the soil with a hand magnet. Some are melted, spherical in shape, and composed mainly of glass. Others are vesicular and complex in shape and contain large cavities and fragments of crystalline rock.

Scanning electron microscopic examination showed that metallic areas occur both within and on the surface of the soil particles. The metal content varied greatly from one particle to another. The metal inclusions in the soil particle are small ($< 30\ \mu m$) and often rounded. They are swathed in troilite, and their microstructure indicates shock-hardening.

Two metal areas, less than 10 μm in the largest dimension, were analyzed. One contained 13 percent Ni, 85 percent Fe, approximately 0.9 percent Co, and 0.4 percent P. The other contained 10 percent Ni, 85 ± 5 percent Fe, approximately 0.6 percent Co, and 0.35 percent P.

Another rounded metallic phase in a frothy complex soil particle is composed of essentially Fe and 0.4 percent Co. Nickel and P were not detected.

The metallic sample from the breccia is irregularly shaped and about 0.7 mm in its longest dimension. In a polished section, it exhibits a eutectic-like structure consisting of a very fine dispersion of phosphide and metal with lesser amounts of sulfide and carbide.

Extensive electron microprobe analysis of this particle shows the following. The metallic area surrounding the eutectic structure consists mainly of Fe with about 2 percent Ni, 1 ± 0.2 percent P, and no Co. The eutectic-like area contains on the average 6 ± 1 percent Ni and 1 to 1.5 percent P with small amounts of S and C. Electron microprobe scans show a strong correlation between Ni and P in the eutectic with the highest Ni region adjacent to the eutectic area. The carbides contain about 6.5 percent Ni and up to 8 percent P. The sulfides also contain Ni in solution. The amount of Ni in the phosphides [$(Fe\text{-}Ni)_3P$] was 10 percent as contrasted to that of the adjacent metal with 6 ± 1 percent Ni and less than 1 percent P.

Our findings bear out the suggestion made by PET (*1*) that the terrain from which these samples were collected is internally generated igneous rock overlain by an impact-formed breccia with some meteoritic material.

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References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
2. We thank F. Wood, Jr., W. Kouns, A. Doan, and C. Inman for their assistance.

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Mineralogical and Petrological Investigations of Lunar Samples

Abstract. *Fragments of igneous rocks and breccias, and one coarse-grained rock with thin sections, have been studied. Minerals found include pyroxene, plagioclase, olivine, ilmenite, troilite, ulvöspinel, native iron, cristobalite, tridymite, alkali feldspar, apatite, and quartz. Textures are described and interpreted. Among features revealed by optical, microprobe, x-ray diffraction, and electron microscope methods are extreme zoning and unmixing in pyroxene grains, compositional variations in ilmenites, and effects of shock metamorphism. Some trace elements were determined by x-ray fluorescence analysis.*

Work we have carried out so far has been primarily on particles and dust (10085,2) from the 1- to 10-mm fraction of the bulk sample, and on rock 10044 (rock specimen 10044/43, covered section 10044/42, polished section 10044/41). In this report specimens from 10085,2 are given the prefix B followed by our own laboratory serial number.

In the igneous rocks grain size has been found to vary from one rock fragment to another, and associated with varying grain size there tend to be characteristic textures. No phenocrysts have been observed in any rocks. The coarsest rock examined (10044/43) has equant pyroxenes up to 2 mm across, skeletal-to-acicular ilmenites up to 2 mm, and plagioclase laths up to 1.5 mm in length. With decreasing grain size, the ilmenites change from skeletal (up to 0.5 mm across) through acicular grains and a dendritic variety to equant ilmenites (~ 0.1 mm) in the finest rock. These changes are paralleled by the plagioclases. The pyroxenes, on the other hand, are anhedral and subophitic. Within the range outlined, six distinct textural types have been seen: (i) medium-grained equant (up to 2 mm): 10044/41, B4; (ii) acicular plagioclase and ilmenite with anhedral pyroxene of medium to fine grain size (up to 0.5 mm): B3, B8, B9; (iii) fine-grained rock (up to 0.15 mm) with characteristic sets of thin subparallel ilmenite lamellae: B1; (iv) granular fine-grained rock (up to 0.1 mm): B5; (v) rock characterized by plumose intergrowths of plagioclase and pyroxene (0.25 mm) resembling chondritic texture: B18a; (vi) vesicular glass with rounded ilmenites: B18b. The principal minerals in types i to v are the same, although the proportions vary (see Table 1).

The modal analyses of the different igneous rock types (Table 1) show a remarkable consistency in pyroxene content, an inverse relation between plagioclase and ilmenite, and an increase in ilmenite content with decreasing grain size. A very high content of ilmenite is notable in all of the rocks.

