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New geological findings in Apollo 15 lunar orbital photography

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Abstract—The panoramic and metric camera systems, which were flown for the first time on Apollo 15, obtained a total of 4,140 photographs with a resolution of 1–3 m and 25–30 m respectively. Data derived from the metric camera system will allow mapping the overflown 12% of the lunar surface at 1:250,000 scale with 50 m contours; those of the panoramic camera will produce large scale maps (up to 1:10,000) with 5–10 m contours. The Hasselblad camera was also utilized to obtain oblique views with color film. The combined data represent the most thorough photographic coverage of any Apollo mission to date. Photogeologic interpretation of these data and correlation with other remotely sensed data, both from earth and from lunar orbit, will allow extrapolation of knowledge gained by surface exploration to large segments of the moon.

Several new features of probable volcanic origin were detected: (1) dark-haloed cones in the Apollo 17 Taurus-Littrow landing site. These "cinder cones" may have brought to the surface pyroclastic fragments from deep within the moon in the post-mare period of lunar surface history; (2) a D-shaped structure with light-colored units and blister-like smooth domes in its floor. The structure is believed to be a young collapsed caldera; (3) what appears to be a lava lake on the lunar farside with "lava marks" and evidence of lava drainage into prominent fissures; (4) unusually large (up to 40 km in diameter) domes near Rima Schroedinger I on the southern farside; and (5) numerous lava flows in western Mare Imbrium, some of which cross mare ridges.

Other features on which new data were obtained include: (1) two lineated units that are interpreted as landslides or rock avalanches: one on the northwestern rim of Tsiolkovsky (approximately 80 km long), and a smaller one (approximately 5 km long) in the Taurus-Littrow site; (2) unusual light-colored swirls in Mare Inginii, Mare Marginis, and Oceanus Procellarum. These sinuous markings may have been produced by alteration of the materials at the antipodal areas of impact points; and (3) man-caused changes in albedo, observed for the first time from lunar orbit, which include: brightening of the surface area beneath the LM, probably due to compaction during descent; and darkening of the areas around Rover and astronaut foot tracks, probably due to destruction of the (less than 1 mm) photometric layer

INTRODUCTION

TWO NEW PHOTOGRAPHIC systems were carried for the first time on Apollo mission 15: a 24-inch panoramic camera and a 3-inch mapping camera system. The new cameras were housed in the scientific instrument module (SIM) bay and operated from the Command Module. The Command Module pilot (CMP) also operated the Hasselblad camera to take oblique views of specific targets using color film that accentuates subtle color-tone and textural variations of lunar surface units. The combined results of these systems constitute the most thorough photographic coverage of any Apollo mission to date.

The metric camera system is composed of (1) a terrain camera that took stereo photographs of the lunar surface at 25–30 m resolution; (2) a stellar camera that simultaneously took photographs of a star field for orientation; (3) a laser altimeter that made simultaneous measurements of the spacecraft altitude with 2 m precision; and (4) a clock that recorded the time of terrain camera exposures. This combination of data allows mapping the overflown 12% of the lunar surface (Fig. 1) at 1 : 250,000 scale with 15 m heighting accuracy, which will allow drawing 50 m contours.

The 24-inch panoramic camera took stereo photographs along all the groundtracks at 1–3 m resolution. A single frame covered an area 22 km × 340 km. The central portion of the frames can be rectified to produce high quality photobases at 1 : 10,000 scale with 3 m accuracy, which will allow drawing 10 m contours. The basic data reduction scheme for Apollo 15 photography is summarized by Doyle (1972).

Because of the high inclination of Apollo 15 orbits, the returned photographs contain an unmatched wealth of data pertaining to numerous lunar surface features and processes. Because of space limitations, only a selection of the new findings will be given in this paper. Additional examples are given in El-Baz (1972a).

GEOLOGIC FEATURES OF APOLLO 17 LANDING SITE

On February 16, 1972 the National Aeronautics and Space Administration announced that Taurus-Littrow is to be the landing site for Apollo mission 17. The announcement came after thorough analyses and investigations of the scientific and operational aspects of the last Apollo lunar landing. The Taurus-Littrow area was considered by the Apollo site selection board because of the new findings from Apollo 15: Among the important considerations were the visual sightings from lunar orbit of cinder cones in this area and the variety of geologic features detected in the panoramic camera photography.

The Taurus-Littrow site is located on the southeastern rim of Mare Serenitatis south of the crater Littrow (20° 10′N, 30° 48′E). The Taurus Mountains, which bound eastern Mare Serenitatis, are clusters of massive peaks interconnected with old crater rims and light-colored, plains-forming highland materials. The relationship between the Taurus Mountains and the Serenitatis Basin is much like that between the Apennine Mountains and the Imbrium Basin. The Imbrium Basin, however, is younger than the Serenitatis Basin (Wilhelms and McCauley, 1971) and the Apennines are, in general, less degraded than the Taurus Mountains.

The geomorphological characteristics of Mare Serenitatis and the surrounding topography indicate that Mare Serenitatis is an impact basin that was filled with volcanic lava flows. The mare materials appear to have been deposited in two major episodes: an early event that left a light-colored mare surface in the middle portion of the basin and a later occurrence that deposited a dark-colored mare unit in an outer annulus or concentric zone (Fig 2). A concentric ridge system corresponds closely with this division of the mare units of Serenitatis. The ridges may have been formed by relatively viscous, extrusive volcanic materials along buried concentric fractures. This hypothesis is supported by the fact that the outer zone of the basin displays numerous concentric fractures and faults in the form of arcuate rilles, for example, the Sulpicius Gallus Rilles on the west rim, the Menelaus and Plinius Rilles to the south, and the Littrow and Chacornac Rilles to the east.

As shown in Fig. 2, a still darker unit occurs within the southwestern corner of the Taurus Mountains (the southeastern corner of the Serenitatis rim). In fact, this

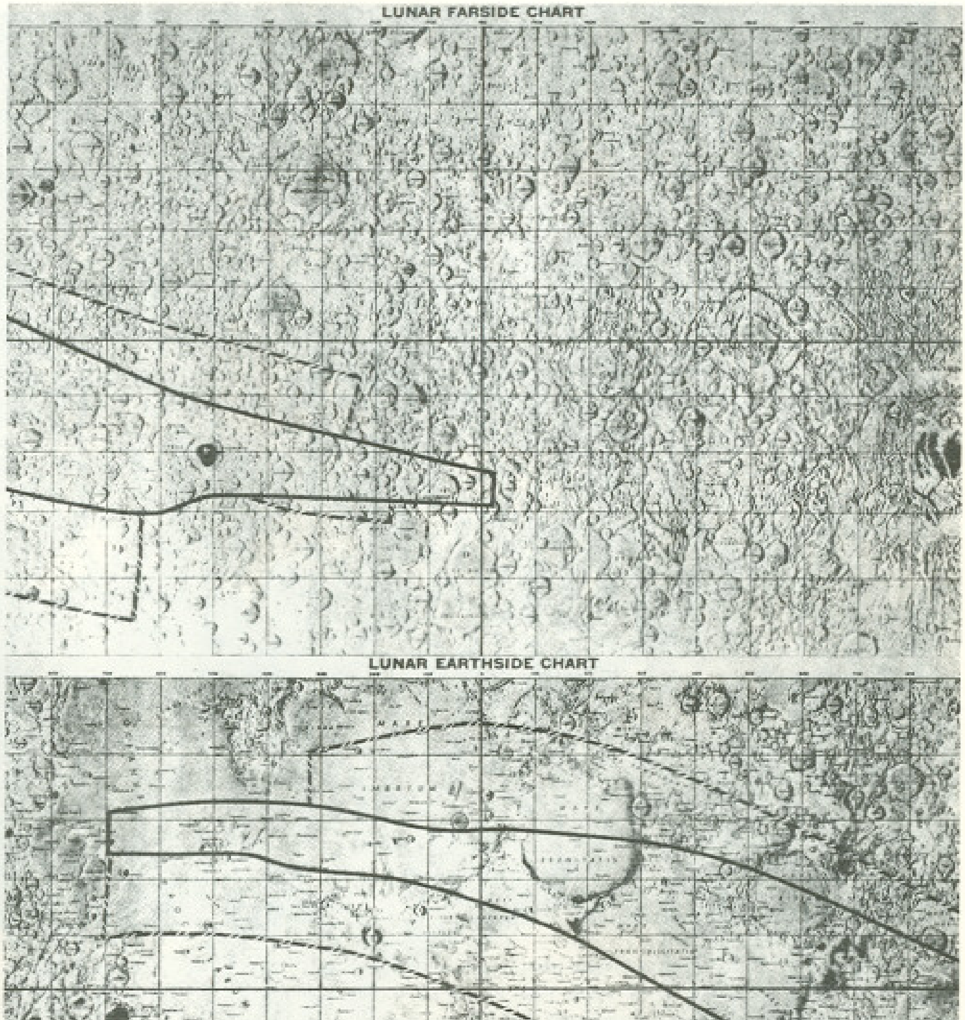

Fig. 1. Photographic coverage of the service module camera systems on Apollo 15. Area enclosed by black lines (about 12% of the lunar surface) is that covered vertically by the mapping camera. This coverage also corresponds with that of the rectifiable portions of the panoramic camera photography. Enclosed by the dashed lines are areas covered obliquely by the mapping camera.

