Apollo 17 Report on the Valley of Taurus-Littrow

A geological investigation of the valley visited on the last Apollo mission to the moon.

Harrison H. Schmitt

The Apollo 17 mission visited the Valley of Taurus-Littrow, in the mountainous southeast ring of the great plain of Mare Serenitatis (Figs. 1 and 2). From 11 to 14 December 1972, Eugene A. Cernan, commander of the mission, and I conducted 22 hours of surface exploration and experimentation in this valley (*1*). We made investigations of six major geologically defined units within the valley and in the mountains surrounding it. We visited 11 major sampling locations, traversed and observed 30 kilometers of the valley floor, collected 97 major rock samples and 75 soil samples, and obtained 2200 documentation photographs. The nearly flawless characteristics of the mission plans and equipment and the close cooperation of the science team provided a much more extensive delineation of the geological context of our investigations than had ever before been possible on the moon.

It now appears that at Taurus-Littrow we have looked at and sampled the ancient lunar record ranging back from the extrusion of old mare basalts, about 3.8 billion years ago, through the formation of the Serenitatis mountain ring, and thence back into crystalline materials that may reflect the earliest evolution of the lunar crust itself. Also, we have found and can now study materials and processes that range forward from the formation of one of the earliest mare basalt surfaces through 3.8 billion years of modification of that surface. The early portion of this modification included the addition of layers of glassy, orange, and black spheres which may be the culmination of processes once active within the deep interior of the moon.

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Exploration Plans

The photogeology of the Valley of Taurus-Littrow and exploration plans based on that geology have been described in detail elsewhere (*2, 3*). The stratigraphy and historical sequence of events in the Taurus-Littrow area were thought to be understood before the Apollo 17 mission. This sequence as then understood, from older to younger events, can be summarized as follows.

1) *Pre-Serenitatis events* included the original evolution of the lunar crust and subsequent impact processes. Most materials representing these events were thought to be coherent rocks composed of fragments of other rocks (breccias) or of previously melted materials, both types of rock probably having been generated through processes associated with the formation of large basins. Igneous processes, however, could not be ruled out by the available evidence.

2) *The Serenitatis event* included the formation of the major mountain ring of uplifted crustal rocks and the initial formation of radial grabens such as the Taurus-Littrow valley. Uplift of the valley walls may have continued for an extended time after the Serenitatis event. Major breccia units probably were created in the area as a result of this event.

3) *Nectaris and Crisium events* may have contributed ejecta blankets of breccia that extended across the Taurus-Littrow area.

4) *The Imbrium event*, in addition to contributing ejecta to the area, may have accented the formation of grabens like that of Taurus-Littrow. This graben is radial to both the Imbrium and Serenitatis basins.

5) *Post-Imbrium materials* partially filled and leveled the valley floor after graben formation was complete or near completion. These materials formed coherent blocks in the walls of craters and were thought to be either breccia or basalt.

6) *Old cratering events*, such as formed the crater Camelot, exposed post-Imbrium materials in the valley floor. Although these events were probably impacts, the possibility remained that the craters were maar-type volcanoes. Associated crater materials appeared to be partly mantled by dark material.

7) *Young cratering events*, such as formed the crater Steno, consisted of the formation of craters similar to but less subdued and less mantled than craters of Camelot age.

8) *Dark mantle deposition* included mantling of older features on a regional scale. The deposits were interpreted as probably being pyroclastic in origin with a relatively young age of deposition, possibly as little as 1 billion years.

9) *Lee-Lincoln scarp formation* was apparently superposed on North Massif talus. The age relation of this fault or flow scarp to the dark mantle material remains uncertain.

10) *Light mantle deposition* was superposed on the dark mantle and the Lee-Lincoln scarp. It appeared to be an avalanche deposit of massif materials covering older materials on the valley floor.

11) *Very young cratering events*, such as formed the craters Shorty and Van Serg, created small and relatively sharp craters in the older surfaces of the dark and light mantles. It was thought that both impact and volcanic craters might be present.

12) *Regolith and talus formation.* It was assumed that impact-generated regolith formed on all exposed surfaces as a continuing process. It was similarly assumed that talus had accumulated continuously at the base of all steep slopes.

Our purpose during the Apollo 17 mission was to make detailed field observations of the stratigraphic sequences that could be correlated with this general regional sequence of events. Our actual traverses are given in (*4*, figure 2). These traverses were very close to those planned for the mission. We planned to investigate the old Serenitatis and pre-Serenitatis materials at the bases of both the South and North Massifs (see Fig. 2), station 2, and stations 6 and 7, respectively, and possibly at the base of the Sculptured Hills at station 8. Wherever possible, large blocks would be studied preferentially over other features. Post-Imbrium materials present beneath the valley floor and the nature of the major craters of the valley would be studied specifically in the walls and on the rims of several large craters; that is, at station 1 on Emory (later moved to between Steno and Powell), at station 5 on Camelot, and at station 10 on Sherlock (later eliminated). These large crater localities and the surface near the landing point were also intended to be prime areas for investigating the dark mantle materials. A possible sampling of massif stratigraphy preserved within the light mantle was planned for stations 2, 3, and 4. Little work on this problem was done at station 4; on the other hand, a new station on the light mantle, station 2A, was added during the actual mission. Finally, a study of more recent cratering events, apparently impact but possibly volcanic in origin, was set for station 4 at Shorty and station 9 at Van Serg.

Several special observational and sampling projects were delineated based on the implications of certain lines of interpretation for the origin and nature of various valley features. These special projects included investigations of (i) coarsely crystalline rock suites associated with the massifs; (ii) evidence of alteration caused by secondary fluids (fumarolic); (iii) evidence of a source or vent of volcanic materials; (iv) fragments of rocks (xenoliths) contained within igneous materials; (v) undisturbed glass masses that might have cooled through their curie point in situ. To greater or lesser degrees, each of these projects received special attention during our explorations.

Observational Considerations

The raw data of our observations during the exploration of the Valley of Taurus-Littrow exist only in our verbal transcripts, in video tapes, and in our minds. The synthesis of the data contained in transcripts and video tapes is relatively straightforward and constitutes the foundation of this article. The synthesis of the data contained in the mind is more difficult. Unlike normal field work on Earth, the pressures of time and total efficiency may often prevent the conscious mental recording of visual images. Many images are recorded, to be sure, but some are not subject to direct recall. Not only does it often take an external stimulus, such as a photograph or a question to release these data, but there is a continued problem, which increases as time passes, of separating purely objective observational data from more subjective feelings acquired since the mission. Recognizing this problem, I have leaned heavily on the transcripts and tapes for verification of observations. Possible interpretive explanations and alternatives will be identified as such.

The observational environment in the valley is superb. Unrestricted sunlight is an excellent light for visual investigation. When this light is combined with generally clean rock surfaces, there is little difficulty in distinguishing mineralogical and textural differences. Albedo and textural differences in soil and rock surfaces also are readily apparent. For the most part, the sampling of rocks and soils was based on visually detectable differences or similarities. These characteristics are recognizable in spite of an overall brownish patina on most rock surfaces. Unfortunately, photographs cannot record much of the more subtle information available to the human eye.

