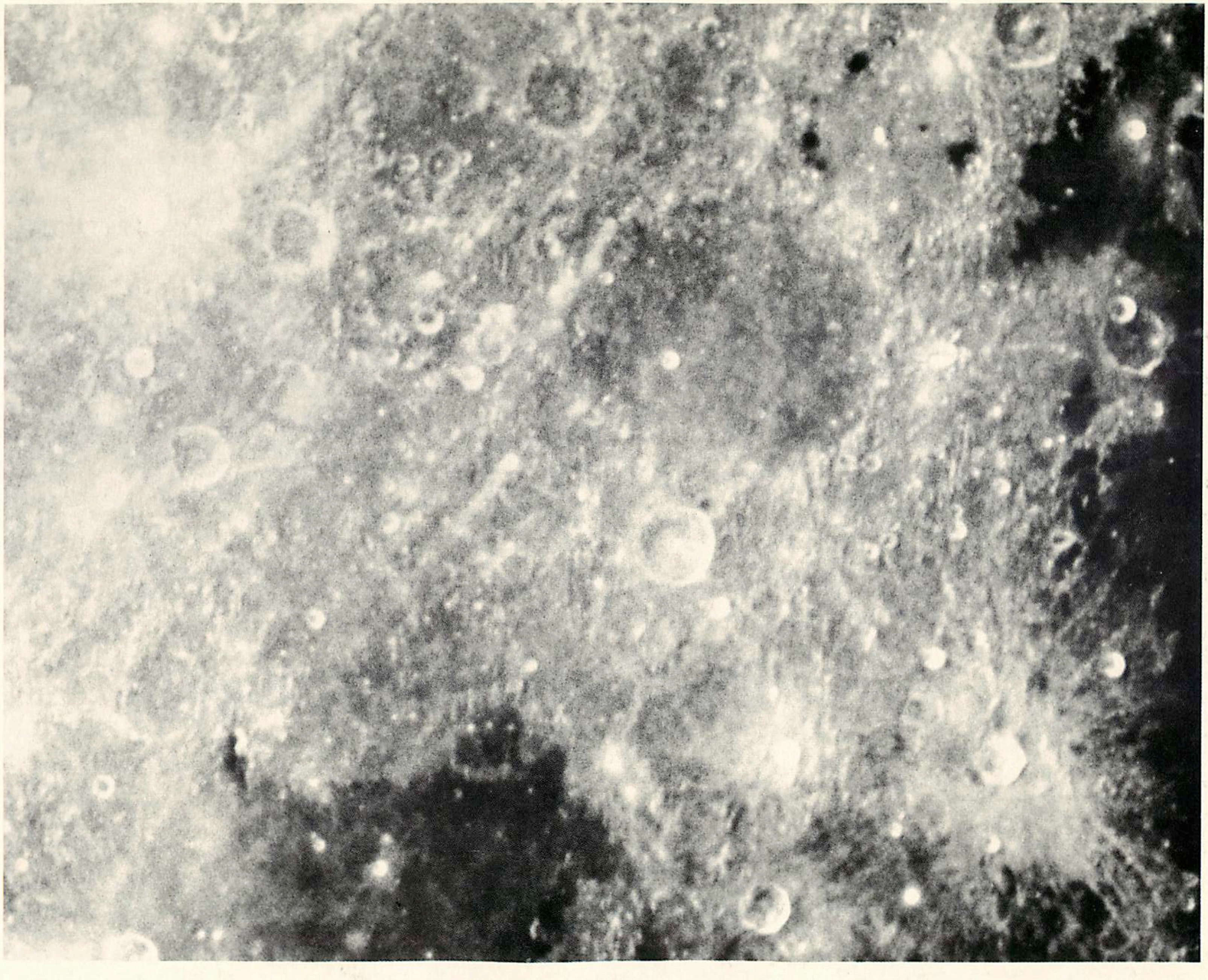


Plate 24.14.—Region of Ptolemaeus. Comparison of this high-lighting view with Plates 24.13 and 24.15 reveals the differences in tone among apparently smooth regions, e.g., Sinus Medii vs. floors of Ptolemaeus and Albategnius. Not rectified; Y466; scale ca. 3 km/mm (1:3,000,000); col. 63°.1.

Plate 24.15.—Region of Ptolemaeus. Cf. Plates 24.13 and 24.14. Not rectified; W119; scale ca. 3 km/mm (1:3,000,000); col. 172°0.

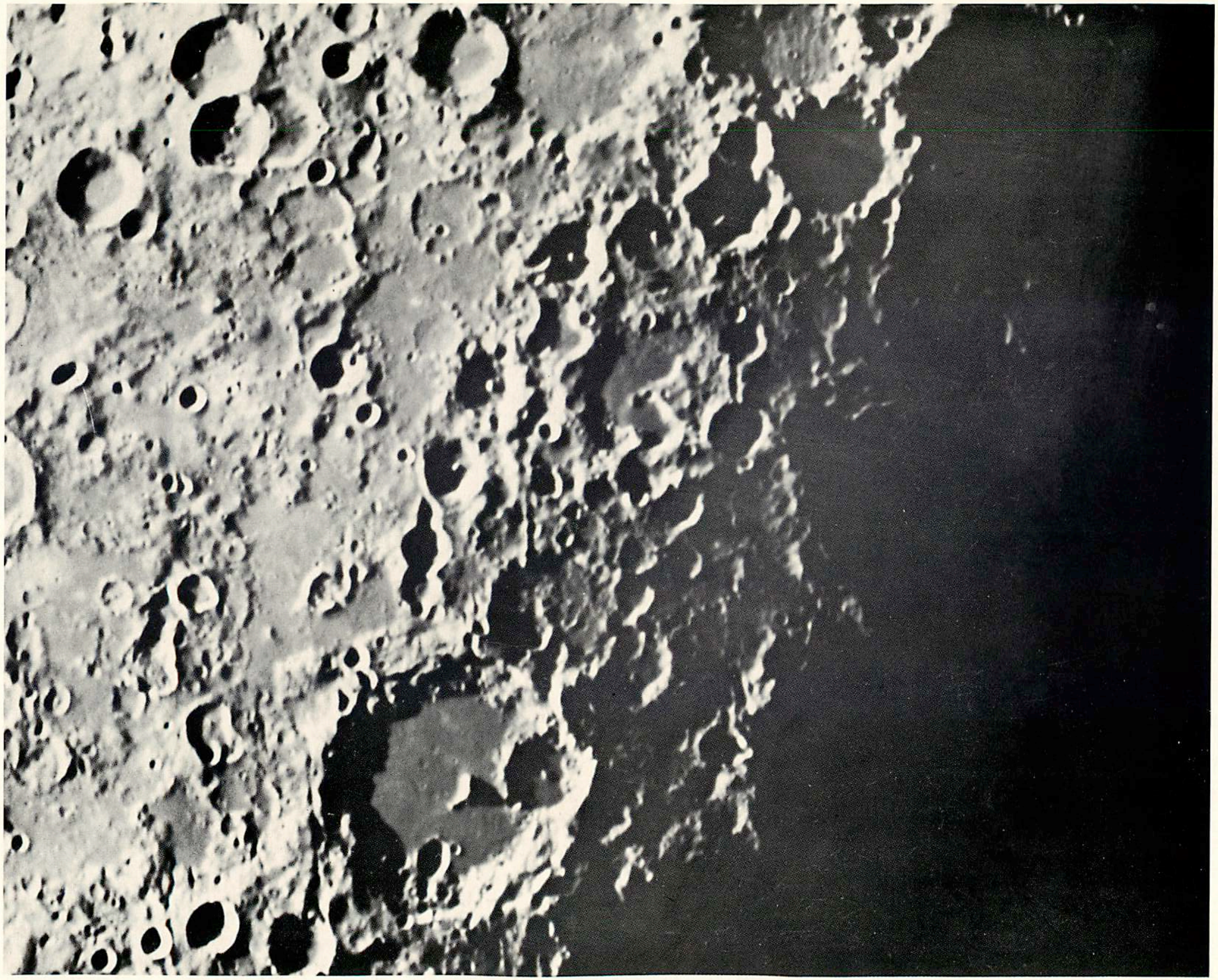


Plate 24.16.—Region of Arzachel. Comparison with Plate 24.17 indicates the distribution of the radial valleys at all levels through the uplands. Not rectified; Y1254; scale ca. 3 km/mm (1:3,000,000); col. 1°2.

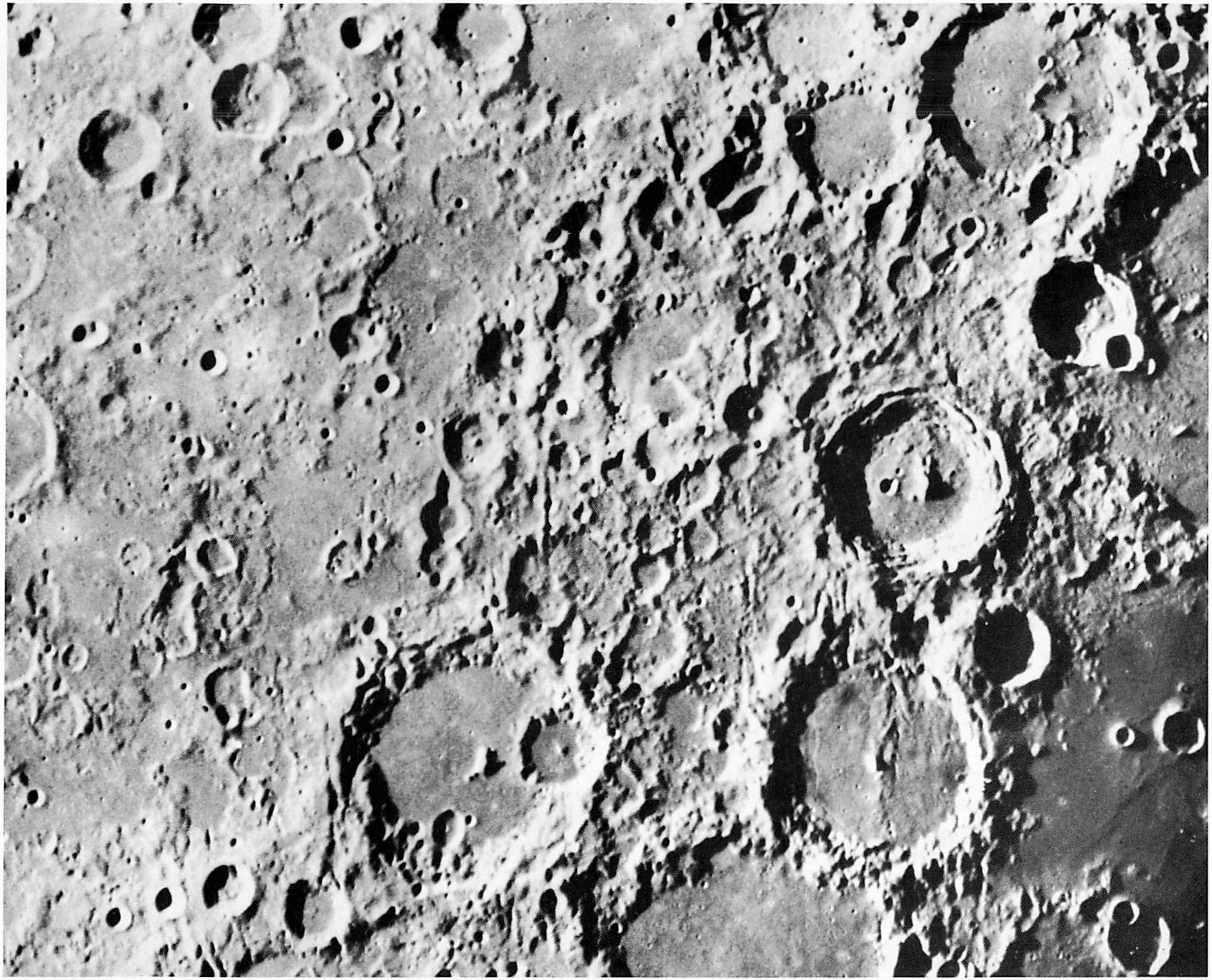


Plate 24.17.—Region of Arzachel. Not rectified; Pic du Midi 34; scale ca. 3 km/mm (1:3,000,000); col. 10°.5.