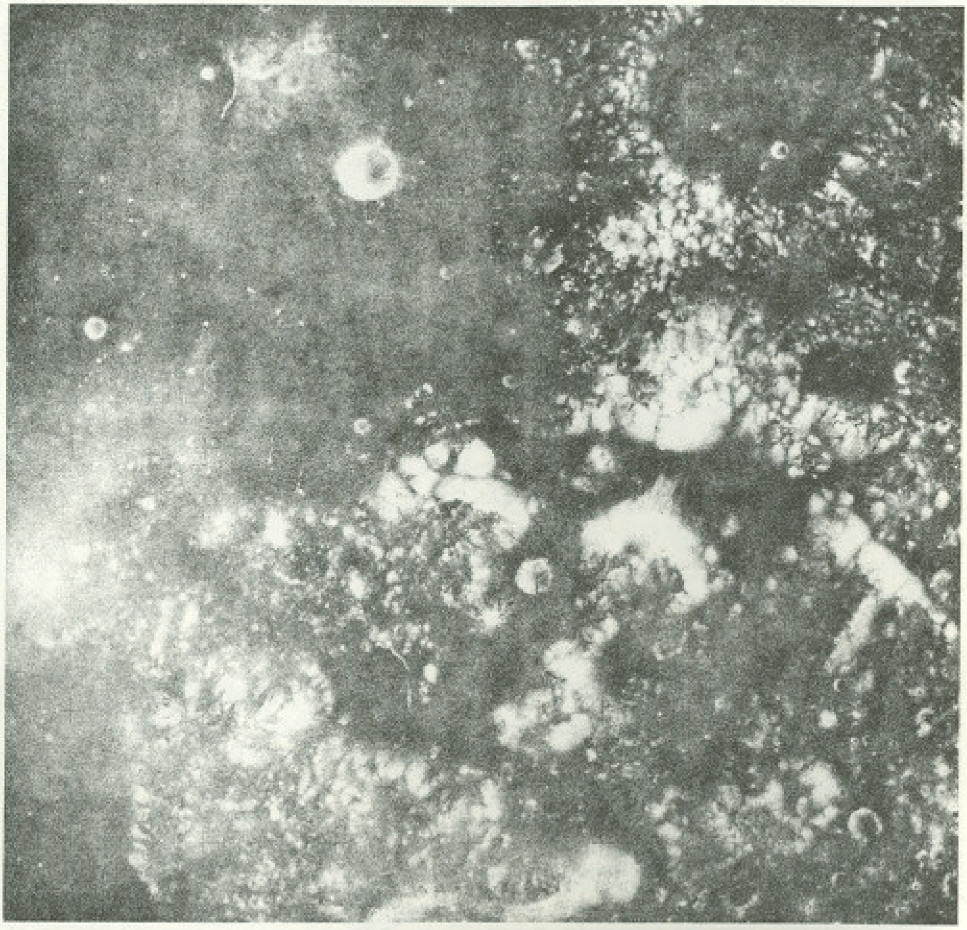

Fig. 2. Portion of mapping camera photograph of the south-eastern rim of Mare Serenitatis. The crater Littrow is in the upper right corner of the photograph; Mt. Argaeus is at the bottom. Note the dark-colored unit that fills the flat areas between the highland units; a detail is shown in Fig. 3 (metric camera frame 1113).

unit constitutes the darkest surface material on the lunar near side (Pohn and Wildey, 1970) and, probably, on the whole Moon. The unit is centrally located between the crater Littrow to the northeast, the crater Vitruvius to the southeast, and Mt. Argaeus to the southwest. It appears to mantle the highland materials as well as the Serenitatis mare materials. The unit was mapped as the Sulpicius Gallus formation by Carr (1966) and is considered volcanic in origin.

Earth-based multispectral data indicate that the dark color of this unit is probably related to compositional characteristics as discussed by McCord (1969). Radar data also indicate that the unit is relatively smooth, with a small number of blocks. The apparent young age of the dark unit is indicated by the relatively low density of craters on its surface (R. Greeley, personal communication).

The regional geologic setting of the area is discussed by Carr (1972). The local setting and the relationship of the dark deposit to surrounding geologic units is discussed by El-Baz (1972b). During the Apollo 15 mission the dark deposit and its probable source were the objects of visual observations, which indicate that the unit probably consists of volcanic ash or pyroclastic deposits that came to the surface through a multitude of cinder cones.

As shown in Fig. 2, the dark material appears to embay the highland massif units. A panoramic camera view of part of the unit is shown in Fig. 3, in which the dark material is visible both in the lowlands between the mountains and, rarely, on top of massif units that display nearly level or depressed surfaces. Thus, the dark material probably was deposited from above; that is, by settling after ejection from beneath the surface.

In addition, remnants of the dark deposit can be distinguished on some of the massif slopes. This observation also tends to support deposition from above, followed by mass wasting down steep slopes. The dark material, therefore, would be mixed with the light-colored, fine-grained highland material as evidenced by the fact that gradational contacts occur between the dark lowland fill and the mountain fronts.

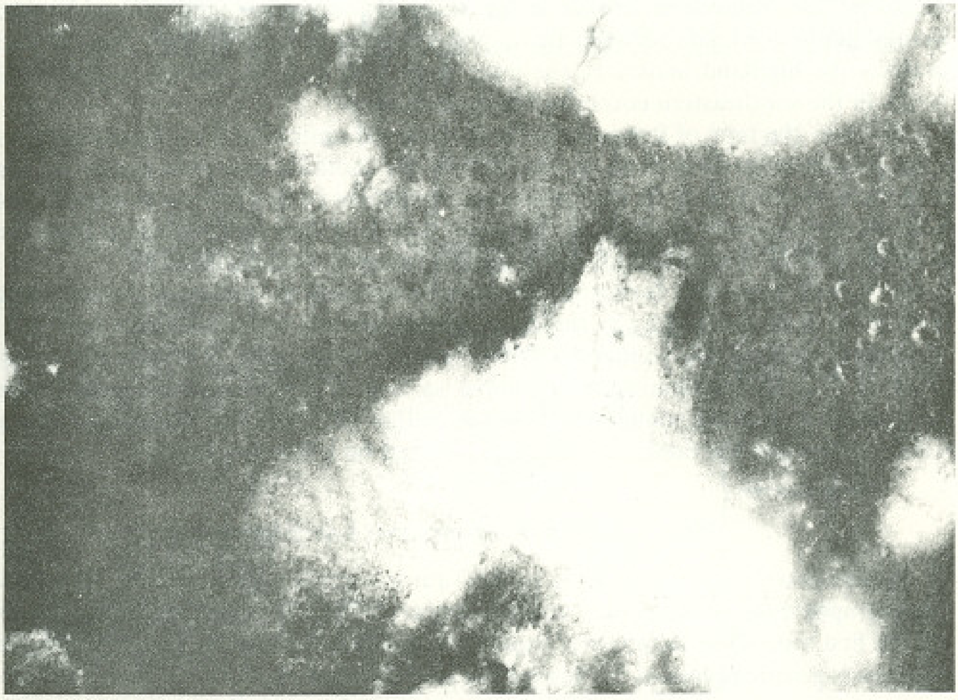

Fig. 3. Apollo 15 panoramic camera view of the Apollo 17 Taurus-Littrow landing site. The two massif units to the north and south constitute the southwestern corner of the Taurus Mountains. The bright area between the two units is interpreted as a landslide that originated at the southern massif unit (see also Fig. 4). (Central portion of panoramic camera frame 9559).

Based on the Apollo 15 photographs (Figs. 2 and 3), a geologic sketch map shown as Fig. 4 was made of the area. From this data the geologic history of the region may be summarized as follows:

1. The Serenitatis Basin was formed by a giant impact, which formed a 700 km-wide depression and at least two major systems of fractures, one concentric with the basin and the other radial to it. Massif units of the Taurus Mountains appear to have been uplifts along the concentric fault system, and they display fractures parallel to both.

2. A major episode of basin filling by Imbrian basaltic flows occurred. This episode probably ended about 0.5 billion years later (estimated by extrapolation of data acquired at previous Apollo landing sites). Another episode of filling followed, ending perhaps another 0.5 billion years later (Eratosthenian in age), during which the darker annulus surrounding the older mare material was formed (estimated on the basis of age dates of Apollo 12 and 15 basalts as opposed to Apollo 11 basalts, as well as relative ages in Wilhelms and McCauley, 1971). One of the latest manifestations of mare material extrusion was the formation of the wrinkle ridges now visible on the mare surface.

3. After the completion of basin filling by mare materials, volcanic eruptions began in the southwestern corner of the Taurus Mountains. Cinder cones, located mainly in the lowlands between the massif units, deposited the dark blanket that mantles the highland materials, the mare materials, and the grabens and wrinkle ridges in the southeastern corner of Mare Serenitatis.

4. From the time of formation, scarps of massif units of the Taurus Mountains were subjected to mass wasting. (Blocks on the foothills and their tracks on the slopes are shown in Fig. 3). One of the manifestations of this process is a unit, with north-south lineaments, which is interpreted as a landslide that originated from the southern massif unit and which has a distinct trough at its base (Fig. 4).

5. A fault scarp was formed by the relative upward movement of the materials west of the fault line and/or by the downward movement of the materials east of it. The fault is among the youngest tectonic features in the area; it bisects the oldest material (Taurus Mountains massif units) as well as the younger formation (the dark, ashlike mantling material). However, within the latter the scarp looks like a wrinkle ridge and the fault may have been draped by a thin ash deposit.

