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Apollo 17 Lunar Samples: Chemical and Petrographic Description

Apollo 17 Preliminary Examination Team

The returned samples from five previous Apollo and two Luna missions include basaltic rocks and soils from four mare basins, glassy to crystalline breccias and soils from the Fra Mauro formation and Apennine Front, and highly aluminous, crystalline breccias and soils from two lunar highland sites. Isotopic dating of mare basalts (*1*) indicates that mare volcanism covered a time span of 600 million years beginning about 3.7 billion years ago. Similar studies of breccias (*2*) indicate an intense period of crystallization and imply that formation occurred over a period of less than 200 million years, beginning about 4.0 billion years ago. Some anorthositic breccias from the 2-millimeter to 4-millimeter fragments of Apollo 16 soils have somewhat older crystallization ages of about 4.1 to 4.2 billion years (*3*) and may be remnants of earlier periods of formation. The breccias have undergone many generations of crushing, partial melting, and recrystallization which has changed the initial textures of rocks from the early lunar crust.

These data raise important questions about the history of both the lunar and solar systems. Do the measured basalt ages truly represent a restricted period of lunar volcanism or may there be evidence of younger or older volcanism in unsampled areas? Answers to such questions are crucial to understanding the moon's thermal history and the origin of lunar magmas. Do the ages of breccia formation truly represent a restricted period of the major impacts which shaped the lunar surface or have we sampled only the breccias associated with the last few major impacts? Answers to these questions are of profound importance to studies of the particle flux and accretionary history of the early solar system. Are the breccias too highly modified to identify initial textures of the early crustal rocks from which they were formed? To determine whether the early crust consisted of volcanic material, layered gabbroic complexes, or other possible rock types we must study the textural relations among remnants of these materials.

For the final Apollo mission it was imperative to choose a site that might provide answers to as many of these (and other) questions as possible. From orbit on the Apollo 15 mission the command module pilot reported seeing dark patches that resembled young cinder cones southeast of the Serenitatis basin in the Taurus Mountains–Littrow region (*4*). Steep-walled valleys with more than 2000 meters of relief were also evident in this area. The possibility of relatively young volcanic activity and mountains consisting of a sequence of old, large-scale ejecta blankets made an attractive site for further exploration.

Analysis of high resolution photographs obtained during the Apollo 15 mission showed that a valley, 6 to 10 kilometers in width, between the second and third rings of the Serenitatis basin allowed access to two steep-sided mountains and a dark-mantled valley floor that might produce evidence of young volcanism (*5*). Detailed mapping provided five major photogeologic units for sampling: dark mantling material, a valley-filling rock unit below the mantle, a light gray mantle that was apparently deposited by a slide or avalanche which spread across part of the valley floor, a group of domical, closely spaced hills ranging from 1 to 5 km in diameter (Sculptured Hills), and two steep mountains (North and South Massifs) whose slopes showed boulder tracks that were traceable from possible outcrops to the base of the slopes where some of the boulders lay within sampling range. These boulder tracks originate at various elevations on the massifs and may represent rock types from several different units in what might be a sequence of ejecta blankets from several major impacts.

The lunar module landed within 200 m of the targeted landing point (20°9′55″N, 30°45′57″E) and three traverses were completed (*6*). All traverse stations and geographic locations are identified in an accompanying article (*6*). Three hundred and thirty-five rocks (fragments greater than 1 centimeter across), 73 soils, eight drive tubes, and the deep drill string were collected. Several samples from large boulders were collected at stations 2, 6, and 7. From studies of samples it is clear that the valley fill and dark mantle are mare-type basalts or soils derived from them while the two massifs and the light mantle are various types of breccias and their derivatives, re-

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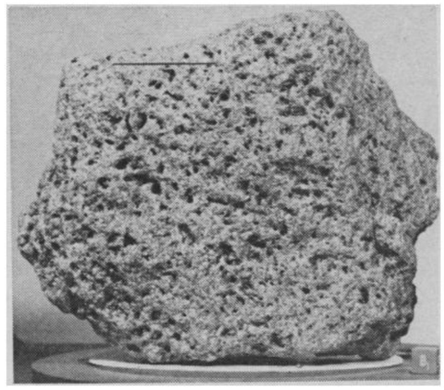


Fig. 1. Typical example of vesicular to vuggy basalts (sample 70017) from the valley floor. Note the coarse diabasic to subophitic texture. The scale is 4 cm.

spectively. At present, it is not clear whether a specific set of rocks can be associated with the Sculptured Hills. In this article we summarize the chemical and petrographic characteristics of a representative suite of the Apollo 17 rock and soil specimens.

Petrographic Characteristics

The Apollo 17 rocks are the most variable returned by any mission. Some have the cataclastic, highly crushed textures common in the Apollo 16 return. Many are crystalline breccias whose petrographic characteristics indicate varying degrees of recrystallization or partial melting. Others are friable and dark gray like the many regolith breccias of previous missions. Others display features typical of the lavas returned from the Apollo 11, 12, and 15 mare sites and a few have the coarse-grained igneous textures typically developed during the slow crystallization from basaltic melts.

In the preliminary examination all rock samples were cleaned with a jet of nitrogen gas to remove dust coatings from their surfaces. The surfaces were then examined and described with a low power binocular microscope. In addition, thin sections from 35 rocks were prepared and studied by conventional petrographic methods. From these examinations the rocks may be placed into seven broad groups plus a few miscellaneous types:

1) Basalts
2) Dark matrix breccias
3) Glass-bonded agglutinates
4) Vesicular green-gray breccias (called anorthositic gabbros by the Apollo 17 crew during the lunar traverses)
5) Blue-gray breccias
6) Layered, foliated, light gray breccias
7) Brecciated gabbroic rocks
8) Miscellaneous: crushed dunite and black, fine-grained material from a dike

Basalts. The basalts are generally vesicular to vuggy (Fig. 1) and similar in both composition and texture to the

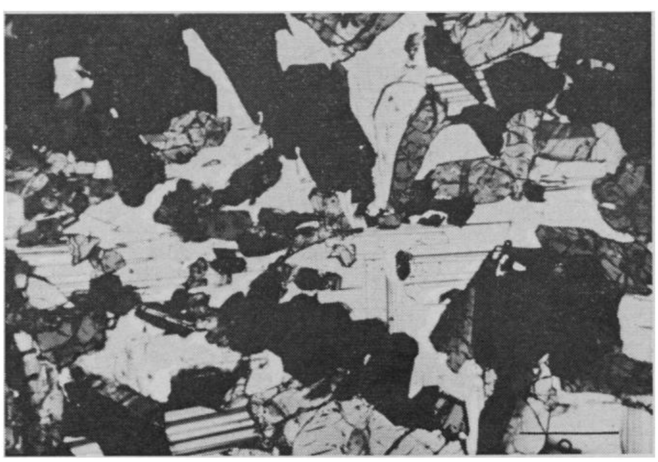
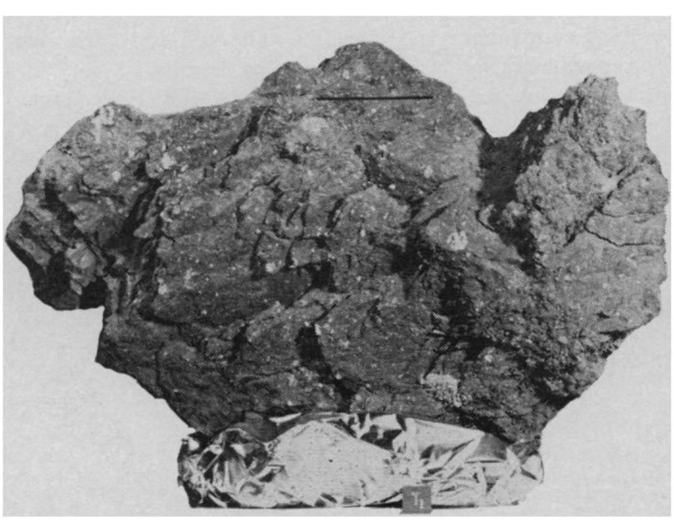


Fig. 2 (left). Thin section of coarse-grained basalt (70035,14) showing late development of twinned, poikilitic plagioclase (light gray) enclosing earlier formed pyroxenes (gray) and opaque minerals (black). The scale is 0.5 mm (crossed polars). Fig. 3 (right). Needles and plates of armalcolite and ilmenite (black) plus skeletal olivine crystals (white) in a devitrified matrix of dendritic intergrowths of pyroxene and plagioclase (74235,11). The scale is 0.5 mm (plane light).



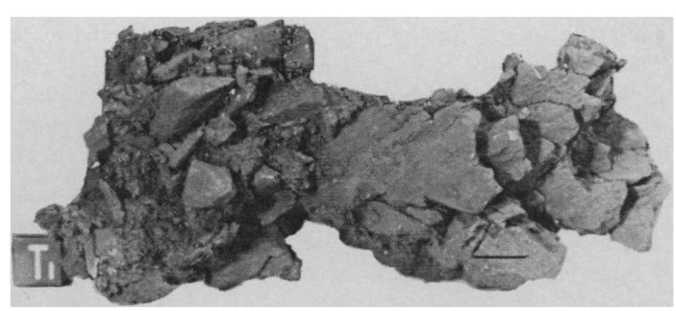


Fig. 4 (left). Dark matrix breccia from Van Serg Crater ejecta (79135). Although this material is coherent enough to maintain fractures which produce small plates and wedges, the fragments are friable and break from the specimen during handling. Note the various light gray clasts some of which are feldspathic breccias. Scale is 4 cm. Fig. 5 (right). One of the large glass-bonded agglutinates of dark matrix breccias (70019) collected from bottom of 3-m-diameter crater. Scale is 1 cm.

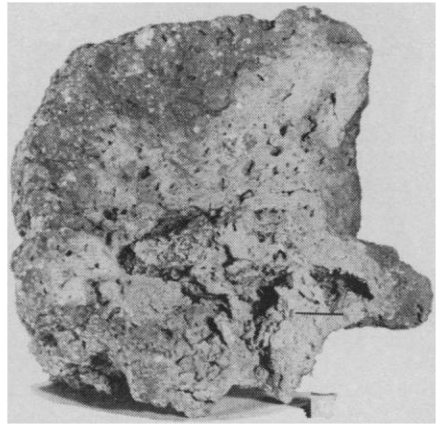


Fig. 6. Green-gray breccia (76015). Although some cavities are smooth walled many have drusy linings, especially the larger ones. The dark gray coating (patina) with numerous zap pits is typical of the exposed surfaces of this rock type. Note the scarcity of macroscopic clasts. The scale is 2 cm.

