jectiles from a single impact of a large meteorite on the lunar surface. These projectiles could be expected to exhibit a wide range of velocities including hypervelocities, and this is reflected in the variation in the types of pits. By inference some or all of the pits on lunar rocks also may result from impacts in one or more impact plumes, and therefore the relative densities of pits on rocks may not be a satisfactory indicator of length of exposure on the lunar surface.

Gradations between the completely covered and smooth spherules were also found. In several cases the two types were welded together, and both may have been formed in the same event. Nickel-iron droplets were found on both types of spherules.

A considerable variation existed in the composition of the glass particles in the fines and breccia. Some single glass spherules were homogeneous; others contained zones or flow bands of different compositions. This is not surprising in view of the number of different ways in which glass spherules were formed and the possible variations in temperatures and mixing. At least six mechanisms produce lunar spherules. These include (i) expansion and tearing apart of large masses of molten glass formed toward the center of major impacts, (ii) the breakup of impact-produced liquid jets into droplet trains, (iii) splash and rebound from objects hitting molten glass, (iv) drag of splattered glass over hard nonwetted surfaces, (v) condensation from a vapor, and (vi) vesiculation of impact-produced or volcanic magma. The production of glass spherules by vesiculation may be a major lunar mechanism and occurs when segments of broken bubble walls are pulled together by surface tension (*4*).

A typical homogeneous spherule in breccia 10068,32 contains 41.8 percent SiO_2, 14.7 percent Al_2O_3, 7.0 percent TiO_2, 12.2 percent CaO, 8.5 percent MgO, 14.0 percent FeO, 0.07 percent K_2O, and 0.17 percent Na_2O. This breccia contains two unusual glass fragments which are similar in texture and contain about 30 percent euhedral to subhedral mostly equant olivine crystals averaging 20 to 50 μm in diameter. The glass matrix contains 45.2 percent SiO_2, 15.5 percent Al_2O_3, 0.3 percent TiO_2, 9.9 percent CaO, 13.5 percent MgO, 13.6 percent FeO, 0.2 percent K_2O, and 1.4 percent Na_2O. The normally zoned olivine ranges from 85 to 92 (mean, 88) mole percent forsterite. The fragment may be a partly quenched glass resulting from the impact melting of pyroxene and plagioclase, or it may contain chondritic material.

A chrome titanium spinel of unusual composition was analyzed in a small fragment of crystalline rock in breccia 10068,32. This opaque phase contains 41.5 percent FeO (total iron), 24.5 percent TiO_2, 21.4 percent Cr_2O_3, 4.6 percent MgO, 6.5 percent Al_2O_3, and 0.3 percent SiO_2. Several small (15 to 30 μm) grains of this phase are present and are homogeneous at the scale of the electron beam (1 μm).

A slightly botryoidal coating (Fig. 2C) on the wall of a broken vesicle in a breccia glass fragment has a very high concentration of silica and contains about 5 percent K_2O. This coating may constitute a condensate from a silicate vapor formed when the glass was heated by impact. Condensed silicate vapor has been observed during volcanic eruptions (*5*), has been produced experimentally (*4, 5*), and has been produced in nuclear explosions (*6*). Material formed in this way may have complex and variable composition and morphology, and our search for such material in the lunar fines is continuing.

Fisher and Waters (*7*) have discussed the possible characteristics of lunar base surges. The lunar breccias show many features which could be explained if they were the deposit from a hot base surge produced from a large impact event. Turbulence in the base surge could build the observed accretionary rims (*8*) on nuclei of glass spheres and crystal fragments by rolling and tumbling action. Coarse layering in some of the breccias (*1*) corresponds to the bedding which is often characteristic of base surge deposits. After the flow had stopped, sintering of the finest glass fractions in the still hot deposit lithified the matrix which bonded the accretionary lapilli to each other. Partial devitrification of some glass fragments took place during cooling. Additional heat or thicker deposits could produce a more densely welded rock with a dense crystal-bearing glass as the final product in a sequence analogous to the formation of terrestrial welded ash flow tuffs. Sintering of lunar base surge deposits may proceed at temperatures which produce no sintering in the earth's atmosphere. Air interacts with gold particles (*9*) and MgO particles (*10*) to inhibit sintering by comparison with that which takes place in a vacuum. A similar vacuum enhancement of lunar glass sintering might be expected.

