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Preliminary Examination of Lunar Samples from Apollo 11

A physical, chemical, mineralogical, and biological analysis of 22 kilograms of lunar rocks and fines.

The Lunar Sample Preliminary Examination Team (*1*)

This is the first scientific report on the examination of the samples returned from the Apollo 11 landing in Mare Tranquillitatis on 20 July 1969. The lunar samples have been in the Lunar Receiving Laboratory (LRL) at the Manned Spacecraft Center in Houston, Texas, since 25 July 1969, undergoing preliminary physical, chemical, mineralogical, and biological analysis.

In 1963, when serious planning for the return of lunar material began, it was decided that the material should be handled in vacuum, at least until it was determined whether or not any sample degradation occurred upon exposure to terrestrial atmospheric gases. A complicated vacuum chamber with space-suit arms good for 1 atmosphere of differential pressure was constructed for this purpose.

In 1964, a study by the National Academy of Sciences (*2*) led to the conclusion that it would be necessary to quarantine any returned lunar material for a period of time to study possible pathogenicity (*3*). The possible consequences are so far-reaching that it was decided to quarantine the lunar material for a period of 1 month or more in order to make a series of biological tests to determine if it was safe to release the material. The possibility of mixing two ecologies has well-known disastrous effects.

These decisions led to the construction of the Lunar Receiving Laboratory at the Manned Spacecraft Center in Houston, Texas (*4*). Functions of this laboratory are as follows: (i) to quarantine the lunar material for an appropriate period of observation; (ii) to perform a preliminary examination of this material (chemical, mineralogical, and other examinations); (iii) to perform certain time-critical experiments which could not wait until the end of quarantine; and (iv) to distribute the lunar samples to approved investigators and to be the depository for the permanent collection of lunar materials.

The purpose of the preliminary examination [item (ii)] is to collect enough information about the lunar samples in order to distribute them in an intelligent manner to the scientists who will perform the detailed measurements.

Several widely used techniques are missing from the LRL because it seemed inappropriate to use them in a preliminary analysis. For example, there is no electron microprobe to study samples in the LRL.

A series of committees was established by NASA to provide advice on the early design of the laboratory. For the past 2 years, a group called the Lunar Sample Analysis Planning Team (LSAPT) has helped NASA by reviewing the program for the lunar laboratory and suggesting amplifications and modifications for sample-processing techniques (*5*). More recently, LSAPT has helped develop plans for distributing the lunar samples to the 140 principal investigators around the world who will shortly receive this material. A group of visiting scientists and resident NASA scientific staff with appropriate specialties, known as the preliminary examination team (PET), was formed to carry out the preliminary examination of the samples and to obtain the basic data which would be used to determine sample allocation. The results of this preliminary examination by PET, other NASA staff, and the support contractor team is the subject of this report.

Apollo 11 Mission

The extravehicular activity (EVA) on the lunar surface was carefully programmed and simulated before the mission down to items of approximately 5 minutes in a time line shown in Fig. 1. The length of the EVA was based on the capabilities of the life support system, including a water supply capable of handling 4800 British thermal units of heat generation by each astronaut and based on an expected metabolic usage of 1600 Btu per hour. This would allow a 3-hour EVA which, with a 20-minute safety factor, resulted in the planned 2-hour 40-minute EVA. Three separate samples (contingency sample, bulk sample, and documented sample) were collected on the lunar surface.

Contingency sample. The contingency sample was approximately a 1-kilogram sample of surface material collected early in the EVA in a Teflon bag to assure that some lunar material would be returned in the event that EVA had to be terminated early. Armstrong collected the contingency sample at a distance of 1.5 meters from the lunar module (LM) and included several small rock fragments.

Bulk sample. One of the two special sample-return containers (Fig. 2) was filled about halfway through the EVA by using the scoop (Fig. 3). Little care was planned for sample selection in this box. The idea was to collect a large amount rather rapidly, again to ensure that an adequate amount of material was returned to earth. However, in filling this box, Armstrong did considerably more than had been initially anticipated. He specifically set about collecting a substantial number of rocks up to 10 meters from the base of the LM.

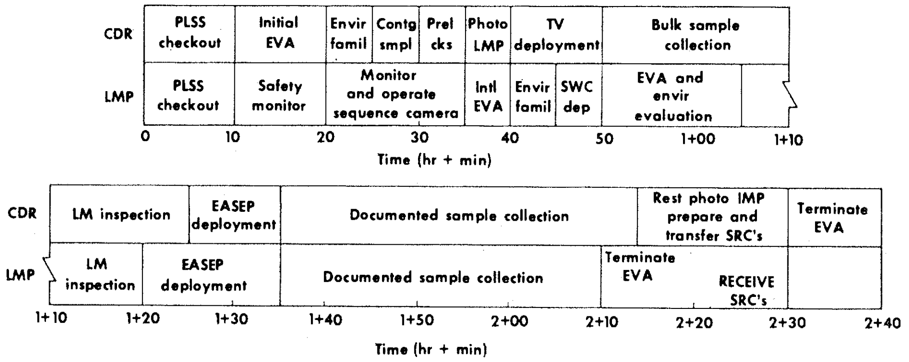
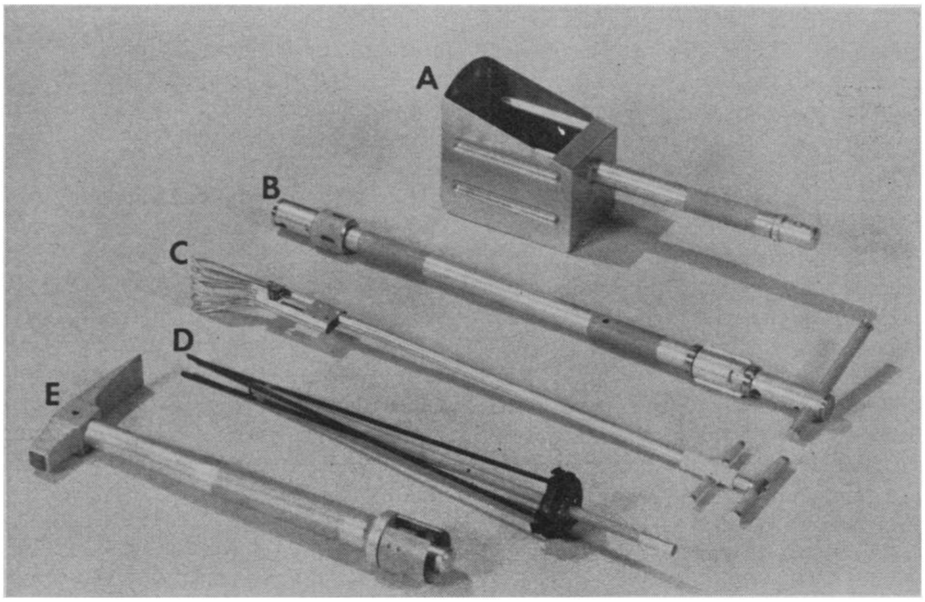


Fig. 1. Time line for EVA on the lunar surface during Apollo 11.

Fig. 2 (left). Photograph of the lunar sample container showing the steel mesh lining and packing bricks, the bag the samples are packed in, and the two special sample containers.

Fig. 3 (below). Photograph of the lunar land tools used on Apollo 11. (A) Scoop for collecting small rocks and fines; (B) extension handle used with the scoop and hammer; (C) tongs for collecting rocks; (D) gnomon for photographing the documented samples (not used in Apollo 11); (E) hammer.



Documented sample. The documented sample consists of about 20 rocks that were individually selected by Armstrong during a 3.5-minute period late in the EVA. The second sample-return container also contained two core tubes, filled by Aldrin, and the solar wind foil.

Both sample containers were sealed on the lunar surface, transferred into the LM, bagged, and, after rendezvous, transferred into the command and service module (CSM). They were removed from the command module (CM) on the carrier *Hornet*, transferred into the Mobile Quarantine Facility (MQF) where the containers were put in a second bag; after decontamination, the sample containers were transferred out of the MQF into two aircraft that returned them to the LRL on 25 July 1969.

Lunar Receiving Laboratory Operations

The LRL is divided into three areas:

1) The crew reception area (CRA) is the area where the crew stayed in quarantine after return from the moon until 21 days had elapsed. They were released from quarantine when no significant medical problems developed.

2) The Sample Laboratory (SL) is where all the lunar samples are processed behind biological barriers for 50 days until the end of a series of biological tests designed to determine their pathogenicity. If the lunar samples are safe for release, they are distributed for scientific use.

3) The support and administrative area is outside the biological barrier.

The biological barrier in the SL is actually a double barrier. The primary barrier consists of vacuum chambers and special biological cabinets (class-3) inside which the samples are handled. The sealed walls of the building constitute a secondary barrier. The inside of the CRA and SL are operated at a small negative pressure so that any leakage will be inward. Similarly, SL primary barrier cabinets are operated at negative pressure with respect to the rooms in which they are located. The biological barriers are two-way barriers. They prevent any unsterilized lunar material from contaminating the atmosphere of the earth and also prevent any terrestrial contaminants from getting into the samples.

The lunar samples in the rock boxes were brought into the SL and put into decontamination chambers where terrestrial contamination was removed by a peracetic acid spray. The documented sample box was opened in the vacuum chamber and the rocks were examined, described, photographed, weighed, and chipped for (i) physical and chemical analysis and (ii) biological testing. The bulk box, contingency sample, and core tubes were opened in dry nitrogen inside one of the special cabinets after it had been properly determined that no serious short-term degradation of the sample occurred on exposure to oxygen, moist air, and carbon dioxide. Approximately 50 grams of the core-tube material and 500 grams of the fines from the bulk box were removed for biological testing.

Most of the remaining material is now stored in nitrogen inside the biological cabinets, and the rest is stored under vacuum.

Geologic Setting

Apollo 11 landed in the southwestern part of Mare Tranquillitatis at 0.67°N, 23.49°E, approximately 10 kilometers southwest of the crater Sabine D. The landing site is approximately 25 kilometers southeast of the landing site of Surveyor 5 and 68 kilometers southwest of the crater formed by the impact of Ranger 8. This part of Mare Tranquillitatis is crossed by relatively faint, but distinct, north-northwest trending rays associated with the crater Theophilus, which lies 320 kilometers to the southeast. A fairly prominent north-northeast trending ray lies 15 kilometers west of the landing site. This ray may be related to Alfraganus, 160 kilometers to the southwest, or to Tycho, about 1500 kilometers to the southwest. The landing site lies between major rays but may contain rare fragments derived from Theophilus, Alfraganus, Tycho, or other distant craters.

Approximately 400 meters east of the landing point is a sharp-rimmed ray crater, approximately 180 meters in diameter and 30 meters deep which has been informally named West crater. West crater is surrounded by a blocky ejecta apron that extends almost symmetrically outward about 250 meters from the rim crest. Blocks as much as 5 meters across occur on the rim and in the interior of the crater. Rays of blocky ejecta with many fragments 0.5 to 2 meters across extend beyond the ejecta apron west of the landing point. The LM landed in an area between these rays, which is relatively free of extremely coarse blocks.

At the landing site, the lunar surface consists of unsorted fragmental debris which ranges in size from particles too fine to be resolved by the naked eye to blocks 0.8 meter across. This debris forms a layer, the lunar regolith, that is porous and very weakly coherent at the surface. It grades downward into similar but more densely packed material. The bulk of the regolith consists of fine particles, but many rock fragments were encountered in the subsurface as well as on the surface.