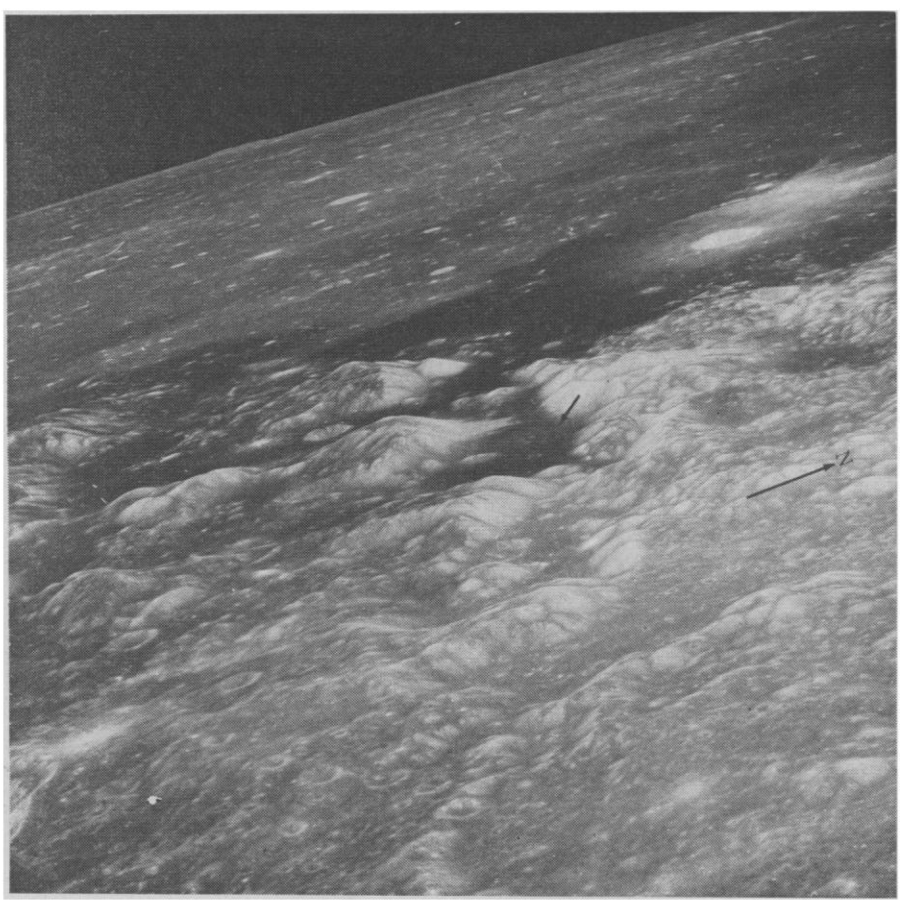

Fig. 1. The Valley of Taurus-Littrow (center of field), a dark bay-like indentation in the broken mountain chain that defines the edge of Mare Serenitatis (distant smooth surface). Coordinates of the landing site (arrow) are 20°9′55″ N latitude and 30°45′ 57″ E longitude. The view is toward the northwest from a 120-km orbit around the moon. The central width of the valley is about 7 km.

Nomenclature

The terminology used in this article is consistent with our field (transcript) terminology except in a few instances. The term "anorthositic gabbro" has been dropped in favor of "tan-gray matrix-rich breccia." The term "blue-gray breccia" has been subdivided into "blue-gray matrix-rich breccia" and "blue-gray fragment-rich breccia." Finally, the term "dark mantle" has been replaced by "dark floor material" in deference to objectivity. In most cases, breccias are distinguished as "matrix-rich" or "fragment-rich" depending on which textural component is visually dominant in a given boulder.

The use of the term "vesicular" is not necessarily meant to imply an igneous origin, only that smooth walled holes exist in the rock. In a similar vein, all descriptive terms should be taken as nongenetic unless otherwise indicated.

Field Observations

North Massif—breccias. The North and South Massifs, which form the majestic walls of the Taurus-Littrow valley, rise to heights of 2000 and 2300 meters, respectively, with flanking slopes of about 25°. They represent the major structural boundaries of the valley, and their faces contain intermittent exposures of thick sections of premare crustal rocks. Numerous fields, or "source-crops," of boulders are present on the upper half to two-thirds of the slopes of both massifs. Boulder tracks indicate that blocks have rolled into the valley from such sources. Several of these blocks were the prime field objectives of our visit to the valley.

The source-crops for the boulders on the slopes of the North Massif are linear but discontinuous. They are roughly horizontal in apparent orientation and each are a few hundred meters in length. The large boulder investigated at station 6 has a well-defined track above it and appears to have originated from the lowermost source-crop band about one-third of the way up the slope.

The geologic complexity of the boulders at stations 6 and 7 was unexpected based on what had been seen on previous lunar missions. Here, for the first time we were able to observe and sample across a major lithologic and structural contact. This contact was exposed sharply in boulders large enough that outcrop investigative techniques could be applied. But, as always, time was relentless and many questions were only partially answered. Still, much was learned.

Three major categories of stratigraphic materials were studied and sampled in the boulders at stations 6 and 7. A younger finely crystalline, strikingly vesicular, tan-gray *matrix-rich* breccia is apparently in intrusive contact with an older very finely crystalline, blue-gray *fragment-rich* breccia. There are inclusions of blue-gray breccia in the tan-gray breccia at the station 6 contact. A blue-gray *matrix-rich* breccia is the material in direct contact with the tan-gray breccia at both the contacts investigated. This blue-gray matrix-rich breccia forms a contact zone about 1 m wide that is apparently gradational with the blue-gray fragment-rich breccia at station 6. The large vesicles in the tan-gray breccia are ellipsoidal in cross section and are generally aligned parallel to the contact with blue-gray breccia. There are some small spherical vesicles in the blue-gray breccia near this contact.

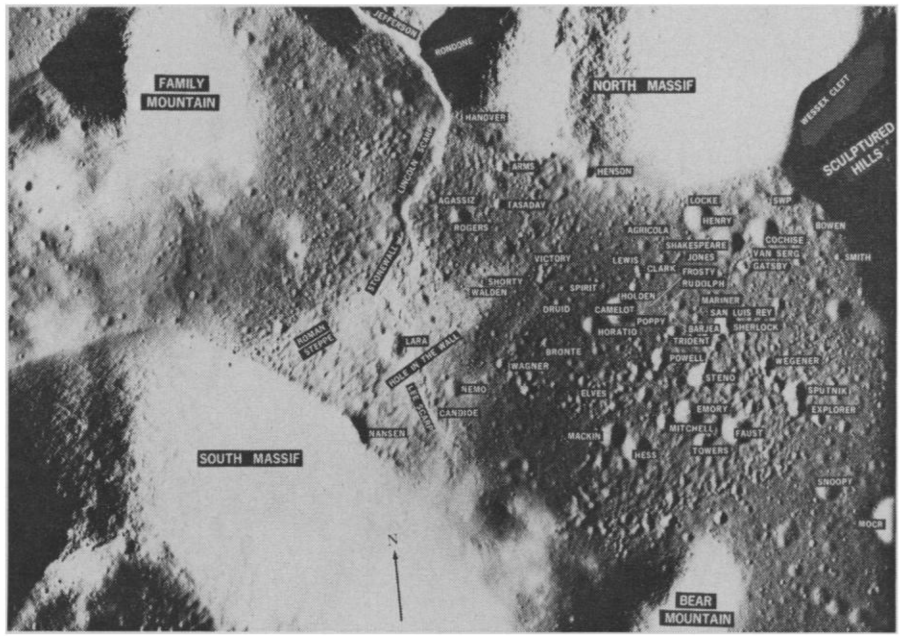

Fig. 2. Apollo 17 panoramic camera photograph of the Valley of Taurus-Littrow with the informal names of various topographic features indicated. The central width of the valley from Nansen to Henson is about 7 km.