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4 January 1970

Mineralogy and Petrography of Lunar Samples

Abstract. *The lunar samples consist largely of augite, calcic plagioclase, and ilmenite. Olivine is a minor constituent of some rocks, as is cristobalite. Other minerals present in small amounts include tridymite, chromite, kamacite, taenite, and troilite. The principal rock types can be broadly grouped into ilmenite basalts and breccias. Except for their high ilmenite content, the lunar rocks resemble the calcium-rich achondritic meteorites (eucrites and howardites) in composition and structure. Evidence of a meteoritic increment in the lunar soil is provided by the presence of nickel-iron particles in glass and breccia, and the occurrence of metal-troilite spheroids; the breccias contain occasional silicate aggregates that resemble meteoritic chondrules. The lunar fines contain 325 parts of water-soluble calcium per million.*

We have confirmed the presence of plagioclase, pyroxene, ilmenite, olivine, cristobalite, tridymite, chromite, kamacite, taenite, and troilite in the lunar samples. Microprobe analyses show a range of plagioclase compositions from An_{70} to An_{100}, individual grains being zoned with increasing An content to-

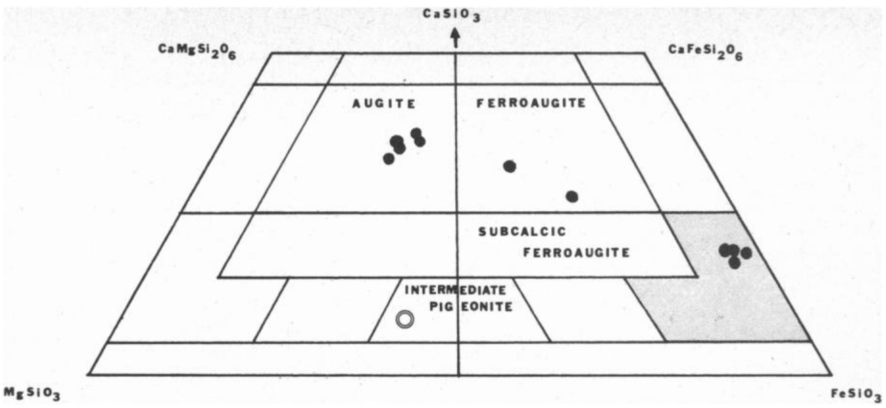

Fig. 1. Augite and ferroaugite compositions in lunar crystalline rock 10047, and the composition of the yellow pyroxenoid mineral in the shaded field, a compositional region for which natural pyroxenes were previously unknown. Also shown (open circle) is an intermediate pigeonite grain, found in crystalline rock 10003.

wards the center. Pyroxene is also zoned and shows a range of composition, falling in the fields of augite, ferroaugite, and pigeonite; some grains show exsolution lamellae of hypersthene or clinohypersthene. Microprobe analyses of pyroxenes in one rock (10047), recalculated in terms of the $CaSiO_3$ (Wo), $MgSiO_3$ (En), and $FeSiO_3$ (Fs) components, range from $Wo_{40}En_{36}Fs_{24}$ to $Wo_{28}En_{21}Fs_{51}$ (Fig. 1). Associated with the pyroxene in 10047 is a yellow mineral (*1*); microprobe analyses of this mineral show that its mean composition is $Wo_{18}En_4Fs_{78}$, and J. V. Smith (*2*) has identified it as a pyroxenoid mineral with the pyroxmangite structure. Olivine occurs in small amounts in some of the lunar rocks and has a composition near Fa_{30}. Ilmenite is universally present, usually as idiomorphic platy crystals. Cristobalite is interstitial to the other minerals and is evidently a late crystallization. Rare grains of tridymite were found in a low-density fraction of the lunar soil. Chromite is present as an accessory mineral. Trace amounts of kamacite and troilite are present in the crystalline rocks, frequently as globules in the mesostasis. Taenite, probably of meteoritic origin, occurs as metal particles in the breccias and lunar soils; these metal particles contain up to 30 percent nickel.