Apollo 11 type B basalts (7) except for some of the detailed relations between opaque minerals and pyroxene zonation. Modal estimates indicate 45 to 55 percent clinopyroxene (both pigeonite and augite), 25 to 30 percent plagioclase, 15 to 25 percent opaque minerals, and small amounts of olivine. In some instances the olivine occurs as cores of pyroxene but usually it occurs as phenocrysts which generally make up only a few percent of a rock but occasionally up to 20 percent. Grain sizes range from coarse (1 to 2 millimeters) through fine to vitrophyric. In some coarse-grained rocks the clinopyroxene may occur both as coarse, sectorially zoned phenocrysts and as finer grains in poikilitic plagioclase (Fig. 2). There may be also fine, fibrous, or plumose intergrowths of plagioclase and clinopyroxene. Traces of cristobalite, tridymite, an unidentified needle-shaped phase, and very fine perhaps partly glassy material occur interstitially to the larger grains. The vitrophyres (now largely devitrified) contain skeletal crystals of olivine (Fig. 3) which in some instances display overgrowths of clinopyroxene, skeletal ilmenite and armalcolite, and a few patches of plumose intergrowths of plagioclase and pyroxene. For a given sampling area the entire range of textures may be present.

Opaque minerals in the subfloor basalts are present in abundances up to about 25 percent (by volume); most rocks average about 20 percent. Ilmenite, armalcolite, chrome spinel, ulvospinel, rutile, metallic Fe-Ni, and troilite have been identified optically; all of these minerals occur in most of the rocks. Ilmenite is by far the most abundant oxide mineral (about 15 to 20 percent by volume); reflection pleochroism and color indicate that much of it is Mg-rich. Ilmenite crystals in the coarser grained rocks may be blocky or display rectangular cross sections in addition to the usual lath-shaped morphology suggesting that ilmenite may be a pseudomorph of an earlier phase. Ilmenite, especially in the coarser grained rocks, contains abundant lamellae and irregular masses of rutile on rhombohedral planes, and lamellae of a Cr-rich spinel phase parallel to the basal plane. Some metallic Fe is associated with these phases as blebs and narrow fracture fillings. In rocks of intermediate grain size blocky grains of ilmenite occur in a matrix rich in feathery ilmenite laths (for example, sample 72135). Vitrophyric and fine-grained basalts are rich in prisms and lozenge-shaped grains of armalcolite rimmed by a selvage of ilmenite. Trace amounts of chrome-spinel and Cr-ulvospinel occur in almost all basalts; ulvospinel commonly shows evidence of subsolidus reduction to ilmenite plus metallic Fe. Metallic Fe occurs as blebs in troilite and as discrete grains, similar to Fe seen in other mare basalts.

The similarity of basalt composition and textural variation throughout the landing site suggests a similar source for all of these rocks. On the basis of the petrographic data it is difficult to determine whether the samples represent several separate flows or different parts of a single relatively thick flow which may be at the top of a thick sequence of flows filling the valley.

Dark matrix breccias and agglutinates. The dark matrix breccias range from friable "soil" breccias to a more coherent type crossed by closely spaced fracture sets which form a delicate set of irregularly shaped plates (Fig. 4). Clasts in the breccias are primarily basalt, but at station 9 (Van Serg Crater) the breccias contain a variety of clasts including basalts, several types of glasses, some breccia fragments with accretionary coats, and a variety of re-

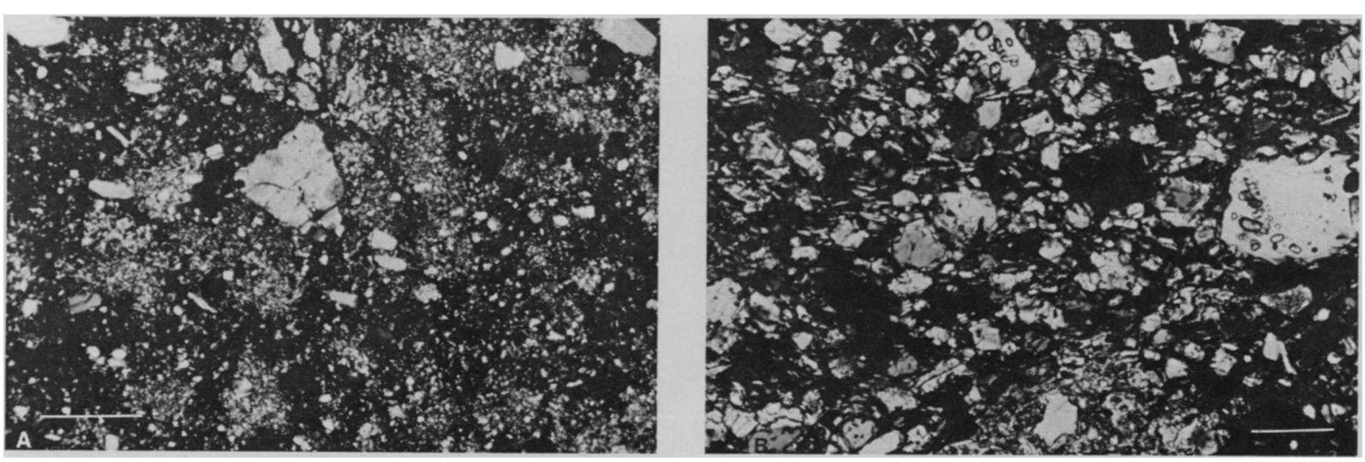


Fig. 7. (A) Thin section of green-gray breccia (77135,7) showing lighter gray areas of poikilitic orthopyroxenes which make up over 50 percent of matrix and contain numerous chadacrysts of plagioclase along with some olivine. Subrounded to subangular clasts are principally olivine and plagioclase. The scale is 0.5 mm (crossed polars). (B) Alignment of small plagioclase laths (white) is common in some areas of green-gray breccia matrices, generally in areas between oikocrysts. Several larger blocky grains of plagioclase occur as clasts (white and black). Olivine grains also occur as larger clasts (medium gray) and smaller grains whose origin is less certain. Note that the small laths "wrap" around the clasts (76055,11). The scale is 0.1 mm (crossed polars).

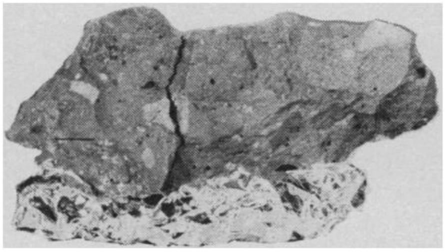


Fig. 8 (left). One of the more vesicular varieties of blue-gray breccia (72435). A variety of subangular to rounded, feldspathic clasts are apparent. Cavities are generally smooth walled. The scale is 1 cm.

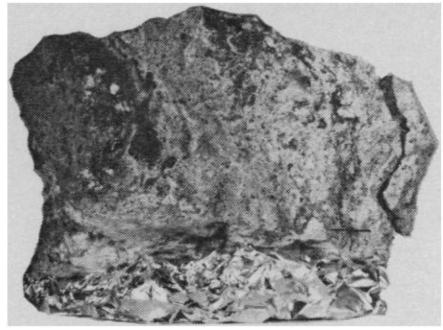


Fig. 9 (right). Banded blue-gray and tan breccia (76255). The lighter areas (tan) seem to intrude the darker (blue) areas. The coarser grained nature of the lighter areas can be seen clearly as can the foliated nature of the light material. The scale is 1 cm.

crystallized feldspathic rocks presumed to be derived from the surrounding highlands. Orange glass, similar to that found at station 4, occurs in limited quantities in most breccias throughout the landing site. Matrix material is largely dark brown glass which imparts the dark color to these rocks.

A few large samples of glass-bonded agglutinates (Fig. 5) occur at several sampling stations. Fragments are predominantly dark matrix breccias and some basalts cemented by dark gray glass. On the lunar surface the crew noted that these rock types occur in glass-lined bottoms of small (up to 3 m in diameter) craters. Although most breccias and agglutinates appear to have formed by induration of the present regolith, the breccias at Van Serg are more complex and appear to reflect multibrecciation events rather than a simple induration of present-day regolith.

Green-gray breccias. The green-gray breccias are very coherent and consist almost entirely of a vesicular to vuggy matrix, rich in poikilitic orthopyroxene (Fig. 6). The degrees of both vesicularity and development of poikilitic texture vary significantly from sample to sample, and in some cases the vesicles or vugs are several centimeters across. Mineral clasts of olivine and plagioclase plus a few lithic clasts make up a small percentage (5 to 20 percent) of each rock. One of these breccias, sample 76055, contains two distinct textures: a poikilitic, almost nonvesicular set of fragments in a nonpoikilitic, vesicular matrix in which the vesicles are planar and well-foliated, curving around the more dense fragments as in a flow structure.

The matrix of the green-gray breccias generally consists of at least 50 percent poikilitic orthopyroxene (some may be pigeonite) with numerous small laths of plagioclase both inside and outside the oikocrysts (Fig. 7). Small olivine grains occur in the oikocrysts but are generally concentrated along with opaque minerals outside the oikocrysts. A few rounded to angular, larger clasts are scattered throughout the rock and consist primarily of plagioclase and olivine. The oikocrysts range from well-developed (up to 2 mm long and enclosing 70 percent of the matrix) to poorly developed (up to 0.1 mm across and enclosing 5 percent of the matrix). Lithic clasts are rare and are chiefly feathery to equigranular, fine-grained, and rich in plagioclase.

Green-gray breccia occurs as a major rock type collected from boulders and smaller fragments sampled at stations 2, 6, and 7 and as smaller fragments in the light mantle at station 3; it must be considered as a major stratigraphic unit of the North and South Massifs. These rocks are similar in texture, mineralogy, and chemistry to the poikilitic rocks collected at the Apollo 16 site (*8*). They are also chemically similar to the brown glass matrix breccias from the Apennine Front (*9*).

