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Geology of Hadley Rille: Preliminary report

by

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Details of illustrations in this document may be better studied on microfiche

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ABSTRACT

Hadley Rille generally trends in directions that are controlled by pre-mare structures. The southern half of the rille, south of the Apollo 15 site, follows a mare-filled graben that is concentric to the Imbrium basin; however, the zigs and zags in the course are mainly north and east-northeast, directions that do not reflect pre-mare structures in adjacent highlands. The northern half of the rille follows a general direction that is parallel to pre-mare Imbrium-radial faults, is less sinuous than farther south, and intersects several fault-like features, all of which suggest some structural control along this part of the course. At the Apollo 15 site, the east rim is 30-40 m higher than the west rim as if the rille were a normal fault. The rille cannot be a simple fault, however, because the two sides do not match; instead, at bends, the outside has less curvature than the inside, which is partly attributed to recession of the rims by mass-wasting.

The rille owes much of its present profile to collapse, as if into a buried conduit or deep, narrow trough. Northwest of the Apollo 15 site, interruptions in the rille are interspersed with rimless, elongate bowl-shaped depressions that appear to be formed by collapse. Incipient slumps are clearly recognizable, and the mare surface is downbowed immediately adjacent to this part of the rille. South of this area the rille is continuous, but still the deepest parts are the widest. This is a different relationship from that shown by river channels in which depth and width vary inversely so that the cross-sectional area tends to remain constant. The geometry of the rille can, however, be explained by collapse with more extensive foundering at the widest points. Most of the rille has a V-shaped profile apparently formed by recession of the rims and coalescence of talus aprons from either side. Depth-to-width ratios increase toward the south, showing that the slopes of the rille walls steepen southward.

The possibility that the mare surface subsided differentially approximately 100 m after it crusted over is suggested by an unevenness of the surface, a cap of mare-like rocks on North Complex, a possible high-lava mark on the base of Mount Hadley, and grabens at the margin of the mare. Such a subsidence could have resulted from drainage into and along a lava tube that became the rille.

Regolith and the underlying mare basalt are exposed along the upper walls of the rille. Blocky talus derived from the outcrops occupies the lower parts of the rille walls. The rille is a depository for local impact ejecta, so that regolith is eroded off the rim and tends to collect at the bottom of the rille.

Details of the outcrops of mare basalt are well displayed in telephoto stereophotography of the southwest wall of the rille near the Apollo 15 site. Exposures there are mostly restricted to the upper 35 m of the wall, but locally extend as far as 60 m below the rim. Differences in aspects of the outcropping rocks suggest that more than one flow unit of basalt is present. Most of the outcrops are massive units, averaging at least 10 m thick. Some of these massive outcrops are pitted and break irregularly, others break cleanly along joints, and others show discontinuous horizontal planar parting. They vary also in albedo. Crude, subvertical columnar joints are present locally. One series of massive outcrops is characterized by inclined joints. Below this series is a well layered outcrop 8 m thick; several vertical fractures cut across more than one of the layers, suggesting the layers may be within the same cooling unit. Locally, above the massive outcrops, is a poorly exposed, dark, hackly-surfaced and crudely layered unit no more than a few meters thick. One light-toned slabby outcrop near the mare surface resembles shelly pahoehoe. Numerous talus blocks derived from the massive outcrops are 10 m across or more; blocks of basalt this large are rare on Earth, demonstrating that the lunar basalt flows are both thick and remarkably unjointed compared to terrestrial counterparts.

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The outcrop ledge is absent where the rille abuts Apennine massifs rather than mare basalt. Southward along the rille, the outcrop ledge in the upper walls of the rille thickens and is more continuous which suggests a regional variation in the thickness of mare strata. Soft regolith material above the massive outcrops also thickens southward, from 5 m at the Apollo 15 site to 15-25 m south of Hadley C; possibly pyroclastics are present in the south, in addition to a regolith produced by impact gardening.

Talus slopes below the outcrops show gentle subhorizontal benches, inflections, and concentrations of blocks which may indicate subtalus stratigraphy.

INTRODUCTION

Study of the sinuous Hadley Rille (fig. 1) was a primary goal of the Apollo 15 mission. The visit to the rille by the Apollo 15 crew produced a wealth of geologic data that will provide new constraints on hypotheses of origin of this impressive canyon. The origin of sinuous rilles has been one of the big puzzles of lunar geology. Pre-mission studies of Hadley Rille suggested to Greeley (1971), Carr and El-Baz (1971), and Howard (1971) that the rille can be explained best as a lava channel and collapsed lava tube; the rille is of enormous proportions, however, compared to possible counterparts on Earth. Other explanations proposed for sinuous rilles include erosion by water, derived either from a primitive hydrosphere (Firsoff, 1961) or from permafrost released by volcanic or impact heating (Lingenfelter and others, 1968; Schubert and others, 1970); erosion by ash flows (Cameron, 1964); surface collapse resulting from intrusive stoping (Fielder, 1965); fluidization of regolith by outgassing through fractures (Schumm and Simons, 1969; Schumm, 1970); or open fracturing (Quaide, 1965; Howard, 1971). Comments on the various hypotheses of origin are summarized in table 1.

Considerations of its origin aside, Hadley Rille offers a new perspective into lunar geology inasmuch as it acts as a

Figure 1. Apollo 15 metric-camera photograph of Hadley Rille. NASA photograph AS15-M3-0414.

Table 1. Major hypotheses of origin for lunar sinuous rilles

Possible origin or process	Major characteristics	Comments
Tectonic or fracturing origin (Quaide, 1965)	Many sinuous rilles parallel major fractures and are related to major regional tectonic trends. Rille walls are usually sharp and parallel.	These theories were based on telescopic observations; mature sinuosity, meanders, and goosenecks seen in subsequent Lunar Orbiter photos suggest that the majority of sinuous rilles are not of tectonic origin. Linear rilles and some rilles of very low sinuosity are almost certainly of tectonic origin. However, regional orientation and azimuth of flow may be controlled by fractures or tectonic grid systems (e.g. Hadley parallels both the radial and concentric fracture systems of the Imbrium basin, but is generally sinuous in nature.) In addition, fractures may modify rille walls. Hadley Rille winds irregularly in an arc of more than 180°; this precludes extension faulting or rigid plates, but could be explained by contraction of the material.
Erosion by volcanic ash flows (Cameron, 1964)	Terrestrial examples of trenches carved by volcanic ash flows are grossly similar to some lunar sinuous rilles. Volcanic ash combines with steam to form a turbulent density flow (nuée ardente) which moves down slope eroding a channel.	It is possible that some short lunar sinuous rilles were eroded by volcanic ash flows. However, terrestrial ash flow channels do not show the mature sinuosity, double channels, and considerable lengths characteristic of the majority of lunar sinuous rilles. The largest terrestrial trench (formed by the Kambara nuée ardente) is only 10 km in length whereas Hadley is over 100 km long and others are as long as 400 km. Behavior of ash flows in a vacuum is not well understood.
Fluidization (Schumm, 1970)	In simple experiments, emission of gas from vents of differing size and pattern through varying thicknesses of granular material fluidized the material and produced fluidization craters with low rims and flat floors. Coalescence of craters above a series of vents or emission of gas along a linear or sinuous vent produces a fluidization trough similar to many sinuous rilles.	These experiments may be oversimplified in terms of sinuous rilles. Many extremely sinuous rilles (Rima Plato II, Rima Prinz) could be interpreted as coalesced craters, but underlying fracture patterns would have to be extremely complex. Also, the width of the rilles and the exposed layering in rilles like Hadley suggest that fluidization would have to be a process capable of eroding the thick bedrock layer to appreciable and fairly regular widths. For Hadley, fluidization seems incompatible with the rille characteristics.
Water erosion (Schubert and others, 1970)	The striking similarity between lunar sinuous rilles and terrestrial river channels (mature meanders, goosenecks, and other features) suggests that water erosion may be a factor in the origin of rilles.	Behavior of water in a vacuum supports this mode of origin as shown by Schubert and others (1970), because a protective ice coating can be formed over the channel. However, the lack of water in returned Apollo samples argues strongly against the presence of water as a factor in sinuous rille origin.
Lava channels and collapsed lava tubes (Oberbeck and others, 1969; Kuiper and others, 1966)	Basaltic lava samples returned from Apollo 11 and 12 indicate that the maria are filled with lava. Since lava channels are known to be sinuous and are commonly bridged over to form lava tubes, the majority of lunar sinuous rilles may be related to this origin.	Detailed work on terrestrial lava tubes and channels shows considerable similarities to lunar rilles. Apparent lava tubes may be seen outlined in lunar flows; partially collapsed lava tubes, apparent lava channels, and combinations of these structures can also be seen. This evidence suggests that the majority of lunar sinuous rilles may be related in origin to lava flow channels and lava tubes.

window into the subsurface and exposes strata in cross section. The main intent of this report is to provide a description of the form of the rille and the materials exposed in the rille walls.

Hadley Rille is one of the freshest appearing of the Moon's sinuous rilles, and outcrops are abundant along the upper part of its walls. Compared to other sinuous rilles it is one of the longer and wider ones (fig. 2). Figure 2 (bottom) shows that it is typical in the ratio of its width to length.

Before the Apollo 15 mission, a description of the rille was given by Greeley (1971), and geologic maps of the area were prepared by Carr and El-Baz (1971) at 1:250,000 scale, Howard (1971) at 1:50,000 scale, and Schaber and Head (1971) at 1:25,000 and 1:12,500 scales. Figure 3 is based largely on the map by Carr and El-Baz, and figure 4 is updated from the maps by Howard and by Schaber and Head. In this report we discuss data learned subsequently, partly from detailed study of Orbiter V high-resolution photographs but mainly from results of the Apollo 15 mission.

The rille was visited or seen from four localities by Astronauts Scott and Irwin (stations 1, 2, 9a, and 10; fig. 4). In addition, many photographs were taken from the Apollo 15 command module which flew over the rille many times. The astronauts made excellent visual observations and descriptions, mainly on the ground, but also from orbit. Television was transmitted live from a camera mounted on the Rover, including zoom closeups of the rille walls. A series of photographic panoramas was taken from the ground using Hasselblad cameras with 60 mm lenses. The rille walls were photographed telescopically from the ground using a Hasselblad camera with a 500 mm lens. Sixteen millimeter motion picture photography of the rille was made during ascent of the lunar module from the lunar surface. The rille and surrounding region were photographed from orbit at various sun angles, using hand-held Hasselblad cameras and the automated metric camera and panoramic camera. Photographs from the last two cameras have so far been examined

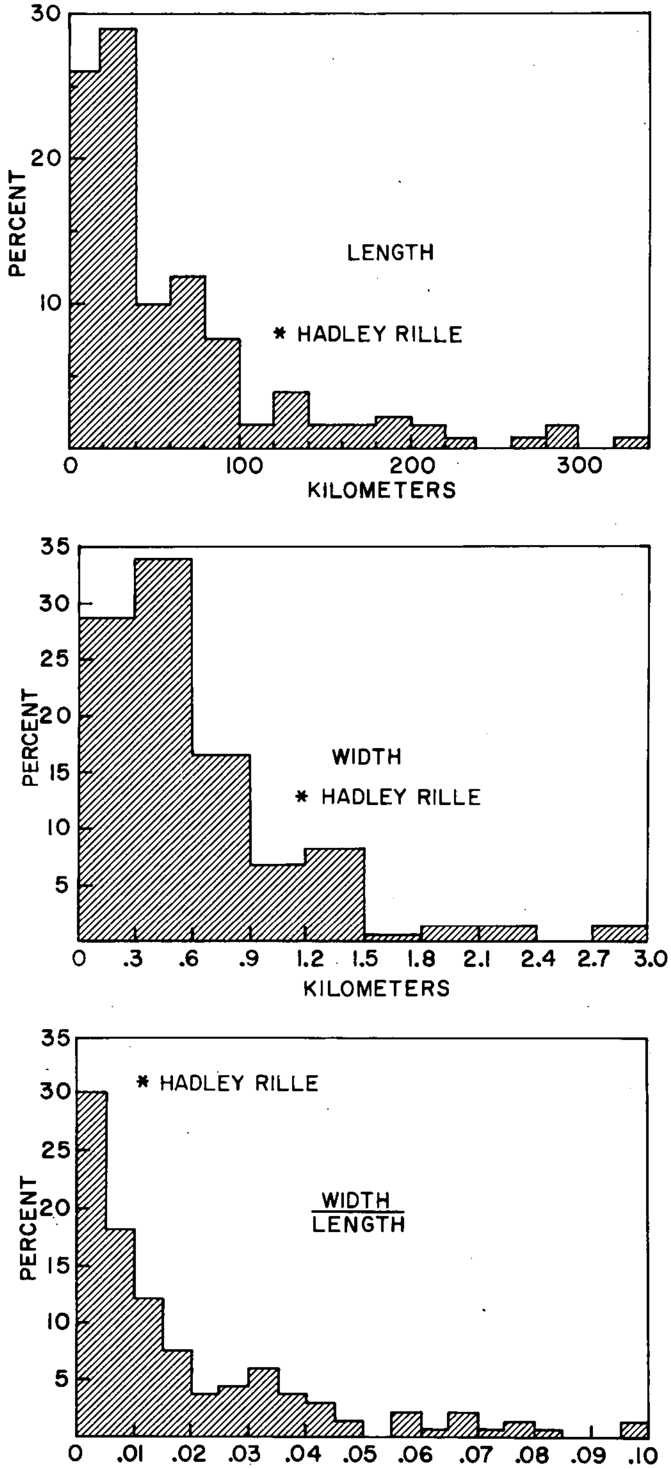

Figure 2. Histograms of the length, width, and width:length ratios of lunar sinuous rilles, showing how Hadley Rille compares with others. After Schubert and others, 1970.

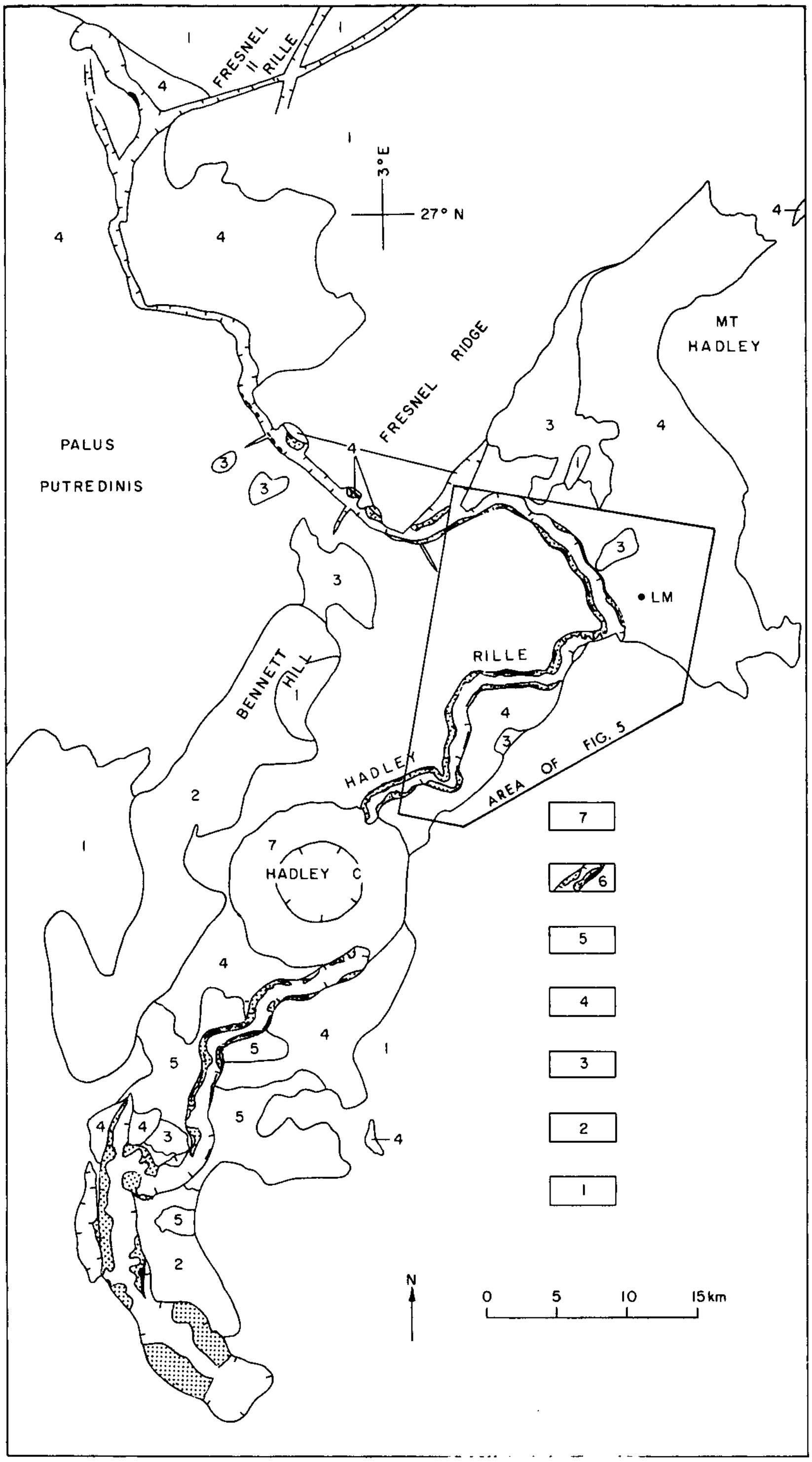

Figure 3. Geologic map of Hadley Rille, modified from Carr and El-Baz (1971). 1) Materials of pre-mare highlands. 2) Very dark mantling materials on highlands. 3) Material of low hills with same albedo as adjacent mare material. 4) Dark mare basalt. 5) Mare basalt with slightly higher albedo than 4. 6) Rille or depression. Outcrop shown in black. Bright rocky talus shown shaded. 7) Crater material.

in a preliminary fashion, and much additional data are promised when they can be studied in detail.

