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Astronaut observations from lunar orbit and their geologic significance

FAROUK EL-BAZ
Bell Telephone Laboratories, Washington, D.C. 20024
A. M. WORDEN AND V. D. BRAND
NASA, Manned Spacecraft Center, Houston, Texas 77058

Abstract—To supplement orbital photography and other remotely sensed data, visual observations were made of 15 lunar surface targets during Apollo mission 15. The 30 m resolving power of the eye and its special sensitivities to subtle differences in texture and color-tone, when coupled with the interpretative powers of the brain provide a system of unmatched quality for lunar exploration. The extraordinary success of performing the task proves the outstanding capabilities of man and his use in spaceflight.

Among the significant results are (1) characterization of the floor material of Tsiolkovsky as no darker than the average (Eratosthenian) mare material, and interpretation of the lineated unit on the crater rim as a rock avalanche; (2) identification of layers on the wall of the crater Picard, which is probably volcanic in origin, (3) explanation of the ray-excluded zone of the crater Proclus as the result of structurally controlled ray shadowing; (4) observation of cinder cones in the Littrow area with dark haloes that probably are composed of pyroclastic deposits; and (5) recognition that the termini of numerous sinuous rilles in Oceanus Procellarum are flooded with younger mare materials that may have covered older terminal deposits.

INTRODUCTION

VISUAL OBSERVATIONS BY an astronaut from lunar orbit can be used in conjunction with photography and other remotely sensed data. The unique capabilities of the trained human observer are well known to all of us from everyday experience. It is not surprising that a highly trained observer can enhance significantly the scientific returns from the orbital flight portion of a lunar mission. Special characteristics of the human eye and interpretive powers of the brain give man an observing capability that cannot be matched by camera systems in certain respects.

The unaided eye has a resolving power of about one-sixtieth of a degree. This corresponds to recognition of an object 30 m in diameter from an orbital altitude of 110 km. The eye also detects patterns or lines formed by objects that are smaller or beyond the limit of visual resolution. (For example, there have been visual sightings of railroad beds and narrow roads from earth orbit.)

The eye is very sensitive to subtle differences in brightness, color tone, texture, and changes in topographic expression. Given sufficient time, the eye adapts to extreme lighting conditions. Visibility is possible in areas that would appear as hard shadows or bright "washout" regions in photographs. The eye also can see the lunar surface in earthshine.

The human eye has the capability to scan broadly over a wide field of view or to concentrate on small local areas as required. Visual targets can be studied continuously as the viewing angles and sun elevation angles are changing. In this way the observer can obtain impressions of a target that could never be obtained from one or a few photographs.

The trained astronaut can integrate all of the above mentioned information to make on the scene comparisons and interpretations. By making successive observations he can refine or verify his first impressions. He can also gain insight to be used for subsequent picture taking and photo interpretation.

PURPOSE

The objective of visual observations from lunar orbit was fulfilled for the first time, and with extraordinary success, on Apollo mission 15. The purpose of the observations was to complement photographic and other remotely sensed data from lunar orbit. Geologic descriptions of the regional or local settings of particular lunar surface features and processes were obtained. These descriptions provided solutions to geologic problems that were difficult to solve by any other means. As explained above, they constitute a significant complement to instrument-gathered data and can be accomplished only by man.

Of the many interesting features overflown by Apollo 15, the first author selected 15 targets for detailed study (Table 1). The targets were discussed in detail with the second author (the Command Module Pilot, CMP) and the third author (the backup CMP). Segments of time in the flight plan were allocated to the task, and photographs of the features and a list of the questions to be answered were carried onboard the spacecraft Endeavour. An example of these photographs and questions will be presented later in this report.

Observations were made from the Command Module windows without disturbing the operations of the Scientific Instrument Module. Data were acquired on all visual observation targets, including two not scheduled in the flight plan (Table 1). On farside passes, observations were recorded on the onboard tape recorder; and

Table 1. Apollo 15 visual observation targets.

Target No.	Target designation	Spacecraft Longitude Start	Spacecraft Longitude Stop
1	Northwest of Tsiolkovsky	135°E	125°E
2	Crater Picard	60°E	55°E
3	Crater Proclus	53°E	45°E
4	Cauchy Rilles	51°E	40°E
5	Littrow Area	35°E	27°E
6	Crater Dawes	31°E	26°E
7	Sulpicius Gallus Rilles	18°E	9°E
8	Hadley-Apennines	10°E	2°E
9	Imbrium flows	15°W	24°W
10	Harbinger Mountains	35°W	44°W
11	Aristarchus Plateau (in earthshine)	46°W	52°W
11	Aristarchus Plateau	44°W	54°W
12 and 13	Post-transearth-injection views	not applicable	
14	Mare Ingenii (unscheduled)	170°E	157°E
15	Ibn Yunus area (unscheduled)	96°E	80°E

on nearside passes, observations were recorded by real-time voice communications with the Mission Control Center (NASA, 1971a). The third author communicated questions to the CMP during the mission, in real-time. After the mission, a debriefing was held during which the features studied and their geologic significance were discussed (NASA, 1971b). Excerpts from both the real-time comments and the debriefing statements (edited for clarity) will be given in the following discussion.

Significant Results

We have recently summarized results of Apollo 15 observations (Worden and El-Baz, 1971; and El-Baz *et al.*, 1971). An attempt will be made here to present in detail some results and to point out their geological significance. Because of the limitations of space, only five visual observation targets will be discussed in the order of location relative to the mission groundtracks, from east to west (Fig. 1).

Dark floor and rim flow of Tsiolkovsky

Tsiolkovsky is a 200 km diameter crater that dominates a large area on the lunar farside. It is a relatively fresh crater, probably of Eratosthenian age, and its ejecta blanket is bright at high sun illumination angles. The crater displays a relatively flat, smooth floor, which appears in all photographs to be extremely dark. On the floor is a large central peak consisting of segments arranged in the shape of the letter "W."

The continuous ejecta blanket of Tsiolkovsky can be traced about one crater diameter out from the rim crest; secondary craters and crater chains originating from Tsiolkovsky are superposed on older surface units and formations for greater distances. On the northwestern rim of the crater is a lineated unit that displays characteristics of a flow of some sort.

Most of the aforementioned features of the crater Tsiolkovsky and its environs were the subject of visual observation target number 1 on Apollo 15 (Fig. 2). Excerpts from real-time CMP descriptions arranged in the sequence in which they appear in the air-to-ground transcript follow. The lunar revolution (LR) and ground-elapsed time (GET) in days, hours, minutes, and seconds will be provided for each entry (NASA, 1971a).

Tsiolkovsky is large enough that the CMP had the impression that the central peak was higher than the rim. The CMP also noted indications of layering on the central peaks.

"The central peak of Tsiolkovsky is very large; spur peaks on the south and east sides, being blocky on the north side. What appears to be some layering is visible on the south and west exposed scarps of the peak, dipping to the north at about 30°." (LR34/05: 23: 36: 31 GET).

The lineated segment of the northwestern rim of Tsiolkovsky, which has an area of approximately 80 km^2, was interpreted during the flight as a landslide or rock avalanche.