In the vicinity of the LM, the mare surface is pockmarked with small craters ranging in diameter from a few centimeters to several tens of meters. Just southwest of the LM is a double crater 12 meters long, 6 meters wide, and 1 meter deep with a subdued raised rim. Approximately 60 meters east of the LM is a steep-walled (but shallow) crater 33 meters in diameter and 4 meters deep which was visited by astronaut Armstrong near the end of the extravehicular activities (Fig. 4).

All of the craters in the immediate vicinity of the LM have rims, walls, and floors of relatively fine-grained material with scattered coarser fragments that occur in about the same abundance as on the intercrater areas. These craters are about 1 meter deep or less; evidently they have been excavated entirely in the regolith.

At the crater 33 meters in diameter east of the LM, the walls and rim have the same texture as the regolith elsewhere; however, a pile of blocks occurs on the floor of the crater (Fig. 4). The crater floor probably lies close to the base of the regolith. Several craters of about the same size, with steep walls and shallow flat floors, or floors with central humps, occur in the area around the landing site. From the depths of these craters, the thickness of the regolith is estimated to range from 3 to 6 meters.

Coarse fragments are scattered in the vicinity of the LM in about the same abundance as at the Surveyor 1 landing site (*6*). They are distinctly more abundant than at the other Surveyor landing sites on the maria, including the landing site of Surveyor 5 northwest of the LM. Surveyor 1 landed near a fresh blocky rim crater but beyond the apron of coarse block ejecta, as did Apollo 11. It may be inferred

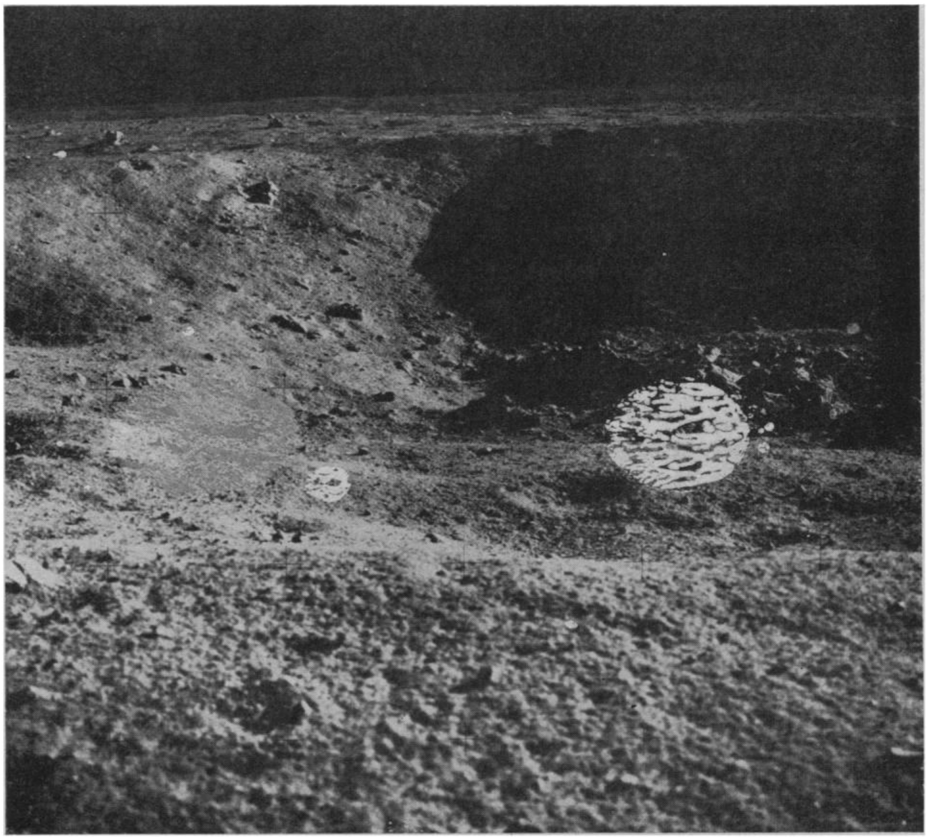


Fig. 4. Photograph of crater (33 meters in diameter) east of the lunar module taken by astronaut Neil Armstrong. The pile of blocks in the floor of the crater suggests that the floor lies close to bedrock.

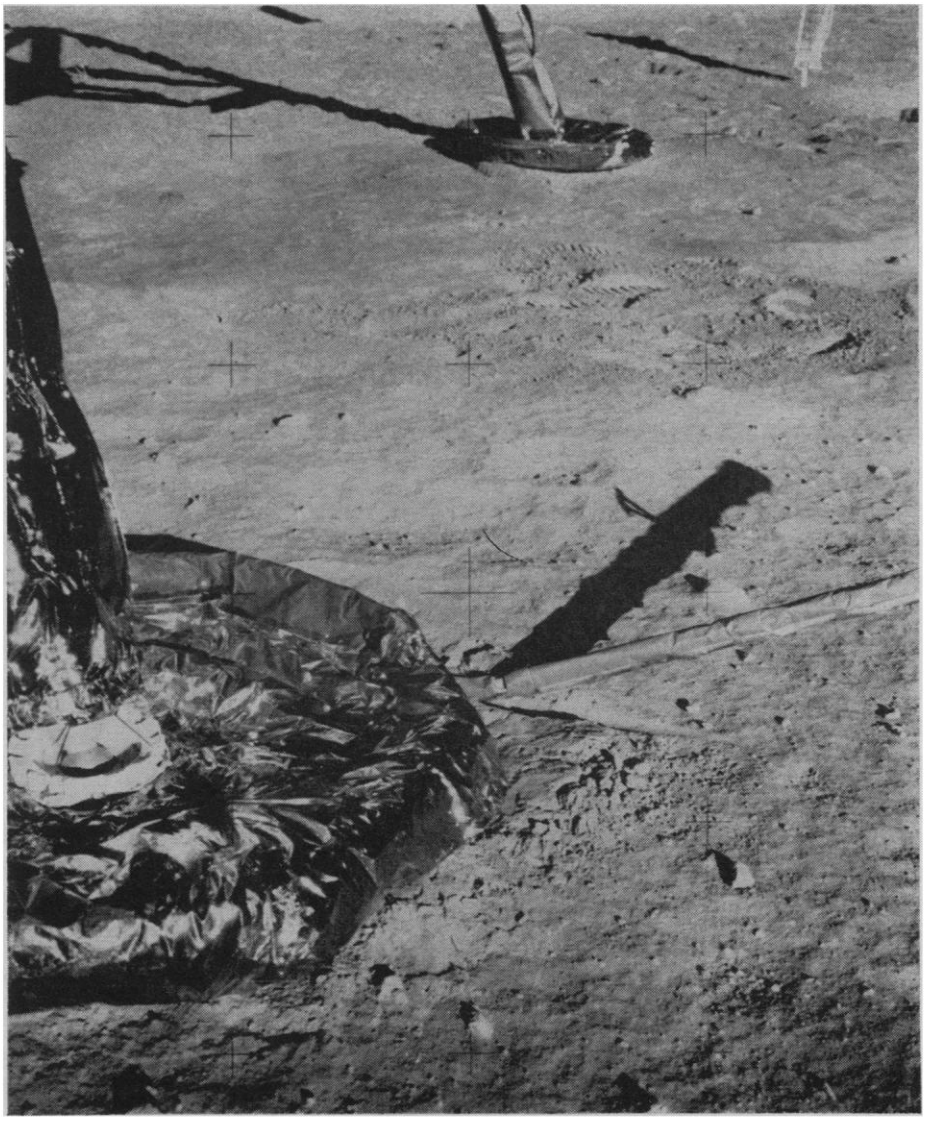


Fig. 5. Lunar module footpads on lunar surface showing footpad penetration and general appearance of surrounding lunar surface.

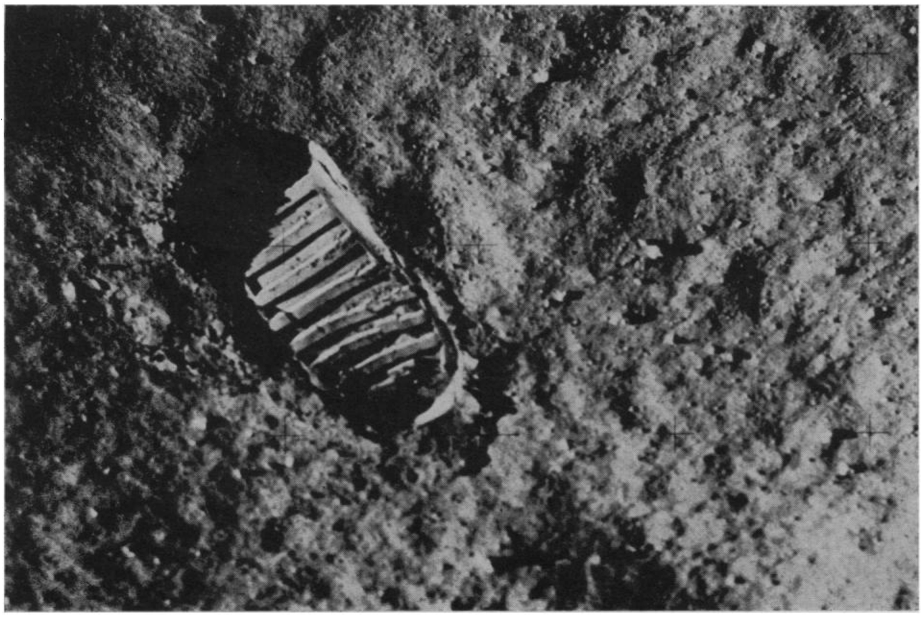


Fig. 6. Astronaut footprint on lunar surface showing sinkage and cohesive characteristics and mode of deformation of lunar surface material.

that many rock fragments in the immediate vicinity of the spacecraft, at both the Surveyor 1 and Apollo 11 landing sites, were derived from the nearby blocky rim crater. Fragments derived from West crater may have come from depths as great as 30 meters beneath the mare surface.

Rock fragments at the Apollo 11 landing site have a wide variety of shapes and most are embedded to varying degrees in the fine matrix of the regolith. A majority of the rocks are rounded to subrounded on their upper surfaces, but angular fragments of irregular shape are also abundant. A few rocks are rectangular slabs with a faint platy structure. Many of the rounded rocks, when picked up, were found to be flat or of irregular angular shape on the bottom. The exposed part of one unusual rock, which was not collected, was described by Armstrong as resembling a distributor cap. When this rock was dislodged with a kick, the sculptured cap was found to be the top of a much bigger rock, the buried part of which was larger in lateral dimensions and angular in form.

The evidence suggests that processes of erosion are taking place on the lunar surface which lead to the gradual rounding of the exposed surfaces of rocks. Several processes may be involved. On some rounded rock surfaces, individual clasts and grains (of which the rocks are composed) and glassy linings of pits on the surfaces of the rocks have been left in raised relief by general wearing away or ablation of the surface. Rocks which exhibit this differential erosion most prominently are microbreccia. The ablation may be caused primarily by small-particle bombardment of the surface.

Some crystalline rocks of medium grain size have rounded surfaces that have been produced by the peeling off of closely spaced exfoliation shells. The distributor-cap form observed by Armstrong may have developed by exfoliation. It also could have been produced by spalling of the free surfaces of the rock as a result of one or more energetic impacts on the top surface.