Many of the photographs can be viewed stereoscopically. Of further great value for geologic interpretations are preliminary topographic maps (figs. 4, 5) prepared photogrammetrically from the panoramic-camera photography (Wu and others, 1972; Swann and others, 1972). Figure 6 shows a generalized version of the topography from figure 5. Additional topographic mapping will add greatly to the geologic picture of Hadley Rille.

REGIONAL SETTING

Hadley Rille lies at the base of the Apennine Mountains, which form the southeast boundary of the large multi-ringed Imbrium basin. The mountains have prominent fault patterns trending northeast and northwest, respectively concentric and radial to Imbrium (Hackman, 1966; Carr and El-Baz, 1971). For much of its course, Hadley Rille follows a mare-filled graben valley, trending northeast between two high mountain massifs (fig. 3). Most of the rille is incised into mare material, but locally the rille cuts into the pre-mare mountains. Regional relationships indicate that the materials upon which the mare rock rests may include faulted pre-Imbrian rocks, ejecta of the Imbrium basin, and light plains-forming units such as the Apennine Bench Formation (Carr and El-Baz, 1971). To the northwest the mare plain and the rille extend through a gap in the mountains to join the main part of Palus Putredinis (the Marsh of Decay). Continuing north, the rille becomes shallower and indistinct, ultimately intersecting a segment of the linear rille Fresnel II.

The south end of the rille adjoins an elongate cleft-like depression that cuts into dark highlands. This cleft is compared to the source craters of terrestrial lava channels (Greeley, 1971; Carr and El-Baz, 1971). The southeast part of the cleft appears to be controlled by fractures related to the Imbrium basin (Carr and El-Baz, 1971), and the crew of Apollo 15 emphasize that the

EXPLANATION

COPERNICAN SYSTEM

Cc6, Cc5, Cc4, Cc3, Cc2, Cc1

CRATER MATERIAL
Debris of circular impact craters, classified in an age sequence according to freshness.
- Cc6 craters very sharp, very blocky, bright halo;
- Cc5 craters sharp, blocky; have bright halos;
- Cc4 craters sharp and somewhat blocky;
- Cc3 craters slightly subdued;
- Cc2 craters moderately subdued;
- Cc1 craters subdued, lack large blocks.

Rocks are derived from formations penetrated by crater

Csc

MATERIAL OF SECONDARY CRATERS
Fragmental debris produced from mare basalt by impact of secondary projectiles from Autolycus or Aristillus. Craters in south cluster are subdued and bowl-shaped; ejecta is blocky. Craters in north cluster are very subdued gentle depressions; no blocks; secondary origin uncertain

RAY
Very diffuse slightly bright area radial to Aristillus and Autolycus; boundaries gradational. May include a thin deposit of dominantly light-colored clasts, and possibly dark glass fragments

COPERNICAN AND ERATOSTHENIAN SYSTEMS

CEt

TALUS DEPOSITS
Blocky debris with some fines. Blocks as large as 20 m. Derived from ledgy outcrops of mare basalt. Basalt blocks tend to be more tan than fresh cliff exposures

CEd

DEBRIS OF MASSIF MATERIAL
Mainly fines; blocks rare. Fills floor of rille, rounding the bottom

ERATOSTHENIAN SYSTEM

Ec

CRATER MATERIAL
Mainly fine fragmental debris in and around shallow very subdued impact craters

ERATOSTHENIAN AND IMBRIAN SYSTEMS

EIm

MARE BASALT
Vesicular and vuggy basalt; locally has pahoehoe-like surfaces. Thickness unknown but locally exposed as thick as 60 m in Hadley Rille. Outcrops locally layered: some massive outcrops 20 m thick. Moderately to sparsely jointed. Albedo of outcrops 15-20 percent; variable. Mare surface covered by several meters of regolith except near bedrock exposures at lip of Hadley Rille

IMBRIAN SYSTEM

Ic

MATERIAL OF ST. GEORGE CRATER
Fragmental debris generally broken down to fines but locally including blocks. Produced from massif material by the impact that excavated St. George crater

PRE-IMBRIAN OR IMBRIAN SYSTEM

IpIm

MASSIF MATERIAL
Breccia and microbreccia that have dark and light clasts. Either pre-Imbrian impact breccias or impact breccia from the Imbrium impact, or both, mixed by down-slope mass wasting. Thick regolith with few blocks

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Contact, dashed where position uncertain

Slump fault, ball on downthrown side. Dashed where uncertain

Slope gradient

Gentle scarp, barb points downhill

Lineament

Traverse, solid where LRV tracks visible on panoramic camera photographs, dashed where inferred

Station location

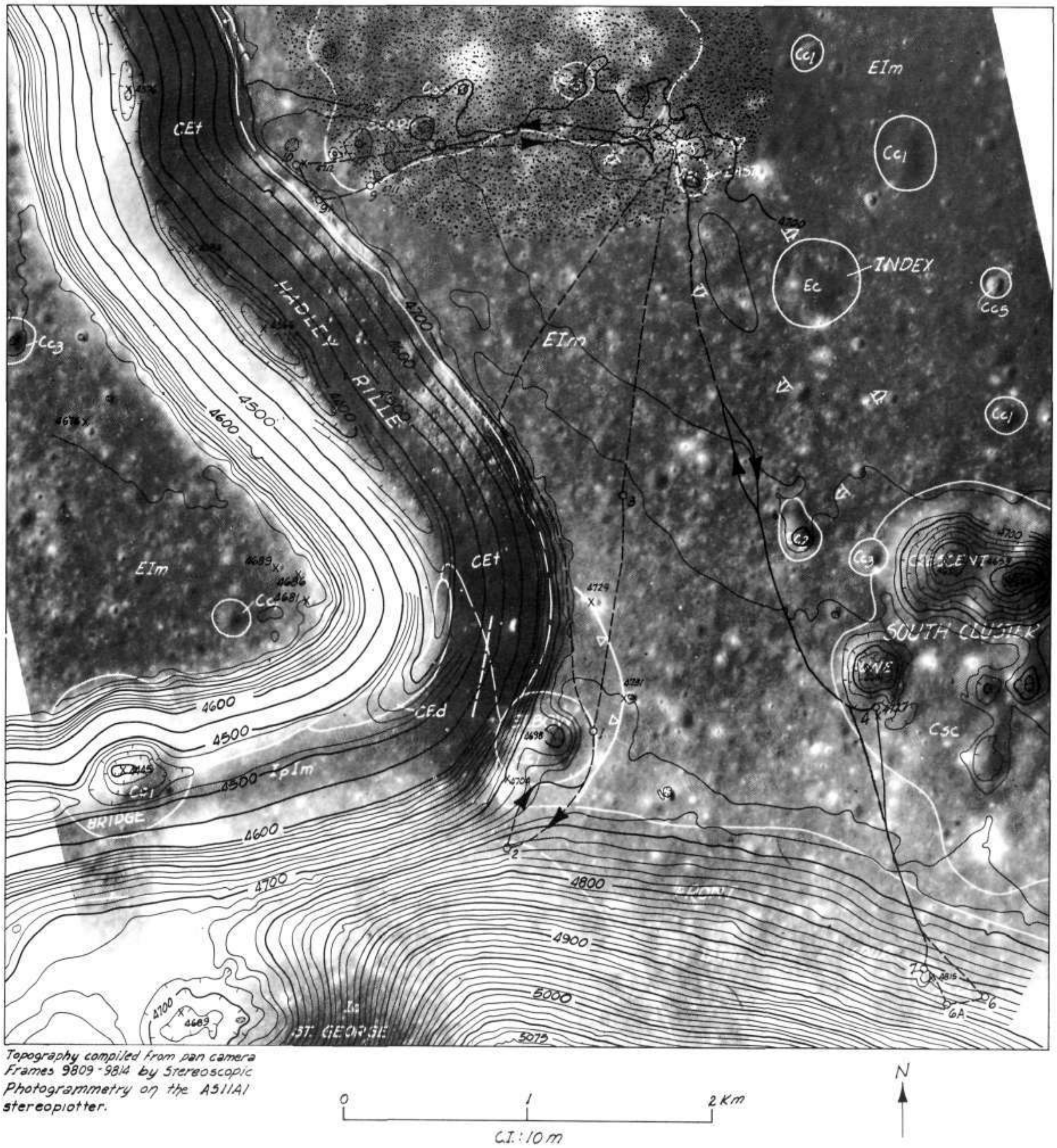


Figure 4. Geologic map of the Apollo 15 landing site (After Swann and others, 1972).

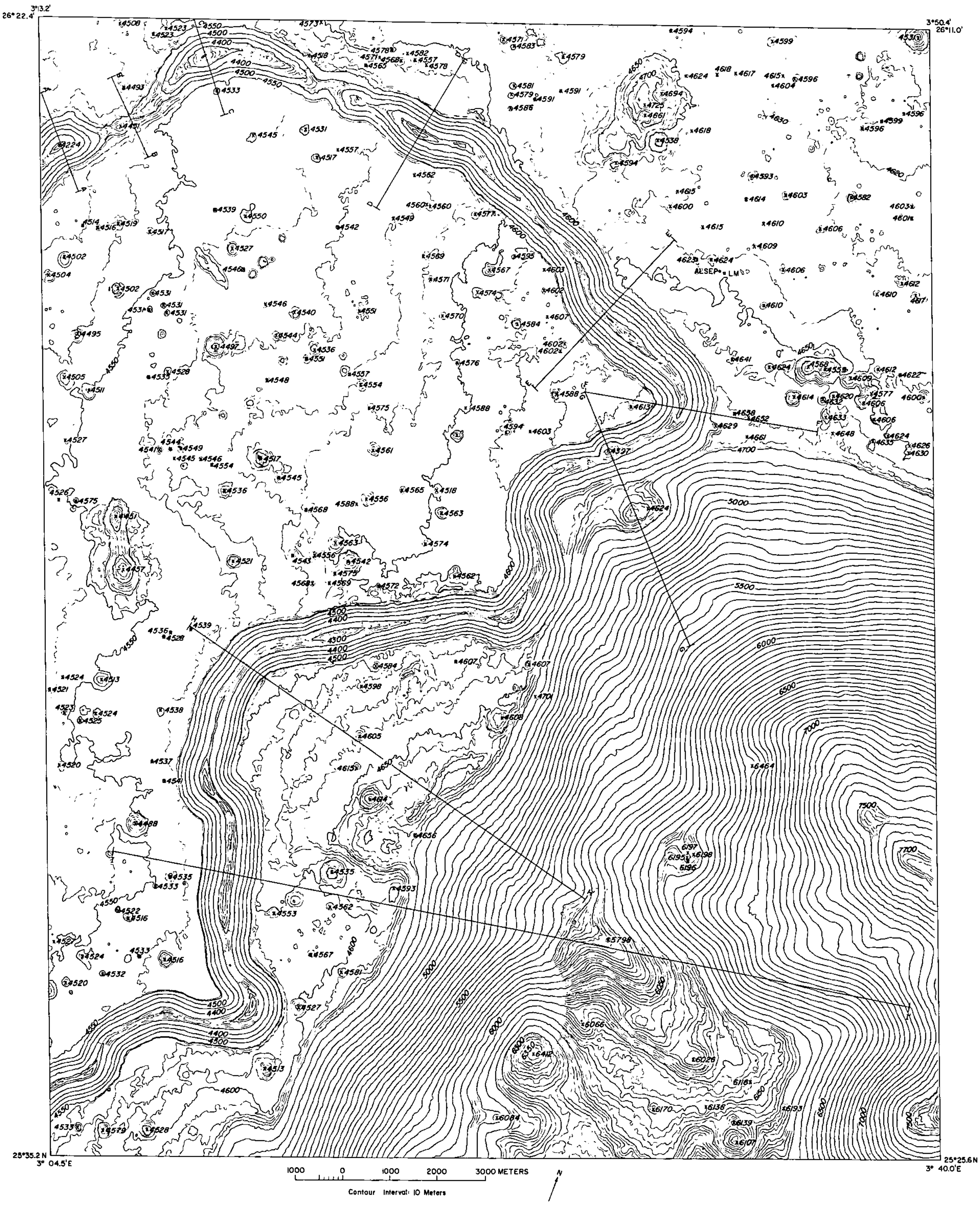


Figure 5. Contour map of part of Hadley Rille area (area is outlined in figure 3). (Map prepared photogrammetrically from Apollo 15 panoramic-camera photographs by Wu and others, 1972)

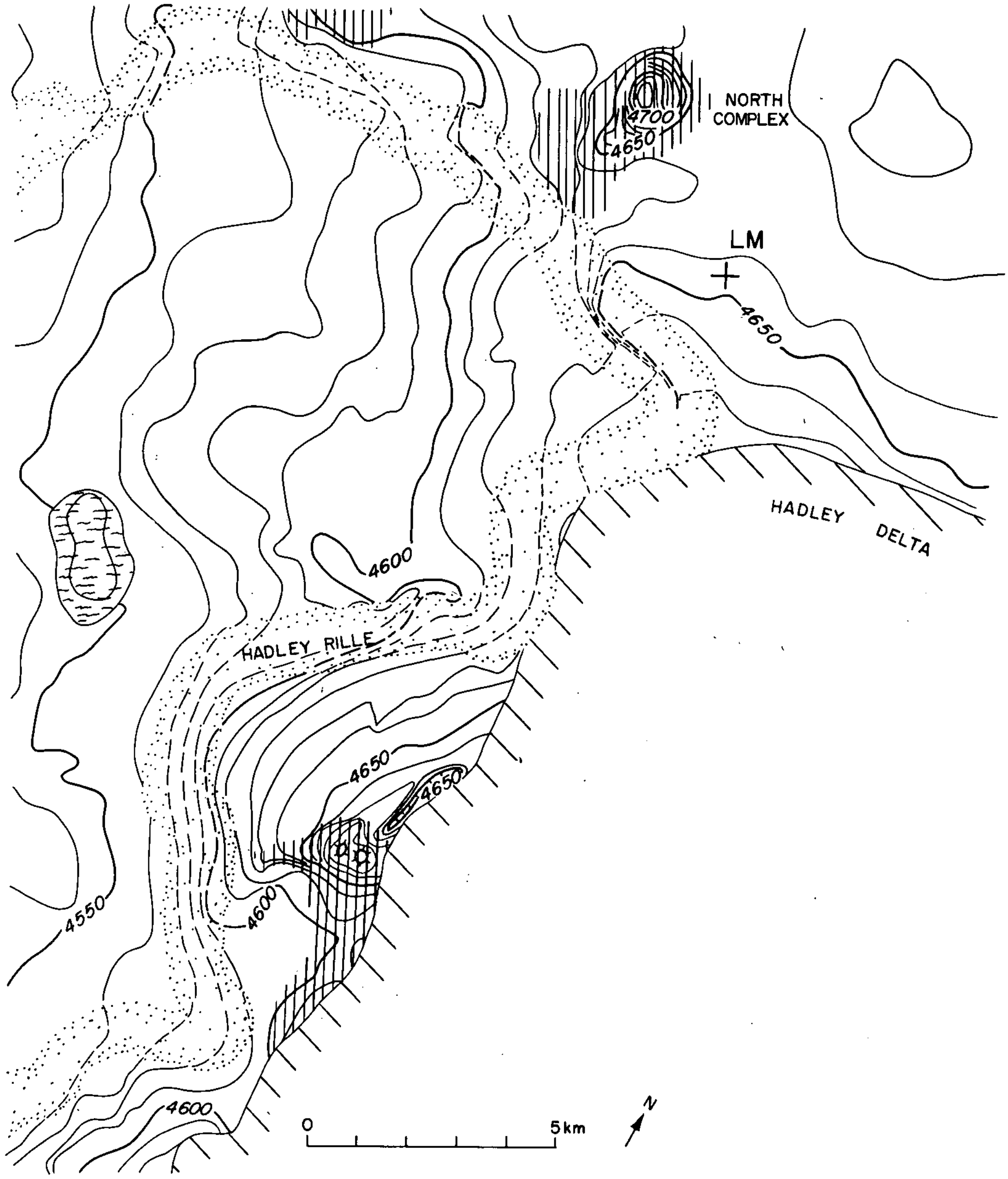


Figure 6. Map adapted from figure 5. Hadley Rille is stippled. In the mare area, contours are generalized (C.I.=10 m). The contours are extrapolated across the rille as dashed lines to contrast elevations and slopes on either side of the rille. Vertically ruled areas are dark low hilly regions, which were shown on pre-mission geologic maps (Carr and El-Baz, 1971) as hilly material coated by a dark mantle. Slant hachures indicate Apennine massif. Wavy horizontal pattern denotes materials of a crater doublet of probable volcanic origin (Carr and El-Baz, 1971; Howard, 1971).

cleft merges with a fracture that cuts far into the highlands to the southeast. The cleft is curved, and its northern part near the mare has a northerly trend that does not reflect fracture trends recognizable in the highlands.

