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

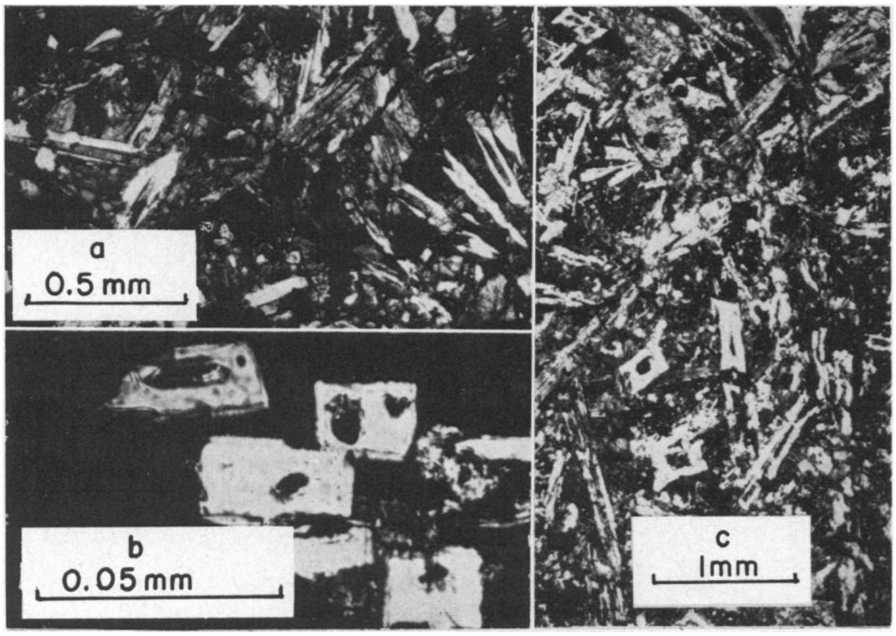

Fig. 1. Calcic plagioclase mantling pink clinopyroxene in mafic holocrystalline lithic fragments in Tranquillity Base sample 10046. Plane polarized (a) and crossed polarizers (b). (c) Identical texture in terrestrial rock with similar major mineralogy from the Patuki Volcanics (Permian), South Island, New Zealand (plane polarized light).

(0.05 to 0.2 mm) idiomorphic mixture of stubby pyroxene (colorless cores with narrow pink margins) and platy ilmenite set in a very fine matrix of fibrously intergrown pyroxene and plagioclase(?) dusted with opaque granules, and (ii) "ophitic" plagioclase enclosing subequant grains of pyroxene and ilmenite.

Monomineralic polycrystalline plagioclase rock fragments occur in sample 10085,11 and also in several thin sections of microbreccias. Other fragments contain sparse olivine or pyroxene. Most appear to be, or have been, relatively coarse-grained and to be derived from an anorthositic assemblage. Many, if not most, show severe granulation of plagioclase with relics of coarser grains grading into an extremely fine matrix. Plagioclase colors of the larger grains range from medium to light gray, gray-green, and white. This rock type is not represented in the larger specimens returned by Apollo 11. The microporphyritic fragment mentioned earlier is too fine-grained for certain determination of the feldspar composition by optical methods, but a few of the phenocrysts appear to be optically positive, suggesting calcic plagioclase and a rock name of "andesite" or "volcanic anorthosite." This rock may be from surface volcanic flows in the Sea of Tranquillity; however, the possibility that the anorthosite originated from the lunar highlands cannot be overlooked. The other light-colored rock fragments appear to be very fine-grained and shocked particles similar in mineralogy to the mafic holocrystalline rock fragments, but with very low ilmenite contents.

The microbreccia fragments have a wide range of induration from easily friable to very hard. These are mostly typical microbreccia fragments with a fine-grained groundmass composed mostly of thetomorphic and fused mineral and rock glass. Many fragments contain regularly shaped glass particles and generally light-colored lithic fragments. Thin sections of most microbreccias, such as 10068,36 contain fragments of preexisting microbreccias. Three of the microbreccia fragments in 10085,11 contain reddish-brown glass that appears to have been produced *in situ*. Although positive petrographic evidence has not been found, we believe that the microbreccias are shock-welded pieces of the lunar regolith. One large fragment of mafic holocrystalline rock has glass that is apparently derived from it. This glass is reddish-brown to brown and contains numerous microlites, and has a mean n of 1.552, ranging from 1.550 to 1.554. The microbreccias contain abundant evidence of shock metamorphism and multiple shock.

