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Lunar Science Prior to Apollo 11

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On June 5, 1969 the Institute for Space Studies of the Goddard Space Flight Center, the Lamont-Doherty Geological Observatory of Columbia University, and the Space Science and Applications Division of the Manned Spacecraft Center held a conference in New York on current problems in lunar science, with participants drawn from the earth sciences, astronomy and physics, and representing various schools of thought on the origin and history of the moon. The conference organizers felt that the scientific returns from the lunar landing would yield greater scientific returns if the major issues and the principal items of evidence relating to lunar science could be freshly reviewed immediately prior to the landing.

The spirited discussion that took place during the conference failed to produce a consensus on any of the major controversies in the field. However, the conference succeeded in exhibiting and clarifying the central issues in lunar

science, and in identifying much of the primary pre-Apollo observational material.

Part I of the present report has been prepared in lieu of a conference summary. We hope that it will be useful to the person without a specialized knowledge of lunar science, as an introductory review and preliminary guide to the literature.

Because the ideas and issues in lunar science are drawn from a wide variety of fields, papers containing pertinent evidence and calculations are scattered throughout the periodical literature, and are not available, to our knowledge, in any one place. Part II consists of papers containing observational evidence and theoretical interpretations, offered as a representative selection rather than a complete bibliography. The selection includes descriptive accounts written in general language as well as papers from the technical literature.

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## A. PRINCIPAL ISSUES IN LUNAR EXPLORATION

Two schools of thought exist regarding the history of the moon and the forces that have shaped its surface. One school of thought believes that the moon passed through a period of partial or complete melting at one point in its history and probably is still partly molten today. This view holds that the moon is a differentiated body like the earth, with a dense core, presumably of molten iron, surrounded by a magnesium-rich mantle and a crust low in magnesium and iron. This school sees evidence of extensive and continuing volcanism on the moon's surface today, and quotes "strong circumstantial evidence that melting has occurred on the moon, and ... that this may have been true over a major fraction of the moon's history" (Gault, et. al., this report, II-45).

According to this view, the scientific value of lunar exploration is enhanced because the moon and the earth are basically similar planetary bodies. Their similarity permits the geologist to apply his knowledge of the earth's history,

and the forces that have shaped its surface features, directly to the unravelling of the history of the moon.

The differences between earth and moon, although minor, are also important in this view, because they make the moon a showcase of geological events. Several circumstances tend to conceal the surface of the earth from the eyes of the geologist: three-quarters of the surface is covered by deep bodies of water; large areas of the land are covered by plant life, which conceals and transforms surface features; and, land forms are rapidly modified and worn away by running water, and to a lesser extent, by wind. The surface of the moon, on the other hand, is bone-dry, lifeless, and the rate of erosion of its landforms is hundreds to thousands of times less than on the earth, because of the absence of water and winds. As a result, surface manifestations of internal activity, such as volcanic domes, tension cracks in the crust, lava flows, and also the marks of external bombardment by meteorites and asteroids, stand out clearly on the moon and make it a fascinating source of planetary information.

The second school of thought in lunar science cites evidence to prove that "the moon was accumulated at low temperatures with only local or temporary melting, (and) that the surface

features were mostly formed by collisions of objects with its surface" (Urey and MacDonald, I-14). This school believes that the moon is an exceedingly different kind of planet from the earth, with a surface shaped by forces entirely different from those that have molded the surface of the earth.

Its proponents often cite the density of the moon as clear evidence of gross differences between the earth and the moon. The earth, if the compression produced by its own pressure field were not present, would have a mean density of 4.7, whereas the mean density of the moon is 3.3. The most plausible explanation of the difference is that the moon has a deficiency of iron relative to the earth as a whole. Because of this difference in bulk composition, it is suggested, direct application of terrestrial geology to the moon can be attempted only with great caution.\*

In this view, it is the fact of major differences between the earth and the moon that make the moon scientifically interesting. The moon is believed to be a relatively cold, rigid, mechanically strong body, undifferentiated, with lumps

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\* It is interesting to note that the same facts regarding the density of the earth and the moon are sometimes cited as evidence for the opposing view. That is, the fact that the moon and the earth's mantle have similar densities is taken as evidence that the composition of the moon is similar to the composition of the earth's mantle and, therefore, that the terrestrial experience of geologists, based on the study of mantle and crustal rocks, is directly applicable to lunar problems.

of iron distributed throughout the silicate minerals of its interior. The mass movements within the earth's mantle, accompanied by tectonic and orogenic processes on the surface -- processes which, together with erosion, control the earth's surface features -- are missing from the moon, if it is a cold planet.

These beliefs lead to the conclusion that the moon's surface has changed little since the time of its formation, that the materials on the surface are on the average far older than the surface materials of the earth, and that some parts of the moon's surface, unlike any parts of the surface of the earth, may date back to the beginning of the solar system.

Thus, for entirely different reasons, both groups entertain high hopes regarding the scientific value of lunar exploration.

## 1. THE CASE FOR VOLCANISM

### Appearance of the Maria

The evidence favoring a geologically active moon, with a structure and history similar to that of the earth, is derived principally from the examination of the moon's surface features. The dark, irregularly shaped regions, in particular Mare Tranquillitatis and Oceanus Procellarum, immediately strike the eye as extensive flows of lava, presumably from a molten or near-molten interior. These regions resemble large lava flows on the earth such as the Columbia River plateau, the Pihana field in Brazil, or the Deccan lava field in India.

On the earth, such large lava flows, covering areas on the order of millions of square kilometers, and with a maximum thickness of two or three kilometers, are formed as a result of repeated flows of lava through multiple cracks or fissures in the crust, each flow spreading out over a portion of the field with a thickness of five or ten meters. The lava field builds up steadily to its final extent and thickness over the course of tens of millions of years.

## Other Explanations of the Maria

Impact Melting. Other explanations have been offered for the origin of the dark material in the maria. It has been suggested that the material filling the ringed maria, such as Imbrium, consists of lava that melted as a result of the energy released in the impact of the Imbrium object with the moon's surface (Urey and MacDonald, I-14). This hypothesis disagrees with the observed fact that when a high speed projectile penetrates a surface and explodes, most of the energy of the explosion goes into ejecting debris from the explosion crater, and very little goes into the melting of material.

However, the last remark is based on terrestrial bomb explosions and laboratory scale experiments whose scaling up to Imbrium-sized craters may not be reliable, particularly if the surface or upper mantle temperatures are already close to the melting point. The alternative of impact melting cannot be excluded on the basis of terrestrial cratering experiments alone. There is stronger evidence against impact melting in the chemical analysis of the lunar samples.

It is also possible that a deep subsurface layer directly under the impact zone was close to the melting point at the time of collision, and that the temperature increase produced

by the shock of the collision would be sufficient to bring this material above the melting point.

Sediments. It has also been suggested that the maria are filled with thick sedimentary deposits, consisting of material transported to the mare basins from the surrounding highlands, either by water or by dry transport mechanisms (Gilvarry, III-39).

Rubble-Covered Ice. Finally, it has been suggested that the maria are sheets of ice covered by rubble (Gold, in "Nature of the Lunar Surface", 1966). There are strong objections to this hypothesis. First, if the maria contained beds of ice or even permafrost, under a few meters of rubble, the blocks of material ejected from meteorite craters would consist in part of ice fragments or mixtures of rock and ice. When the ice evaporated the fragments would crumble and disintegrate in an easily recognizable way. Such piles of rubble, suggesting the decayed remains of blocks of rocky ice, have not been noticed in the Orbiter and Apollo photographs, and if they exist at all, they must be extremely uncommon.

Second, whatever water the moon contained initially would have been chemically combined into hydrated minerals. This combined water must be extracted by some process, in order to form the necessary ice layer. On earth, the only known natural process of separating the combined water from silicates is by an igneous process -- melting of the rocks and release of contained volatiles -- "degassing." If a similar mechanism has operated on the moon, the water would emerge on the lunar surface as steam. While it would freeze during lunar nights, it would vaporize during days, and would not last long enough to build up into ice sheets.

#### Surveyor Chemical Analysis

The theory of a volcanic origin for the mare material is supported by the chemical analysis carried out on the Surveyor spacecraft, using alpha particle back-scattering as the analytical tool. The analysis yielded a composition resembling that of terrestrial basalts.

The final results of the data analysis for Surveyor 5 recently have been published by Turkevich (this paper, II-30). The data agree with the oceanic basalts within the probable errors for all major constituents with the exception of sodium and titanium. According to the Surveyor 5 data, the

abundance of sodium in the mare material is half that of the basalts and the abundance of titanium is 60 percent greater.

### Morphological Evidence for Volcanism

The Lunar Orbiter photographs show surface features which resemble structures produced by volcanism on the earth, and have apparently been internally generated. These features include:

(1) A substantial number of domes resembling terrestrial volcanic domes, as, for example in Oceanus Procellarum.

(Fig. 1)

(2) Craters arranged in rows rather than the random pattern characteristic of impact features. Such rows of craters appear on the earth as volcanoes which are located over zones of weakness extending into the mantle, and the presumption is that crater rows on the moon also represent fissures or zones of weakness extending into the lunar interior. Sometimes the rows of craters are located within a rille and provide a particularly clear demonstration of internal origin; the Hyginus Rille, located almost precisely in the center of the moon's near side, is a conspicuous example; another example is a row of craters nearer to Gruithuisen.

(Figs. 2, 3)

(3) Lunar Orbiter photographs showing features that look like flow fronts, apparently marking the edges of individual lava flows; these flow fronts are five to ten meters in height, and have a slope, at the point of contact with the flat mare floor, that corresponds to the viscosity of some types of terrestrial lava. (Fig. 4)

(4) Photographs showing rilles originating in craters, for example, Cobra Head (also known as Schröter's Valley) and Marius Hills Rille. These features are ambiguous; they resemble dried out river beds, but they also resemble channels eroded by lava flows on earth. (Figs. 5, 6)

(5) Some wrinkle ridges look as though they were originally rilles out of which lava welled in sufficient amounts to convert the rille to a ridge. A striking example is found again in the Marius Hills region in which what appears to be a single feature is converted gradually from a rille to a ridge. (Fig. 6)

(6) Finally, outgassing has been observed from some lunar craters, and other craters, while not emitting gases at the present time, are visibly blackened for some distance around the crater rims, as if by volcanic gases. The degree of outgassing is modest and not an indication of extensive volcanism, but offers some support for the hypothesis of a volcanic moon.