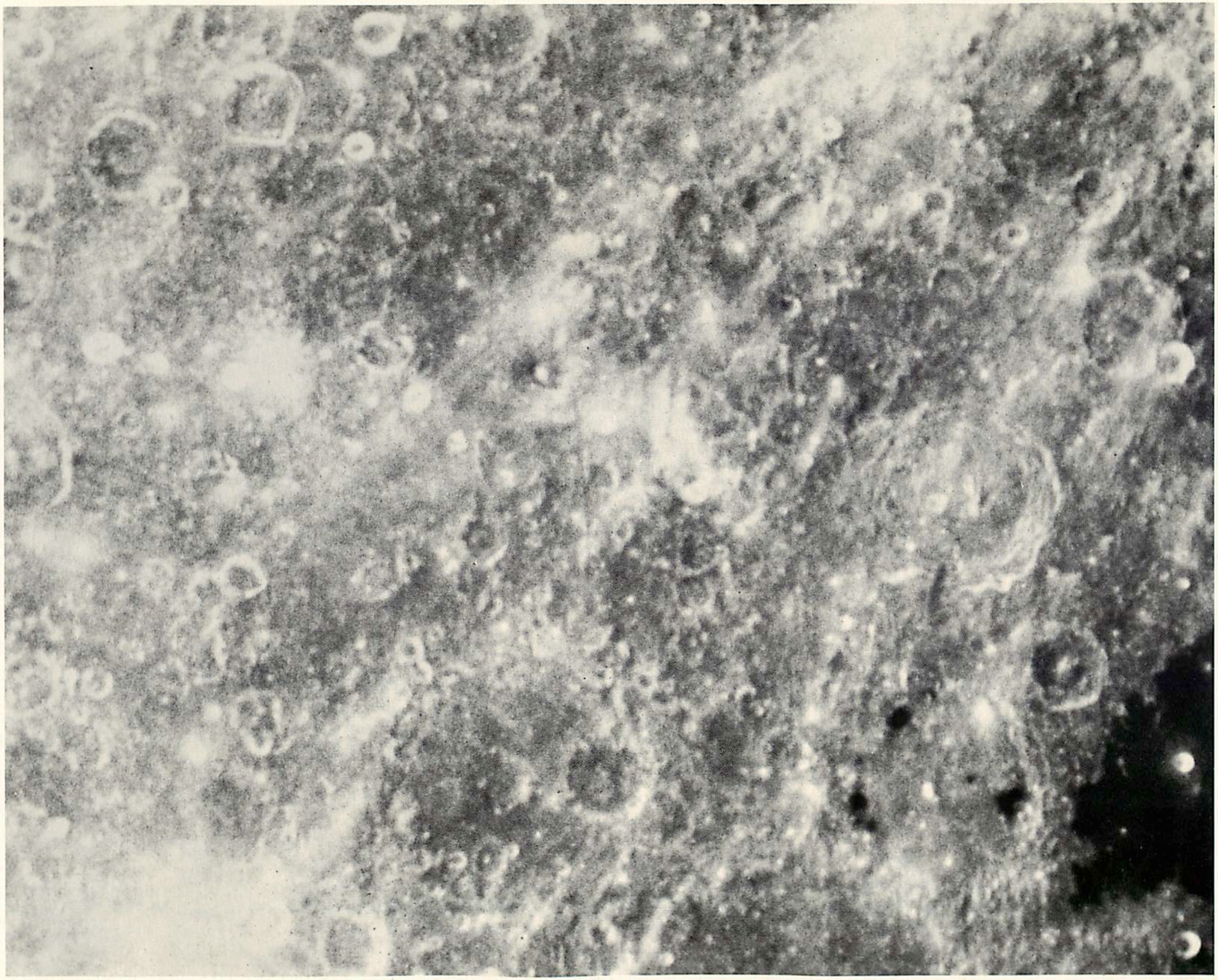


Plate 24.18.—Region of Arzachel. This high-lighting view indicates the tendency for the radial valleys to have bright walls, but darker floors. Not rectified; Y466; scale ca. 3 km/mm (1:3,000,000); col. 63°.1.

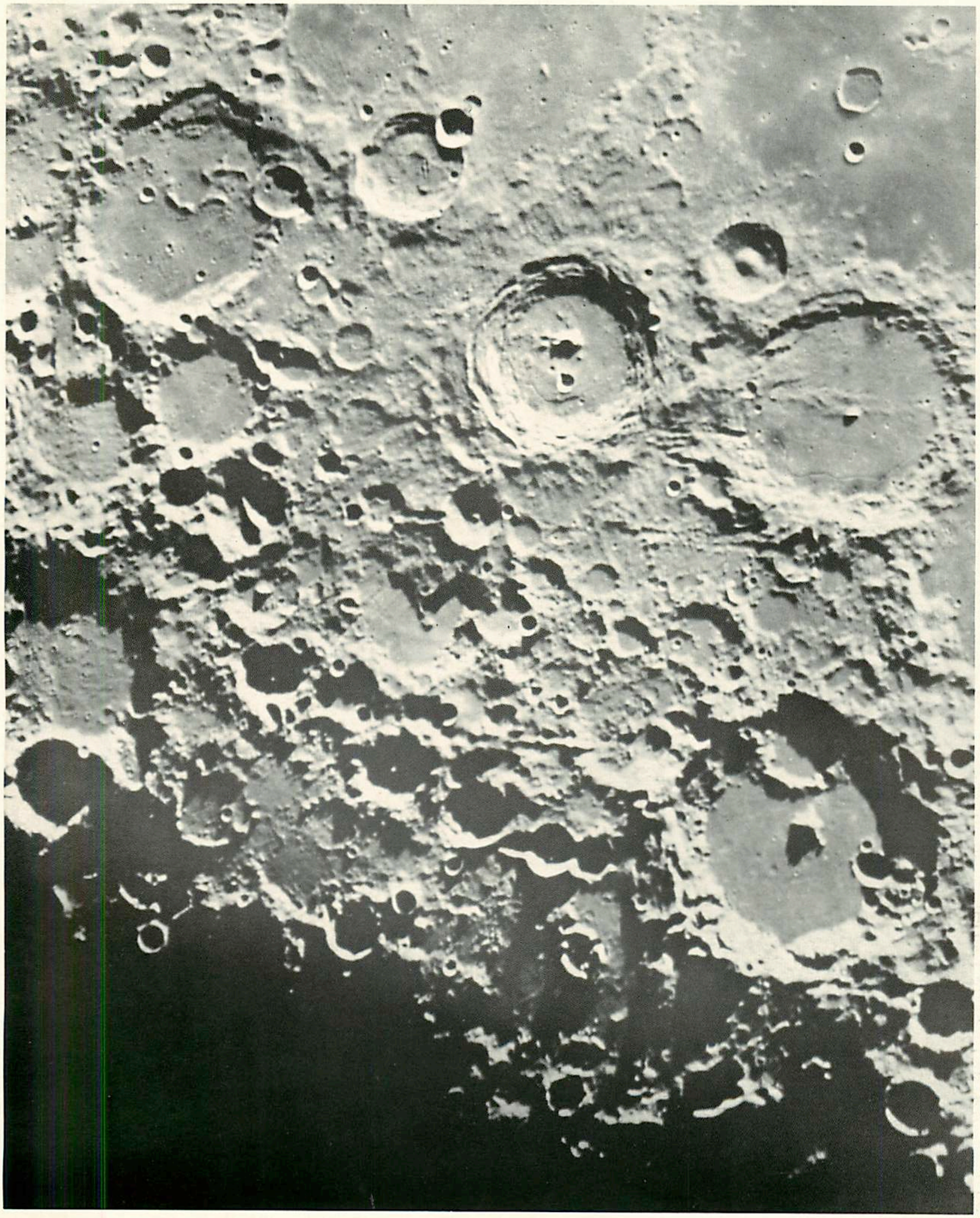


Plate 24.19.—Region of Arzachel. Not rectified; W119; scale ca. 3 km/mm (1:3,000,000); col. 172°0.

