Lunar Soil: Size Distribution and Mineralogical Constituents

Abstract. *The lunar soil collected by Apollo 11 consists primarily of submillimeter material and is finer in grain size than soil previously recorded photographically by Surveyor experiments. The main constituents are fine-grained to glassy rocks of basaltic affinity and coherent breccia of undetermined origin. Dark glass, containing abundant nickel-iron spheres, coats many rocks, mineral, and breccia fragments. Several types of homogeneous glass occur as fragments and spheres. Colorless spheres, probably an exotic component, are abundant in the fraction finer than 20 microns.*

Material finer than 1 mm constitutes approximately 90 percent of the two core tubes returned by Apollo 11 and a similar proportion of that of the bulk sample box. Our sample consisted of 15 g of submillimeter material from the bulk sample box, necessarily studied without orientational context, on which we have made size analyses and morphological and mineralogical descriptions which bear on the petrology of the source rocks and the mode of development of the soil. Our work was accomplished on a split of half the original sample, and various analyses were made on smaller splits, ranging from 300 mg to about 2 g.

The size distribution was determined by wet and dry sieving (wet sieving below 67 μm) and by Coulter electronic counter for the fraction finer than 125 μm. In the sieve determinations, all fractions were weighed before and after sieving and the data corrected for small losses of material. The Coulter counter has the advantage of operating on a total sample. Particles suspended in electrolyte are drawn through an aperture and the resistivity change, as electrolyte is displaced in the aperture, is amplified and counted for individual particles. The sample was run using a 200 μm aperture, was allowed to settle to remove the coarser constituents, and was then run using a 50 μm aperture to obtain good resolution of the distribution down to 1 μm.

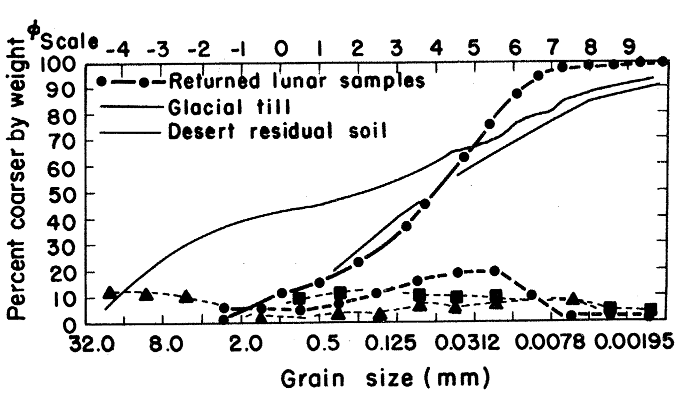
Distributions obtained by the two methods are consistent and give a median grain size of 62 μm and a modal grain size of 20 μm for the total sample. To obtain the distribution for the whole sample, we assumed that our sample had the same proportion of submillimeter material as the core tubes studied in the preliminary examination (*1*). The distribution is compared in Fig. 1 with those of a residual desert soil and a glacial till, in which mechanical weathering has been the dominant comminution process. The lunar sample is not as poorly sorted as the residual soil but resembles the glacial till in size distribution. However, the lunar soil is asymmetrically skewed to finer grain size, whereas the glacial till is skewed toward coarser grain size. The lunar soil is notably deficient in material finer than 15 μm, containing less than either of the terrestrial examples.

Figure 2 compares the size distribution for our sample with photographic determinations made for Apollo 11 in the preliminary examination (*1*) and from Surveyor photography of other uplands and maria sites. The distribution is consistent with the interpretation of Apollo 11 photographs and is similar in slope to other maria sites studied by Surveyor. The data consistently indicate that the Apollo 11 site has a greater abundance of fine material than other sites that have been photographed.