NEW VOLCANIC FEATURES AND LANDFORMS

In addition to the cinder cones in the Taurus-Littrow region, Apollo 15 orbital photography exhibits numerous volcanic features that were observed on the moon for the first time. Detailed study of these structures will further our understanding of lunar endogenetic processes. Following is a brief description of four of these features.

D-shaped structure southwest of the Haemus Mountains

The hilly upland units between the circum-Serenitatis Haemus Mountains and the circum-Imbrium Apennine Mountains is characterized by isolated mare-like

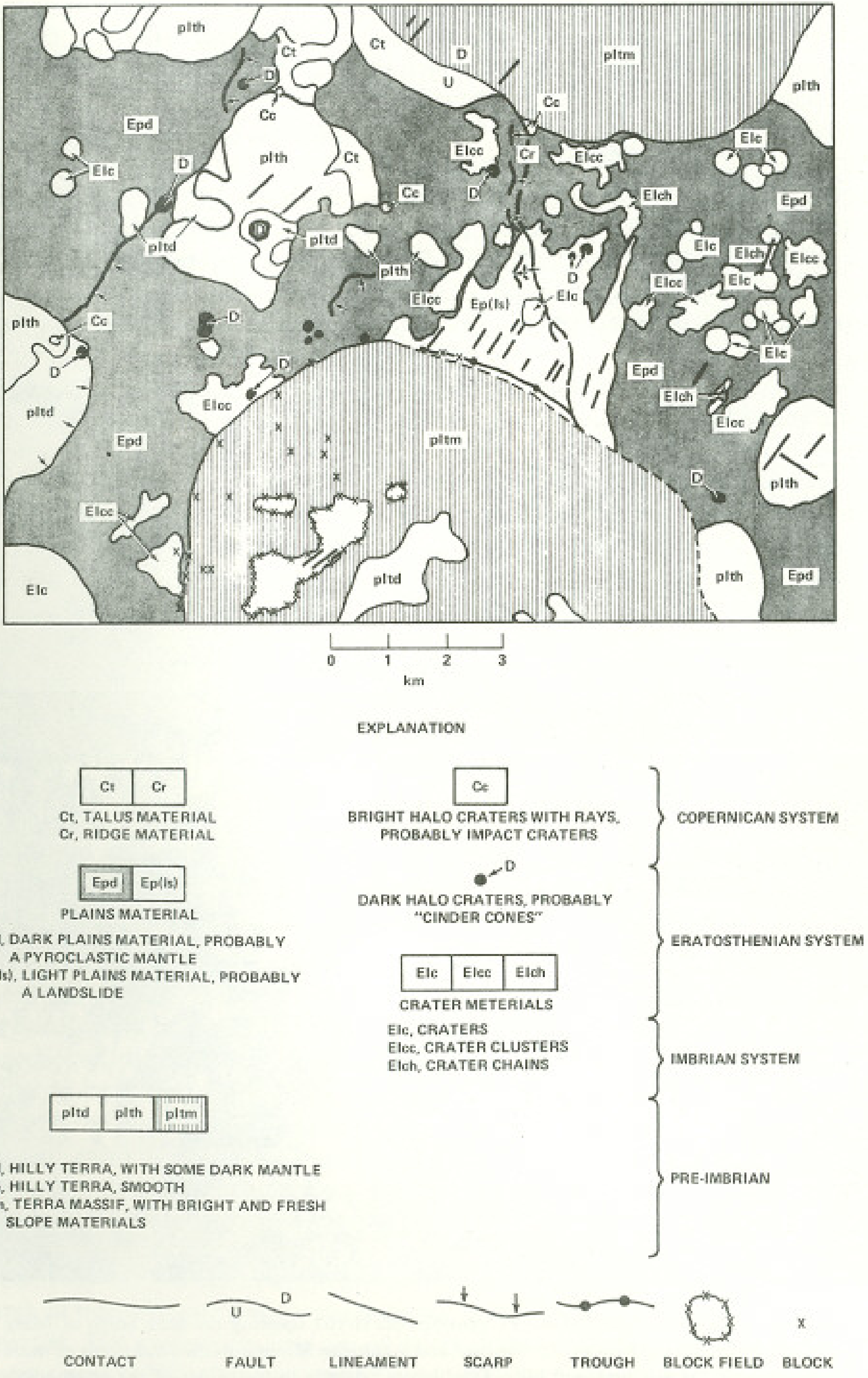

Fig. 4. Geologic sketch map of the area shown in Fig. 3.

patches. These dark patches are relatively younger mare flows that are superposed on the highland materials (Fig. 5). Within one of these patches the Apollo 15 panoramic camera photographs reveal a D-shaped structure with unusual characteristics (Whitaker, 1972a).

The structure is located at 18° 40′N, 5° 20′E and is about 3 km along the straight part of the rim. It is a depression with a raised rim and an outer topographic rise that extends to a maximum of about 4 km. The rim deposit is somewhat darker than the surrounding mare material, but exhibits similar textural characteristics. As shown in Fig. 6, the floor of the depression displays three different units: (1) a slightly undulating, hilly and domical, light-gray unit that occupies the central and north-eastern portions of the floor, (2) a very bright, almost white unit that makes an annulus occupying the outer part of the depression, and (3) a unit made of about 50 disconnected, slightly sloping positive structures, which produce a blister-like appearance. They are reminiscent of volcanic domes and a few display distinct summit craters in the middle.

These characteristics indicate that the structure is of volcanic origin. It is my opinion that we are dealing here with a caldera with several stages of extrusion and intrusion in the central part. The blister-like domes appear to constitute the latest events. The unusual low density of craters within the structure suggests that it may be among the youngest lunar formations of volcanic origin.

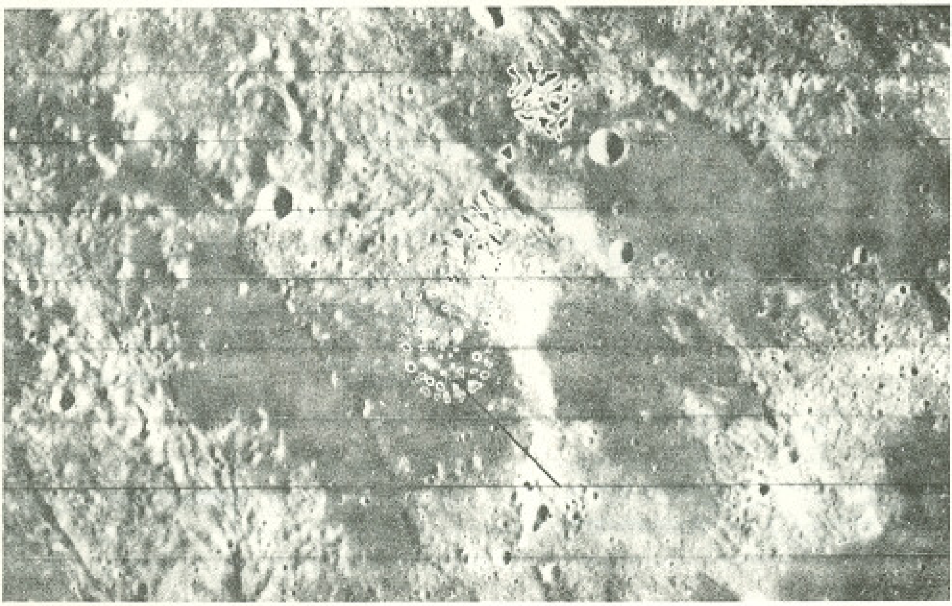

Fig. 5. Portion of Lunar Orbiter IV photograph H-102 showing the area north of Mare Vaporum on the foothills of the Haemus and Apennine Mountains. Several pools of mare units overlie the low highland hills. The "bimat" defects in the center of the photograph partly mask the structure shown in Fig. 6 (arrow).

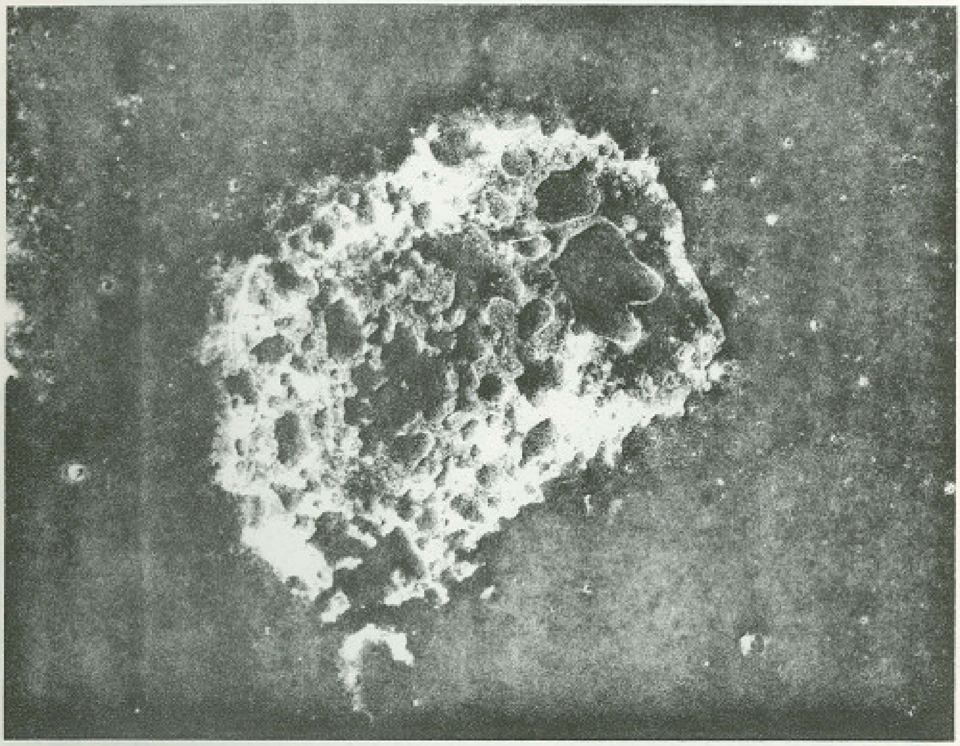

Fig. 6. D-shaped structure that is interpreted as a caldera. The straight segment of the rim is approximately 3 km long. Note the light-colored annulus in the floor, which is also exposed in the wall of the crater on the lower left corner. The blister-like domical hills have summit vents and appear to be completely void of impact craters, suggesting a very young age. Apollo 15 panoramic camera frames 0176 and 0181 make a stereo pair of the structure.