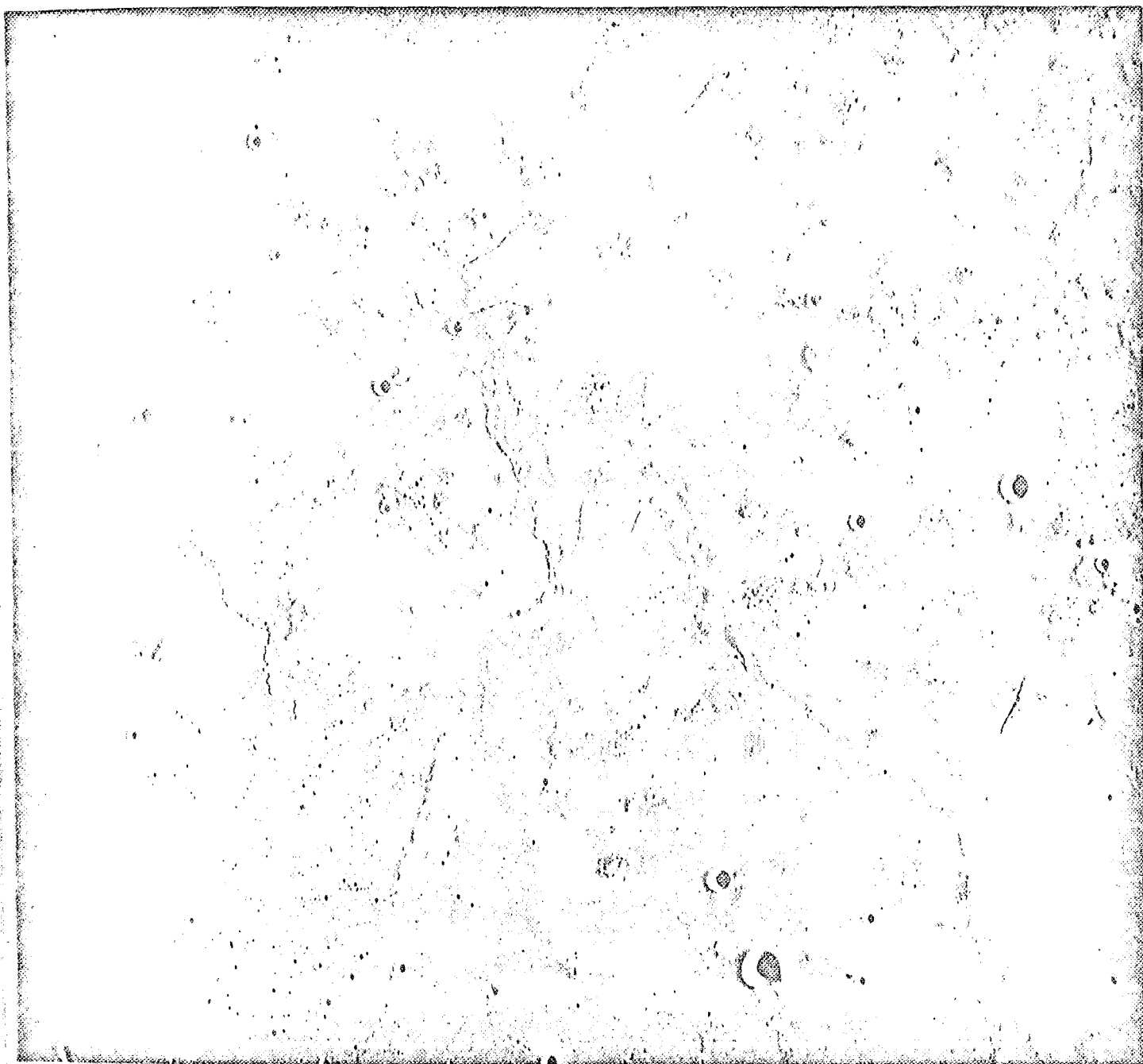


Figure 1. Vertical view of domes in Marius Hills region of Oceanus Procellarum. (Following p. 9.)



Figure 2. Row of craters in Hyginus Rille. (following p. 10)

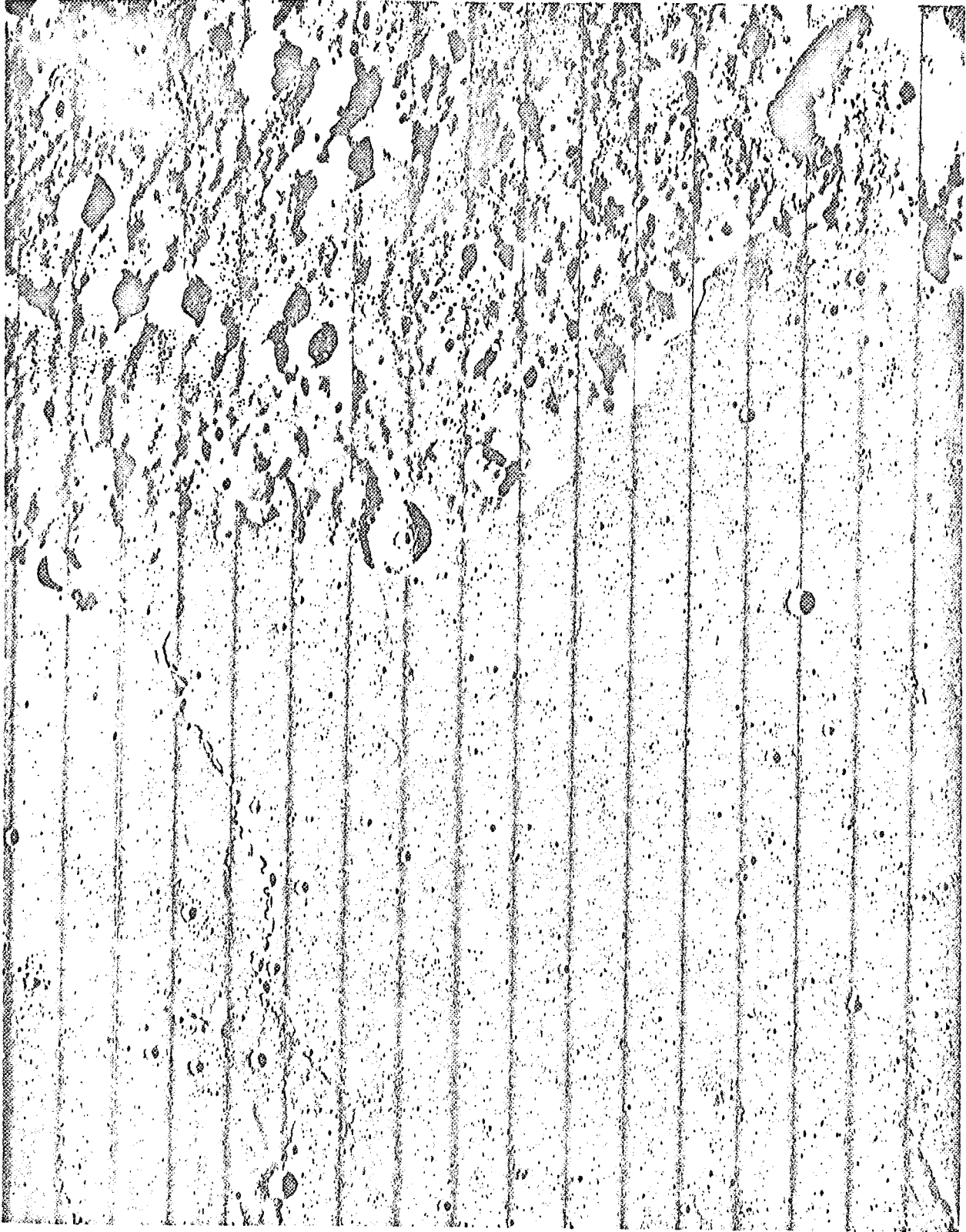


Figure 3. This rille with a chain of craters gradually turns into a wrinkle ridge. (Following p. 10.)