The lunar crystalline rocks (types A and B) (*1*) form a mineralogically uniform group. Although they range widely in grain size, they consist of the three principal minerals augite, plagioclase, and ilmenite in order of decreasing abundance. Modal analyses of five samples (10003, 10020, 10047, 10049, 10050) gave very small variations. Augite ranges from 47.7 to 53.4 volume percent and averages around 50 percent. The range in plagioclase and ilmenite is larger: 24.4 to 36.9, and 9.8 to 18.5 percent, respectively. The average grain size ranges from about a few hundredths of a millimeter up to nearly 2 mm. By terrestrial standards, this includes rocks ranging from basalts (less than 0.5 mm) to dolerites (less than 2 mm) and approaches the grain size of gabbros (greater than 2 mm). This grain-size comparison suggests that the finest grained lunar rocks correspond to quenched surfaces of flows, or ejected cinders or bombs, and the coarser grained samples correspond to flow interiors or perhaps to the interior of thin dikes or sills. Perhaps the simplest hypothesis is that all the crystalline rocks are fragments of a single flow blown to their present sites by meteorite impact.

The coarser grained rocks (type B) show a clear-cut crystallization sequence. Ilmenite is one of the first minerals to crystallize, and appears to be followed shortly by augite. When present, olivine crystallized largely before augite, and is commonly mantled by it. The crystallization of ilmenite and augite precedes and overlaps that of plagioclase. In general, the sequence follows the well-known Bowen reaction series. Progressive crystallization eventually produced residual liquids enriched in FeO and SiO_2 and depleted in CaO, MgO, and Al_2O_3 compared to the parent liquids. From these residual liquids, cristobalite and the peculiar Fe-Ca pyroxenoid crystallized, with possibly apatite and other phases.

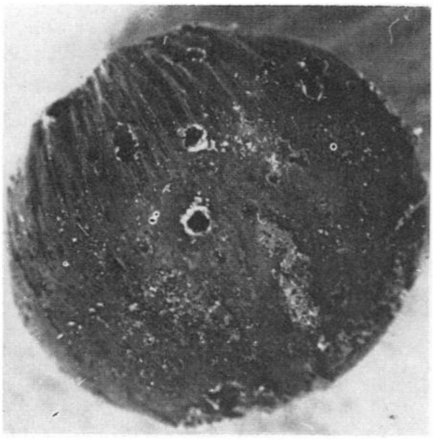

Fig. 2. Nickel-iron pellet, 3.5 by 3.2 by 2.3 mm, weight 88 mg, found in lunar sample 10085. Note furrowing, small craters, and partial coating of silicate glass.

The lunar rocks are comparable in some regards to terrestrial basalts. As in the lunar samples, plagioclase and augite are the principal phases in terrestrial basalts. However, ilmenite is rarely abundant, and normally there is more plagioclase than augite. The high content of pyroxene plus ilmenite in the lunar samples justifies calling them ilmenite melabasalts or ilmenite meladolerites, following the nomenclature of Johannsen (*3*). Although the lunar igneous rocks can be classified by a terrestrial scheme, there remain fundamental chemical and mineralogical differences between the lunar rocks and common terrestrial basalts (*1*). Compared to tholeiitic basalts of comparable grain sizes, the lunar rocks contain very little mesostasis or glass. They appear to have come from melts that are very difficult to quench, and thus perhaps of quite low viscosity. Among terrestrial basalts, low-silica magmas, particularly those of the alkaline basalt family, are similarly difficult to quench even when rapidly cooled.

One of the most striking features of the coarser grained lunar rocks is a well-developed ophitic texture, that is, a texture composed of large pyroxene crystals enclosing a number of plagioclase crystals. This is the commonest texture of terrestrial intrusive basaltic rocks. Although the texture appears to indicate early crystallization of plagioclase followed by augite, it has more often been taken to indicate simultaneous crystallization of the two phases (*4*).

There are certain analogies between the iron-bearing basalts of Disko Island, Greenland, and the lunar basalts. The main similarity is the occurrence of kamacite in both. As in the lunar samples, the kamacite in the Disko basalts commonly occurs in interstitial areas and is associated with sulfides. Some of the Disko basalts have high FeO contents and crystallized under low oxygen fugacities, as did the lunar basalts. Eventually one may find the Fe-Ca pyroxenoid in the Disko basalts. We have examined one of these basalts but find the most iron-rich pyroxenes to be ferriferous pigeonite.