Minute deep pits, a fraction of a millimeter to about 2 millimeters in diameter, occur on the rounded surfaces of most rocks. They were observed by Armstrong, who recognized that they had been produced on the surface of the rocks and that they were distinguishable from vesicles. As described below, many of these pits are lined with glass. They are present on a specimen of microbreccia which has been identified in photographs taken on the lunar surface and for which the orientation of the rock at the time it was collected is known. The pits are found primarily on the upper side; they clearly have been produced by a process acting on the exposed surface. They do not resemble impact craters produced in the laboratory, and their origin remains to be explained.

Another discovery made by Armstrong was the presence of blebs of material with specular surfaces partially covering areas 2 to 10 centimeters wide in the bottom of six or eight raised-rim craters 1 meter in diameter. These apparently glassy blebs, which resembled drops of solder, were observed by Armstrong only in craters. The form of the blebs suggests they have been formed by the splashing of molten material that impacted at low velocity. Their distribution suggests the blebs are natural features on the lunar surface, but there is a remote possibility that they are artifacts produced by the landing of the LM.

Lunar Soil Mechanics

The upper few centimeters of the surface material in the vicinity of Tranquility Base are characterized by a brownish, medium-gray, slightly cohesive granular soil, largely composed of bulky grains that range in size from silt to fine sand. Angular to subrounded rock fragments ranging up to 1 meter in size are distributed throughout the area. Some of these fragments are lying on the surface, some are partly buried, and others are barely exposed.

The lunar surface is relatively soft to depths ranging from 5 to 20 centimeters. It can be easily scooped, offers low resistance to penetration, and offers low lateral support for staffs, poles, or core tubes. Beneath this relatively soft surface, the material's resistance to penetration increases considerably.

The mechanical behavior of the lunar soil can be summarized as follows:

1) Confinement of the loose surface material leads to a significant increase in resistance to deformation, which is a characteristic of soils deriving a large portion of their strength from interparticle friction. The relatively small LM footpad penetrations of 2.5 to 7.5 centimeters and astronaut footprint depth of up to 5 centimeters can be seen in Figs. 5 and 6. These correspond to average static-bearing pressures of 0.6 to 1.5 pounds per square inch.

2) The soil possesses a small amount of cohesion. This was evidenced by the following observations: (i) it possesses the ability to stand on vertical slopes and to retain the detail of a deformed shape; the sidewalls of trenches dug with the scoop were smooth with sharp edges; (ii) the fine grains stick together,

Fig. 7. Surface pits in breccia (× 5) [NASA photograph S-69-47905].

and, in some cases, it was hard for the astronauts to distinguish soil clumps from rock fragments; (iii) the holes made by the core tubes were left intact upon the removal of the tubes; and (iv) the material collected at the bottom of the core tubes did not tend to pour out when the core bit was unscrewed.

3) Natural clods of fine-grained material crumbled under the astronauts' boots. This behavior may be indicative of some cementation between the grains although in LRL tests the soil grains were found to cohere again to some extent after being separated.

4) Most of the footprints at the low loads imposed by the astronauts caused compression of the lunar surface soil, although in a few instances bulging and cracking of the soil adjacent to the footprint occurred. The latter observation indicates shearing rather than compressional deformation of the soil.

5) At the LRL, the specific gravity of lunar soil was measured as 3.1, considerably higher than the average value (about 2.7) for terrestrial soils. Based on the value obtained for the lunar soil and the measured bulk densities, the void ratio of the material in core 1 is 0.87 and in core 2 is 1.01. The respective porosities are 46.5 and 50.1 percent. Because of the disturbance involved in sampling, these values may not be representative of the material's properties in place.

6) In the LRL, material finer than 1 millimeter size obtained from the lunar bulk sample was placed loosely in a container and the bulk density of the material was found to be 1.36 grams per cubic centimeter. In a second test, the soil was compacted to a dense state with a bulk density of 1.80 grams per cubic centimeter. In the compact state, the bearing capacity of the material was determined by a small penetrometer. From these tests the cohesion of the material was estimated to be in the range between 0.05 and 0.20 pound per square inch. The above experiments were performed in a nitrogen atmosphere.

In summation, the lunar soil is similar in appearance, behavior, and mechanical properties to the soil encountered at the Surveyor equatorial landing sites. Although the lunar soil differs considerably in composition and range of particle shape from a terrestrial soil of the same particle size distribution, it does not appear to differ significantly in its mechanical behavior.

Mineralogy and Petrology

The lunar sample returned by Apollo 11 totals 22 kilograms, of which 11 kilograms are rock fragments over 1 centimeter in diameter and 11 kilograms are smaller particulate material. The documented sample box was filled by picking up selected rocks by tongs and therefore contained a variety of large rocks (total weight, 6.0 kilograms). The bulk sample totals 14.6 kilograms. It contains 4.2 kilograms of rock fragments over 1 centimeter in size, and 10.4 kilograms of material in the range below 1 centimeter.

The following discussion is based on stereomicroscopic examination of the samples aided by random grain mounts under the polarizing microscope. Some of the provisional identifications were reinforced by limited further investigation with the aid of spindle stage and x-ray powder diffraction methods, together with a study of thin sections of two of the crystalline rocks which became available near the close of the preliminary examination. In spite of the handicap of an adherent layer of dust, all the rocks were examined. Only the contingency samples and small chips taken from the samples in the rock boxes were free of dust when they were examined.

The returned samples may be divided into four groups: (i) type A, fine-grained vesicular crystalline igneous rock; (ii) type B, medium-grained vuggy crystalline igneous rock; (iii) type C, breccia; and (iv) type D, fines. The term "rocks" is applied to fragments larger than 1 centimeter in diameter; "fines" applies to fragments smaller than 1

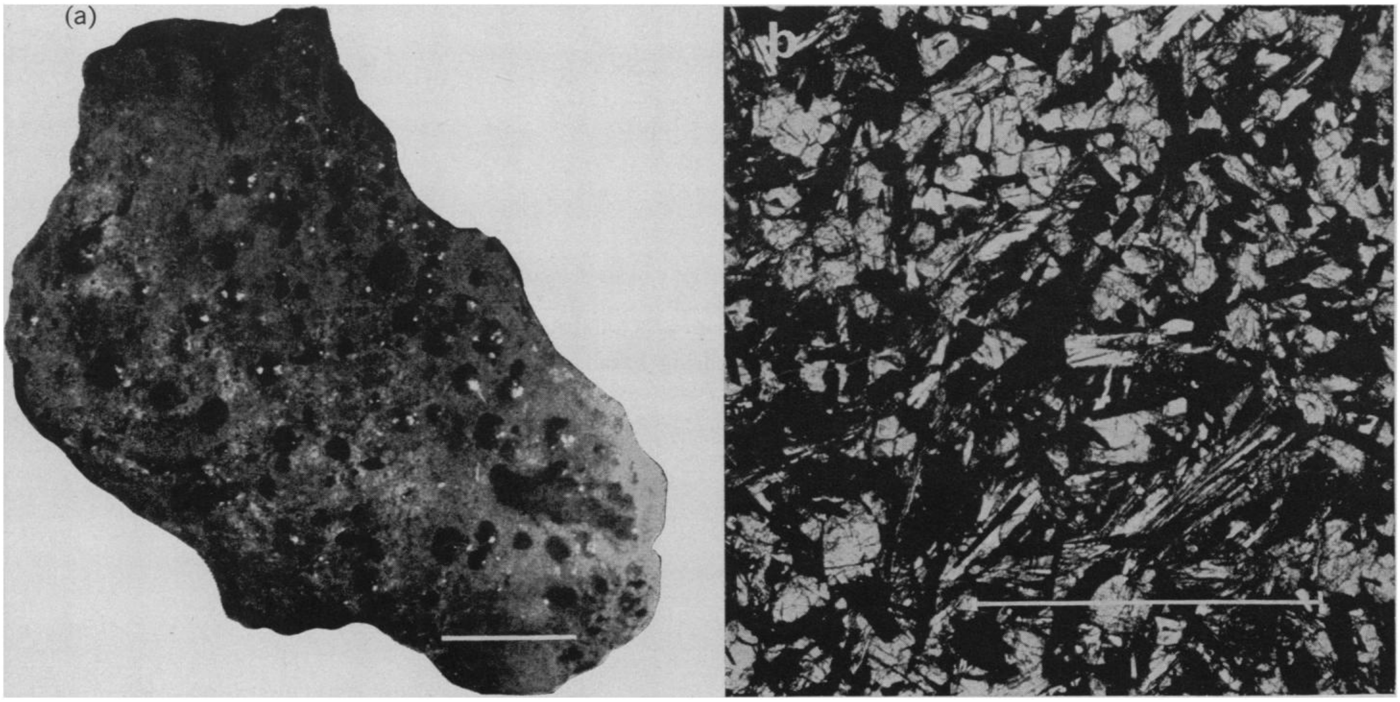


Fig. 8. A typical type-A crystalline rock. (a) Sample 10022; scale, 1 centimeter [NASA photograph S-69-45209]; (b) photomicrograph of sample 10022; scale, 1 millimeter.

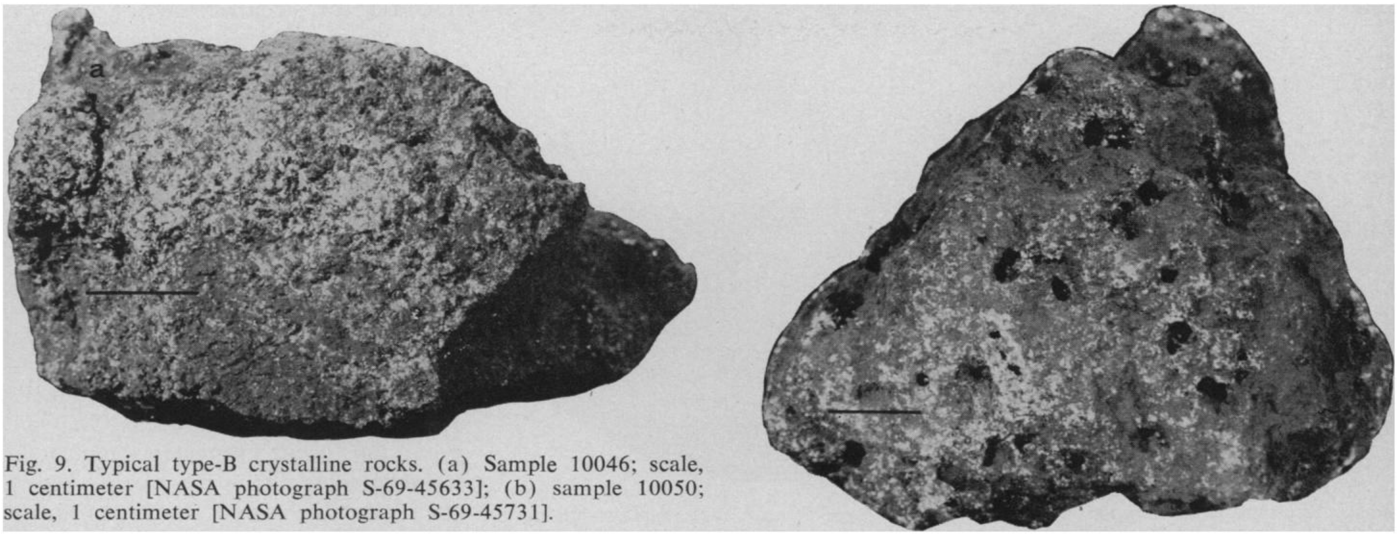


Fig. 9. Typical type-B crystalline rocks. (a) Sample 10046; scale, 1 centimeter [NASA photograph S-69-45633]; (b) sample 10050; scale, 1 centimeter [NASA photograph S-69-45731].

centimeter. All the rocks and many smaller pieces show unearthly surface features (Fig. 7) that are discussed in the following paragraphs.