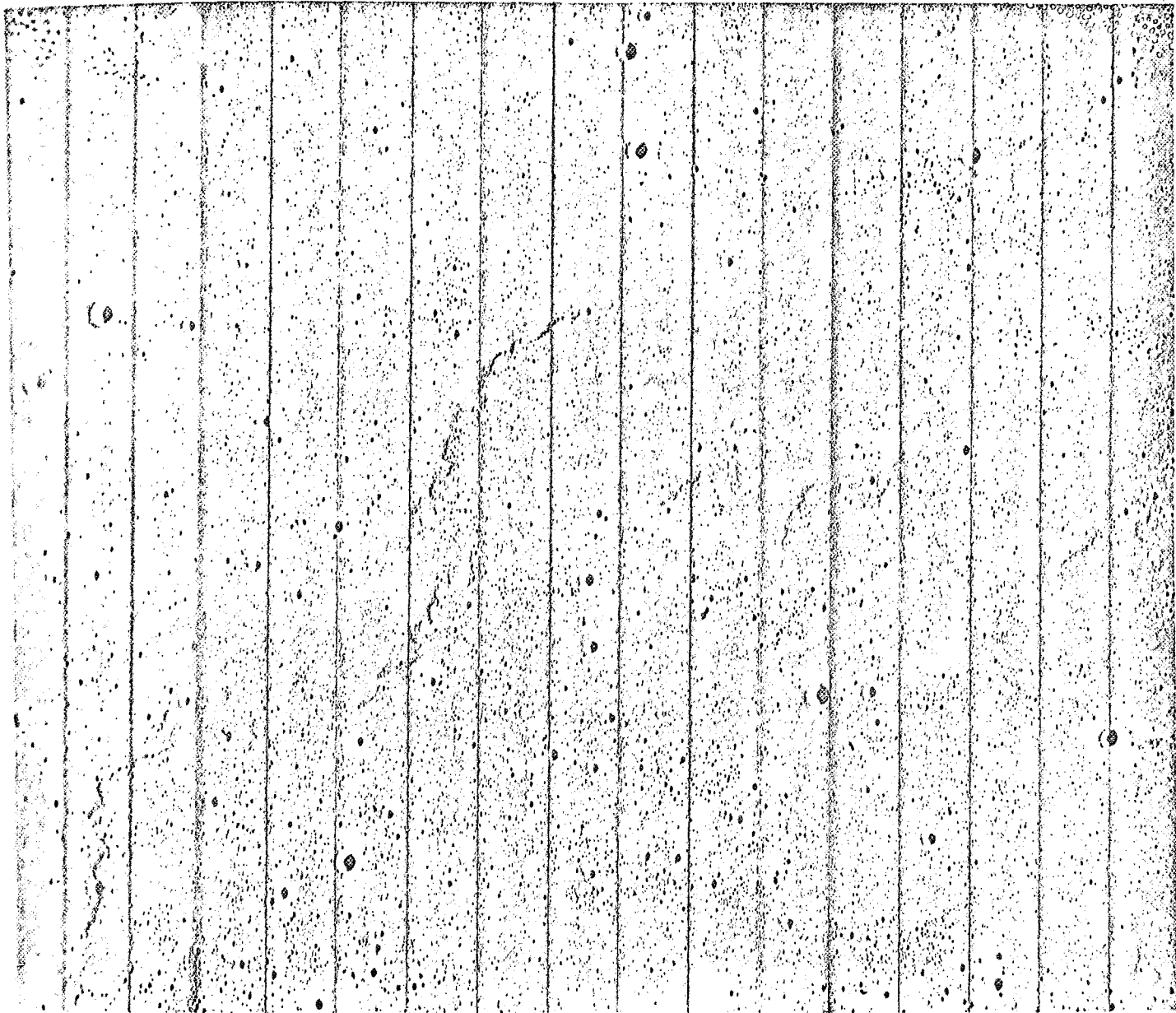


Figure 4. Flow front in Mare Imbrium. (Following p. 10.)

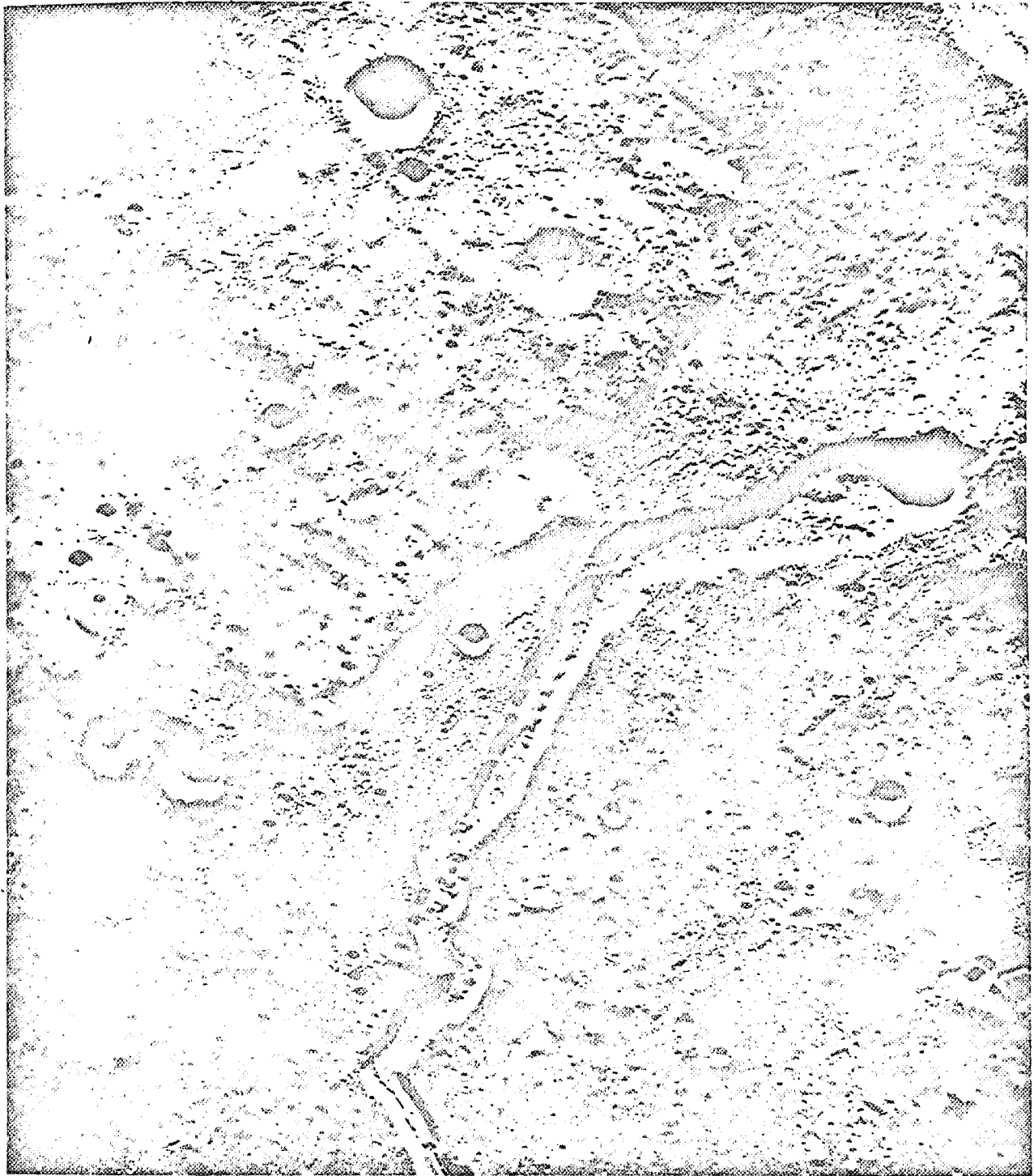


Figure 5. The Cobra Head or Schroter's Valley. The rille emerges from a crater. Note meandering rille within rille. (Following p. 10.)

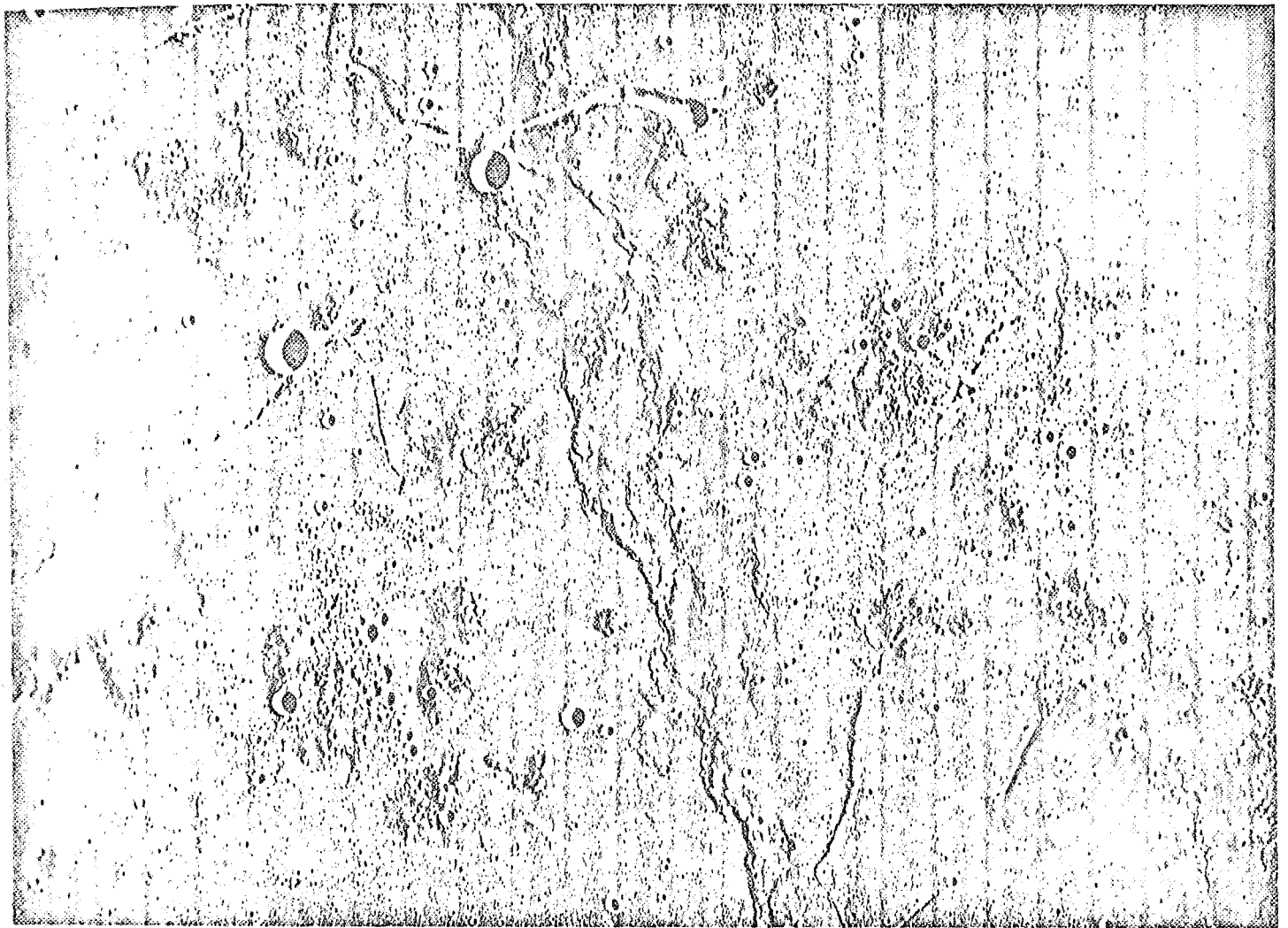


Figure 6. Rille starting in a crater in Marius Hills region.  
(Note rille changing into ridge.) (Following p. 10.)

In summary, the pre-Apollo arguments in support of lunar volcanism are (1) resemblance of the maria to extensive terrestrial lava flows; (2) surface forms closely resembling terrestrial volcanic forms; and (3) Surveyor analysis of chemical composition indicating basaltic composition.

