Reports

Apollo 16 Exploration of Descartes: A Geologic Summary

Abstract. *The Cayley Plains at the Apollo 16 landing site consist of crudely stratified breccias to a depth of at least 200 meters, overlain by a regolith 10 to 15 meters thick. Samples, photographs, and observations by the astronauts indicate that most of the rocks are impact breccias derived from an anorthosite-gabbro complex. The least brecciated members of the suite include coarse-grained anorthosite and finer-grained, more mafic rocks, some with igneous and some with metamorphic textures. Much of the traverse area is covered by ejecta from North Ray and South Ray craters, but the abundance of rock fragments increases to the south toward the younger South Ray crater. The Descartes highlands, a distinct morphologic entity, differ from the adjacent Cayley formation more in physiographic expression than in lithologic character.*

Orion, the lunar module (LM) of Apollo 16, landed at latitude 8°59′29″S and longitude 15°30′52″E, at the west edge of the Descartes Mountains. It was about 50 km west of the Kant Plateau, part of the highest topographic surface on the near side of the moon (Figs. 1 and 2). This was the only planned landing in the central lunar highlands. The crew explored and sampled an area characteristic of both cratered terra plains and rugged hilly and furrowed terra, units never before directly sampled. The area is underlain by thick impact breccias rather than the volcanic rocks predicted from photogeologic studies.

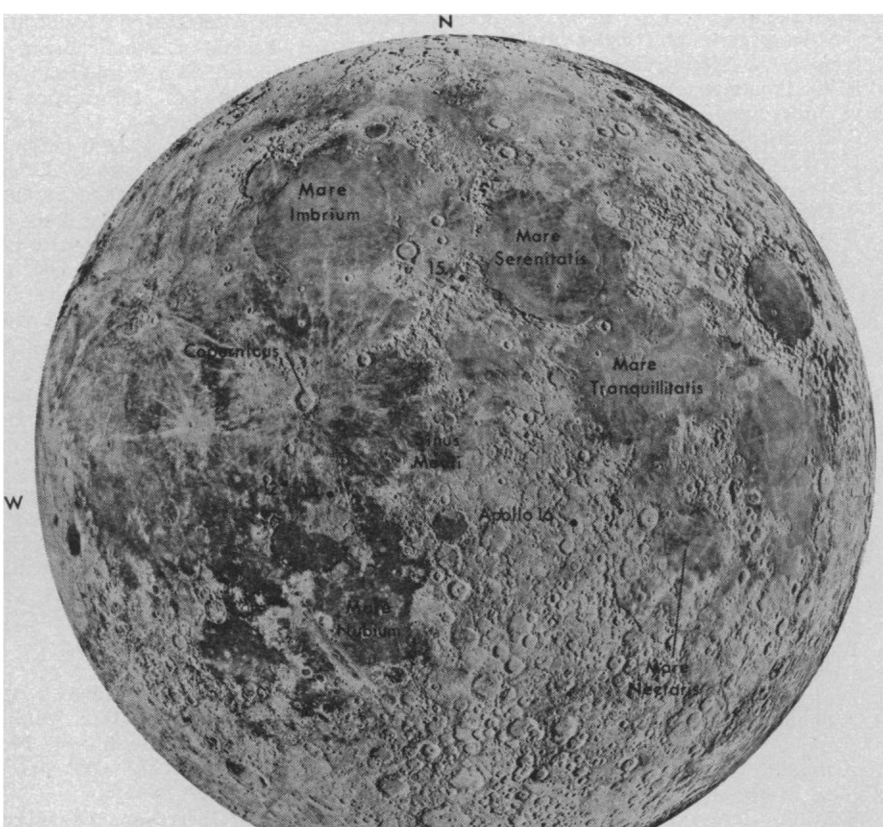


Fig. 1. Composite photograph of the full moon showing the maria surrounding the Apollo 16 central highlands area and the Apollo landing sites to date.

The three sorties by vehicle from the LM extended 1.4 km west, 3.7 km south, and 4.4 km north, comprising a total traverse distance of 20.3 km. Ninety-five kg of rocks and soil were collected, 1765 photographs were taken on the surface, and the total time spent outside the LM was 20 hours, 14 minutes. The lunar locations of all samples and the lunar orientations of 45 rocks have been determined.

Geologic studies of the Descartes region began more than 10 years ago with telescopic observations (*1, 2*) and continued with the better resolution of Lunar Orbiter and Apollo photography (*3–6*).

Upland plains-forming units, such as the Cayley formation, cover about 7 percent of the near side of the moon and occupy more area than any other identifiable unit except mare material. Characteristically, they form low-relief plains in the floors of older depressions. Craters with diameters of 300 m to 2 km are abundant on most of the surfaces. Near the landing site the formation is divided into smooth and irregular subunits (*5*), but only the irregular unit occurs within the planned traverse area. A volcanic origin was preferred by most workers (*1–8*), although it was recognized that photogeologic studies could not preclude impact or mass-wasting origins (*1, 6*). Elsewhere, Cayley materials appear to lie on Fra Mauro deposits and, in turn, are covered by mare basalts (*2, 7*).

On the three traverses two distinct morphologic units were investigated, the terra plains mapped as Cayley formation, and the Descartes Mountains or highlands (Fig. 2). Specifically, the study of the Cayley formation was planned to determine the lateral variation of the stratigraphic section between North Ray and South Ray craters (Fig. 3), the petrology of the formation, and the characteristics of the regolith throughout the area. The prime Cayley sampling areas were at the LM and west of it, where Flag and Spook craters would permit sampling to depths of about 60 m. Deeper parts of the Cayley formation, which have been excavated by the larger North Ray and South Ray impacts, were accessible for sampling on the rim of North Ray crater and in the bright ray deposits of South Ray.