Blue-gray breccias. The blue-gray breccias form the most complex group of rocks. These consist predominantly of a very coherent, slightly vesicular, blue-gray matrix containing angular to subrounded white clasts (Fig. 8). But there are some rocks where the blue-gray breccia seems to exist as fragments in a tan matrix or there may be a banded relation between blue-gray and tan matrix breccias (Fig. 9). These rocks have no poikilitic matrix, but may contain poikilitic clasts as well as mineral clasts of plagioclase, pyroxene, and subordinate olivine. Many of these

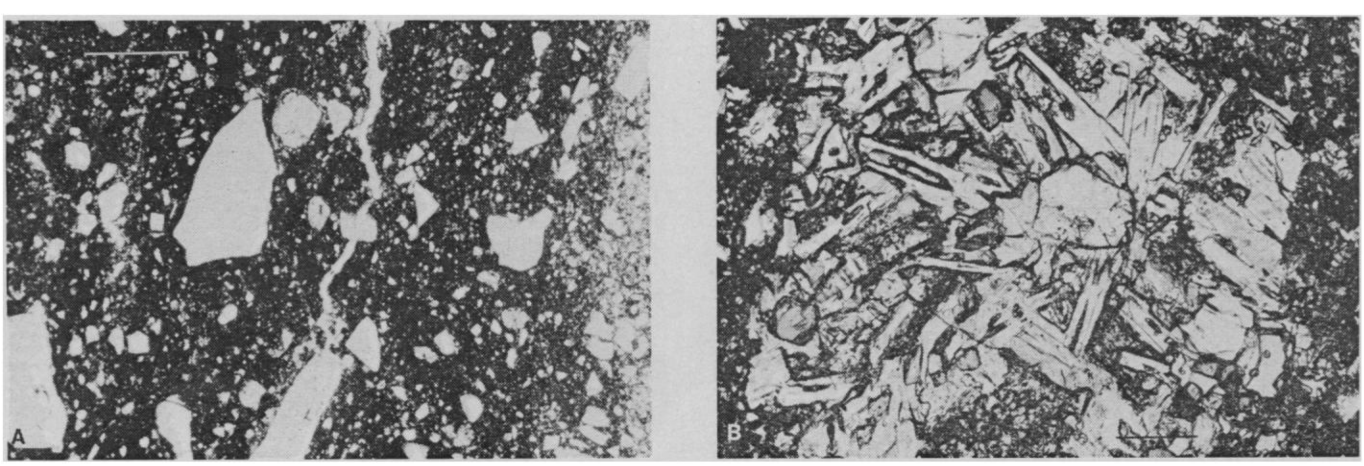


Fig. 10. (A) Thin section of clasts and very fine-grained dark matrix of blue-gray breccia (76315,11). Note the alignment of elongate clasts and foliation of light and dark streaks in matrix. Several pink spinels (medium gray) occur in the light band along edge of photograph. The scale is 0.5 mm (plane light). (B) Thin section of clast in blue-gray breccia (76315,11). Several equant, pink spinels (medium gray) occur in this plagioclase-olivine clast suggesting a source for the crushed material in the spinel-bearing light band of Fig. 10A (plane light).

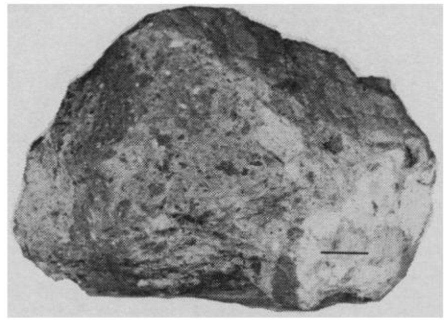


Fig. 11. Layered, foliated, light gray breccia from boulder at station 2 (72215). The darker areas which appear in some instances to be clasts are very fine-grained, probably devitrified, but the lighter areas which appear to be veins are essentially crushed crystalline material. The scale is 1 cm.

mineral grains have been shocked. A few mineral clasts have fine-grained rinds which may have been partially glassy at some stage of development. The matrix also contains traces of glass (sample 73235) or devitrified glass and displays some thin bands and oriented clasts (Fig. 10A); some bands of crushed minerals contain pink spinel which also occurs in clasts (Fig. 10B). The tan material is considerably coarser than the blue-gray and contains numerous brown mineral fragments which, in a thin section of rock 76255, appear to be inverted pigeonites with relatively coarse exsolution lamellae.

The blue-gray matrix ranges in texture from very fine to coarse grained. The fine-grained matrix consists of intergrowths of pyroxene and plagioclase only a few micrometers in size in some examples, whereas the coarse-grained matrix consists of subophitic pyroxene and plagioclase where some plagioclase laths may reach 50 to 100 micrometers in length. In contrast to the green-gray breccias a large proportion of the mineral clasts are pyroxenes of various types. Lithic clasts include very fine-grained, probably devitrified material, poikilitic rocks, relatively coarse-grained anorthositic types, feathery feldspar intergrowths, and basalts.

This rock type occurs as a major part of the boulders and smaller fragments at stations 2, 6, and 7 and in the fragments in light mantle at station 3 and must be considered as a major stratigraphic unit on both massifs. The blue-gray breccia was reported by the crew as being a major part of the large boulder at station 6, where it was in contact with the green-gray breccia. The latter contained inclusions of blue-gray breccia near the contact suggesting that the green-gray type was largely fluid at the time of incorporation.

Layered, foliated, light gray breccias. The layered, foliated, light gray breccias contain about 60 percent matrix and are less coherent than the green-gray and blue-gray breccias. There is some variability in the coherence of this breccia type, apparently as a result of the degree of annealing of an originally glassy matrix, some of which remains as glass. On a macroscopic scale these breccias are nonvesicular to very slightly vesicular. A large proportion of clasts in this breccia have white feldspar-rich cores rimmed by a dark gray, glass-rich material. In the less coherent breccias clasts stand out in relief on eroded surfaces. On both macroscopic and microscopic scales there occur white veins, layers, and lenses which in some cases appear to intrude the light gray matrix (Fig. 11).

The light gray matrix consists of numerous small fragments of lithic debris, plagioclase, olivine, pyroxene, and opaque minerals set in a brown, glassy to very fine, devitrified mesostasis. The white veins and lenses contain no brown interstitial material but consist of a few lithic fragments of the gray matrix breccias plus mineral debris which is largely feldspathic. Mineral fragments are mostly plagioclase but include olivine, pyroxene, and spinel. Lithic fragments are primarily breccias but include anorthositic types, basalts, and poikilitic rocks. Some clasts show accretionary structures consisting of brown glass matrix mantles surrounding lithic cores (Fig. 12). Breccia clasts within breccia clasts indicate a complex history for the formation of this rock type.

Such light gray breccia is found as a boulder at station 2 and among the smaller fragments in the light mantle at station 3, and hence appears to be associated with the South Massif.

Brecciated gabbroic rocks. A number of samples consist of brecciated or crushed anorthositic to gabbroic rocks. Some of these show evidence of crushing with little or no mixing, thus allowing possible reconstruction of original textures. For example, a coarse norite, sample 78235, shows a good cumulate texture on a macroscopic scale (Fig. 13) even though the plagioclase appears glassy and the pyroxene is crushed. On a microscopic scale both glass and crushed pyroxene are con-

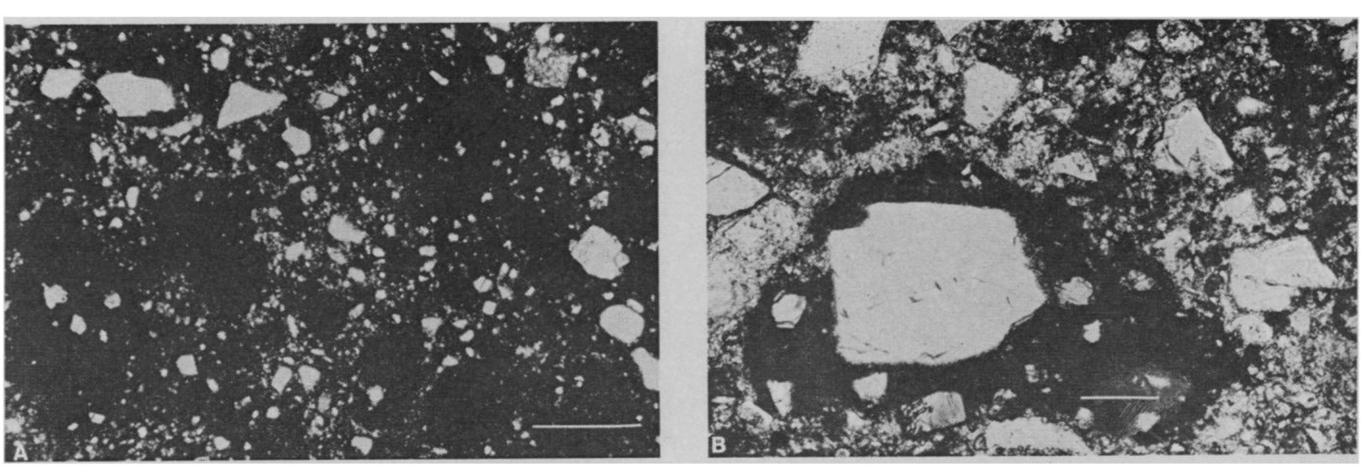


Fig. 12. (A) Thin section of light gray breccia showing glassy to devitrified, rounded clasts (black) in a matrix of more crystalline debris. However, the matrix at top of photo is more glass-rich and similar to clasts (72275,11). The scale is 0.5 mm (plane light). (B) Thin section of light gray breccia showing crystal clasts in a brown glass matrix (black) which itself forms a clast in a matrix of glass and crystalline debris (72255,7). In some cases these brown glass matrix clasts contain breccia clasts in addition to mineral fragments. The scale is 0.1 mm (plane light).

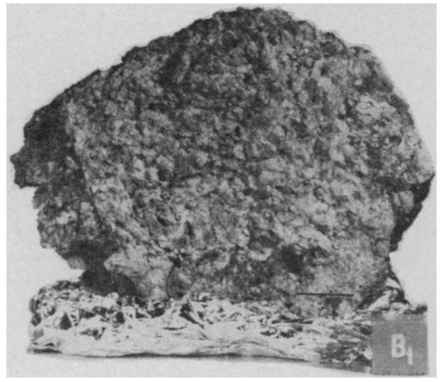


Fig. 13. Coarse-grained norite (78236) with glassy-appearing plagioclase and crushed pyroxene. Note the dark glassy coating on lower right side of rock. This glass occurs also as veins in the rock. The scale is 1 cm.

firmed (Fig. 14). On the other hand, a gabbro, sample 78155, has been highly crushed and may be mixed as well (Fig. 15). One rock, 76535, is a coarse-grained norite and shows no signs of having been sheared (Fig. 16) and although there are no thin sections of this rock, it may well have maintained its original texture. In another sample, 77017, the degree of crushing appears to vary from a margin injected with glass veins to a less-disturbed inner region of cumulate plagioclase and olivine in clinopyroxene oikocrysts (Fig. 17). Two crushed and recrystallized rocks were sampled from large clasts in the blue-gray breccia portions of the boulders at stations 6 and 7 and may present some clues to the source region of this breccia. Some of the less-crushed and mixed samples of these originally coarse-grained rocks may present the best opportunities from all of the Apollo missions for reconstructing the textures and mineral compositions of rocks from the early lunar crust.