"I look at it every time I go by, and there is no question in my mind at all that it is a rock avalanche. It does have some interesting qualities about it. And it is

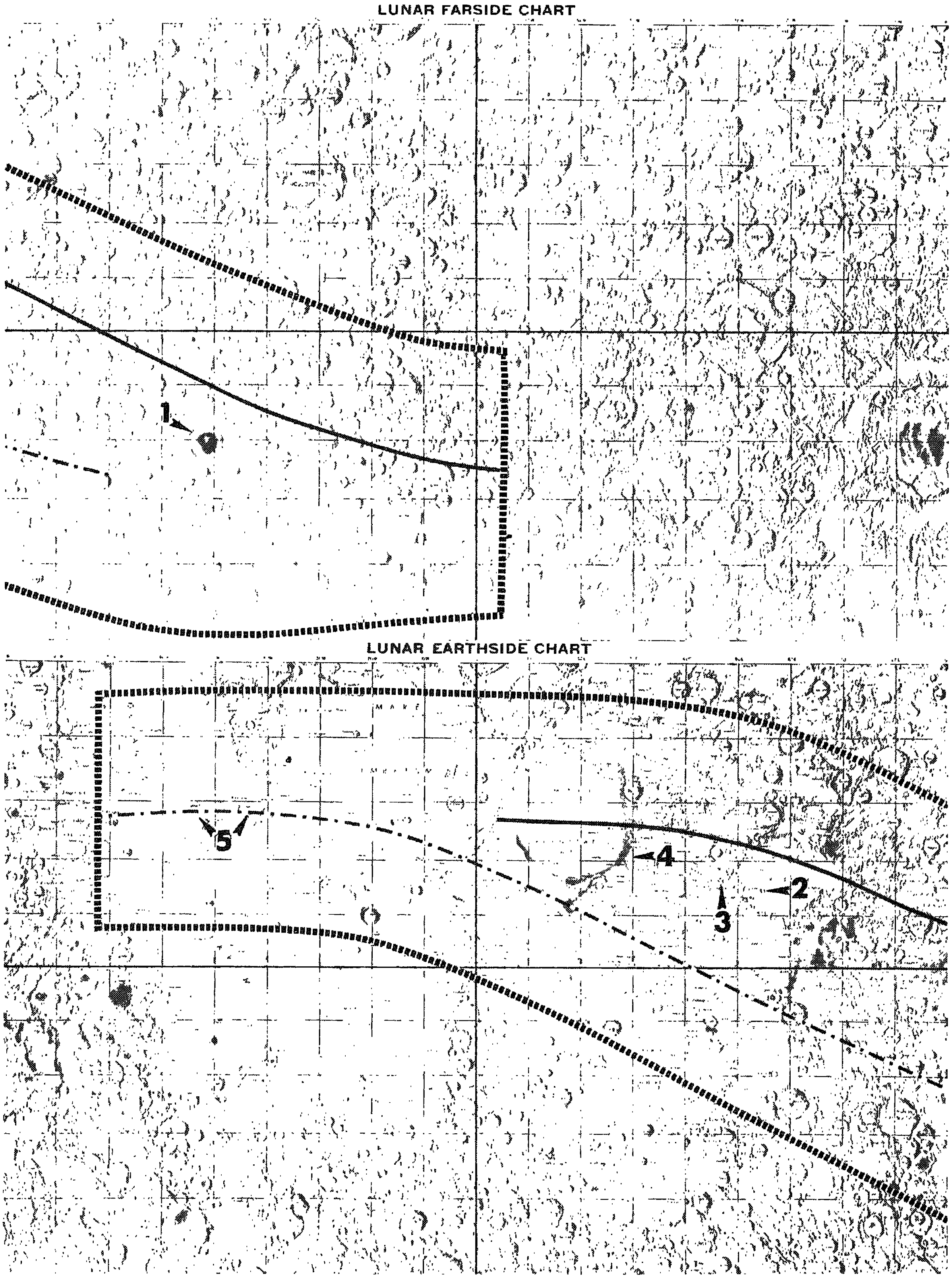


Fig. 1. Lunar groundtracks of the Apollo 15 mission on the moon's farside (top) and nearside (bottom). The solid and dashed-dotted lines represent the groundtracks of the first and last (75th) orbits respectively. The outer envelope marks the spacecraft horizon—the maximum area visible from the Command Module windows. Numbered are the features discussed in this paper: (1) the farside crater Tsiolkovsky, (2) the crater Picard in Mare Crisium, (3) the crater Proclus, (4) the Littrow region on the southeastern rim of Mare Serenitatis, and (5) the Harbinger Mountains-Aristarchus Plateau region.

somewhat hard for me to decipher right now, but it seems like the density of crater impacts in that slide is greater than in the surrounding terrain, even though the slide had to be emplaced on top of the surrounding terrain. May be it is just that the craters are fresher looking in that particular material, but there is no question about the lineaments being parallel to the direction of travel of the flow; all the characteristics of a rock avalanche." (LR33/05: 22: 26: 28 GET).

"On the west side, the rim is a very large, steep scarp; it continues from the basin floor to the rim crest in one large chunk. That scarp appears to define the limits of two fault zones that go through the rim of the crater Tsiolkovsky. But they are very distinct in the wall itself. The fault zones coincide with or occur in the same location as the southernmost edge of what appears to be a rock glacier. The latter has all the flow banding and the loping toes, which we consider characteristic of a rockslide. However, one feature about that slide that I mentioned before is that it has what looks like fairly fresh craters; in other words, a higher density of craters than on the surrounding floor of Fermi, although the Fermi floor looks much older; it is much smoother and more like the Cayley Formation." (LR34/05: 23: 37: 30 GET).

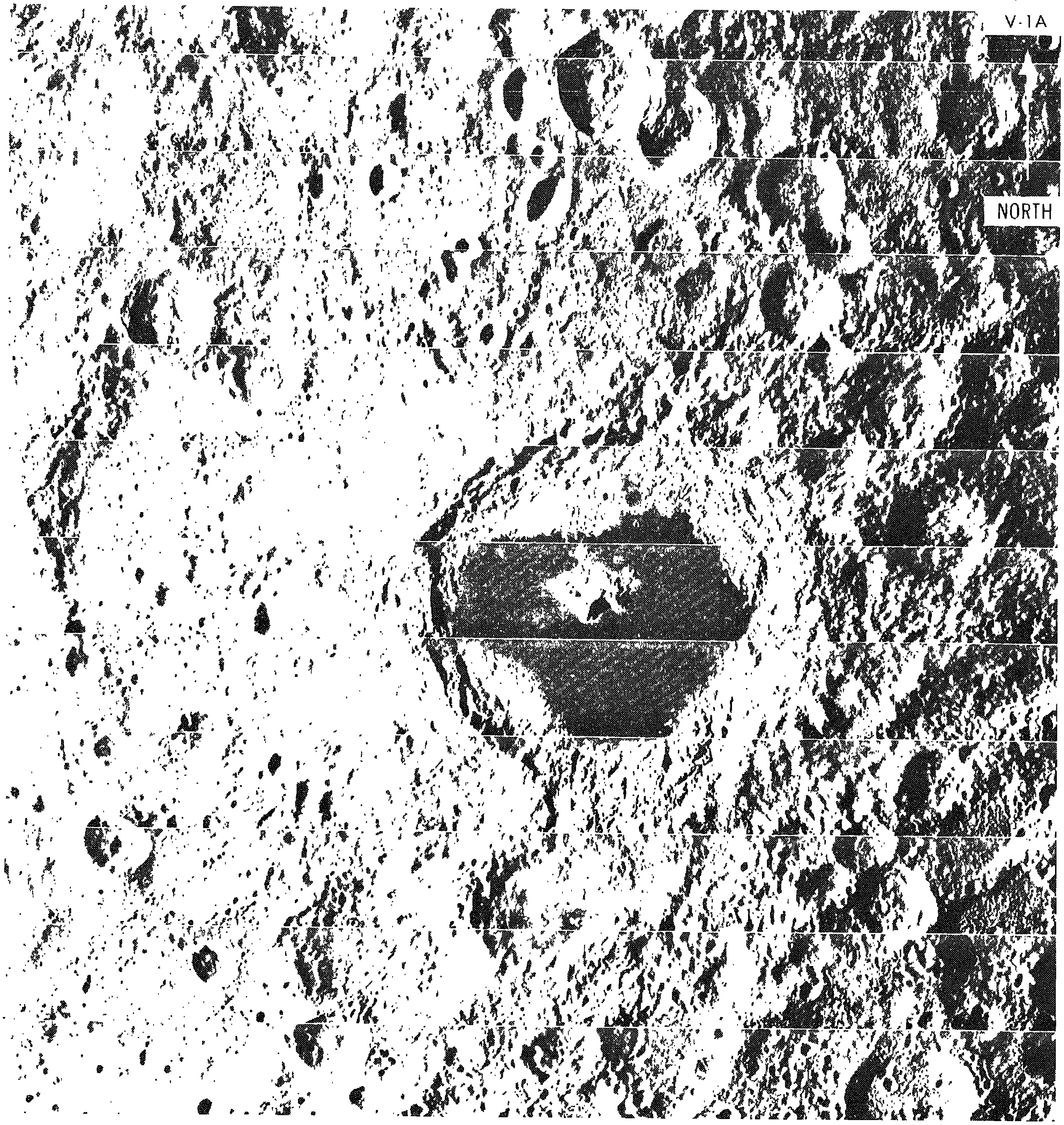
The mention during the flight of the higher frequency of craters on the rock avalanche or landslide on the northwestern rim of the crater Tsiolkovsky was the one item related to this visual observation target that could best be checked by studying the returned photographs. A photograph of the terminus of the landslide where the lineaments are radial to Tsiolkovsky and parallel to the flow direction is shown in Fig. 3. It clearly shows that a greater number of more sharply defined and smaller craters occur on the relatively younger flow unit than on the relatively older floor fill of the Fermi Basin to the west.