Among meteorites, there are close analogies in composition and structure between the lunar basalts and the Moore County eucrite, a calcium-rich achondrite consisting of calcic plagioclase, pyroxene, and tridymite, with accessory chromite and ilmenite; however, this meteorite contains only a little titanium.

The lunar breccias are composed of rock, mineral, and glass fragments in a comminuted matrix of the same materials; irregular fragments of nickel-iron and of silicate aggregates resembling chondrules are present in small amount. They range from friable to hard and completely indurated. Effects of shock metamorphism are pronounced. For example, plagioclase grains are typically chalky white in hand specimen, and in thin section are seen to be partly or wholly converted to maskelynite. The breccias appear to be shock-lithified lunar soil and contain much glass which is highly variable in color, refractive index, and composition. Some of this glass is present as transparent orange-brown spheres that are superficially similar to chondrules in meteorites. Urey (*5*) has proposed that chondrules (and hence chondritic meteorites) originate on the moon, impacts on the lunar soil having produced considerable quantities of molten droplets. However, the Apollo 11 site cannot be the source of presently known chondritic meteorites, because the chemical and mineralogical compositions of the lunar samples are quite different from those of these meteorites. However, the structure of the breccias is very similar to that of the howardite meteorites (calcium-rich achondrites) such as Kapoeta (*6*), and they have comparable compositions, except for the high titanium content. Duke and Silver (*7*) have suggested a lunar origin for the calcium-rich achondrites.

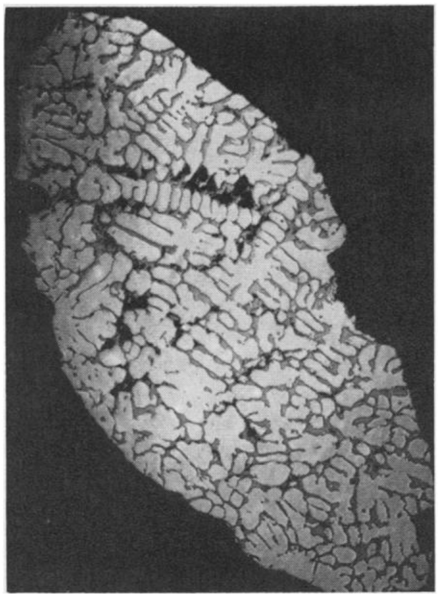

Fig. 3. Polished section of nickel-iron pellet, showing dendritic aggregate of taenite (white) and troilite (gray); length of section is 2.5 mm.

The lunar soil (material <1 mm diameter) comprises fragments of basalts and breccias, single mineral grains, and much glassy material. Some fragments of a type not seen in larger pieces were noted, in particular a fine-grained rock consisting of subequal amounts of anorthite (An_{95}) and colorless glass, this glass having the approximate composition (weight percent); SiO_2, 43; Al_2O_3, 13; TiO_2, 1.3; FeO, 13; MgO, 17; CaO, 8; Na_2O, 0.6. The x-ray powder photographs of different size fractions from the lunar soil show uniform proportions of augite, plagioclase, and ilmenite throughout. The finest component (<10 μm) consists largely of glass shards, and electron micrographs show that these are vesicular on a submicron scale, individual vesicles being as small as 100 to 200 Å in diameter.

We sieved our specimen of lunar fines (10084) and obtained more than 2 g of −325-mesh material. Since this material was destined for eventual mineral separation, we decided to extract it first with triply distilled water and to determine the water-soluble cations. A control experiment without sample yielded less than 1 ppm of the cations determined. A sample of the Allende meteorite was extracted for comparison. The values obtained [lunar sample, Allende sample (in ppm)] were : K, <5, <5; Na, 21, 288; Mg, 16, 77; Fe, <5, <5; and Ca, 325, 95. The high amount of extractable calcium is noteworthy. We do not know what anions balance this calcium, but we do not believe that they are halogens. Sulfate or carbonate are distinct possibilities.

Evidence for a meteoritic increment on the lunar surface is provided by the nickel-iron fragments in the breccias and the occurrence of nickel-iron pellets in the soil, such as that illustrated in Figs. 2 and 3. This pellet has a lensoid form with one surface (here referred to as the upper surface) with a greater radius of curvature than the other. This upper surface has a series of furrows, evidently produced by shrinkage during solidification; since these furrows are confined to the upper surface, this indicates that the upper half cooled more slowly than the lower half, presumably because the latter was in direct contact with the lunar surface and lost heat by conduction rather than by radiation. The upper surface shows a partial polish, probably the result of dust abrasion, whereas the lower surface has a rough matte-like texture.