The field interpretation of these relationships led to the tentative conclusion that the blue-gray fragment-rich breccia had been intruded by a partially molten, and subsequently highly vesicular, tan-gray matrix-rich breccia. In the contact zone the blue-gray fragment-rich breccia appears to have been metamorphosed, locally partially melted, and locally included in the tan-gray breccia. The metamorphism and partial melting are indicated by the transition in the blue-gray breccias from a fragment-rich to a matrix-rich texture and the presence of vesicles in the matrix-rich portions nearer the contact.

In addition to the common small blue-gray fragments which dominate the blue-gray fragment-rich breccia, there are distinctive clasts of light gray breccias and crystalline anorthositic and mafic rocks. Within the contact zone at station 7, one of these clasts is veined by blue-gray matrix-rich breccia. The clasts also appear deformed and partially mixed with blue-gray material in the station 6 boulders.

The distinctive clasts are apparently the oldest stratigraphic materials sampled at the Taurus-Littrow site and some of these materials appear to have originated by deeply seated igneous processes. Scattered distinctive light-colored clasts also are present in the tan-gray breccia; however, their stratigraphic relations to either the blue-gray breccias or its included clasts were not apparent. They may be more refractory portions of the unmelted parent rock of the tan-gray breccia or inclusions picked up during its intrusion.

A marked brown patina is well developed on all weathered rock surfaces in the valley. It is most prominent on the surfaces of the massif breccias, including the fractured surfaces of the blocks with well-preserved boulder tracks above them at station 6.

The light gray walls of craters on the slopes of the North Massif and light gray material we uncovered with our boots suggest that this type of fine debris, mixed with boulders, forms the bulk of the talus at the base of the massif. Fillets of this material are largely absent around boulders except on some uphill sides. Overlying the light gray, fine-grained talus is a medium gray surface material that is generally a few centimeters thick. Overhangs of the sides of boulders over this surface material are common.

South Massif—breccias. The rocks of the South Massif (Fig. 3) constituted our prime geological objective, although their location clearly taxed the operational limits of our surface exploration capabilities. An hour-long dash to the edge of Nansen Crater at the base of the massif, for about 60 minutes of exploration, meant that any difficulty occurring during the remainder of this excursion might place us

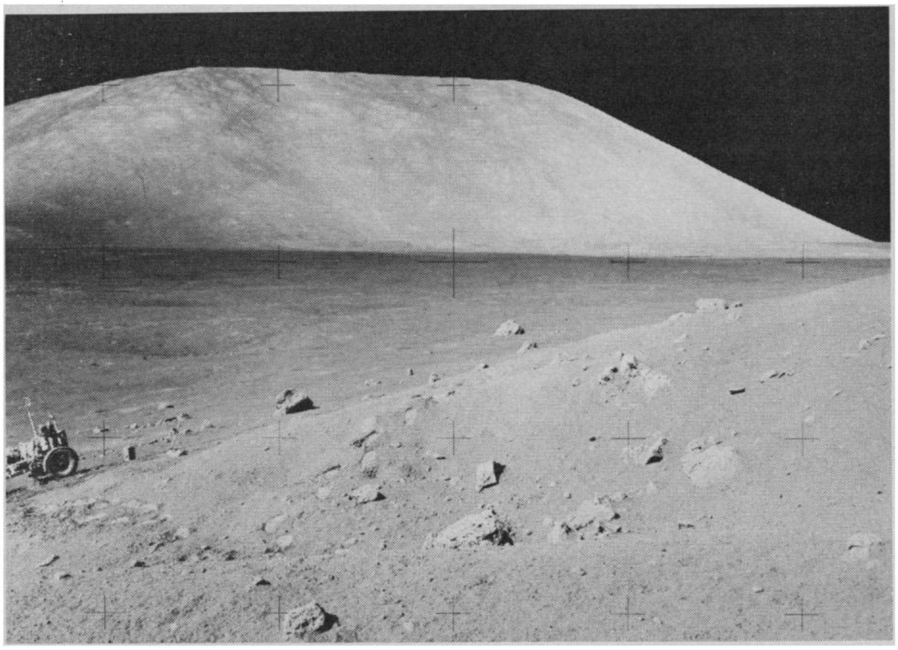

Fig. 3. Southwest-looking view of the 2300-m-high South Massif as seen from station 6 at the base of the North Massif. Station 2 is located very close to the center of the photograph and is about 10 km away. North Massif talus debris, cut by a boulder track, is in the foreground. The talus has the typical distribution of boulders present along the base of the massif.

in the position of being unable to return safely to the lunar module (LM). The boulders that were our specific objectives held the promise of an unparalleled view into the history of the lunar crust. Although overshadowed by more spectacular later discoveries, we were not to be disappointed by "old station 2."

The most obvious sources for the boulders near station 2 are on the upper one-quarter of the massif slope. Visual inspection from a distance indicated that linear source-crops on this part of the massif and subtle linear color variations of blue-gray lying over tan-gray have an apparent dip of 10° to 15° to the west. Offsets of the color changes, downward to the east, suggest that normal faults dipping steeply eastward cut this apparent massif structure.

Although certainly internally complex, the dominant fabric of the North Massif is apparently that of roughly horizontal structural units that may be depositional or intrusive layers. In the South Massif these units appear to be tilted westward or southwestward. High angle normal faulting and tan-gray breccia intrusions apparently break the continuity of the structural fabrics in both massifs. The tilting and faulting of massif units may relate to their uplift during the Serenitatis impact event or subsequent major basin events.

The boulders investigated at station 2 included crystalline, tan-gray matrix-rich breccia and blue-gray matrix-rich breccia but no contact relations were observed. The tan-gray breccia is less vesicular and more heterogeneous in texture than its North Massif counterpart. The sampled blue-gray breccia is similar to that found in the contact zones of the North Massif boulders. From a distance, boulders of both these rocks have a tan-gray hue very similar to the materials below the blue-gray tones in the high portions of the South Massif.

The distinctive clasts of contrasting shades and hues in the tan-gray and blue-gray breccias of the South Massif generally appear similar to those in the North Massif breccias. However, one bimodal, greenish crystalline clast in the boulder of blue-gray matrix-rich breccia has proved to be composed largely of olivine (*5*). The preliminary examination of rocks from both the South and North Massifs also suggests that various crystalline mafic rocks and some ultramafic rocks make up a significant portion of the distinctive clast population.