Miscellaneous. The miscellaneous rocks include a dunite sample from a large clast in one of the boulders at station 2 and a fine-grained black dike with a very-fine-grained, igneous-looking matrix from the large boulder at station 7. The dunite contains more than 95 percent olivine as millimeter-sized fragments in a crushed matrix of the same material (Fig. 18). Chemical analysis of this rock indicates an olivine in the $Fo_{85\text{-}90}$ range. The black dike appears to originate within the blue-gray breccia part of the station 7 boulder and crosscuts an anorthositic norite clast. Although the dike contains about 15 percent mineral clasts, the remainder consists of 5 by 10 μm plagioclase laths in 30 by 50 μm pyroxene oikocrysts. Within 0.5 mm of the contact the vein material decreases in grain size and the plagioclase becomes more skeletal in form.

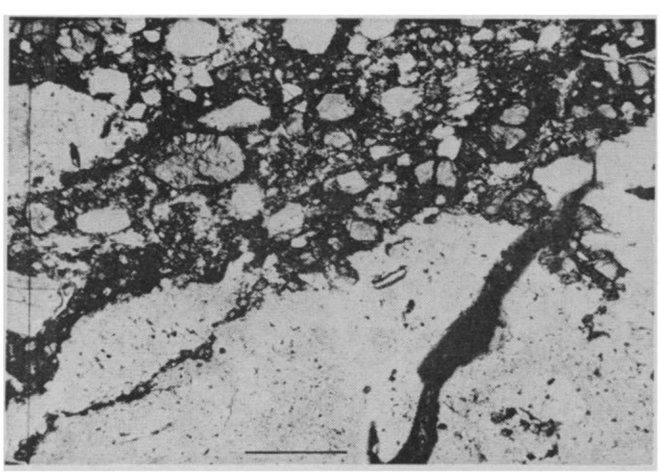
Soils

Soils were collected by the Apollo 17 crew to aid in characterizing four major photogeologic units determined by preflight studies: (i) the dark mantle which appeared to cover the plains surface and was interpreted as a possible pyroclastic deposit overlying basalt flows; (ii) the South Massif and the "light mantle" which was interpreted as an avalanche deposit from that massif; (iii) the North Massif, interpreted as highland breccias or possibly volcanic domes; and (iv) the Sculptured Hills, which were interpreted as highlands terrain made up of breccias.

Six core tubes, one drill core 2.92 m in length, and 73 soils, including both surface samples and samples from a number of trenches, were collected. All were described macroscopically in the lunar receiving laboratory; 64 soils were sieved into fractions of five different sizes and 18 were studied further in thin section and by additional sieving.

Grain size analyses. The methods of grain size analysis were outlined by McKay *et al.* (*10*). The mean grain size of soils from the black-mantled terrain ranges from near the average mean grain size for lunar soils (about 70 μm) to 125 μm. Soils from the North and South Massifs are fine-grained (coarse silt size) with mean grain sizes of 45 to 64 μm. As in most lunar soils, nearly all are very poorly sorted. Soils from station 4, composed predominantly of glass spheres, have median grain sizes of 40 to 43 μm and are poorly sorted.

Soils from the "dark mantle." Soils from stations 1 and 5 and the lunar module (LM) area are mostly the comminuted products of basalt. The bulk of these soils is composed of basalt fragments, agglutinates, and grains of clinopyroxene, plagioclase, and ilmenite. The basalt fragments exhibit a range of texture and composition, although two types are most common: (i) Equigranu-



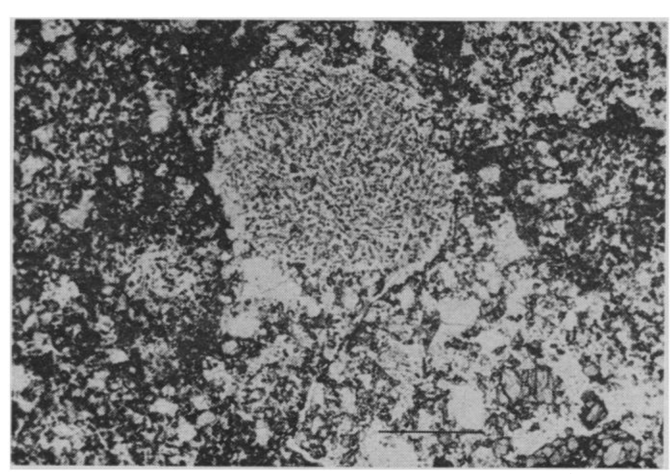


Fig. 14 (left). Thin section of coarse norite of Fig. 13 showing area of crushed plagioclase and pyroxene (top half of photo), large plagioclase crystals which are largely isotropic (white), and a brown glass vein (lower right). The scale is 0.5 mm (plane light). Fig. 15 (right). Thin section of crushed and stirred anorthositic rock (78155,8). Texture ranges from a very-fine-grained clastic mixture of plagioclase (white) and pyroxene (gray) to lathy diabasic patches. The scale is 0.5 mm (plane light).

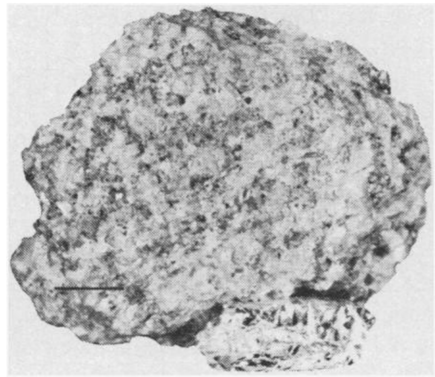


Fig. 16. Coarse-grained norite (76535) with fresh-appearing plagioclase (white to light gray) containing typical striations of albite twinning and orthopyroxene (medium gray). Although pyroxenes are fractured along cleavage planes they do not appear badly crushed. Scale in centimeters.

lar to subophitic, medium to coarse crystalline basalt containing 50 percent clinopyroxene (augite, pigeonite), 25 percent feldspar, and 25 percent ilmenite. Olivine, cristobalite, and opaque phases are present in lesser amounts. (ii) Finely crystalline, variolitic basalt with Ti-augite, ilmenite, and plagioclase.

Agglutinates, a ubiquitous component of lunar soils (*10, 11*), consist of mineral and lithic detritus bonded by grapelike clusters of nearly opaque, brown glass. In soils from the plains floor, the agglutinates have a dull, nearly metallic luster in contrast to those in soils from the massifs. Coarse-grained agglutinates (250 to 500 μm) are very vesicular and contain irregular, coalescing cavities 5 to 150 μm long.

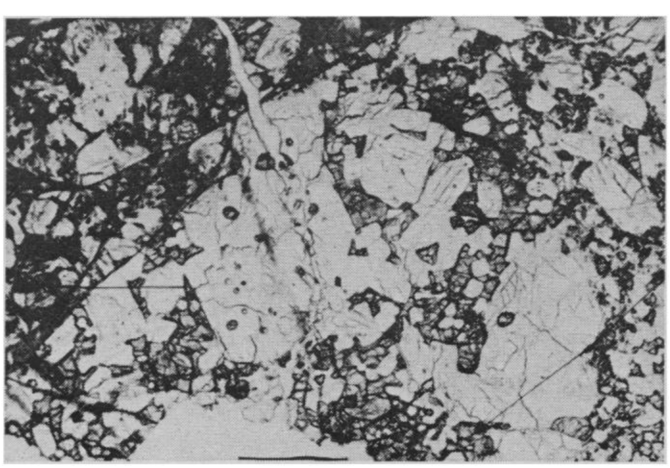
In the fraction with grain sizes less than 1 mm in diameter there is a considerable difference between samples collected at the surface and at the trench bottom (17 cm deep) at station 9. The surface sample contains twice as much agglutinate as the trench bottom sample and contains very different breccias. The finer fractions may be mostly comminution products of the dark gray vitric breccias which are the most common rock types at station 9.

Station 4 is on the rim of Shorty Crater, which appears to be a crater that penetrated the thin white mantle and ejected mostly dark plains material. It is here that three of the most unique "soils" from the Apollo 17 site were collected: orange, gray, and black. The orange soil forms a band with sharp boundaries between two gray soils. A core driven through the band penetrated a black soil. The three soil types are present within a few square meters.

The orange soil (sample 74220) consists of cohesive clods which withstood transport back to Earth. At least one of these clods exhibits color zoning, with a pale orange-brown center and moderate orange-brown rim; contacts between the zones are sharp. Superficially, the soil is composed of ruby-red to black, glass spheres and broken spheres which, in thin section, are homogeneous, pale orange, and nonvesicular. There is no evidence of included detritus in the orange glass, but there is a trace of olivine phenocrysts. Nearly half of the orange glass spheres are partly or completely crystallized to small sheaflike bundles of very fine crystals to parallel bars of ilmenite and olivine.

Black soil from the bottom of the core at station 4 (sample 74001) consists mostly of barred spheres or broken spheres. These are distinctly different from the orange glasses, consisting of olivine and orthopyroxene (?) phenocrysts in a very small amount of brown glass. The spheres are crossed by ragged, thin ilmenite plates which impart the black color to this soil. Traces of spinel and metal are present. The core soil also contains 10 to 20 percent completely devitrified brown glass spheres which are purple in thin section.

The "gray" soils (samples 74240 and 74260) which flank the band of orange soil contain a variety of components including a significant amount of "ropy" glass as light gray, spindle-shaped droplets with abundant fine-grained, angular detritus welded to the grain surfaces. The various orange and black soil components are present in nearly all of the "dark mantle" soils in portions of 5 to 20 percent of the total mass of the sample (average, 10 percent). They are also present in low-grade breccias from the plains. A surface sample (70180) at the LM site contains about 8.1 percent, by weight, of these "exotic" components, mostly in the soil fractions with grain sizes of less than 100 μm. The wide distribution of these glasses beyond the limits of Shorty Crater is a possible indication that layers of this material are present to depths of tens of meters below the present valley floor and pene-



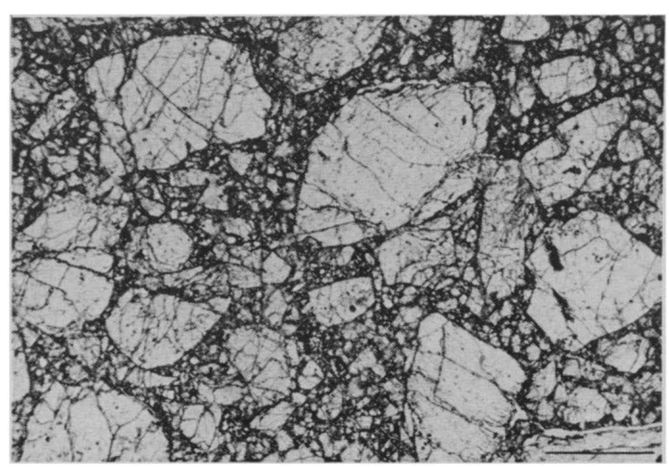


Fig. 17 (left). Section from an anorthositic rock having a generally crushed texture (77017,11). This thin section of one area with essentially no crushing shows several blocky to lath-shaped plagioclase grains (white) in optically continuous augite (gray) which extends over most of the photo except the upper left corner. A few very thin glass veins (black lines) occur throughout the section. The scale is 0.5 mm (plane light). Fig. 18 (right). Thin section from large dunite clast (72415,12). Large olivine crystals set in a crushed matrix of the same material comprise this entire clast. The scale is 0.5 mm (plane light).

trated by the deeper impact craters. The uniformity of composition (*12*) and morphology of the "exotic" component supports a theory that these are droplets formed during lava fountaining which would form lenses or layers within the strata underlying the Apollo 17 landing site. It is possible that they were subsequently buried by lava flows; because they contain no agglutinates they appear to have had no history of exposure at the lunar surface before they were exhumed as ejecta at Shorty Crater.