The mean density of the submillimeter fraction is estimated to be 3.01 g/cm^3 on the basis of an examination of its suspension in a density gradient (methylene iodide–dimethyl formamide) from 2.0 to 3.32 g/cm^3. The range of grain densities is from less than 2.2 to greater than 3.32 g/cm^3. The mean density is less than the density of the larger rock fragments, which range from 3.2 to 3.4 g/cm^3 (*1*), and is less than the mineral density of the core tubes, 3.1 g/cm^3 (*1*). The lower density is due to increased amounts of glass in the submillimeter fraction. A large amount of the breccia and glass fraction can be removed from the sample by a hand magnet. The nonmagnetic fraction is much denser than the magnetic fraction, about 70 percent of this material being denser than 3.32 g/cm^3.

There are four principal constituents of the soil:

1) Rock fragments, which can be placed in three groups on the basis of grain size: equigranular, 0.1 to 0.5 mm; equigranular, 0.05 to 0.1 mm; wholly crystalline or partly glassy, with grain size generally less than 0.05 mm. The coarser rock fragments consist primarily of clinopyroxene and feldspar, blocky ilmenite (rarely with rutile lamellas) and cristobalite, with minor troilite, which contains blebs of metallic iron with about 0.5 percent nickel. The very fine-grained to glassy material varies in texture. Fragments in polished section



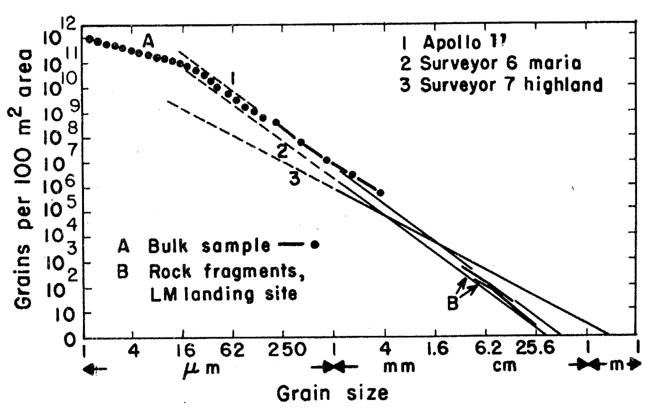


Fig. 1 (left). Cumulative size distributions and histograms for lunar soil, residual desert soil, and glacial till. Fig. 2 (right). Comparison of size distribution for lunar fines and distributions determined photographically for Apollo 11 and by two Surveyor experiments. Our data have been converted to area by assuming particles to be spherical and of constant density.

can be characterized by the form of the ilmenite, which occurs as blebs or as skeletal crystals of different growth stages. The silicates vary from wholly crystalline to glassy, commonly with pyroxene skeletal crystals interspersed with lamellas of glass rich in silicon, calcium, and aluminum, and poor in iron and titanium. Sulfides are not abundant, nor is metal, and these fragments are not separated into the magnetic fractions.

Table 1. Analyses of glasses from the submillimeter fraction. Analyses performed by electron microprobe; data are uncorrected for absorbtion or fluorescence: 1, irregular glass common in the fraction finer than 10 μm; 2, amber glass sphere; 3, olive-brown glass sphere; 4, black opaque glass sphere; 5 and 6, dark amber glass spheres; 7, deep red-brown glass; 8, pale green glass sphere; 9, colorless glass sphere, 8 μm diameter; 10, pale green sphere; 11 and 12, pale green spheres.

Oxide	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	45.2	45.5	43.0	38.1	34.9	37.7	41.9	44.5	49.5	55.4	47.0	41.7
TiO_2	2.0	3.1	6.5	10.4	9.8	10.4	9.3	0.1	0.5	0.9	0.2	0.4
Al_2O_3	29.4	14.0	11.7	4.5	13.5	5.0	8.5	14.6	28.0	1.4	24.9	6.5
Cr_2O_3	<0.1	0.1	0.2	0.4	0.2	0.5	0.3	0	0	0	<0.1	0.4
FeO	6.4	12.0	14.0	23.8	15.8	23.6	17.4	15.0	2.5	10.4	4.0	14.7
MgO	3.1	8.0	7.2	11.9	8.3	12.3	6.9	9.6	2.0	16.7	7.5	23.6
CaO	13.0	12.0	10.6	7.8	14.8	8.2	11.0	11.8	14.0	20.1	13.7	6.8
Na_2O	<0.1	<0.1	0.4	0.9	0	0.1	0.4	0.5	<0.1	0	0	0
Total	99.1	94.6	93.7	97.6	97.1	97.9	97.1	96.1	96.5	105.2	97.3	94.1