The third boulder examined at station 2 is a strongly foliated and layered fragment-rich breccia that is much less coherent than either the tan-gray or blue-gray breccia types. This foliated layered breccia contains large clasts of both dark- and light-colored older breccias in a generally light-colored matrix. There are also small clasts with distinctive dark coronas around them. From a distance this boulder has a blue-gray hue very similar to the blue-gray materials observed near the top of the west portion of the South Massif.

Along the boundary between the South Massif and the valley floor there is a trough. This trough is much broader and more continuous than had been apparent before the mission. The trough is a few hundred meters wide at the station, flat floored, and seems to include the crater Nansen as an integral, although much deeper, topographic unit.

A final interpretation of this boundary trough is not yet possible, but it seems likely that it may relate to subsidence of the South Massif after the deposition of the materials filling the valley floor. Similar subsidence of the North Massif is suggested by the Jefferson scarp which has an apparent normal fault relationship where it girdles the southwestern and western slopes of the massif. This scarp may be a reactivation of the original bounding fault around the massif.

The observed properties of the talus material at the base of the South Massif are very similar to those observed at the North Massif. In Nansen it is also clear that at least some of the South Massif talus forms a younger toe of debris over the valley floor, in particular, over the light mantle deposits in Nansen. It seems probable that talus formation is a continuous process; however, movement downslope may occur in discrete pulses.

Sculptured Hills—unknown bedrock. The interlocking domes of the Sculptured Hills form the northeast wall of the Valley of Taurus-Littrow. The origin of this unusual physiographic unit remains unknown, although some relation to the processes associated with the Serenitatis impact event is indicated by morphologically similar units near other large lunar basins (*2*).

Our investigation at station 8 on the lower slopes of the Sculptured Hills gave no definitive evidence about the nature of bedrock units. Concentrations of boulders were observed only near the top of the hills and no boulder tracks were apparent above the few blocks visible on the lower slopes. The surface texture of the slope material on the Sculptured Hills is of much finer scale and is more wrinkled in appearance than comparably lighted slopes on the massifs.

Of the six blocks examined in the

vicinity of station 8, five are composed of crystalline basalt similar to that in the Camelot-Steno area. The sixth block is coarsely crystalline, coated with black glass, and made up of approximately equal parts of a yellowish mafic mineral and white to bluish-gray plagioclase and maskelynite. This apparently exotic fragment was unfilleted and projected only a few centimeters into the underlying soil. Other exotic white fragments in small secondary craters appeared to be anorthositic matrix-rich breccias.

The soil on the slope at station 8 has a uniform grain size and is medium to dark gray in color in a trench dug to a depth of 30 cm. In this regard the Sculptured Hills slope materials resemble the soils on the dark floor in the valley rather than those on the massifs or on the light mantle.

It appears likely that most of the basalts and soils investigated at station 8 form parts of ejecta blankets from nearby craters such as SWP. An alternative interpretation of the presence of the basalt blocks is that the Sculptured Hills bedrock was formed by a more viscous phase of the basalt extrusions that partially fill the valley. However, the similarity in the observed regional characteristics to those of impact-generated materials around other large basins suggests that the Sculptured Hills are composed of material related to the Serenitatis event.

Valley floor—basalt and dark floor. The dark floor of the Valley of Taurus-Littrow is underlain by a body of material that has formed a roughly level plain between the bounding massifs. Since the formation of this material, it has been subjected to a variety of cratering, depositional, structural, and possibly volcanic processes. In addition to the investigation of block fields in the valley, our goals included the study of the Camelot- and Steno-age cratering events, the depositional characteristics of the dark floor material, the structural history of the valley floor, and any volcanic features we might encounter.

The block fields concentrated near and in the large craters in the Camelot-Steno area allowed a rather comprehensive investigation of the material beneath the valley floor. The blocks are mostly massive, tan to pinkish-gray, coarse-grained, ilmenite basalts having a generally coarsely ophitic and vesicular texture. Isolated examples of egg-sized vesicles were observed near the crater Bronte. Locally, there is a strong foliation formed by parallel parting planes and fractures. The blocks on the rim of Camelot at station 5 showed parallel layers defined by differences in vesicle concentrations.

Only two fragments of aphanitic basalt were observed even though this variety was searched for at each sampling site. Both fragments are finely porphyritic, and the one from the crater Shorty is very coarsely vesicular. Other fine-grained to aphanitic basalt fragments are present in the suites of small fragments collected in rake and soil samples (*5*).

In some blocks, finely textured blue-gray basalt forms isolated irregular lenses within the coarse-grained, tan-gray basalt. Material of a similar blue-gray color was seen from a distance in the west wall of the crater Cochise, where it forms a unit several tens of meters thick over a tan-gray unit. The contact has an apparent dip of about 20° to the north. The units in Cochise could be the two varieties of subfloor basalt. In general, however, the tan-gray, coarsely vesicular variety of subfloor basalt is dominant (at least 95 percent) in the basaltic block fields along our traverses.

The uniformly coarse textures of most of the observed basalt blocks, including those derived from depths on the order of 120 m around Camelot, suggest that a very thick cooling unit exists in the valley. One or more thin, fine-grained flows may have been present above this thick unit. The absence of significant numbers of large fragments of these rocks indicate that, if present, they and the top of the thick unit have been pervasively broken and incorporated in the local regolith.

There is a general absence of obvious shock effects in the blocks of basalt we studied in the field. Other than the pervasively fractured basalt block at Shorty Crater and possibly the very fine-grained mylonitic zones along isolated fractures in other blocks, the basalts seemed to have been little metamorphosed by the formation of large craters in the valley. In spite of the paucity of shock effects, the morphology of the large craters is consistent with their being impact craters of at least two general age groups which have been subsequently modified by the deposition of the dark floor material. Our observations, however, cannot completely eliminate the possibility that these craters are maar-type volcanoes.

The floor of the valley is largely covered with dark floor material. Below the dark floor surface there are probably interlayered ejecta blankets from the various large craters. Boulders in these ejecta blankets project above the surface in the LM and Steno Crater areas.

The regolith on the dark floor material consists of loose, fine seriate debris with few fragments larger than about 1 cm. It is a sparkling dark gray at the surface with even darker gray material just below the surface, although this contrast may only be present in the area near the LM which has been optically lightened by the descent engine.

Locally, the fragment populations on the dark floor material are quite variable. In the general vicinity of the Steno-class craters that form the cluster of craters south of the landing point, the fragment abundance is higher by a factor of 4 or 5 than it is near the Camelot-class craters or in areas along the traverse west of Camelot and near Shakespeare. Coherent soil breccias were searched for in this general area but were not recognized although a few examples were collected (*5*) as an inadvertent consequence of attempts to sample fine-grained basaltic materials. The absence of such breccias draws a sharp contrast between this site and the Apollo 11 site. The interpretation of this contrast may be important to an understanding of regolith and soil breccia formation.

The dark floor material itself has many field characteristics that suggest it is a mantling deposit, just as do its characteristics as seen from orbit and in orbital photographs (*6*). The field characteristics are as follows:

1) The block fields associated with large craters are made up of angular basalt fragments up to several meters in average diameter. The blocks are largely confined to the inner walls of the craters. The rims of these craters are generally covered by dark floor material for distances of 20 to 30 m down the crater wall from the rim. Locally the block fields of the crater walls extend up to but rarely over the rim crest. In these few places, the edge of the block field terminates sharply against the dark floor material outside the crater. No differences were observed between dark floor material on or away from crater rims.