Materials of the Descartes highlands form hilly and mountainous regions that are topographically higher than the Cayley Plains (Fig. 2). The Descartes unit is one of the better examples of rugged terrain that does not appear to be related to craters or multiring basins. Milton (*2*) pointed out that the unit forms a deposit of considerable thickness, perhaps 1 km, and that its relief is largely intrinsic. Milton (*2, 7*) and Trask and McCauley (*6*) interpreted positive landforms in the Descartes highlands as volcanic. The stratigraphic relationships with the adjacent Cayley formation were ambiguous, so that younger, older, and contemporaneous interpretations all were possible. The north flank of Stone Mountain was the principal sampling area for Descartes highland materials (Fig. 3).

The Kant Plateau occupies much of the central region of the Theophilus quadrangle (*2*) (Fig. 2). Materials of the Kant Plateau were not believed to underlie the Apollo 16 site, but ejecta derived from the plateau might be present in the traverse area. Materials

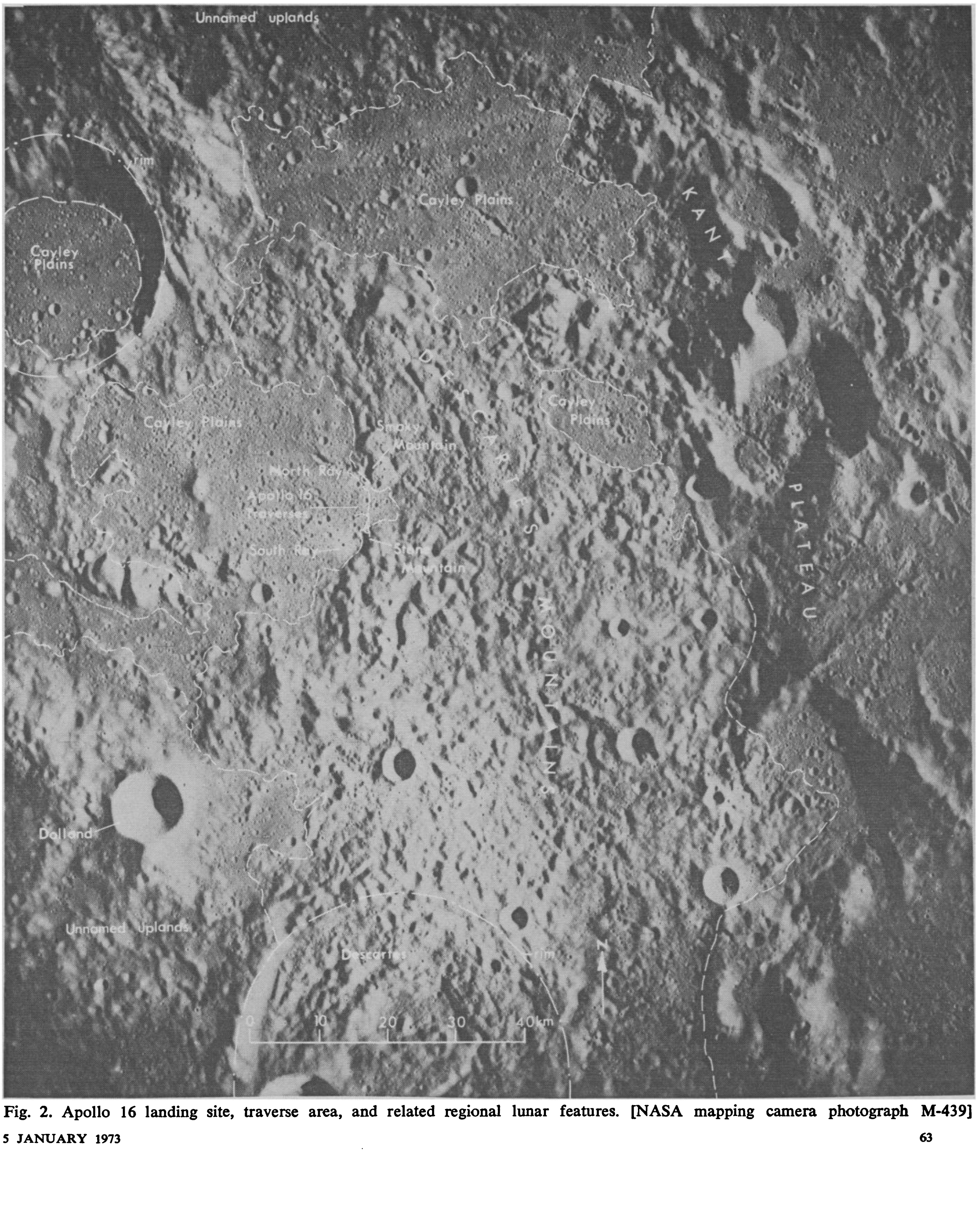


Fig. 2. Apollo 16 landing site, traverse area, and related regional lunar features. [NASA mapping camera photograph M-439]

of the plateau were interpreted by Milton as volcanic, although he noted a lack of distinct volcanic landforms.

Ray materials from North Ray and South Ray craters were shown on premission maps as mantling a considerable part of the traverse area, both on the plains and on the adjacent highlands (*4, 5*). Impact craters of Imbrian to late-Copernican age were mapped throughout the region. In addition, rimless to low-rimmed elongate