Dark mare materials may have been derived, in part at least, from the cleft at the south end of the rille. In support of this contention, two small dark mare patches occur on either side of the north end of the cleft (fig. 3). Possibly related to the emplacement of mare material is a darkening of some of the adjacent older hills (fig. 3) (Carr and El-Baz, 1971). Hasselblad and metric-camera photographs show that the darkened highlands west of the rille--Bennett hill and the ridge south of it--are muted and smoothed. This suggests that a thin mantle of material, such as pyroclastics, may be responsible for the darkening. One Hasselblad color photo (AS15-97-13232) shows that the ridge is darker than the mare and that the abrupt albedo boundary coincides with the topographic break. This implies that the mare material overlaps the dark mantling material and is younger. A further indication of this superposition is observable at a bright east-facing scarp on Bennett hill (fig. 3). Bright highland material originally positioned beneath the dark mantle appears to be exposed by mass wasting. The downslope products of the mass wasting are not visible and are presumably buried under mare material. If the dark mantle consists of basaltic pyroclastics, these materials may have been deposited from early source vents in the graben now flooded by mare basalt flows.

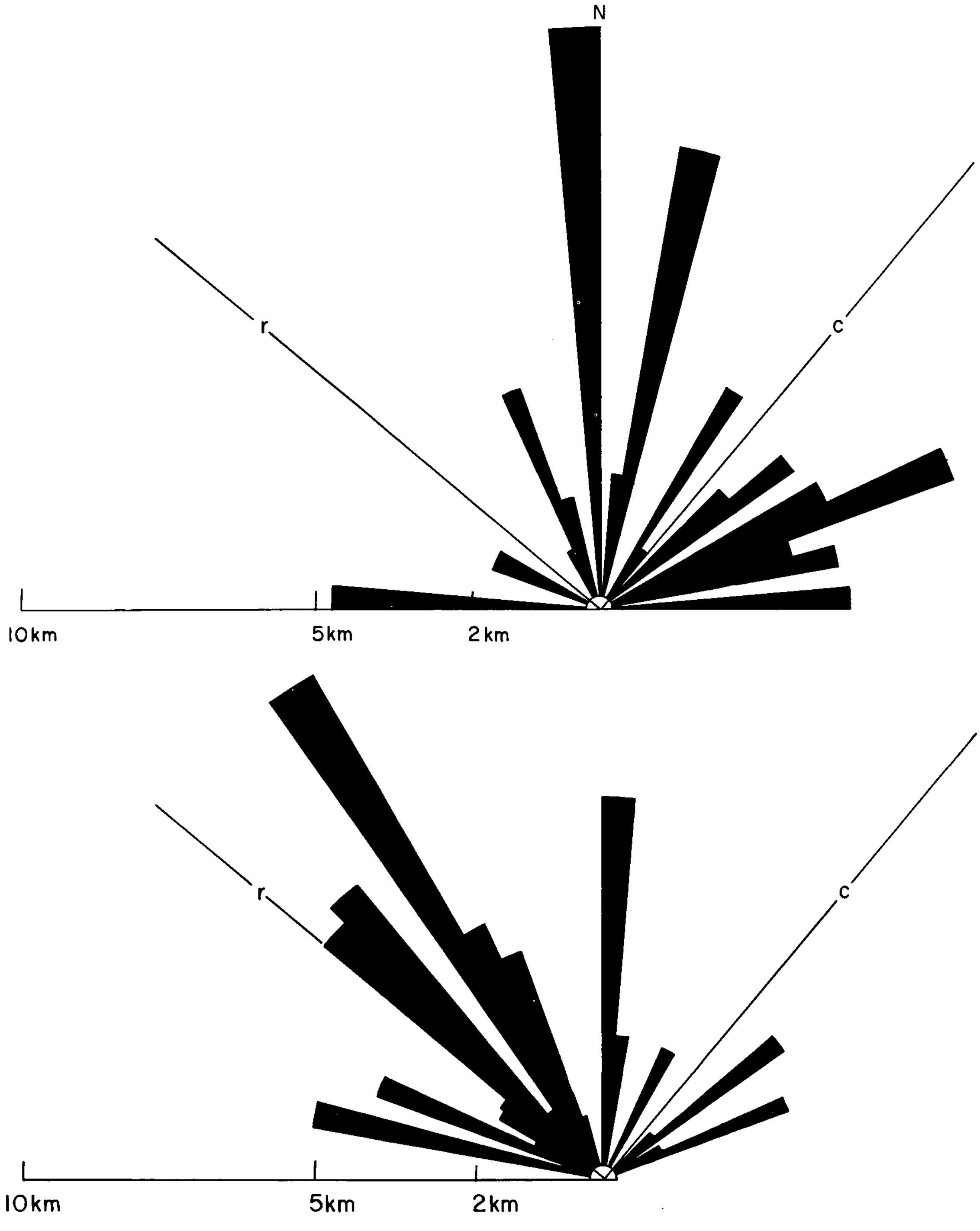
Near the landing site are several low dark hills (such as North Complex) that have the same albedo as surrounding maria. These hills may be coated with mare lava. One of the hills, 13 km southwest of the LM site, forms the apex of a fan-shaped surface on the mare, descending toward the west (fig. 6). The rille curves around the base of this fan. If the mare lava surface subsided soon after it congealed (Howard, 1971; Swann and others, 1972), then possibly the hill is coated by lava and the fan represents a differentially lowered part of the lava surface that remained higher than the mare surface. The fan is unlikely to be younger than the mare because its northern part is cut by a collapse area 1 km across which resembles an original lava-surface feature (Howard, 1971). The south edge of the hill drops abruptly 100 m to the mare surface, so the lava subsidence here suggested must be about 100 m. This is about the same amount of subsidence as suggested for North Complex and the base of Mount Hadley by Swann and others (1972). Differential subsidence of the mare lava also may explain the unusually high elevation of the mare just south of the LM, adjacent to Hadley Delta (fig. 6). Astronauts Scott and Irwin felt that the mare surface slopes down away from highlands both south and east of the landing site.

West of the rille is a crater doublet of presumed volcanic origin (Carr and El-Baz, 1971; Howard, 1971) (fig. 6). The topography of the mare is not modified adjacent to this doublet; apparently the craters were not an important source for mare lava.

EXTERNAL SHAPE OF THE RILLE

To test whether individual segments of the sinuous rille may parallel fault structures in the surrounding highlands, rose diagrams have been prepared showing cumulative lengths versus azimuth of the rille (fig. 7). Figure 7a shows that, for the southern half of the rille between the cleft and the Apollo 15 landing site, the dominant trends are north and east-northeast. These directions are at substantial angles to the trend of the circum-Imbrium basin graben which the rille follows, and are oblique also to Imbrium radial structures. This suggests that individual segments of this part of the rille are not controlled by structures oriented similarly to those in the adjacent highlands. The northerly trend of rille segments parallels part of the cleft-like depression.

Figure 7b shows that, in the northern half of the rille northwest of the Apollo 15 site, individual segments tend to



Figures 7a and 7b. Azimuth-frequency diagrams of Hadley Rille, by 5° increments. "c" and "r" represent trends of structures in the Hadley-Apennine area that are concentric and radial to the Imbrium basin. a) Southern part of rille, between cleft-shaped depression and Apollo 15 landing site. b) Northern part of rille, between Apollo 15 site and the intersection with Fresnel II Rille.

follow the main course of the rille, which is northwest and roughly parallel to Imbrium radial structures. This part of the rille therefore is less meandering and appears more closely related to structures in the highlands. The impression of structural control is enhanced by fault-like features that intersect this section of the rille (fig. 3). These features include a complex of intersecting troughs including Fresnel II Rille at the northwest end of Hadley Rille, and four small troughs near Fresnel Ridge. Alternative explanations for the four troughs are that they are distributary (Greeley, 1971) or tributary (Howard, 1971) lava channels.

In detail the course of the rille is smoothly curved. In any one reach the width of the rille is constant, so that at each curve the outside has less curvature than the inside. This is illustrated by the sharp bend at Elbow crater (fig. 4). This geometry cannot result from simple distension by fracturing, because the two sides do not match. Instead it can be caused by drainage and erosion in the rille, through carrying material along its course and by back wasting of the slopes.

In some areas the mare surface differs in elevation or in slope on opposite sides of the rille (fig. 6). The differences are emphasized by extrapolating contours of the mare surface over the rille. Near the Apollo 15 landing site, the contours break sharply at the rille because the mare on the east side is higher and slopes northeast instead of west. This marked difference from one side of the rille to the other can be seen also in photographs (fig. 8) looking across the rille from station 9a. These photographs were taken from a vantage point just below the northeast rim but show that the mare surface on the opposite side is visible for some distance, and so is lower. Elsewhere in figure 6 the break in elevation across the rille is smaller or indeterminate, but in every place where there is a break, the west side of the rille is lower.

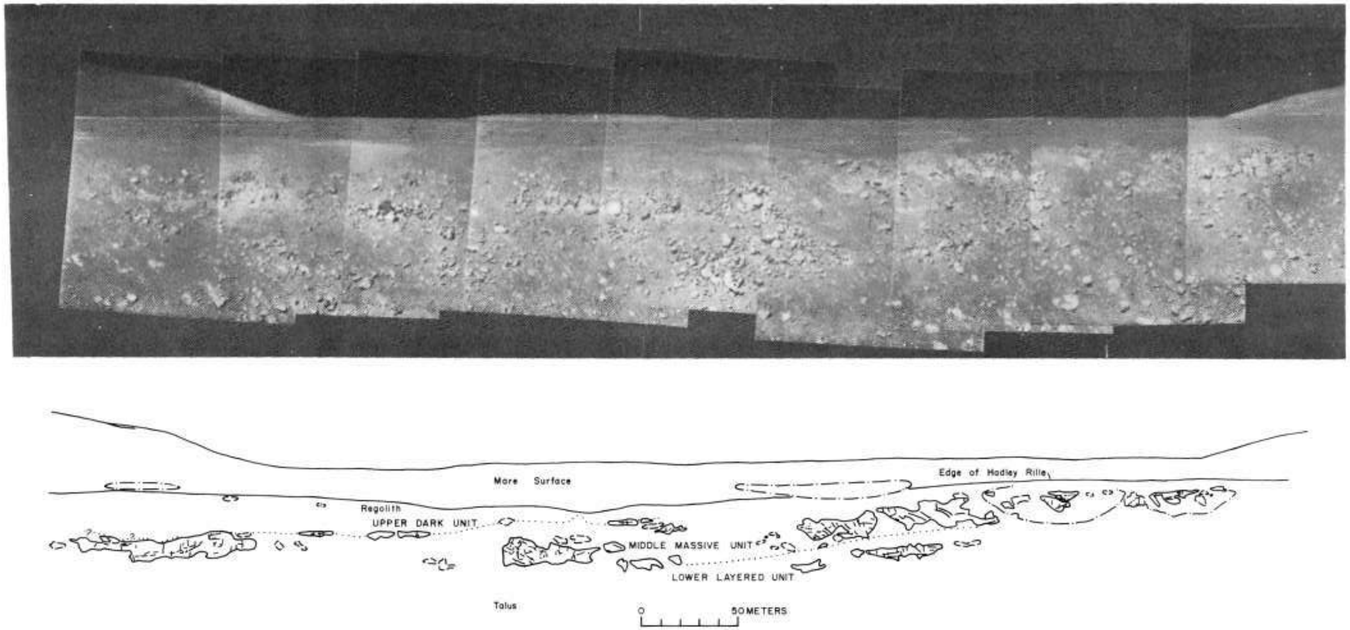


Figure 8. Top: telephoto mosaic of upper wall of the rille west of station 10 (a in fig. 18). Area shown is approximately 800 m wide. NASA photographs AS15-89-12099 to 12116. Bottom: map of same area showing outcrops (enclosed in solid lines) and possible outcrops (enclosed in dashed lines). Lines within outcrops indicate fracturing and layering. Dotted contacts indicate major units. Dash-dot lines indicates crater rims.

Subtle raised rims may be locally present along the rille. A gentle rise between Elbow crater and station 9a (fig. 4) shows on the topographic map (figs. 4, 6) and was described by the crew. It is uncertain, however, whether this rise is related to the rille or is instead a regional trend in the mare unrelated to and truncated by the rille. Elsewhere in the topographically mapped area (fig. 6), the presence of raised rims is uncertain.

INTERNAL SHAPE OF THE RILLE

The south half of Hadley Rille is characterized by a deep V-shaped profile, which appears to be a consequence of recession of the walls by mass wasting so that the talus aprons of the two sides coalesce (fig. 9). Thick rock ledges crop out in the upper part of the walls. Between the LM site and Fresnel ridge to the northwest, the rille is discontinuous and consists of a series of coalescing bowl-shaped depressions that are almost certainly due to collapse (Greeley, 1971; Howard, 1971). Some parts here are shallow and relatively narrow. The topographic map (Wu and others, 1972) shows that the marginal lip of the rille is lower and less distinct here than elsewhere, partly because the immediate mare surface slopes down toward the bowl-shaped depressions. This suggests that the mare rocks above the lip have slumped toward the rille. Beyond Fresnel ridge to the northwest, the rille is U-shaped in profile. Apparently the rille here is shallow enough that talus from the two sides does not coalesce.

Analysis of detailed topography of the part of the rille shown in figure 5 indicates an intriguing relation between depth and width (fig. 10); the rille is deepest where it is widest. This is an opposite relationship than that shown by river channels in which depth and width vary inversely so that the cross-sectional area remains approximately constant. It could result if Hadley Rille was formed by incomplete collapse of a buried tube, with more extensive foundering at the widest points.