Rocks. The crystalline rocks are volcanic. The term as used here implies surface lavas or near-surface igneous rocks. It carries no connotations regarding impact-generated or triggered volcanism as opposed to volcanism in the common terrestrial sense.

The rocks contain pyrogenic mineral assemblages and gas cavities, an indication of crystallization from melts. The major minerals can be assigned to known rock-forming mineral groups. The unique chemistry of the magmas has resulted in mineral ratios unlike those of known terrestrial volcanic liquids, yet not greatly different from some terrestrial cumulates, at least in the major elements.

Twenty crystalline rocks, most of which are over 50 grams in weight, were returned. The largest rock weighed 919 grams. These rocks have been classified as belonging to a fine-grained vesicular type (type A, Fig. 8) and a coarser-grained, vuggy microgabbroic type (type B, Fig. 9), but they may be members of a textural and compositional series.

A chip from a dark gray vesicular rock with subophitic texture (type A) has a bulk density of about 3.4 grams per cubic centimeter. Vesicles are mostly spherical, but some are ovate and they range between 1 and 3 millimeters in diameter. Coalescence has modified other vesicles, thus creating irregular-shaped cavities larger than single vesicles. The vesicles are faced with brilliant reflecting crystals of the groundmass minerals. Such vesicles contain no transecting crystals or sublimate minerals. In addition to the spherical vesicles, there are minor irregular-shaped cavities or vugs into which groundmass and accessory minerals locally project. Vugs tend to take the place of spherical vesicles in the more coarse-grained rocks; euhedral crystals projecting into vugs are common.

Preliminary modal analysis of this type-A specimen, recalculated for 15 percent void space, yields: clinopyroxene, 53 percent; plagioclase, 27 percent; opaques [abundant ilmenite and minor troilite (?) and native iron (?)], 18 percent; other translucent phases (at least two), 2 percent; and minor olivine. Notable are rare grains of olivine showing marginal transformation to clinopyroxene. The olivine grains are as much as 0.5 millimeter long, whereas most other mineral grains range between 0.05 and 0.2 millimeter in diameter. In vuggy regions, there is a slight increase in grain size. Except for the very high content of opaques, which reflects the high Fe and Ti content of the magma, the rock resembles some terrestrial olivine-bearing basalts. Mineral grain sizes and vesicle sizes, shapes, and distribution suggest that the rocks originated near the top or bottom of a lava flow or lava lake.

Nine other rocks of type A are similar to the one described above; although most have smaller vesicles. The most notable variation among them is in their olivine content, which ranges from zero in some to approximately 10 percent in others.

The dark brownish-gray speckled rock of type B (Fig. 9) has irregular cavities and a bulk density of about 3.2 grams per cubic centimeter. The texture is granular; in general appearance, it resembles the microgabbroic textures of segregation veins and pods in some terrestrial basalts.

The grain size in rocks of type B varies from 0.2 to 3.0 millimeters. Preliminary modal analysis yields: clinopyroxene, 46 percent; plagioclase, 31 percent; opaques (mainly ilmenite), 11 percent; low cristobalite, 5 percent; and others, 7 percent. The largest crystals, many of which are euhedral, project into cavities. Olivine is not present in this rock or others like it. The others include an unidentified yellow mineral that seems to be concentrated in vuggy areas of the rock and a colorless phase with a high refractive index.

The crystalline rocks present a series based on groundmass grain size ranging from about 0.1 to 1 millimeter, with larger crystals in vuggy zones up to 3.0 millimeters in the coarser-grained rocks. In general, abundance of vugs increases and abundance of vesicles decreases with increasing grain size. Olivine is found only in the finer-grained rocks and the unidentified yellow phase is found only in the coarser-grained rocks. Ilmenite seems less abundant and low cristobalite more abundant in the coarser-grained rocks. The three major minerals (clinopyroxene, calcic plagioclase, and ilmenite) are present in all of the rocks.

The apparent complete absence of hydrous mineral phases is notable, as is the extremely fresh appearance of the interiors of all crystalline rocks, in spite of their microfractures and high K-Ar age.

Fig. 10. Photograph of sample 10045 illustrating a type-B rock that displays evidence of original position. The upper-right portion of the sample shows rounding, glass-lined pits, and a light color, whereas the lower-left part of the sample shows sharp angular outline, few pits, and a dark color. It appears that this sample was partially buried on the lunar surface with its upper-left part exposed; scale, 1 centimeter [NASA photograph S-69-45585].

All the breccias examined (type C, Fig. 7) are mixtures of fragments of different rock types and are gray to dark gray in color, with specks of white, light gray, and brownish-gray rock fragments. Most breccias are fine-grained, with fragments smaller than 1 centimeter in diameter, and mostly smaller than 0.5 centimeter. Only a few fragments in the beccias are rounded. The fragments consist of either rocks or minerals, similar to those described previously but with the distinction that a large number show a greater population of closely spaced microfractures and various degrees of vitrification. In addition, angular fragments and sperules of glass in a wide range of color and refractive indices are present which also are characteristic components of the lunar fines. In several specimens, vesicular fine-grained crystalline rock constitutes a major fraction of the larger fragments. In other specimens, mineral fragments and small fragments of the coarser microgabbroic type predominate.

Although the rock fragments are small, they seem to have a wider range of variation in modal mineral composition and shock metamorphism than the large crystalline rock samples. Several minor rock types, one predominantly light gray in color and one predominantly pale yellow, occur in breccia but are not represented among the larger individual rocks. Some breccias contain crystal fragments larger than 3 millimeters in diameter, thus indicating that there exist on the moon more coarsely crystalline rocks than those returned.

The finer fraction of the breccias is gray and granular in appearance and consists largely of glass particles (both angular and rounded) and fragments of birefringent minerals, coated in part with glass or with opaque or fine-grained dusty material. The glass particles, forming most of the matrix, are similar to the glass of the fines. Many single glass particles are composed of more than one type of glass and therefore are unlike glass shards of common terrestrial volcanic processes. Some of the breccias are transected by vesicular "glass" veins or contain particles of glass either formed in place or injected along fractures.

The degree of induration and the history of subsequent deformation of the breccias are varied. Some breccias are very poorly consolidated and are soft and friable. Others have coarse layering. Still others have closely spaced fracture systems and are as hard, if not harder, than the hardest of the crystalline rocks. Many of the broken fragments of crystalline rocks in the breccias, and the breccias themselves, are composed of impact ejecta.

Two types of unique surface features occur on all rocks of the lunar samples. These are small pits lined with glass and glass spatters not necessarily associated with pits. In addition, the crystalline rocks show a generally lighter-colored surface compared to the interior, which appears to be related to microfracturing of surface crystals.

The diameter of pits averages somewhat less than 1 millimeter. Diameter-to-depth ratios of the pits have a range of values, but it appears that the ratio is smaller for pits in the breccias than for pits in crystalline rocks. A few of the rocks examined show pitting on rounded sides but no evident pitting on one (generally flat or irregularly rough) surface. The surfaces of the glass in the pits are bright-reflecting and commonly uneven and botryoidal. Botryoidal surfaces are more common in pits in breccias than in crystalline rocks. Raised glassy rims occur in greater abundance in surrounding pits in the breccias. The glass extends beyond some pit rims. Fractures and rare glass veinlets radiate out from some pits. The pits are presumably caused by the impact of small particles on the surfaces of the rocks.

In addition to glassy pits, thin glass crusts occur that appear to be the result of spattering. Spatter crusts more than 1 centimeter in diameter occur both on breccia and crystalline rock surfaces. These may be related to nearby impact events.

The surfaces of the crystalline rocks show whitish blotches and halos around the glassy pits. This whitish color is at least partially attributable to intense microfracturing of minerals, particularly feldspar and pyroxene, and it does not penetrate more than 0.5 to 1.0 millimeter below the surface in most cross sections examined. In some crystalline rocks, whitening may be so widespread on some surfaces that the whole surface is lighter in color than the interior. This feature is particularly noticeable in fine-grained rocks, which are dark gray on freshly broken surfaces.

The most noticeable surface feature of the rocks is the rounding of one or more edges and corners. The most striking example of rounding, and perhaps the most common, is that in which one side of a rock is nearly flat and the remainder of its surface is rounded. Rounding appears to be more pronounced in the softer, more friable, breccias than in the crystalline rocks. The original surfaces of breccias commonly have coarser grains projecting above the surface, which suggests that the finer grains surrounding them have been eroded away. The appearance is thus similiar to that of friable sedimentary rocks of a wide range of grain size which have been sandblasted. Both the rounding and the detailed surface appearance indicate that some sort of erosional process has acted on the rocks.

The surface features of some rocks allow conclusions to be made regarding the orientation of the rock on the surface (Fig. 10).

Fine Material. Two core samples, each 2 centimeters in diameter, were returned: core tube 1 contained 10 centimeters, and core tube 2 contained 13.5 centimeters of material. The cores are composed predominantly of particles with diameters from 1 millimeter to 30 micrometers, with admixed angular rock fragments, crystal fragments, glass spherules, and aggregates of glass and lithic fragments in the coarser-sized fraction. When the upper half of the split-tube core liner was removed, the material sustained its cylindrical shape perfectly. Both the material in the tubes and the fines in general are medium to dark gray with a tinge of brown.

When prodded with a small spatula, the material disintegrates particle by particle or forms extremely fragile ephemeral units of subangular blocky shapes.

Neither core sample shows obvious grain-size stratification. The core from tube 2 has a slightly lighter zone about 6 centimeters from the top surface which is 2 to 5 millimeters thick with a sharp upper boundary and a gradational lower boundary. This lighter zone is not megascopically different in grain size or texture from the dark material.

Sieve analyses of material from the two core tubes, a sample from the documented Apollo lunar surface return container (ALSRC), and a sample from the bulk ALSRC are shown in Fig. 11. These distributions are replicable by simple dry sieving but may be biased by aggregation of fines. Core 1 has a bulk density of 1.66 ± 0.03 grams per cubic centimeter, and core 2 has a density of 1.54 ± 0.03 grams per cubic centimeter.

The fines consist chiefly of a variety of glasses, plagioclase, clinopyroxene, ilmenite, and olivine. Very rare spherules and rounded fragments of Ni-Fe up to 1 millimeter in size were observed. The glass, which constitutes about half of the material, is of three types: (i) botryoidal, vesicular, and globular dark gray fragments; (ii) pale or colorless, or more rarely brown, yellow, or orange, angular fragments ranging in index of refraction from about 1.5 to about 1.6; and (iii) spheroidal (Fig. 12), ellipsoidal, dumbbell-shaped, and teardrop-shaped bodies, most smaller than 0.2 millimeter, which range in color from red to brown to green to yellow. Indices of refraction range from somewhat less than 1.6 to more than 1.8 and are generally higher for the more intensely colored glass. Material with a refractive index above 1.7 is less common than that with a lower index. The colorless or pale angular glass, by far the more abundant type, is in part turbid or weakly birefringent. Unlike normal droplets from quenched magmas and glasses from terrestrial volcanic sources, many single glass particles are inhomogeneous.