This evidence for volcanism indicates that at some point in the moon's history its interior has been molten or partially molten. Thus, some degree of differentiation must have occurred; the moon cannot be homogeneous and entirely undifferentiated. This is not to say that the differentiation has proceeded as far as on the earth, i.e., to the point of an iron-nickel core at the center, surrounded by a magnesium silicate mantle, and capped by a granitic crust with a very low iron-magnesium content. That question is still open.

## 2. THE CASE AGAINST VOLCANISM

The evidence usually cited for lunar volcanism is balanced by other information indicating that the entire moon, or a large fraction of it, has always been at a relatively low temperature.

### Moment of Inertia

Recent determinations of the moon's moment of inertia have been cited as evidence for a homogeneous, undifferentiated structure, implying that the moon has never been melted. Two recent determinations for the moon's moment of inertia give values which are within one percent of  $\frac{2}{5} MR^2$ , the value for a homogeneous sphere. However, the reasoning is based on the unstated premise that the moon has a substantial amount of iron. If that were so, and extensive melting occurred, the iron would collect at the center to form a dense core, as in the case of the earth, substantially reducing the moment of inertia below  $\frac{2}{5} MR^2$ . The argument is weakened by the fact that the density of the moon is very low in comparison with the density of the earth, indicating that the moon has relatively little iron, amounting to perhaps 10 percent of its mass. This amount of

iron, even if collected at the center in a dense core, would not appreciably reduce the moon's moment of inertia below the homogeneous value.

#### Figure of the Moon

More substantial evidence for a low-temperature history is provided by the figure of the moon. (Urey and MacDonald, this paper, p. I-14) If the moon has a warm and plastic interior, it must assume a shape dictated by hydrostatic equilibrium. In hydrostatic equilibrium, the moon will bulge to a slight degree at the equator as a result of the rotation about its axis every 27.3 days. There will also be a bulge along the earth-moon line as a result of the earth's gravitational attraction.

The calculated bulge at the equator is 16 meters, and the magnitude of the bulge produced by the earth's tidal pull is 48 meters. The magnitude of the equatorial bulge can be determined separately from observations of the rate of precession of the moon's orbit plane which is proportional. The result is an equatorial bulge of about 1 km. The tidal bulge can be determined from the moon's physical libration in longitude, which is proportional to the height of the tidal bulge. The result of this determination is a tidal bulge again equal to about 1 km. These values deduced from observation, which are two orders of

magnitude greater than the calculated values, indicate major departures from hydrostatic equilibrium within the moon. Assuming a uniform distribution of density varying only with distance from the center, the "observed" values of the equatorial bulge and the tidal bulge imply that stress differences of 10 to 20 bars are being supported over large regions of the moon's interior. According to Urey and MacDonald, "For a body as large as the moon not to have adjusted in shape by one kilometer to relieve these stresses indicates that remarkable strength has existed in the deep interior since the present irregular shape was formed. No general melting of the moon can therefore have occurred since then." (Urey and MacDonald, Geophysics of the Moon, Science Journal, May 1969)

### Mascons

Mascons provide evidence for a mechanically strong and therefore cold moon. Twelve of these gravitational anomalies have been discovered, distributed on the near side of the moon, occurring with both signs and with magnitudes ranging up to approximately 750 milligals when extrapolated to the lunar surface. (Muller and Sjogren, III-1) Additional mascons may exist on the far side of the moon but the tracking data, whose analysis led to the discovery of the near-side mascons, are not

yet adequate to settle this point. Each of the six circular maria on the near side contains a large, positive mascon. These mascons represent localized departures from hydrostatic equilibrium, i.e., departures from isostasy, that would produce stress differences of 10 to 20 bars in the moon's interior.

If the interior of the moon were warm enough to be near the melting point, it would yield under the weight of these mascons. The material of the moon's mantle would slowly flow out to either side until the number of grams per square centimeter over a mascon is the same number of grams per square centimeter over adjoining regions, i.e., until the gravitational effect was no longer detectable on the surface. The fact that they still exist indicates that the outer layers of the moon have been strong and cold since the time of their initial formation.

Several theories have been advanced to account for the mascons. One view holds that they are accumulations of lava that have come up partly through fissures and pipes from below the impact basin. (Wise and Yates, III-15) Urey believes that the mascons in the ringed maria are the remains of the meteorites or asteroids that created the basins of these maria. (Urey, III-12) Whatever the origin of the mascons may be, the most significant fact about them is their continued existence, which

offers additional evidence that the moon's interior is strong and therefore cold.

#### Evidence from Conductivity

Additional evidence for a cold moon comes from an analysis of the effect of the moon on the interplanetary medium in its vicinity. (Ness, IV-20) The interplanetary medium consists of the solar wind and an accompanying interplanetary magnetic field. The moon has no detectable magnetic field of its own and therefore has no magnetic effect on the solar wind. However, as a conducting body it does have an effect on the interplanetary magnetic field. If the moon's electrical conductivity were infinite, the interplanetary magnetic field would be unable to penetrate it, and the lines of force in this field would pile up against the side facing the sun, leading to the development of a pseudo-magnetosphere and a bow shock wave. There is no sign of these phenomena in the magnetic field data from a number of spacecraft that have probed the magnetic field in the moon's vicinity. This means that the lines of force of the interplanetary magnetic field pass through the moon as though it were magnetically transparent.

That fact, by itself, however, does not indicate anything about the value of the moon's conductivity except that it is

finite and not infinitely high. Given sufficient time, a magnetic field will penetrate into and pass through any body of finite conductivity.

In order to measure the moon's conductivity, it is necessary to follow a pulse or disturbance in the interplanetary magnetic field as this pulse approaches the moon, observe when the pulse enters the surface of the moon, and finally observe when the pulse reappears on the other side of the moon. The time required for the pulse to travel through the moon is the dispersion time of a magnetic field in the moon's interior, which is proportional to its average conductivity. Ness reports that such disturbances take 60 seconds to travel through the moon, from which he concludes that the main thermal conductivity of the moon's core -- the region of radius 1300 km, lying inside the insulating shell of approximately 400 km -- is  $10^{-4}$  mhos per meter. According to calculations of the electrical conductivity of the moon,  $10^{-4}$  mhos per meter corresponds to a temperature of  $1000^{\circ}$  K. Ness estimates a probable error of  $\pm 200^{\circ}$  on this value.

Ness's analysis leading to a value of  $1000^{\circ}$  K for the average temperature of the inner 1300 km of the moon, seems to

be very strong evidence against melting or partial melting. The probable range of melting point temperatures for lunar material at a depth of 400 km is  $1300 \pm 100^\circ$  K, well outside the error limits of Ness's result. (The quoted uncertainty is a result of uncertainties in the mineral content and water content of the hypothetical lunar material.)

Since this conductivity-derived temperature refers to the inner part of the moon, it is even stronger evidence for a solid moon than the evidence provided by the existence of mascons on its surface.

However, some factors weaken the force of the argument. First if the temperature of the moon rises during its history, local hot spots will appear and lead to the formation of pockets of magma before a large part of the moon's interior is at the melting point. Thus, these pockets of magma may develop when the average internal temperature of the moon is  $100^\circ$  to  $200^\circ$  below the melting point, i.e.,  $1200^\circ$  or  $1300^\circ$  K. This circumstance brings the minimum temperature required for partial melting nearly within the limits of Ness's value. Second, Ness's determination of the diffusion magnetic time through the moon, and the corresponding electric conductivity of its interior, may be accurate to within the 20 percent probable error quoted, but uncertainties are introduced by calculations connecting

conductivity and temperature, whose accuracy is unknown. It seems reasonable to allow for these uncertainties by adding a few hundred degrees to the error limits assigned by Ness, bringing the final result well within the temperature range needed for partial melting.

In summary, Ness' data are evidence for cold moon, but if allowance is made for uncertainties and the connection between conductivity and temperature, the results may be compatible with a partially molten interior.

### 3. THE HEAT FLOW MEASUREMENT: A CRITICAL EXPERIMENT

The Surveyor chemical analysis suggests an igneous origin for at least some lunar surface rocks. The question still remains whether these rocks were melted by the heat released in a major collision, or were the result of internal melting. The critical factor in determining this issue is the concentration and distribution of the radioactive elements which provide the internal heat sources. Are these limited to a thin surface layer, or are they representative of the moon's bulk composition? How far into the interior does the surface concentration of radioactive elements extend? This question can be answered by measurements of the flow of heat through the lunar surface.

One heat flow measurement will not suffice. The Surveyor data suggest that the surface of the moon, like the surface of the earth, is chemical heterogeneous and may be expected to have different concentrations of radioactive elements and therefore different heat fluxes in different regions. Measurements of the heat flow in a typical maria area and in a typical highland area are an essential minimum.

Why are heat flow measurements so important? These measurements indicate the amount of energy available for volcanism and also for every other internally generated lunar process. Most of the basic issues in lunar science depend on the moon's supply of internal energy. Are its internal energy sources as large as those within the earth, or larger? If so, the moon has had a geologically active history, with surface features molded by forces similar to those that mold the face of the earth. Are its internal energy sources considerably smaller than those of the earth? If this is the case, the moon has surely been a geologically inactive body throughout most of its history, with its surface features determined largely by high-energy collisions and not by subsurface melting. In that event, the moon is a very different body from the earth, and the experience of terrestrial geologists is not directly applicable.

Moreover, the outgassing from the interior -- which is generally considered to be the source of the earth's oceans and atmosphere, and the atmospheres of Mars and Venus -- is controlled by the rate of internal heat generation. While the origin and evolution of the moon's exceedingly thin atmosphere are not problems of major interest, the understanding of the origin and evolution of the atmospheres of Mars and Venus are

problems that stand in the forefront of objectives, of planetary exploration. Because of these considerations, involving volcanism and outgassing, heat flow measurements must be placed alongside seismic measurements as the two most significant geophysical experiments that can be performed on any terrestrial planet.

## B. GEOLOGICAL STUDY OF THE LUNAR SURFACE

### LUNAR STRATIGRAPHY

The principle of superposition provides a meaningful framework for correlating information acquired at the various lunar exploration sites. That is, it is assumed that younger lunar formations overlie older ones or overlap against them. This reasoning has already been applied to the moon, using earth-based photographs, to establish a sequence of events in lunar history which form the elements of a stratigraphic column. The aim is to establish a relative time scale for the entire front face of the moon.

