was originally part of a meteorite that impacted the moon. The impact produced molten nickel-iron droplets which fell into the lunar soil. Solidification took place quickly (within minutes), but cooling was more rapid on the lower than on the upper surface. After the pellet solidified it was hit by high-velocity particles, thereby producing craters. Some abrasion and polishing by drifting dust has also occurred.

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Phase Chemistry, Structure, and Radiation Effects in Lunar Samples

Abstract. *Phase chemistry, structure, and radiation effects were studied in rock, breccia, and soil samples. The regolith apparently developed in the final stages of accretion and was modified by later impact processes and radiation weathering. Exposure ages indicate transfer of buried igneous rock fragments to the near surface late in lunar history. With a few exceptions igneous rock fragments, soil, and breccia share the same distinctive chemistry, probably acquired before accretion of the moon. The igneous rocks texturally resemble basaltic achondrites, and the soil and breccias contain glassy spheres analogous to chondrules.*

Polished thin sections from three igneous rocks (10024, 10017, and 10057) and one breccia (10018), plus rock fragments, glass, and mineral grains from the soil (*1*) were examined optically and analyzed by electron microprobe. Samples of soil and of the surface and interior of 10017 were examined by x-ray diffraction, electron diffraction, and transmission and scanning electron microscopy.

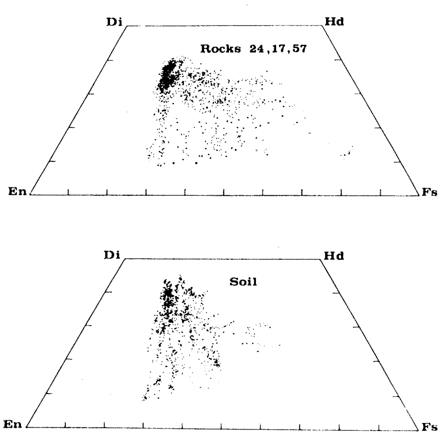

Fig. 1. Ranges of compositions measured in pyroxene grains from igneous rocks and soil. The trend toward high iron values reflects zoning, and the spread in calcium values is largely due to exsolution.

Analytical work was directed toward establishing the major element composition of pyroxene, feldspar, and ilmenite. Other phases analyzed are discussed briefly, but no effort was made to identify all phases present in each assemblage.

Ilmenites in the rocks and soil have essentially the same composition ($Mg_{.04}Fe_{.93}Ti_{.99}Cr_{.02}Al_{.01}O_3$) with no zoning or exsolution. Plagioclase composition ($Or_1Ab_{20}An_{78}$) is also remarkably similar in the various igneous rocks. Plagioclase grains in the soil have a wider range of compositions (An_{51} to An_{96}) with an average composition ($Or_1Ab_{13}An_{86}$) more calcic than that of the igneous rocks. Potassic feldspar is present in minor amounts in rocks and soil.

In both rocks and soil the dominant pyroxene is an augite with minor amounts of Al_2O_3 and TiO_2. A combination of zoning and exsolution, with lamellae too narrow to be resolved by microprobe techniques, results in extreme compositional heterogeneity within individual pyroxene grains (Fig. 1). The range of pyroxene compositions, the average composition ($Wo_{31}En_{44}Fs_{25}$), and the clustering of analyses around $Wo_{36}En_{46}Fs_{18}$ are essentially the same for the igneous rocks and the soil. Both rocks and soil contain troilite, commonly as small rounded interstitial grains. Metallic iron with 0.4 to 1.1 percent nickel by weight occurs as tiny blebs within or adjacent to sulfide.

The fine-grained interstitial material, which apparently was the last liquid fraction to crystallize, contains a variety of phases, including silica, potassic feldspar, calcium phosphate, zirconium silicate, and zirconium oxide. Partial analyses were made of some of these to determine the location of minor elements present in anomalous proportions (*2*). About two-thirds of the Zr occurs as silicate and oxide. The remainder is largely in ilmenite, ranging from 300 to 3000 ppm with large variations from grain to grain and within single grains. The extensive and variable Zr substitution in ilmenite is consistent with high temperatures of formation and rapid cooling. Zr/Hf atomic ratios (150–250) in the high Zr phases fall in the upper range of terrestrial values. A major portion of the yttrium is in the phosphate. Y/Yb atomic ratios (150–250) in the high centrates from rock 10017 and the soil are comparable to meteorite and terrestrial ratios and considerably below initial estimates (*2*). Barium is concentrated in the potassic feldspar.