Broken crystal fragments make up approximately 10 to 15 percent of the submillimeter fraction. Crystal fragments as large as 1 mm are not common, suggesting that medium- and coarse-grained rocks are not generally abundant. Olivine is present in the crystal fragments but was not observed in the rock fragments. Many of the crystal fragments are conspicuously deformed; some of them are translucent and polycrystalline, giving stretched spot patterns and line patterns in x-ray diffraction studies of individual grains.

From the observed abundance of definable rocks and broken crystal fragments, the crystalline components of the lunar soil represent near-surface igneous rocks of basaltic affinity in the proportions: very fine to glassy varieties, 50 percent; fine-grained equant varieties, 30 percent; fine- to medium-grained varieties, 20 percent.

2) Breccia fragments are a principal constituent of the soil, constituting approximately 25 percent of the 500 to 1000 μm fraction and a larger proportion of finer size fractions. These fragments are typically gray, with irregular shapes and surface textures. Many of them are quite porous with many reentrant surfaces; others are compact, hard aggregates including crystal, rock, and irregular glass fragments in a matrix of glasses of variable composition similar to that shown in analyses 1 and 2, Table 1. The rock fragments, vesicular glass fragments, and glass spherules observed in the breccia indicate that it originated as a surficial debris layer. It does not contain as much highly magnetic glass as the total soil sample and apparently represents a rock type of complex history, rather than simply fused soil.

3) Dark, magnetic glass, varying in color from dark olive brown to black in large grains but generally colorless to brown in very thin flakes, is a major constituent of the soil (20 to 25 percent). It occurs in a variety of shapes, including irregular masses, commonly coated with fine particles, surficial coatings on breccia and other rock fragments, and as incipient and well-formed spherules. The glass is inhomogeneous, containing partially resorbed crystals of feldspar and ilmenite. It is generally similar in composition to the bulk soil sample (see analyses 3 and 4, Table 1). The glass contains abundant metal spheres, with nickel contents ranging from about 4 to 15 percent, which are submicroscopic to a few micrometers in diameter. The intensity of color appears to be related to the abundance of tiny inclusions. Flow structures are present, and in some instances strings of metal spheres are concentrated along flow bands. The glass is typically vesicular, but the vesicles are not always related to the surface. Where it covers breccia or crystalline material, cavities tend to be concentrated at the contact of glass and rock, suggesting that cavities are due to surface tension effects as liquid flowed imperfectly over the rock. Surfaces may be covered by cavities or by nodes, which give the surface a lumpy appearance. The nodular surface texture of the melted material is possibly due to preferential fusion of fine-grained particles, which stick and fuse to the glass surface.

The morphology and composition of the glass suggest that it represents very briefly melted material. The presence of nickel-rich metal spherules indicates that temperatures were locally and briefly above the melting temperature of the rock and suggests that the glass originated as the melted ejecta from relatively nearby meteorite impacts, predominantly on soil.

4) Transparent glass of a variety of colors, including amber, deep red brown, pale green, yellow and colorless, makes up a conspicuous but relatively small proportion of the soil. These glasses are homogeneous, in contrast to the brown and black spheres associated with the glass described in 3). They rarely contain incompletely melted ilmenite grains. Most occur as irregular fragments and as spheres, rods, and dumbbells. The proportion of spheres and related forms increases with decreasing grain size, reaching approximately 4 percent in the fraction finer than 10 μm. The proportion of spheres by color varies also with grain size: amber spheres are dominant in most size ranges but are most prevalent in the fractions between 37 and 250 μm; yellow and green spheres are generally about 10 percent of the sphere population at all grain sizes; and the colorless, or very pale spheres, are highly concentrated in the fraction finer than 20 μm.