Shock or impact metamorphism of lunar samples. Evidence of impact metamorphism is widespread in the lunar samples, particularly in the loose fine-grained materials and in the breccias. In contrast, most of the crystalline rocks, although commonly fractured or crumbled on the surface, show negligible or weak shock effects on their interior. A small number show evidence of strong shock. Crystalline minerals underlying glass-lined pits are crushed or powdered, but not strongly shocked. Such areas are of limited to wide distribution on the surface of the crystalline rocks.

Many phenomena were observed in the loose material and breccias that are strongly suggestive of melting induced by strong and intense shock. These include: (i) glass dumbbells, teardrops, and other forms of evolution; (ii) vesicular and flowed glass containing at least two types of glass; and (iii) Ni-Fe spherules. The abundance of vitrified mineral fragments is evidence of moderate to strong shock. Unshocked minerals or lithic fragments are found in the loose materials and in breccia, but such fragments are less abundant. Most of the birefringent crystal fragments in the fines show pronounced straight to mosaic undulatory extinction, and some lamellar microstructures, an indication that these fragments have suffered weak to strong shock.

Clear evidence of a multiple shock

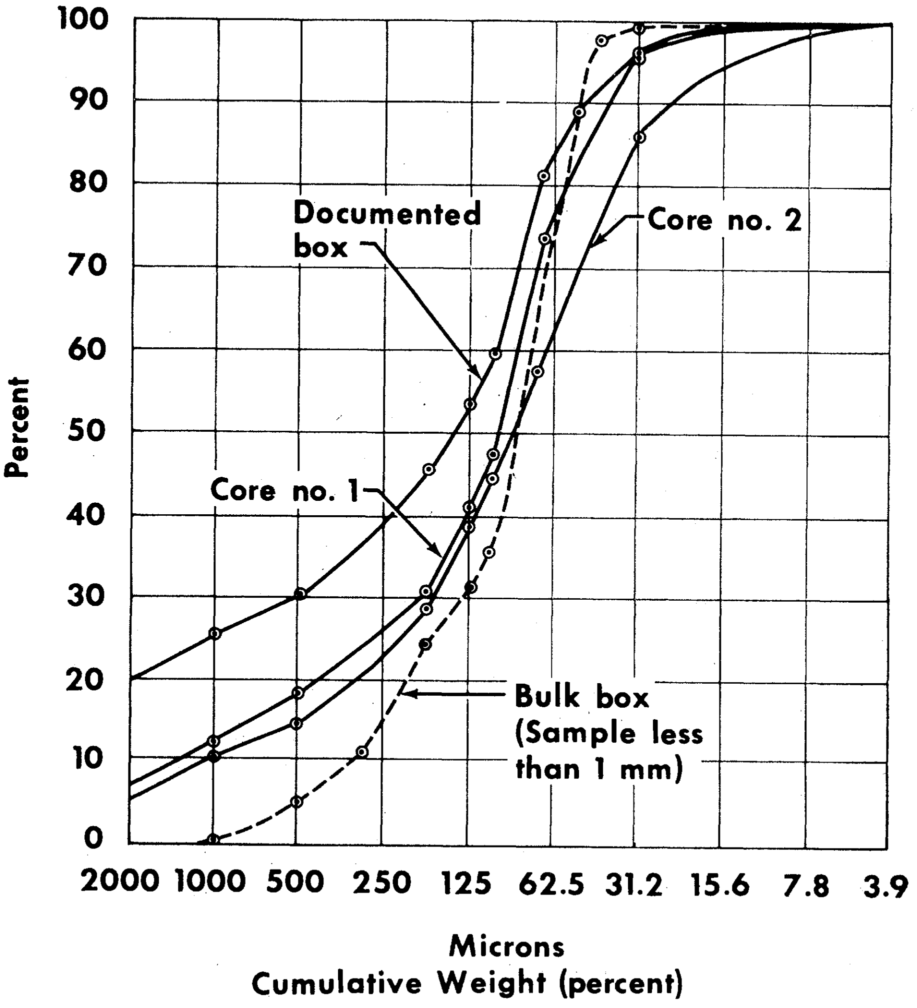


Fig. 11. Grain-size distribution in the lunar fines.

history is shown by fragments of breccia within breccia, and by breccias containing spherules of glass from prior impact events which are splashed with glass from subsequent impact events. Each breccia sample contains a wide variety of mineral and lithic fragments of various degrees of shock, and each sample appears to have a complex history.

Mineralogy. Clinopyroxene is present in all of the rocks examined. The most widespread variety is cinnamon-brown to resin-brown in reflected light and pale reddish-brown to pinkish-brown in transmitted light, with little or no pleochroism. The habit of clinopyroxene in the crystalline rocks is generally stubby prismatic or anhedral, but sheaflike intergrowths with feldspar are also present. Some crystals are strongly zoned from the center outward, as indicated by an increasing positive optic angle from near 0° to near 50° together with an increasing refractive index and intensity of color. Optical properties so far determined would appear to fit the pigeonite-augite series and do not exclude titaniferous varieties. Cinnamon-brown pigeonite in samples of fines was identified by x-ray diffraction measurements.

Olivine containing between 65 and 75 mole percent forsterite is a subordinate phenocrystic constituent of several of the finer crystalline rocks and occurs sporadically as crystal fragments in the breccias and dust. It is clear and pale greenish-yellow in the crystalline rocks but may range in color from greenish-yellow through honey-yellow and orange-yellow in the breccias and dust. The presence of olivine was confirmed by x-ray diffraction methods.

Plagioclase is likewise widespread but generally subordinate in amount to the ferromagnesian minerals. Optical properties indicate it to be calcic (mostly between 70 and 90 mole percent anorthite), with compositional zoning in some rocks. The habit is commonly lath- and plate-shaped, with lamellar twinning parallel and transverse to the plates. The presence of calcic plagioclase was confirmed by x-ray diffraction methods.

Ilmenite, as identified optically and by x-ray diffraction methods, is present in relatively large amounts in the crystalline rocks, where it occurs as plates and well-formed skeletal crystals. Ilmenite is also common in the breccias and dust, as a constituent of the lithic fragments and as isolated crystal fragments.

Low cristobalite is present as thin clear coatings and euhedral crystals. It occurs in cavities, and fills interstices between plagioclase plates in some of the coarser crystalline rocks. It is characterized by a crackly surface and complex twinning.

Unidentified yellow transparent crystals occur interstitial to the plagioclase crystals and in cavities. The mineral is a characteristic accessory in several of the more coarsely crystalline rocks.

Troilite (?) occurs in small amounts

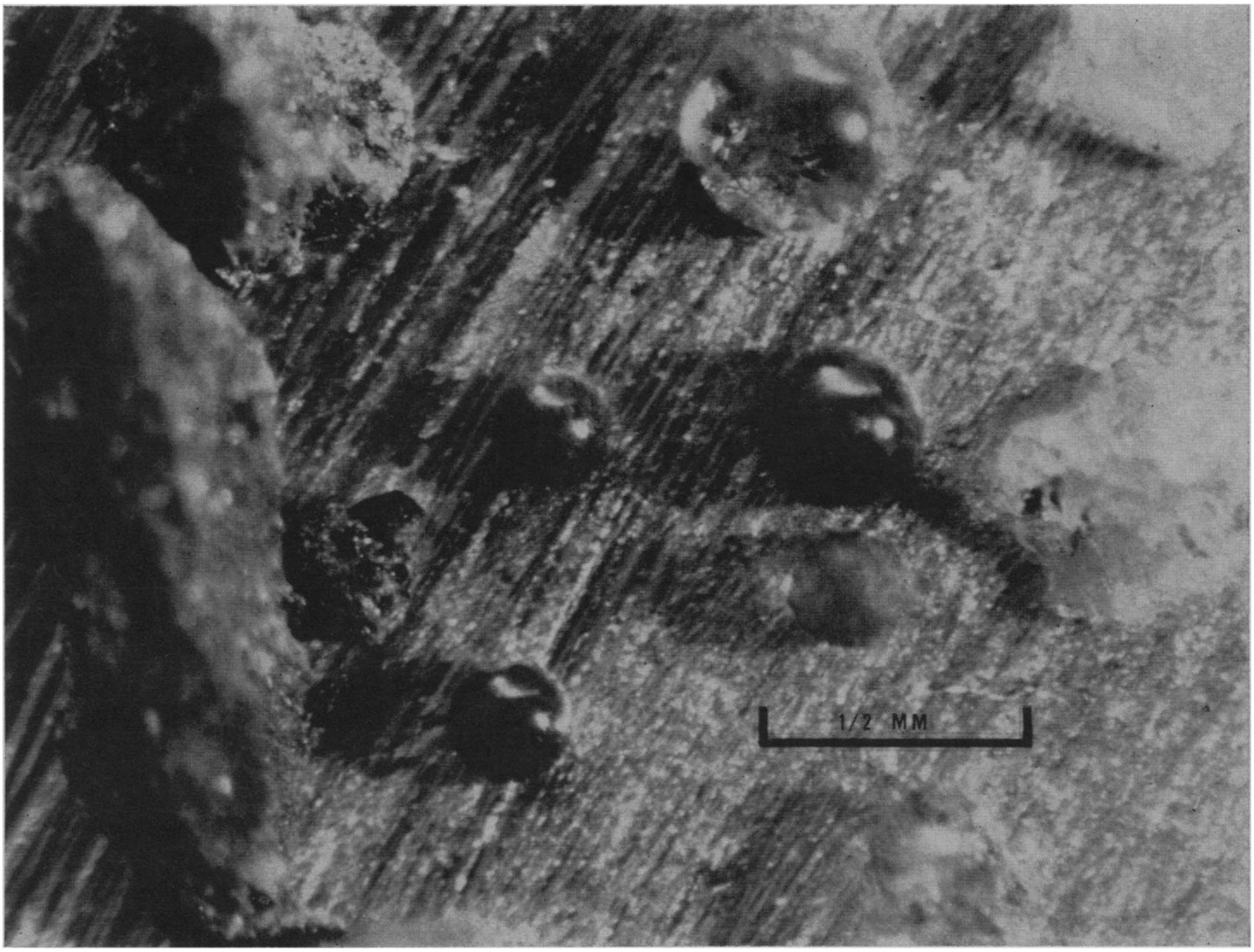


Fig. 12. Photograph of glass spherules of various colors found in fine grained material [NASA photograph S-69-45182].

as rounded masses in the interstices separating plagioclase, clinopyroxene, or ilmenite of some coarser crystalline rocks. Native iron (?) occurs as scattered blebs up to 10 micrometers in diameter within the troilite masses. Several other accessoy minerals occur which have not yet been identified.

Chemistry

Chemical analyses of the samples were made principally by optical spectrographic measurements conducted inside the biological barrier. A Jarrell-Ash Ebert instrument with a dispersion of 5.2 angstroms per millimeter was used. Three separate techniques were used: (i) determination of Si, Al, Fe, Mg, Na, K, Ca, Ti, Mn, and Cr with Sr used as the internal standard; (ii) determination of Fe, Mg, Ti, Mn, Cr, Zr, Ni, Co, Sc, V, Ba, and Sr with Pd used as the internal standard; and (iii) determination of Li, Rb, Cs, Pb, Cu, and other volatile elements with Na used as the internal standard.