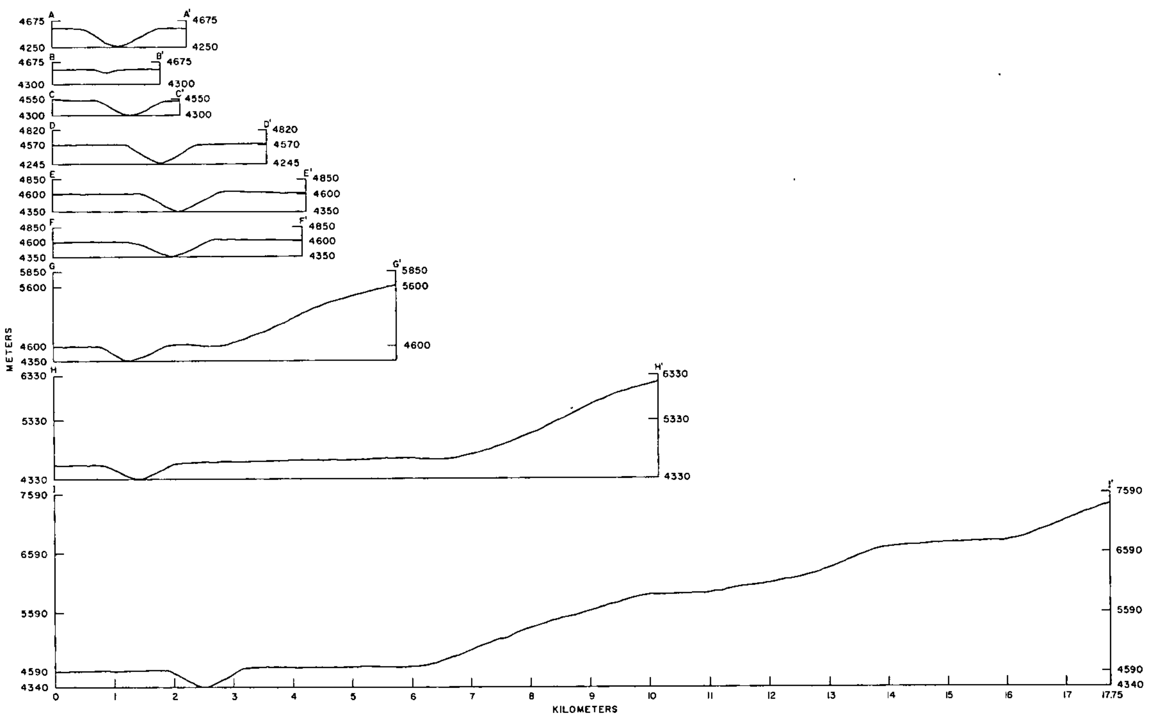


Figure 9. Topographic profiles across Hadley Rille. Lines of profiles are indicated in figure 5 (After Wu and others, 1972).

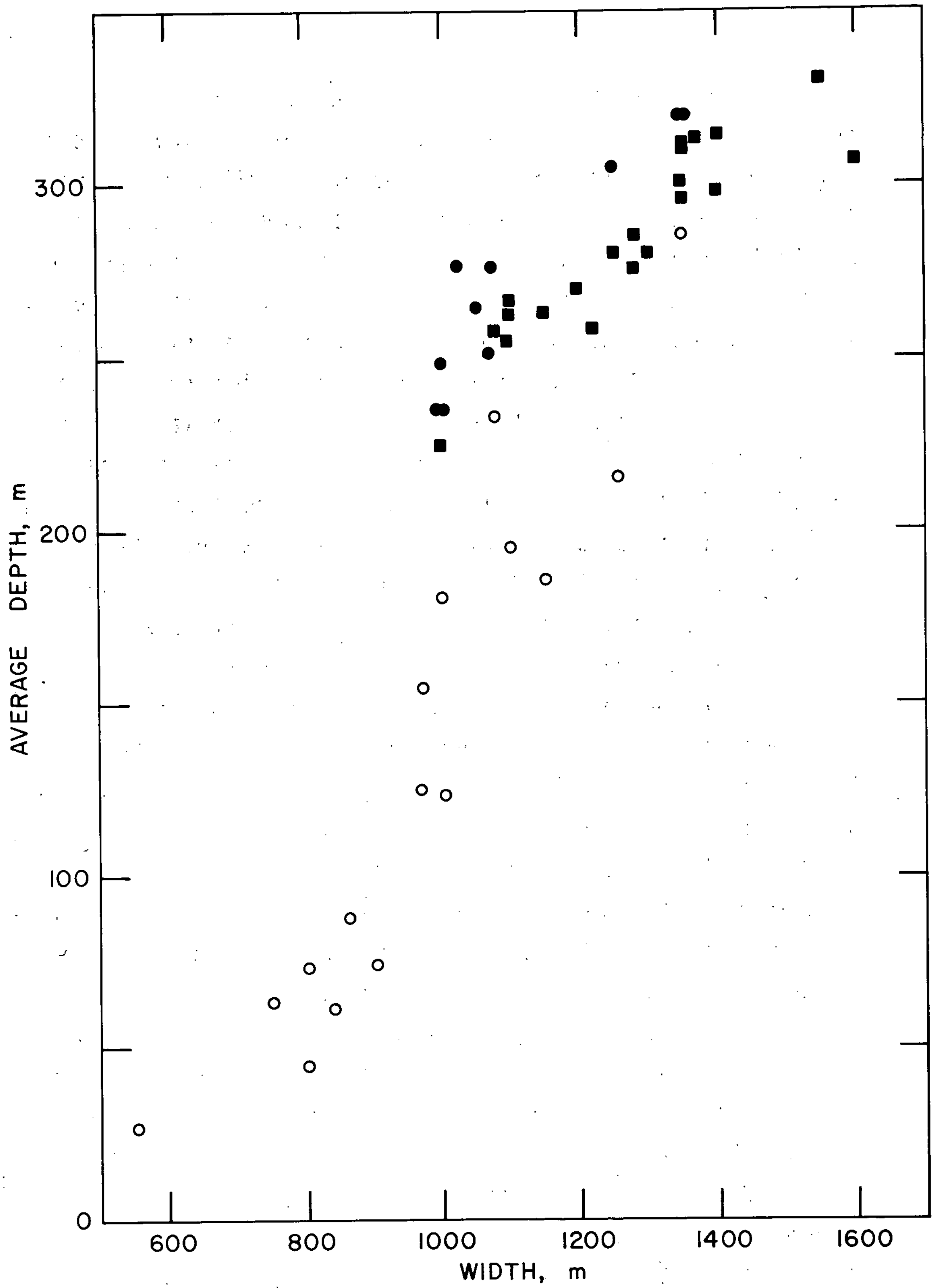


Figure 10. Graph of width of Hadley Rille in the area of figure 5 plotted against depth. Dots indicate localities along segment 1 (southern 8.6 km of the rille in fig. 5); squares indicate segment 2 (next 24.9 km); circles indicate segment 3 (northwestern 8.4 km).

The depth-to-width ratios are highest in the southern segment and lowest in the northwestern segment (figs. 9, 10). These differences indicate that the slopes of the rille walls steepen toward the south, where the photographs show that outcrops are thickest and most continuous. Depth-width relationships are shown separately in figure 11 for sharp bends in the rille, and for points where the rille abuts the Apennine massif. Both localities have lower depth-to-width ratios than normal for the segment of the rille in which they occur. An explanation for the decreased depth near massifs is that fine debris from the massif partly fills the rille, which indicates that the massif materials are more susceptible to mass-wasting into the rille than are the mare materials. This filling is shown near Elbow crater on figure 9 (profile G-G') and can also be observed where the rille abuts Fresnel ridge in Orbiter V photograph 106H.

South of Hadley C (figs. 3, 12) the walls of the rille have the characteristics illustrated schematically in figure 13. The rounded lip of the rille consists of easily eroded material with blocks, possibly regolith (fig. 13, unit A). The thickness of the easily eroded material, however, is 15-25 m, which is several times the average regolith thickness of 5 m. Below is a cliff unit (fig. 13, unit B) characterized by outcrops 5-25 m in length arranged in irregular lines parallel to the rim of the rille. The thickness of unit B appears to range from 30-60 m. There are suggestions of three subunits within this cliff unit. Below the cliff unit three surficial units make up the lower part of the wall. The uppermost (fig. 13, unit C) is composed of fine debris forming cones or aprons beneath the cliff. More than 90 percent of the material appears to be smaller than 5 m in diameter and contrasts markedly with coarser material below (fig. 13, unit D). Unit D is bright blocky talus characterized by blocks 2-10 m across that have collected at a bench or break in slope. The break in slope is seen in grazing sunlight and is also indicated by several boulder trails that terminate at this level.

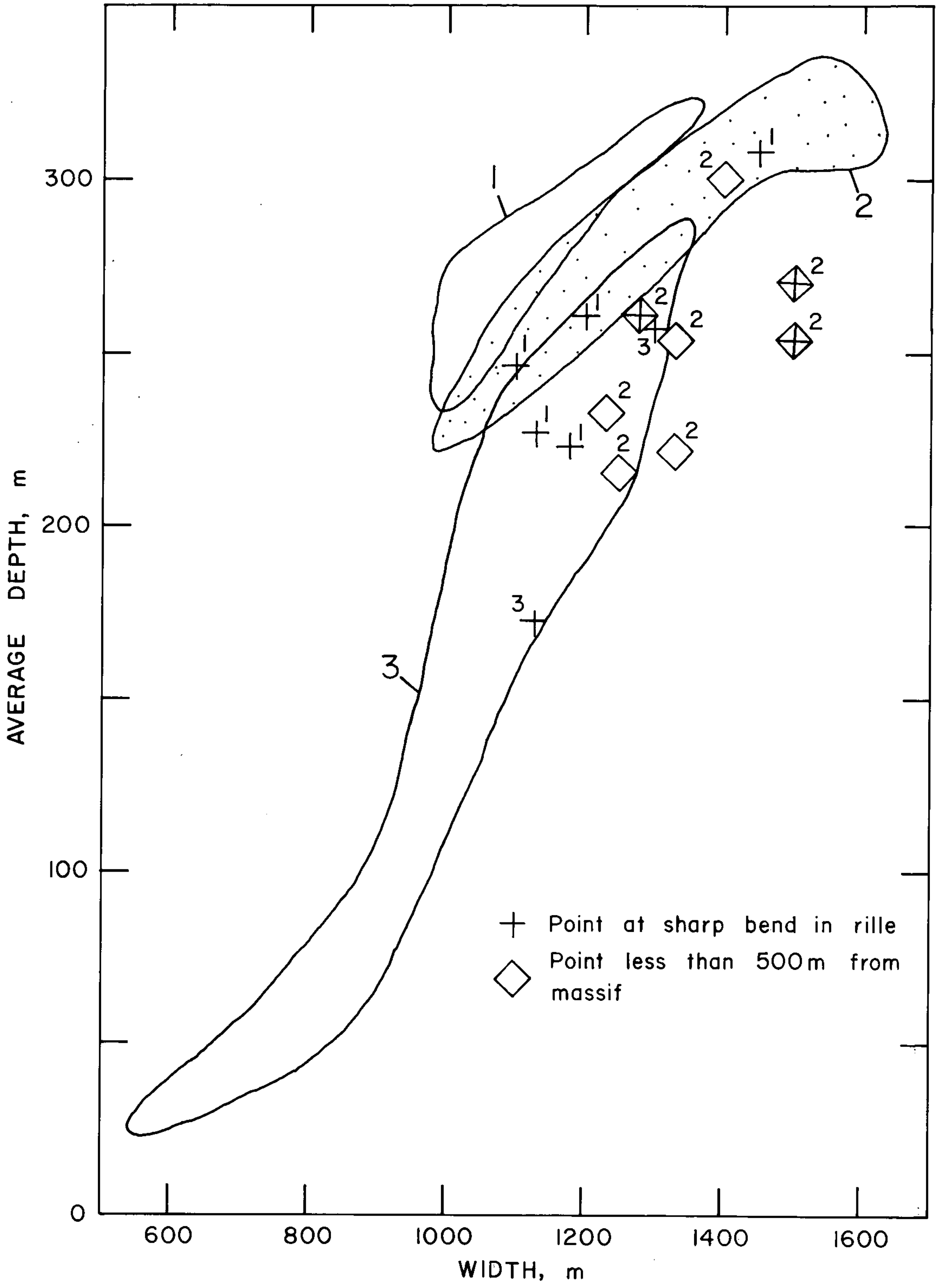


Figure 11. Width versus depth of Hadley rille at sharp bends or near massifs along the portion of rille shown in figure 5. Numbers indicate segment of the rille. Trends shown in figure 10 for the three segments are outlined. Note that the numbered points for the three rille segments do not coincide with the trends as determined in figure 10.

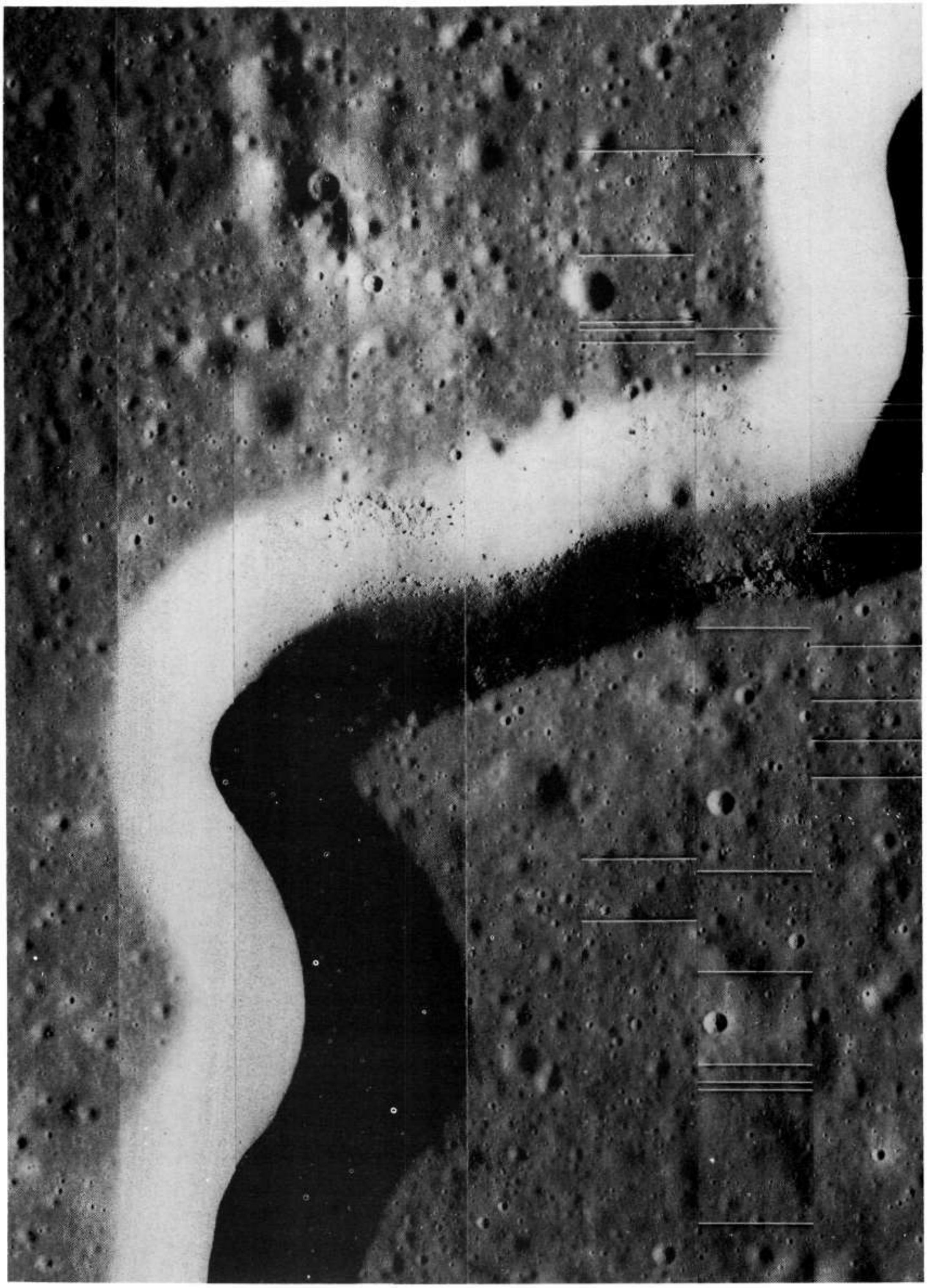


Figure 12. Part of rille south of crater Hadley C. Lunar Orbiter V frame 105H.