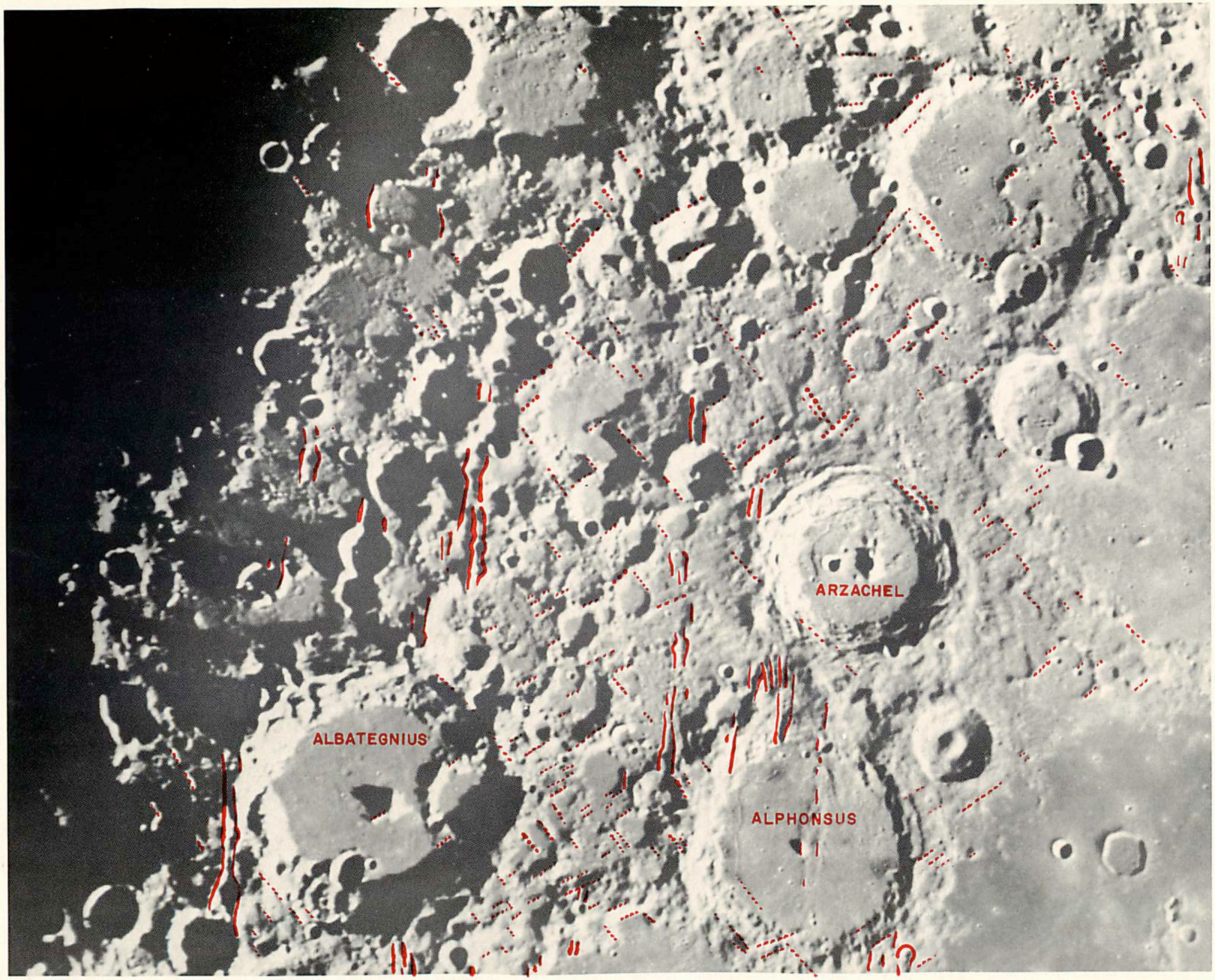


Plate 24.20.—Region of Arzachel with overlay identifying craters referred to in text and outlining some of the more prominent radial structures. Dotted lines mark some "grid system" components. Cf. Plate 24.19. Not rectified; W119; scale ca. 3 km/mm (1:3,000,000); col. 172°0.

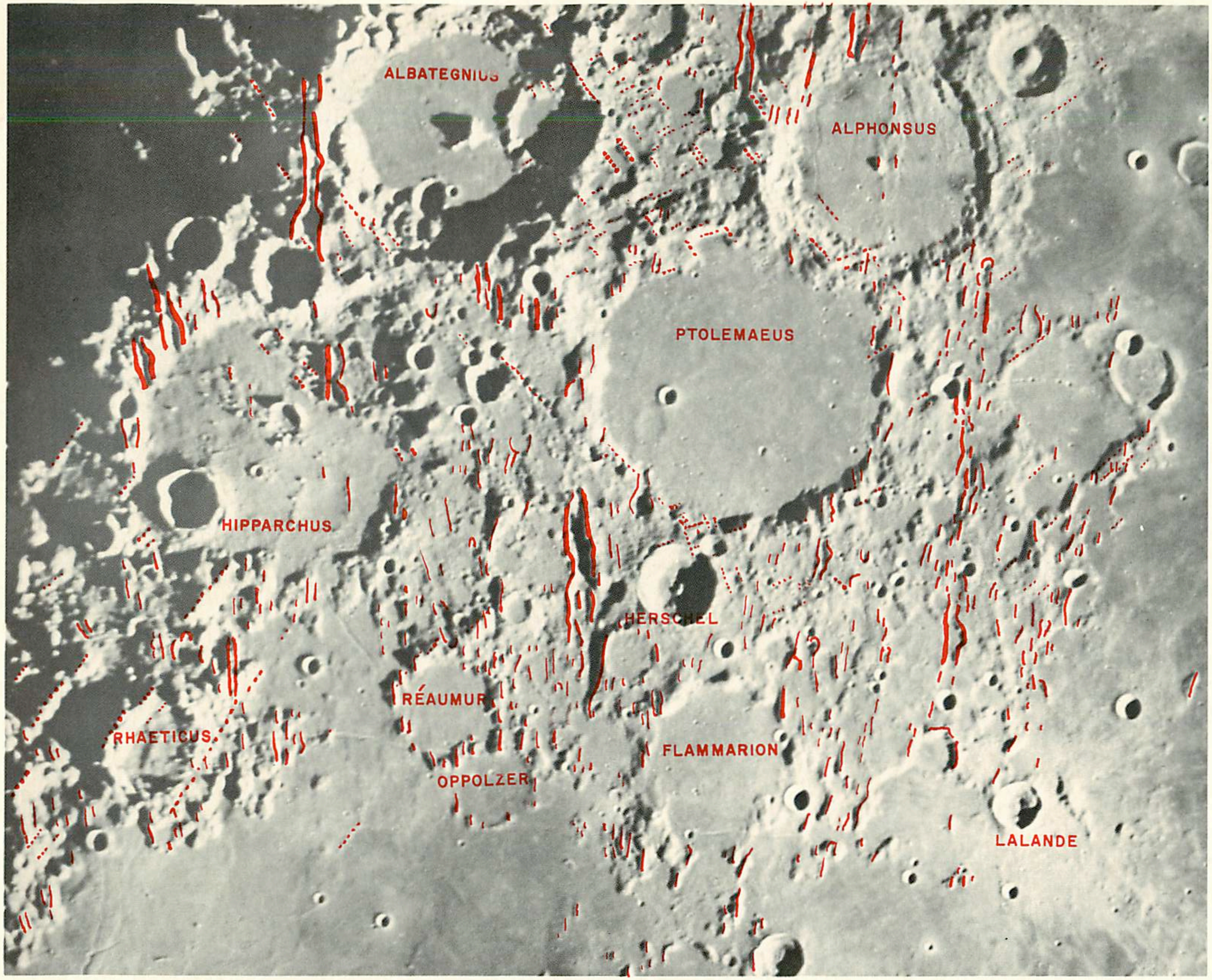


Plate 24.21.—Region of Ptolemaeus with overlay identifying craters referred to in text and outlining some of the more prominent radial structures. Dotted lines mark some "grid system" components. Cf. Plate 24.15. Not rectified; W119; scale ca. 3 km/mm (1:3,000,000); col. 172°0.

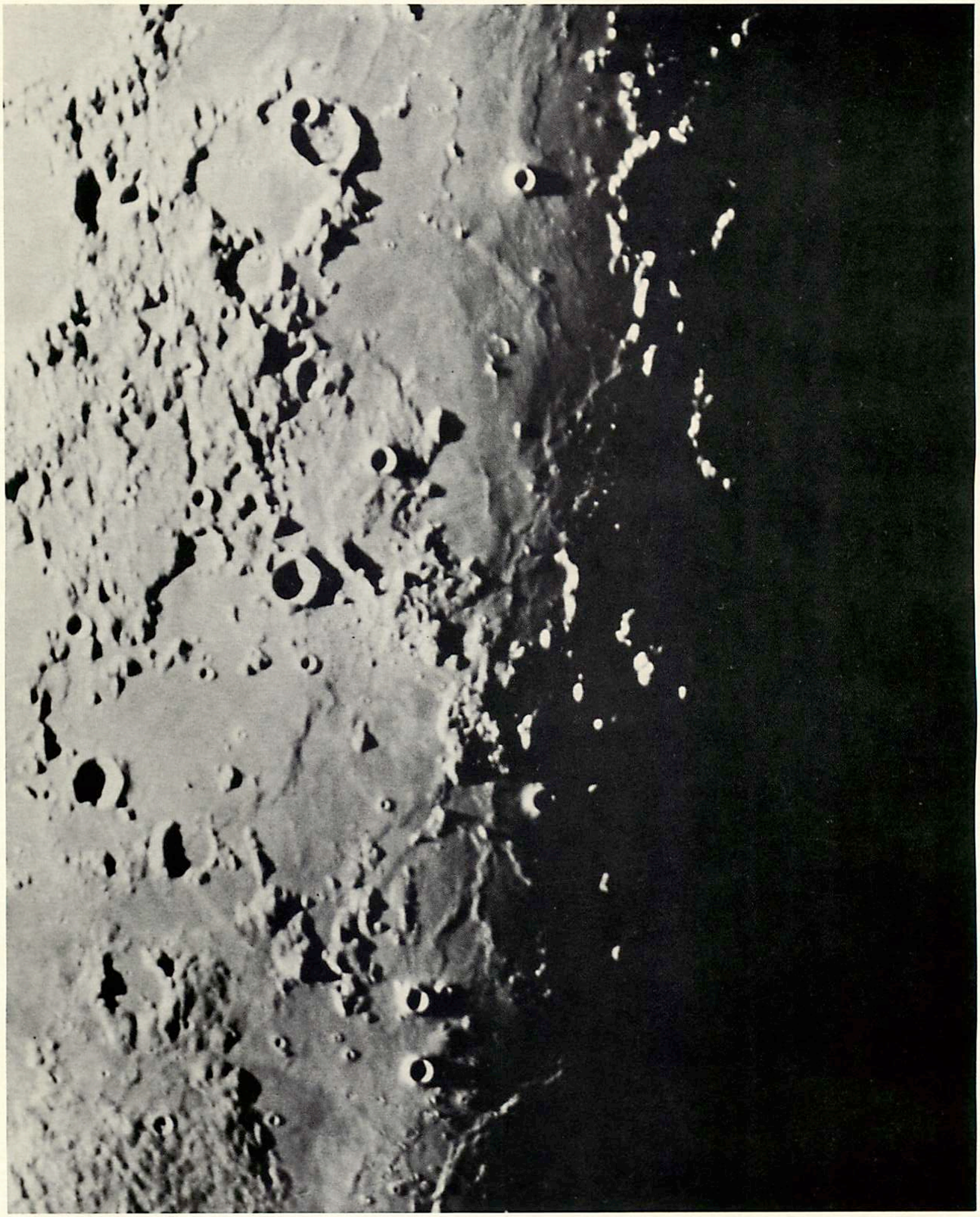


Plate 24.22.—Region of Fra Mauro. Low lighting reveals the complex low relief in the mare surfaces. Not rectified; Y1267; scale ca. 3 km/mm (1:3,000,000); col. 13°5.