The surface of the pellet is cratered, more abundantly on the upper than on the lower half. These craters were evidently formed by the impact of small silicate particles, the remains of which form a glassy coating on their interior. There are at least three types of craters, each with raised or overturned rims; with increasing ratios of depth to diameter they may be described as (i) saucer craters; (ii) bowl craters; (iii) flask craters (in which a tubular neck leads into a spherical cavity).

A density determination of this pellet gave a value of 7.36; this would indicate a bulk composition of about 85 weight percent nickel-iron and 15 percent troilite, but these figures are approximate because of the presence of some silicates on the surface. The internal structure is a dendritic intergrowth of taenite and troilite. Microprobe analyses show a variation from 14 to 16 percent nickel in the taenite, with the higher nickel values at the margins of the dendrites. The troilite contains a small and variable amount of nickel, usually 0.1 to 0.5 percent, sometimes as high as 0.9 percent. Inclusions of chromite are present in the troilite, and a small amount of silicate. At the interface of the taenite and the troilite there is a narrow rim of a distinct and separate nickel-iron phase, visible only after etching. This phase has sharply defined edges, and has a variable nickel content, usually 32 to 36 percent but occasionally as high as 45 percent.

The taenite in this pellet has a pseudo-martensitic structure, which may be interpreted either as shock-induced or as the result of rapid cooling. Buchwald (*8*) has produced similar structures by quenching a synthetic nickel-iron alloy with 15 percent Ni and 0.2 percent P from 1100°C. The structure of the taenite-troilite intergrowth is remarkably similar to that described by Begemann and Wlotzka (*9*) from the Ramsdorf meteorite, a highly shocked chondrite; they also produced similar structures by melting pieces of the Pantar chondrite and cooling in a vacuum.

From these data we infer the following history for this pellet. Its material 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.

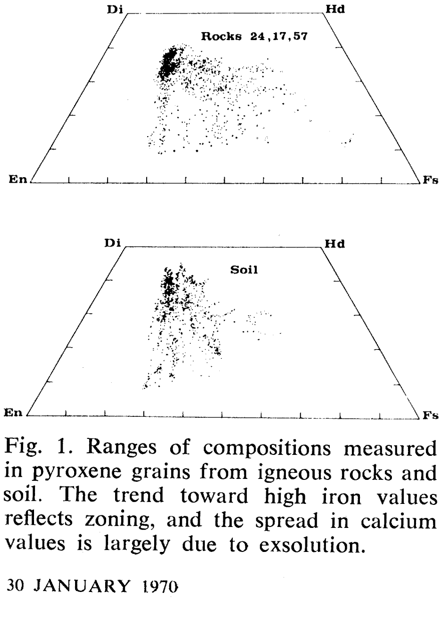

Fig. 1. Ranges of compositions measured in pyroxene grains from igneous rocks and soil. The trend toward high iron values reflects zoning, and the spread in calcium values is largely due to exsolution.

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

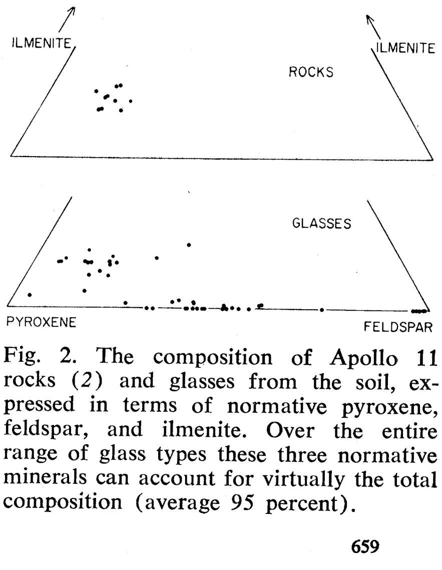

Fig. 2. The composition of Apollo 11 rocks (*2*) and glasses from the soil, expressed in terms of normative pyroxene, feldspar, and ilmenite. Over the entire range of glass types these three normative minerals can account for virtually the total composition (average 95 percent).