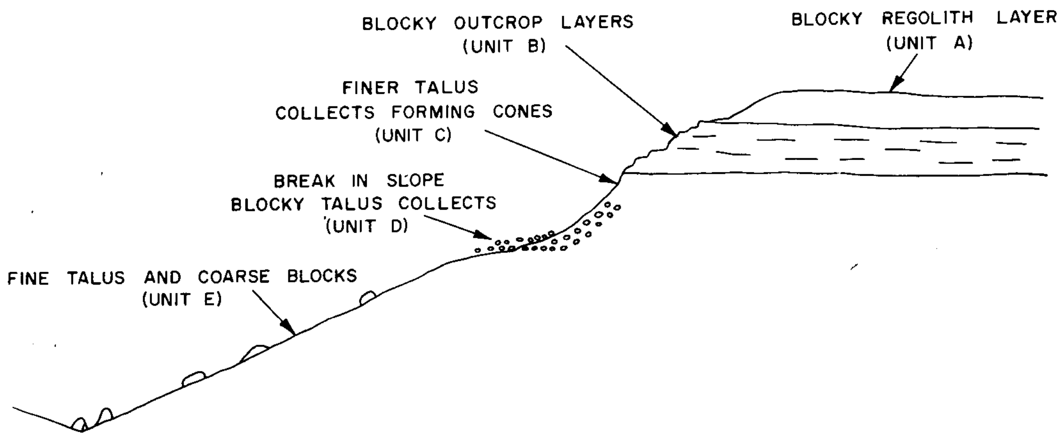


Figure 13. Schematic profile (exaggerated) showing characteristics of the rille wall south of Hadley C as seen in Lunar Orbiter V frame 105H. Rille is approximately 300 m deep.

Below the bench, the lower talus slope (fig. 13, unit E) includes fine debris as well as numerous blocks up to 20 m across. Tracks made by the blocks suggest that they originated at the cliff (fig. 13, unit B) in the upper wall.

Near the Apollo 15 site the characteristics of the wall are somewhat different (fig. 14). Soft regolith making up the rounded lip of the rille is only about 5 m thick. Below that are bedrock exposures to about 60 m from the top, but they are less massive and less continuous than those south of Hadley C. Talus extends to the bottom; fragments range in size from fine-grained soil to blocks as much as 30 m across. These materials are described in detail in the following section. In profile the rille resembles a V that has a rounded bottom and slightly concave sides (fig. 9). The walls are uneven in detail, as illustrated schematically in figure 14. Below the semicontinuous scarp formed by outcrops near the top there is generally a narrow, rather flat bench of coarse talus. This gradually slopes off, commonly to one or a series of convexities and inflections in the talus. The inflections tend to be elongate or semicontinuous along the rille.

MATERIALS IN THE RILLE NEAR THE APOLLO 15 SITE

Lithologies

The geologic unit below the regolith, along most of the length of the rille, is mare basalt. At the edge of the rille, the astronauts described, photographed, and sampled rocks from the top of the outcrop ledge and from the overlying regolith. Other sampling locations in the mare include Elbow and Dune craters, both of which were excavated to depths of 50 to 100 m (stations 3 and 8 away from the rille); and a small crater (station 9) near the rim of the rille (fig. 4).

The local section of mare rocks consists of vuggy to vesicular porphyritic basalts. These basalts were sampled at the top of an outcrop on the lip of the rille at station 9a and also at

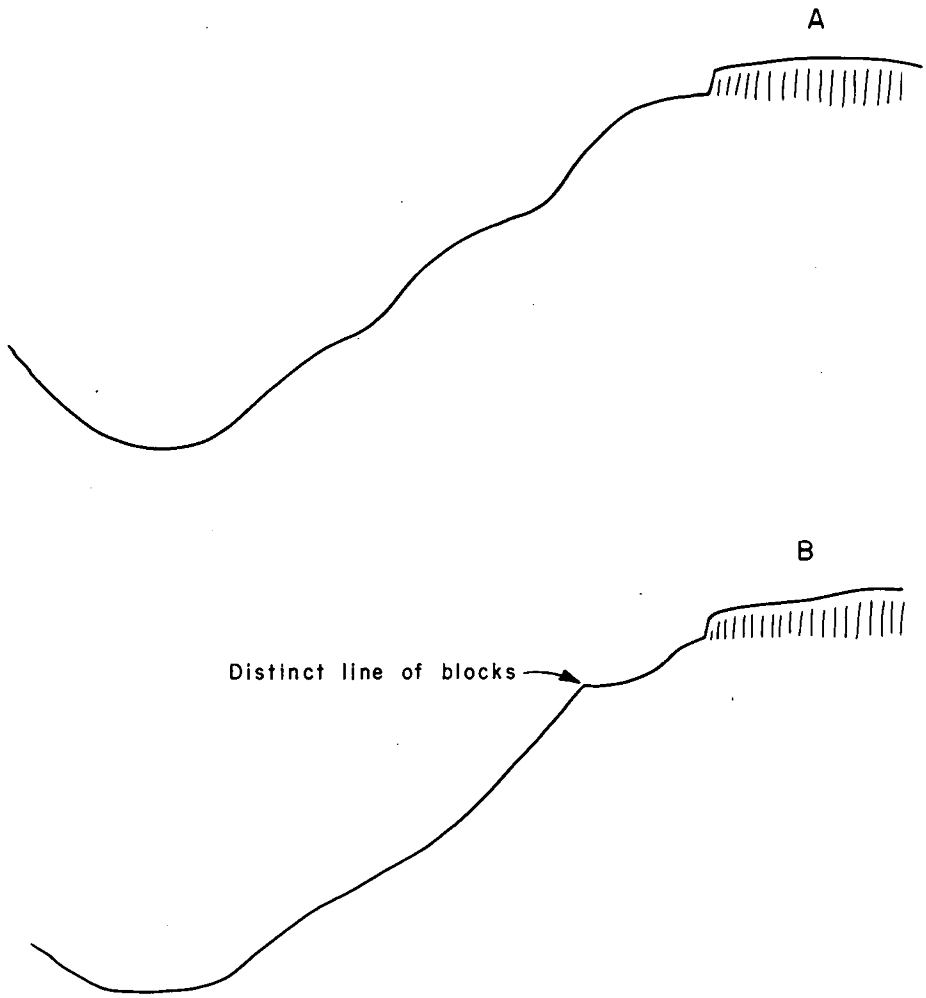


Figure 14. Profile sketches to show subtle benches and inflections on the northeast wall of Hadley Rille as seen in Apollo 15 panoramic camera photographs. Greatly exaggerated. "A" is 2 km northwest of stations 9a and 10; "B" is between station 9a and Elbow crater.

the rims of Elbow and Dune craters. To the extent that these crater rims consist of material excavated from the craters from depths of 50 to 100 m, this basalt may extend down that far. Mare basalt also comprises most or all of the fragments in the regolith above the lip of the rille at station 9a; and outcrops of hard basalt such as that sampled at station 9a are the obvious source of most talus blocks in the rille walls.

Material of the Apennine massif is present on the rille wall below St. George crater, and is distinguished from mare material by the general lack of blocks. This pre-mare material was sampled near the rille at station 2 and found to be breccia. The lack of blocks denotes a large degree of disintegration and a relatively thick regolith.

Regolith

At the top of the rille above the outcrops is an excellent cross section of the lunar regolith. The vertical distance of outcrops below the general mare surface indicates that the regolith is normally about 5 m thick and has an irregular base. As the rille is approached from the crest of the rim, the surface slopes gently downward and the regolith thins and becomes coarser. Within about 25 m of the sharp lip of the rille, regolith is essentially absent, so that numerous blocks and protuberances of bedrock 1 to 3 m across are exposed (fig. 15). This thinning is inferred to result from loss of material into the rille by impacts near the rim as shown in figure 16.

Rock fragments are more abundant in the vicinity of the rille rim than they are on the mare surface to the east. The increase becomes noticeable about 200 to 300 m east of the lip of the rille where most of the fragments are a few centimeters across. The size of the fragments increases markedly as the surface begins to slope gently down toward the rille, and bedrock is reached at the lip.

Figure 15. Large blocks and bedrock protuberances at the lip of the rille (station 9a). NASA photograph AS15-82-11147.

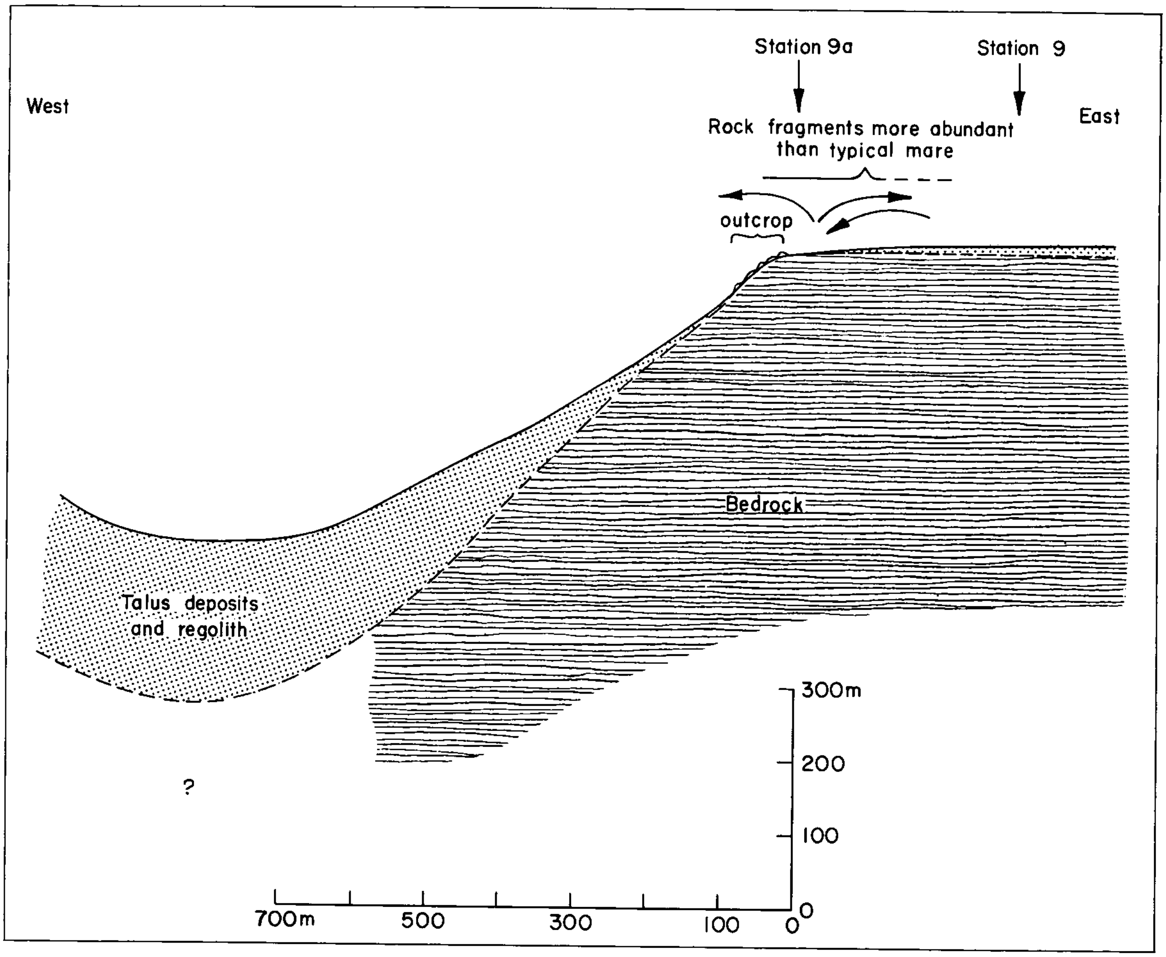


Figure 16. Diagram to illustrate winnowing of regolith into the rille. Impacts on the rim eject material in both directions, but the rim receives ejecta only from one side. The result is a net movement of regolith material into the rille.

The abundance of rocks in the 200 to 300 m belt along the rim of the rille is related to the depth to solid basalt. All craters greater than a half meter or so in diameter in the narrow belt along the lip penetrate through the fine-grained material and therefore the ejecta consist primarily of rock fragments. Beyond this belt, in the areas of normal regolith thickness, only those craters greater than 20 to 25 m in diameter penetrate through the regolith, and even then most of the ejecta consist of fine-grained material from craters up to 100 or so meters in diameter. Therefore the blocky nature of the 200 to 300 m belt along the rille is due to the nearby source of rocks in the area of very thin regolith along the rille rim.

At the bottom of the rille (fig. 17) the size-frequency distribution of debris is bimodal. Numerous large blocks are present, which are broken off the outcrops above and were large enough to roll over the fines to the bottom of the rille. The rest of the material is mainly fine grained, and probably consists mostly of the fines that have been ejected into the rille by cratering processes. Filling of the bottom by these fines has rounded the V-shape. Where the rille abuts against the pre-mare massif, its wall is made of fine-grained debris, and the bottom of the rille is shallower and flatter than elsewhere. This indicates a considerable amount of fine-grained debris derived from the massif.

Talus

The talus slopes that make up the main walls of the rille are blocky compared to many lunar landscapes (figs. 17, 19). Loose debris is approximately at the angle of repose. Recent instability of the blocks is shown by two tracks made by rolling boulders visible on the slope opposite Elbow crater; larger boulder tracks are evident farther south along the rille in Lunar Orbiter photographs. Talus is especially blocky where penetrated by fresh craters (fig. 19). The obvious source of most

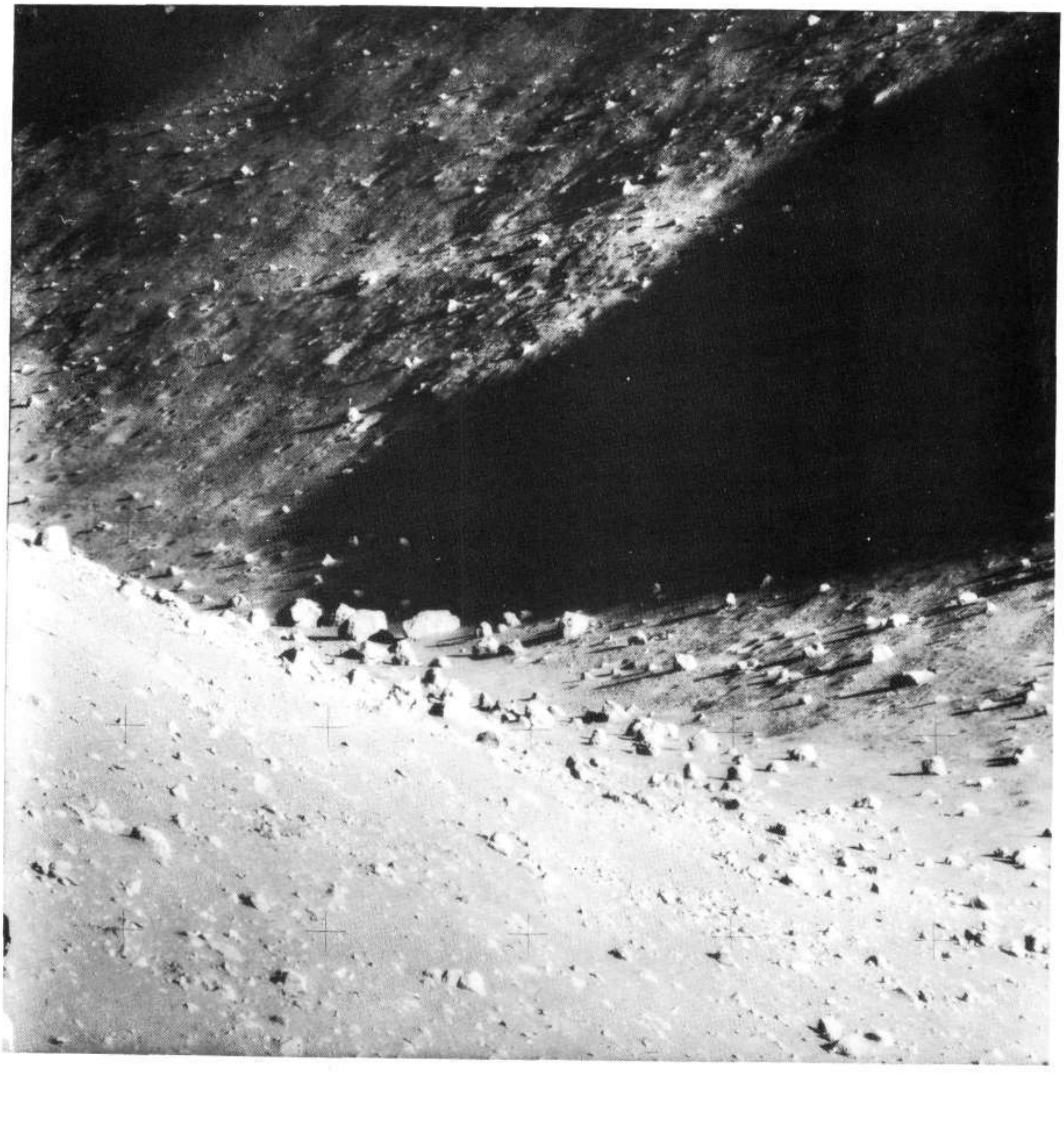


Figure 17. Bottom of the rille, looking north from station 2. The largest block is 15 m across. NASA photograph AS15-84-11287.