2) Dark floor material locally extends over crater walls in long downwardly pointing fans that apparently bury the wall block fields. The crater floors are universally covered by the same material.

3) Dark floor material constitutes

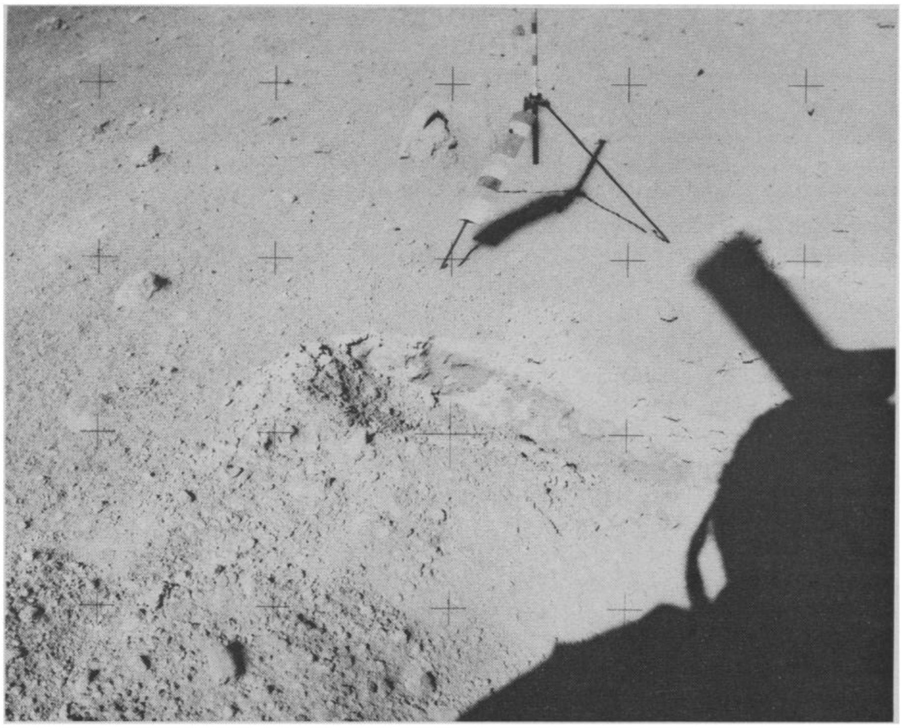

Fig. 4. The fine-structure of the ejecta on the rim of Ballet Crater at station 3. This trench exposed the first such structure observed in situ on the moon. The visible portion of the gnomon rod is about 40 cm long.

the interblock material in all block fields. If the large blocks are assumed to be generally equidimensional in shape, then they are approximately half-buried in the dark floor material which surrounds each individual block. However, no dark floor material distinctly mantles the top of any block.

4) All craters observed in dark floor material which are between about 5 and 80 m in diameter have dark floor material on their ejecta blankets, rims, walls, and floors. However, there is no indication of extensive filling of such craters. Van Serg is the only crater around which we observed a clearly defined blocky rim. Fresh craters less than 5 m in diameter have coverings of weakly coherent soil breccia fragments.

5) The orange and black soil at Shorty Crater partially mantles that crater. These glasses are present in the fine-grained fractions of the dark floor material (*5*).

Boulders are generally free of dust except in depressions on horizontal surfaces where dust and relatively coarse rock and mineral debris have accumulated. Fillets tend to be low on boulders on the valley floor, although isolated exceptions of high fillets were observed, particularly near the deployment site of the Apollo lunar scientific experiment package (ALSEP). These exceptions may be due to local cratering events.

The generally clean boulder surfaces, the low fillets, and the partial burial of the large blocks suggest that dark floor material tends to be deposited more rapidly than fillets are formed as the blocks erode. On the other hand, sandblasting by locally produced secondary ejecta appears to clean blocks more rapidly than dark floor material is deposited. This sandblasting causes any mantling material to be redeposited at some undetermined distance from the block.

An indication of the average depth of regolith on a surface is given by the relation between the depth and size of craters that have formed at every point on that surface. The apparent size of craters that have saturated the surface on the dark floor material is about 0.5 m, which suggests a 10-cm-deep regolith (ratio of crater depth to diameter is 1:5). Mechanical penetrability decreased markedly below about 10 or 15 cm and hand penetration with a core tube was impossible below about 25 cm under the lunar module.

Light mantle area—talus debris. The plume- or ray-shaped light albedo area that extends northward from the South Massif is known as the light mantle. Photogeological interpretation suggested that this is a relatively young mantling material derived from the South Massif talus (*3*). The geometry of its contact and the dark material excavated by some of the larger craters on it strongly suggest that the light mantle deposition occurred after most of the dark floor material was distributed.

The surface of the light mantle is composed of loose, medium gray, finely seriate debris with an apparently large deficiency of fragments in size ranges greater than about 1 cm. Very few rock fragments or boulders larger than a few centimeters were observed, a characteristic which contrasts sharply with the talus debris on the South Massif. The general visual character of the light mantle surface was very similar, however, to the fine debris surface on that talus slope. Fragments of breccia similar to those at station 2 were found slightly concentrated on the rim and inside the 30-m-diameter Ballet Crater in the light mantle at station 3. In general, fragment concentrations were present on the rims and in the walls of craters greater than about 5 m in diameter.

The above observations on fragment distribution as a function of depth indicate that the depositional process that formed the light mantle resulted in at least a gross vertical sorting of rock fragments. This strongly suggests that a fluidization process like that of an avalanche was involved.

Radar data obtained before the mission had indicated that the relative abundance of rock fragments 2 to 10 cm in size in the upper portions of the light mantle would be comparable to that of the talus slopes on the massifs and significantly greater than that in the upper portions of the dark floor material (*7*). Our observations of the surfaces of these units did not completely confirm these predictions. To be sure, the talus slopes clearly have a higher rock fragment abundance than does the average surface of the dark floor material; however, the surface of the light mantle has a distinctly lower fragment abundance than either of these other units. The same relations hold for fragments that are larger than 10 cm.

Light gray material is present 5 to 10 cm below the medium gray surface material at all localities investigated in the light mantle area. It is also present in the walls of all craters in this area that are greater than about 1 m in diameter. This soil profile is very similar to that developed on the massif talus slopes.

A distended and inverted section of

the light mantle may be present in the fine-grained debris just outside the rim of Ballet Crater. A trench in this rim showed the debris to be layered from the surface down as follows (Fig. 4): (i) Approximately 0.5 cm of medium gray surface material similar to the surface layer on the light mantle. This may be new regolith formed since the crater was created. (ii) Approximately 3 cm of light gray material similar to the average subsurface material of the light mantle. (iii) At least 15 cm of medium to dark gray material into which light gray material is irregularly marbled.

The contacts between the light mantle and both the dark floor material of the valley and the dark material around Shorty are gradational in albedos over about 10 m. A distinct difference in the albedos of the two types of surfaces is visible when viewed at zero-phase angle. Also, the color of the walls of craters greater than 1 m in diameter is obviously a lighter gray in the light mantle than in the dark floor material. No topographic expression related to the contacts was detected.