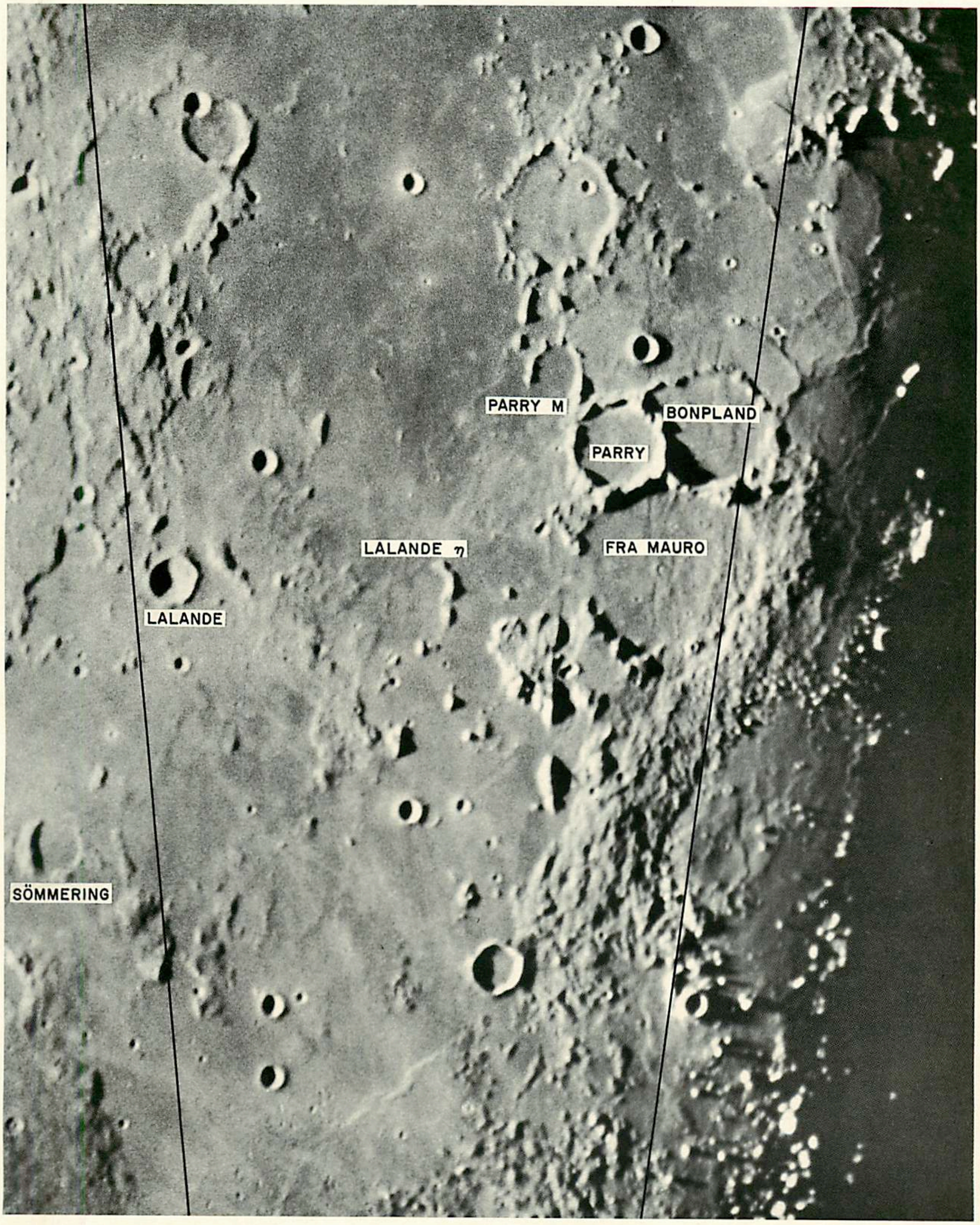


Plate 24.23.—Region of Fra Mauro. Some features mentioned in text are identified. Lines show directions radial to Imbrium. Alignment of ridges and crater walls is revealed. Not rectified; M285; scale ca. 3 km/mm (1:3,000,000); col. 20°.7.

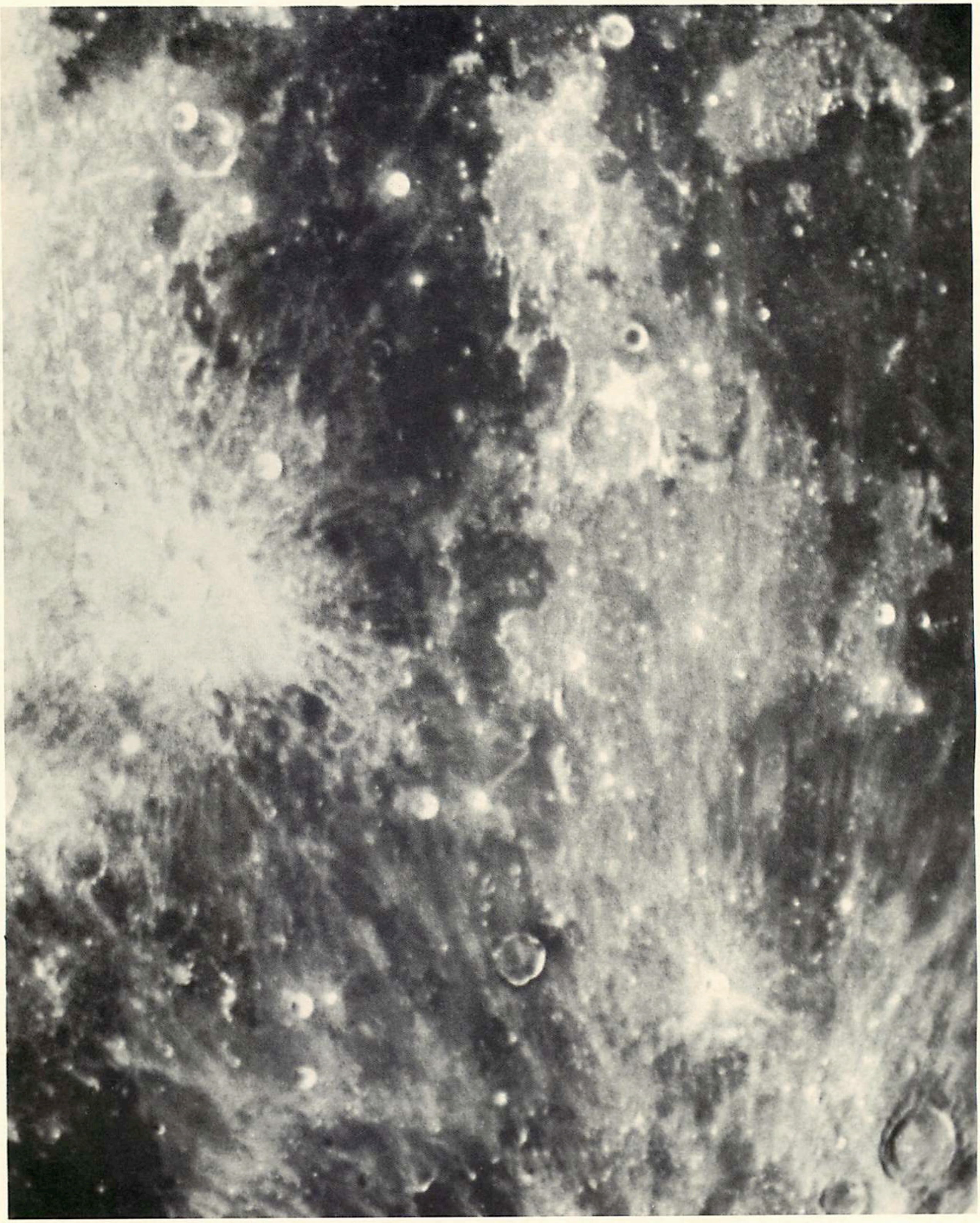


Plate 24.24.—Region of Fra Mauro. This high-lighting view reveals the extent of "flooding" around the Fra Mauro uplands. Prominent rays in lower part are from Copernicus. Not rectified; Y466; scale ca. 3 km/mm (1:3,000,000); col. 63°.1.

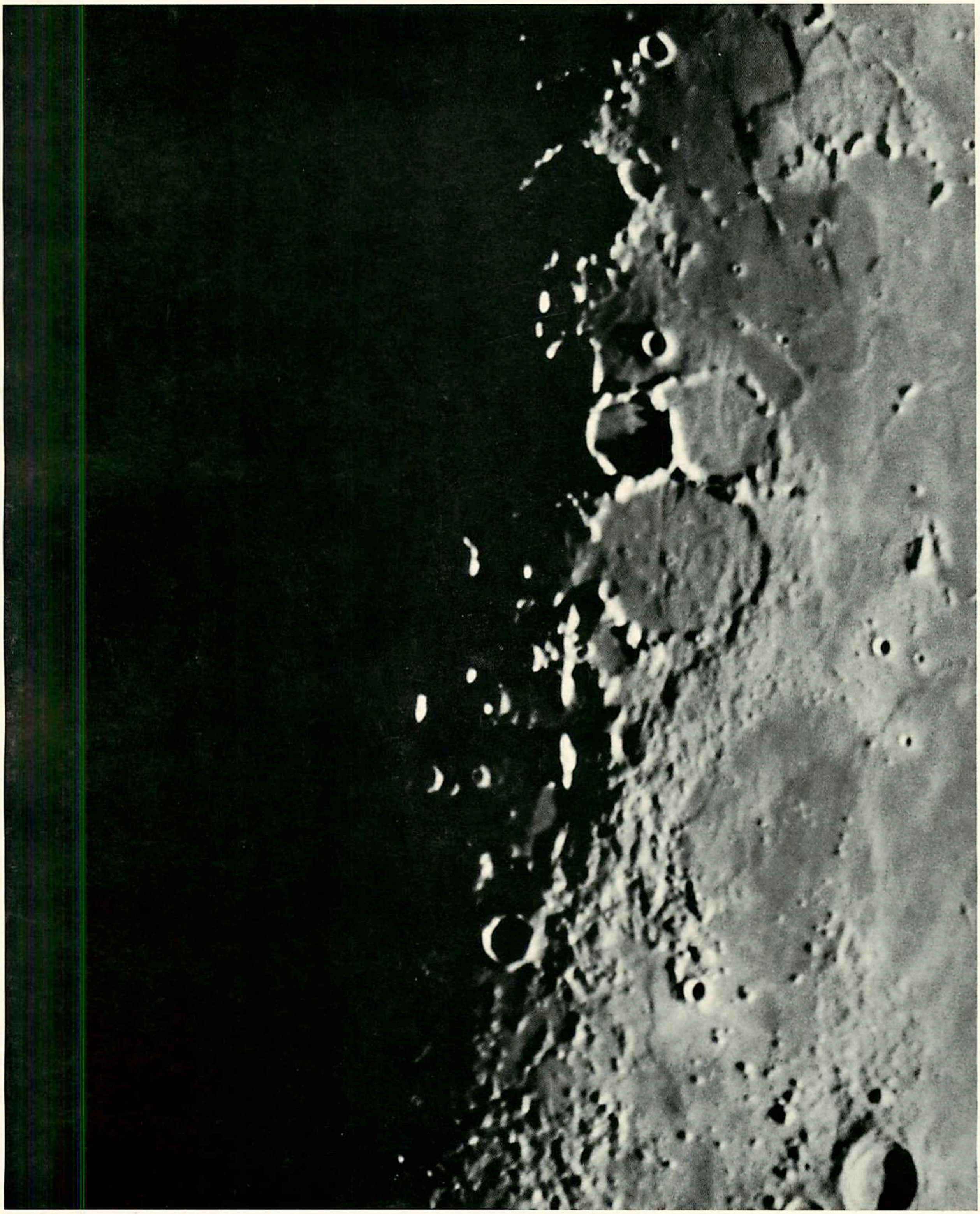


Plate 24.25.—Region of Fra Mauro. This low-lighting view reveals the linear structures on the floor of Fra Mauro. Not rectified; Y1247; scale ca. 3 km/mm (1:3,000,000); col. 193°9.

Plate 24.26.—Carpathian Mountains, showing alignment of linear ridges. Not rectified; Y163; scale ca. 3 km/mm (1:3,000,000); col. 35°1.