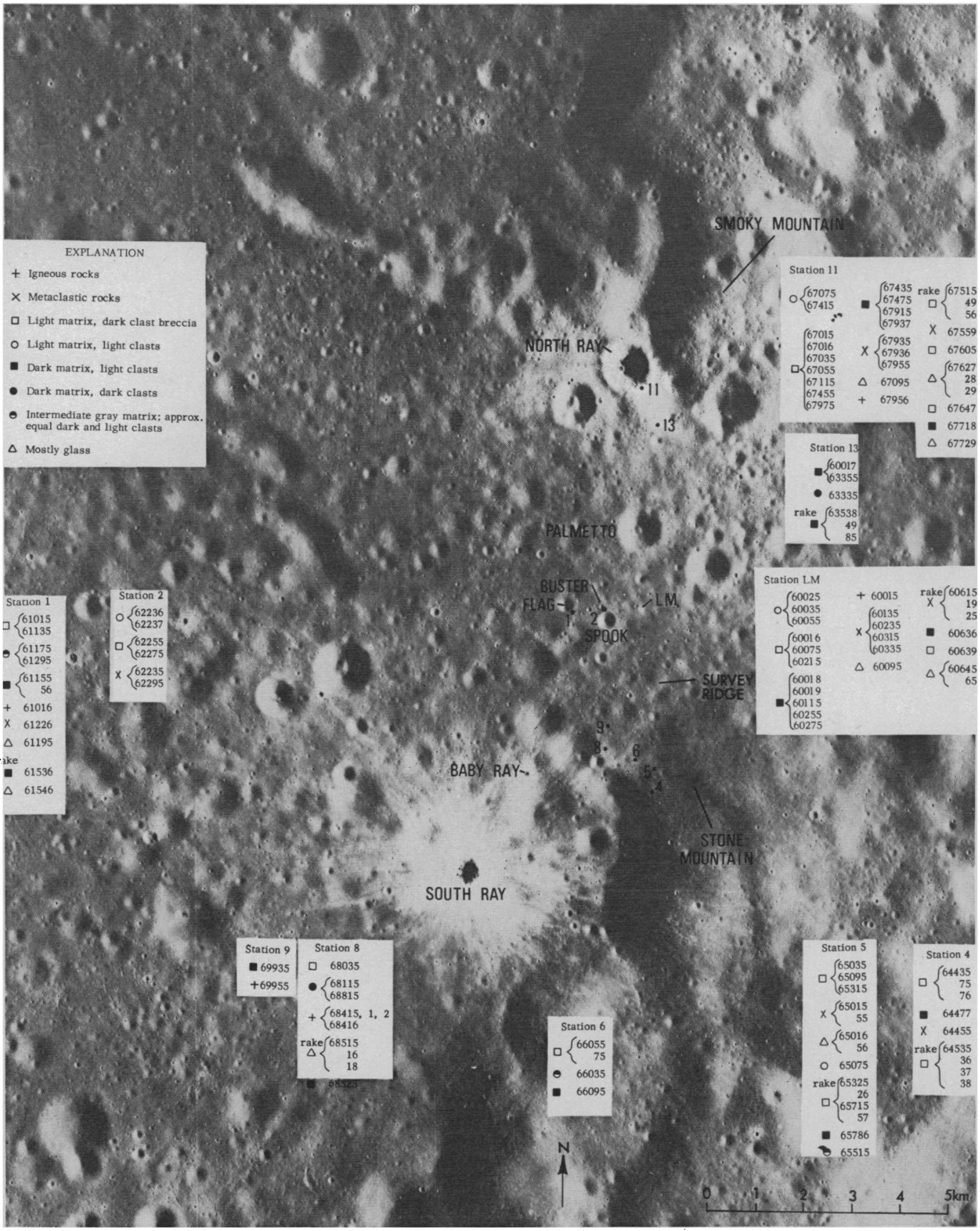


Fig. 3. Apollo 16 traverse stations, craters, and other local landmarks, and the distribution of rock samples larger than 25 g. The preliminary rock classification was based on megascopic observations. [NASA panoramic camera photograph 4623]

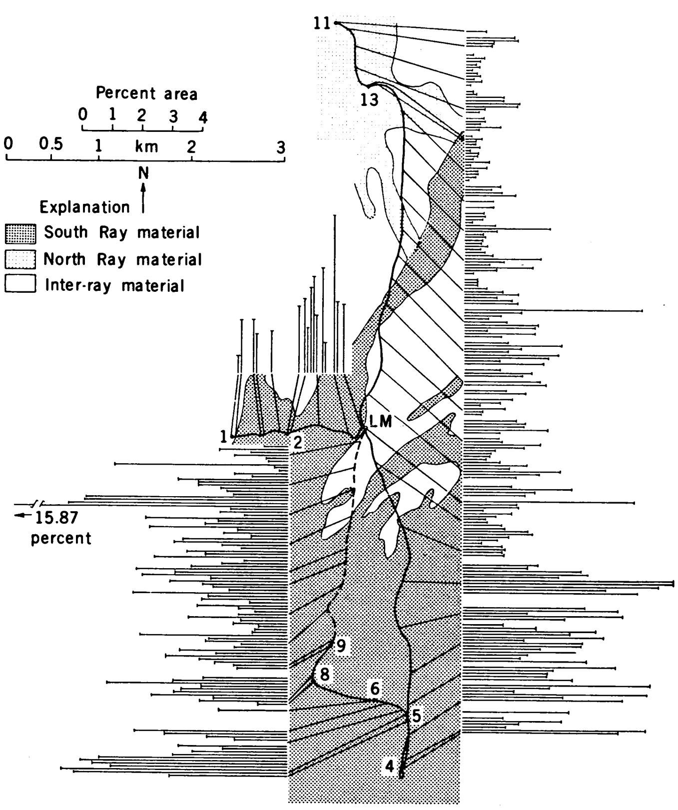
depressions that were interpreted as either secondary craters from Theophilus or of internal origin were mapped. The rarity of volcanic rocks observed or sampled suggests that the secondary crater hypothesis is probably the correct one. Topographic benches on the flanks of Stone Mountain, and ledges and albedo bands in the walls of several craters suggest internal layering in some exposed slopes.

Surficial materials. Broad areas of fresh, blocky debris on the surface correspond roughly to the radial ray patterns mapped around North Ray and South Ray craters, the two most apparent sources of surface debris on the Cayley Plains (Fig. 3). The abundance of rock fragments greater than 2 cm across increases progressively from north to south over the entire traverse area (Fig. 4). Typically, fragments greater than 2 cm in the ejecta of North Ray crater cover considerably less than 1 percent of the surface area (Fig. 5a), whereas abundances of as much as about 7 percent are common south of the LM area in rays from South Ray crater (Fig. 5b).