South Massif and "light mantle." The South Massif and "light mantle," or avalanche, deposits were sampled at stations 2, 2a, and 3. These appear to be the comminution products of a variety of breccias with a trace of mare basalt.

The coarser fractions, viewed superficially, consist of mostly medium gray, fine-grained breccia. In lesser amounts are dark gray breccias with white clasts less than 1 mm in diameter.

Vitric breccias of low metamorphic grade, grades 1 to 3 of Warner (*13*), contain 1- to 200-μm-long clasts of mineral and lithic detritus in matrices of brown, colorless, and banded glass. Most of the clasts consist of angular feldspar grains with lesser amounts of clino- or orthopyroxene; some grains, however, contain a myriad of clast types.

Breccias of medium metamorphic grade, grades 4 to 6 of Warner (*13*), have fine- to coarse-grained equigranular textures; they are composed of mostly feldspar and orthopyroxene, with traces of ilmenite and olivine.

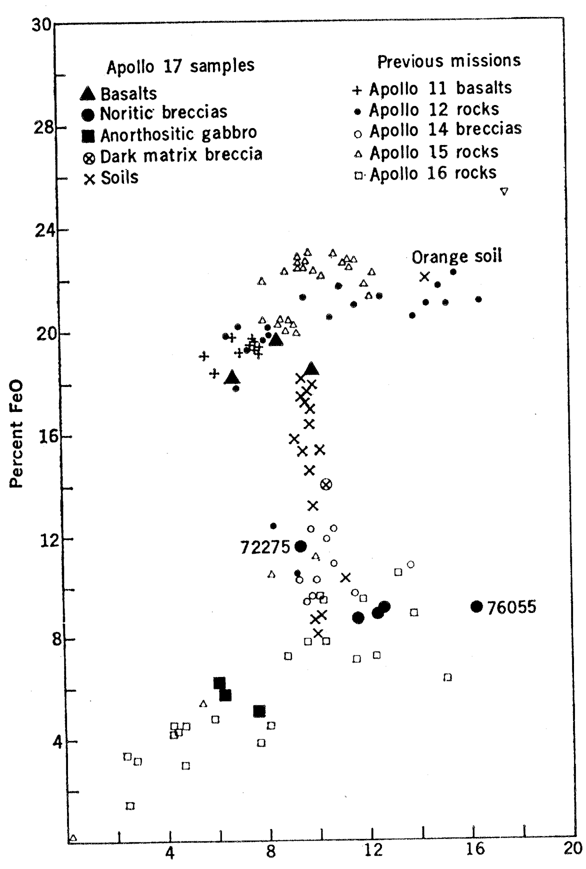
White and gray marbled units from the trench at station 3 have nearly the same mineralogic composition; but the gray layer has a higher agglutinate content. Similar white and gray units exist in a mottled texture at station 2a. If one assumes that the gray, agglutinate-rich units represent surface layers, it is possible that a layered regolith sequence was mixed as it avalanched down the slopes of the South Massif. Soils from the South Massif and the light mantle contain the lowest content of mare basalt and largest variety of breccias of any Apollo 17 soil; this is in good agreement with the interpretation of the light mantle being an avalanche deposit from the South Massif.

North Massif. The coarse fraction of soils from stations 6 and 7 consist of mostly patchy, medium to dark gray breccias, with lesser amounts of white breccias and agglutinates. The fraction with grain sizes less than 1 mm is characterized by abundant plagioclase and pyroxene grains, low-grade brown glass breccias, and medium-grade breccias. Some of the medium-grade breccias have a poorly defined poikilitic texture.

North Massif–derived soils have more breccias of medium metamorphic grade and a higher plagioclase content than South Massif soils. They are not, however, greatly different from South Massif soils.

Sculptured Hills. At station 8, one surface soil and a soil from the bottom of a trench 25 cm in depth differ mainly in their relative maturity; the trench soil contains twice the amount of agglutinates. Breccia types are nearly the same as in soils from the South Massif; but there is a greater amount of basalt in both of these soils compared to those from the South Massif.

At station 9, located between the Sculptured Hills and the LM area in the "dark mantle," the soil composition appears to be transitional between the two stratigraphic units. The coarse-grained fraction of these soils consists of dark gray, fine-grained, vitric breccia fragments and aphanitic basalt.



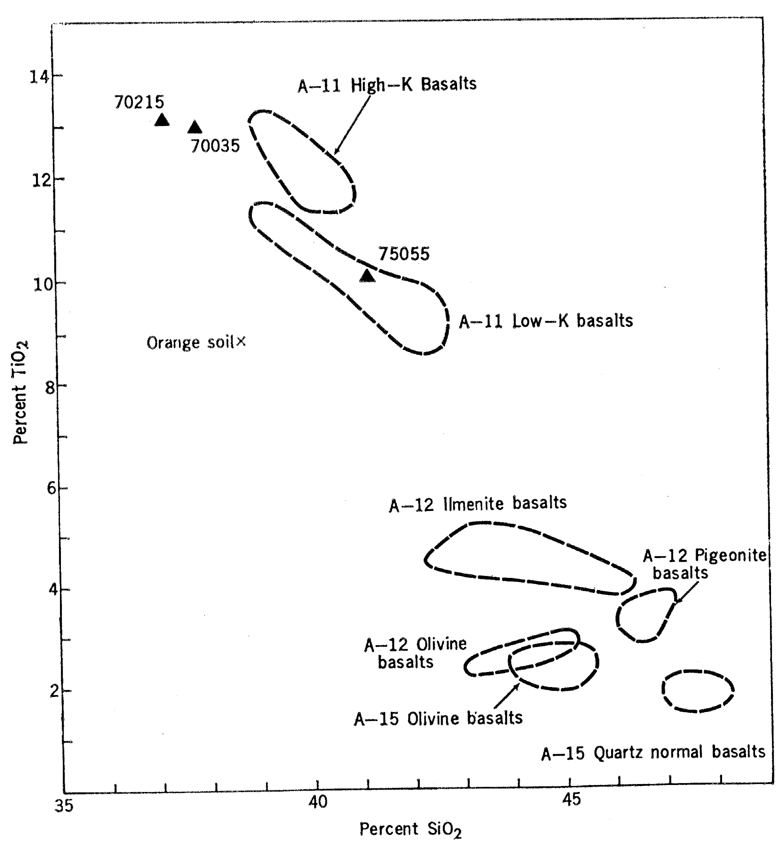


Fig. 19 (left). The MgO and FeO content of Apollo 17 lunar rocks and soils compared with data for rocks from previous missions. Fig. 20 (right). The SiO_2-TiO_2 variation in Apollo 17 and other mare basalts from previous missions.

Chemical Characteristics

Nearly all of the chemical characteristics of the Apollo 17 rocks can also be found in rocks from previous missions. Mare basalts with high FeO and TiO_2 contents, noritic breccias with major element composition broadly similar to KREEP [here called KREEP-like rocks; containing high concentrations of K, rare-earth elements (REE), and P] but with roughly one-half the minor and trace element content, and brecciated anorthositic gabbros with relatively high CaO and Al_2O_3 contents have all been observed previously. However, unusually high zinc concentrations in the orange soil and the exceptionally low Ni content of the basalts suggest different source materials than for previously returned igneous rocks. The trace element contents of the anorthositic rocks are significantly different from nearly all of those previously returned, again suggesting variations in the source regions.

Basalts. Basalts exhibiting wide textural variation have been extensively sampled in the vicinity of Steno and Camelot craters (stations 1 and 5), the LM and the Apollo lunar surface experiments package (ALSEP) site, and also from Shorty Crater (station 4). Analyses of three of these samples are given in Table 1. They are characterized by high FeO contents and by correspondingly high FeO/MgO ratios (Fig. 19) and hence are similar to other mare basalts sampled at the Apollo 11, Apollo 12, Luna 16, and Apollo 15 landing sites. These characteristics together with low Na_2O concentrations distinguish mare basalts from all terrestrial basalts.

In detail they have high TiO_2 and correspondingly low SiO_2 concentrations and are broadly comparable with basalts from Mare Tranquillitatis (Figs. 20 to 22). The sulfur content of these rocks, about twice that found in the Apollo 12 and 15 basalts, also compares closely with the Apollo 11 basalts. The nickel content (about 2 parts per million) is exceptionally low, even for lunar rocks, much lower than in previously sampled mare basalts except for Apollo 11.

One sample (75055) is slightly quartz normative and compares closely in both major and trace element chemistry with the low-K basalts typical of those from Apollo 11. The other two analyzed basalts (samples 70035 and 70215) differ from 75055 in that they are olivine normative and higher in TiO_2 (Fig. 20) and MgO than Apollo 11 low-K basalts, and are correspondingly lower in SiO_2,

Table 1. X-ray fluorescence analyses of Apollo 17 rocks (*24*). In each sample number, the figure after the comma refers to the split that was analyzed.