The light mantle surfaces above, on, or below the Lee-Lincoln scarp show no discernible differences in crater population, fragment population, or surface texture. This indicates that the mantle deposition occurred after the scarp was formed and that the scarp had little local effect on that deposition.

Small craters less than about 5 m in diameter have a consistent morphology whether in light mantle, dark floor material, or massif talus. In summary, the freshest of these craters have the following characteristics:

1) The crater ejecta, rim, wall, and floor are covered with fragments of weakly coherent soil breccia up to 10 to 15 cm in average diameter. The albedo of these soil breccias is much higher in the light mantle than on the dark floor material.

2) The soil breccia fragments inside the crater tend to be oriented with their long axes radial to the center of the crater.

3) There is a central pit in an otherwise relatively flat floor. The diameter of the pit is approximately one-quarter to one-fifth of the rim diameter of the crater. The pit is generally shallow and in most cases is less than one-tenth of the depth of the crater; however, this depth does vary and in one instance the pit was nearly one-half the depth of the crater and roughly cylindrical in shape.

4) The central pit is glass-lined with the glass forming a coating and partially cementing the soil breccia fragments.

5) The relative geometry of the pit with respect to the crater appears to be constant and independent of crater size or of geologic unit.

6) Overall, the albedo of the crater and its ejecta is noticeably higher than that of its surroundings.

As the crater ages, the order of the disappearance of primary features is first the albedo contrast, then the glass in the central pit, then the soil breccias, and finally the central pit itself.

The most likely origin for these small craters is that they result from hypervelocity impacts. The apparent contrast between their detailed characteristics and those of most small craters observed on previous missions may be related to differences in the mechanical characteristics of local regolith materials.

Shorty Crater—orange and black soil. One of the alternatives around which we planned before the mission was the possibility that the 110-m-diameter crater called Shorty is a volcanic vent. Its general morphological appearance is that of a dark-rayed impact crater that had penetrated the light mantle exposing dark floor material. Still, the darkness of Shorty held out the possibility of young volcanism. Other than Shorty, possible sources for the potential pyroclastic deposits of the dark floor material were hard to delineate. The observations and sampling at Shorty Crater did not reveal directly what we had hoped for; however, the results of the investigation may yield equally important information from unanticipated directions.

All of the now classic difficulties in conducting geological operations on the surface of the moon faced us at Shorty Crater. To begin with, we had

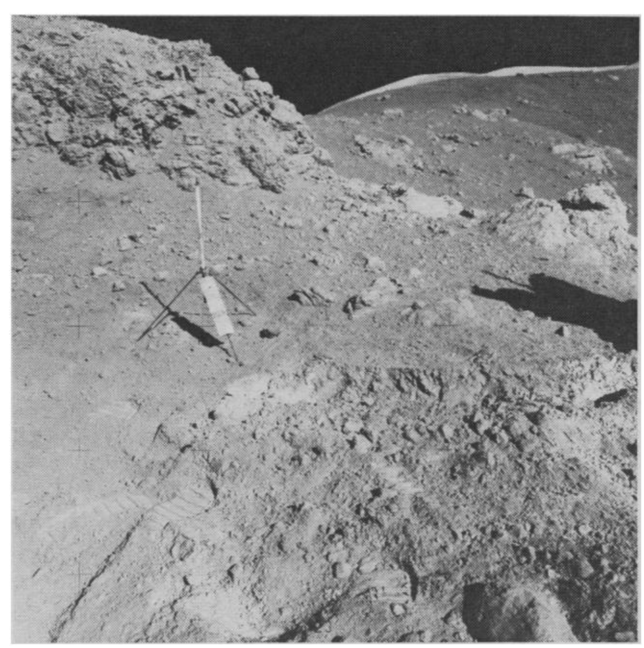

Fig. 5 (left). View of the northwest wall of Shorty Crater (about 110 m in diameter). Note the blocky, irregular floor and the relatively unblocky, smooth walls and rim. Fig. 6 (right). A trench across the deposit of orange soil in the south rim of Shorty Crater. The orange soil is the relatively dark material in the center portion of the trench. The pervasively fractured rock in the background is coarse-grained basalt. The gnomon rod is 46 cm long.

made earlier decisions to spend extra time at previous localities not knowing what awaited us. Our oxygen supply limited the time we could spend at Shorty to a clearly nonnegotiable 35 minutes. The normal "housekeeping" duties of dusting and reading the gravimeter demanded their usual but necessary due. Then, in addition to the expected complexities of lunar impact geology, there was an unexpected discovery.

Shorty Crater has features consistent with an impact origin although no one feature is conclusive in itself (Fig. 5). Subfloor basalt appears to dominate the few blocks at the rim. One of these blocks is pervasively fractured and may be shocked. The crater wall is locally blocky, but for the most part covered by fine debris. It has several radial and transverse changes in texture and albedo. There is no continuous bench in the crater wall; however, several well-defined lobes of coarse and fine debris, similar to that in the walls, extend out on the floor and may be the relics of such a bench. The blocky materials on the flat floor are highly fractured but otherwise are uniform in texture. Parallel fracture organization is strong in some blocks.

Full interpretation of these crater features would require more extensive field investigation than was possible. The distribution and character of the basalt blocks, the flat, blocky floor of the crater and the lack of a continuous bench suggest that the crater-forming event penetrated to a relatively resistant bedrock unit after excavating a heterogeneous regolith zone about 10 m thick. Within the regolith zone, however, there are probably discontinuous zones of material of varying texture and color that have caused local irregularities in slumping and in albedo.

The unexpected discovery at Shorty was the presence of at least three deposits of very fine-grained orange soil (Fig. 6). There were also numerous indications of fine-grained black soil deposits which, along with the orange soil, were subsequently determined to consist almost entirely of glass spheres and devitrified glass spheres of uniform basaltic composition (*5*). Two of the orange soil deposits are near the rim crest of the crater, whereas the other deposit is exposed on the west wall. The appearances of the deposits have many of the characteristics of fumarolic alteration halos and it was in anticipation of this perhaps being a lunar fumarole that we conducted our observations and sampling activities.

One deposit of orange soil was trenched across its trend along the crater rim. Here it was sampled in detail and the following relationships were observed:

1) The deposit is about 1 by 4 m in area at the surface and is elongate parallel to the rim crest.

2) It has no topographic relief relative to other rim surfaces (also true for the other rim deposit).

3) Dark gray surface material forms a surface layer about 0.5 cm thick over both the deposit and surrounding light gray materials. There is an orange tint to this surface material directly over the deposit.

4) The contact of the deposit with light gray debris on either side is irregular in detail but essentially vertical to a depth of at least 20 cm.

5) From both vertical contacts inward, the deposit grades from a yellowish orange to a reddish orange over about 10 or 15 cm.

6) The reddish-orange inner portion of the deposit is moderately coherent and is crossed by at least two apparent joint sets.

7) After the mission, it was observed during the unpacking of a sample from the reddish-orange zone that a clod was sharply and concentrically zoned inwards from orange brown-gray to bluish gray.

8) Examinations of the outer surface of the core tube drawn from the deposit showed that the orange soil changes sharply to a black soil at a depth of about 25 cm. The black material extends to a depth of at least 70 cm.