Among breccias two distinct and several intermediate types can be distinguished. The first consists of fragments of igneous rocks, single mineral grains, and a matrix of fine-grained dust. Ilmenites in these breccias frequently show evidence of shock. The second type of breccia is predominantly glassy, containing angular fragments of low-reflectivity glass in a glassy matrix of slightly higher reflectivity. Specks of nickel-iron up to 40 μm in diameter have been seen. This breccia may be the product of more severe shock metamorphism. A spherule from within it has the composition $Fe_{94.0}\ Ni_{4.8}\ Co_{0.9}$, which is similar to that of a spherule from impactite glass from Lake Bosumtwi Crater, Ghana (*1*). No oxides or sulfides are present in the breccia.

Intermediate between these two types are breccias consisting of varying proportions of glass as well as mineral and rock fragments. Vesicles have been observed in many of these breccias. Flow textures occur in some of the glassy portions. Native iron occurs both as minute spherules and as larger (up to 50 μm) fragments with serrated rims.

Ilmenites in various rock types were surveyed. They display minor variations in TiO_2:FeO ratios within single rock types ranging from 60:40 to 50:50 (molecular proportions) and are free of Fe_2O_3. Single grains, however, are homogeneous, with one exception, where part of a grain has distinctly lower reflectivity.

The ilmenites investigated are free of any large-scale exsolution or replacement phenomena. However, minute lamellae (up to 10 μm) of a gray mineral occur in some ilmenites parallel to (0001).

The effects of shock metamorphism on ilmenite are represented by sets of twinning lamellae (sometimes bent and folded) following mostly one, but occasionally two, directions. Lamellar ilmenites are widespread in the breccias, but they also occur in some igneous rocks.

Ulvöspinel usually occurs intergrown with ilmenite in the medium-grained igneous rocks. Quantitatively, it is insignificant (less than 0.01 percent of the rock). Its presence does, however, support the assumption of an oxygen-deficient environment of formation.

The particle size of the dust-like fraction from the bulk sample was suitable for transmission electron microscopy. About 50 percent of the particles (both spherical and angular) gave only diffuse electron scattering, a result that indicates a glassy nature. Glassy spherules have diameters down to about 1000 Å, and many of them have adhering crystalline particles. Ilmenite grains were recognizable as thin (0001) plates, often with hexagonal outline and characteristic electron diffraction pattern. These showed an extremely high density of dislocations as compared with ilmenites from within rock 10044/43, and a higher degree of stacking disorder could also be inferred from the diffraction pattern. The increased dislocation density and stacking disorder are probably associated with a higher degree of shock metamorphism.

Several black, glassy-looking spheres with diameter approximately 0.1 mm were found among the fines. X-ray diffraction analysis of these indicated the presence of glass and some α iron, either as cores or adhering to the surface. They are probably similar to the spherules found within the glassy breccia. X-ray fluorescence analysis of 0.5 g of the dust gave the following concentrations: Nb, 16 ppm; Zr, 265 ppm; Y, 140 ppm; and Sr, 215 ppm. One colorless crystal from the "fines" was identified as α quartz.

In rock 10044/43 the principal phases which can be seen in transmitted light are clinopyroxene, opaque minerals, plagioclase, cristobalite, and tridymite (mode in Table 1); apatite and K-feldspar are also present. In reflected light some areas exhibit a fine-grained, simplectite-like texture. The dominant opaque phase is ilmenite, but there are also troilite, native iron, and ulvöspinel.

Table 1. Modal analyses by volume. The mode of thin section 10044/42 was determined by the conventional method. Other modes were determined by superimposing a transparent grid on reflected-light photographs.

Sample	B4	B8	B3	B9	B1	B5	10044/41	10044/42
Plagioclase	24.2	34.8	33.9	36.2	26.8	24.4	33.1	34.1
Pyroxene	64.2	50.5	48.8	48.5	48.5	47.0	47.3	46.4
Ilmenite *	9.8	14.7	18.3	15.3	21.7	25.4	14.4	12.3
Cristobalite and tridymite							5.2	6.3

* Ilmenite here includes pyrrhotite, native iron, and ulvöspinel.

The pyroxenes as compared with those in most terrestrial rocks are remarkably free of inclusions of oxides and sulfides. Many grains show shadowy extinction and regions with different birefringence but similar refractive index, probably indicating misorientation at grain boundaries; similar subgrain boundaries have been observed by electron microscopy (Fig. 1). Other grains are zoned both in color and birefringence, and electron-probe analyses show these to have Mg-rich cores and Fe-rich margins ranging from augite to ferroaugite. The $2V_\gamma$ for different grains ranges between 37 and 48½° and some show simple (100) twinning. On the margins of some pyroxene grains crystals occur devoid of Mg and with unusually low Ca content (Fig. 2).