The discrepancy in crater density is restricted only to small craters. The excessive population of these craters on the younger of the two units may be due to one or both of the following reasons:

1. The presence of drainage craters, which may have developed by the seismic shaking of the surface and by drainage of the material in the void spaces initially sealed over by flow layers and large blocks.
2. The absence of a thick regolith on the rock avalanche because of the relative youth (small impact craters would tend to appear fresher and to "live longer" on such a unit) as compared to the floor of the crater Fermi that exhibits the characteristics of a relatively thick regolith.

During the post-mission visual observation debriefing one important aspect of Tsiolkovsky was stressed; namely, the apparent color of the crater floor. "The floor is a gun-metal-gray color. It is about the color of a metal cabinet. Everything was that same gray color; so the only apparent aspects were the differences in texture. In fact, the floor of Tsiolkovsky is lighter than some other mare areas." (NASA, 1971b, pp. 1–2).

Orbital photography of the crater Tsiolkovsky, obtained both by the unmanned Lunar Orbiters and by Apollo crews, show the floor of Tsiolkovsky to be extremely dark. Therefore, this mare unit was thought to be among the youngest on the moon. However, the visual impressions indicate that the mare material on the floor of



V-1A TSIOLKOVSKY REGION (128.5°E, 20°S)

Describe pertinent details relative to:
1. Structures and possible layering on the central peaks of Tsiolkovsky.
2. Nature of light-colored floor material and relationship to surrounding units.
3. Variations in texture and structure along segments of the wall of Tsiolkovsky.
4. Rim deposits due south of the crater and possible volcanic fill of the crater Waterman.
5. Origin and inter-relationship of crater pair due north of Tsiolkovsky.

Fig. 2. The crater Tsiolkovsky and its environs; an example of the materials that were carried onboard the spacecraft on Apollo 15 to support the task of visual observations from lunar orbit.

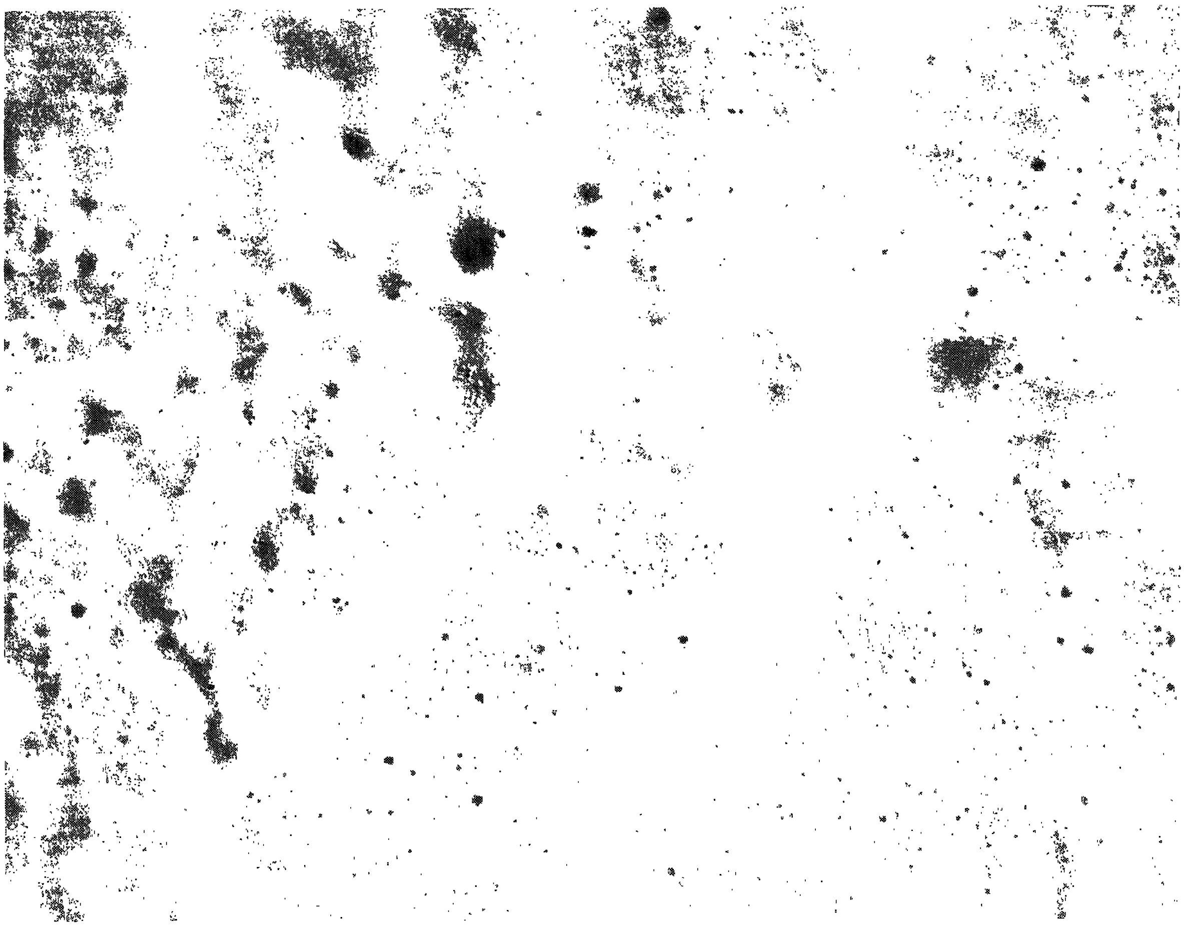


Fig. 3. Detail of the terminal portion of the lineated landslide on the northwestern rim of Tsiolkovsky. Note the relatively high density of small, fresh-appearing craters on the landslide, right, as compared to that on the older floor materials of the crater Fermi, left (Apollo 15 frame 12818).