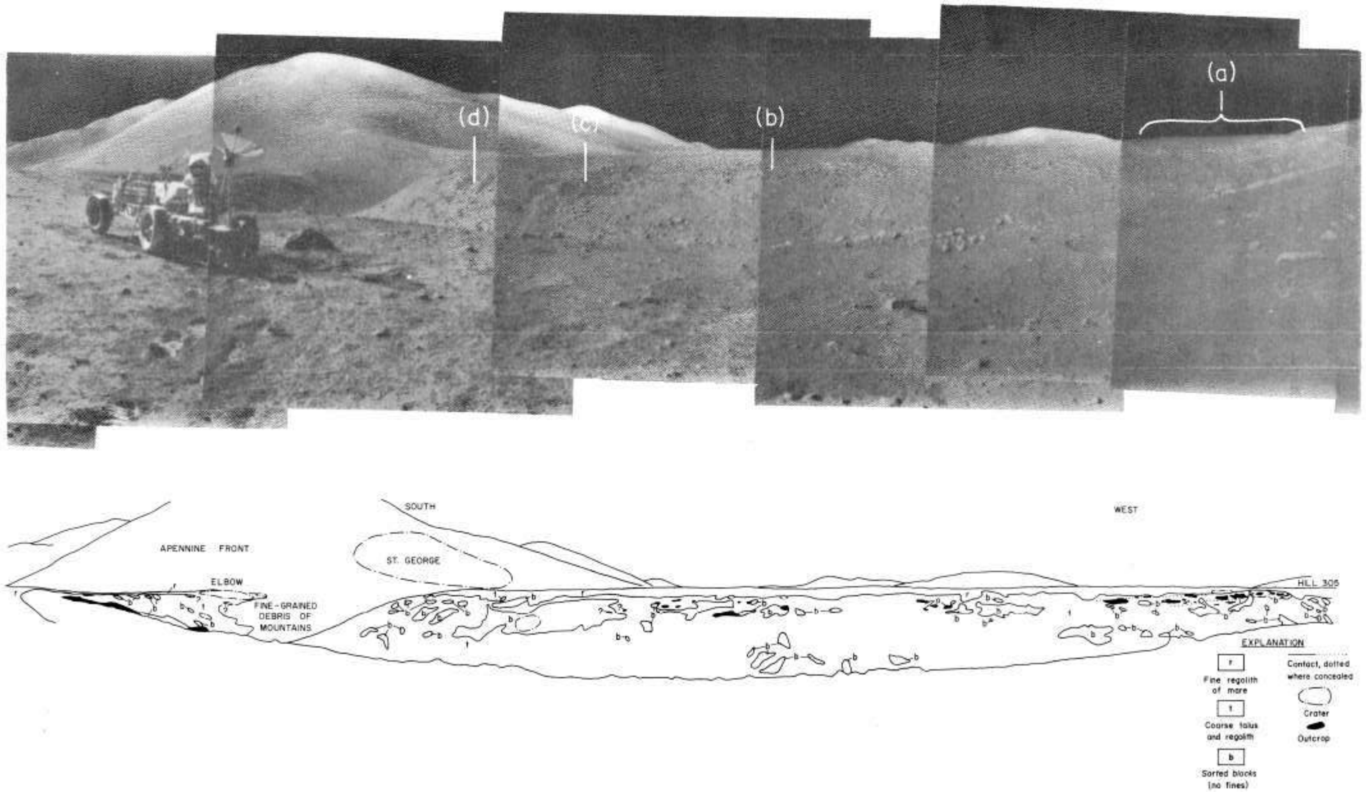


Figure 18. Top: panorama of the rille from station 9a. Letters indicate locations of telephoto illustrations as follows: a) figure 8; b) figure 27; c) figure 19; d) figure 20. NASA photographs AS15-82-11110 to 11120. Bottom: map of panorama showing distribution of outcrops.

Figure 19. Rocky 100 m crater (lower left) in the southwest wall of the rille (c in figure 18). Lip of rille is just above the blocky areas, and beyond is the mare surface. Large block at upper right, with elliptical cavity, is 16 m across. NASA photograph AS15-89-12069.

coarse talus is the outcropping ledges of mare basalt near the top of the wall. Loose blocks that lie above the level of outcrops can be accounted for as blocks produced by impact gardening.

Outcrops and blocky talus both are absent below the Apennine front and St. George crater. A few large blocks on this slope are visible from station 1 but most of these are directly opposite Bridge crater and probably were ejected from Bridge crater on the opposite side of the rille. At least one boulder that had rolled down the slope was described by the astronauts. The contact in the rille wall, between the mainly fine-grained debris of the Apennine front and the blocky talus derived from mare rock, extends under Elbow crater (figs. 4, 18 bottom), suggesting that at Elbow crater the Apennine material dips shallowly under the mare fill. The section of ledgy basalt that provides blocky talus thins southward under Elbow crater.

The blocky talus deposits are commonly more poorly sorted and contain a larger component of fine-grained debris as compared to talus slopes on Earth. This difference is undoubtedly due to impact comminution of the lunar talus, and to the addition of fine-grained ejecta from the mare surface beyond the outcrops in the walls of the rille. Many patches of talus in the rille have accumulated so recently, however, that fine-grained debris does not fill the interstices (figs. 19, 20). Where aligned with fractured outcrops, some of these block fields give the appearance of being jumbled but not of having moved far from their source, similar to fields of frost-heaved blocks that cover outcrops on some terrestrial mountain peaks. In other patches, blocks have accumulated on gentle benches or inflections in the slope, which mark either old craters, or possibly topography that is controlled by underlying stratigraphy or structure. As seen in figure 18 (bottom), many accumulations of blocks are elongate horizontally, either along outcrops or discontinuous benches. Near the top of the rille wall, horizontal lines of blocks in places underlie finer regolith, and represent rocks that are apparently close to

Figure 20. Wall of rille across from Elbow crater, looking south from station 9a, (d in fig. 18). Large layered block is 30 m long. NASA photograph AS15-89-12081.

their bedrock source. On the northeast wall there is commonly an accumulation of blocks on a bench just below the outcrop scarp, and farther down the wall blocks are commonly concentrated on the steep lower parts of local convexities in the slope. A few patches of blocks on the opposite wall (fig. 18) are elongate down the slope like stone stripes on Earth.

Several blocks in the talus are more than 10 m across. For example, the largest blocks in the bottom of the rille in figure 17 are 10 to 15 m across. The large irregular block near the top of the wall in figure 19 is 16 m across. The layered rock in figure 20, now split by fractures, is 30 m long and 8 m across the layering. A block half way down the rille wall south-southwest across from station 9a is 15 x 18 m, and two blocks at an equivalent level to the west-southwest across from station 9a are 11 x 14 m and 10 x 11 m. The largest blocks are about the same size as, or a little larger than, the thickness of the unbroken outcrops (figs. 21, 22). Unbroken blocks of basalt this large are uncommon on Earth, demonstrating that these lunar basalt flows are both thick and remarkably unjointed compared to many terrestrial counterparts. The maximum size of talus blocks offers a potential means of estimating the minimum thickness of the source layers all along the rille.

The blocks in the talus show a variety of shapes and surface textures in telephoto pictures. Future detailed study of these offers promise of a better understanding of structures in lunar basalt flows and also of processes of lunar weathering and erosion. For example, one subrounded boulder contains many large cavities--apparently vesicles--20 to 50 cm in diameter. The surface of one small block has several crescentic ribs that resemble ropy pahoehoe. Many blocks are layered; one of the best examples is the large one in figure 20. Vesicular layering in a block was described at station 9a by the astronauts. One large block near the top of the talus appears to be bounded by columnar joints (a in figure 23). A rimmed elliptical cavity 3 x 5 m across occurs

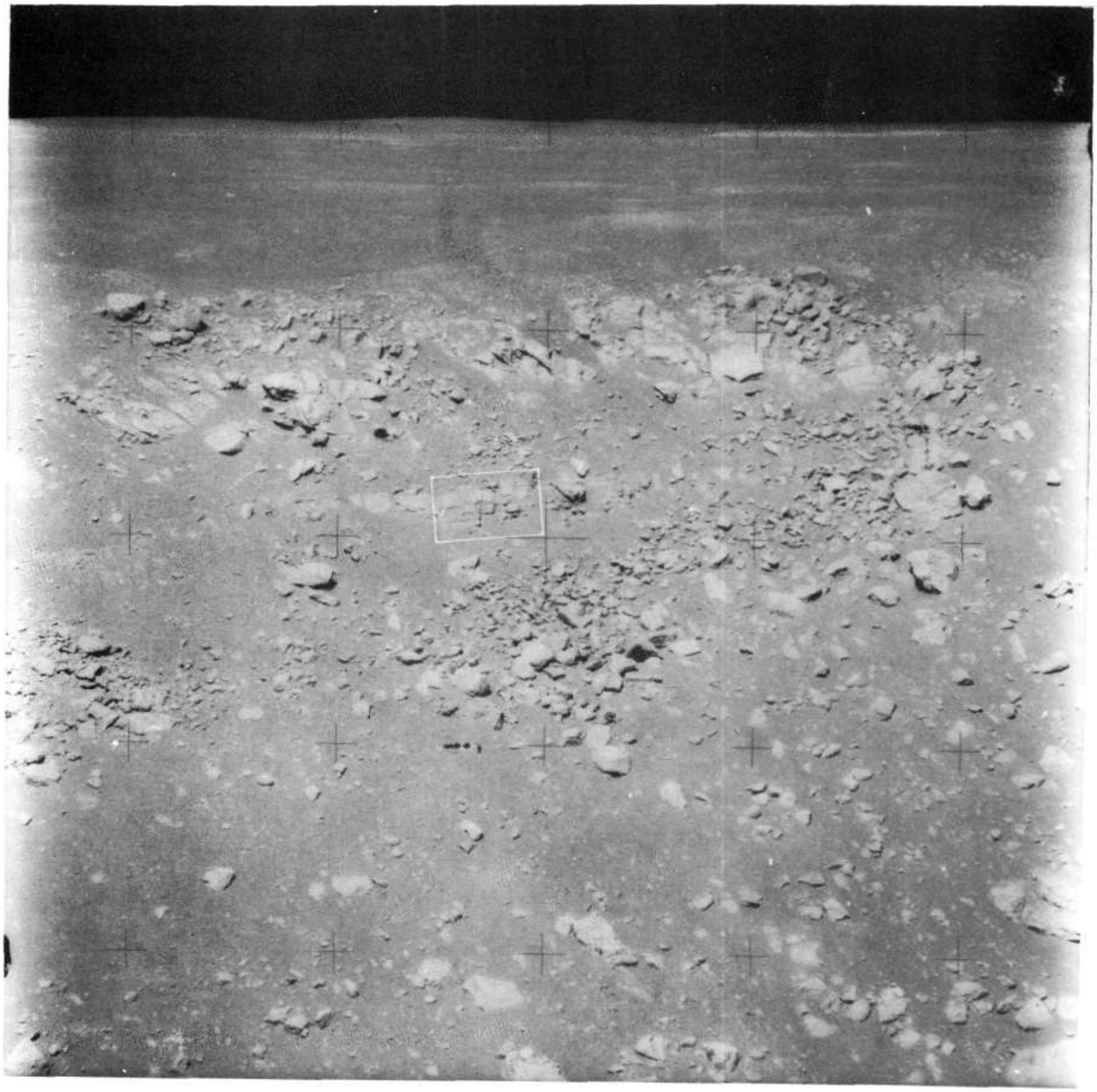


Figure 21. Outcrops in the central part of the area shown in figure 8. Total thickness of out-cropping units is approximately 35 m. A massive light-toned unit with northwest-dipping fractures overlies a darker layered unit. Part of layered outcrop indicated is shown in figure 26. Talus blocks have accumulated on a bench beneath the outcrops. Subdued crater on mare surface just beyond the rille is about 130 m across. NASA photograph AS15-89-12157.

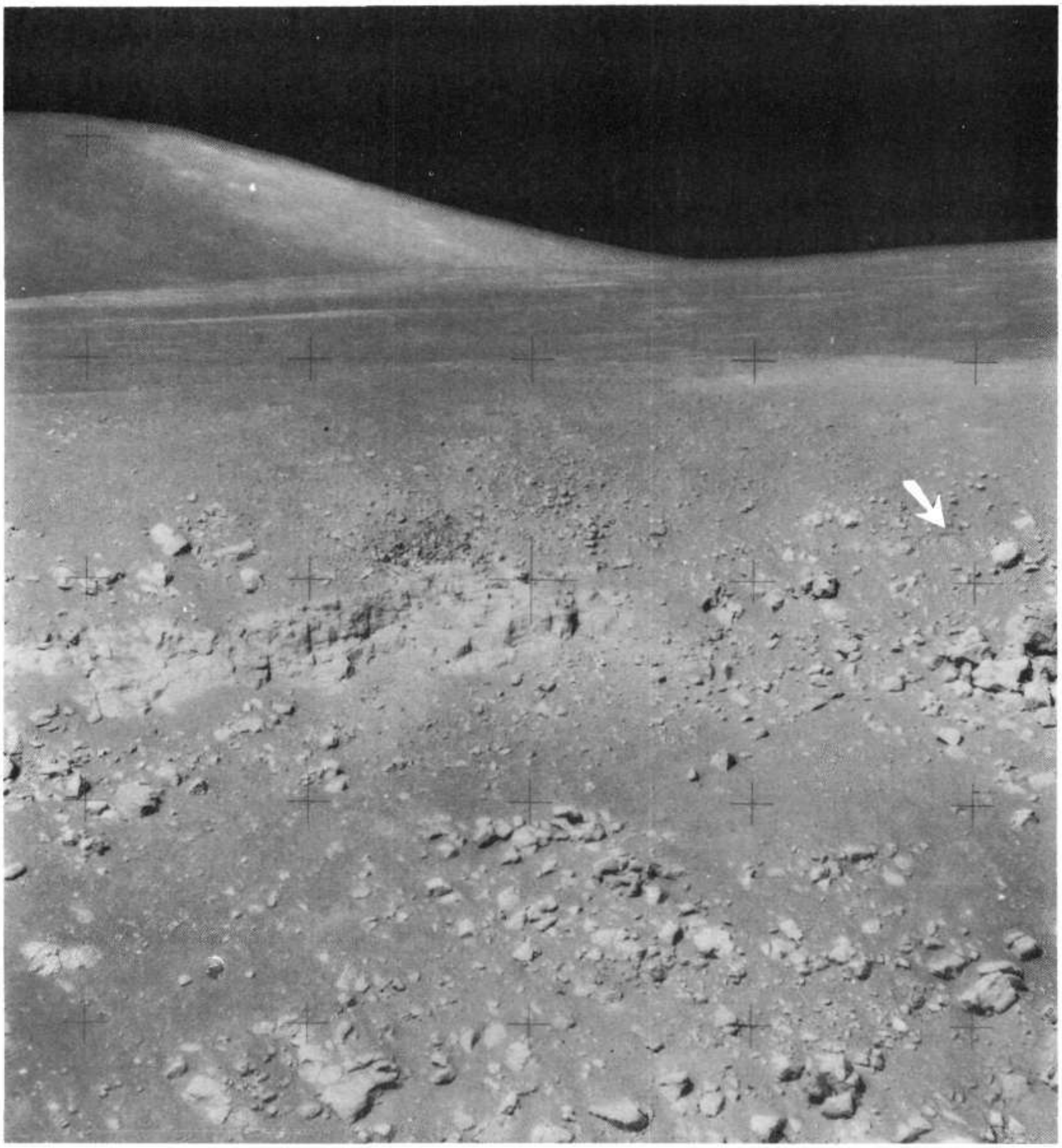


Figure 22. Outcrop approximately 20 m thick at left end of figure 8. Arrow points to thin layered outcrops of upper dark hackly rock. NASA photograph AS15-89-12115.