Inspection of the photographs makes it clear that the maria are younger than the highlands since they encroach on the edges of the highlands and also partly submerge many craters near the highland boundaries. For example, Sinus Iridum, Plato and Archimedes are older than Mare Imbrium, because they are flooded by the mare material. Similarly, Copernicus is younger than the mare material

on which it rests, since its rays cover the adjacent areas and indeed extend for hundreds of miles over the moon's surface. Tycho is even younger than Copernicus, because its ray system overlaps that of Copernicus.

In this way, Shoemaker (V-I) has constructed a lunar stratigraphy, or relative geological time scale, for the area around Copernicus. He has grouped the deposits into five classes: (1) pre-Imbrian, (2) Imbrian, (3) Procellarian, (4) Eratosthenian, and (5) Copernican, which correspond to five intervals of time.

The Imbrian system: the stratigraphically lowest and oldest exposed system consists of those structures which pre-date the maria filling. These include material deposited on old craters and the Carpathian and Apennine Mountains. The Procellarian system is made up of the smooth, dark material filling the Oceanus Procellarum, Mare Imbrium and Sinus Aestuum, as well as domes resembling basaltic shield volcanoes. This has been succeeded by old, rayless craters otherwise resembling Copernicus but covered by its rays. Examples include Eratosthenes, Reinhold and Lansberg. These comprise the Eratosthenian system. The stratigraphically youngest Copernican system includes the rays and ejecta of Copernicus, Hortensius and a bright ray crater east

of Gambart. Among the youngest features are the deposits of dark halo craters, superposed upon the ejecta and rays of Copernicus. These have also been included in the Copernican system.

The second criterion of relative age is the crater density. Assuming that craters are formed by a random impacting process of uniform rate, then the more heavily cratered a given area, the older it is. The lower crater density of the maria indicates that the maria are younger than the highlands -- a conclusion consistent with the principle of superposition.

Finally, the general appearance of the crater is a guide to its relative age. The younger the crater, the brighter it is, the more sharply defined its rims and rays. Some slow erosional process on the moon gradually wears down craters with time, making them dull and fuzzy in outline.

The foregoing arguments give relative ages, but not absolute ages. It is impossible to tell whether the heavily cratered highlands, in particular, represent a continuum of ages ranging up to a relatively recent point of time in the moon's history, or have, instead been formed by a brief and intensive bombardment early in the history of the moon.

## 2. RELATION OF SPECIFIC EXPLORATION SITES TO MAJOR LUNAR PROBLEMS\*

Landing sites near the Hyginus Rille and in the Marius Hills region will provide information directly bearing on the question of lunar volcanism. Censorinus, Tycho and Copernicus are relatively new craters in the stratigraphic sequence of lunar features. Absolute age measurements of the materials collected from these sites will establish a marker in the lunar time scale towards the end of the process of bombardment. Censorinus and Tycho in addition are located in the highlands area and offer the opportunity to study the composition and ages of highlands material and the maria surfaces.

The Apennine Mountains are of broad geological interest because of the fact that they form the border between Mare Imbrium and the highest regions of the lunar highlands and they present an opportunity to study a border between two of the major lunar features. This is somewhat analogous to the borders between continents and oceans on the earth, for example, the Andean trench between the Pacific and South America.

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\*This material is adapted from an article prepared by Gast Hess, Kovach and Simmons for SCIENTIFIC AMERICAN.



Figure 7. Oblique view of domes in Marius Hills region of Oceanus Procellarum. (Following p. 26.)

Finally, an extended lunar transverse starting in the Apennine Mountains and going across Mare Imbrium would indicate the magnitude and extent of large-scale variations in composition and structure on the moon and might possibly determine the nature of the mascons.

### Marius Hills

Marius Hills is one of the several regions in which constructional features, i.e., domes and built-up cones, predominate over impact craters. It is associated with one of the longest ridge systems observed on the moon, which in turn crosses a very large expanse of Oceanus Procellarum in the eastern half of the near side of the moon. The tectonic setting and morphology of this region are in fact similar to that of terrestrial volcanic fields like Iceland and the Azores. This suggests that it is a region of volcanic activity in which igneous material has been added to the surface through localized vents.

Lunar Orbiters II, IV and V obtained excellent photographs of this region. Vertical and oblique pictures from these missions are shown in Figs. 1, 6 and 7. The small domes comparable in size to common terrestrial volcanoes are easily seen here

(see Fig. 7). The origin and age of these features are of general importance in understanding the evolution of the lunar surface. Terrestrial volcanic features are built up in very short times compared to the entire history of the earth. Even an extensive region like the entire Hawaiian Islands volcanic chain covers a time less than 10 million years. The absolute age and length of time involved in building up the domes seen here will be of great interest in characterization of lunar volcanism.

The Marius Hills region is much more extensive than the area that can be covered in a single Apollo mission. Fortunately, a number of characteristic smaller scale features can be visited within a region as small as 5 to 10 km in diameter. A mission in this area would be able to sample and study (1) impact cratered plains areas similar to maria regions, (2) a number of small domes 50 to 100 meters in elevation with convex upward slopes, (3) steep-sided domes with rough intricate surfaces, (4) steeply convex upward or bulbous domes that are smooth and generally equidimensional in plan, (5) steep-sided cones with circular depressions, (6) narrow steep-sided ridges, (7) a variety of impact features similar to those seen in this region are not exposed within 5 km of areas chosen for study.

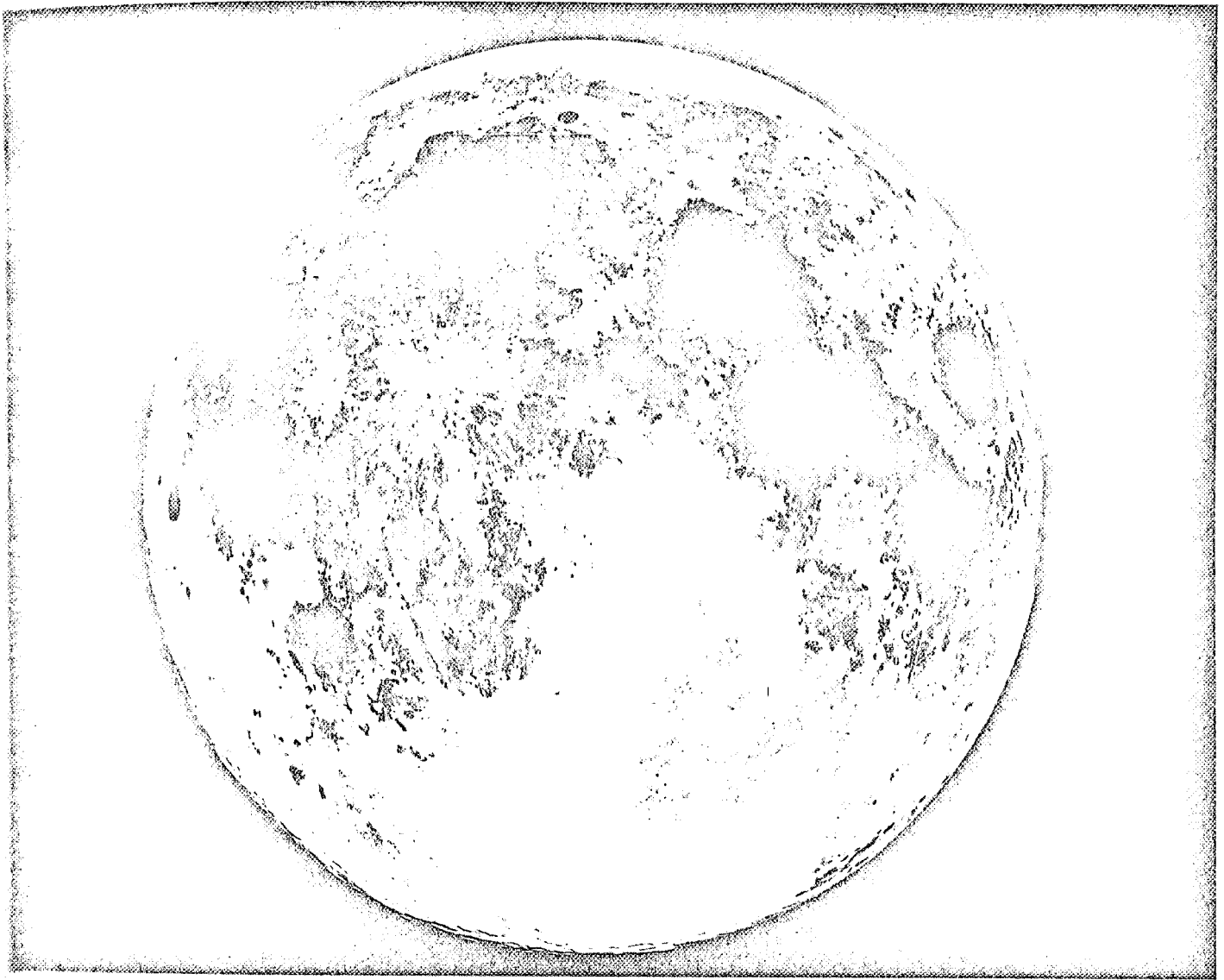


Figure 8. Earth-based photograph of full moon, showing the prominent ray system of Copernicus and Tycho.  
(Following p. 28.)