Component	Rock type and sample number												
	Basalts			Noritic breccias					Anorthositic rocks			Dunite clast	Soil breccia
	75055,6	70035,1	70215,2	72435,1	72275,2	76315,2	77135,2	76055,5	78155,2	77017,2	76230,4	72415,2	79135,1
						Data expressed as percentages							
SiO_2	41.27	37.84	37.19	45.76	47.54	45.82	46.13	44.65	45.57	44.09	44.52	39.93	42.29
TiO_2	10.17	12.97	13.14	1.54	0.91	1.47	1.54	1.24	0.27	0.41	0.20	0.03	5.15
Al_2O_3	9.75	8.85	8.67	19.23	17.01	18.01	18.01	16.47	25.94	26.59	27.01	1.53	15.08
FeO	18.24	18.46	19.62	8.70	11.58	8.94	9.11	9.11	5.82	6.19	5.14	11.34	14.01
MnO	0.29	0.28	0.28	0.11	0.18	0.11	0.13	0.11	0.10	0.08	0.06	0.13	0.19
MgO	6.84	9.89	8.52	11.63	9.35	12.41	12.63	16.33	6.33	6.06	7.63	43.61	10.42
CaO	12.30	10.07	10.43	11.72	11.71	11.06	11.03	9.93	15.18	15.43	15.17	1.14	11.44
Na_2O	0.44	0.35	0.32	0.52	0.38	0.57	0.53	0.48	0.33	0.30	0.35	<0.02	0.40
K_2O	0.09	0.06	0.04	0.23	0.28	0.27	0.30	0.20	0.08	0.06	0.06	0.00	0.10
P_2O_5	0.07	0.05	0.09	0.27	0.35	0.29	0.28	0.19	0.04	0.03	0.05	0.04	0.07
S	0.19	0.15	0.18	0.08	0.08	0.08	0.08	0.07	0.04	0.15	0.03	0.01	0.10
Cr_2O_3	0.27	0.61	0.42	0.20	0.36	0.19	0.20	0.19	0.14	0.13	0.11	0.34	0.39
Total	99.92	99.58	98.90	99.99	99.73	99.22	99.97	98.97	99.84	99.52	100.33	98.12	99.64
Quartz	1.97	—	—	—	—	—	—	—	—	—	—	—	—
Orthoclase	0.53	0.35	0.24	1.36	1.65	1.60	1.77	1.18	0.47	0.35	0.35	0.00	0.59
Albite	3.72	2.96	2.71	4.40	3.22	4.82	4.48	4.06	2.79	2.54	2.96	0.00	3.38
Anorthite	24.36	22.40	22.10	49.46	43.88	45.79	45.88	42.20	69.07	71.03	71.95	4.17	39.05
Diopside	30.00	22.11	23.81	5.74	10.01	5.96	5.81	4.78	4.91	4.37	2.44	0.99	14.12
Hypersthene	19.41	24.53	23.97	23.23	36.91	24.66	25.49	19.21	16.52	10.09	8.74	1.53	19.76
Olivine	—	1.72	0.33	12.01	1.13	12.70	12.72	24.52	5.31	10.01	13.25	90.91	12.30
Ilmenite	19.32	24.63	24.96	2.92	1.73	2.79	2.92	2.36	0.51	0.78	0.38	0.06	9.78
Apatite	0.15	0.11	0.20	0.59	0.76	0.63	0.61	0.42	0.09	0.07	0.11	0.09	0.15
Total	99.46	98.81	98.32	99.71	99.29	98.95	99.68	98.73	99.67	99.24	100.18	97.75	99.14
						Data expressed as parts per million							
Sr	209	176	121	165	121	175	172	155	145	141	145	11	166
Rb	0.7	0.7	<0.2	3.8	8.7	5.8	7.3	5.1	2.3	1.2	0.3	<0.2	2.1
Y	112	75	75	107	129	111	107	76	16	14	12	1.1	55
Zr	272	205	183	450	613	510	494	341	59	50	42	2.6	185
Nb	25	20	20	30	32	33	33	23	4.8	4.1	3.2	0.3	14
Ni	2	2	2	112	67	149	110	155	53	95	166	173	218
Zn	7	4	5	2	3	4	4	1	4	4	2	4	72

Al_2O_3, CaO, and the trace elements rubidium, zirconium, yttrium, and strontium. Although chemically comparable, these two basalts differ in texture. Sample 70215 is very-fine-grained (probably a devitrified vitrophyre), whereas 70035 is a coarse-grained (1 to 2 mm) vesicular basalt. The aphyric texture of sample 70215 indicates that high titanium magmas have been erupted onto the lunar surface, and that rocks of this composition are not necessarily of cumulate origin. The compositional differences observed between sample 75055 and the other two samples are too large to have been produced by near-surface crystal fractionation, indicating that at least two basalt types have been sampled at the Apollo 17 site.

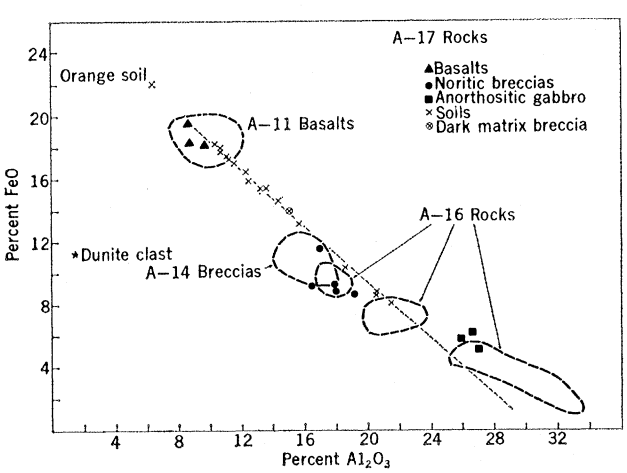
Massif rocks. Rocks from the South and North Massifs have been sampled at stations 2, 3, 6, 7, and 8. Analyses of representative samples are given in Table 1. In contrast to the wide textural and petrographic variations observed in these rocks, two distinct, chemically defined, rock types can be recognized. These are (i) noritic breccias, corresponding to the petrographically defined suites of green-gray, blue-gray, and light gray breccias; and (ii) anorthositic gabbros, corresponding to the petrographically defined suite of brecciated gabbroic rocks. The latter group is found as clasts in the noritic breccias and as isolated samples at stations 6, 7, and 8. Figures 21 and 22 show that both rock types plot close to the plagioclase-control trend that is typical of highland rocks, particularly those from the Apollo 16 site.

The Apollo 17 noritic breccias are characterized by about 50 percent normative plagioclase and are broadly comparable in bulk chemistry with KREEP-like rocks sampled on previous missions (for example, samples 15265, 62235, and 60315). They have slightly higher Al_2O_3 concentrations and MgO/FeO ratios than typical Apollo 14 breccias (Fig. 21) and in this respect are more closely comparable with the Apollo 16 KREEP-like rocks (Figs. 21 and 22). Although closely comparable in major element chemistry, they are lower in Na_2O, K_2O, and P_2O_5 than the Apollo 14 breccias, but resemble the broadly defined composition of low- to moderate-K Fra Mauro basalt composition proposed by Reid *et al.* (*14*) on the basis of glass compositions in the Apollo 15 soils. Elements that are abundant in KREEP, such as rubidium, yttrium, zirconium, and niobium, are also lower in these rocks than in the Apollo 14 breccias. Figure 23 shows that in comparison with their abundances in Apollo 14 breccias, these elements are depleted in rocks with the major element composition of KREEP from the Apollo 15 and 16, as well as 17, sites. In all cases potassium and rubidium are more depleted than sodium, phosphorus, yttrium, zirconium, and niobium, but strontium is only slightly depleted. The Apollo 17 noritic breccias together with the brown matrix breccias from the Apollo 15 site are more depleted in these elements than are the KREEP-like rocks from the Apollo 16 site.

Figure 23 also serves to illustrate some internal variation within the Apollo 17 noritic breccias. Sample 72275, classified petrographically as a foliated light gray breccia, is characterized by lower strontium and sodium and higher phosphorus, yttrium, and zirconium concentrations than the other breccias. These differences in minor and trace element abundances accompany small but important differences in major element chemistry. These include higher FeO and CaO in sample 72275 for a given Al_2O_3 content, together with distinctly lower MgO/FeO ratios, reflected in a higher normative orthopyroxene content relative to plagioclase and olivine. These differences indicate that the foliated, light gray breccias are derived from a different lithological unit than the other noritic breccias. This distinction is emphasized by the much lower nickel content of this rock in comparison with the other noritic breccias (Table 1). If the nickel is largely of meteoritic origin then the possibility exists that the foliated gray breccias form a stratigraphic unit whose materials have undergone a much shorter period of surface exposure than other analyzed materials from the South and North Massifs.

In addition to the clasts of anorthositic gabbro, clasts of dunite and olivine are also present in the noritic breccias. An analysis of a large dunite clast (sample 72415) from station 2 is given in Table 1. Abundant inclusions of olivine and dunite in sample 76055 are reflected in the high MgO content and low trace element abundances in comparison with the other breccias (Fig. 23). Figures 21, 22, and 25 show sample 76055 to be slightly displaced in composition toward the dunite clast (sample 72415) from the other noritic breccias.

Three samples of anorthositic gabbro have been analyzed (Table 1). They are of restricted composition, all containing just over 70 percent of nor-



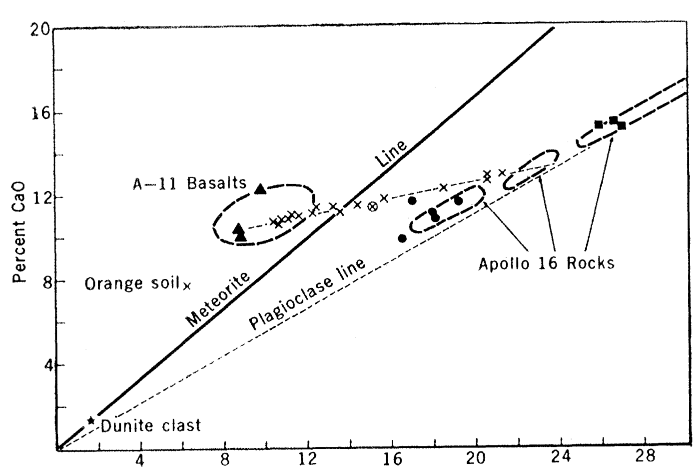
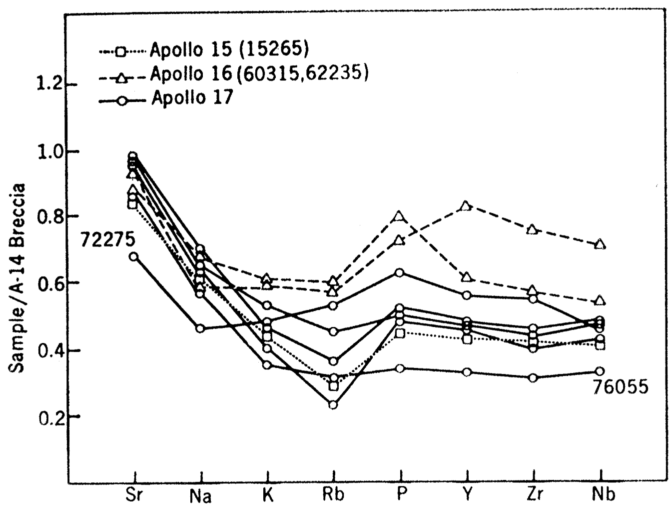


Fig. 21 (left). The FeO-Al_2O_3 variation in Apollo 17 rocks and soils in comparison with data for previous missions. Fig. 22 (right). The CaO-Al_2O_3 variation in Apollo 17 rocks and soils and in rocks from the Apollo 11 and 16 missions.