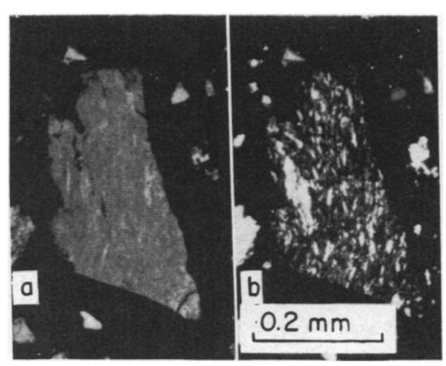

Fig. 2. Microporphyritic felsite, showing subparallel alignment of microphenocrysts and microlites of feldspar in a distinctly trachytic texture. (a) Plane polarized light; (b) under crossed polarizers.

Agglomerates and glass spatter consist chiefly of vesicular, irregularly shaped brown to gray and black glass masses commonly including and cementing together numerous mineral grains and small polymineralic rock fragments from the regolith. The refractive indices of these glasses have a narrow range compared with the glass spherules, and they are mostly translucent, containing abundant, dust-size mineral grains and microlites. These glasses are generally very similar in their optical properties, color, and morphology and may have originated from the same nearby impact event, or from similar events in similar parent materials.

Regularly shaped glass in the form of spherules, dumbbells, teardrops, and modifications of these forms are relatively rare in the coarse fines, but are abundant in the finer sizes and breccias (Fig. 3, a–d). These range in color from almost colorless to gray-green, green, yellow, orange-brown, to deep wine red. The refractive indices generally correlate well with the increasing depth of color if there are not abundant microlites or evidence of devitrification. Refractive indices are: light-green homogeneous glass spherule, $n = 1.580 \pm 0.002$; grass-green grain with surface flow grooves, $n = 1.601 \pm 0.002$; brown heterogeneous glass spherule, $n = 1.608$ to 1.620 ± 0.002; dark red to red-brown glass fragment, average $n = 1.716 \pm 0.002$. Surfaces of spherules range from highly reflective and regularly spherical to completely dust-covered and irregular. The dust-covered surfaces of glass spherules have mineral and glass particles up to 10 μm, but mostly less than 2 μm, stuck in their surfaces. Some flattened spherules have dust adhering only to one of the flattened sides as if the spherule had struck the regolith before it was completely solid, and was able to stick dust to the side that impacted the surface, the impact slightly flattening the spherule. The surfaces of some spherules, as well as of some mineral grains, have excellently preserved hypervelocity im-