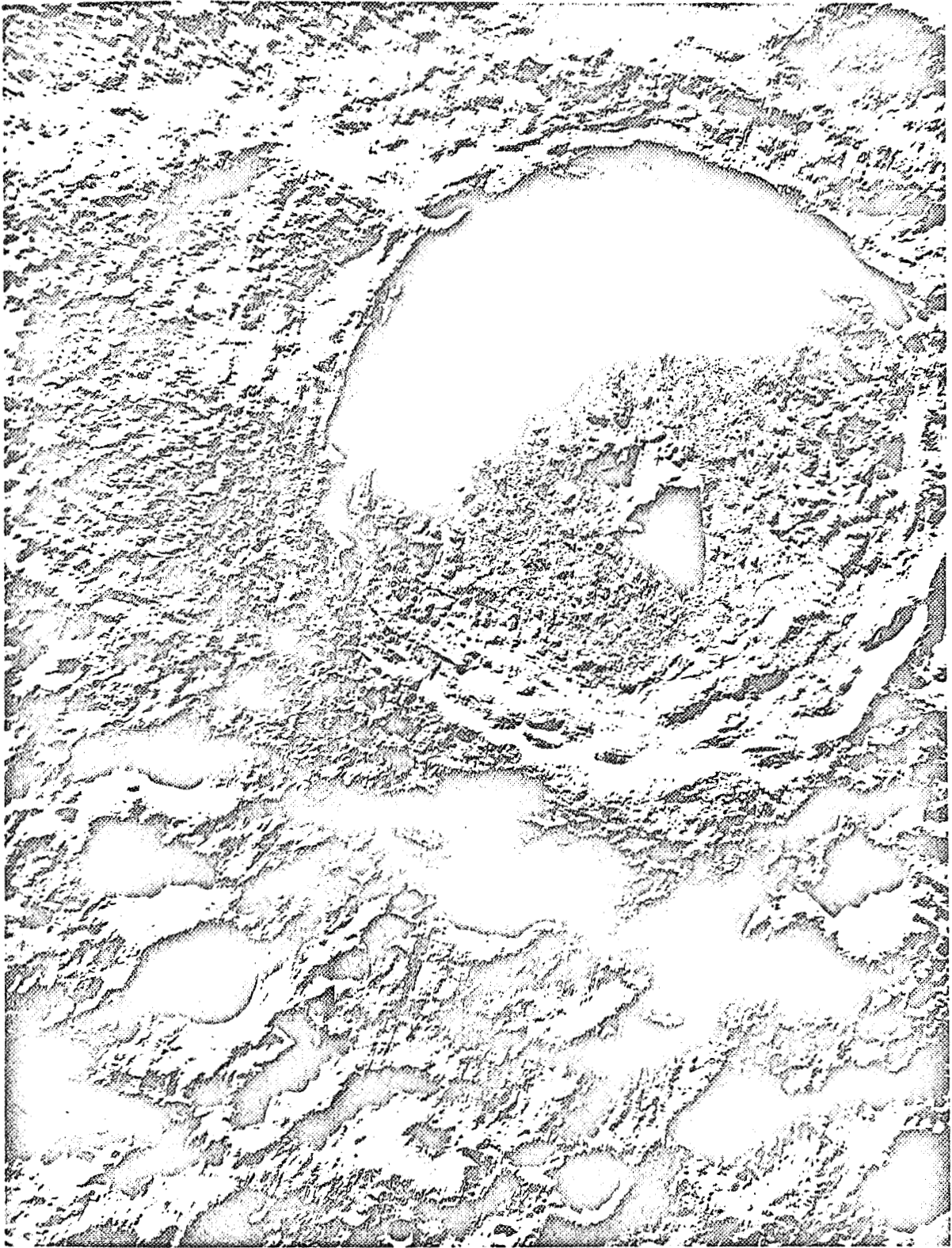


Figure 9. Close-up of Tycho from Orbiter V. (Following p. 28.)

## Tycho and Copernicus

A much more ambitious exploration goal is the exploration of one of the major craters on the lunar surface. Two of the most prominent craters, both relatively young, are Copernicus and Tycho. Both are about 70 km in diameter and have a central peak within the crater. Copernicus is on the southern edge of Mare Imbrium, in the Oceanus Procellarum. The ejecta from Copernicus cover a significant fraction of the earth facing side of the moon. This is well illustrated in the earth-based full moon telescopic pictures (Fig. 8). The ejecta from this crater cover more than one tenth of the front face of the moon. The ejecta blanket marks a major horizon in the upper part of the lunar stratigraphic column. Tycho is located in the middle of the southern highlands and forms the center of the prominent ray system (and ejecta blankets) seen on most whole moon photographs (Figs. 8, 9). The relief within the Copernicus crater is greater than 15,000 feet +, i.e., comparable to the height of most mountainous regions on earth. These large craters are of interest not only because they represent major events in the history of the moon, but because by analogy with much smaller terrestrial craters, they should expose materials from a range of depths as great as 10 or more km. It has been suggested that

the central peaks in these craters may consist of material from 10 to 15 km or more. Thus, even though they may be very jumbled and broken and badly deformed by shock processes, the materials in a major crater may provide a quite varied and diverse sample of the lunar crust and the history that formed it. A landing site and a variety of possible excursions in the Copernicus crater are shown in a medium and high resolution Orbiter photograph (Figs. 10A, 10B). Clearly it is not possible to accomplish even a small fraction of the exploration of this kind of lunar feature without mobility devices on the lunar surface.

### Censorinus

Censorinus crater and also Mösting C are extremely fresh craters, as evidenced by their brightness in the infrared study of Shorthill and Saari and by the high resolution Orbiter pictures which show many abundant angular blocks in the ejecta blanket of these two craters. The major objectives of a landing on the rim of this crater are (1) to establish the age of an apparently young feature on the lunar surface, (2) to investigate and characterize an unquestioned impact feature of modest size, and (3) to obtain a sample of materials from a region in the highlands. A possible landing site and approach path to this

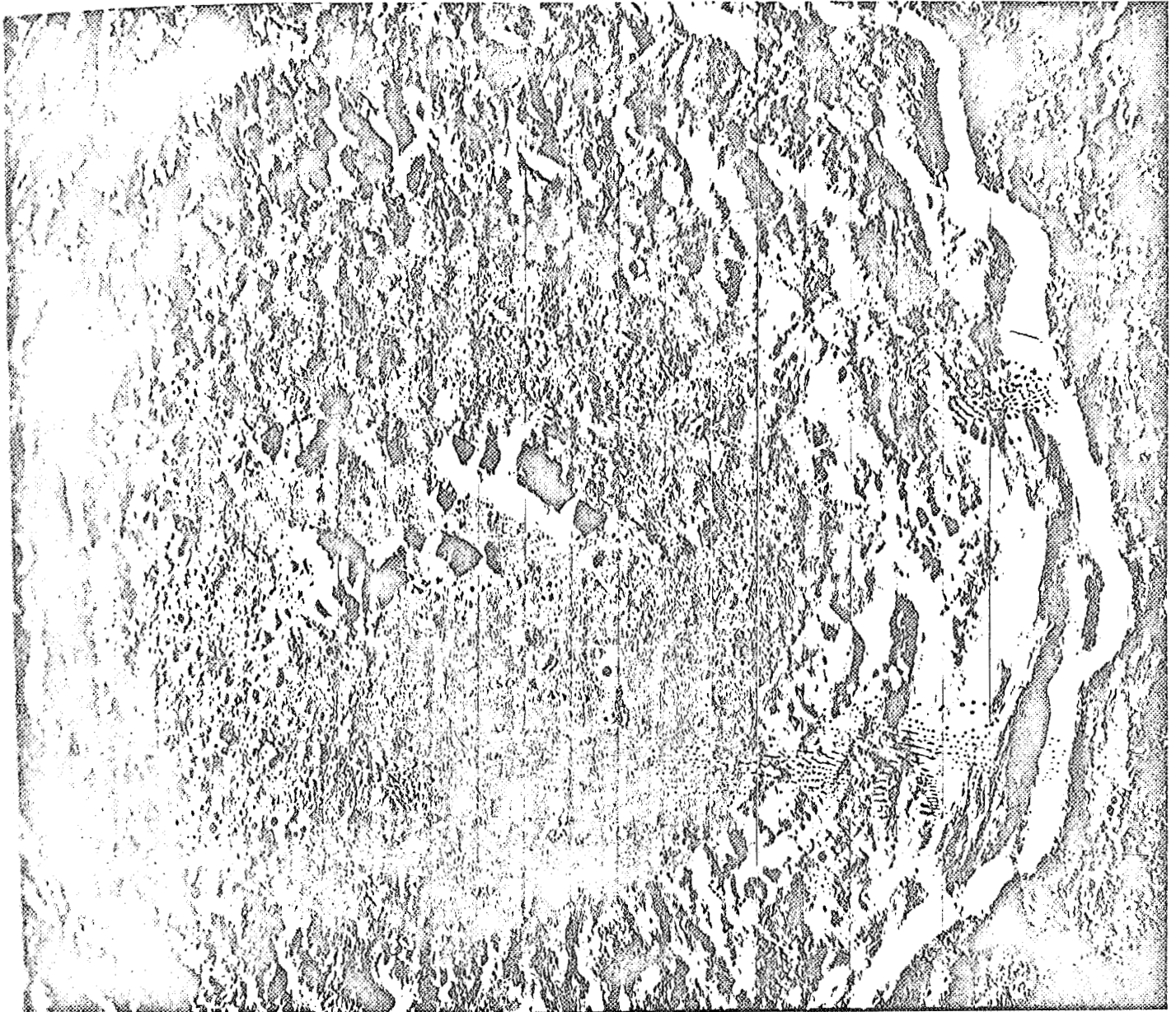


Figure 10 (a). Close-up of Copernicus (medium resolution).  
(Following p. 29.)



Figure 10 (b). Copernicus- an oblique view. (Following p.29.)