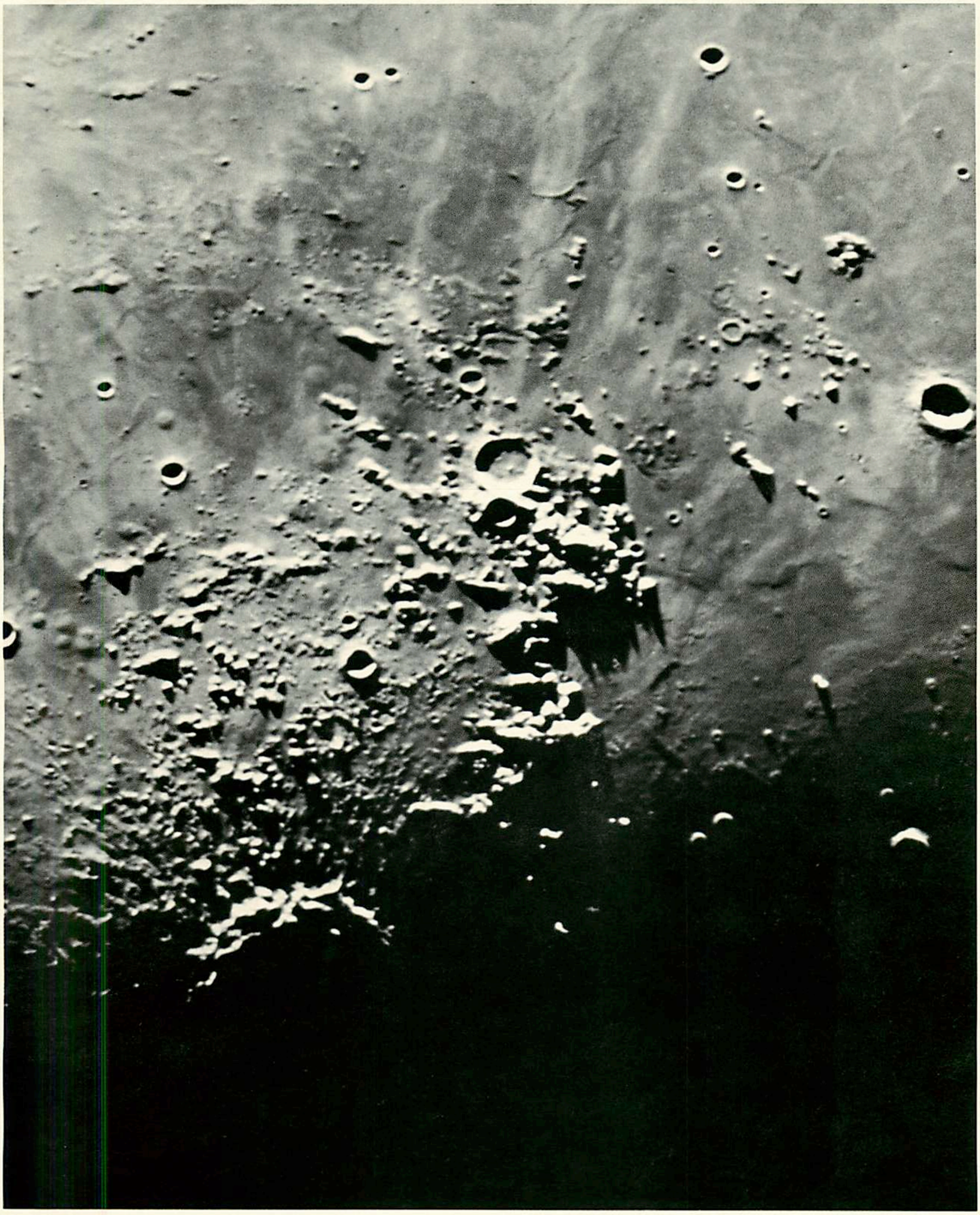


Plate 24.27.—Carpathian Mountains. Cf. Plate 24.26. Not rectified; M184; scale ca. 3 km/mm (1:3,000,000); col. 201°·8.

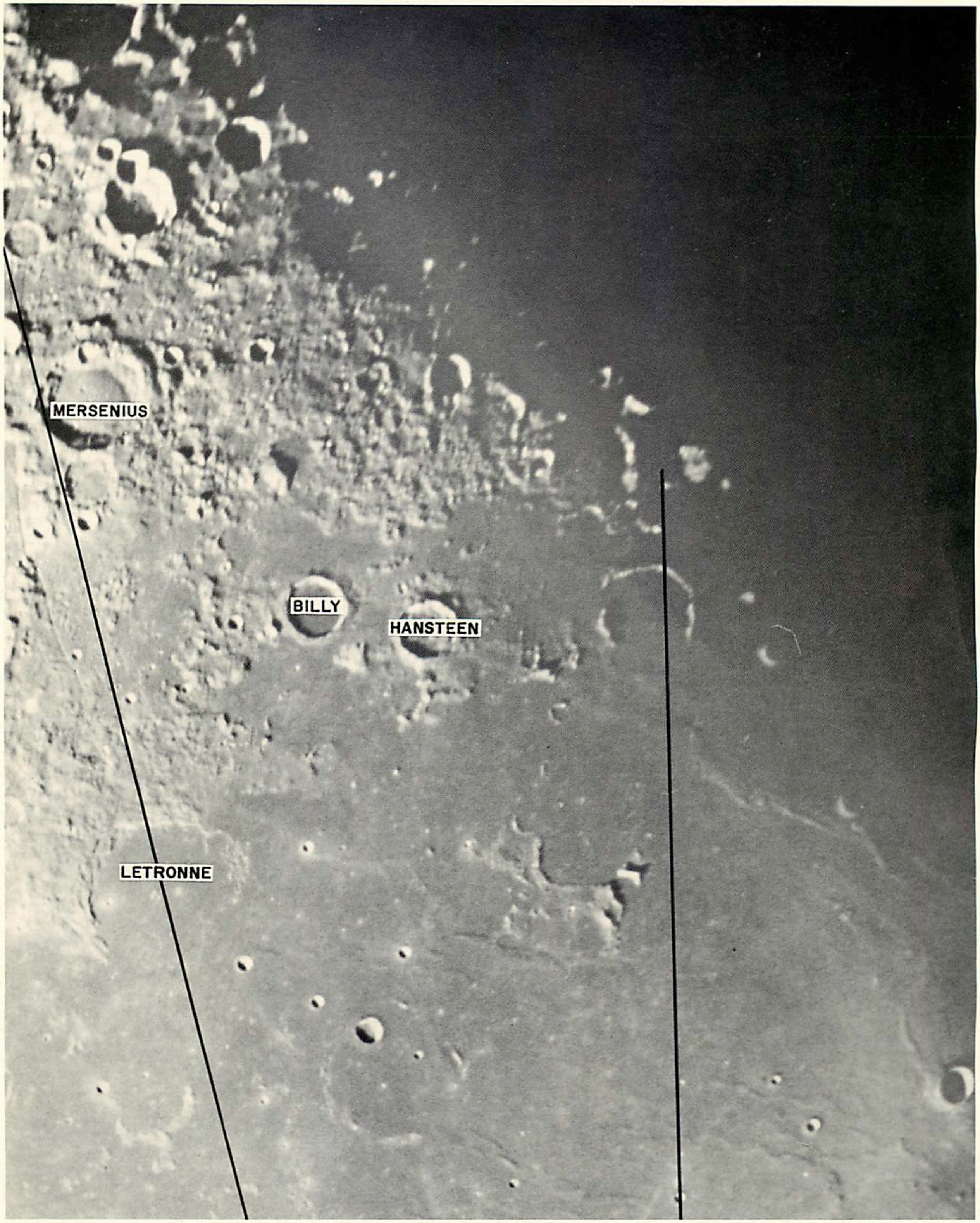


Plate 24.28.—Region of Hansteen, showing some linear crater walls and ridges. Lines show directions radial to Imbrium. Rectified; M694; scale ca. 4.5 km/mm (1:4,500,000); col. 57°.7.

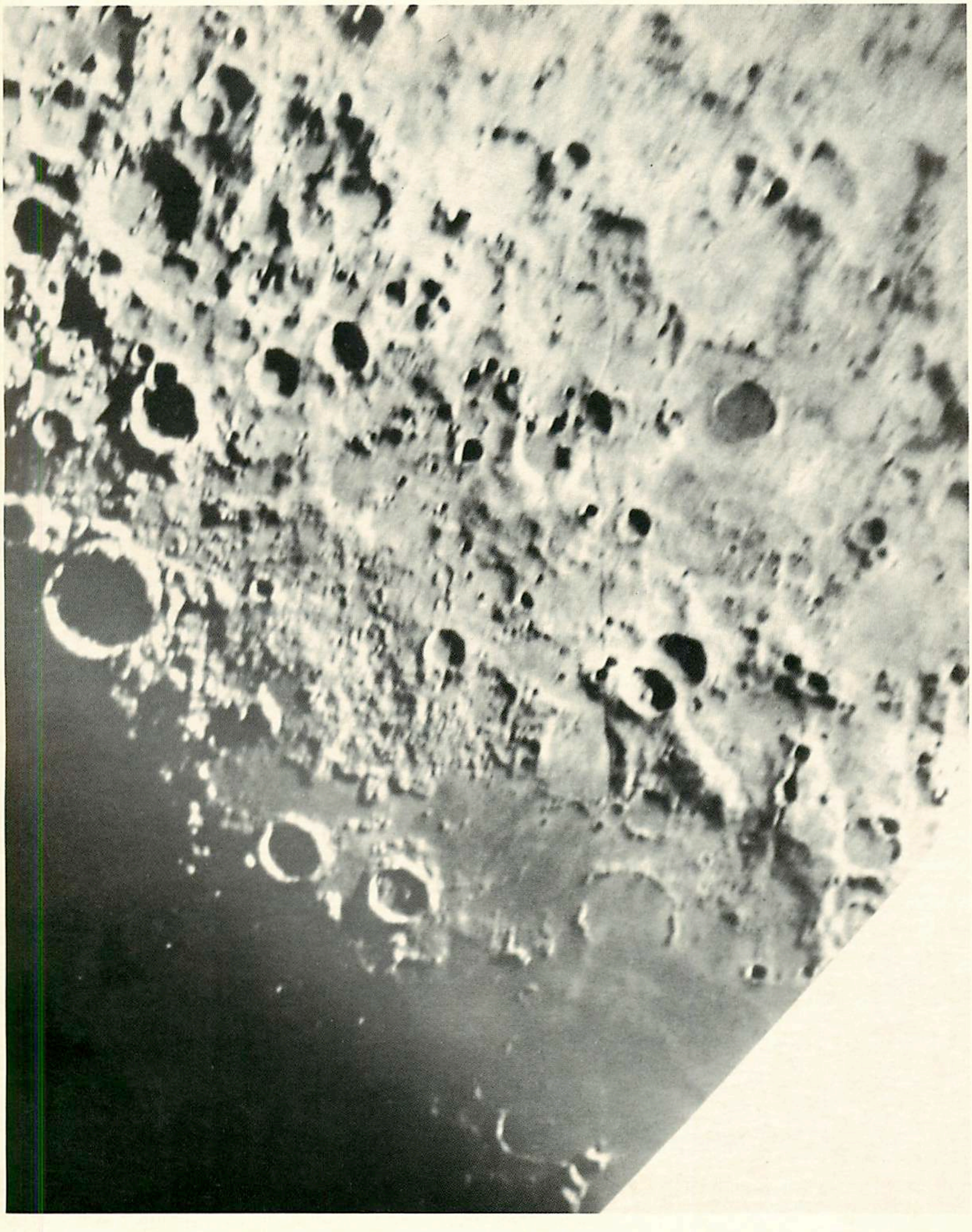


Plate 24.29.—Region SW of Hansteen. Parallelism in upper right is directed toward the Orientale basin. Cf. Plate 24.28. Rectified; W230; scale ca. 4.5 km/mm (1:4,500,000); col. 229°1.