The most ambiguous feature in the structure is the light-colored unit. It is suggested by Whitaker (1972a) that this highly reflective material probably is sublimates. It is evident from Fig. 5 that the exposure on the bright crater wall near the southwest corner of the structure represents a difference of materials within a unit that was dug up by that crater.

It must be stated that the general area between the Haemus and Apennine Mountains exhibits an anomalous Al/Si ratio. As reported by Adler *et al.* (1972), the average ratio over mare areas is 0.67 and over highland areas 1.13. The region in question shows a median ratio of about 0.85. This apparently is due to the mare patches within the highland units. The area also is the seat of the A-7 zone of moonquake activity as reported by Latham *et al.* (1972). Movements along fractures within this area of intersection between the Imbrium and Serenitatis fracture systems is not unexpected. The apparent young age of the D-shaped caldera within the region also indicates a possibility of volcanic eruptions and/or readjustments to relatively recent volcanic deposits.

Lava lake southwest of the crater Perelman

At 103°E, 25°S, southwest of the crater Perelman, occurs an isolated patch of dark mare-like material. The area is elongate, measuring 120 km by 40 km, and the patch is surrounded by cratered plains (Fig. 7). The high resolution panoramic photography displays numerous probable volcanic craters, domes, and viscous flows, as shown in Fig. 8.

The northern part of the region is enclosed in a breached crater and displays a relatively smooth surface with numerous rimless depressions. The dark material appears on at least three different levels (Fig. 8). The highest level topographically is

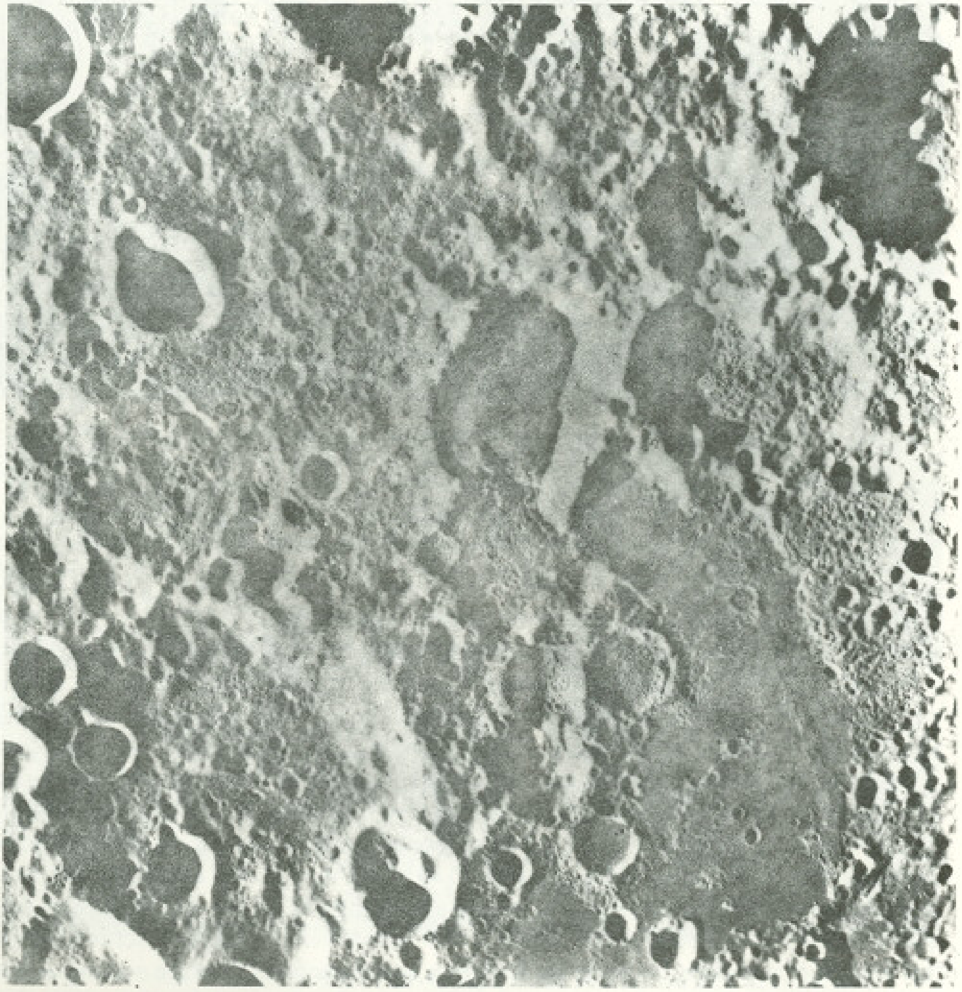

Fig. 7. Dark mare-like material that floods an area southwest of the farside crater Perelman, upper right corner. The image area is approximately 160 km on each side. A detail is shown in Fig. 8 (metric camera photograph 2628).

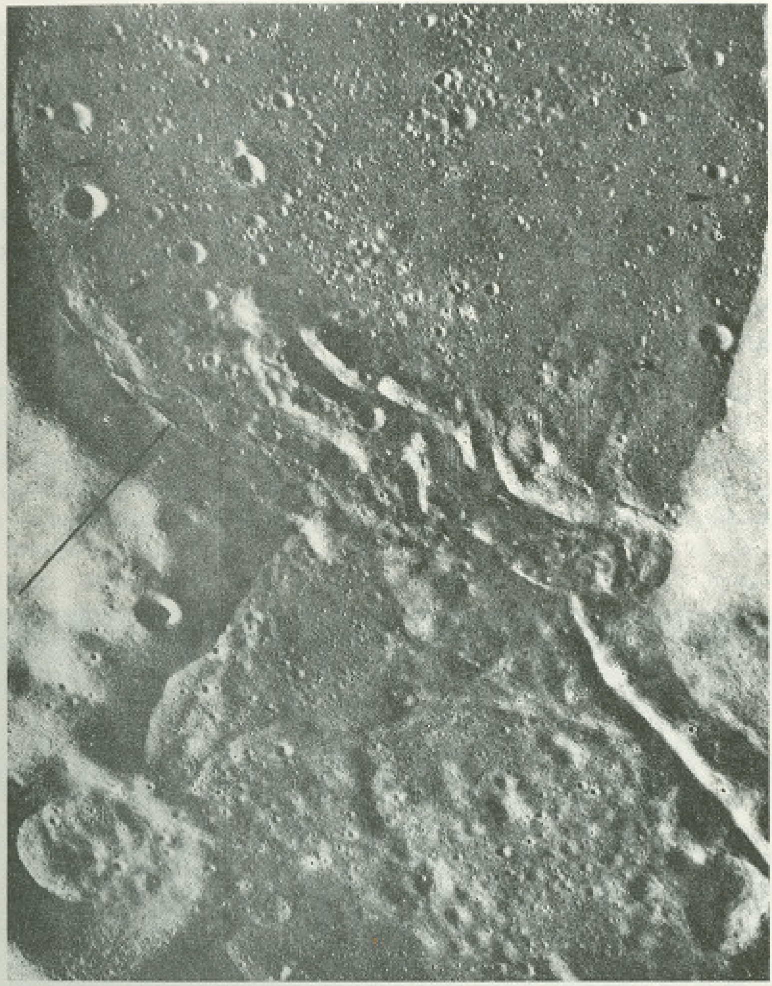

Fig. 8. Apollo 15 panoramic camera view of portion of the caldera-like structure showing a "lava mark" on the western wall (arrow) and a level of subsidence that is marked by an annulus of topographically higher floor material near the rims (arrowheads). Drainage channels may be seen near the fissure, which trends in a northwesterly direction (panoramic camera frame 9965).

on the wall of the crater and shows best in the partly shadowed western wall. It is represented by a thin layer that produces a sharp scarp, and is best described as a "lava mark" where the infilling lava must have filled the crater to that high level and later receded leaving a mark, much like the "water mark" described by the Apollo 15 crew on the slope of Mt. Hadley.

The second level is represented by an annulus about one-tenth of the way inward. It produced an inward facing slope toward the third and lowest level, which makes up the rest of the area. This second level also is indicative of lava recession following extrusion. Flow channels leading into the fissure, which bounds the area to the south and trends in a northwesterly direction, suggest drainage.

These characteristics suggest that the features are the result of drainage of a lava lake. Textures and evidence of flow indicate that the original lava probably resembles that of the basaltic maria. Drainage of the lava following extrusion is a common occurrence on earth. This usually happens through the fractures that served as channelways for lava extrusion. It is, therefore, reasonable to conclude that the fissures and rille-like structures served as conveyors of the lava as well as drainage channels following extrusion.