Tsiolkovsky is no darker than other mare regions of Eratosthenian age. A post-mission crater density comparison between the floor of Tsiolkovsky and Eratosthenian mare units in Oceanus Procellarum indicates a similarity in age.

The reason for the apparently spurious darkness of the floor material in Tsiolkovsky is therefore that photographic exposures depend on average scene brightness. Because Tsiolkovsky is surrounded by very bright highlands, photographs taken of the crater and its environs will expose mostly for the surrounding highlands and, therefore, underexpose the mare fill in the floor. The human eye has an advantage, however. It responds to the scene as a whole and makes the relative brightness levels of each and every unit distinctly separable.

Layering in the crater Picard

Picard is a 30 km crater located in the western part of Mare Crisium. The interest in the crater itself and the surrounding mare material (Fig. 4) springs from the variations in texture and albedo, and perhaps color-tone, as indicated by existing

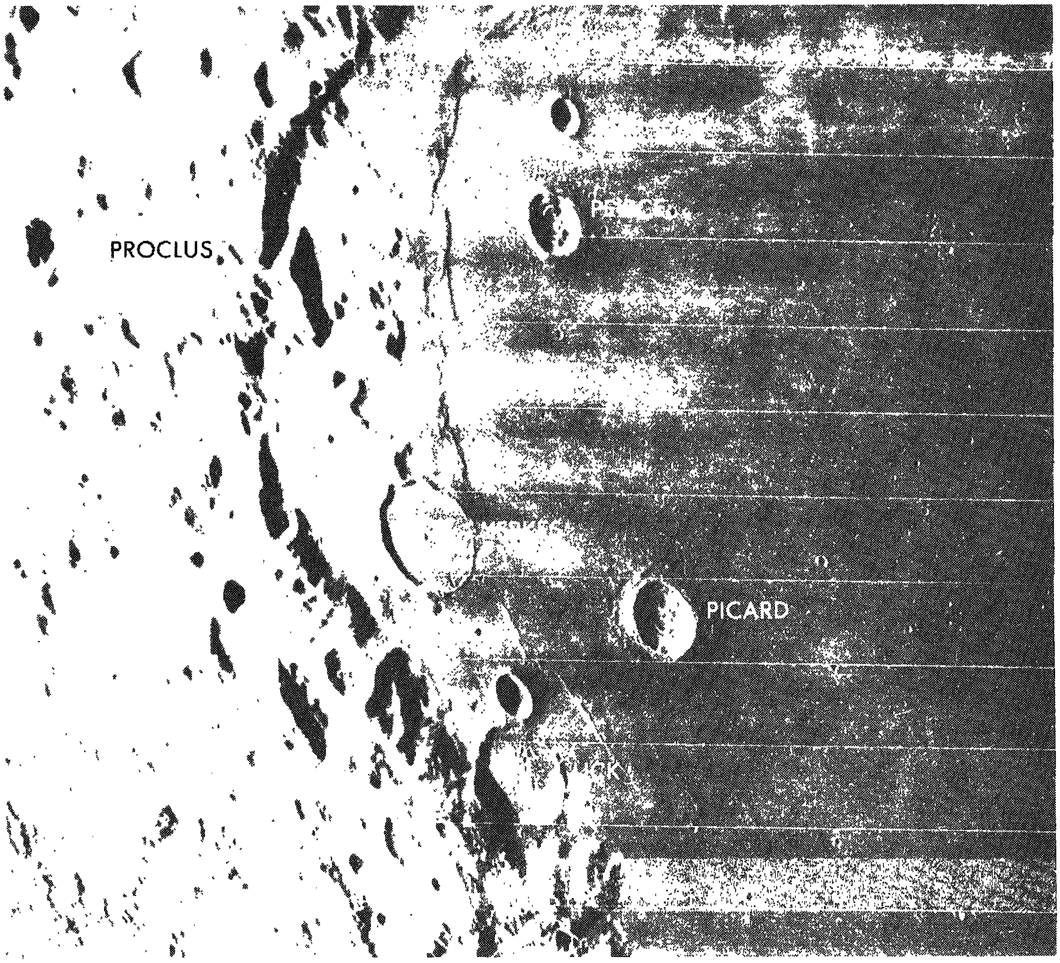


Fig. 4. Crater population of western Mare Crisium. Note the slightly dark haloes around Picard and Peirce (see detail in Fig. 5). At this low sun illumination the rays of Proclus are barely visible.

photography and remote sensing data. Following is a selection of comments made by the CMP during the flight.

"I am just coming over Picard at the present time and wanted to make a comment that it looks like there are several ring structures inside the crater itself. They are all concentric, and I do not see a great deal of relief on those that look like they are in the bottom of the crater. But, looking at the scarps around the outer ring, Picard displays characteristics of caldera-type craters. The scarps look like fault planes along the outside. And I can see in the outer wall very distinct layering. For instance, right on the top is a very thin dark layer that runs all the way around. And there is a light-colored layer. And then there are alternating dark and light layers all within about the same distance from the top of the crater, all the way around." (LR26/05: 08: 03: 45 GET).

"Endeavour is coming up over Picard. Considering the color variations, Picard is a slightly different color than the rest of the mare basin. I would consider Crisium to be a light brownish gray. Picard itself is more of a brown tone and has a darker halo around it. I can see some of the brown material just on the outside of the rim, and outside of that is some darker material that gradually turns into the gray of Mare Crisium. Within Picard, I can see six distinct rings that go all around the crater interior. And the walls of Picard are very shallow. It looks like a very shallow dish-like basin. And I can see some definite layering, particularly in the upper boundary of the rim." (LR34/05: 23: 49: 24 GET).

The freshness of detail in the crater Picard and its layering (Fig. 5) was compared to the situation in other, nearby craters.

"We are looking down at Picard, Peirce, and Lick D. These craters display similar characteristics; they all look alike. They all have the same ring structure and show comparatively low rims. The rims look very shallow compared to the rims on the other craters in the area. Also, they all have a slightly darker halo effect around the entire crater. But the color difference is very subtle." (LR36/06: 01: 48: 01 GET).

Fig. 5. Apollo 15 panoramic camera view of the crater Picard in western Mare Crisium. The width of the wall materials is about one-third of the crater diameter, and its heart-shaped floor is rather hummocky. Note that the wall is terraced, as many as 6 levels, and that there appears to be a number of layers within the terraces. The layers are visible especially on the northern part of the wall (mosaic of frames 9214 and 9216).

These characteristics contrast with those of other large craters in the same region, namely Lick and Yerkes, which display different features.

"Lick appears to be almost completely obscured. It looks very much like a collapse. All I can see is a small remnant ring, a color variation, with some positive relief. The interior of the crater appears to be similar to the surroundings, as far as the color and the texture are concerned. However, it does appear to slope gently in towards the center. Lick appears to be like a very large collapse feature, with the same kind of material both inside and outside the crater. And I would make the same comment about Yerkes." (LR34/05: 23: 49: 24 GET).

Ray-excluded zone of Proclus

The classical example of ray-excluded zones around impact craters is that of the crater Proclus on the western rim of Mare Crisium (El-Baz, 1969). Rays from Proclus extend in all directions except for a segment on the west-southwest (Fig. 6). Following are observations of the regional and local settings made from lunar orbit.

"The rays extending from Proclus are very light in color for about 240° to 260° around, and then there is a region of dark albedo. But the inner walls of Proclus are very light in color, almost white. The outer ring has a somewhat light gray appearance, and the difference in the rays is really between a light and a dark gray, as distinguished from the inner walls, which are quite white. The walls exhibit some debris on the upper slopes, maybe the upper 30 percent." (LR1/03: 07: 18: 37 GET).