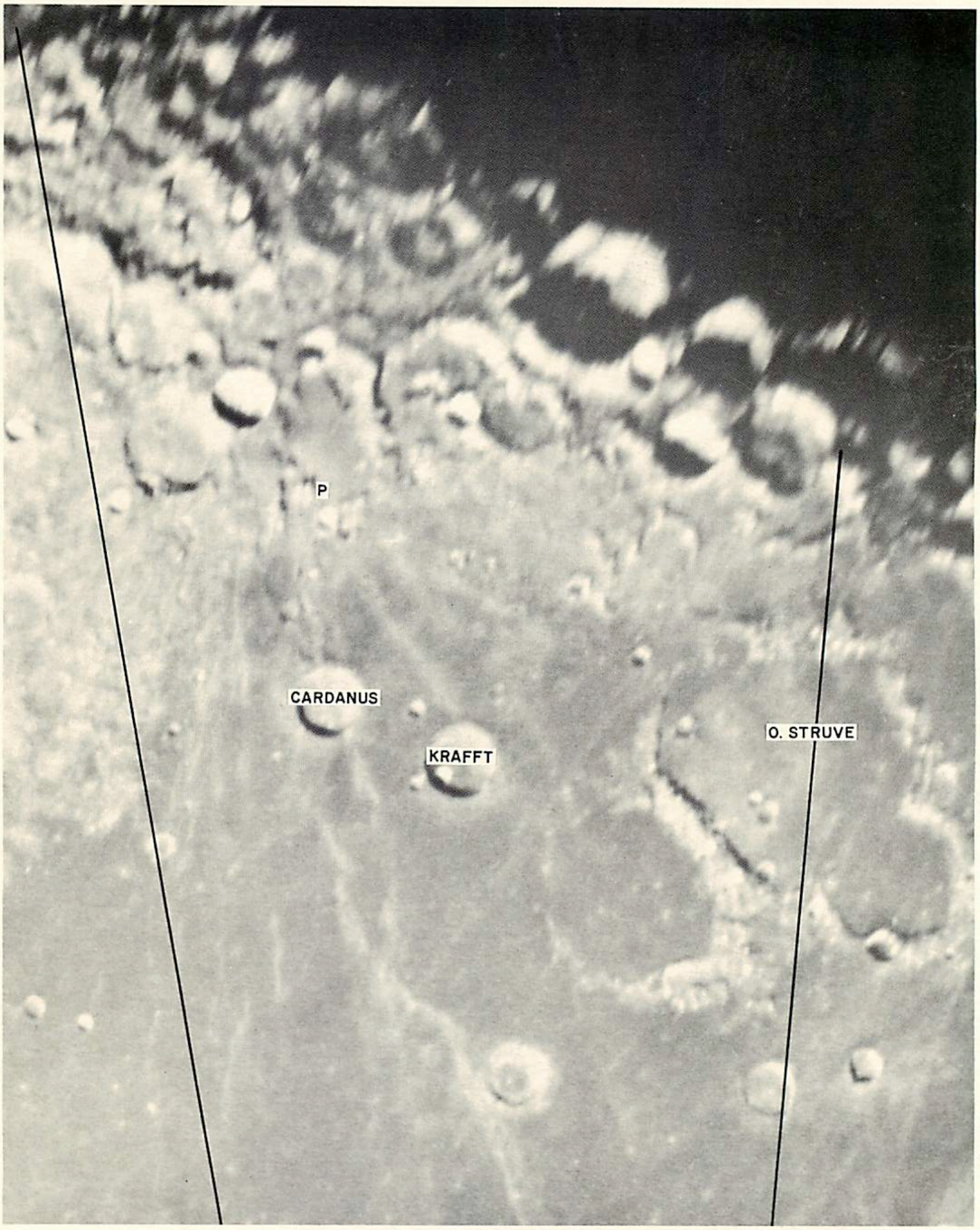


Plate 24.30.—Region of O. Struve, showing linear structures in uplands and in the walls of O. Struve. Lines show directions radial to Imbrium. *P* indicates grooved peak similar to those in Haemus Mountains. Rectified; M373; scale ca. 5 km/mm (1:5,000,000); col. 85°7.

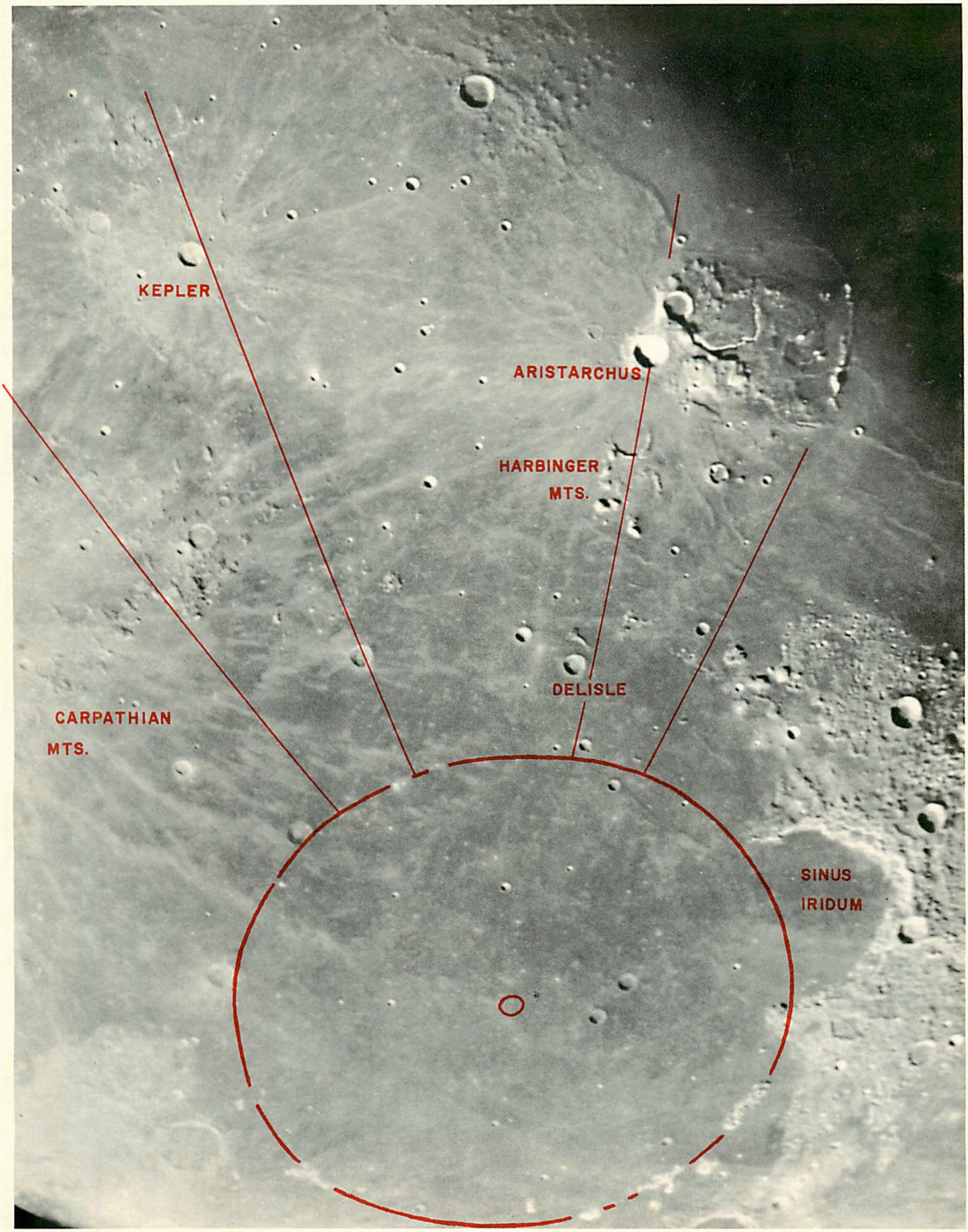


Plate 24.31.—Western reaches of Mare Imbrium. Overlay outlines ring of peaks defining the Inner Basin and shows lines radial to the Imbrium center for comparison with local structures. Radialism may be seen in ridges in Carpathians, near Kepler, and in parts of Aristarchus plateau. Rectified; M700; scale ca. 6.5 km/mm (1:6,500,000); col. 57°.8.

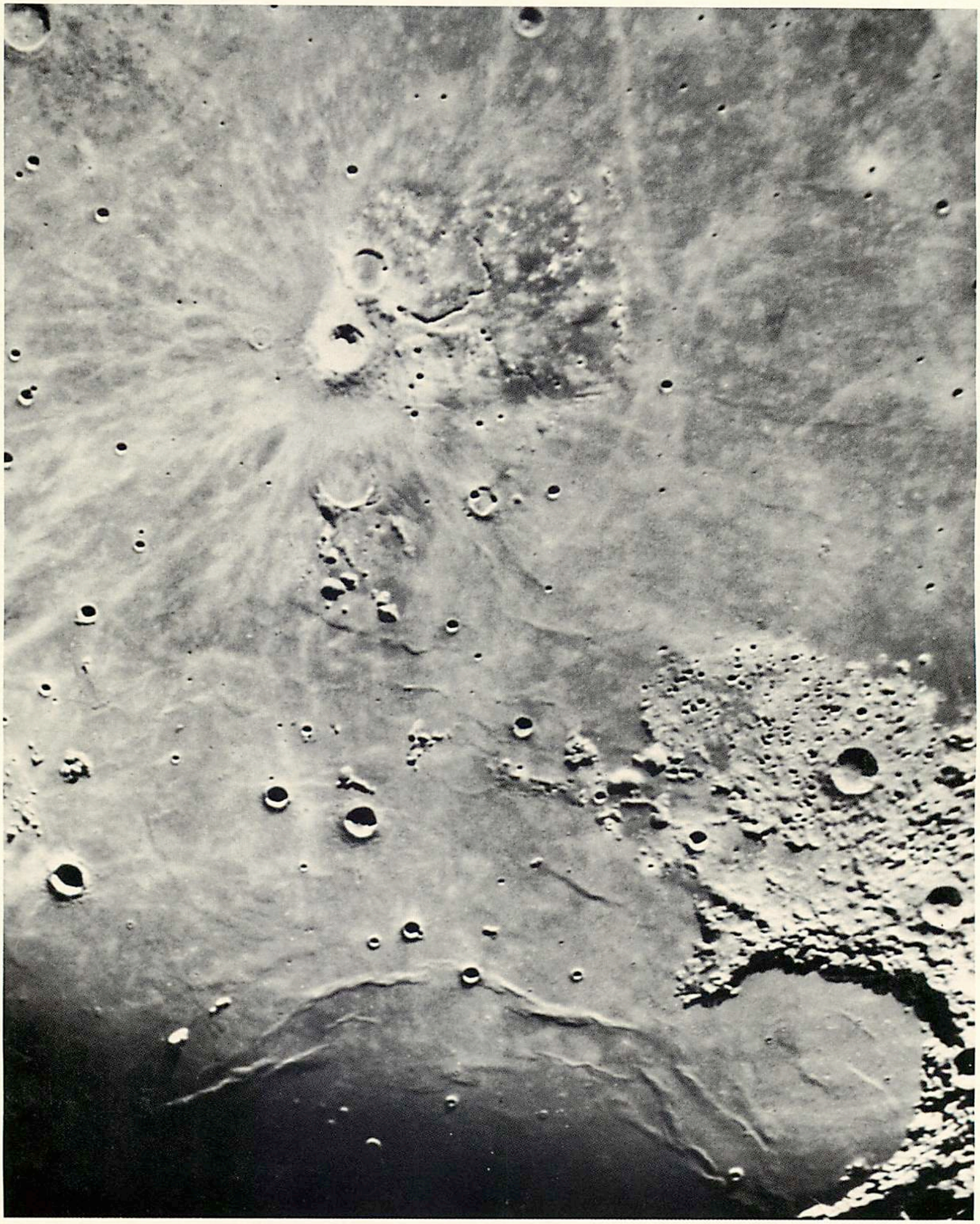


Plate 24.32.—Aristarchus plateau and western reaches of Mare Imbrium. Note dark tone of plateau surface. Rectified; W173; scale ca. 5 km/mm (1:5,000,000); col. 202°.8.