Gigantic domes near Rima Schroedinger I

Schroedinger is a farside basin, 300 km in diameter, near the moon's south pole and from its rim emanate two large straight depressions or rilles. The western rille displays sharp boundaries and is as much as 20 km wide. Photographs of this rille, which show the domes described below, were obtained following trans-earth injection (TEI) using the Hasselblad camera with the 250 mm lens and color film.

As shown in Fig. 9, the photographs reveal in an area centered around 105°E, 60°S, a cluster of about six unusually large domes. The larger domes are 40 km in diameter. They display somewhat undulating surfaces and are reminiscent of mare domes in western Oceanus Procellarum on the moon's nearside. These features also appear to be made of extrusive volcanic deposits.

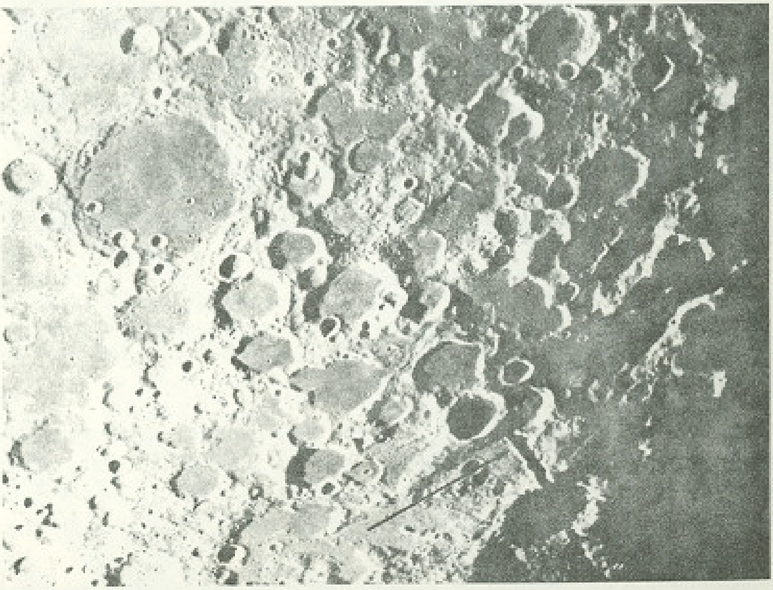

Fig. 9. Post-trans-earth injection view showing probable volcanic domes near Rima Schroedinger I (arrow). Note the dark mare-like material that fills the level areas in and around craters (Apollo 15 Hasselblad camera frame 13090).

The domes are located in an area of cratered highlands. However, relatively dark plains-forming materials fill most craters as well as flat areas between them. One unusual feature is a wrinkle ridge, which starts at the area where the domes are clustered. This occurrence of a wrinkle ridge is in the highlands and suggests that ridges of mare-like material may represent extrusive volcanism along pre-existing fractures, whether in the maria or the highlands.

Flow front in western Mare Imbrium

Apollo 15 photographs of the southwestern portion of Mare Imbrium are an excellent illustration of the utility of oblique metric camera photography (Fig. 10). In this area a system of lava flows stretches diagonally within Mare Imbrium near the crater Euler (23°N, 29°W). The system has been known from earth-based telescopic observations and photography (Strom, 1965).

As discussed by Whitaker (1972b), examination of the Apollo 15 photographs leaves little doubt that the source of the material comprising the major flows is situated to the west of the crater Euler and south of the limits of the photographic

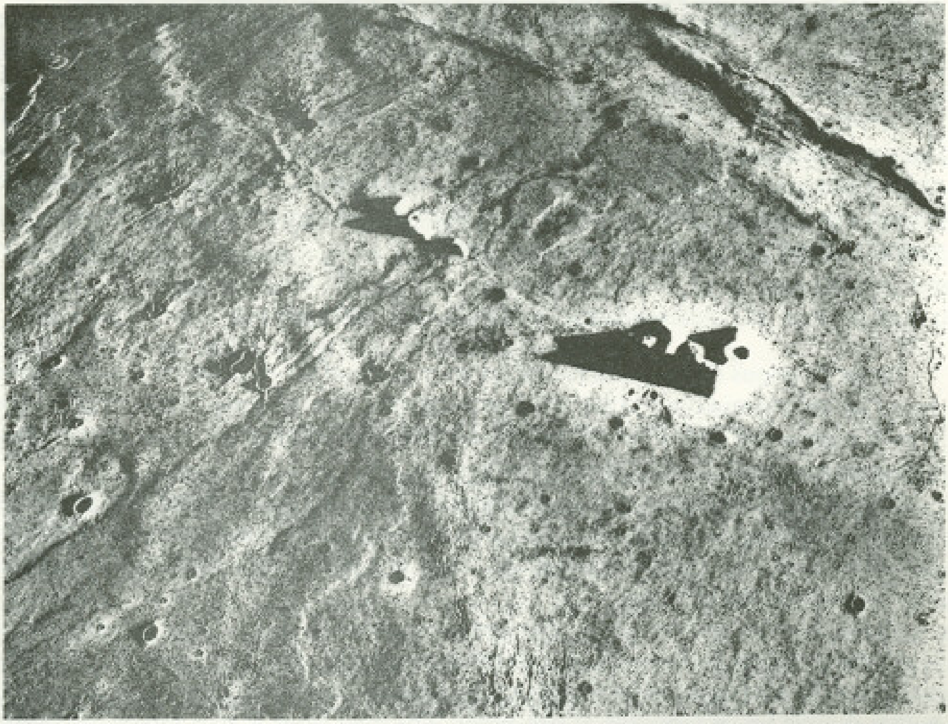

Fig. 10. Oblique view (40° north) of the flow edges in western Mare Imbrium. The largest flows that extend from the left to the right are deformed by a prominent mare ridge (Apollo 15 metric camera frame 1556).

coverage. Some lava-flow channels located west-northwest of Euler are similar to features found on Mauna Loa and other terrestrial volcanic fields. The lavas, in the present case, have flowed in a general northeasterly direction, indicating the direction of slope that existed in Mare Imbrium at the epoch of the eruption. The point of termination of the flow system, near the crater Le Verrier, is close to the center of Mare Imbrium. This implies that the older filling of lavas never completely obliterated the shape of the pre-lava basin and that the later flows simply ran downhill to the lowest area at the center.

Several flows appear to cross ridges of substantial elevation without deviation, ponding, or change in thickness. This would have been unlikely if the ridges had preceded the flows; thus most, if not all, of the mare ridges included were formed after the solidification of the flows.

It must be stated that the area, where the flows appear to originate, corresponds with the highest γ-ray counts on Apollo 15 (Metzger *et al.*, 1972). Although it was suggested that the anomaly may be due to ray materials in the area, this author proposes a subsurface origin at the source of the flows, e.g., higher concentration of radioactive materials in the last stages of magmatic extrusion, which resulted in the formation of the complex system of broad wrinkle ridges. It must be stated that the anomaly is removed from the fairly thick Lambert ejecta by approximately 300 km. Also, rays from larger craters (Copernicus, Kepler, and Aristarchus) are neither more abundant nor any different than in other overflown regions of both Mare Imbrium and Oceanus Procellarum.

Strom (1965) and Whitaker (1972b) have shown that these Imbrium flow boundaries correspond with distinct color differences. The younger units are bluer and the older units are redder. This distinction also corresponds with the moon-wide geological classification of mare units into older (redder) units of Imbrian age, and younger (bluer) flows of Eratosthenian age.

LANDSLIDE OF THE CRATER TSIOLKOVSKY

In the previous discussions, examples were given of photogeologic interpretation based on the examination of returned photographs. The purpose of this brief section is to illustrate the utilization of metric camera photography to make topographic measurements and provide terrain profiles.

The case in question is that of the lineated flow unit on the northwestern rim of the crater Tsiolkovsky (Fig. 11). This 80 km-long unit is interpreted as a landslide that originated near the rim crest of the crater and flowed in a westerly direction on the floor of the crater Fermi.

Preliminary terrain profiles of this unit are shown in Fig. 12. These were generated by partial levelling of a model on a stereo plotter (APC-type) and plotting elevation points of the surface along a traverse. The profiles show that the unit slopes gently with a double lip or terminus at one point. The flow front is also somewhat raised, which is not uncommon in landslides or debris flows on earth.

The landslide exhibits a larger number of fresh, small craters than on the older Fermi crater floor. Many of these are rimless and appear to have been the result of

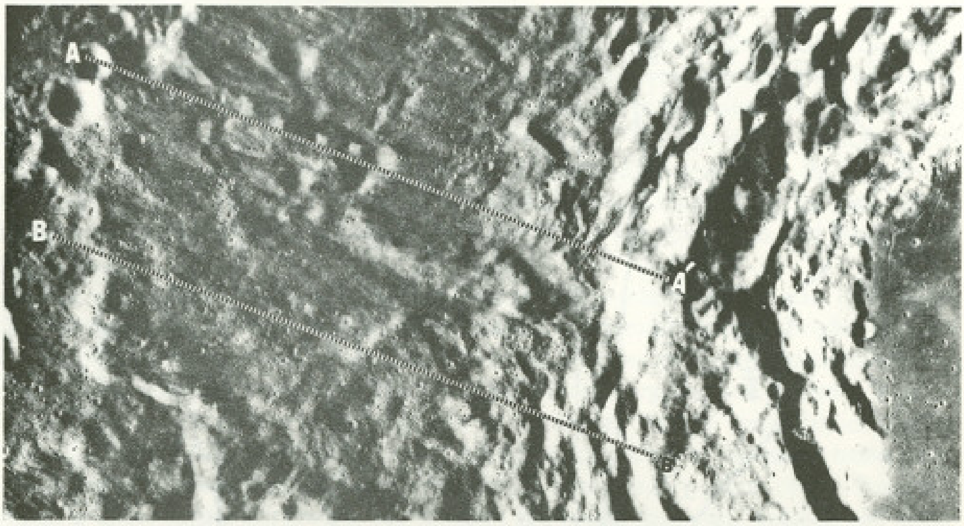

Fig. 11. The landslide on the northwestern rim of the farisde crater Tsiolkovsky. The lineations are parallel to the direction of flow. The two lines AA′ and BB′ indicate the traces of the terrain profiles in Fig. 12 (Apollo 15 metric camera photograph 1034).

drainage of the fine-grained material into void spaces initially sealed over by larger blocks in the landslide.