"The excluded zone in the ray pattern is just very distinct at this point. And,

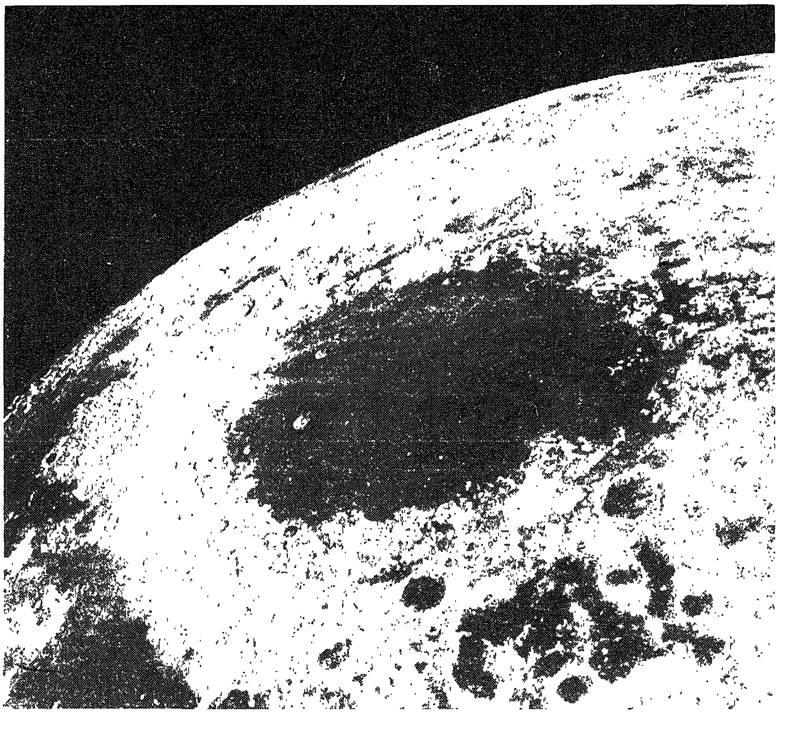


Fig. 6. At high sun illumination conditions the rays of the crater Proclus display a shadowed or excluded zone to the west-southwest. In an easterly direction, rays of Proclus extend over much of Mare Crisium. A detail is shown in Fig. 7.

from this angle looking at Proclus, about a crater diameter out to maybe a diameter and a half or so, you can see many small, bright, fresh craters, which appear to be in the general direction of a ray, like part of the ejecta blanket. They occur within a diameter to a diameter and a half of Proclus, and they are about the same brightness as the inner walls of Proclus, and they are small craters. I do see one which you might call a loop, which would suggest secondaries. They just seem to lie in the general direction of the rays of the ejecta from Proclus." (LR2/03: 09: 22: 54 GET).

During the debriefing, the CMP commented, "It is very strange the way the ejecta from, particularly, Proclus crosses Crisium. It is almost like flying above a haze layer and looking down through the haze at the surface. Ejecta from that crater does not look like it is resting on top of Crisium. It looks like it is suspended over it. It gives a very filmy, very gauzy appearance to the whole thing. It must be very thin. And I guess the reason it appears as if it is draped or suspended is that the ray material is visible no matter what it crosses. The ejecta forms lines when it goes through a crater, a wrinkle ridge or any topographic feature. It does not make any difference from what angle you view them; those lines of the ejecta material are straight. When the ray goes through a topographic prominence or a negative depression of some sort, you still see the ray through that." (NASA, 1971b, pp. 8–10).

The visual observation of Proclus was planned to determine the probable origin or cause of the ray-excluded zone. These zones occur around a number of lunar impact craters, and the cause for such zones may be one or more of the following:

1. The obliquity of the approach angle of the projectile would cause ejecta to be distributed all around the crater except for a segment directly below the path of the projectile. In some of these cases, a "rooster tail" pattern develops by the ejection of material in a direction opposite to that of the impact.
2. Topographic "shadowing" by a positive prominence would shield a segment around a crater against deposition of ejected ray material.
3. If differences exist in the materials in which the crater is situated, the two types of materials may respond differently to the impact pressure.
4. Deposition of younger units over the ray material.

Observations of Proclus from lunar orbit suggest a fifth class of reasons for ray exclusion; namely, structural control (Fig. 7). In the case of Proclus, a fault zone appears to have predated the crater. When the impact occurred, the fault plane formed part of the wall of the crater, and a broken-off segment of material may have been uplifted during the impact to inhibit the rays beyond it, later collapsing westward from the fault plane. This interpretation may, on first glance, appear complicated. Oblique missile impacts at White Sands show asymmetrical ejecta blankets (Moore, 1971). However, the probable role of structural control in the case of Proclus appears feasible and is based on the following comments:

"Something about Proclus was not obvious from the pictures we have seen before. The segment of the crater in the excluded zone seems to be discordant with the rest of the crater. In other words, if you made a circle to represent the crater, then this segment would lie outside of that circle. And I cannot see anything close to the rim that would account for any physical shadowing of the ray pattern. But I can see a diagonal fault zone that runs down into that little segment, and runs into

Fig. 7. Apollo 15 metric camera photograph of the crater Proclus and surrounding terrain. The lip on the southwestern corner of the rim corresponds with the ray-excluded zone. The straight segment of the wall nearest this lip may have been the result of a pre-crater fault which may have caused the ray-excluded zone as explained in the text (frame 0960).

it from the east side. I could not pick one out on the west side, but it is very distinct on the east side. And, in addition to that, I did not see a great deal of difference in the terrain or in the structure of the terrain across the excluded zone." (LR26/04: 08: 07: 19 GET).

"There is a tremendous variation in the wall [of Proclus] which does line up with the ejecta pattern. There is almost a straight wall on the side of Proclus that shows a ray-excluded zone. Also there is some breakthrough directly in the middle of that wall, which makes Proclus look like it is almost a circular crater. However, Proclus appears to be an elongate crater with one wall dipping quite steeply into the crater. Also the wall is oriented perpendicularly to a line bisecting the excluded zone, dipping into the crater. And then right in the middle of that portion, it looks like a small piece of that wall was also ejected, but it was only at the top part of the fault scarp. And so, if you look at it from the right angle, you can see almost a flat plane, which appears to have cut right into Proclus; and to the north and east of that flat plane is the crater Proclus, and to the south and west is a small chunk out of the top of it that coincides with the central part of the excluded zone." (LR34/05: 23: 52: 18 GET).

Cinder cones in the Littrow area

It was planned that the second author would study the geologic setting of the Littrow area. Special emphasis was to be placed on the nature and origin of the dark deposit on the southeastern rim of Mare Serenitatis between the upland massif units of the Taurus Mountains (Fig. 8).

"We are coming up over Serenitatis now. We are almost over Le Monnier at the present time, and we can see the Littrow area just out in front of us. And it is, in fact, about three different shades (Fig. 8). You can see in the upland area and particularly what looks like down in the valleys a darker color, and it does look like it is a light powdering or dusting over the entire area. And then, as you get out further into Mare Serenitatis, there is another zone which is somewhat lighter in color. And then, out at the last edge of the wrinkle ridge, out beyond that is the last zone, and the rest of Serenitatis looks fairly light in color. So it appears that the central part of Serenitatis is light, out beyond the first wrinkle ridge is a darker zone, and

Fig. 8. Southern part of Mare Serenitatis as displayed in this telescopic photograph (Lunar and Planetary Laboratory, C2544, September 1966). A dark annulus of mare material surrounds the lighter-colored interior zone. The basin is rimmed by the Sulpicius Gallus Rilles to the west, the Menelaus and Plinius Rilles to the south, and the Littrow and Chacornac Rilles to the east.

we are not up close enough to see what it is yet, and then as you get up into the highlands around Le Monnier and Littrow, there is what appears to be a light dusting of dark material, and it certainly looks volcanic from here." (LR1/03: 07: 23: 11 GET).