The above geometric constraints and the lack of contamination, the age relations, and the petrographic characteristics (*5, 8, 9*) of this orange/black soil deposit require that the following hold true: (i) The glasses were deposited at the lunar surface on top of a major unit of subfloor basalt or on an early regolith unit derived from the subfloor basalt. (ii) The glasses were then almost immediately protected from regolithic mixing at the surface, by a thin basaltic flow, or some other blanketing unit, for about 3.7 billion years (*8*). (iii) They were then ejected onto or intruded into the rim of Shorty less than 9 million years ago (*9*), producing very restrictive geometric relations.

Van Serg Crater—dark breccia. It was hoped that the relatively fresh appearing 90-m-diameter crater named Van Serg would provide an impact-generated sample of the section of units lying above the basalts of the valley. Located just south of the craters Cochise and Shakespeare, Van Serg might penetrate and provide samples of ejecta from these much older craters. After the discoveries at Shorty, it also was considered that the crater might provide additional insights into the possible fumarolic or volcanic origin of the orange soil. As with Shorty Crater, the unexpected again was encountered.

All of the observed features of Van Serg are consistent with an impact origin (Fig. 7). However, unexpected dark matrix-rich regolithic breccias, clearly different from the massif breccias, were found to be the dominant rock type on the blocky rim and equally blocky ejecta blanket. The dark breccias contain a few percent of light-colored clasts, later found to resemble rocks in the massifs (*5*). Such breccias had not been recognized elsewhere in the valley during our investigations.

A few of the Van Serg breccias are intensely fractured and very friable and others are mixed or covered with black glass. No basalt was recognized although one fragment was obtained as a glass-coated grab sample (*5*). A dark surface-cover a few centimeters thick exists over a light gray debris in at least some of the interblock areas and may cover all of the ejecta blanket and rim. Most blocks are partially embedded in this material.

The crater wall is very blocky and is interrupted by a nearly continuous bench about halfway down into the crater. Rocks below the bench are slightly darker in color than those above. Fans of fine dark gray debris locally cross over the rim and down the upper wall but generally terminate at the bench. The crater floor is also very blocky with some intense shattering of blocks, although in contrast to Shorty Crater, the blocks are much larger. Some of the floor blocks are coarse blue-gray fragment-rich breccias with light-colored clasts up to 1 m in diameter. No examples of these coarse breccias were recognized on the rim, suggesting that they form the top of a distinct older breccia unit.

Field interpretation of the features of Van Serg Crater suggests that the crater-forming event penetrated through a few meters of dark floor material into a relatively resistant and structurally continuous layer of dark matrix-rich breccia. This breccia probably was ejected from the craters Shakespeare or Cochise. The structural continuity of the upper surface of the breccia layer is also suggested by the presence of the continuous bench in the crater wall. Also, the nature of the ejected fragments of these breccias on the rim and ejecta blanket of Van Serg suggests that they are largely impact-indurated equivalents of dark floor material. Finally, the blue-gray fragment-rich breccia in the bottom of Van Serg indicates another debris blanket at depth.

The general blue-gray and coarsely fragmental nature of the floor breccias of Van Serg, and the distant visual observation of a thick northward dipping blue-gray unit above the subfloor basalt in the north wall of Cochise opens the possibility of a major new breccia unit in this portion of the valley. No investigation of this possibility could be made and the possible origins and structural implications of such a unit are not yet clear.

The interpretation of the dark surface over light gray debris at Van Serg, and also at Shorty, is not clear. It may be caused by a combination of the disintegration of dark matrix breccias and of regolith formation. On the other hand, the same process that produced the mantling relationships of the dark floor material may have acted at both Van Serg and Shorty.

Stratigraphic Summary

It is premature to come to any final conclusion on major portions of the stratigraphic sequence in the Valley of Taurus-Littrow or on the nature of the processes by which this sequence came into being. The laboratory and photogeological investigations have yet to be completed and integrated fully with the field observations. However, it is possible now to summarize the probable stratigraphic sequences indicated by the field data and to list some of the alternative interpretations for the petrogenesis of the major rocks and soils of the valley.

The massifs. The oldest through youngest stratigraphic units which are present as bedrock in the North and South Massifs are as follows: (i) Light gray breccia and crystalline rock as distinctive clasts in the blue-gray breccias. (These clasts may be closely related to the differentiates of an early melted lunar crust.) (ii) Crystalline blue-gray fragment-rich breccias and their metamorphic equivalents. (These breccias are possibly quenched and brecciated impact melts produced during the formation of the large lunar basins or even older events.) (iii) Crystalline, vesicular, tan-gray matrix-rich breccia and any metamorphic effects associated with its intrusion into the blue-gray breccias. (These intrusions may be partially molten impact breccias, possibly of Serenitatis-age, or polygenetic tuff-breccia eruptives of undetermined origin.) (iv) Foliated layered breccia of low metamorphic grade which is rich in a variety of breccia clasts and which appears to correlate with units near the crest of the South Massif. (These rocks may be representative of the youngest ejecta blankets from large basins.)

There is a general similarity in the visual and lithologic characteristics of the tan-gray breccias and the blue-gray breccias studied at the North and South Massifs. This suggests that a general lithologic correlation can be made across the valley. The differences in rock characteristics may be explained by different ages of formation through similar processes or by different depths of burial. These burial depths are about 1.5 km in the North Massif and about 0.5 km in the South Massif.

The valley floor. Some of the most intriguing stratigraphic and structural problems in the Valley of Taurus-Littrow are those of the valley floor itself and the materials beneath it. Basalt that was taken from the rim of Camelot Crater and that appears to represent the major unit in the valley has been dated at about 3.8 billion years (*8, 9*). Since this basalt cooled, the valley floor has been subjected to a very complex sequence of events. This complexity is indicated by two factors. First, there is the very great *absolute* age, about 3.7 billion years (*8*), of the orange/black glass deposit at Shorty Crater and its relatively young, most recent *exposure* age of approximately 9 million years (*9*). Second, there is the discovery of thick breccia units of regolithic character at Van Serg Crater.

Glasses similar to the orange/black glasses have been reported mixed with basaltic debris in the dark floor materials (*5*). The apparently recent mantling over the valley craters by dark floor materials and the apparently thin rego-