Plate 24.33.—Aristarchus plateau, showing relief at western edge (top). Note similarity of "trough" along N (right) edge with that through the Haemus Mountains (cf. Pl. 24.12 at same scale). Cf. Plate 24.34. Rectified; M700; scale ca. 3 km/mm (1:3,000,000); col. 57°8.

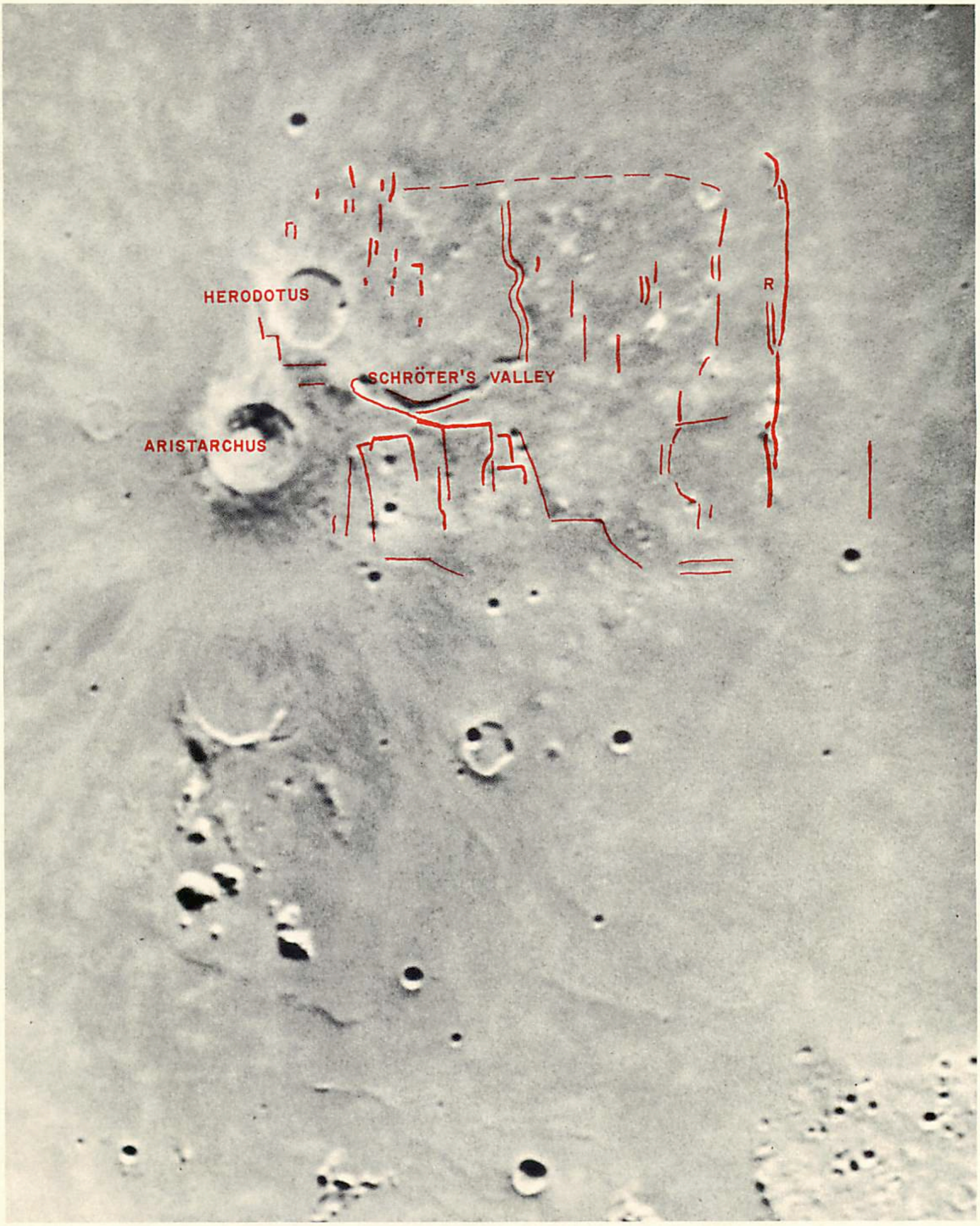


Plate 24.34.—Aristarchus plateau. This high-lighting view shows the unusual similarity in tone between the mare and upland surfaces. Linearities are indicated. *R* marks grooved ridge similar to those in Haemus Mountains (cf. Pls. 24.35 and 24.7). Rectified; M184; scale ca. 3 km/mm (1:3,000,000); col. 201°8.

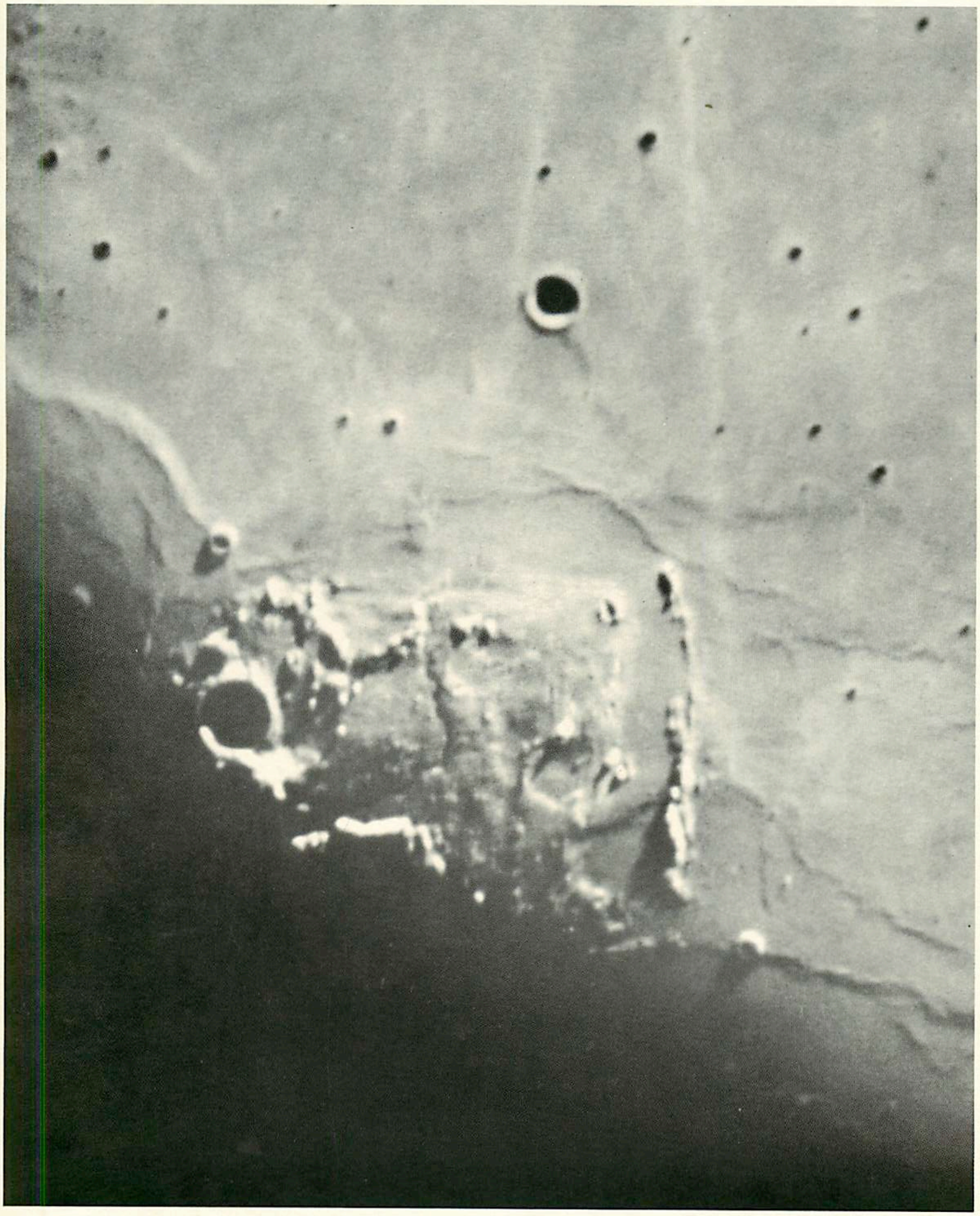


Plate 24.35.—Aristarchus plateau. Some linear grooves and ridges on the plateau surface and the "trough" at the N edge are well shown. Cf. Plate 24.34. Rectified; W231; scale ca. 3 km/mm (1:3,000,000); col. 229°.1.

Plate 24.36.—Region of W. Bond, showing numerous valleys and rectilinear craters. Compare "troughs" bordering W. Bond with that on the N edge of Aristarchus plateau (cf. Pl. 24.32 at same scale). Some apparent linearity is introduced by distortion in rectification (see upper left corner). Approximately rectified; Y1350; scale ca. 4.5 km/mm (1:4,500,000); col. 163°.7.