"I am directly over Littrow at the present time. And I can see all the way around to the Apennine Front, encompassing all of Serenitatis between here and there except to the north over by Posidonius. So I have a very good view of Sulpicius Gallus. And the observation I wanted to make, in particular, pertains to the distinct way that the rilles do follow the old mare basin. And the fact that the second color band that we discussed in Littrow seems to be continuous across the basin into Tranquillitatis and on around—almost a shelf, a continental shelf appearance—into the Sulpicius Gallus area. There is a darker coloring in the uplands in Littrow and closer to the front or closer to the basin scarp." (LR23/05: 02: 18: 17 GET).

"If I had to give you the opinion right now, I would say the dark area in Littrow was some kind of ash. I am not sure it is a flow. But it certainly looks like a deposit over the entire surface. You can see it mostly in the upland areas, some in the mare areas, but mostly in valleys and in depressions. This mantle seems to have collected almost like there was some mass wasting down the hills, making the valleys darker in color and maybe a little thicker with this kind of material. But there are still at least three different distinctive color bands in the Littrow area, going from dark gray to a sort of brownish color. And it was the dark gray that looked like it was an ash fall to me." (LR25/05: 06: 17: 03 GET).

During the following revolution came the most important single observation of the entire flight: "I am looking right down on Littrow now, and a very interesting thing. I see the whole area around Littrow, particularly in the area of Littrow where I have noticed the darker deposits; there is a whole series of small, almost irregular-shaped cones, and there exists a very distinct dark mantling just around those cones. It looks like a whole field of small cinder cones in the area. And I say cinder cones because they are somewhat irregular in shape; they are not all round. These positive features display very dark haloes. The haloes which surround individual cones are mostly symmetric, but not always." (LR26/05: 08: 12: 46 GET).

Later during the mission, when asked whether the cinder cones were evenly distributed or whether they are concentrated in spots on the darkest unit, the CMP explained that they are concentrated in spots on the darkest unit, and that the darker the unit, the more cones: "Also, within the darker units, there are relatively high concentrations of these small cones, and then a few scattered ones in the outlying areas. But I would say they were concentrated within the darker areas, more on the flat land side, in the valleys and in what looks like the lower areas. And within concentrations of cinder cones, there seems to be one locus of major activity, one locus of the greatest number of cones, and then they thin out beyond that." (LR37/06: 05: 58: 59 GET).

Discovery of the cinder cones in this area, which was later confirmed by the panoramic camera photographs (e.g. Fig. 9), and delineation of the dark deposit as an ash fall suggest late volcanism that postdates the major episodes of mare material extrusion. The dark deposit is relatively younger than Eratosthenian-age mare

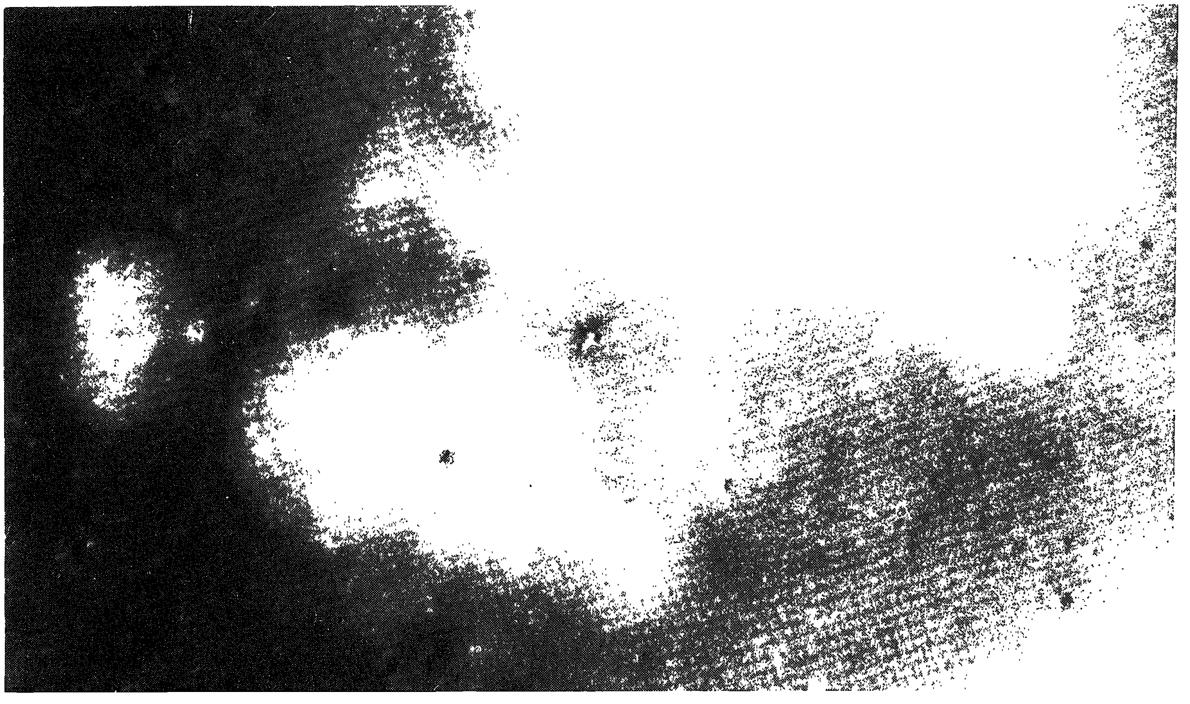


Fig. 9. Portion of an Apollo 15 panoramic camera photograph showing the largest symmetrical "cinder cone" in the Littrow area. The crater on the apex of the cone is about 75 m across and the symmetrical basal deposits form a dark halo, about 250 m across. A larger apron (as much as 1500 m in diameter) of ejecta can be seen as a thin mantle; it covers the light-colored highland material of the hill on which the cone is situated. Many other and smaller cones can be seen within the dark deposit, see for example, the lower right corner (frame 9554).

materials; that is, younger than about 3.2 billion years. The unit and the source vents appear much younger than any formation in the surrounding mare material. The cinder cones, as observed during the flight, "were very sharp, very distinct, and quite small. Most were orderly symmetrical structures. They were not broken down any way that I could see. They did not give the appearance of much degradation since they first formed. I did not see any of them partially obscured by an impact. Some of the aprons around them are symmetrical, some asymmetrical. Around the cones themselves, there is certainly a blanket that was laid down that is even darker than the surrounding material. The black spots are what drew my eye to the cinder cones." (NASA, 1971b, pp. 23–24).

Terminal portions of sinuous rilles

A problem of lunar sinuous rilles has been the uncertainty of definite terminal deposits or other indications that something had flowed out of the rilles onto the mare plains. The Apollo 15 groundtracks were well-suited for study of sinuous rilles because they covered innumerable rilles in Mare Imbrium and Oceanus Procellarum. Two rille complexes received particular attention: Rimae Prinz in the Harbinger Mountains region, and numerous rilles associated with the Aristarchus Plateau including Schroeter's Valley.