The precision of the determinations is ± 10 percent of the amount present. Accuracy of the results was controlled by use of the international rock standard samples (G-1, W-1, Sy-1, BCR-1, DTS-1, PCC-1, G-2, AGV-1, and GSP-1) for calibration. Analyzed terrestrial basaltic rocks (Hawaii and Galápagos), chondritic meteorites (Forest City and Leedey), and achondrites (Sioux County and Johnstown) provided additional calibration points. All spectrographic line identifications were checked against the spectra of individual elements and, in addition, against the M.I.T. wavelength tables and U.S. Bureau of Standards tables.

The spectrographic plates have been examined to establish the presence or absence of all elements which have spectral lines in the wavelength regions covered. A list of elements which were not detected is given in Table 1.

Line interferences by Ti, Cr, and Zr lines in particular were checked for all analytical lines. Wavelengths of the several principal lines were checked for those elements which were not detected, since line interferences due to other elements were visible on some lines.

Three samples which were brought from behind the biological barrier after sterilization procedures were analyzed by atomic absorption procedures for Fe, Mg, Ca, Ti, Na, K, and by a colorimetric procedure for Si.

Sample weights were small, typically from 10 to 50 milligrams. Larger amounts (150 milligrams) were available from those samples brought out from behind the barrier, notably the 500-gram sample for biological testing. A total of 23 analyses were made. Analytical data are given in Table 2 for a suite of 12 typical lunar samples.

The samples are apparently free from inorganic contamination either from the rock box or the lunar landing module. Niobium, which constitutes 88 percent of the skirt of the descent engine exhaust, was not detected (detection limit, 50 parts per million); indium, which forms the seal of the rock box, was not present (detection limit, 1 part per million).

Differences among the various samples are less apparent than the overall similarity in composition (for example, no samples contained less than 5 percent TiO_2). In detail, significant variations are shown by many of the trace elements, notably Ni, Zr, Rb, and K.

The major constituents of the samples are Si, Al, Ti, Fe, Ca, and Mg. Sodium, Cr, Mn, K, and Zr are minor constituents with concentrations between a few hundred parts per million and 0.5 percent (by weight).

The most striking features of the chemical composition of lunar rocks in comparison with terrestrial rocks, meteorites, or cosmic abundance estimates are the high concentrations of Ti, Zr, and Y. In comparison with chondritic meteorites, the concentrations of Fe and Mg are lower, and the concentrations of Ca and Al are higher.

Among the trace and minor constituents, Zr, Sr, Ba, Y, and Yb are enriched by one to two orders of magnitude, as compared to the chondritic abundances of these elements. Potassium and Rb are present in similar amounts, and Ni and Co are depleted by large factors, compared to the amounts of these elements in chondrites. Nickel was not detected (less than 1 part per million) in several rock samples. However, the Fe content remains high in these samples and the ratios of Fe to Ni are very high. The concentration of Zr is only equaled by that of alkali-rich rocks such as nepheline syenites in the crust of the earth.

Ratios of Rb to Sr are low, approaching those of oceanic basaltic rocks on the earth. Barium is relatively abundant and its concentration levels resemble those of continental basaltic rocks, as does the Li content (about 10 parts per million). Chromium is notably abundant as a minor constituent and Sc is also present at higher levels than generally found in terrestrial basalts. Conversely, V is much lower in abundance.

The volatile elements (Pb, Bi, Tl, and the like) in general are below the limits of detection of the spectrographic techniques employed; also the elements of the Pt group, Ag and Au, were not detected. Thus, the lunar rocks exhibit numerous differences in detail from terrestrial or meteoritic samples previously available for analysis.

Rare-Gas Analytic Results

The gas analyses were made with a 6-inch 60° magnetic deflection mass spectrometer. The spectrometer is operated with a sensitivity of about 2×10^{-10} cubic centimeter per millivolt for He, Ne, and Ar, and about 3×10^{-13} cubic centimeter per millivolt for Kr and Xe. Samples were prepared under N_2 and under air. Chips of rock were taken, weighed, wrapped in aluminum foil, and sterilized by heating from 125° to 150°C for time periods of 5 to 24 hours. The effect of the sterilization heatings was such as to release less than 1 percent of the gases present.

The samples were melted by radiofrequency induction heating in a molybdenum crucible. Vacuum was maintained by a water-cooled glass furnace with low helium-diffusion characteristics. The gases released were chemically purified with a hot Ti getter. The heavier noble gases were condensed, and the noble gases were introduced into the mass spectrometer for measurement under static vacuum conditions in three fractions: (i) He and Ne, (ii) Ar and Kr, and (iii) Xe.

In general, after each sample was analyzed, a second heating was performed to make certain that all the gas had been released and to serve as a blank correction. The entire procedure was standardized by introducing into the mass spectrometer a calibrated amount of the different rare gases.

The rare gases in the lunar samples show three general patterns which correspond to the three rock types (breccias, igneous rocks, and fines). In general, the breccias and fines show extremely large contents of rare gases. Large amounts of noble gases are found in both surface and subsurface material of the breccia. From the amounts and the isotopic ratios, it is almost certain that the predominant source for this gas is the solar wind.

Table 1. Elements detected.

Element or oxide	Type A rocks (vesicular)				Type B rocks (crystalline)				Type C rocks (breccias)		Type D fine material	Bulk Bio-Pool sample
	22*	72	57	20	17	58	45	50	21	61	37	54
					Elemental abundances							
Rb (ppm)	†	6.5	6.0	1.5	6.0	1.6	1.9	0.8	†	3.1	2.2	2
Ba (ppm)	100	130	180	50	120	85	115	60	105	90	68	65
K (%)	0.17	0.17	0.15	0.053	0.18	0.09	0.084	0.053	0.12	0.15	0.10	0.11
Sr (ppm)	110	55	230	85	55	190	60	140	150	60	90	140
Ca (%)	6.4	6.8	7.1	7.1	7.1	7.5	7.1	7.1	7.9	7.9	8.6	8.3
Na (%)	0.30	0.44	0.40	0.44	0.48	0.41	0.38	0.38	0.15	0.37	0.40	0.38
Yb (ppm)	7	2	6	2.5	†	5	1.3	2.7	4.5	1.8	2.5	2.5
Y (ppm)	230	210	310	185	310	230	100	130	300	115	130	200
Zr (ppm)	1000	850	>2000	980	1250	250	700	700	1500	400	400	500
Cr (ppm)	2800	4700	6500	2100	4600	3700	3500	4800	2500	3000	2500	2800
V (ppm)	36	30	40	20	30	32	40	80	22	32	42	30
Sc (ppm)	110	45	110	110	55	130	90	170	68	55	55	60
Ti (%)	6.6	6.0	7.5	7.2	6.6	5.4	4.8	5.4	5.2	5.4	4.2	4.2
Ni (ppm)	320	‡	25	‡	‡	‡	‡	55	215	235	250	120
Co (ppm)	15	12	22	3	10	7	7	10	13	12	18	11
Cu (ppm)	†	5	†	4.5	3	†	6	10	†	8	†	†
Fe (%)	16	13	15.5	14	14.7	13	14	15.5	14.8	12.4	12.4	12.1
Mn (ppm)	2000	2800	3800	2460	2700	4300	2100	3900	1700	2400	1750	2600
Mg (%)	3.9	4.8	5.7	4.8	5.1	3.9	4.2	6.0	4.5	5.4	4.8	4.6
Li (ppm)	11.5	14	22	15	25	19	15	10.5	†	12.5	15	15
Ga (ppm)	†	†	†	5	†	†	4	8	†	†	†	†
Al (%)	4.1	4.8	5.8	5.8	5.3	6.9	6.9	5.8	5.8	5.8	6.9	6.9
Si (%)	20	21	16.8	17.8	18.7	20	19.6	17.8	20	18.7	20	19.6
					Abundances expressed as weight in percent oxides							
SiO$_2$	43	45	36	38	40	43	42	38	43	40	43	42
Al$_2$O$_3$	7.7	9	11	11	10	13	13	11	11	12	13	13
TiO$_2$	11	10	12.5	12	11	9	8	9	8.6	10	7	7.0
FeO	21	17	20	18	19	17	18	20	19	16	16	15.6
MgO	6.5	8	9.5	8	8.5	6.5	7	10	7.4	9	8	7.6
CaO	9.0	9.5	10	10	10	10.5	10	10	11	11	12	11.6
Na$_2$O	0.40	0.60	0.54	0.59	0.65	0.56	0.51	0.51	0.20	0.48	0.54	0.50
K$_2$O	0.21	0.20	0.18	0.064	0.22	0.11	0.10	0.064	0.15	0.17	0.12	0.14
MnO	0.26	0.36	0.49	0.32	0.35	0.55	0.27	0.50	0.22	0.41	0.23	0.34
Cr$_2$O$_3$	0.41	0.69	0.95	0.31	0.67	0.54	0.51	0.70	0.37	0.69	0.37	0.41
ZrO$_2$	0.14	0.11	>0.27	0.13	0.19	0.03	0.095	0.095	0.20	0.04	0.05	0.07
NiO	0.04	†	†	†	†	†	†	0.007	0.03	0.04	0.03	0.015
Total	99.0	100.5	101.4	97.8	100.5	100.8	99.5	99.9	99.8	99.8	100.3	98.2

* Laboratory number. † No data. ‡ Not detected.

The only other possible major source is rare gases condensed in lunar materials early in the history of the solar system. The igneous rocks in general show smaller amounts of rare gases than the other rocks. This can be interpreted to mean either that there was a loss of rare gases during formation or that the igneous material represents subsurface lunar material which has not been exposed to the solar wind except as a solid. Temperature-release studies on both the fines and breccias reveal that the noble gases are tightly bound and thus do not occur as simple surface-absorbed gases.

It appears that the breccias are formed near the surface of the moon from the fines as a result of some compacting process, possibly shock. This agrees with petrological evidence. The noble gases in the solar wind may be driven into the separate grains as a result of these shock events.

The results shown in Table 3 indicate large amounts of rare gases of solar composition. No isotopic ratios have been measured previously from the sun; however, from theoretical considerations it is generally accepted that nuclear processes take place which increase the ratio of neon-20 to neon-22 over that of the atmosphere of the earth. This enrichment is clearly present in all of the samples measured. In addition, the abundance of He on the surface of the sun should be close to that of the original He content of the solar system. A ratio of helium-4 to helium-3 of about 2600 is in good agreement with earlier theoretical estimates. The low value of the ratio of argon-40 to argon-36 is also exactly what would be expected for solar isotopic composition. The relative elemental ratios for the noble gases are those that would be expected in the sun if one assumes that considerable He and some Ne are lost from the lunar surface during the hot lunar day.

Table 4 presents isotopic ratios for Xe, presumed to be of solar origin, in the fines and in a breccia. The same amount of each Xe isotope is present in the two samples. The isotopic pattern closely resembles that of trapped Xe found in carbonaceous chondrites, except for a small addition of the lighter Xe isotopes, presumably from spallation reactions, and a deficiency of ^{134}Xe and ^{136}Xe. The ratio of ^{129}Xe to ^{132}Xe in the material measured is essentially the same as that in carbonaceous chondrites. Data on krypton isotopes for the fine lunar material are less precise but resemble Kr found in carbonaceous chondrites.