Rays from South Ray crater extend at least 9 to 10 km from the crater into areas west and southeast of North Ray crater. They are superposed on the older North Ray ejecta. South Ray crater ejecta also appear to mantle much of the surface of Stone Mountain in the vicinity of stations 4 and 5 (Fig. 3). The wide extent of these rays greatly increases the possibility that ray material rather than materials derived from local bedrock was sampled at many of the traverse stations. Ejecta from Baby Ray crater overlie those of South Ray and are therefore youngest of all; samples from this smaller and very fresh crater might have been found at stations 8 or 9. The mapped ejecta of North Ray extend shorter distances outward (less than 3 km south into the traverse area) than do those of South Ray, and bright rays are not so prevalent. This apparent difference in distribution presumably is the result of the greater age of North Ray crater and a greater amount of "weathering" of its ejecta.

Rocks exposed on the lunar surface tend to become more rounded, more deeply buried, and more filleted with age. Boulders in the vicinity of South Ray crater and in its mappable rays are more angular than those in the vicinity of North Ray crater. However, the angularity of blocks must be used with caution in distinguishing South Ray from North Ray ejecta when the relative resistance to erosion is not known. By the same reasoning, estimates of relative ages are risky except when rocks of similar strength can be compared. Useful measurements were made, however, on the size-frequency distribution of fragments along the Apollo 16 traverse routes, partly shown in Fig. 4. Most resolvable fragments range in size from 2 to 40 cm; a few are as much as 90 cm in diameter. Larger blocks are present locally, but they are commonly too distant from the camera to be included in the measurements. The most abundant resolvable fragments are in the size class 2 to 5 cm, which typically constitutes 25 to 90 percent of the area covered by fragments. Those in the size class 5 to 10 cm are second in abundance.

On all the Apollo missions it has been difficult to determine the nature of the local bedrock by sampling through a regolith of surficial debris,



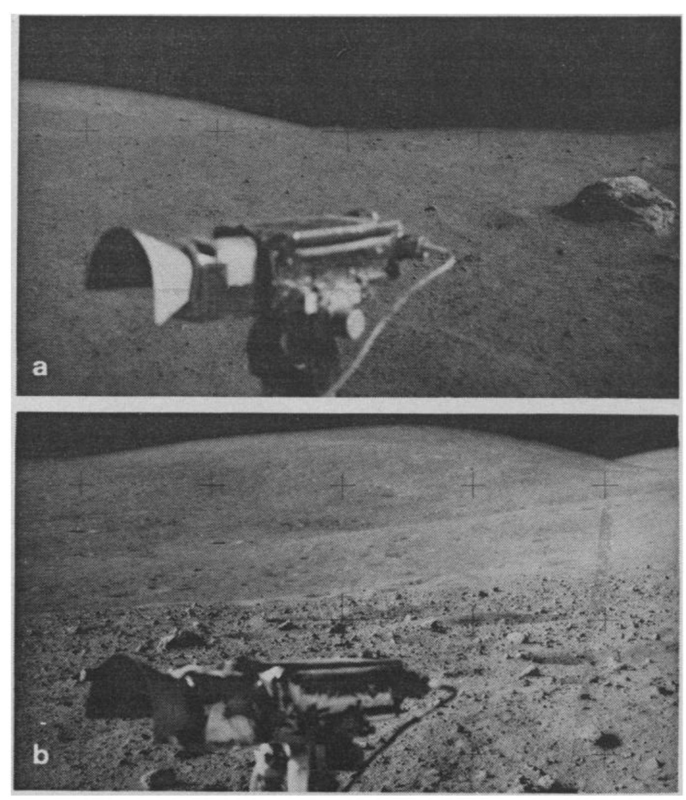


Fig. 4 (left). Frequency distribution of fragments larger than 2 cm counted in 324 surface photographs taken from the vehicle along the Apollo 16 traverse routes. The varying bar lengths represent the percentages (percent area scale) of the area covered by the fragments. The kilometer scale refers to the traverse map, where the lines show the traverse route and the numbers refer to sampling stations. Fig. 5 (right). (a) Typical fragment population about 1 km southeast of the rim of North Ray crater. Fragments cover 0.2 percent of the surface. The large rock to the right is approximately 2 m in diameter. [NASA photograph AS16-111-18146] (b) Fragment population in the bright ray area (Survey Ridge) about 5 km northeast of South Ray crater. Fragments cover 7 percent of the area. [NASA photograph AS16-110-17895] a heterogeneous mixture of rocks and soils derived from underlying bedrock or older regolith and contaminated by an unknown amount of ejecta from distant impact events. The Apollo 15 crew found outcrops of mare basalt at the edge of Hadley Rille. The Descartes terrane in the area traversed by Apollo 16 does not contain bedrock protruding through the regolith; therefore, the astronauts had to rely on fresh, blocky crater rims and bright ray deposits to provide samples derived from beneath the regolith. On the basis of the smallest blocky and flat-bottomed craters, the regolith thickness is estimated to be 10 to 15 m over the site. Blocky debris with recognizable planar structures forms a bench about 10 m below the crater rim of Buster crater at station 2 (Fig. 3). This bench is interpreted as local bedrock or possibly an overturned layer of Spook crater rim material; it could, however, be an isolated large block within the regolith.

The bulk chemical compositions of Cayley soils determined by the Preliminary Examination Team (*9*) show a surprising uniformity throughout the traverse area. The rock compositions show a slightly larger range, but still have remarkably little variation. The rocks are roughly equivalent in composition to anorthosite and anorthositic gabbro. This indicates that the criteria of texture and albedo used in distinguishing the several breccia types probably reflect variations in their history rather than in their source materials (*10*).