The smaller (5 km) landslide in the Taurus Littrow region (described above) is not identical to that of Tsiolkovsky. The Littrow landslide appears more hummocky and shows more small-scale undulations. Both landslides, however, are blocky. This has significant implications in the case of the Apollo 17 landing site where the landslide may provide blocks of varying sizes from the whole of the stratigraphic section from which it was derived. Thus, its sampling would provide the best method of sampling the mountain scarp from which it originated.

Unusual and Man-made Albedo Variations

The photometric properties of lunar surface materials are not yet fully understood. Gross variations in albedo can be correlated with material (chemical and/or physical) differences. In some cases, however, the surface brightening and darkening are caused by unknown factors. This is due primarily to the lack of knowledge of the characteristics of the lunar photometric layer—the upper few hundred microns of the soil. An understanding of this layer is fundamental to a better comprehension of the albedo of lunar surface materials and its variations. It is also important in interpreting results of many remote sensing techniques, which depend on the properties of the uppermost layer of the surface. Apollo mission 16 will provide us, for the first time, with a sample of this layer for detailed analysis and study. This section will be devoted to descriptions of unusual light-colored markings in three lunar surface regions and to man-caused albedo variations in the Apollo 15 landing site.

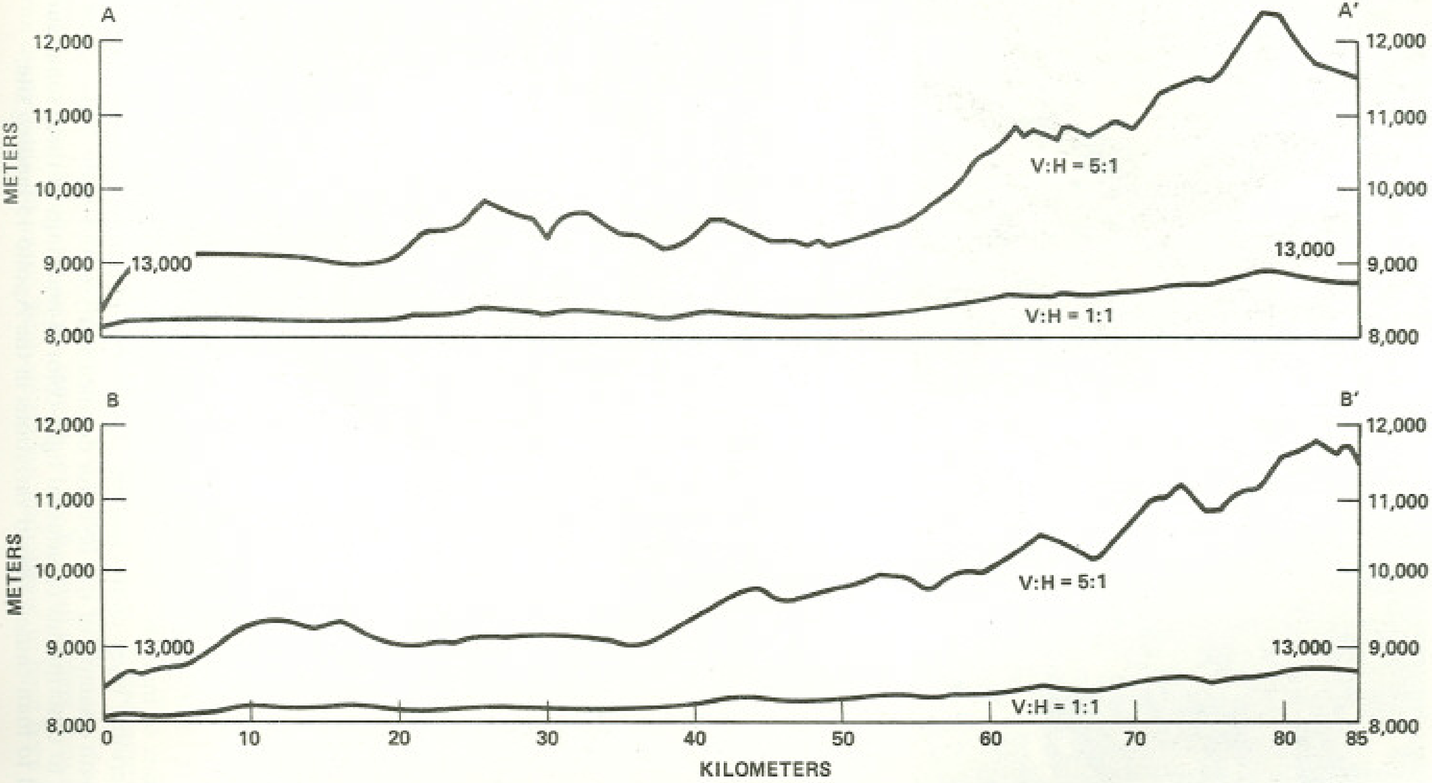

Fig. 12. Two profiles of the Tsiolkovsky landslide with the two different ratios of the vertical to horizontal scales (1 and 5); Courtesy of S. C. Wu, U.S. Geological Survey.

Unusual markings in the lunar maria

Rays and ejecta blankets of impact craters make up the majority of very bright and light-colored units on the Moon. An excellent example is given in Fig. 13, which shows a 5.5 km crater and surrounding ejecta. The crater is located on light-colored highlands near Gagarin on the lunar farside (145°E, 17°S). The ejecta, which is very blocky and hummocky, extends to about 1.5 crater diameters from the rim crest. Beyond this zone the rays extend in a radial pattern. Alternating light-and-dark streaks are common; the dark streaks are due to surface roughness and small-scale undulations.

The aforementioned brightness is at least easily correlated with ejecta, even if not fully understood. In three regions on the moon, there exists surface brightness that is not related to observable features. These are swarms of light-colored markings that display sinuous patterns in Mare Inginii, Mare Marginis, and Oceanus Procellarum. The swirls of bright materials in Mare Inginii on the lunar farside are as much as 120 km long, and occur in the southwest quadrant of the mare basin (Fig. 14). It must be noted that they appear old because secondary crater chains from the crater O'Day, to the northwest, cut through the bright material. Because the latter is exposed on the walls of the crater chains, the brightness seems to extend downward.

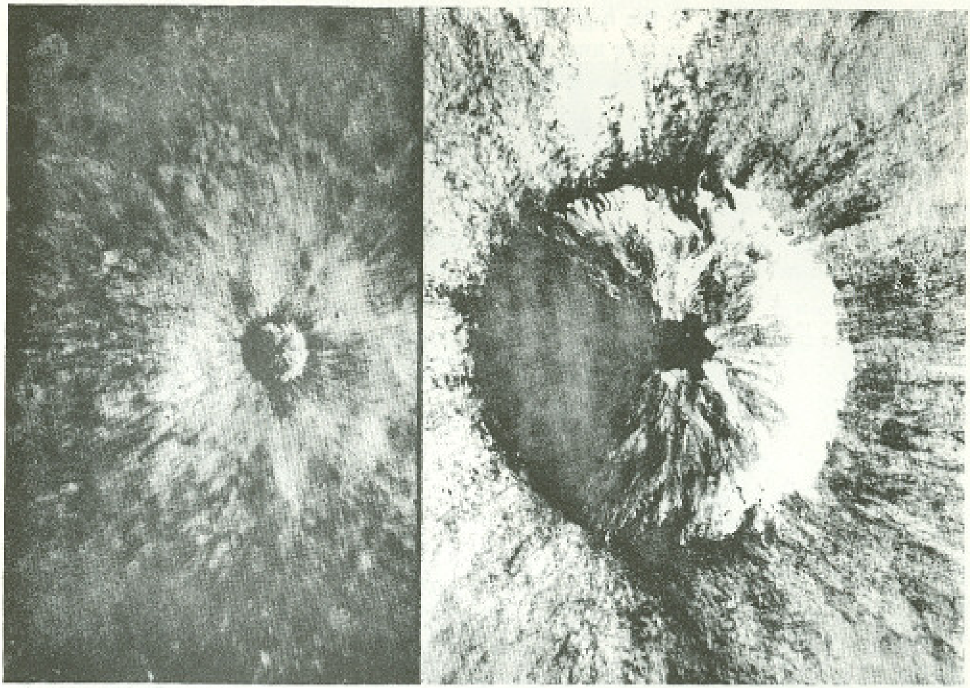

Fig. 13. Apollo 15 panoramic camera view of a sharp, bright-haloed crater near the northwestern rim of the farside crater Gagarin. Note the ejecta blanket and the radial ray system (left), and the blocky, streaked ejecta (right).