Electron microprobe analyses of glasses are given in Table 1. Most of the glass spheres are not simply melted mineral grains but some type of composite. Many amber spherules are similar in composition to the bulk rock (*1*). The lighter-colored spheres tend to have less iron and titanium, greater magnesium/iron ratios, and higher calcium and aluminum contents. The amber color appears to be related to high titanium content (compare analyses 7 and 8). Because the compositions and size distribution of colorless spherules are distinctive, we consider these to be exotic constituents of the sample, and it is tempting to compare them with the sample analyzed at Tycho by Surveyor 7 (*2*), which has similar characteristics.

There are three obvious differences in the soil as a function of grain size: (i) The proportion of magnetic material, consisting largely of glass, increases markedly with decreasing grain size, from 50 percent at 500 μm to 75 percent at 37 μm. (ii) The proportion of identifiable crystalline rock fragments decreases and the proportion of crystal fragments, including intergrowths of minerals, increases with decreasing grain size; however, the finest-grained to glassy rocks are identifiable in the range below 37 μm. (iii) The composition of the soil is more homogeneous at finer grain size, containing more glass and glass of a more limited compositional range. Most of the glass in the fraction finer than 10 μm is of a low-titanium, low-iron, high-aluminum type similar to that shown in analysis 1, Table 1 (about 60 percent), with 20 percent of glass similar to the amber glass (analysis 2). Feldspar, pyroxene, and ilmenite in approximately equal proportions make up the remainder. In coarser size fractions, low-titanium glass is less abundant and more variable in composition, and the variety of glasses and crystals is greater (*3*). The low-titanium glass has some compositional affinities with a low-melting fraction of the bulk rock. The relatively high abundance of ilmenite in the fines probably is due to its resistance to melting during formation of impact glasses.

The following summarizes our interpretation of the lunar soil: (i) It has been formed primarily by comminution of fine-grained, near-surface basaltic rocks and breccia of uncertain origin. (ii) Melting is a conspicuous feature tending to cause consolidation of the soil into clumps, and it may be a partial explanation of the deficiency of the sample in very fine-grained material. (iii) Metallic spherules in the glass, colorless and pale spheres, and possibly some other minor constituents are exotic material, but their abundance is certainly less than 0.1 percent of the total sample.

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References and Notes

1. *Apollo 11, Preliminary Science Report, NASA SP-214* (National Aeronautics and Space Administration, Washington, D.C., 1969), size frequency of core tubes, p. 128; photographic determinations, p. 47; density of rocks, p. 124-126; density of soil, p. 115; chemical composition, p. 132.
2. A. L. Turkevich, E. J. Franzgrote, J. H. Patterson, *Science* **162**, 117 (1968).
3. The pyroxene assemblage in the soil is variable, containing predominantly subcalcic augite and augite, with minor pigeonite. A few grains low in calcium are probably orthopyroxene (with higher Mg/Fe than most of the augite). Some of the yellow grains left undescribed by the preliminary examination team are hedenbergitic pyroxene and fayalitic olivine. One grain of an opaque mineral, occurring as an inclusion in olivine, is a chrome-titanium spinel, with composition FeO, 47.6; MgO, 4.6; CaO, 0.1; Al_2O_3, 5.3; TiO_2, 24.5; and Cr_2O_3, 18.7 (all percent by weight).

4. The contributions of the following people were essential: R. Fuhrman, C. Merrill, P. Rosenfield, and R. Commeau. Publication authorized by the Director, U.S. Geological Survey.