The presence of high-albedo regolith under a darker surface layer at all sample stations, with the possible exception of station 5, suggests that the surface material darkens with time and that the entire thickness of the high-albedo regolith layer was deposited in a single event. Studies of the returned cores should shed light on the time sequence of the layers preserved.

Cayley formation. The Cayley formation has been penetrated by craters to a depth of approximately 200 m at North Ray crater (Fig. 6), to depths of 50 to 60 m west of the LM, and to unknown depths at several localities over a distance of about 4 km between the LM and Stone Mountain. Sampling of South Ray ejecta from its conspicuous rays may have provided both light and dark materials from as deep as 150 m. The light rays near the crater give the highest albedo readings yet measured (55 percent). These are presumably a result of the anorthositic composition of the ejecta, and are measurable with the high resolution of the telephoto camera system. North Ray and South Ray craters have penetrated a topographic range of more than 300 m (Fig. 6); this could represent the stratigraphic range of Cayley samples if essentially horizontal layering is assumed.

Heterogeneous fragmental rocks are the dominant lithology of the Cayley formation at the Apollo 16 site. The rocks closely resemble in texture some samples collected by the Apollo 15 crew from the Apennine front and do not exhibit the extreme multiple brecciation and metamorphism of the Apollo 14 samples. Although several distinctly different rock types are present, breccias with light and dark matrices dominate the surface debris that was sampled and photographed. Significant variations in the proportions of breccia types appear in the ejecta of each major crater sampled, but there do not appear to be any basic differences between the rock assemblages collected from North Ray and South Ray craters.

The few crystalline rocks collected range from anorthosite to feldspar-rich gabbros and include minor amounts of fine-grained, highly feldspathic vuggy

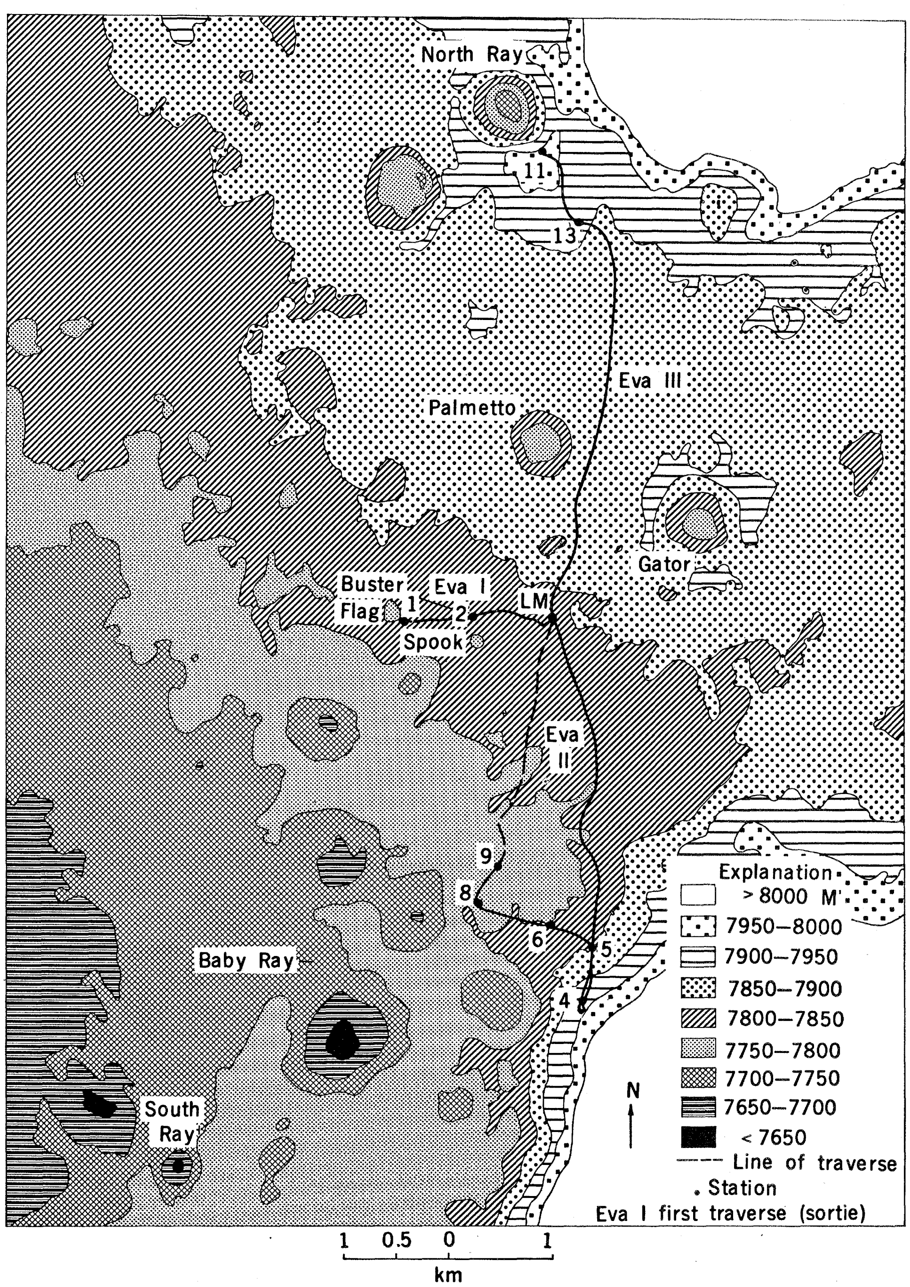


Fig. 6. Hypsographic map of the Apollo 16 landing area showing the regional distribution of topographic zones in 50-m increments. The elevations are from a topographic map of Descartes (*19*). The depth of South Ray crater was modified from postmission photography. The line of traverse is dashed where approximate.

igneous rocks (Fig. 3). These were collected from the ray deposits from South Ray crater, the deepest available source of fresh rocks from the Cayley formation. One rock of this type was collected on North Ray crater; it is of uncertain origin with respect to South Ray crater. The more abundant type of crystalline rock is metamorphic, probably representing recrystallized fragmental rocks composed of similar feldspar-rich materials, and was collected throughout the site. These are the metaclastic rocks of Wilshire *et al.* (*11*). They have also been interpreted as products of contact metamorphism (*9*).