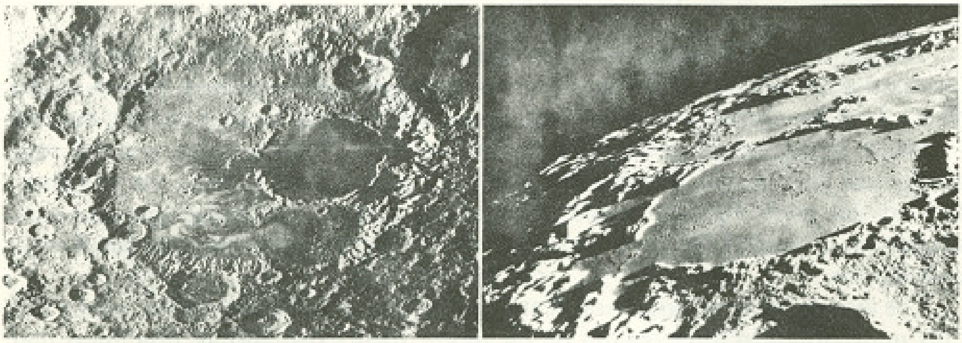

Fig. 14. Left, portion of Lunar Orbiter II photograph M-75 showing Mare Inginii with the light-colored swirls in the southwest quadrant. Secondary crater chains of the crater O'Day on the western rim of the basin cut across the swirls. Right, oblique view (looking southward) of Mare Inginii showing the lack of topographic relief of the light-colored sinuous markings, upper right (Apollo 15 Hasselblad camera frame 11724).

A similar group of light-colored swirls occur in the northern part of Mare Marginis; however, individual swirls are smaller in this case (Fig. 15). They are concentrated in two areas: west of the crater Goddard, in the mare materials; and northeast of Ibn Yunus, in the highland materials. A somewhat atypical occurrence is that of the Reiner-γ structure and associated bright markings in western Oceanus Procellarum. This is atypical because only one swirl and a long bright line form the structure.

In all three cases the swirls are best seen at small phase angles; however, because of their very high albedo they are detectable at low sun (Fig. 14). From both photography and visual observations from orbit, these markings appear to have no topographic expressions associated with them. Also as pointed out previously (El-Baz, 1971), the following relationships are significant: (1) the swirls in Mare Inginii lie

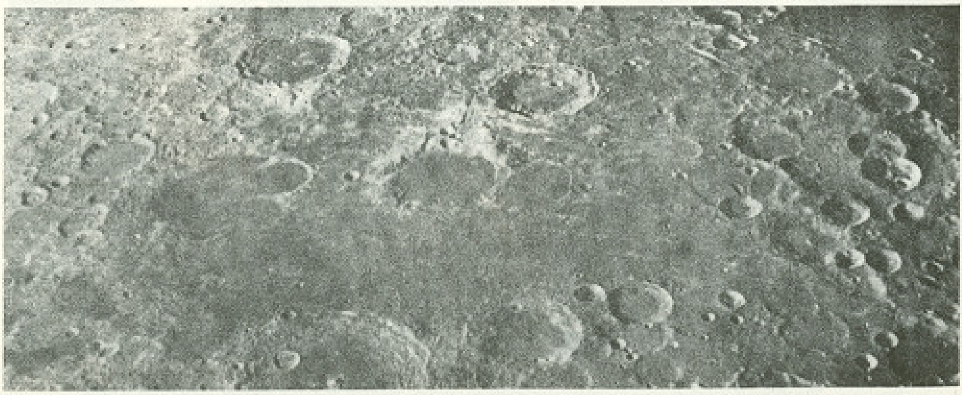

Fig. 15. Swirls of light-colored markings in the area north of Mare Marginis on the eastern limb of the moon (Apollo 15 Hasselblad camera frame 13094).

diametrically opposed to the center of Mare Imbrium, (2) the bright swarms in Mare Marginis lie on the opposite side of the moon from Mare Orientale, and (3) the Reiner-γ markings in Oceanus Procellarum lie opposite to a point within one crater diameter of the crater Tsiolkovsky.

Because of these characteristics and relationships it was proposed by El-Baz (1971) that these swirls probably are produced as a result of disturbances caused by major impacts; the disturbances may have been caused or triggered seismically at the antipodal areas of impact points. It is further speculated that converging seismic waves may have facilitated the release of trapped gases in the lunar interior; the gases may have penetrated the materials through fractures and chemically altered them. "Alteration" along fractures, although on a much smaller scale, appears feasible based on the occurrence of such cases in the Apollo 15 basalts (see Swann *et al.*, 1972, p. 82).

Man-caused albedo variations on the lunar surface

High resolution panoramic photographs of the Apollo 15 landing site show, for the first time, the LM structure on the moon as evidenced by reflected light and by a shadow. This was most convincingly demonstrated by before and after photography of the landing site (Hinners and El-Baz, 1972). The post-landing photographs (Fig. 16) show a bright halo, approximately 150 m in diameter, roughly centered on the

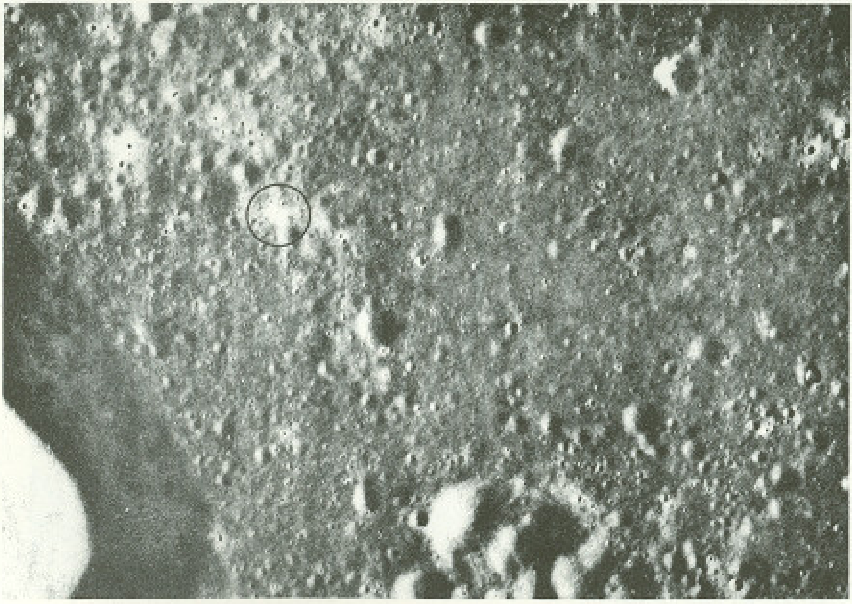

Fig. 16. Panoramic camera view of the Apollo 15 landing site taken two revolutions after landing. The circle encloses the landing site with a prominent bright halo, which may have been produced as a result of compaction of the surface material during the Lunar Module descent.

LM. The halo is attributed to an increase in mare surface brightness caused by the landing. The symmetry of the halo precludes reflected sunlight as a cause; reflected light should be observed largely only to the east. A relatively bright area southeast of the LM also is visible. This area, in contrast to the halo, is also relatively bright in the pre-landing photographs, and this brightness is attributed to the eastward-sloping wall of an old, subdued crater. However, some enhancement of the brightness as a result of the LM landing is not ruled out.

That a surface alteration occurred during landing is not surprising, because, in each Apollo mission, the descent engine exhaust plume has caused significant lunar surface erosion at LM altitudes below approximately 30 to 50 m. However, most surface disturbances seen at both the Surveyor and Apollo sites resulted in a darkening of the surface. This darkening appears to be caused by the destruction, by removal or covering, of a very thin (less than 1 mm) high albedo skin layer by darker subsurface material. Such a disturbance can be seen in Fig. 17, which shows a panoramic camera photograph taken during the first extravehicular activity. It shows a dark path leading from the LM to the Apollo lunar surface experiments package (ALSEP) deployment site. This darkening is caused by a coating of subsurface soil kicked up by the lunar roving vehicle (Rover) wheels and by the astronaut walking next to the Rover en route to the ALSEP site and by the Rover wheels alone on the return trip.

Considering the above, one would predict that exhaust-induced erosion would destroy the thin, high albedo skin, leaving a dark halo surrounding the landing point, in direct contrast to what is observed. As detailed by Hinners and El-Baz (1972), the probable answer to the problem lies in a consideration of the lunar photometric function: a decrease in porosity will result in a photometric brightening of the surface.

It is suggested, therefore, that the bright halo surrounding the LM is a photometric effect caused by the compaction of the lunar soil under the influence of the dynamic pressure of the descent engine exhaust gases. The darkening of the lunar surface (seen

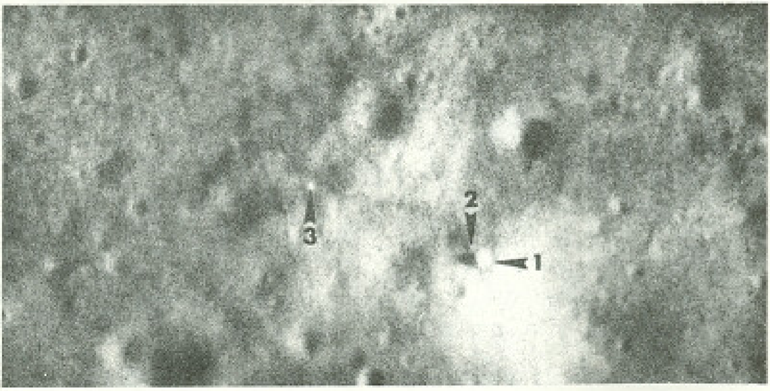

Fig. 17. Fifty times enlargement of panoramic camera frame 9430 of Apollo 15 landing site showing the LM with its prominent shadow (1) and the Rover which is parked near the northwest corner of the LM structure (2) and the ALSEP station (3). The tracks of the Rover to and from ALSEP are displayed by subtle surface darkening.

from orbital photographs, Fig. 17; and photographs taken on the surface, Fig. 18) along the Rover traverses is due to the destruction of the uppermost photometric layer.