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Mineralogy and Petrology of Coarse Particulate Material from Lunar Surface at Tranquillity Base

Abstract. *Five grams of coarse fines (10085,11) contains 1227 grains, mostly mafic holocrystalline rock fragments, microbreccia, and glass spatter and agglomerates with less abundant anorthosite fragments and regularly shaped glass. The crystalline lithic fragments in the coarse fines and microbreccias represent a closely related suite of gabbroid igneous rocks that have a wider range of modal analyses and textures than seen in the larger crystalline rock samples returned by Apollo 11. Petrographic evidence of shock metamorphism is common, and the abundant glass is almost all shock-produced. None of the glass observed is similar to tektite glass.*

This work is based chiefly on a nondestructive study of sample 10085,11, a 4.92-g sample of coarse fines (1 cm to 1 mm), and work with two microbreccia petrographic thin sections 10046,65 and 10068,36. In addition, some of the coarser grains from a 15.28-g sample of fines (less than 1 mm) 10084,80 have been examined, and preliminary studies have been made of thin sections of the following samples: 10020, 10045, 10048, 10049, 10062, 10065, 10072.

Sample 10085,11 contained 1227 grains as follows: mafic holocrystalline rock fragments, 585; microbreccia, 395; glass spatter and agglomerates, 204; regularly shaped glass (spherules, dumbbells, and so forth), 6; anorthosite and other light-colored rock fragments, 37. Of the holocrystalline rock fragments 428 were unshocked or only mildly shocked and 157 grains were moderately to strongly shocked, as judged by microfracturing and vitrification of feldspars. Of the microbreccia fragments 135 have portions of their surface covered with glass.

Mafic holocrystalline rock fragments are dominantly gabbroid with the basic mineralogy of clinopyroxenes, ilmenite, calcic plagioclase, and accessory olivine. Relative proportions of these minerals and textures show considerable variation, and there is a wide range of shock effects. Glass is very rare, except for probable impact metamorphism products. Preliminary measurements on optical properties show a relatively wide range for the clinopyroxenes which is consistent with titaniferous augite, normal augite, ferroaugite, subcalcic augite, and pigeonite: for example, $2V_z$ of 22 grains (U-stage and spindled) ranges from 21° to 48°, with dispersion of $2V_z$ $r>v$ dominant with grains with axial angles greater than 40° and $r<v$ dominant in grains with axial angle between 28° and 38°. Values for $2V_z$ of 34° and 46° with opposite dispersion of $2V$ occur in a single rock fragment. Badly fractured grains with undulatory extinction illustrate apparent shock damage. Plagioclase optics of a few grains fit low-temperature plagioclase, An_{85-90} ($n_\beta = 1.578 \pm 0.001$, $2V_x = 78 \pm 2$), but zoning has not been checked in detail and a wider range is indicated. Olivine optics place it in the range Fo_{75-80} ($n_\beta = 1.696$ to 1.713, each $\pm$ 0.003; $2V_x = 87° \pm 3°$).

A considerable range of crystallization textures is displayed in the various crystalline rock types in the breccias, but most are familiar basaltic and gabbroid varieties. Grain sizes range from 0.01 to 1 mm. The more common relations are ophitic and subophitic pyroxene molded onto euhedral to subhedral laths of plagioclase, both intergrown with platy to irregular ilmenite. Pyroxene is also commonly intergranular euhedral or anhedral. In a few rocks subhedral plagioclase mantles rod-shaped cores of pink pyroxene (Fig. 1, a and b). This texture with similar mineralogy is known in terrestrial rocks such as the Patuki Volcanics (Permian) from South Island, New Zealand (Fig. 1c) (*1*). Except for two fragments, no porphyritic textures were seen. One exception is a microporphyritic felsite with distinctly fluidal (trachytic) texture consisting of subaligned seriate phenocrystic laths in a similarly aligned matrix of microlites and possibly minor glass (Fig. 2). A second porphyritic relation occurs in an ilmenite-rich basaltoid rock in which a 0.1-mm olivine grain is set in an intergranular matrix of 0.01-mm grains of pyroxene, ilmenite, and sparse plagioclase. Rock sample 10045 shows similar olivine phenocrysts in a diabasic matrix. The most striking exceptions to common terrestrial textures are: (i) an even-grained