Rock fragments from the soil and breccias have the same distinctive bulk chemistry as the igneous rocks, while displaying a range of crystallite sizes. Some chemically dissimilar rocks sampled in the coarser soil fraction (1 mm to 1 cm) include fragments that are almost wholly feldspar (anorthosite) and one with a high proportion of calcic plagioclase (An_{95}) coexisting with olivine (Fo_{80}) and orthopyroxene

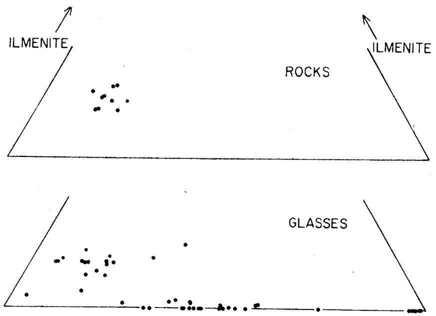

Fig. 2. The composition of Apollo 11 rocks (*2*) and glasses from the soil, expressed in terms of normative pyroxene, feldspar, and ilmenite. Over the entire range of glass types these three normative minerals can account for virtually the total composition (average 95 percent).

($Wo_{4.5}En_{71}Fs_{24.5}$) containing exsolved blebs of clinopyroxene ($Wo_{36.5}En_{47}Fs_{16.5}$). Olivine ($Fo_{67}$), orthopyroxene ($Wo_{3}En_{80}Fs_{16}$), maskelynite, graphite (one grain, about 1 mm), and two phyllosilicates (discussed below) were also found in the soil.

A major component of the soil is glass. Flow structure and bubbles are common in the darker glasses, which are richer in Fe, Mg, Ti, and Cr. The lightly colored glasses are generally devoid of flow structure and bubbles, and approach feldspar in composition. All the glass types occur both as spheres and as angular fragments, and are more abundant in the fine fraction of the soil. Many of the spheres are coated by largely crystalline excrescences.

The glass compositions could be produced by melting together various proportions of the minerals in the igneous rocks (Fig. 2). There are apparently no glasses with high normative ilmenite, and crystalline ilmenite occurs within glass grains. The trend toward high normative feldspar values (Fig. 2) suggests that these compositions are favorable for formation and preservation of glass. The normative feldspar calculated from the glass analyses is, for many samples, more calcic than the igneous rock feldspar, suggesting loss of alkalis.

The effects of exposure on the lunar surface were studied on grains from the soil and on a fragment of rock 10017 that had approximately 1 cm^2 of the original upper surface. The surface was readily distinguished from the interior by its dull appearance and by cosmic ray particle track densities ($2–7 \times 10^7$ cm^{-2} at the surface compared with $3.5–7 \times 10^6$ in the interior). The surface has an abundance of minute cracks, and near-surface grain boundaries are filled with loose material.

On the surface of rock 10017 we found hexagonal platelets about 0.5 to 1 μm wide showing a hexagonal diffraction pattern ($a_0 = 5.3$ Å, $b_0 = 9.2–9.3$ Å on orthogonal axes). Similar material and also hexagonal platelets with different morphology and unit cell size ($a_0 = 5.1–5.2$ Å, $b_0 = 8.89–9.00$ Å) were observed in the soil. Both phases show only two-dimensional diffraction on tilting and become amorphous on prolonged exposure to the electron beam. These materials are almost certainly phyllosilicates. Controls indicate that they are not talc from the gloves used at NASA–MSC or contaminants from our laboratory. The possibility that these phases result from contamination from other sources or from reaction of radiation-damaged material with the terrestrial atmosphere cannot yet be eliminated. A most interesting possibility is that the phyllosilicates did form on the moon. One possible process is hydroxylation of silicates by proton bombardment (*3*) followed by crystallization; another is silicate-water interaction on the moon.

Fig. 3. Electron transmission image and electron diffraction pattern of a hexagonal flake ($a_0 = 5.15$ Å; $b_0 = 8.90$ Å) from the lunar soil (× 10,000).

The Apollo 11 samples all share the same distinctive chemistry. As impact processes have played a role in the formation of the soil, it probably contains material from a much wider area than the astronauts could sample directly. The unusual composition consequently is not a local phenomenon but is typical of a large area.