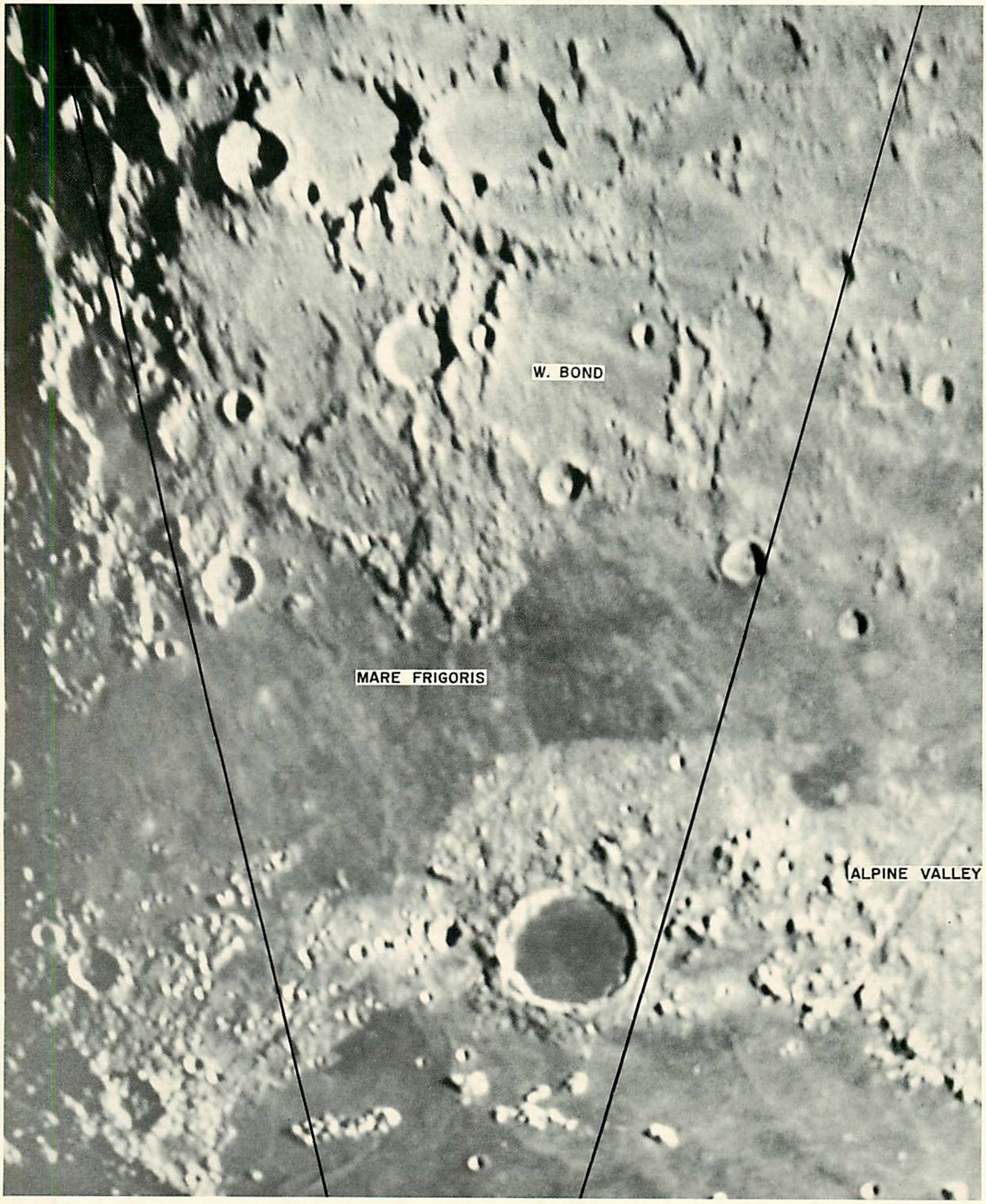


Plate 24.37.—Region of W. Bond. Cf. Plate 24.36. Lines show directions radial to Imbrium. Approximately rectified; Y160; scale ca. 4.5 km/mm (1:4,500,000); col. 35°1.

Plate 24.38.—Region of J. Herschel. Uplands exhibit structure similar to that near Ptolemaeus. Lines show directions radial to Imbrium. Cf. Plate 24.15. Rectified; M10; scale ca. 4 km/mm (1:4,000,000); col. 62°7.

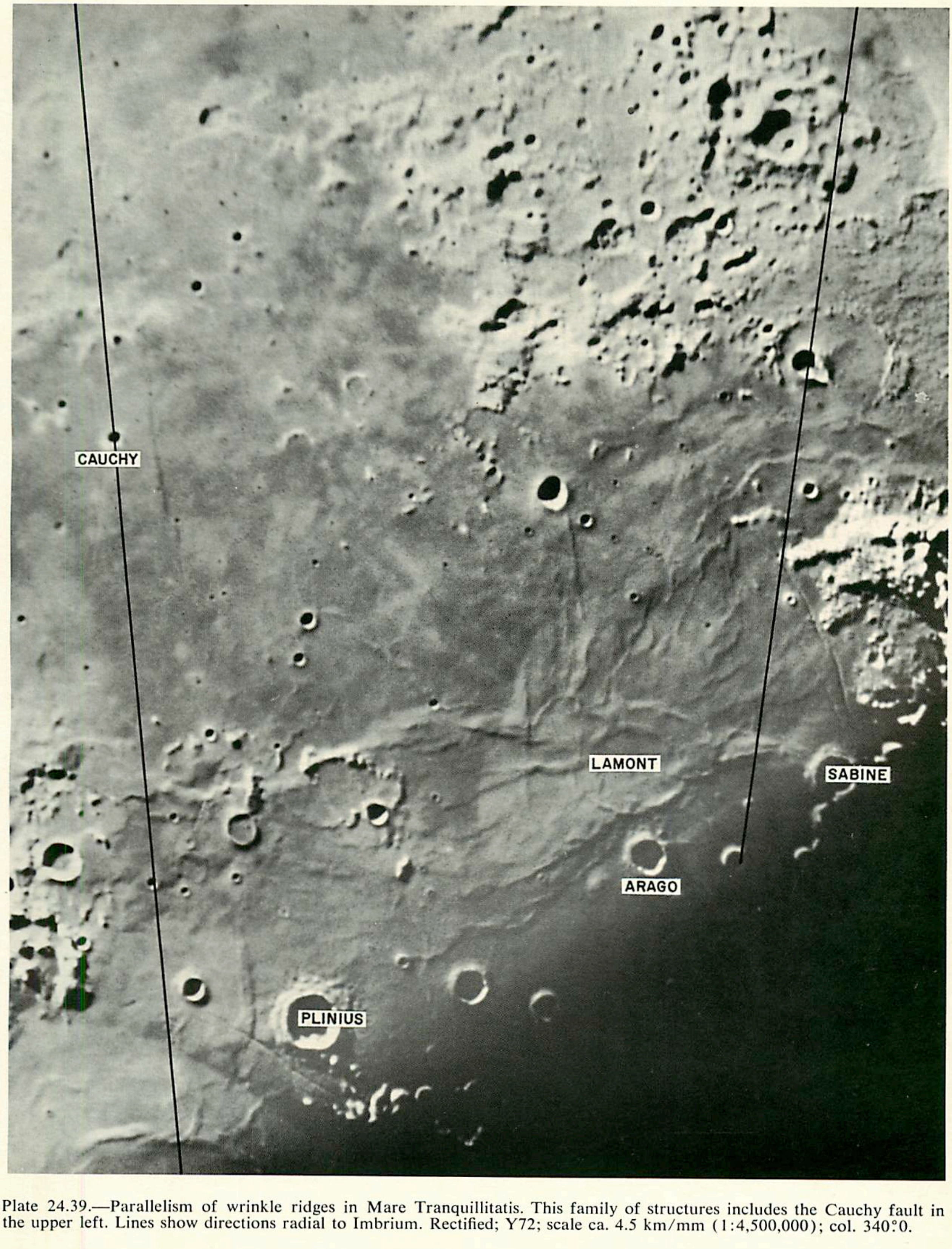


Plate 24.39.—Parallelism of wrinkle ridges in Mare Tranquillitatis. This family of structures includes the Cauchy fault in the upper left. Lines show directions radial to Imbrium. Rectified; Y72; scale ca. 4.5 km/mm (1:4,500,000); col. 340°0.

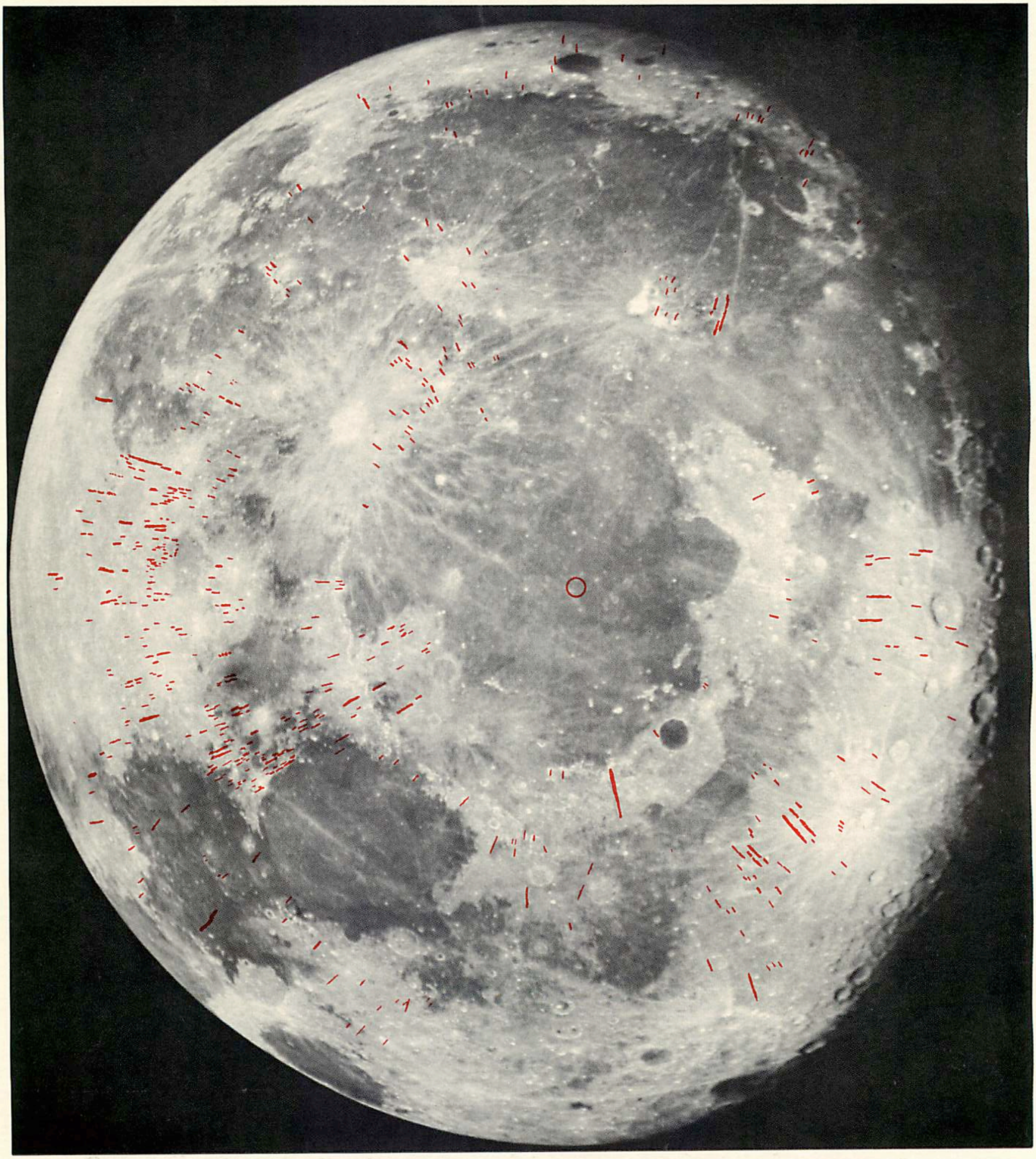


Plate 24.40.—View of moon from above the Imbrium center at an altitude corresponding to 10,500 km. Overlay shows position of radial structures. Cf. Figure 2 for this distribution and the Imbrium concentric system without the photographic background. Rectified; Y577; scale ca. 18 km/mm (1:18,000,000); col. 87°.8.