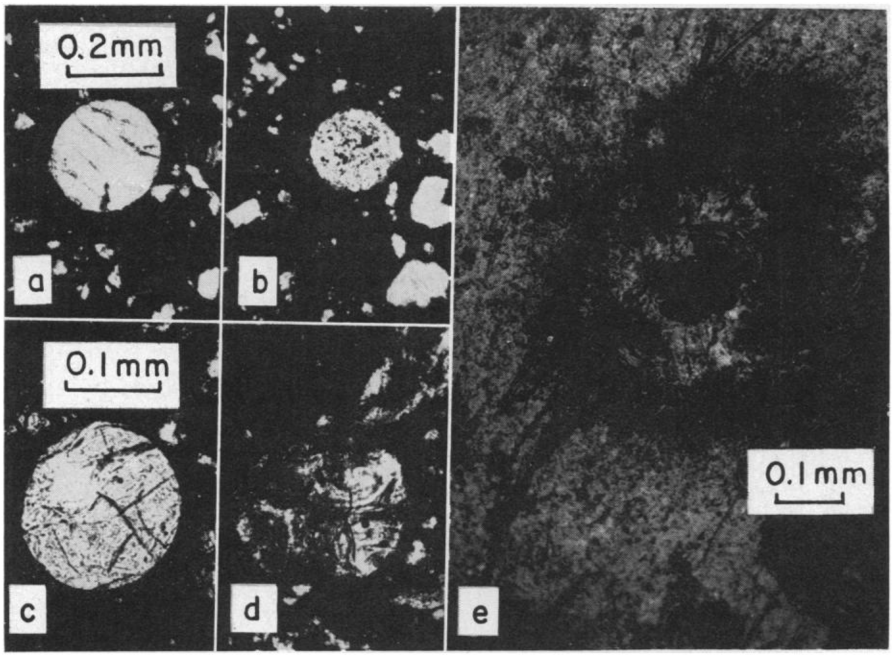

Fig. 3. (a) Homogeneous glass spherule, yellow to slightly greenish-yellow, fractured, holohyaline with no mineral inclusions or devitrification (10065). (b) Slightly irregular orange glass spherule with abundant mineral inclusions (10065), scale same as in (a). (c) Yellowish-brown glass spherule with flow structure, fractured with incipient devitrification and few small mineral inclusions (10048). (d) Mixed glass spherule of yellowish-green and orangy-brown glass with contorted flow structure and moderate devitrification (10065), scale as in (c). (e) Hypervelocity impact crater on surface of dark-red glass fragment (10085,11), incident light. (a–d) Plane polarized light.

pact craters (Fig. 3e). These range in size from a few tenths of a millimeter down to the limit of resolution of the binocular microscope and probably represent the impacts of very small meteoroids and high-velocity secondary particles. Some glass fragments are parts of spherules that appear to have been split apart by one of these impacts. The morphology of these small impact craters is remarkably uniform with an approximately hemispherical central crater lined with glass, a slightly raised lip, grading outward into a highly fractured and crushed ring syncline surrounded by a wide zone of thin, platelike spalls and an outer zone of redeposited ejecta commonly having a ray-like structure. One glass spherule has been observed that has a light, silvery-colored metallic coating on a portion of the surface, possibly nickel-iron. None of the glasses yet examined are similar to tektites in refractive index or general petrography. Almost all of the glass spherules contain spherical vesicles, and these have a wide range in size and abundance. In general, the heterogeneous and mixed glass spherules with obvious flow structure have more vesicles than the homogeneous spherules with little or no flow structure.

In the initial processing of sample 10085,11, the material was washed with acetone to remove much fine dust adhering to the larger grains. The fine material has a mean grain size of less than 5 μm, but a diffractogram demonstrated that clinopyroxene, calcic plagioclase, and ilmenite are the major constituents in this size range, similar to the larger particles. No fragments of meteoritic material, stony or iron, have been recognized in the coarse fines from sample 10085,11.

Coarse fines from Tranquillity Base contain fragments of a closely related suite of igneous rocks that have a wider range of modal analyses and textures than that seen in Apollo 11 samples larger than 1 cm (*2*). The textures of many of the mafic holocrystalline rocks are similar to those of terrestrial volcanic and shallow intrusive rocks. Fragments of anorthosite occur in the coarse fines and microbreccias, but this rock type is not represented in the larger rocks returned by Apollo 11. Anorthosite may originate from pods or crystal cumulates in the surface material at or near Tranquillity Base, but may have come from the lunar highlands. Petrographic evidence of shock metamorphism and meteoritic impact is much more common in the holocrystalline rock fragments in the coarse fines than in the larger holocrystalline rock samples. Almost all of the glass in the samples examined has apparently been produced by the impact of meteoroids or high-velocity secondary particles. None of the glass yet examined is similar to tektite glass. This observation tends to reinforce strongly the previous conclusions of many workers that tektites do not originate from the moon (*3*).

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References and Notes

1. M. F. Carman, *Trans. Roy. Soc. N.Z.* 1968, 6, 8, 91 (1968).
2. Lunar Sample Preliminary Examination Team, *Science* 165, 1211 (1969).
3. E. A. King, Jr., *Guidebook, Meteoritical Society, 32nd Annual Meeting* (1969).
4. We thank the staff of the Lunar Receiving Laboratory and the Lunar Sample Preliminary Examination Team for documenting the relationship of our sample to the total sample returned by Apollo 11 and for providing background information. Sponsored by the National Aeronautics and Space Administration under contract NAS 9-10373.

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High Crystallization Temperatures Indicated for Igneous Rocks from Tranquillity Base

Abstract. *Complex intergrowths of troilite (FeS) and iron in the igneous rocks from Tranquillity Base contain 8.4 percent native iron by volume. The intergrowths were derived from an initially homogeneous sulfide liquid that separated immiscibly from the magma at 1140°C or above. Textures show that the sulfide liquid formed late in the crystallization and cooling history of the igneous rocks and after the major ilmenite and pyroxene had formed.*

Two textural varieties of igneous rocks were among the rocks returned from Tranquillity Base. They have been arbitrarily called type A, "a fine-grained vesicular" rock, and type B, "a medium-grained vuggy" rock (*1*). Two samples of type A rocks (10062 and 10072) and one of type B (10050) have been ex-