The igneous rocks appear to be a single generation of material crystallized from a wholly liquid melt. The homogeneous melt cooled rapidly at first with little or no removal of early formed phases, and the cooling rate diminished with time allowing development of zoning and then exsolution in the pyroxene. The rocks formed at high temperatures (probably 1200° to 1500°C), low pressures (near surface), and low oxygen fugacities. No rock fragments have been found with compositions comparable to the residual liquid fraction (that is, enriched in alkalis, Ba, Y, rare earths, Zr, Si, and P). Although a wide range of grain sizes was observed, neither very rapidly cooled glassy rocks nor truly plutonic rocks were found.

If the melt from which the Apollo 11 igneous rocks crystallized was derived from material akin to the common meteorites or terrestrial rocks, then the differentiation process must have been unlike terrestrial crustal processes. Reduction and removal of a metallic fraction might explain the near absence of nickel and the noble metals, and loss of volatiles at very high temperatures may explain the low alkali content and concentration of the more refractory elements. Serious problems remain, however, in trying to explain the concentrations and proportions of the group 3b and 4b elements. The unique nature of the differentiation process, and the absence of rocks with related compositions, that is, members of a differentiation sequence, coupled with physical evidence such as the high density of the lunar surface, suggest that the Sea of Tranquillity rocks attained their distinctive chemical composition prior to lunar accretion, and that this composition must differ from that of the lunar interior.

The soil is a loose aggregate of rock fragments similar to the major igneous rocks, mineral fragments from such rocks, and a variety of glasses. As several glass fragments contain spherules of nickel-iron (some with associated phosphide and sulfide) analogous to the spherules found in terrestrial impactites, it is apparent that the soil formed in part by melting and comminution of the igneous rocks by meteorite impact. The paucity of meteorite material in the soil suggests that most of the impacting material was not meteoritic. If much of the soil was formed in the terminal stages of accretion, then the impacting material may have had a composition like that of bulk Apollo 11 material. The original regolith appears to have developed early in lunar history and has been modified by later impacts and only to a small extent by radiation weathering.

Basement rocks such as 10017 have been transported, presumably by impact, to the near surface late in lunar history. Rock 10017 has a much lower exposure age ($10 \pm 5 \times 10^6$ years), as determined from counts of particle tracks, than the soil from the same area ($\geq 10^9$ years). Preliminary studies of the distribution of grains with high particle track densities indicate that there is some vertical mixing in the soil, but the process is extremely slow.

The glass spheres resemble meteoritic chondrules, particularly in the breccias, where some of the spheres have crystallized. Compositionally these spheres are quite unlike chondrules, but they do illustrate a mechanism whereby chondrule-like bodies can develop. The glass beads probably formed by melting different proportions of minerals from a preexisting rock. Thus the bulk composition may vary considerably, but certain element ratios (reflecting phase compositions in the parent rock) will be preserved. This suggests a possible explanation of one of the puzzling characteristics of ordinary chondrites, where chondrules vary in bulk composition but contain olivine and pyroxene of fixed compositions.

There are many similarities between the Apollo 11 samples and basaltic achondrites, despite the obvious differences in bulk composition and the nature of the pyroxenes. Textures are remarkably similar, as are the development of zoning and degree of exsolution, apparent cooling rates, depth of burial and oxygen fugacities, the range of textures for similar bulk compositions, and the common occurrence of monomict breccias. The lunar surface may not have the appropriate composition to generate basaltic achondrites, but the necessary environments and processes probably did exist.

In the terminal stages of lunar accretion the material being added had a very distinctive chemical composition. Local melting formed a shallow liquid silicate pool that cooled rapidly. Impacts destroyed the uppermost surface and formed a soil layer over the igneous rocks very early in lunar history. There has been no major exchange of material between the surface and the deep interior, and the moon retains its accretionary stratigraphy. Later impacts and radiation effects have modified but not destroyed the imprint of these early processes.