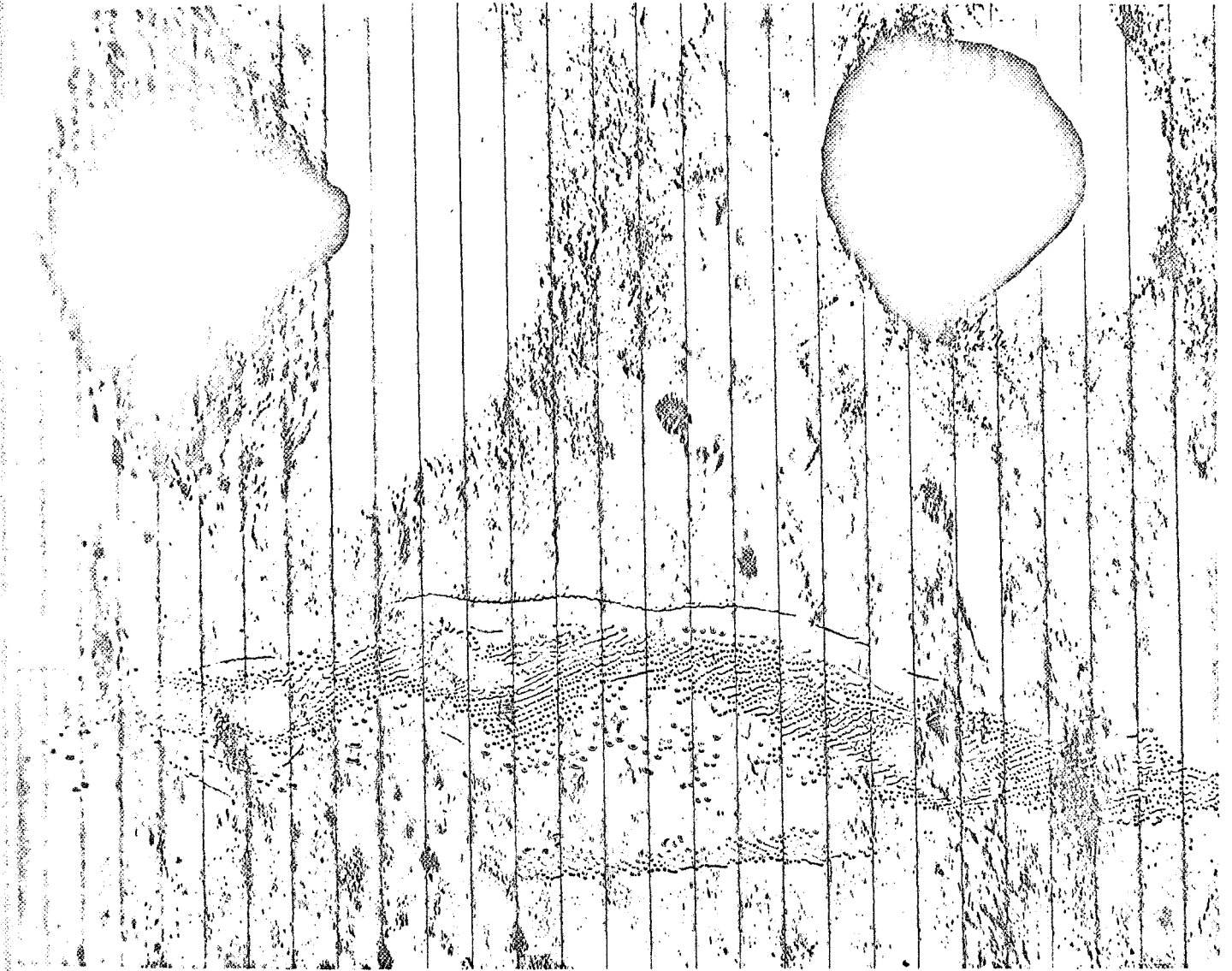


Figure 11. Censorinus- a young crater. (Following p. 29.)

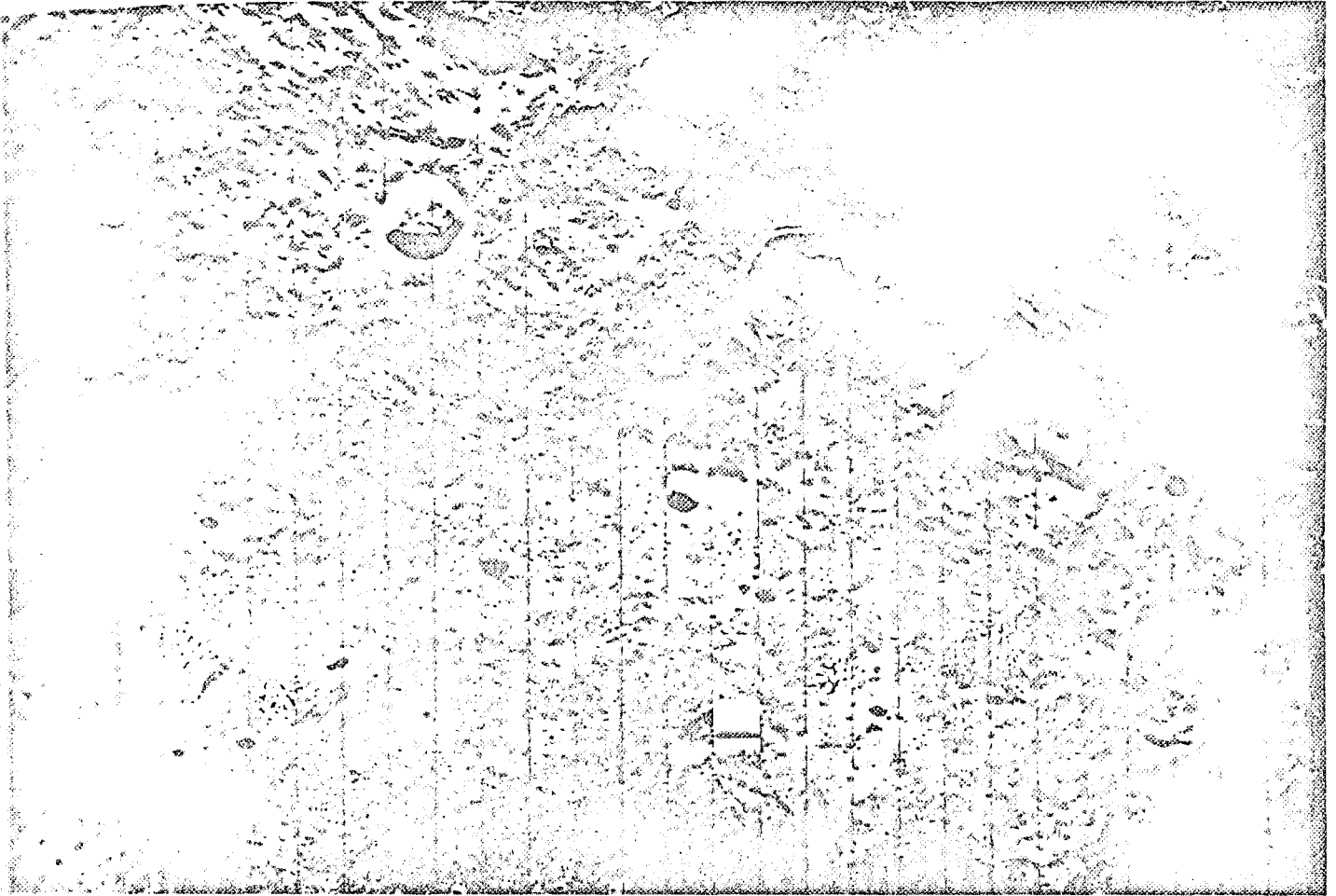


Figure 12. Apennine Mountain Front. (Following p. 30.)

site is shown in the Apollo 10 photographs of this area shown in Fig. 11, which is a high-resolution Orbiter photograph of Censorinus and contains several possible exploration sites.

### Apennine Mountains

The Apennine Mountains, which roughly mark the southeastern boundary of Mare Imbrium, are the most impressive of all the lunar mountain ranges. These mountains also form the northwestern leg of a triangular shaped elevated highland area bounded by Mare Imbrium, the southwestern boundary of Mare Serenitatis and the northern part of Mare Humorum. The Apennine Front rises 1,280 meters above the adjacent mare level to the west.

Two landing sites have been proposed near the Apennine Front which are within 5 km of some important lunar features. Figure 12 is a closeup Lunar Orbiter photograph showing the Apennine Mountain front.

Examination of this photograph reveals several interesting features. Notice the V-shaped serpentine feature running in a northeasterly direction parallel with the Apennine Front. Such winding (or meandering) lunar features, reminding one of stream

channels are termed sinuous rilles. This particular rille is Rima Hadley. In the vicinity of the proposed landing sites one can also see a small, but conspicuously sharp and round crater which appears to cover part of the rille.

What can we learn about the moon by visiting this location? The Apennine Front is a major physical feature of the moon's surface and an extensive vertical section, 1,280 meters thick, is exposed for sampling and examination. Here is an opportunity to sample perhaps an extensive portion of lunar history. Are the rocks in this area uniform or physically and chemically heterogeneous? How old are they? Are they stratified? Are they fresh or altered? - and so on. Answers to such questions as these, obtained from examination of samples collected over such a range of depths in the moon can have a profound impact on our thoughts concerning lunar history.

The sinuous rille, Rima Hadley (see Fig. 13) also holds some clues for understanding the moon's history. Broadly speaking this feature looks as if it has been worn by erosion -- but is it a near surface flow channel or a collapsed lava tube? It has been speculated that this flow channel has been formed by water. If erosion by water has occurred on the moon, where did the water come from and what prevented its immediate evaporation from the lunar environment?