If the igneous rocks represent large clasts within the deepest breccias sampled from beneath the Cayley Plains, then it is reasonable to propose a succession of increasingly fragmented rocks toward the surface that would account for the textural and albedo differences (for example, the glass content) in all the rocks which otherwise may have similar bulk compositions. This model would also explain the combined features of crude local stratification and complex discontinuities within the same crater wall, like those in both South Ray and North Ray craters.

Evidence for layering within the Cayley formation is derived from both the surface photography and the distribution of rock types, as classified by Wilshire *et al.* (*11*) (Fig. 3), and is shown by North Ray and South Ray craters (Figs. 7 and 8 and cover). Our classification scheme differs from that used by the Preliminary Examination Team (*9*): It involves a megascopic division of breccia types according to the proportions of light and dark materials in both clasts and matrix, and the assumption that both single- and multiple-impact breccias are present and can be separated into classes. If an anorthositic complex is the target rock for a major impact, then breccias will be produced in which metaclastic debris or partial melts of the parent material, or both, will constitute a dark matrix surrounding shocked light-colored anorthosite clasts. If this, in turn, is the target rock for a second impact, it will produce clasts derived both from the dark matrix and from the coherent parts of the light clasts. The remaining light anorthosite debris will be mobilized to become the light matrix of a mixed light- and dark-clast breccia. The different proportions of clast types will produce striking differences in the appearance of the hand specimens, but will not appreciably change the bulk chemical composition of the resulting rocks.

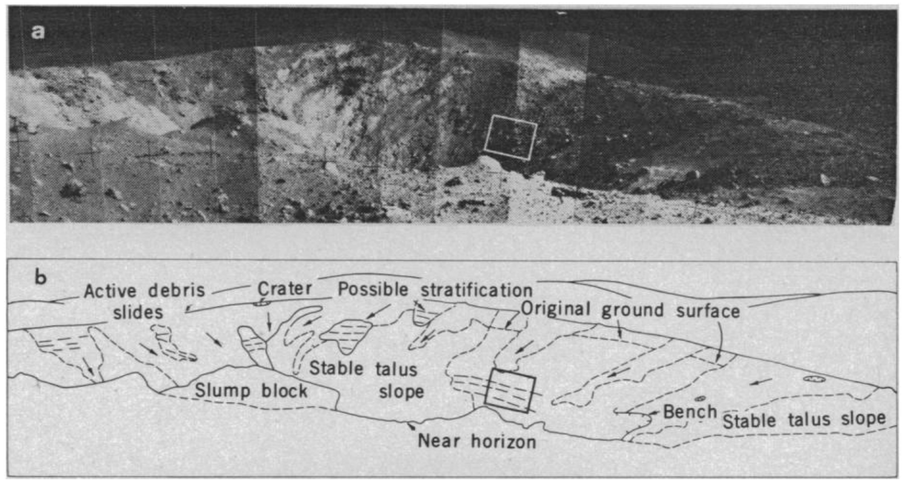


Fig. 7. (a) North Ray crater wall photographed from the southeast rim near station 11. The opposite rim is about 1 km away. House Rock is to the right of the panorama. [NASA photographs AS16-106-17252 to AS16-106-17262] (b) Sketch of features observed in (a). The area marked by the rectangle is the location in the cover picture.

The sequence inferred, from bottom to top of the Cayley formation, is as follows:

1) A breccia of anorthositic gabbro and metaclastic crystalline rocks exposed in the lower half of South Ray crater (below the bench in Fig. 8b) and distributed as hard white angular fragments throughout the ray-covered south half of the landing site. This constitutes nearly 25 percent of the fragment population at stations 8 and 9. The metamorphic or metaclastic crystalline rocks are first-cycle or contact-metamorphosed breccias from the upper zone of this body and are distributed as sparse clasts throughout the site.

2) Very coherent breccias with a dark matrix, which are first-generation breccias derived largely from crystalline rocks (*11*). This unit is approximately 30 m thick, above a bench in South Ray crater, and it is apparently also penetrated by Baby Ray crater. It may be correlative with the lowest stratigraphic horizon in North Ray crater, as represented by House rock and Shadow rock, which were sampled by the crew on the North Ray rim at stations 11 and 13. These dark-colored breccias dominate the fragment population on the Cayley Plains in the southern half of the site.

3) A friable and poorly consolidated light-colored stratum 50 to 100 m thick. It is inferred that this unit lies above the dark-matrix rocks (Fig. 8a), and is the source of the fine light "soils" distributed thinly over much of the rim of North Ray crater. It apparently fills the interstices and thinly covers the blocky ejecta blanket. It may account for the anomalously low proportions of fragments shown in Figs. 4 and 5a.

4) More blocky breccias with a light matrix in the upper 90 to 100 m of North Ray crater wall (cover). The unit appears to be locally stratified as shown by discontinuous linear patterns of coherent blocks in Fig. 7 and the cover picture. These rocks dominate the fragment population of the southeast rim of North Ray crater. They are interpreted by Wilshire *et al.* (*11*) as second-generation breccias. This unit may represent the higher Cayley surface that extends from a scarp about 0.5 km north of the LM to the ridge 50 m high penetrated by North Ray crater (Figs. 3 and 6).

5) Rim materials of an older regolith and mixed debris from the underlying units on North Ray crater rim. This local unit is the overturned flap comprising approximately the upper 30 m of the crater wall (Figs. 7 and 8).