From the soil standpoint, there is evidence of a coarser grain size in the Apollo 15 LM area than in adjacent undisturbed areas (McKay *et al.*, 1972). One would expect, therefore, that LM exhaust would both erode the uppermost photometric layer as well as compact the layers beneath it. The Apollo 16 sampling of this photometric layer, discussed above, should shed light on these relationships.

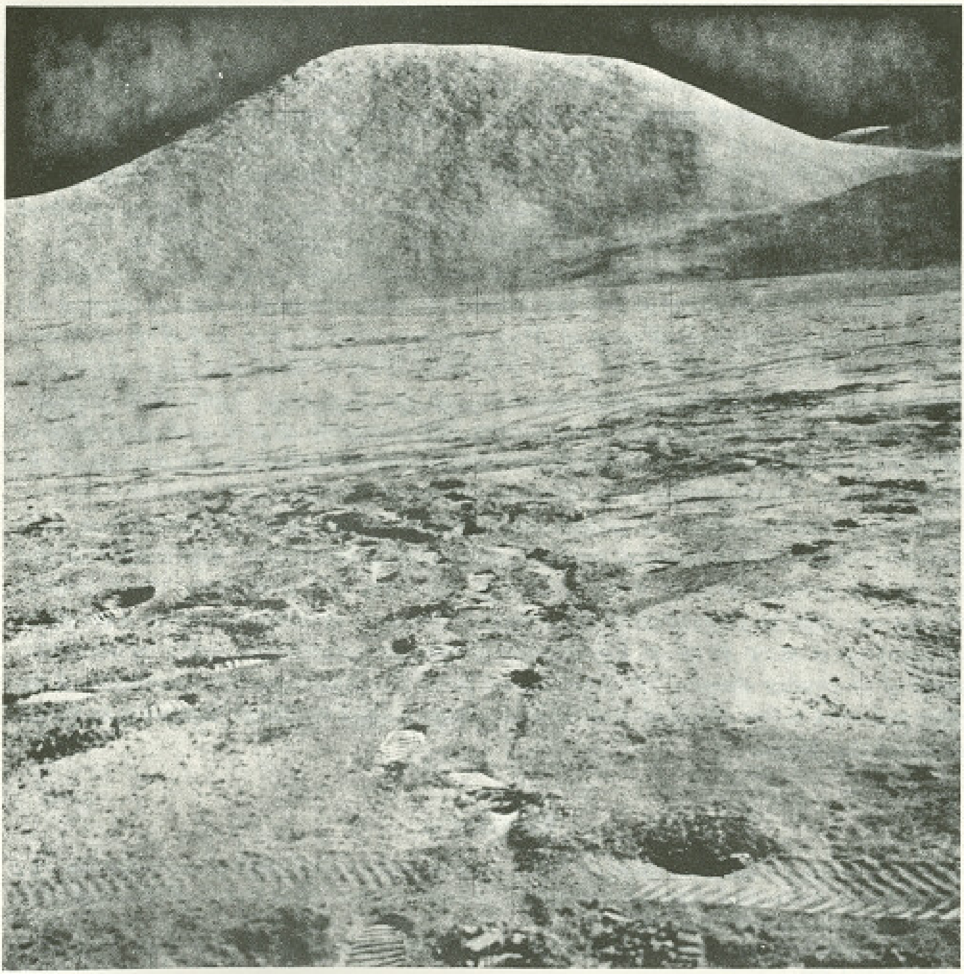

Fig. 18. Surface disturbances in the Apollo 15 landing site: Mt. Hadley is in the background. Astronaut footprints are bright, probably due to compaction; the areas where the dust had spread over around the footprints are dark. A similar situation is portrayed by the Rover tracks in the foreground (Apollo 15 Hasselblad camera frame 11793).

CONCLUSIONS

Several new features of probable volcanic origin were detected in the Apollo 15 photographs: (1) cinder cones in the Taurus-Littrow region that may have brought to the surface pyroclastic fragments from deep within the moon in the post-mare period of lunar surface history; (2) a D-shaped structure which appears to be a collapsed caldera with light-colored floor units with smooth and relatively younger domes. The feature may be among the youngest lunar formations of volcanic origin; (3) a lava lake on the lunar farside near the crater Perelman with lava marks and evidence of subsidence due to drainage into prominent fissures that display drainage channels; (4) domes near Rima Schroedinger I, which range in size to as much as 40 km in diameter; and (5) numerous lava flows in western Mare Imbrium, some of which cross mare ridges.

Other features include two lineated units that are interpreted as landslides. The larger (approximately 80 km) originated at the northwestern rim of the farside crater Tsiolkovsky; and the smaller (approximately 5 km) apparently originated on the steep slope of a 2 km high massif unit of the Taurus Mountains in the Apollo 17 landing site area. The landslide in the Taurus-Littrow region will provide an excellent opportunity to sample the massif materials during the Apollo 17 mission.

Unusual, light-colored markings in three mare regions (Mare Inginii on the farside, Mare Marginis on the eastern limb, and western Oceanus Procellarum) are interpreted as indications of chemical differences. These swirls may have been caused by alteration of the material by escaping gases at the antipodal areas of large and relatively young impact sites. Other albedo markings seen for the first time from orbit include: brightening of the surface area beneath the LM probably due to compaction; and darkening of the areas around the Rover tracks, probably due to destruction of the thin (less than 1 mm) photometric layer of the lunar surface.

Geologic interpretation of orbital photography is best done by correlation with remotely sensed data. Examples are given of successful correlation with data obtained by the geochemical sensors from orbit, e.g., the x-ray and γ-ray data. Photographic results may also be correlated with earth-based remote sensing; examples were given of good correlation between photogeologic interpretations and earth-based multispectral and radar studies. The ultimate value of photogeologic interpretation of the returned data is the extrapolation of knowledge gained by direct sampling to larger areas of the moon.

REFERENCES

Adler I. Trombka J. Gerard J. Lowman P. Yin L. and Blodgett H. (1972) Preliminary results from the S-161 x-ray fluorescence experiment (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 4–6. Lunar Science Institute Contr. No. 88.

Carr M. H. (1966) Geologic map of the Mare Serenitatis region of the moon. U.S. Geol. Surv., Misc. Geol. Inv., Map I-489.

Carr M. H. (1972) Sketch map of the region around candidate Littrow Apollo landing sites. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-63–25-65.

Doyle F. J. (1972) Photogrammetric analysis of Apollo 15 records. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-27–25-36.

El Baz F. (1971) Light colored swirls in the lunar maria. *Trans. Amer. Geophys. Union* **52**, No. 11, 856.

El-Baz F. (1972a) Geologic conclusions from Apollo 15 photography (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 214–216, Lunar Science Institute Contr. No. 88.

El-Baz F. (1972b) The cinder field of the Taurus Mountains. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-66–25-71.

Hinners N. W. and El-Baz F. (1972) Surface disturbances at the Apollo 15 landing site. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-50–25-53.

Latham G. Ewing M. Press F. Sutton G. Dorman J. Nakamura Y. Toksoz N. Lammlein D. and Duennebier F. (1972) Moon quakes and lunar tectonism—results from the Apollo passive seismic experiment (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 478–479, Lunar Science Institute Contr. No. 88.

McKay D. S. Clanton U. S. Heiken G. H. Morrison D. A. and Taylor R. M. (1972) Vapor phase crystallization in Apollo 14 breccias and size analysis of Apollo 14 soils (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 529–531, Lunar Science Institute Contr. No. 88.

Metzger A. E. Trombka J. I. Peterson L. E. Reedy R. C. and Arnold J. R. (1972) A first look at the lunar orbital gamma ray data (abstract). In *Lunar Science—III* (editor C. Watkins), pp. 540–541, Lunar Science Institute Contr. No. 88.

Pohn H. A. and Wildey R. L. (1970) Photoelectric-photographic study of the normal albedo of the moon. U.S. Geol. Surv., Prof. Pap. 599-E.

Strom R. G. (1965) Map, in Interpretation of Ranger VII Records. Calif. Inst. of Tech. JPL-TR-32-700, p. 32.

Swann G. A. Bailey N. G. Batson R. M. Freeman V. L. Hait M. H. Head J. W. Holt E. A. Howard K. A. Irwin J. B. Larson K. B. Muehlberger W. R. Reed V. S. Rennilson J. J. Schaber G. G. Scott D. R. Silver L. T. Sutton R. L. Ulrich G. H. Wilshire H. G. and Wolfe E. W. (1972) Preliminary geologic investigation of the Apollo 15 landing site. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 5-1–5-112.

Whitaker E. A. (1972a) An unusual mare feature. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-84–25-85.

Whitaker E. A. (1972b) Mare Imbrium lava flows and their relationship to color boundaries. In *Apollo 15 Preliminary Science Report*, NASA SP-289, pp. 25-83–25-84.

Wilhelms D. E. and McCauley J. F. (1971) Geologic map of the near side of the moon. U.S. Geol. Surv., Misc. Geol. Inv., Map I-703.