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Mineralogy, Petrology, and Surface Features of Lunar Samples 10062,35, 10067,9, 10069,30, and 10085,16

Abstract. *The primary rocks are a sequence of titanium-rich basic volcanics, composed of clinopyroxene, plagioclase, and ilmenite with minor olivine, troilite, and native iron. The soil and microbreccias are respectively loose and compacted mixtures of fragments and aggregates of similar rocks, minerals, and glassy fragments and spheres. Impact events are reflected by the presence of shock metamorphosed rock fragments, breccias, and glasses and their resulting compaction to form complex breccias, glass-spattered surfaces, and numerous glass-lined craters. Chemistry of the glasses formed by the impact events is highly variable, and the high iron and nickel content of a few moundlike features suggests that at least some of the projectiles are iron and nickel-rich meteorites.*

Samples 10062,35; 10067,9; 10069,30; and 10085,16 have been analyzed. Samples 10062,35 and 10069,30 are thin sections of rocks; sample 10067,9 is a thin section of a microbreccia, and sample 10085,16 is a 10-g portion of lunar soil.

Sample 10062,35 is composed of radiating lathlike and acicular calcic-plagioclase crystals that enclose irregular grains of clinopyroxene and olivine. Skeletal crystals up to 1.5 mm of ilmenite occur throughout the section, and irregular patches of troilite with rounded exsolution blebs of iron are common. The plagioclase and clinopyroxene have a patchy extinction. The ilmenite has two types of exsolution features; the first occurs as bluish-gray elongated blebs, probably a spinel, and the second as fine whitish-gray lamellas of rutile. The overall texture of the section is very similar to a rapidly quenched silicate liquid of low viscosity. The mineralogy indicates that the liquid had the composition of a titanium-rich olivine basalt.

Sample 10069,30 is composed of euhedral to subhedral clinopyroxene and stubby subhedral to lathlike ilmenite in a matrix of poikilitic calcic-plagioclase. Small amounts of troilite with small exsolved blebs of native iron occur in irregular and rounded patches. The clinopyroxene crystals are either zoned or show a patchy extinction, suggesting compositional variation. In many crystals the cores contain numerous inclusions that are less than 1 μm in diameter. The plagioclase crystals

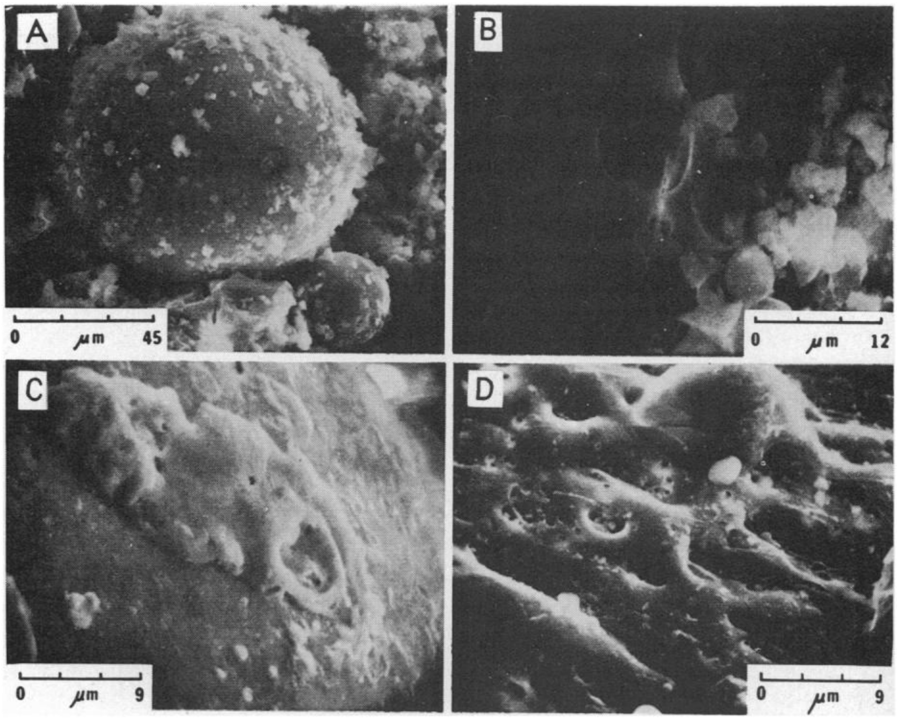

Fig. 1. Scanning electron micrographs (*2*). (A) Sphere with adhering dust fragments in a typical angular microbreccia matrix; (B) vesicular glassy fragment in microbreccia; (C) irregular glass bleb on glass sphere; and (D) ropy glass spatter on glass.