Figure 7 is constructed from one of three sets of photographs taken through a polarizing filter from a single station. The polarimetric data provide additional evidence that only highly shocked breccias, or regolith derived from this type of material, are exposed on the inner walls and rim of North Ray crater; no basalt is identifiable. Telephoto pictures like that on the cover also show that the large blocks are predominantly light-matrix breccias and have a crude planar structure.

In summary, the Cayley formation at the Apollo 16 site appears to be a thick (at least 200 m, possibly more than 300 m), crudely stratified breccia

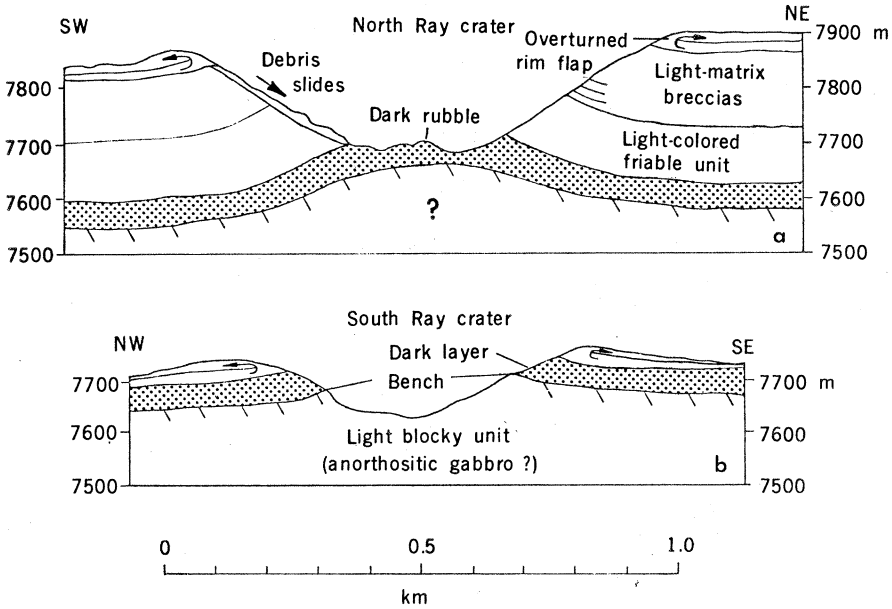


Fig. 8. Schematic geologic cross sections of (a) North Ray and (b) South Ray craters, showing the possible correlation of the dark layer (stippled).

unit whose components are derived from plutonic anorthosite, feldspathic gabbro, and metamorphic rock of similar composition. The elemental composition of the Cayley formation is similar to that observed over large regions of the lunar highlands, as shown by the orbital x-ray experiments of Apollo 15 and Apollo 16 (*12, 13*). The textures and structures of the breccias and the clasts within them resemble those of terrestrial impact breccias. They do not resemble those of volcanic rocks.

Descartes highlands. The materials of the Descartes highlands were the sampling objectives at stations 4 and 5 on Stone Mountain (Figs. 2 and 3). The traverse route in this area is heavily mantled by angular blocky debris, apparently ejected from South Ray crater. The regolith under this blocky material is relatively fine grained, with a few coarse fragments. The crew observed no craters that appear to penetrate bedrock or that expose coarse blocks of underlying materials.

Most of the rock samples collected at stations 4 and 5 on Stone Mountain are light-matrix breccias (Fig. 3). The photographic evidence weighs in favor of a South Ray origin for most of these rocks. However, their similarity to the high concentration of light-matrix breccias at North Ray suggests, as an alternative explanation, that the light-matrix breccias are representative of Stone Mountain as well as the comparably higher elevations on North Ray crater, and thus both may be considered to be true Descartes material.

At station 5, the crew sought and collected a number of more rounded fragments that did not appear to be associated with rays; they were generally from the shielded locations in the crater walls and probably include some Descartes materials, but none has yet been uniquely identified as such.

Seven soil samples, including one double drive tube, were taken at stations 4 and 5. Although variable dilution by South Ray fines is expected, these samples may be dominantly Descartes materials. However, comparisons of these soils with soils from the Cayley Plains (*9*) show marked compositional similarities, adding support to the evidence from the rock collections that the Descartes materials are lithologically similar to the Cayley formation.

The precise nature of the Descartes highlands materials has not yet been established. The available evidence indicates that the Descartes highlands differ from the adjacent Cayley formation more in physiographic expression than in lithologic character. It may be, however, that Descartes material was simply not available for collection at the surface in the traverse area.

Regional relations. If the rocks sampled at this landing site are typical of the upland terra plains and mountainous highlands, then the premare feldspar-rich basalt (*13, 14*) that has been postulated as a stage in lunar evolution (*15*) is no longer a feasible concept. Postmission analysis of the orbital photography has resulted in a series of studies (*16*) pointing to analogs elsewhere on the moon of features in or near the Apollo 16 landing site. Two of these having a direct relationship to the landing site are briefly mentioned here.

Eggleton and Schaber (*17*) present topographic and photogeologic data supporting the hypothesis that the Cayley formation is highly fluidized Imbrium ejecta filling the topographic low areas in the central highlands that surround the Apollo 16 landing site.

Soderblom and Boyce (*18*) determined the ages of nearside and farside terra plains by using the Apollo 16 metric photography. They concluded that all the terra plains studied, including the Cayley Plains of the Apollo 16 landing site, have a narrow range in age and are younger than the Fra Mauro formation, and that the youngest is transitional in age with the oldest mare.

The Apollo 16 results have demonstrated again that the moon is far more complex than predicted on the basis of early studies. The remarkable suite of feldspathic crystalline rocks and breccias from the largest lateral and vertical range sampled to date helps to clarify the origin and history of a significant part of the lunar highlands and make possible more precise statements of new questions.