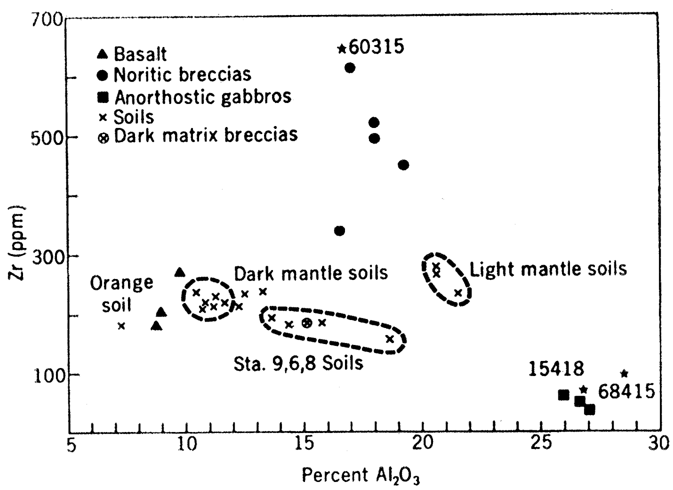


Fig. 23 (left). Concentrations of Sr, Na, K, Rb, P, Y, Zr, and Nb in Apollo 17 noritic breccias, Apollo 16 KREEP-like rocks (*7*), and Apollo 15 brown glass matrix breccia (*8*) relative to Apollo 14 breccias (*25*). Fig. 24 (right). The Al_2O_3-Zr variation in Apollo 17 rocks and soils. Data for previous missions taken from (*7*) and (*8*).

mative plagioclase. They compare broadly in major element chemistry with such samples as 15418 and 68415 and with the "highland basalt" composition (*15*). Figure 21 shows that they are slightly more mafic than comparable rocks from the Apollo 16 site. The trace element contents of these rocks, particularly the zirconium, yttrium, and strontium contents, tend to be lower than in the Apollo 16 rocks, being slightly over half the content of these elements in sample 68415 (*7*). In this respect they are more closely comparable with sample 15418 (*8*) (Fig. 25), providing evidence for a spectrum of trace element concentrations in rocks with the bulk composition of anorthositic gabbro.

Soils. Soils from the Apollo 17 site have a greater compositional range than those found at any previous landing site; they range from soils approaching the basalt in composition to highly aluminous, light mantle soils derived from the South Massif. Analyses of 17 soils from most of the major sampling stations are given in Table 2, together with an analysis of the Apollo 11 soil, sample 10084. The latter is included for comparative purposes and as an indication of the accuracy of the results.

The chemistry of the major elements of these soils appears relatively straightforward, suggesting a simple two-component mixing trend involving basalt and an aluminous end-member intermediate in composition between the noritic breccias and the anorthositic gabbros (Figs. 19, 21, and 22). In detail, however, the mixing is more complex, as three compositional groups can be recognized, largely on the basis of trace and minor elements (Fig. 24). In addition to compositional distinctions, geographic distinctions can be made between these three groups.

1) "Dark mantle" material. Soil samples taken at stations 1 and 5 are considered to be the best candidates for "dark mantle" material, particularly sample 75061, which was obtained from the top of a boulder. They are of uniform chemistry and are compositionally very close to the subfloor basalts (Figs. 19, 21, 22, and 24), which together with orange glass fragments constitute about 80 percent of these soils. The remainder is accounted for by aluminous material from the adjacent massifs. Soils from station 4 and the LM-ALSEP site are slightly more aluminous and less mafic than those from stations 1 and 5, containing slightly more of the massif component.

The nickel content of these soils is fairly constant, averaging about 120 ppm in the soil from stations 1 and 5, but increasing with the increasing aluminous component in the other soils. Since the basalts which account for the bulk of these soils are very low in nickel (Table 1), most of the nickel in the soil is probably of meteoritic derivation, corresponding roughly with a 1 percent chondrite component.

2) Light mantle material. Light mantle soils, derived from the South Massif, have been sampled at stations 2, 2a, and 3. These soils are the most aluminous sampled at this landing site, and, apart from a small (5 percent) basaltic component, are intermediate both in major and trace element chemistry between the noritic breccias and anorthositic gabbros (Figs. 19, 21, 22, and 24). If the light mantle is representative of the South Massif, it implies that the massif

Fig. 25. Comparison of the total carbon abundances for the Apollo 17 samples with those of samples from previous missions. The latter data are from (*7*).

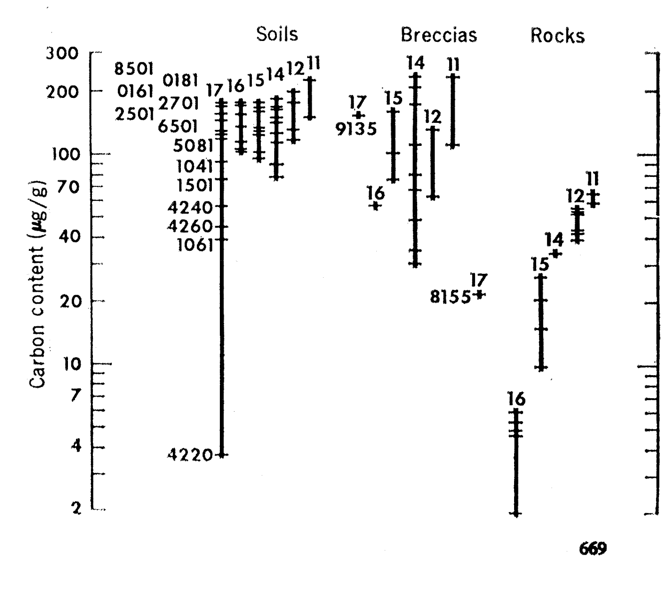


Table 2. X-ray fluorescence analyses of Apollo 17 soils (24). In each sample number, the figure after the comma refers to the split that was analyzed.

Component	Orange soil 74220,3	Sample number 75061,4	71041,3	71501,3	75081,3	71061,3	70161,3	74240,3	70181,3	74260,2	79221,2	79261,2	78501,2	76501,2	72501,2	72701,2	73141,1	Control soil 10084,42
								Data expressed as percentages										
SiO_2	38.57	39.32	39.74	39.82	40.27	40.09	40.34	40.78	40.87	41.22	41.67	42.26	42.67	43.41	45.12	44.87	45.06	41.78
TiO_2	8.81	10.31	9.57	9.52	9.41	9.32	8.99	8.61	8.11	7.68	6.52	6.09	5.47	3.15	1.56	1.52	1.29	7.41
Al_2O_3	6.32	10.42	10.80	11.13	11.31	10.70	11.60	12.54	12.30	13.25	13.57	14.43	15.73	18.63	20.64	20.60	21.52	13.47
FeO	22.04	18.19	17.73	17.41	17.20	17.85	17.01	15.84	16.37	15.31	15.37	14.60	13.15	10.32	8.77	8.65	8.10	15.65
MnO	0.30	0.25	0.24	0.25	0.25	0.24	0.23	0.24	0.24	0.23	0.21	0.20	0.18	0.14	0.11	0.12	0.11	0.22
MgO	14.44	9.53	9.72	9.51	9.59	9.92	9.79	9.15	9.82	9.47	10.22	9.82	9.91	11.08	10.08	9.97	10.04	8.07
CaO	7.68	10.72	10.72	10.85	10.97	10.59	10.98	11.36	11.05	11.37	11.18	11.48	11.77	12.28	12.86	12.80	13.04	12.13
Na_2O	0.36	0.33	0.35	0.32	0.33	0.36	0.32	0.38	0.35	0.38	0.34	0.35	0.35	0.35	0.40	0.40	0.38	0.37
K_2O	0.09	0.08	0.08	0.07	0.08	0.08	0.08	0.12	0.08	0.12	0.09	0.11	0.09	0.10	0.16	0.16	0.15	0.15
P_2O_5	0.04	0.06	0.07	0.06	0.07	0.07	0.08	0.09	0.06	0.09	0.06	0.07	0.05	0.08	0.13	0.15	0.12	0.12
S	0.07	0.13	0.13	0.12	0.12	0.13	0.12	0.14	0.11	0.12	0.12	0.12	0.10	0.07	0.09	0.07	0.06	0.14
Cr_2O_3	0.75	0.48	0.47	0.46	0.46	0.49	0.46	0.41	0.44	0.41	0.42	0.40	0.37	0.26	0.23	0.23	0.21	—
Total	99.47	99.82	99.62	99.52	100.06	99.84	100.00	99.66	99.80	99.65	99.77	99.93	99.84	99.87	100.15	99.54	100.08	99.51
Quartz	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Orthoclase	0.53	0.47	0.47	0.41	0.47	0.47	0.47	0.71	0.47	0.71	0.53	0.65	0.53	0.59	0.95	0.95	0.89	0.89
Albite	3.05	2.79	2.96	2.71	2.79	3.05	2.71	3.22	2.96	3.22	2.88	2.96	2.96	2.96	3.38	3.38	3.22	3.13
Anorthite	15.36	26.72	27.66	28.73	29.14	27.35	29.98	32.16	31.76	34.10	35.24	37.48	41.09	48.97	54.05	53.94	56.57	34.65
Diopside	18.43	21.37	20.54	20.25	20.33	20.29	19.64	19.33	18.57	17.75	16.26	15.59	13.87	9.30	7.29	7.04	6.01	20.42
Hypersthene	20.13	22.84	22.83	23.63	24.05	23.76	23.38	23.09	23.12	22.60	22.27	23.06	22.55	16.98	19.29	19.32	18.22	23.18
Olivine	24.32	5.31	6.22	5.01	4.67	6.46	5.99	4.06	6.83	5.96	9.54	7.95	7.88	14.58	11.62	11.39	12.20	2.76
Ilmenite	16.73	19.58	18.18	18.08	17.87	17.70	17.07	16.35	15.40	14.59	12.38	11.57	10.39	5.98	2.96	2.89	2.45	14.07
Apatite	0.09	0.13	0.15	0.13	0.15	0.15	0.17	0.20	0.13	0.20	0.13	0.15	0.11	0.17	0.28	0.33	0.26	0.26
Total	98.65	99.21	99.01	98.95	99.47	99.23	99.41	99.12	99.24	99.13	99.23	99.41	99.38	99.53	99.82	99.24	99.82	99.36
								Data expressed as parts per million										
Sr	205	166	165	157	165	174	168	163	169	167	156	153	155	147	153	155	148	—
Rb	1.2	1.6	1.1	1.2	1.1	1.1	1.4	2.3	1.9	2.0	1.7	1.9	2.1	2.5	4.2	3.9	3.5	—
Y	49	83	73	74	77	75	77	80	70	75	61	59	58	46	64	54	54	—
Zr	182	237	217	214	229	215	218	235	216	239	193	183	189	158	271	275	236	—
Nb	15	21	19	19	20	19	19	19	18	19	16	16	15	13	18	18	15	—
Ni	83	115	117	131	140	100	161	80	190	99	236	177	194	206	241	227	195	—
Zn	292	25	51	33	35	88	41	83	47	109	51	48	40	29	21	22	18	—

is composed predominantly of noritic breccias and anorthositic gabbros in roughly equal proportions. The average nickel content of these soils is about 220 ppm. If one allows for the high nickel in the source rocks (about 100 to 120 ppm), which may also be of meteoritic origin during an earlier phase of lunar history, then the meteoritic component inferred for these soils is roughly 1 percent, similar to that inferred previously for "dark mantle" soils.