Table 2. Elements not detected.

Element	Detection limits (ppm)	Element	Detection limits (ppm)
Cs	1	Au	10
Be	3	Zn	30
La	30	Cd	10
Nd	30	Hg	100
Hf	50	B	5
Nb	50	Ga	10
Ta	100	In	1
Mo	5	Tl	1
W	20	Ge	5
Re	100	Sn	10
Ru	10	Pb	2
Rh	10	As	100
Pd	10	Sb	20
Ir	50	Bi	20
Pt	50	Te	100

Several of the crystalline rocks measured contain radiogenic ^{40}Ar and noble gases produced by spallation reactions which, when coupled with data on K contents, enable one to estimate ages by K-Ar dating methods and measurements of cosmic-ray radiation. Seven rocks have yielded K-Ar ages, all consistent with a value of $3.0 \pm 0.7 \times 10^9$ years. Radiation ages show a wider variance among different rocks, ranging from about 10×10^6 years to approximately 160×10^6 years. The relative amounts of He, Ne, and Ar produced by spallation reactions differ from those of most stone meteorites and probably reflect the unique chemistry of lunar material.

Gamma-Ray Spectrometry

The Radiation Counting Laboratory (RCL) received eight lunar samples for preliminary study by nondestructive gamma-ray analysis. These included a sample of fines and one rock from the bulk sample box, one rock from the contingency sample, and five rocks from the documented sample box.

Because of the complex operations involved in handling lunar material, preparation of samples for analysis in the RCL was low, and analysis of the first RCL sample could not begin until 29 July 1969. As a result, radioactive species with half-lives of less than a few days were undetectable. In addition, the intense interferences from the gamma-ray spectra of the Th and U decay series in the samples made detection of weak gamma-ray components very difficult.

Low-background gamma-ray spectrometers used in these studies were located 15 meters below ground in a room supplied with radon-free air and shielded by 0.9 meter of compacted dunite inside a welded steel liner of low radioactivity. The principal detector system consisted of two NaI(Tl) detectors (23 centimeters in diameter and 13 centimeters long) at an angle of 180° with the sample between them. Data were recorded in the singles and coincidence modes. Response of the detectors was enhanced by use of a surrounding anticoincidence mantle. Background was reduced further by surrounding the detectors and inner mantle with a thick lead shield, the exterior of which was covered by a thin, meson-sensitive anticoincidence mantle. Spectra were also recorded with a Ge(Li) detector of large volume inside a lead shield 10 centimeters thick. However, all data reported here were obtained from the NaI(Tl) scintillation spectrometer. With the exception of preamplifiers, all ancillary electronic instrumentation was located in an adjacent control room.

For the preliminary investigation the equipment was calibrated with the aid of a series of standards prepared by dispersing known amounts of radioactivity in quantities of electrolytically reduced Fe powder. The weights of the cylindrical, dispersed samples (density, 3.4 grams per cubic centimeter) were both higher and lower than the range of lunar sample weights anticipated. Lunar samples were transferred to the RCL for analysis in a variety of nonstandard containers. The material of the container affects the gamma-ray response through gamma-ray scattering and absorption effects. Where feasible, a library of standard spectra was recorded with dispersed sources inside the type of container used for the actual lunar sample. However, this procedure could not be followed in every case. The activity of each radionuclide was determined by using the method of least squares to resolve the gamma-ray spectra.

Until it is possible to standardize the equipment with phantoms of the same shape and density containing known amounts of the radionuclides of interest, the results of the preliminary studies have been assigned rather large errors. Some of the samples were processed for analysis without weighing. In such cases, the sample weight was estimated by correcting the weight of the sample package for the weight

Table 3. Rare-gas analysis.

Sample type	Helium		Neon			Argon			Krypton	Xenon
	10^{-8} cm^3/g He^4	4/3	10^{-8} cm^3/g Ne^{20}	20/22	22/21	10^{-8}cm^3/g Ar^{40}	40/36	36/38	10^{-8} cm^3/g	10^{-8} cm^3/g
				Lunar soil						
Sample A	10,900,000	2,500	200,000	13	31	39,000	1.1	5.3	38	38
Sample B	19,000,000	2,500	310,000	13	30	42,000	1.2	5.4	36	16
				Typical agglomerate rock						
Sample A	15,100,000	2,900	320,000	13	29	150,000	2.3	5.2	73	46
Sample B	16,000,000	2,700	230,000	13	29	110,000	2.2	5.2	49	42
				Typical crystalline rock						
Sample A	63,000	180	210	3.1	1.3	5,700	96	1.2	0.34	0.65
Sample B	28,000	270	200	7.0	2.3	1,600	42	2.4	0.19	0.16

Table 4. Ratios of ^{i}Xe to ^{132}Xe.

Sample	124	126	128	129	130	131	134	136
Fines	0.0062	0.0071	0.086	1.07	0.165	0.829	0.373	0.306
Breccia	0.0052	0.0057	0.084	1.07	0.164	0.820	0.37	0.304

of the container, packing material, and biological containment bags.

The results are summarized in Table 5. Twelve radioactive species were identified, some tentatively. The nuclides of shortest half-life characterized were ^{52}Mn (5.7 days) and ^{48}V (16.1 days). The concentrations listed in Table 5 represent averages for the whole sample (usually a rock) and therefore are not subject to sampling errors if the rock is inhomogeneous.

The amount of K present is variable and ranges over the average K concentration (0.085 weight percent) for chondrites. On the other hand, the U and Th concentrations are near the values for terrestrial basalts, and the ratio of Th to U is about 4.1, with little variation. Despite variation of a factor of 5.6 in K concentration, the ratio of K to U determined for lunar surface material is remarkably constant (2400 to 3100) and much lower than similar ratios for terrestrial rocks or meteorites.

Yields of cosmogenic ^{26}Al are generally high, and the ratio of ^{22}Na to ^{26}Al is considerably below unity in both the lunar rocks and soil. The high yields of ^{26}Al may be understood in terms of the chemical composition of the lunar material, if the samples in question have been exposed to cosmic-ray bombardment for several half-lives of ^{26}Al (0.74×10^6 years) so that the production of ^{26}Al could reach saturation. Such reasoning suggests, in agreement with the rare-gas analyses, that the material analyzed in these studies has been exposed to cosmic radiation for at least several million years.

Magnetic Measurements

Preliminary magnetic measurements have been completed on 31 samples of crystalline rock and breccia by use of a triaxial flux-gate gradiometer in the vacuum chamber and class-3 cabinets. The level of significance of the results from various samples ranged from 1×10^{-5} to 1×10^{-2} electromagnetic units per gram. The significance level is a function of sample weight, sample shape and intensity of magnetization, and the highly variable magnetic interference generated by the cabinets around the sample.

Of the 13 samples of crystalline rock investigated, seven gave no measurable magnetic response. In six samples, induced magnetization of the order of 1×10^{-4} electromagnetic units per gram was detected in fields ranging from 0.3 to 0.9 oersted and with uncertainties from 25 to 50 percent. One of these six samples also possessed a barely detectable remanent magnetization, about 3×10^{-4} electromagnetic units per gram with an uncertainty of about 50 percent.

The breccias are roughly ten times as magnetic as the crystalline rocks. Eighteen breccias were measured, of which five gave no measurable magnetic response. Seven of the breccia samples show only induced magnetization, whereas both induced and remanent magnetization was detected in five samples. Intensities of induced magnetization in various beccia samples ranged from 1×10^{12} to 1×10^{-4} electromagnetic units per gram in fields ranging from 0.3 to 0.9 oersted and with uncertainties from 10 to 50 percent. The intensity of remanent magnetization in the five samples was approximately 1×10^{-3} electromagnetic units per gram with uncertainties between 20 and 50 percent. The ratio of remanent to induced magnetization for these five samples varied between 0.4 and 0.9 oersted.

Several portions of fines from the contingency and bulk samples were also measured; their specific susceptibilities ranged from 1×10^{-2} to 4×10^{-2} electromagnetic unit per gram, which is roughly ten times greater than those of the breccias.

Investigations in Organic Chemistry

A simple survey method, as well as a more elaborate and specific technique, has been used to estimate the abundances of organic matter in the lunar samples: (i) a pyrolysis–flame ionization detector capable of yielding an estimate of the total organic matter in the sample, regardless of type and origin, and (ii) a computer-coupled high-sensitivity mass spectrometer capable of yielding detailed mass spectrometric data on the volatile or pyrolyzable organic matter, or both, as a function of sample temperature. From the mass spectral data (combined with the vaporization characteristics), an assessment of the relative contributions of terrestrial contaminants as opposed to possible indigenous lunar organic matter may be made.

Pyrolysis–flame ionization detector. Portions (10 to 40 milligrams) of the lunar sample were pyrolyzed at 800°C under H and He, and the resulting volatile products were swept directly into a hydrogen flame-ionization detector. The resulting single-peak area was compared with that from calibrated standards, corrected for the blank, and converted into total organic content for concentrations in the parts-per-million range. This technique estimates total organics, volatile and polymeric, including contaminants arising from sample exposure and processing.

The fines (type D) from the contingency sample, exposed to local atmosphere during return transit and then processed under N, contained 16 ± 7 parts per million of organic material. Outside chips of three rocks from the same bag contained 10, 17, and 44 parts per million, the amount increasing directly with the degree of handling of the sample in the course of other examinations. Both breccia (type A) and crystalline (types B and C) rock chips from the bulk and documented rock boxes were examined, but any correlation or organic content measured as a function of rock type was masked by terrestrial contamination of up to 100 parts per million as a result of sample handling. From this preliminary examination, the indigenous organic content of the lunar samples is estimated (by this technique) to be less than 10 parts per million.

Mass spectrometry. This investigation involved examination of the lunar sample by repetitive mass-spectrometric monitoring of the vapor phase evolved by heating the lunar sample from ambient to approximately 500°C. A Hitachi RMU 6-E mass spectrometer was operated on-line with a Scientific Data Systems Sigma 2 computer. The mass spectrometer was specially designed to meet the LRL biological containment requirements which necessitated a sterilizable inlet system, and the mass spectrometer was equipped with a high-efficiency ion source and high-gain electron multiplier. The on-line computer permitted continuous control of the scanning circuit and recording of the mass spectra as well as calibration of the mass scale, spectrum normalization, and visual display (cathode-ray tube) of the spectrum during each scan cycle.

The lunar material (approximately 50 milligrams) was placed in a Ni capsule, sealed by a cold weld, and transferred to the instrument inlet system. The inlet system made possible the insertion of these capsules into an oven (approximately 500°C) which was connected to the ionization chamber by means of a heated quartz tube 8 centimeters long.

Tabel 5. Gamma-ray analyses of lunar samples. Values for short-lived nuclides have been corrected for decay to 0000 hours, C.D.T., 21 July 1969. TI, tentatively identified.