X-ray diffraction studies of some pyroxene single crystals showed them to be unmixed into monoclinic Ca-rich and Ca-poor components (*2*), the corresponding diffraction spots from each component being joined by streaks indicating either strain or a continuous range of composition. For each component $a \sin \beta$ and b were determined in each of three grains, and their compositions (Fig. 2) were derived on the basis of the data of Brown (*3*) and Viswanathan (*4*). The unmixing was confirmed by electron microscopy which showed (001) lamellae approximately 500 Å apart. Electron diffraction showed the existence of stacking faults as well as other disorder. A lamellar structure is seen in many grains in immersion oil under high power.

A separated pyroxene fraction (density 2.85 to 3.5 g/cm³) gave an x-ray powder pattern with moderately broad peaks yielding cell parameters $a \sin \beta = 9.33_5$, $b = 8.94_5$ Å, and suggesting an average composition of Ca:Mg:Fe = 31:42:27 (*3*).

The plagioclase is twinned on albite, pericline, and Baveno laws; it is slightly zoned. The $2V_\alpha$ ranges from 80 to 84°. A few crystals of a plagioclase separate with density lower than 2.85 g/cm³ were melted; the refractive index of the glass was 1.564 (±0.001), corresponding to An_{88}. Plagioclases from a light fraction of the above separa-

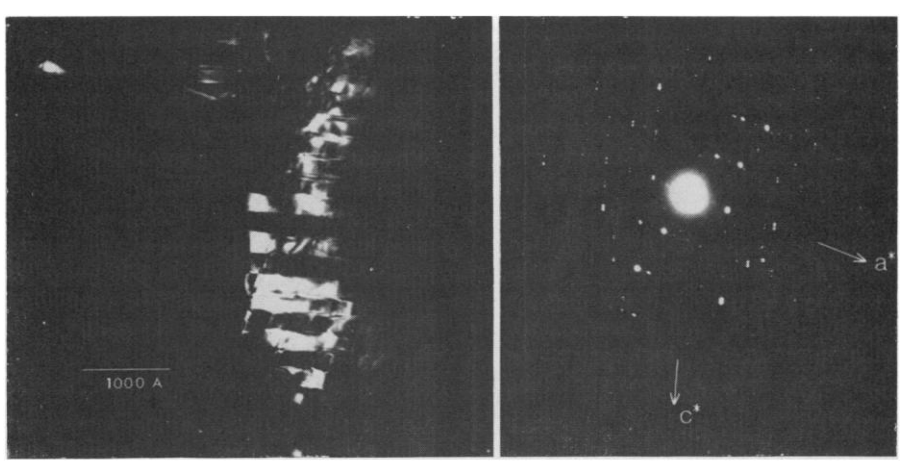

Fig. 1. Electron micrograph (dark field) and electron diffraction pattern from pyroxene grain, showing exsolution on (001) of two monoclinic pyroxenes, dislocations, and subgrain boundary. Streaking between pairs of spots indicates disorder at lamellar boundaries, and streaking parallel to a^* indicates stacking disorder on (100).

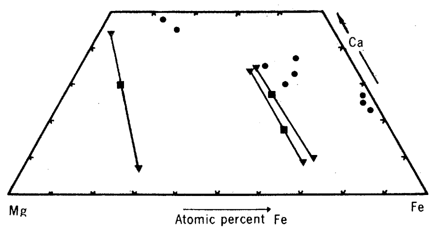

Fig. 2. The pyroxene quadrilateral. Circles, electron-probe analysis from a single grain; triangles, unmixed pairs of pyroxenes determined by single-crystal x-ray diffraction; squares, estimated bulk composition of pairs.

tion gave a glass with a refractive index 1.550 ($\pm$0.001) corresponding to An_{74} (*5*). Electron-probe analyses suggested a range from An_{72} to An_{89} within single grains.

The ilmenite in this rock is relatively free of shock lamellae and has a low density of dislocations and stacking faults. Twinning lamellae are rare, and there is no sign of compositional zoning or inhomogeneities within grains. The TiO_2:FeO ratio is 60:40, but small variations from grain to grain are observed. X-ray powder diffraction from an ilmenite separate gave cell parameters a_{hex} = 5.08, c_{hex} = 14.06 $\pm$ 0.01 Å.

Troilite is the second most abundant opaque phase ($\sim$0.1 percent). It usually contains minute blebs of native iron. Electron-probe analyses show the blebs to be virtually free of Ni and Co, in contrast to the iron spherules in the glassy breccia and to meteoritic iron.