3) North Massif–Sculptured Hills. Soils collected near the North Massif and Sculptured Hills from stations 6, 8, and 9 are more aluminous and less mafic than the "dark mantle" and related soils from the valley floor, and are intermediate in major element chemistry between the basalts and the light mantle soils (Figs. 19, 21, and 22). However, they are depleted in phosphorus, zirconium, and yttrium with respect to a simple mixture of these two end components. This is illustrated in the case of zirconium in Fig. 24. Thus in these soils anorthositic gabbro is more abundant relative to noritic breccias than it is in the light mantle soils, suggesting that anorthositic gabbro may be more abundant in the North Massif or Sculptured Hills, or both, than it is in the South Massif.

Orange soil. The orange soil (74220) sampled at Shorty Crater is composed almost entirely of glass and devitrified glass spherules. It differs markedly in composition from all other soils, including adjacent soils from station 4 (Table 2), and is broadly comparable with the basalts, having high FeO and TiO_2 concentrations. In contrast to these rocks, the orange soil contains 14.4 percent MgO and could be derived from the basalt composition by the addition of about 24 percent olivine (Fo_{66}). However, both the strontium and rubidium abundances (Table 2) are too high in the orange soil with respect to the basalts, thus precluding a direct relationship between the two. The zinc content of 292 ppm is exceptionally high for lunar materials (Table 2), the only other material approaching this composition being the Apollo 15 green glass (60 to 100 ppm) (*16*). The high volatile element content of the orange soil [in addition to zinc, the presence of abundant chlorine, found semiquantitatively by the Preliminary Examination Team, has been confirmed by Reed (*17*)] implies a source different from that of the basalts, irrespective of whether the glass in the soil is of volcanic or impact origin. Furthermore, the high zinc content cannot be attributed to any reasonable amount of meteoritic contamination during impact.

Since zinc concentrations in both the basaltic and massif rocks is low, about 2 to 5 ppm, the higher concentrations observed in the soils (Table 2) must reflect the orange glass (or its devitrified derivatives) content of these soils. On this basis the orange glass content is highest in the other soils from Shorty Crater (27 to 36 percent) and lowest in the light mantle soils (5 percent). The Zn contents of "dark mantle" soils indicate variable amounts of orange glass (7 to 29 percent, averaging about 14 percent). The soils from stations 9, 8, and 6 contain progressively less Zn away from the valley floor. The correlation between modal orange glass content (this does not include devitrified glass) and glass content calculated from the zinc concentrations is positive for the cases where comparison is possible.

Total carbon analysis. The total amount of carbon in the Apollo 17 soils ranges between 4 and 170 ppm. They are similar to those found during earlier missions. The majority of the samples, as shown in Fig. 25, have carbon contents in the 110- to 170-ppm range, typical of mature, dark-colored soils. Exceptions include the orange soil, 74220, and its adjacent soils, 74240 and 74260, and samples 71041, 71501, and 71061 from station 1. The analyzed split of sample 71061 has a noticeably larger grain size than normal fines. Since carbon abundance has been shown to be correlated with surface exposure and proportion of finer material it is not unexpected that the coarser fines would contain less carbon. The results verify previous proposals that the major portion of the carbon found in lunar fines is from solar wind. Although the value recorded for the orange soil, 74220, is 4 ppm, an earlier split was analyzed and had a carbon content of 100 ppm. The 4-ppm value from a carefully selected and handled sample is taken as valid for sample 74220; the earlier high value is attributed to contamination in some form, although real variations in the sample cannot be completely ruled out. The soil breccia, sample 79135, has a normal total carbon content of 150 ppm and the anorthositic gabbro, sample 78155, a carbon content of 21 ppm, similar to anorthositic rocks from Apollo 15 and Apollo 16.

Discussion

The stratigraphic unit that partly filled and leveled the Taurus-Littrow valley is mare basalt similar to that returned from Mare Tranquillitatis. Early studies of the ages of both the basalts and orange glass (*18*) indicate that they are similar but slightly older than the Tranquillitatis samples. Whether these samples represent one or several flows (chemical data suggest at least two) is not clear but it is evident that widespread volcanism involving melts very rich in titanium occurred over much of the eastern limb of the moon about 3.7 to 3.8×10^9 years ago. Thus, the known time span of mare volcanism, about 600 million years, remains essentially the same as before the Apollo 17 mission.

Breccias in various stages of crystallization appear to have been derived from several stratigraphic units present in the massifs. To date the one reported breccia age from Apollo 17 of about 4.0×10^9 years (*19*) does not extend the rather restricted limits mentioned in the introduction. Breccias range from those containing a high percentage of mineral and lithic debris with a small amount of interstitial glass to those containing a small percentage of mineral and lithic debris in well-crystallized poikilitic textures. The extent of partial melting and the origin of the oikocrysts in the latter remain problematic (*20*). Detailed studies of the boulders that contain vesicles and vugs several centimeters across, inclusions of one breccia in another, contact relations between two breccia units, and the black dike which displays evidence of a chilled margin may help to answer these problems. The variety of breccia textures resulted from different extents of melting and rates of heating and cooling associated with large masses of ejecta from major cratering events.

The similarity of both major and trace component concentrations of the brown glass matrix breccias of the Apennine Front, the recrystallized breccias of Apollo 16, and the various crystalline breccias from Apollo 17 suggests that a relationship may exist between the way in which these widespread breccias were derived and KREEP-like chemistry. The occurrence in these breccias of clasts of plagioclase, olivine, and pyroxene similar to those of coarse-grained anorthositic and gabbroic rocks suggests that the latter rocks formed the source of the breccias and provides us with the interesting possibility that partial melting similar to that postulated for the production of KREEP-like melts (*21*) may be associated with large impacting events that produce large volumes of melt (*22*). Grieve and Plant (*23*) have reported an example of a breccia having gabbroic composition and containing interstitial melt and glass veins of KREEP-like composition. As was the case in past missions, anorthositic rocks obtained during the Apollo 17 mission are generally crushed and recrystallized, their original textures being obscured. However, two coarse-grained norites and at least one gabbroic rock with some areas of original texture should offer some insight into the chemistry and perhaps ages of the early crustal rocks.

The occurrence of a large dunite clast in a boulder at station 2 suggests that the source material of the breccias must include coarse-grained segregations of magnesian olivine, thus providing further evidence for an early crust composed of a coarse-grained igneous complex of anorthositic, gabbroic, and ultramafic rocks.

The "dark mantle" consists largely of the products produced by micrometeorite erosion of basalts, 5 to 20 percent of the orange and black glass found in abundance at station 4, and some lithic fragments derived from the massifs. The rather pure orange and black soils at station 4 suggest that there may be layers of these materials in the upper few tens of meters below the surface. If such layers are widespread throughout the valley, cratering events would be expected to excavate this material along with the basalts and produce the 5 to 20 percent orange and black glasses found in the dark mantle soils. Anomalously high values of Zn and Cl plus the relatively high Sr and Rb contents indicate that the orange glass is not directly related to the mare basalt melts unless by some undefined complex fractionation scheme.

Although the soils from the North Massif, South Massif, and light mantle are similar petrographically and appear in binary plots of major elements to be simple mixtures of basalts and anorthositic rocks, the trace elements indicate a more complex pattern. The South Massif and light mantle materials are considerably enriched in Zr and other trace elements relative to North Massif or any mixture of basalts and anorthositic rocks. Thus, a KREEP component must be utilized to explain mixing models for soils and the metamorphosed and partially melted breccias.

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Geologic Exploration of Taurus-Littrow: Apollo 17 Landing Site

Apollo Field Geology Investigation Team

Apollo 17 landed in a deep graben valley embaying the mountainous highlands southeast of the Serenitatis basin. Impact-generated breccias underlie the massifs adjacent to the valley, and basalt has flooded and leveled the valley floor. The dark mantle inferred from orbital photographs was not recognized as a discrete unit; the unusually thick regolith of the valley floor contains a unique high concentration of dark glass beads that may cause the low albedo of much of the surface.

Apollo 17 landed at latitude 20°10′N and longitude 30°46′E on the flat floor of a deep, narrow valley that embays the mountainous highlands at the southeastern rim of the Serenitatis basin (Fig. 1). Serenitatis is one of the major multiringed basins on the near side of the moon and the site of a pronounced mascon (*1*). The Taurus-Littrow valley, which is radial to the Serenitatis basin, is interpreted as a deep graben formed initially by structural adjustment of lunar crustal material to the Serenitatis impact (*2, 3*).

During their stay on the lunar surface, astronauts E. A. Cernan and H. H. Schmitt traversed a total of about 30 kilometers, collected about 110 kilograms of rocks and soil, and took more than 2200 photographs. Their traverses, sampling, direct observations, and photographs spanned the full width of the Taurus-Littrow valley (Fig. 2).

The highlands surrounding the valley can be divided on the basis of morphology into two major units, high steep massifs with slopes of about 25° and smaller, closely spaced domical hills referred to as sculptured hills (Fig. 3). Both units were interpreted in pre-mission studies as deposits of ejecta derived from surrounding basins with major uplift occurring in the Serenitatis event. A possible volcanic origin was also considered but thought to be less likely (*2, 4*). An additional low hills unit adjacent to the massifs was considered to be downfaulted and partly buried blocks of massif or sculptured hills material (*4, 5*). Material from massifs north and south of the valley was obtained by sampling boulders that had rolled down their slopes. These boulders are composed of complex breccias that are generally similar to those returned on Apollo 15 and Apollo 16.

Materials of the valley fill were sampled at many stations. Ejecta around many craters on the valley floor consists of basalt, showing that the graben was partially filled by lava flows. A relatively thick layer of unconsolidated material overlies the subfloor basalt; it consists largely of finely comminuted rock debris.

The material at the surface over much of the Taurus-Littrow region has a very low albedo and was believed be-

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