	Sample number							
	57	72	03	17	18	19	21	02
Weight (g)	897	399*	213*	971	213*	245*	216*	302
Sample type	A	A	B	B	C	C	C	D
K (wt %)†	0.242 ± 0.036	0.232 ± 0.035	0.050 ± 0.008	0.227 ± 0.034	0.144 ± 0.022	0.12 ± 0.02	0.120 ± 0.018	0.11 ± 0.02
Th (ppm)	3.4 ± 0.7	2.9 ± 0.4	0.95 ± 0.14	2.9 ± 0.4	2.3 ± 0.3	1.9 ± 0.3	1.8 ± 0.3	1.6 ± 0.3
U (ppm)	0.78 ± 0.16	0.75 ± 0.11	0.20 ± 0.03	0.70 ± 0.10	0.60 ± 0.09	0.43 ± 0.06	0.39 ± 0.06	0.46 ± 0.10
^{26}Al (dpm/kg)	77 ± 16	70 ± 15	69 ± 14	66 ± 13	100 ± 20	98 ± 20	81 ± 16	97 ± 19
^{22}Na (dpm/kg)	44 ± 9	42 ± 9	41 ± 8	34 ± 7	55 ± 11	47 ± 10	41 ± 8	44 ± 9
^{44}Ti (dpm/kg)	TI	TI						TI
^{46}Sc (dpm/kg)	10 ± 3	13 ± 4	13 ± 3	11 ± 3	13 ± 4	10 ± 4	10 ± 4	9 ± 3
^{48}V (dpm/kg)			TI	TI				
^{52}Mn (dpm/kg)			39 ± 18				36 ± 20	
^{54}Mn (dpm/kg)	40 ± 13	20 ± 8	26 ± 5	38 ± 13	28 ± 14	27 ± 10	15 ± 7	28 ± 9
^{56}Co (dpm/kg)	30 ± 12	30 ± 10	38 ± 6	18 ± 6	33 ± 11	35 ± 11	38 ± 13	27 ± 10
^{7}Be (dpm/kg)	TI		TI	TI				TI

* Weight uncertain; see text. † K determined by arraying ^{40}K and assuming terrestrial isotopic ratios for potassium.

In the calibration of the system, three samples of *n*-tetracosane on clean quartz (at concentrations of 1, 2, and 3 parts per million) were analyzed by means of the mass spectrometer–computer system to determine the total ionization recorded as a function of the amount of organic material present. Concentration levels reported here refer to the equivalent signal of *n*-tetracosane. Such concentrations are relatively large in terms of instrument sensitivity.

The lunar material studied came from three distinct sample types: (i) the core tubes, (ii) fines (type D) from the bulk box, and (iii) interior and exterior chips, fine- and medium-grained (types A and B), and breccia (type C) rocks which were returned in both boxes. Control samples of outgassed clean sand (Ottawa sand), which were exposed to the atmosphere of the sample cabinet for approximately the same length of time as the lunar samples, were analyzed to estimate the degree of organic contamination introduced by exposure to the atmosphere.

It is important that the levels of organic matter observed from this experiment, whether indigenous or of terrestrial origin (contamination), were extremely low (0.2 to 5.0 parts per million). Because of this very low level, the quantity of organic matter determined can vary widely with the slightest amount of organic contaminant from anywhere in the entire sample-handling and storage procedure between the moon and the mass spectrometer. The analyses of blanks and controls from all phases of lunar sample-handling and storage procedures, usually with clean quartz, indicate that most of the organic material observed in the lunar samples is accounted for by organic contamination.

Data on a sample obtained from the core tube and a sample of fines from the bulk box may indicate the presence of an extremely small amount of pyrolyzable organic matter. This is based on the observation that the abundance of ions at *m*/*e* 78 and 91 increased in the spectra obtained later in the heating cycle of these samples. These may be interpreted as ions derived from aromatic hydrocarbon and are indicative of the products of the pyrolysis of indigenous organic matter.

The maximum levels of indigenous organic matter indicated by the observations described in this article appear to be, at best, considerably less than 1 part per million.

Biology

The preliminary examination of samples has included microscopic studies designed to find any living, previously living, or fossil material. No evidence for any such material has been found.

Furthermore, about 700 grams of fines and rock chips have been subjected to an extensive biological protocol. A wide variety of biological systems were challenged with lunar material. These systems included the following: (i) germfree mice; (ii) fish; (iii) quail; (iv) shrimp, oysters, and other invertebrates; (v) several lines of tissue cultures; (vi) several varieties of insects; (vii) a considerable number of plants; and (viii) lower animals, including paramecia. As of 11 September 1969 no evidence of pathogenicity has been observed.

Conclusions

The major findings of this preliminary examination of the lunar samples are as follows:

1) The fabric and mineralogy of the rocks divide them into two genetic groups: (i) fine- and medium-grained crystalline rocks of igneous origin, probably originally deposited as lava flows, dismembered and redeposited as impact debris, and (ii) breccias of complex history.

2) The crystalline rocks, as shown by their modal mineralogy and bulk chemistry, are different from any terrestrial rock and from meteorites.

3) Erosion has occurred on the lunar surface in view of the fact that most rocks are rounded and some have been exposed to a process which gives them a surface appearance similar to sandblasted rocks. There is no evidence of erosion by surface water.

4) The probable presence of the assemblage iron-troilite-ilmenite and the absence of any hydrated phase suggest that the crystalline rocks were formed under extremely low partial pressures of O_2, H_2O, and S (in the range of those in equilibrium with most meteorites).

5) The absence of secondary hydrated minerals suggests that there has been no surface water at Tranquility Base at any time since the rocks were exposed.

6) Evidence of shock or impact metamorphism is common in the rocks and fines.

7) All the rocks display glass-lined surface pits which may be caused by the impact of small particles.

8) The fine material and the breccia contain large amounts of all the noble gases which have elemental and isotopic abundances almost certainly indicative of origin from the solar wind. The fact that interior samples of the breccias contain these gases implies that the samples were formed at the lunar surface from material previously exposed to the solar wind.

9) The ^{40}K-^{40}Ar measurements on igneous rocks show that they crystallized 3×10^9 to 4×10^9 years ago. The presence of nuclides produced by cosmic rays shows that the rocks have been within 1 meter of the surface for periods of 20×10^6 to 160×10^6 years.

10) The level of indigenous organic material capable of volatilization or pyrolysis, or both, appears to be extremely low (that is, considerably less than 1 part per million).

11) The chemical analyses of 23 lunar samples show that all rocks and fines are generally similar chemically.

12) The elemental constituents of lunar samples are the same as those found in terrestrial igneous rocks and meteorites. However, there are several significant differences in composition: (i) some refractory elements (for example, Ti and Zr) are notably enriched, and (ii) the alkali and some volatile elements are depleted.

13) Elements that are enriched in iron meteorites (that is, Ni, Co, and the Pt group) were not observed or such elements are very low in abundance.

14) Of 12 radioactive species identified, two were cosmogenic radionuclides of short half-life, namely ^{52}Mn (5.7 days) and ^{48}V (16.1 days).

15) Uranium and Th concentrations lie near the typical values for terrestrial basalts; however, the ratio of K to U determined for lunar surface material is much lower than such values determined for either terrestrial rocks or meteorites.

16) The high ^{26}Al concentration observed is consistent with the long exposure age to cosmic rays inferred from the rare-gas analysis.

17) No evidence of biological material has been found in the samples to date.

18) The lunar soil at the landing site is predominantly fine-grained, granular, slightly cohesive, and incompressible. Its hardness increases considerably at a depth of 15 centimeters. It is similar in appearance and behavior to the soil encountered at the Surveyor landing sites.

Discussion

The data and descriptive information given here were obtained to characterize the materials that will now be distributed to principal investigators and their associates for specialized and detailed study. The usefulness of this information in the selection of material for particular experiments is well illustrated by the rare-gas data. It would have been impossible to select material suitable for a careful study of the isotopes of Ne, Ar, Kr, and Xe produced by cosmic rays or even for a straightforward determination of the age by K-Ar dating without knowledge of the variations in rare-gas content shown in Table 3. Similarly, the analyses of organic matter provide invaluable guidance in the selection of material for further experiments and the study of organic matter in lunar materials.

In spite of the limited and specific objectives of the preliminary examination, it has provided some significant results on long-recognized questions, as well as a few surprises. The existence of an erosion process on the lunar surface was clearly indicated by both the Ranger and Orbiter photographs. These pictures frequently show very fresh block craters interspersed among smoothed craters. Photographs of individual rocks on Surveyor photographs give further evidence of the rounding and abrasion of hard rocks on the lunar surface. The surface morphology, glass pits, and splashes seen on both hard and fragmental rocks suggest that samples are now available for detailed laboratory examination that may make possible the elucidation of a widespread and important mechanism on the lunar surface. The evidence provided by the first examination of these rocks indicates that this process is unlike any process so far observed on earth.

The chemical composition of the Tranquility Base fines and igneous rocks are unlike those of any known terrestrial rock or meteorite. The unique characteristic is the unusually high Ti, Zr, Y, and Cr content compared to that of other rocks with this approximate bulk composition. Also of great interest is the low Na, K, and Rb content. It is particularly significant that the unique composition is that of a silicate liquid. If this liquid has a volcanic origin, the unique composition implies either that the composition of the rock from which the liquid was derived differs significantly from that of the mantle of the earth, or that the mechanism by which the liquid was formed may also differ from analogous terrestrial processes. The nearly identical composition found for the fines, fragmental rocks, and igneous rocks suggests that the unique composition observed for the materials at Tranquility Base is characteristic of this part of the moon and not due to a local isolated flow or intrusion.

Several specific geochemical observations on the igneous rocks can be made from the present data. The ratio of K to U (2,400 to 3,200) of the lunar materials is unusually low, both by comparison with chondritic meteorites (45,000) and to most common earth rocks (10,000). This ratio is not readily changed by terrestrial igneous processes (*7*). If this generalization is extended to lunar igneous processes, one can infer that ratios observed here are characteristic of the whole moon. Similarly, the Rb/Sr ratio is much more like that of the earth and achondritic meteorites than that of chondritic meteorites and the sun. Both of these chemical characteristics suggest that the moon, like the earth, is depleted in alkali metals above atomic number 11 relative to chondrites (*8*).

Variations in other elemental ratios that are easily fractionated during igneous differentiation processes (for example, Ni/Mg and Ba/Sr) suggest that there has been some chemical differentiation in the formation of the igneous rocks. The abundance of radioactive elements (K, U, and Th) in the surface materials is much greater than that inferred for the mean content of radioactive elements on the moon from thermal models of the moon (*9*). This suggests that the surface materials are chemically differentiated with respect to the whole planet.

The unusually high abundance of elements with high atomic numbers (Fe and Ti) is clearly consistent with the unusually high densities (3.1 to 3.5 grams per cubic centimeter) reported previously. Both the Surveyor alpha-scattering analyses (*10*) and optical studies (*11*) indicate that mare materials may have significantly higher Fe contents than highland materials. Assuming the rather plausible generalization that the densities of rocks at Tranquility Base are characteristic of other mare regions, one can infer that large areas of the lunar surface, in particular the mare regions, may be made up of materials with densities in excess of the mean density of the moon.

Perhaps the most exciting and profound observation made in the preliminary examination is the great age of the igneous rocks from this lunar region. The age determined from K-Ar dating is both intrinsically and experimentally uncertain; nevertheless, there is a very good chance that the time of crystallization of some of the rocks returned by Apollo 11 may be earlier than that of the oldest rocks found on earth. It seems quite likely that if the rocks from Apollo 11 do not take us back to the time of formation of our sister planet, then rocks from other regions on the moon will.

References and Notes

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