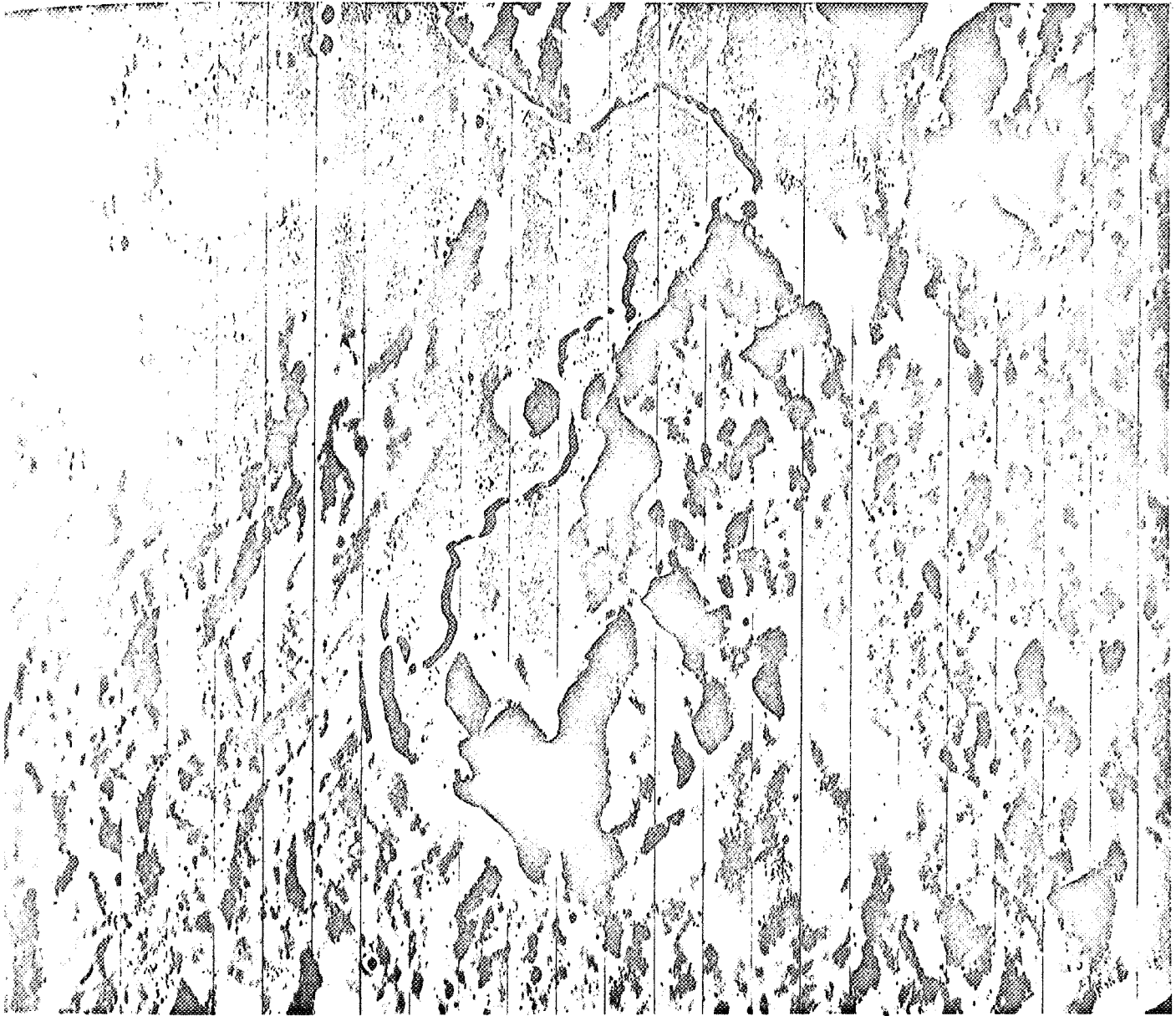


Figure 13. Rima Hadley is a beautiful example of a sinuous rille. Note how rille is influenced by topography, avoiding the crater and mountain base. (Following p. 31.)

Closer examination of the Lunar Orbiter photos of this rille reveals that fresh outcrops of rocks are visible along its walls and that blocks have rolled down the rims to settle on the floor of the rille. Rima Hadley cuts into the floor of a mare and thus exposes a depth and perhaps a cross section of the history of a major lunar feature. Examination of these exposures might yield their share of surprises. Are the lunar maria bedded deposits of lava or ash flows, or sedimentary deposits that contain a sequential history of formation, or are the maria simply the result of an agglomeration of cold particulate matter accreted from space?

As mentioned above, the proposed landing site is located at the boundary between a lunar highland and a mare region. Deployment of a three-axis seismometer and the subsequent recording of seismic waves from different azimuths of approach should tell us something about any deep structural differences between the maria and the highlands. Are the maria and highlands truly analogous to the oceans and continents on the earth in which there are deep-seated structural differences?

## Discussion of Lunar Traverse

After the early fixed station lunar landings at a wide variety of sites, some form of long-range mobile surface exploration will be necessary to greatly increase our scientific knowledge of the moon. Without the provision of additional mobility on the moon's surface, continued repetition of single-station exploration is scientifically unjustifiable. On the other hand, traverses give us the ability to study lateral variations and thus form the bridge between the intensive observations that are made in the vicinity of specific individual landing sites and the extensive averaging observations that can be made from orbit.

There are many exciting possibilities for increasing our mobility on the moon but one technique is of particular interest to lunar scientists. This technique is termed a dual-mode lunar surface roving vehicle system. The term dual-mode is used here because we are considering two separate lunar landings which are some 500 km away from each other but which are located to maximize the scientific return. The dual-mode system would operate in the following manner.

At the initial manned landing, an unmanned roving vehicle is started on an automated traverse. This vehicle proceeds

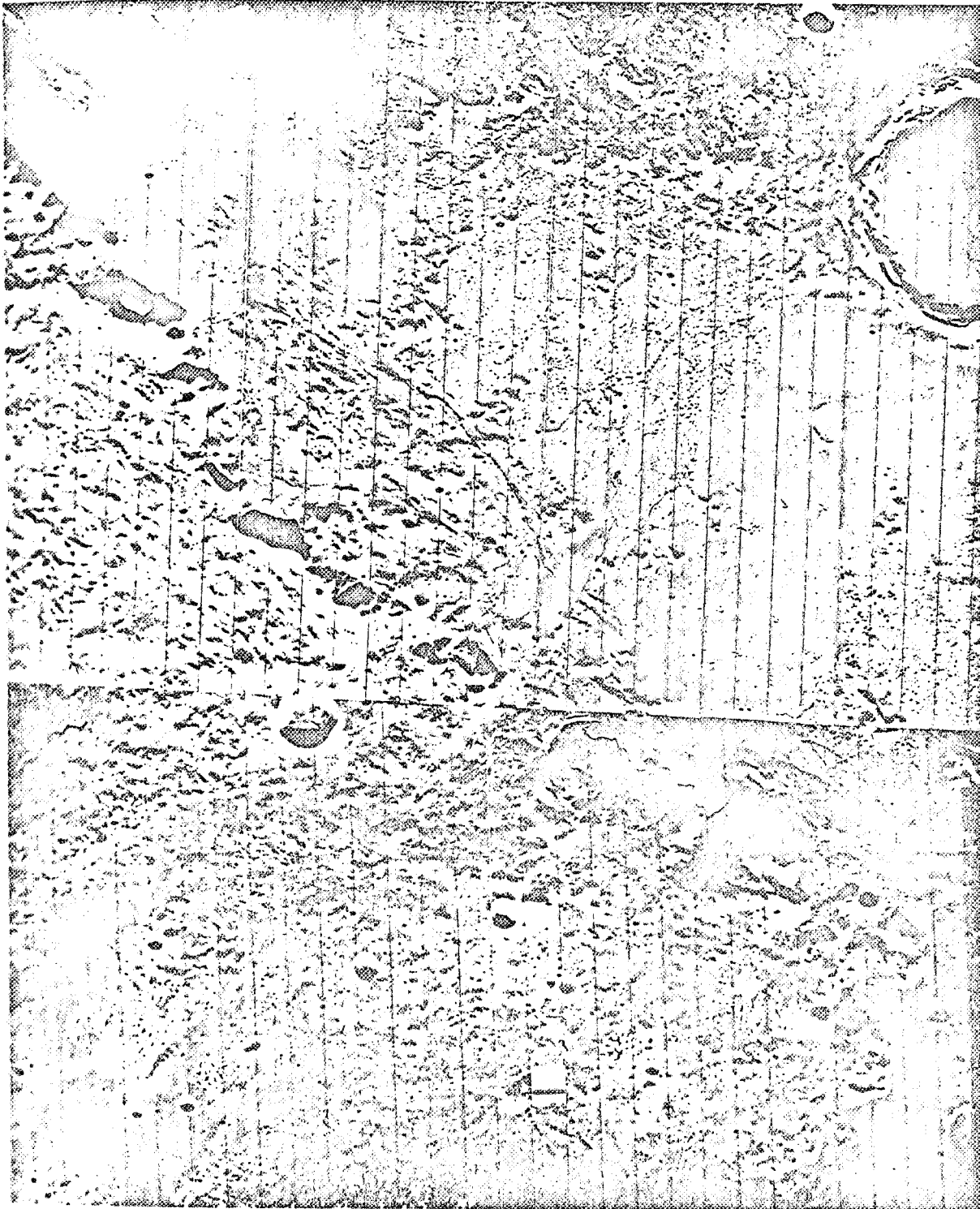


Figure 14. Lunar traverse extending from Rima Hadley via the Crater Archimedes into Mare Imbrium. (Following p. 34.)

to move across the surface of the moon to rendezvous at a distant designated point with the second manned landing several months later. At present, it is not clear what the capabilities of this roving vehicle will be, but the mechanical details are unimportant for this discussion. During this unmanned traverse the roving vehicle would collect samples of rocks and conduct important geophysical experiments. The collected information will then be retrieved at the rendezvous point by the astronauts who can either abandon the vehicle or send it on another automated traverse.

With this mobility capability on the moon where should we go and what do we hope to find out? A successful lunar traverse can provide data which have a bearing on the following questions. What is the magnitude and extent of lateral variations in composition and structure on the moon? What are the lunar "mascons?"

Other important questions can be posed but these will serve to focus out thoughts on one possible long traverse. This traverse goes from Rima Hadley via the Crater Archimedes into Mare Imbrium (see Fig. 14).

As we mentioned earlier a visit to the Apennine Front - Rima Hadley area would give us a chance to sample an extensive

portion of lunar history. From this point a traversing vehicle would proceed into the center of Mare Imbrium. The traverse capability will allow continuous profiling for the monitoring of the variations in gravity, magnetic, electrical and seismic properties at a scale commensurate with the lunar features that are being investigated. This particular traverse crosses into one of the largest of the lunar mascons and provides enough spatial coverage to adequately explore this feature with geophysical techniques.

The continuous monitoring of gravity along this profile will provide information concerning the regional isostatic balance in the moon, that is, are the higher topographic features on the moon compensated by a deficiency of mass at depth or do these features merely represent superincumbent loads placed on the lunar surface? An answer to this question would tell us a great deal about their mechanism of formation.

Gravity information will also give us clues about the maximum depth to which lateral density variations in the moon can exist. If the moon has a crust, analogous to that of the earth, how does it vary between the lunar highlands near Rima Hadley and the center of the Imbrium basin?

Whereas gravity measurements are valuable for regional reconnaissance their value is augmented if they can be combined with seismic information. Seismic measurements can readily resolve details of any layering in the lunar substrata and a properly executed seismic experiment along this particular traverse could quickly tell us if fragments of giant iron asteroids are buried beneath the lunar mascons.