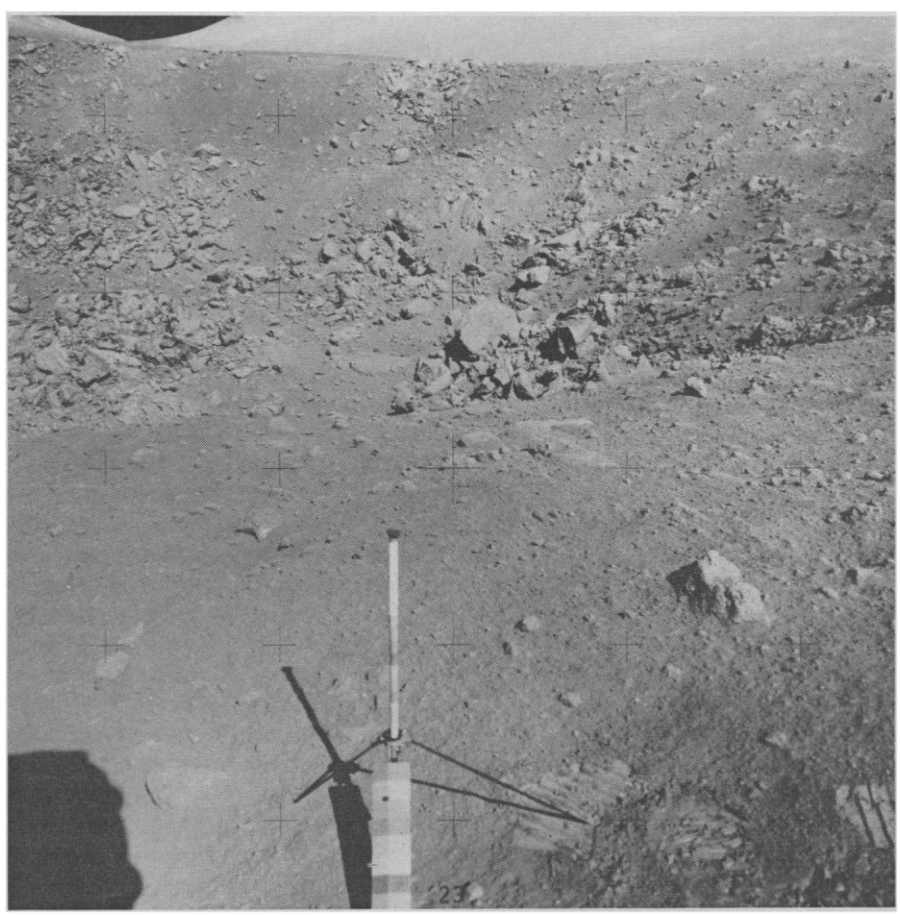

Fig. 7. View of the northwest wall of Van Serg Crater (about 90 m in diameter). The dark fans on the far inner wall terminate at the top of a nearly continuous bench. The extremely blocky nature of the floor, wall, and rim contrast sharply with that of Shorty (Fig. 5). The upper portion of the gnomon rod is about 30.5 cm long.

lith developed on these materials impose other general constraints on their stratigraphy and origin. The indications are very strong that since the formation of a widespread mantling deposit of orange/black glass about 3.7 billion years ago, some other process has acted more or less continuously to recycle this glass and produce the presently observed young mantling relationships.

In view of the presence of certain components that volatilize at low temperatures in the orange/black glasses (*5*), it is possible that impact events in the general size range of Shorty will trigger the release of such gas as a fluidizing medium for local remobilization and extrusion. The previously described field characteristics of the orange/black glass deposits and the dark floor material are reconcilable with a process of this nature acting in and around impact craters 25 to 100 m in diameter. Also, a similar process has been observed to occur at the 500-ton Dialpack event (*10*) in Canada as a result of the explosive pressurization of water-saturated sand in a layer well below the floor of the crater produced by the explosion.

The other complexing factor in the interpretation of the valley floor is the great quantity of coherent regolithic breccias at Van Serg relative to other portions of the valley. This may be related to the position of that crater on superposed ejecta blankets from Cochise and Shakespeare. Also, the apparently rapid degradation of the Van Serg-type, dark matrix-rich breccias in the valley environment may account for their rarity around other, possibly older craters, such as Shorty.

If one takes into account the above considerations and the field evidence described previously, the following composite subsurface sequence seems probable for the valley from the surface downward:

1) An average of 15 to 20 cm of new, very weakly coherent regolith on the present valley floor.

2) An average of 1 to 2 m of mixed basaltic debris and orange/black glass generally having mantling relationships to most large craters and boulders.

3) A zone of variable thickness, possibly from 10 to 20 m, containing interlayered dark floor material and the ejecta blankets from Steno- and Camelot-age impact events. Some of this material may be similar to the Van Serg breccia, but those breccias also suggest much variety in source and texture within the zone.

4) A zone gradational with sequence 3 consisting of regolithic debris derived from the subfloor basalts and possibly interlayered with orange/black soil.

5) A basalt flow a few meters thick, presently discontinuous in distribution, but which protects portions of underlying deposits of orange/black soil.

6) A deposit of orange/black soil of unknown thickness, also presently discontinuous.

7) A few meters of regolith developed on underlying basalt.

8) At least 100 m of coarse-grained subfloor basalt, the fine-grained upper portions of which have been largely incorporated into overlying regolith. The general uniformity in the texture of ejected basaltic blocks throughout the valley strongly suggests a thick cooling unit.

The light mantle. All indications are that the light mantle was deposited as a single dynamic event on the dark floor materials that cover the valley. The materials of the light mantle appear to be identical in type to those of the South Massif talus (*4*) although vertical size-sorting has probably occurred. Our observations tend to support the tentative conclusion of Shreve (*11*) that the light mantle originated through an avalanche, or fluidized flow, of South Massif talus with fluidization provided by solar wind gases adsorbed within the original talus materials. An avalanche origin also is supported by the studies of Howard (*12*); however, Howard discounts the possibility of gas fluidization.

The probable internal structure of the light mantle from the surface down appears to be as follows: (i) Five to ten centimeters of medium gray soil (regolith?). (ii) About 1 m of light gray debris without many fragments greater than a few centimeters in diameter. (iii) Variable thicknesses of light gray material with numerous rock fragments larger than a few centimeters in diameter. (iv) A basal zone of mixing between light mantle and dark floor materials which may be marbled in texture.

Fluidized flows may have been a continuing factor in the depositional history of the valley and, in fact, in the depositional history of any lunar terrain adjacent to steep mountain fronts or crater walls. Their importance may have been much greater in the past than in present, more quiescent times. However, the side effects of such flows may go a long way toward explaining the characteristics of many reported transient events on the moon.

Concluding Remarks

This is the last major report of observations made by the crews during the Apollo explorations of the earth's moon. I am confident that the future holds many other such reports as man continues his exploration of the earth's frontier and his use of the space environment. It is my belief that, as in past explorations, man's abilities and spirit will continue to be the foundation of his evolution into the universe. Full satisfaction from this evolution only comes with being there. The Apollo crews deeply appreciate their singular opportunity of having been there.

Few, if any, exploration efforts in history better illustrate the inherent ability that exists within a large group of experienced and motivated men and women to plan, to implement the plans, and then to react with clear good judgment to the unexpected. The success of this effort in Apollo is to the everlasting credit of the thousands of scientists, engineers, and managers who made it possible. This report is our acknowledgment to them.

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13. This investigation was performed with Captain Eugene A. Cernan and with the able scientific and verbal assistance of Dr. Robert A. Parker. Captain Ronald E. Evans and the National Aeronautics and Space Administration provided transportation to and from the field area. The organization of thoughts and ideas in this report has come in no small way through conversations both before and after the mission with the geologists of the U.S. Geological Survey and the Lyndon B. Johnson Space Center, and with their many associates from the nongovernmental scientific community. Assistance in the editing and production of this report was provided by E. W. Wolfe, W. R. Muehlberger, B. K. Lucchitta, P. R. Brett, L. T. Silver, J. P. Allen, and G. A. Swann. Their help and support is gratefully acknowledged.