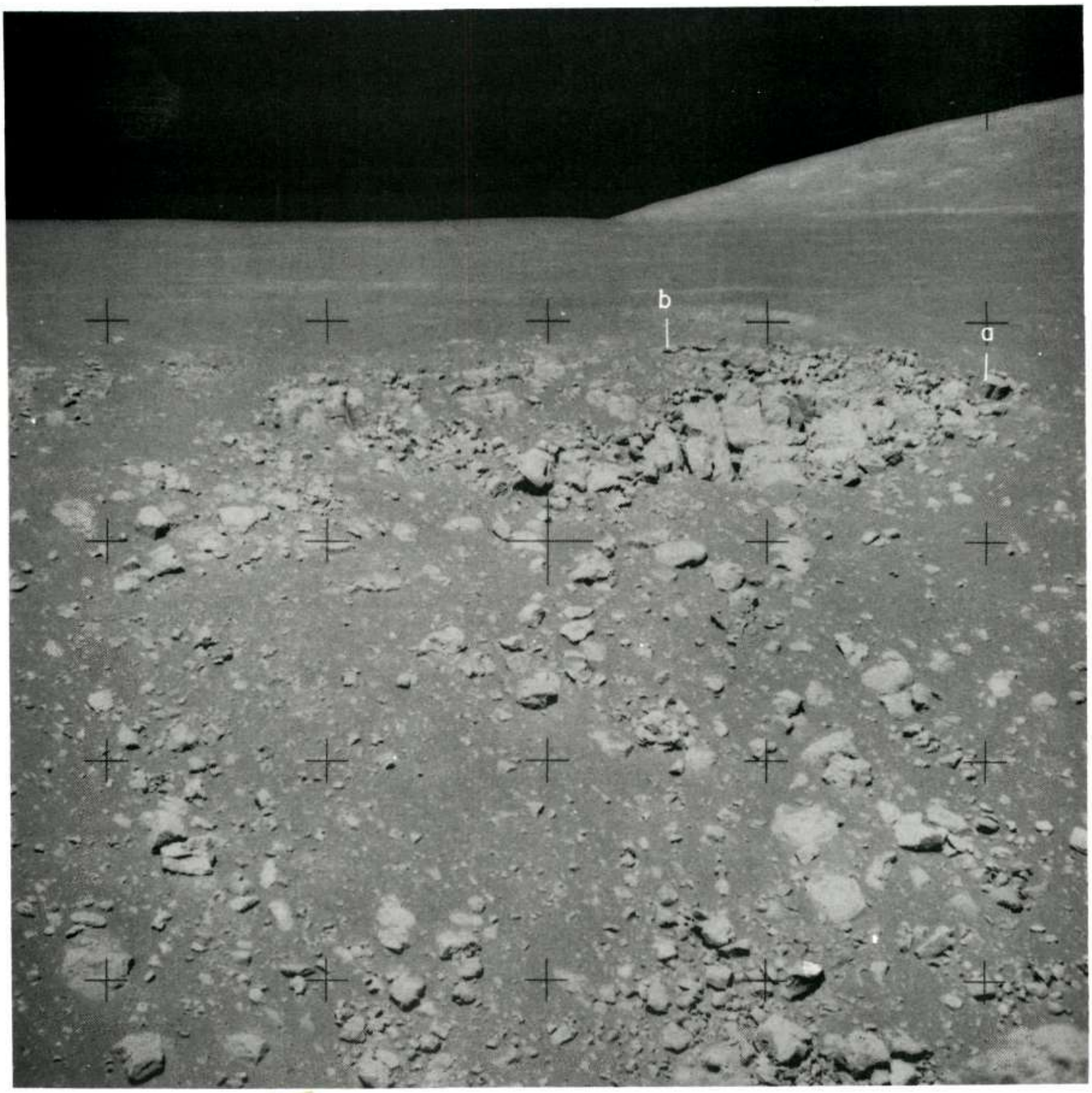


Figure 23. Area at right end of figure 8. A large column-like block is at a, and a platy slab is at b. NASA photograph AS15-89-12100.

in the large block in the upper right part of figure 19. Many large talus blocks have split in their present location (e.g., fig. 20). Other evidence of lunar weathering and erosion of the blocks includes what appears to be differential erosion of layers and the rounding of many blocks.

Outcrops

Rock strata in the rille near the Apollo 15 site crop out discontinuously in the upper 60 m of the walls. These outcrops were photographed through the 500 mm telephoto lens at three places. The first is a single outcrop, which may be slightly rotated out of position, just east of Bridge crater across from station 2 (fig. 24). The outcrop is approximately 18 m long and 6 m high and is made up of two prominent horizontal layers. The second area of outcrops forms a discontinuous string along the top of the northeast wall of the rille between Elbow crater and station 9a, from where they were photographed and sampled. In side view, looking along the slope, these outcrops appear as long subhorizontal bands. The third area of outcrops is across the rille from stations 9a and 10 (fig. 18) where much of a 2 km stretch was photographed stereoscopically and described from the two stations directly across the rille; these areas provide the best observations of outcropping rocks. Most of the following description is based on the outcrops across the rille from stations 9a and 10.

One or more thick units of massive rocks account for most of the outcrops. Below and above these massive rocks are discontinuous exposures that are less massive. These relations are best seen in the area shown in figure 8, where dotted contacts outline the three stratigraphic intervals. Correlation of these as continuous units between outcrops is tenuous due to a cover of talus, but a suggested stratigraphic column for this area is shown in figure 25.

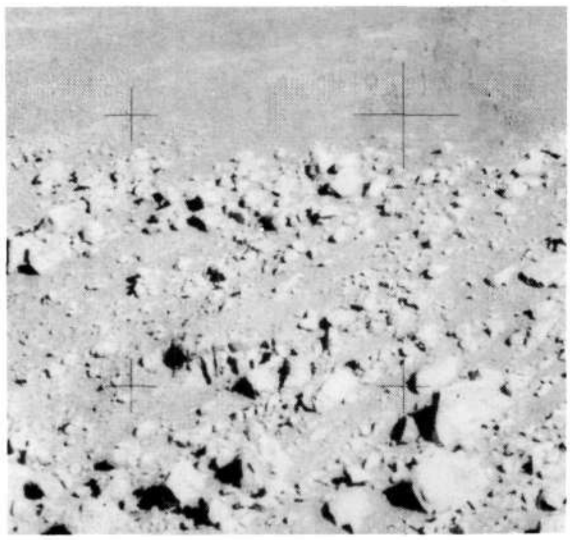


Figure 24. Upper part of rille wall east of Bridge crater, photographed from station 2. Outcrop near center, with a dark layer at its top, is 18 m long. NASA photograph AS15-84-11269.

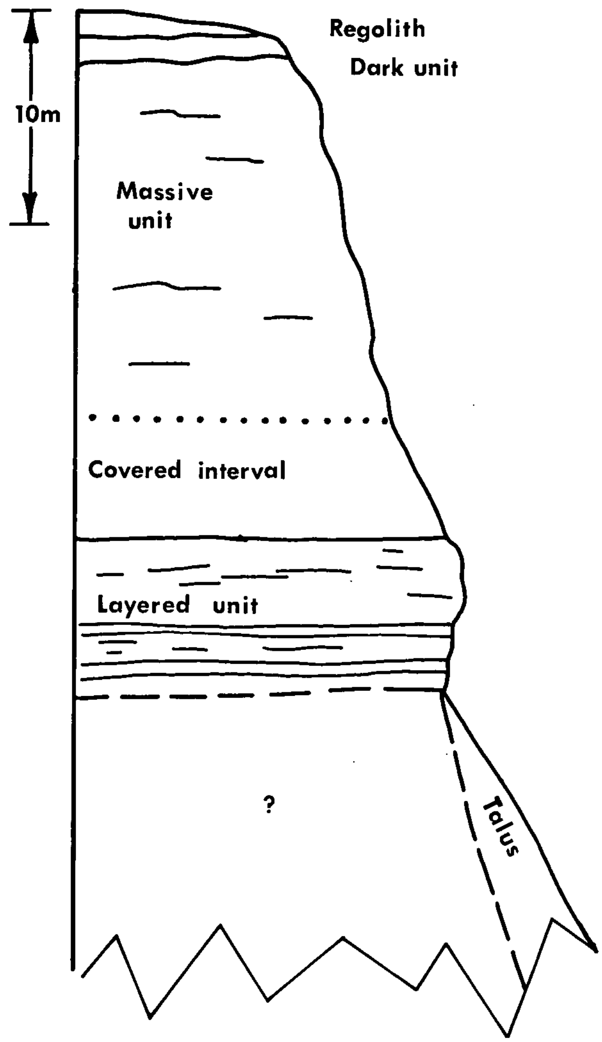


Figure 25. Stratigraphic column showing outcrop units recognized in the area of figure 8.

The lowest unit is prominently layered (lower center of fig. 21) and it is exposed in only one small area. Its base and top are concealed by talus and its apparent thickness of about 8 m may be twice as large if the covered interval above consists of a softer member of the same material. This covered interval might be composed of fragmental material but is unlikely to be an old regolith horizon considering the evenness of its base. Perhaps twelve layers occur in the outcrop (fig. 26). Several of the thicker layers, 1 to 3 m thick, contain less well defined internal layering or parallel banding. Thinner layers less than a meter thick occur together or separate the more massive layers from each other. These thinner layers weather out distinctly as ridges and troughs. Fractures are dominantly vertical or near vertical within this layered interval and cut distinctly across the thicker layers, often continuing across a thinner unit into the next thicker layer. Nearly all the fractures are within 20 degrees of vertical.

Above the overlying covered interval in figure 21 are prominent outcrops 15 to 20 m thick of light-toned rock that is part of the middle massive interval. This massive unit has discontinuous thin layering or partings within it locally, averaging about 0.3 m thick. The most striking aspect, however, is a series of closely spaced (1/2 to 2 m) joints that dip 45 degrees or more to the northwest. This prominent oblique jointing decreases in abundance in the upper 4 to 6 m of the outcrops, where nearly vertical joints begin to dominate.

At the left side of figure 8 is another large massive outcrop (fig. 22). It has more prominent vertical joints and horizontal partings and appears less bright than the outcrops just described. Whether it is a direct continuation of the massive unit in figure 21 or replaces or overlies this unit is uncertain. Figure 27 shows additional clear evidence of two superposed units within the massive interval. An upper unit here (in the upper right part of the photograph) forms outcrops with planar faces

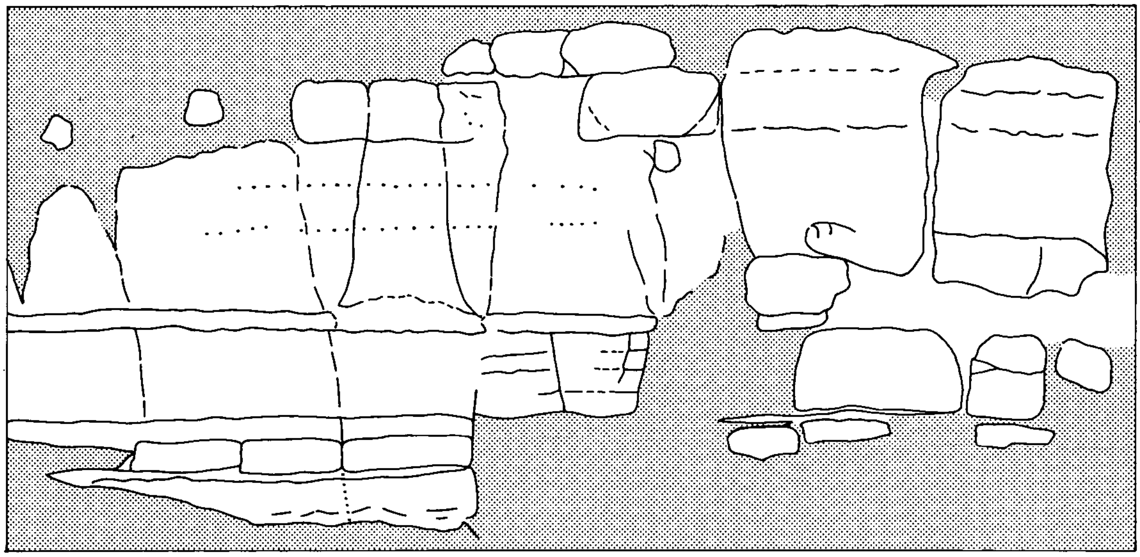


Figure 26. Diagrammatic sketch of layered outcrop indicated in figure 21. Outcrop is approximately 8 m thick.

Figure 27. Outcrops on upper rille wall across from station 9a (b in figure 18). Width of area is approximately 150 m. There are two major massive outcropping units, separated by a covered interval. NASA photograph AS15-89-12075.

with rare fine-scale pits. Horizontal parting is developed in places, especially in areas photographed 150 m to the left of the picture. If the left-central part of figure 27, below some debris, are outcrops of a lower unit. These lower outcrops have irregular rounded faces that are hackly and coarsely pitted, in contrast to those above.

The interval of massive outcrops thus includes more than one unit. The massive units provide most of the outcrops as well as a high proportion of the talus blocks in the rille.

An upper non-massive unit is tentatively identified in small intermittent exposures in the left part of figure 8 and in figure 22. Only 2 to 3 m are exposed below the regolith. The small outcrops in the upper unit characteristically have dark and hackly surfaces and are irregularly layered. A relatively sharp but locally irregular contact between it and lighter-toned massive rocks below is tentatively identified in several places. Some parts of the massive outcrop in figure 22 resemble the hackly upper unit. In regolith above the dark hackly outcrops are numerous massive light-toned blocks, possibly indicating that more rock like the massive unit overlies or is interlayered with the upper hackly unit. In the right half of the area of figure 8, there is little room for the upper hackly unit between the massive outcrop and the mare surface; in fact there is a suggestion that the lower two units bend upward here so that the upper unit may pinch out. However, an exposure of rocks that may be correlative with the upper unit appears far to the south near Bridge crater (fig. 24), where dark hackly surfaced rock is in sharp contact with underlying lighter-toned massive rock. Vertical joints there pass through both units together, suggesting that if a parting plane exists at the contact, it was not an open fracture at the time the vertical joints were formed.

The attitude of all the layering is horizontal or nearly so. Slabs south of station 9a, however, slope very gently away from the rille, indicating that the strata may dip outward a few degrees. This outward dip possibly is related to the raised rim of the rille.

Small scale internal layering is in most places expressed as horizontal recesses in the rock, as in figures 21 and 22, although the upper dark hackly unit displays horizontal projecting ribs. Layering in the massive outcrops such as in figure 22 consists mainly or entirely of discontinuous parting planes or fractures. Layering in the dark and layered units may, however, record successions of strata. Much of the layering is probably analogous to that seen and sampled by the astronauts at the rille edge, where rocks contain vesicular zones that are apparently more easily eroded by repeated small impacts.

Layering of a different type is seen in an irregular slabby outcrop near the mare surface (b in figure 23). An open crack underlies the thin slab and parallels its curving top surface, very much like a shelly pahoehoe where the fluid lava drained from beneath the cooled crust.

Most of the outcrops are jointed. Some of the northwest-dipping fractures shown in figure 21 are filled by a light gray material, which may be either regolith fines or possibly veins. More pervasive than these local inclined joints are vertical joints (fig. 22). Stereoscopic examination of photographs of the area shown in figure 22 reveals that between the more obvious fractures are numerous vertical ribs and troughs, suggestive of incipient jointing. The vertical joints may be cooling joints as in many terrestrial lava flows. Rarely the outcrops break in irregular vertical column-like blocks; the top of one nearly horizontal exposure is characterized by interlocking polygons about 3 m across that resemble columnar jointing.

Some outcrops are irregularly shattered, presumably by impact. The outcrop in figure 28 shows, from right to left, a progressive increase in fractures, and beyond the left end of the outcrop only a rubble of rotated blocks remains.