Rimae Prinz originate at circular depressions on the higher terrain near the rim of the old and particularly flooded crater Prinz. They terminate to the north in open-ended troughs as shown in Fig. 10. It was noted by the CMP that the rilles appear to have formed first in the higher terrain, and later been filled by mare lava flows. The latter appeared to have back-filled into the low terminal portions of the rilles: "Those flow fronts come back up into the rilles and chop off the terminus"; "It looked like this had rising water that went back in and filled up the termini of all the rilles." (NASA, 1971b, pp. 27–29). The interpretation was based on subtle differences in level of brightness, color-tone, texture, and changes in topographic expression. Some insight was probably gained by studying the rilles from various angles. This interpretation is a significant new input concerning the probable origin of sinuous rilles: it means that the probability of existence of terminal deposits prior to later flooding by younger mare material cannot be discarded.

A similar situation was encountered along the western boundaries of the Aristarchus Plateau. In this case two partly sinuous, partly linear rilles can be seen along the edge of the Plateau. They cut through the topographically higher plateau materials but not the surrounding mare of Oceanus Procellarum as illustrated in Fig. 11.

These features were discussed during the postmission visual observation debriefing, from which the following is excerpted: "On the west side of Aristarchus,

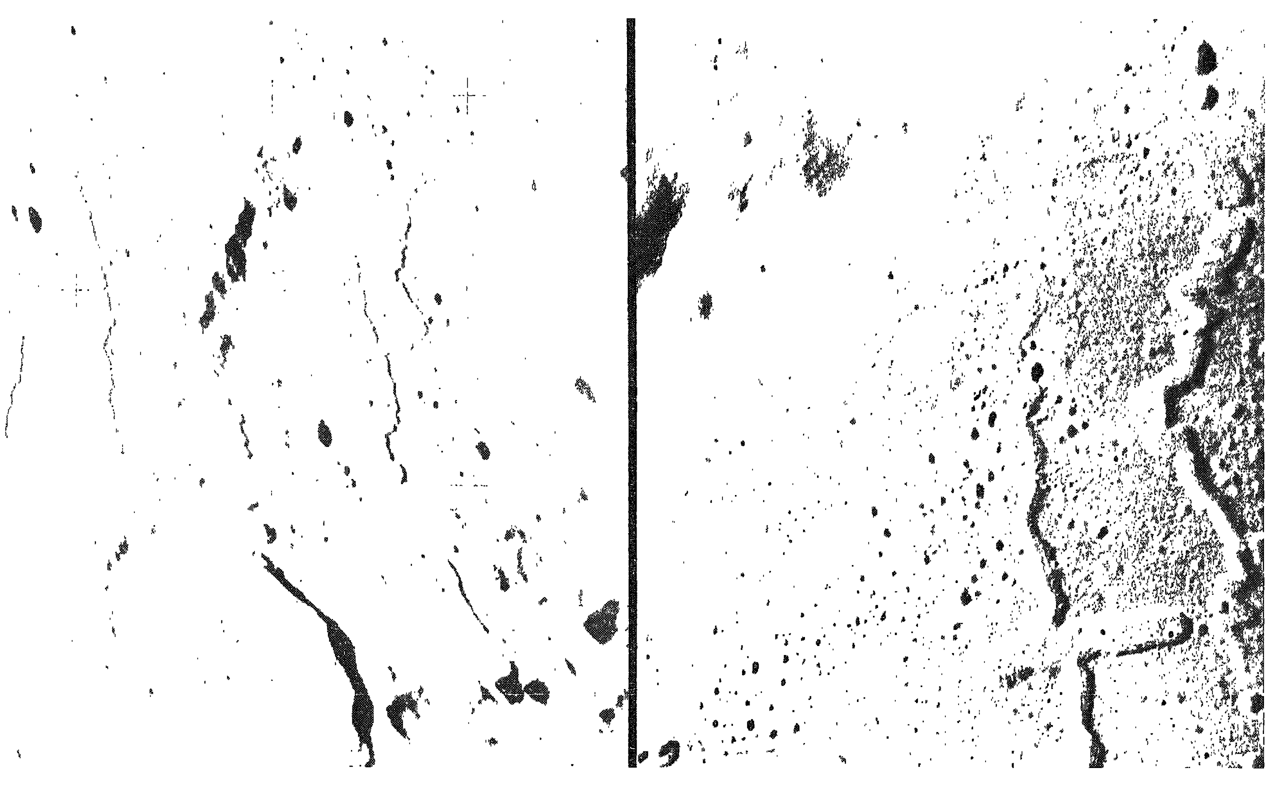


Fig. 10. Apollo 15 photographs of the Prinz Rilles. Left, Hasselblad 80 mm view of the rilles in the Harbinger Mountains region of Oceanus Procellarum (frame 11978). Right, panoramic camera view of the terminal portions showing the flooding of rille floors with mare material (frame 0314).

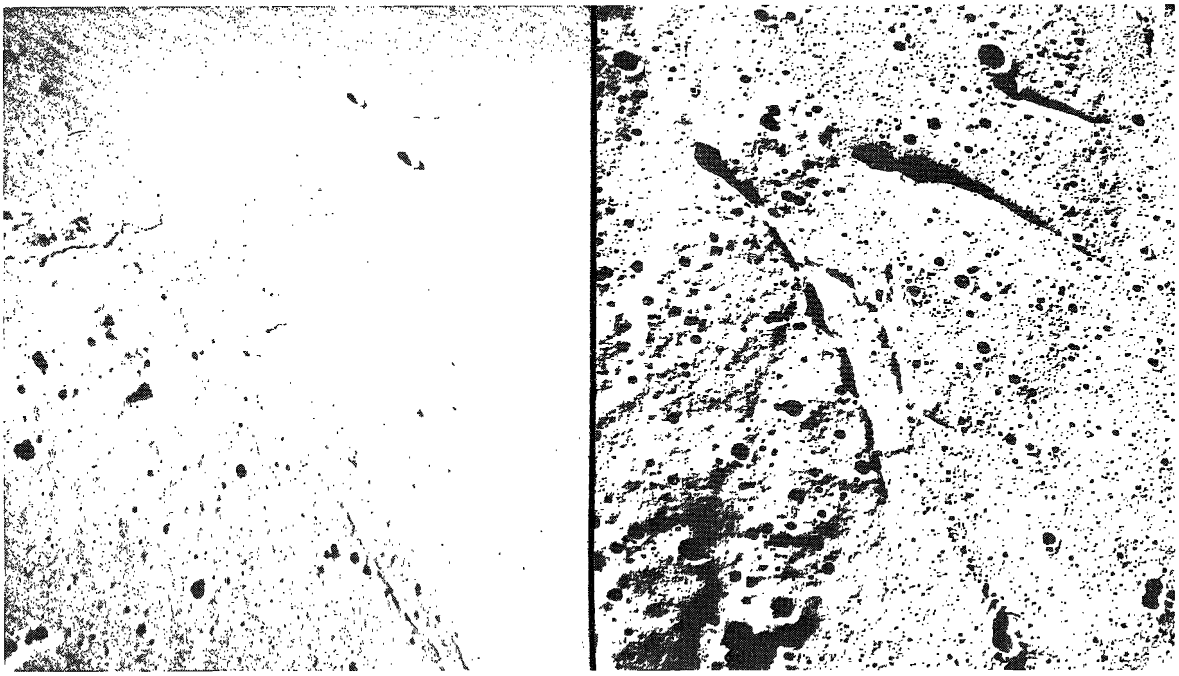


Fig. 11. Apollo 15 photographs of the western part of the Aristarchus Plateau. Left, Hasselblad 80 mm lens view (looking southward) of the plateau materials and the mare materials of Oceanus Procellarum. The terminal portion of Schroeter's Valley can be seen on the left edge of the photograph (frame 12630). Right, Hasselblad 250 mm lens near-terminator view of the central part of the area shown to the left. Note that the mare material of Oceanus Procellarum fills the floors of the rilles that bisect the Aristarchus Plateau materials (frame 13345).

not only do you have the color to help you pick out the flows but you also have the surface texture. The surface texture of the top flow in the lower elevation flows is as shiny as a glass surface. It gives you a patent leather-like appearance and it is brown. Is it very different from the mare outside. It is a dirty brown color; inside the rille, it looks like a muddy river. And all the mare surface below the rille has been covered, too. It looks like a very viscous, muddy river that has somehow stopped in place. Those flow fronts come back up into the rilles and chop off the terminus. The basic mare around this area is gray." (NASA, 1971b, pp. 27–29).