Minor amounts of ulvöspinel (<0.01 percent) occur in association with ilmenite and native iron. Textural evidence suggests that spinel may have formed after ilmenite (a postcrystallization "thermal event"). This possibility is further supported by the occasional occurrence of troilite on minute cracks and fissures.

A small amount of apatite in hexagonal prisms has been seen optically, and its presence has been confirmed by microprobe. Cristobalite (mean r. i. 1.487) with characteristic twinning and tile structure occurs in euhedral crystals and filling interstices, and the presence of acicular tridymite (mean r. i. 1.472) in parallel growth with pyroxene was confirmed by x-ray single-crystal diffraction. A few crystals of K-feldspar were identified optically and by microprobe.

The yellow mineral referred to in the Preliminary Examination Team report (*6*) has been observed, and its cell parameters are being determined. A small amount of purplish mineral with hexagonal habit and a dark brown mineral have also been seen, but the minerals have not been identified.

X-ray fluorescence analysis of 0.5 g of rock 10044 gave the following concentrations: Nb, 41 ppm; Zr, 465 ppm; Y, 215 ppm; Sr, 250 ppm; and Cr, 1180 ppm. Semiquantitative analyses showed that the chromium is present in approximately equal amounts in the light pyroxene fraction and the ore fraction, with lesser amounts in the dense pyroxene fraction.

We also made trace element determinations on 0.5-g samples of rocks 10045 and 10060, which gave Nb, 28 and 38 ppm; Zr, 300 and 565 ppm; Y, 190 and 170 ppm; Sr, 185 and 225 ppm; and Cr 3010 and 2165 ppm.

The lobate embayed textures of the ilmenites and the arrangement of the plagioclase and pyroxene within the lobes suggest that ilmenite was the first phase to begin to crystallize. It was probably soon followed by pyroxene, which shows clear centers to the crystals but plagioclase enclosed in the outer parts. Tridymite is involved in intergrowths with pyroxene and plagioclase and in at least one case with K-feldspar, so it probably crystallized fairly late.

The compositions and mutual relation of the opaque minerals can be used to put limits on fS_2 and fO_2.

For the general evolution of moon rocks we would conjecture that, since lunar gravity and thermal gradient are both low, there has been no crust-mantle recycling. Low-melting silicates may have formed an original crust later to be partially covered by the basic rocks now reported. These may have originated in a deep magma chamber floored by phases in the system Ni-Fe-S.

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References and Notes

1. A. El Goresy, in *Shock Metamorphism of Natural Materials,* B. M. French and N. M. Short, Eds. (Mono, Baltimore, 1968), pp. 531-53.
2. M. G. Brown and P. Gay, *Am. Mineral.* **44**, 592–602 (1959).
3. G. M. Brown, *ibid.*, **45**, 15-38 (1960).
4. K. Viswanathan, *ibid.* **51**, 429–42 (1966).
5. J. R. Smith, *Carnegie Inst. Wash. Yearbook* No. 56 (1957), p. 216.
6. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
7. We thank the Department of Mineralogy and Petrology, University of Cambridge, for mineral separates and loan of a spindle stage, D. L. Hamilton for melting the plagioclases, and J. E. Chisholm for help with x-ray work.

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Mineralogy and Deformation in Some Lunar Samples

Abstract. *Observations on the mineralogy and deformation in samples of crystalline rocks, breccias, and fines from Tranquillity Base provide evidence for magmatic and impact processes. Overall homogeneity, igneous textures, and absence of xenoliths in the crystalline rocks indicate derivation from a common titanium-rich magma by internal, anorogenic volcanism rather than by impact. Crystallization conditions allowed strong compositional variation in pyroxenes, olivine, and plagioclase and the growth of a new mineral, the iron analog of pyroxmangite. Subsequently, impact produced breccias containing shock-deformed crystals and glasses of varying compositions.*

The preliminary examination (*1*) has shown that the Tranquillity Base rocks have undergone igneous and deformational processes in many ways comparable with terrestrial and meteoritic phenomena. The major minerals can be assigned to known rock-forming mineral groups, but their compositional variation, association, and textures demonstrate relationships which complement and extend petrological experience gained from investigations of terrestrial basic rocks and meteorites and from synthetic studies. To this end we have examined four crystalline rocks, seven breccias, and a sample of fines (*2*) by optical, x-ray, and electron microprobe methods.

The major minerals of the crystalline rocks and lithic fragments are, in common order of abundance, clinopyroxene, plagioclase, and ilmenite. Slight differences in mineral proportions between most rocks indicate a general crystal fractionation process, which in a few cases has led to essentially bimineralic plagioclase-ilmenite, clinopyroxene-ilmenite, and plagioclase-pyroxene rocks. In general, strong compositional zoning and grain-to-grain