APOLLO FIELD GEOLOGY INVESTIGATION TEAM*

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* This is a condensation and revision of a report by the Apollo Field Geology Investigation Team for the National Aeronautics and Space Administration, for the Apollo 16 Preliminary Science Report. The condensers, G. E. Ulrich (U.S. Geological Survey, Flagstaff, Arizona) and W. R. Muehlberger, Principal Investigator for Apollo Field Geology Investigations (University of Texas, Austin), assume full responsibility for any distortions of concepts or data developed by other authors of the original report. Very helpful editorial assistance and major contributions to the manuscript were received from G. A. Swann, R. L. Sutton, and M. H. Hait (U.S. Geological Survey, Flagstaff, Arizona) and from H. G. Wilshire (U.S. Geological Survey, Menlo Park, California). Contributions to the work reported here were also made by: R. M. Batson, E. L. Boudette, R. E. Eggleton, D. P. Elston, V. L. Freeman, T. A. Hall, H. E. Holt, J. A. Jordan, K. B. Larson, V. S. Reed, G. G. Schaber, J. P. Schafer, R. L. Tyner, and E. W. Wolfe (U.S. Geological Survey, Flagstaff, Arizona), C. A. Hodges, E. D. Jackson, D. J. Milton, and D. Stuart-Alexander (U.S. Geological Survey, Menlo Park, California), C. M. Duke and J. W. Young (NASA Manned Spacecraft Center, Houston, Texas), A. W. England (formerly at the NASA Manned Spacecraft Center, presently at the U.S. Geological Survey, Denver, Colorado), J. W. Head (Bell Labs, Washington, D.C.), J. J. Rennilson and L. T. Silver (California Institute of Technology, Pasadena).

6 September 1972; revised 17 October 1972

Volatile-Rich Lunar Soil: Evidence of Possible Cometary Impact

Abstract. *A subsurface Apollo 16 soil, 61221, is much richer in volatile compounds than soils from any other locations or sites as shown by thermal analysis–gas release measurements. A weight loss of 0.03 percent during the interval 175° to 350°C was associated with the release of water, carbon dioxide, methane, hydrogen cyanide, hydrogen, and minor amounts of hydrocarbons and other species. These volatile components may have been brought to this site by a comet, which may have formed North Ray crater.*

One of the fundamental characteristics of the moon is its low abundance of the volatile elements hydrogen, carbon, nitrogen, and oxygen and their associated low molecular weight compounds and mineral phases (*1*). Anders (*2*) noted that the low abundances of other volatiles, such as lead, bismuth, and thallium, are probably associated with the accretional history of the moon. The only exceptions to the consistent depletion of volatile elements and compounds in samples from all lunar sites are the enrichments in the soils and selected breccias of elements derived from the solar wind (such as hydrogen, helium, carbon, and nitrogen) (*1, 3*). We now report the first occurrence of a volatile-rich subsurface sample derived from North Ray crater (sample 61221). The volatiles in this sample are believed not to be of solar wind origin, but may have arisen from the cometary impact that created North Ray crater.

Apollo 16 soil sample 61221 contains an unusually large amount of low-temperature volatile components. The sample, collected at station 1 near Plum crater by astronaut Duke, was taken at a depth of about 30 to 35 cm beneath the surface (*4, 5*). It is unusually white in color, much coarser in grain size (median size ranging from 250 to 300 μm compared to 76 to 122 μm for other Apollo 16 soils, exclusive of those from North Ray crater), and distinctly different petrographically from the normal medium-gray surface soil which covered the white soil (*6*). The sample contains an exceptionally small amount of glass agglutinates (8 percent), in contrast to the darker-colored soil 61241 (greater than 50 percent agglutinates) which covers the subsurface sample [table 3 in (*6*)]. McKay and coworkers (*7*) have shown that the percentage of glass agglutinates in a lunar soil provides a relative index of maturity or residence time on the lunar surface; we conclude that the darker upper soil 61241 is a more mature soil than 61221 (*6*). The grain sizes and abundance of agglutinates in 61221 are similar to those of Apollo 16 soils collected at North Ray crater and station 13 (on the ejecta blanket of North Ray crater) (*5, 6*). Further evidence of the similarity of soil 61221 to North Ray crater material is found in the major and minor element chemistry of samples from these two sites. Table 1 gives the composition of these samples as reported previously (*6*). Soils from the North Ray crater site and sample 61221 have low nickel contents (109 to 176 parts per million). The low nickel content, low abundance of agglutinates, large grain size, and major and minor element chemistry of sample 61221 point to a very immature lunar soil, which is probably associated with the North Ray crater event. In contrast, a comparison of the composition of the surface soil (61241) with those of subsurface sample 61221 and of samples collected from stations which are believed to lie on ray material from South Ray crater indicates that the upper material (61241) is probably derived from South Ray crater (Table 1). The relatively nickel-rich soils (316 to 363 ppm of nickel) from the ejecta blanket and rays of South Ray crater (including sample 61241) indicate that it could be the result of the impact of an iron-rich meteorite. Clearly, the mode of origin of North Ray crater was different from that of South Ray crater.

The total carbon analysis of sample 61221 gave 100 ± 10 ppm of carbon, whereas the darker mature soil 61241 overlying it contained 110 ± 10 ppm of carbon (*6*). Moore *et al.* (*3*) have postulated that the majority of the carbon found in lunar soils is derived from the solar wind. In this case, the high carbon content of soil 61221 is inconsistent with its immaturity or apparent lack of exposure to the solar wind. The anorthosite-rich rocks at the Apollo 16 site are extremely low in their carbon contents. Most of the rocks contain less than 6 ppm of total carbon (*6*). Sample 61221, although composed of mostly anorthositic components, typically with less than 6 ppm of carbon, is unusually rich in carbon. Thus, some special origin or genesis is required for this sample to explain its high carbon abundance.

Thermal analysis–gas release studies of 61221 provide further evidence of the unusual nature of this sample. The analyses were carried out by using a computer-controlled interfaced thermal analyzer–quadrupole mass spectrometer