In effect, this description is a characterization of the older Imbrian mare material in Mare Imbrium and farther east as grayish in color. The younger Eratosthenian mare material of Oceanus Procellarum, especially west of the Aristarchus Plateau, is brownish in color. "Imbrium was distinctly gray; Procellarum was distinctly brown."

A different situation, however, was encountered in the case of Schroeter's Valley. As illustrated in Fig. 12 the main valley terminates in an enclosed area within the Aristarchus Plateau. The younger and more sinuous inner rille cuts across the valley rim and terminates in the mare materials of Oceanus Procellarum. A slight topographic elevation can be seen where this rille terminates. That however may be unrelated to the rille. From this it is concluded that there may be different modes of formation of sinuous rilles. Each rille or group of rilles should be treated separately

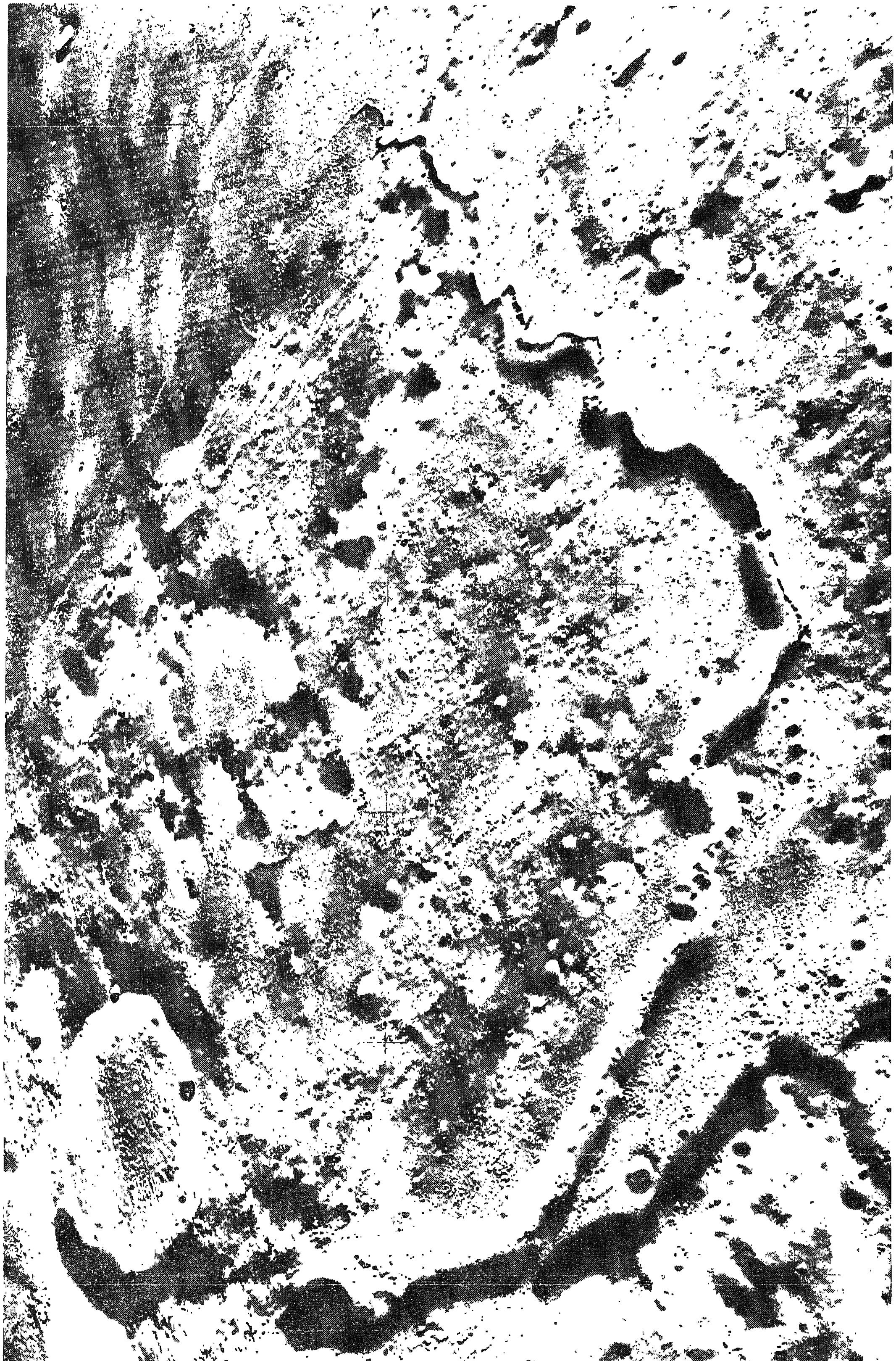


Fig. 12. Oblique (40° south) metric camera view of Schroeter's Valley. Note that the sinuous channel within the valley cuts across the wall and becomes progressively thinner until it terminates in the Oceanus Procellarum mare material (frame 2610).

based on the geomorphologic characteristics and the nature of the surrounding formations.

Conclusions

Before the Apollo 15 mission, observations from lunar orbit did not constitute an objective of the mission and, therefore, received only cursory interest. On the Apollo 15 mission, visual observations were treated as a formal mission objective: the task was conducted systematically, and targets were studied thoroughly. The extraordinary success of this undertaking proved the outstanding capabilities of man and his use in spaceflight. The unusual sensitivities of the human eye, when combined with the interpretive powers of the brain, constitute a combination that cannot be matched by one photographic system. However, this is not a competitive effort. Visual observations were made only to supplement the onboard photographic systems and are considered as a complement to other remotely sensed data.

The most significant results of performing the task on Apollo 15 include:

1. Contrary to photographic evidence, visual observations suggest that the mare fill of the crater Tsiolkovsky is not darker than the average (Eratosthenian) mare surface on the near side of the moon. The flow unit on the northwestern rim of the crater is interpreted as a landslide.
2. Alternating light and dark bands within the walls of the crater Picard are interpreted as discrete layers. The crater displays a brownish color-tone that is different from the surrounding mare materials and is believed to be volcanic in origin.
3. The ray-excluded zone of the crater Proclus appears to have been the result of a fault that predates the crater: when the impact occurred the western segment of the crater appears to have been displaced causing ray shadowing by structural control.
4. The dark deposit on the southeastern rim of Mare Serenitatis is interpreted as fine-grained or pyroclastic material related to explosive volcanic action that produced numerous cinder cones. Observations of cinder cones in the Taurus-Littrow area and subsequent study of the photography stimulated interest in the site which is now designated as the landing site of Apollo mission 17.
5. The termini of numerous sinuous rilles in the Harbinger Mountains—Aristarchus Plateau region appear to have been flooded with younger mare flows. This indicates that terminal deposits at the ends of sinuous channels could have existed prior to later flooding by mare materials.

The above examples illustrate that man does have special capabilities for observation that can be used to complement the orbital science return from a lunar mission. However, it is important to remember that man must be trained to be a good observer, and the task of looking must be planned before flight and conducted systematically. Otherwise, man will look but he may not see.

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