STRATIGRAPHY EXPOSED ON THE RILLE WALL

To summarize the stratigraphy shown by outcrops in the southwest wall of the rille near the Apollo 15 site: several units can be recognized, most of them thick and massive but some that show internal horizontal layering. In figure 8 there is some suggestion

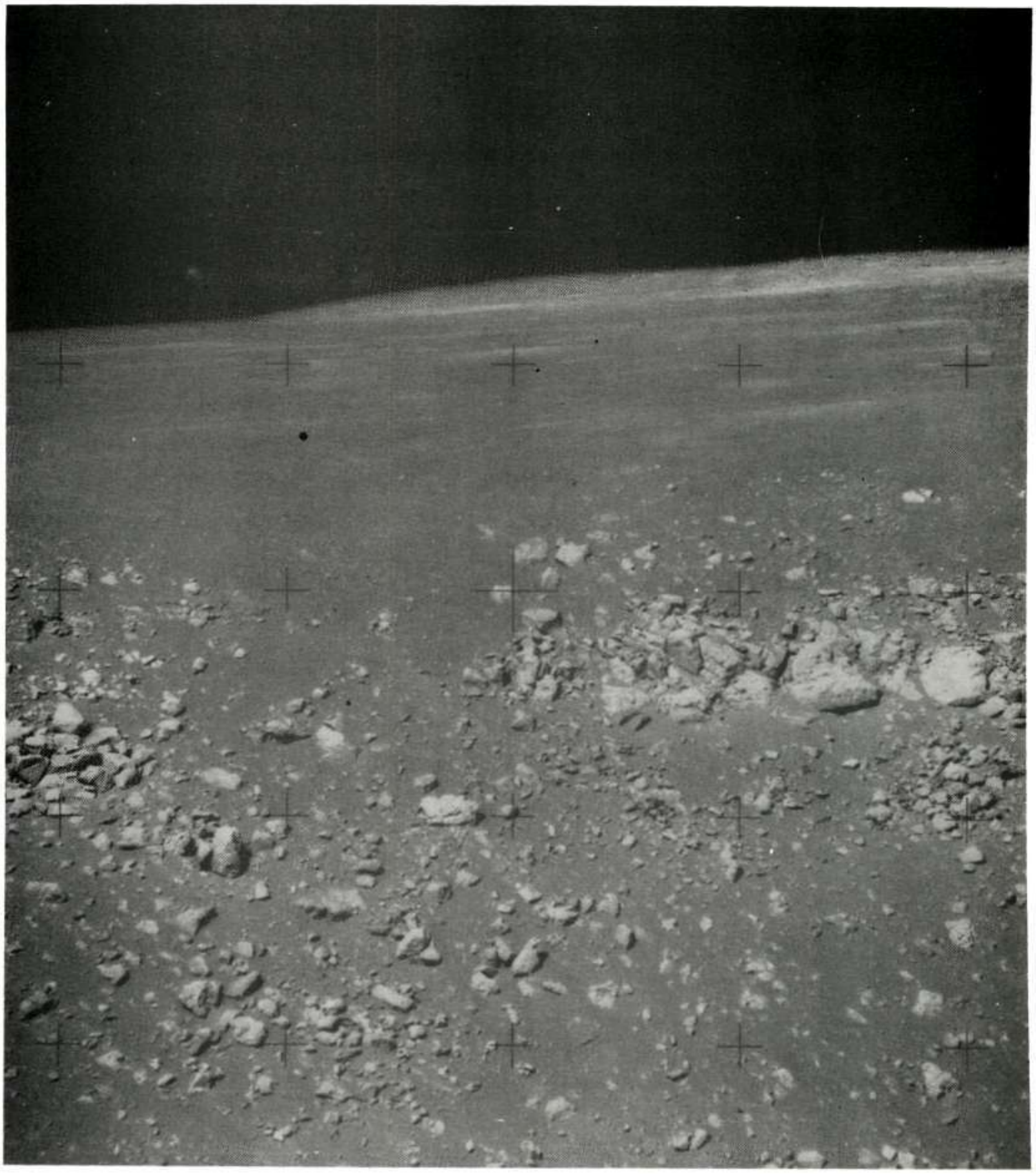


Figure 28. Area between those shown in figures 21 and 22 (see figure 8.) Massive bright outcrop appears to be a continuation of the massive unit in figure 21. Outcrop is progressively more fractured or shattered from right to left. NASA photograph AS15-89-12111.

that units pinch out to the right (northwest), and that the mare surface is underlain by successively lower units in this direction.

The outcrops are limited to the upper 60 m of the wall, which may be significant in terms of regional stratigraphy. On some orbital photographs the outcrops show up as very bright reflectors along the upper part of the sunlit slope. The bright line of outcrops can be followed to the northwest into the area where the rille is interrupted, confirming that the outcrop ledges are essentially continuous.

Where photographed with sunlight just grazing the northeast wall, the outcrop ledge can be identified as forming a nearly continuous scarp just below the rim (fig. 4). At Elbow crater the ledge thins and becomes discontinuous, and the mare basalt pinches out against the Apennine massif as indicated by a change in the character of debris in the rille wall (figs. 4, 18). The full thickness of the basalt was apparently not penetrated by Elbow crater, however, because all samples from its rim and ejecta blanket are either basalts, or breccia and fines derived primarily from basalt. To the northwest, the outcrop ledge is present in the area near the North Complex, where map relations (Howard, 1971) suggest that a buried pre-mare hill may extend to the rille wall.

The uniform base of the outcropping ledge on either side of the rille may represent a stratigraphic discontinuity; beneath the hard rock there may be a stratum of more easily eroded material, such as thinner mare flows or, perhaps, the pre-mare Apennine Bench Formation. Alternatively, the uniform base of the outcrops may only mark the top of a rather uniform talus slope, and thus give no clue to the underlying sub-talus stratigraphy. The possibility of a stratigraphic break here is suggested, however, by the flattish block-covered bench that commonly occurs at the base of the outcrops (fig. 14). Other inflections in the talus slope below (fig. 14) may also be due to sub-talus stratigraphy. Orbital photographs show a prominent terrace between Elbow crater and station 9a about a quarter of the way down the wall, formed by a continuous line of blocks suggestive of an outcrop (fig. 14b). In telephoto frames taken from stations 9a and 10, this line is greatly foreshortened, and whether the rocks are outcrops or merely an accumulation of blocks is uncertain.

The lack of definite outcrops in the long talus slopes below the prominent rimrock indicates that caution must be taken in interpreting sub-talus stratigraphy. There are other possible explanations for benches and inflections in the talus, as shown schematically in figure 29. One possibility is that the benches may be slabs of the rimrock that have tilted and slumped into the rille as the rim receded. Some extension fractures that precede this kind of sloughing may now be present in the rim north of station 10, where there are some irregular troughs just back from the lip of the rille (fig. 4). In some collapsed lava tubes, tilted blocks of this type form long hogback ridges and benches within the collapse trench (Howard, 1969); where weathering breaks up the hogback into blocks, the result is an elongate train of rubble. Possibly the talus benches in Hadley Rille result from a similar process.

Another alternative is that the benches and inflections have formed in talus independently of the underlying structure or stratigraphy. Possibly the impact erosion process causes the rimrock outcrops to wear back faster than the rest of the talus slope. Small impacts on the outcrop would cause broken slabs to fall and slide off, and pile up at the base of the outcrop as a blocky bench. Downward movement along the talus slope would be less rapid because there would be less sliding and falling. The blocky bench at the top of the talus slope could conceivably act as another "outcrop" so that another scarp and another bench could form below it, and so on down the slope. This could explain the more subtle form of each succeeding convexity shown in figure 14.

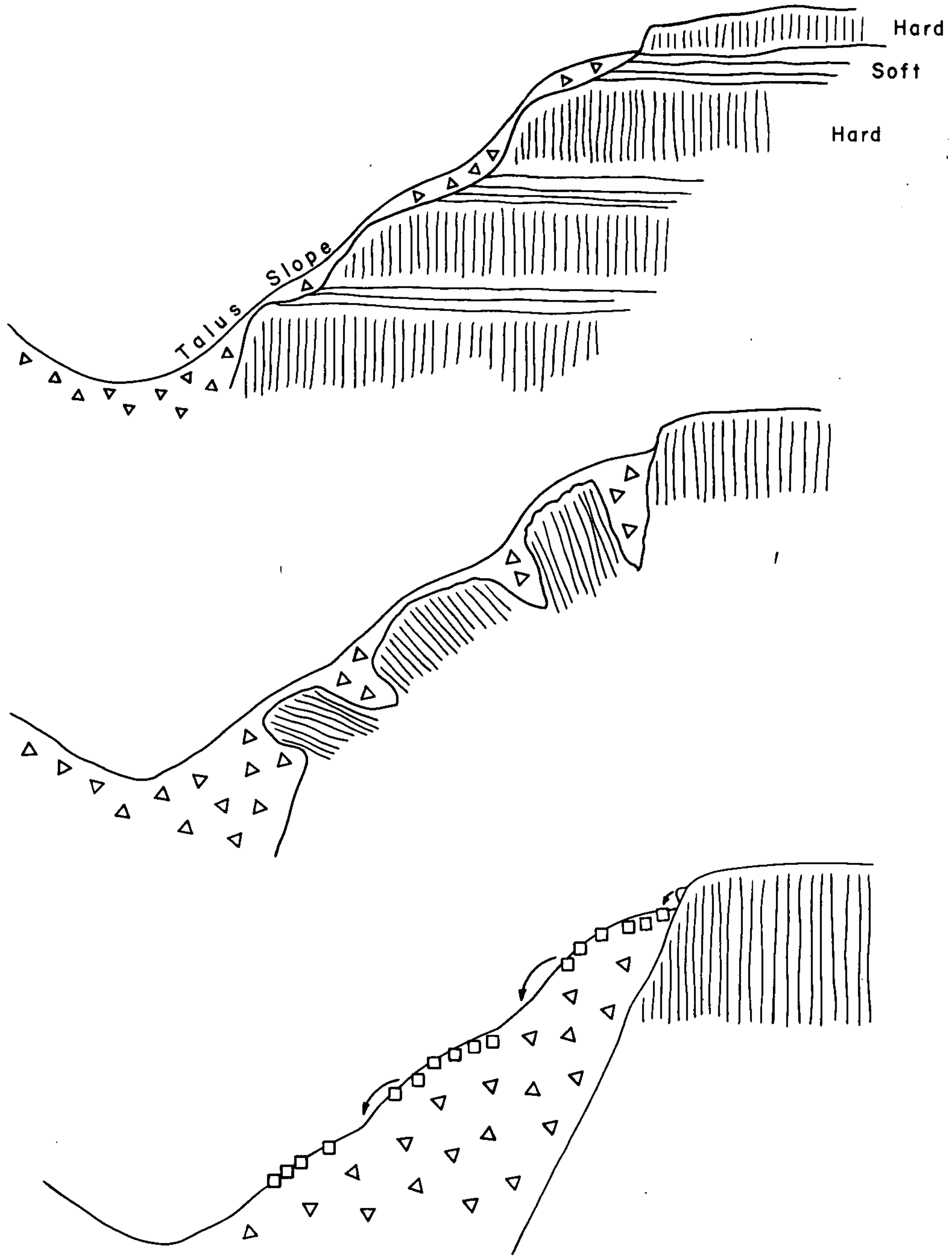


Figure 29. Sketches to illustrate schematically three different explanations for benches and inflections in the talus of the rille walls. Top: alternating hard and soft layers in the subtalus stratigraphy. Middle: tilted slabs from collapse into the rille (slump blocks could be tilted backward instead of forward). Bottom: talus surface bears no relation to subtalus structure or stratigraphy; benches are formed by blocks that have fallen or slid from outcrops or block fields.

The top of the talus slope may bear no relation to a lithologic change beneath the rimrock, but may only indicate that talus deposits fill the rille to a uniform slope. If the mare basalt that was sampled on the rim of Dune crater is representative of material ejected from its estimated penetration depth of nearly a hundred meters, then mare basalt is present well below the base of the rimrock outcrops in Hadley Rille. From direct evidence of outcrops in the rille we can see no more than 60 m below the surface.

South of Hadley C (fig. 13) the profile of the talus differs from that near the Apollo 15 site, and this may indicate that purely mass-wasting processes, which should be uniform along the walls of the rille (except perhaps in the immediate vicinity of the massifs and craters of appreciable size), cannot account for all the inflections in the talus slopes.

The outcrop cliff in the southern part of the rille (fig. 13), however, is definitely more massive, continuous, and generally thicker than that near the Apollo 15 site.

Figure 3 shows the distribution of outcrops all along the rille recognized from several sources. Lines of outcrops identified from surface photographs near the landing site appear as bright streaks on orbital photographs of the brightly lit walls of the rille, and thus, bright streaks elsewhere along the rille are interpreted to be outcrops. On the side of the rille photographed with grazing sunlight, the outcrop ledge can be identified just below the rim. Some thick outcrops are clearly recognizable in Lunar Orbiter V and Apollo 15 Hasselblad and panoramic camera photographs. Again it is apparent that outcrops are most continuous in the south, and that the average thickness of the outcropping ledge appears to diminish northward. Northwest beyond Fresnel ridge the depth of the rille decreases and slopes are evidently not steep enough to expose bedrock.

The thickness of soft material above the top of the major outcropping ledge also decreases towards the north. At the landing site the vertical distance from the rim to the outcrop ledge is a little more than 5 m, approximately the regolith thickness in the mare as estimated from crater shapes. South of Hadley C the thickness is estimated to be 15-25 m, and rocky protuberances in this interval suggest presence of discontinuous or thin strata which do not form good outcrops. Orbital photographs of the south end of the rille show the material above the main outcrop ledge also to be thick (fig. 30). A regolith produced by impact gardening is present everywhere on the mare surface, but this thickened interval above the outcrop ledge apparently includes, in addition to normal regolith, thin flow units and/or pyroclastic material that thin northward toward the Apollo 15 landing site.

The lack of outcrops where the rille abuts pre-mare massifs indicates there may only be a thin veneer of hard mare basalt at these sites, and the rille exposes subjacent friable highland material. A possibly analogous situation is shown in the crater Hadley C (fig. 3). This fresh-appearing 6-km crater postdates Hadley Rille, but remote sensing at various wavelengths shows the crater to be noticeably deficient in blocks, even down to meter and decimeter size (Zisk and others, 1971). Apparently the hard mare basalt is thin so that Hadley C penetrated deep below it and into more friable basement material.

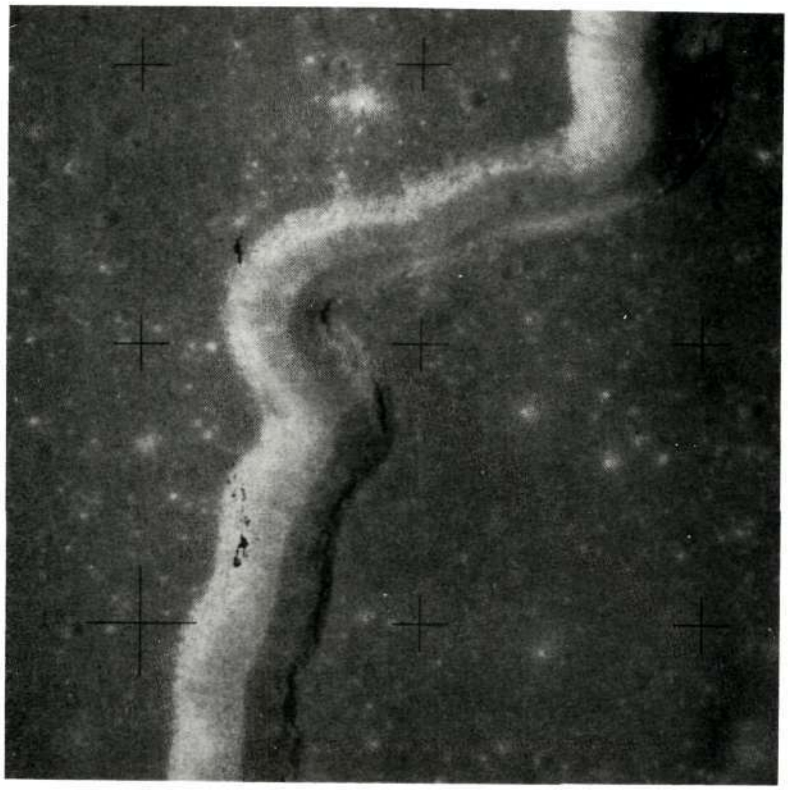


Figure 30. Southern part of Hadley Rille, looking north. The top of the outcropping ledge lies well below the mare surface. NASA photograph AS15-98-10897.

C.2

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