The only objects that could possibly correspond to magnetite are small opaque spheres of steel-gray shine and with reticulated surface. Diameters do not exceed 1 or 2 μm. Their concentration, measured in the total powder and in the concentrates, is less than 1×10^{-6}.

Ilmenite has been found everywhere with a series of habits and dimensions in broken pieces of crystalline rocks. Some fragments have their ilmenites strongly cataclazed and twinned, whereas others show no shock effects at all. The only other oxides found are rutile, chromite, and pseudobrookite (?), all associated with ilmenite.

One of the most frequent varieties of glass is that with spherical inclusions of iron-nickel, twinned ilmenite, bubbles, and flow structures. The ilmenite crystals have their usual fracture form, but with a little rounding of the sharp edges. They have therefore not been completely melted, as opposed to iron and glass (*7*).

Minerals from conglomeratic fragments are made up of all the minerals, rock fragments, and spheres in the fines. The ilmenites are often twinned.

About 50 oxide grains from rock 10072,31 and about 100 from the fines 10084,96 were analyzed by electron microprobe for Fe, Ti, Mg, Cr, and Mn. We did not find any mineral that had Fe as a major element, and that had less Ti than ilmenite. Two high Ti minerals have been found associated with ilmenite: rutile and a gray mineral similar to pseudobrookite (*7*). A few percent of Mg and traces of Mn are generally present in the ilmenites. These elements do not vary very much in relation to habits.

Under the scanning electron microscope the vuggy rock 10072,31 shows black opaque minerals of two basic forms: hexagonal platelets and octahedra. As both are undoubtedly ilmenite, the last pseudo-form can immediately be interpreted as a combination of a trigonal rhombohedron $(10\bar{1}1)$ (?) with the basis (0001) (*8*). Etch pits are absent from both habits, but pseudo-octahedra show a strong tendency to grow as skeletons.

A powder diagram of a pseudo-octahedra group gave all the ilmenite lines and no others (*9*), which confirms the homogeneity observed under the photonic microscope. X-ray diffraction patterns obtained from the heavy fraction showed ilmenite to be the sole constituent.

Concerning the absence of magnetite in crystalline rocks, it has been shown that high concentrations of Ti and low oxygen pressures prevent the separation of a magnetite phase (*10*).

It is difficult at this time to interpret the negative results in relation to the specific problems of carbonaceous meteorites. If the absence of magnetite is confirmed in other indigenous materials, the interpretation of later magnetite finds in the lunar fines from other sites will be made easier.

The total absence in the fines of magnetite crystals typical of carbonaceous meteorites confirms the uniqueness of these materials and suggests that one or more very selective phenomena are active. Several hypotheses may be considered. (i) Indigenous lunar rocks of composition similar to type 1 carbonaceous meteorites are absent from the sampling site. The preservation of ilmenite included in rocks, glass, and conglomerates shows that if such magnetite-bearing rocks had ever existed, this mineral could have withstood impacts at both low and high velocities. (ii) Meteorites of type 1 impinging on the moon with cosmic velocities are completely volatilized. But one may point out that the occurrence of just slightly rounded ilmenite in vesicular glass (see above) and of almost undisturbed magnetites in basalts which have undergone nuclear shocks (*11*) testifies to a good preservation of meteoritic magnetites. (iii) Carbonaceous meteorites of type 1 are rare objects in the solar system. Mixed with very high quantities of indigenous material, the typical crystals could not be found in the fines, even after being concentrated 30 times.

The absence of magnetites of typical habits, and of magnetite in general, shows that Orgueil-like materials are probably not common rocks on the moon's surface. This result gives us a comparison term for the study of other sampling sites, where the specific phenomena responsible for the appearance of Orgueil-like materials could have occurred, such as falls of comets or cosmic dust-balls.

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Quantitative Optical and Electron-Probe Studies of the Opaque Phases

Abstract. *Ilmenite, chrome-titanium spinel, ulvöspinel, troilite, native iron, iron-nickel alloy, and native copper are present. In addition mackinawite is provisionally identified. Three additional opaque phases are present but not identified. Modal analysis indicates that the breccia is enriched in iron relative to ilmenite and troilite, and the high nickel content of this iron suggests that it is largely of meteoritic origin. The bulk composition of liquids corresponding to iron/troilite droplets in the rocks indicates an oxygen fugacity no greater than $10^{-15.5}$ and a sulfur fugacity of 10^{-6} bar. Complete melting of rocks produced a glass containing complex iron/troilite globules and skeletal ilmenites.*

Optical and electron-probe studies of opaque phases in samples 45.35.5, 48. 42, 58.23, 72.46, 84.5, and 85.4 indicate the presence of ilmenite, chrome-titanium spinel, ulvospinel, troilite, native iron, iron-nickel alloy, and native copper. In addition mackinawite is tentatively identified. Two phases, one with very low reflectance, the other with higher reflectance, form fine lamellas in

Table 1. Modal analyses.

Rock type and number	Ilmenite	Troilite	Iron
A (45.35.5)	9.66	0.132	0.028
A (72.46)	12.8	0.210	0.013
B (58.23)	14.2	0.066	0.027
C (48.42)	3.03	0.026	0.022*

* This includes iron-nickel alloy.

ilmenite. These have not yet been identified. A fine flamelike exsolution in troilite is not yet identified.

Ilmenite in rocks of type A (basaltic, specimens 45.35.5 and 72.46) exhibits two modes. The first mode comprises randomly oriented needles up to 1 mm long. They are enclosed within pyroxene crystals but occasionally show slightly indented margins against randomly oriented feldspar laths. The second mode comprises subangular grains molded on feldspar laths but intergrown with pyroxene and represents the major amount of ilmenite in the rock. Small amounts of chrome-titanium spinel are associated with this ilmenite mode. Ilmenite in sample 45.35.5 carries a fine-grained lamellar exsolution parallel to [10$\bar{1}$1] of a brighter, whiter anisotropic phase. This exsolution is sometimes accompanied by a second phase comprising a very dark, finer lamellar phase parallel to [0001]. The brighter phase may occur alone in ilmenite, but the darker exsolution is always associated with the brighter phase and never occurs alone. Textural relationships of these exsolution phases suggest that they developed simultaneously. Well-defined occasional cracks are present in the ilmenites and in the rock as a whole and slightly offset the brighter exsolution lamellas. A hairline crack in ilmenite carries a bright phase which is considered to be troilite. This development is also noted in sample 72.46, where the crosscutting bright phase runs out along the crack a small way into the surrounding silicates.

Ilmenite in rocks of type B (doleritic, specimen 58.23) consists mainly of coarsely crystalline, near-rectangular crystals up to 1 mm long partially molded on feldspar and intergrown with pyroxene. Ilmenite also occurs rarely intergrown with ulvöspinel in fine-grained, late-stage euhedral crystals embedded in pyroxene. These crystals have textural features characteristic of subsolidus unmixing and have a core of what in polished section appears to be a graphic intergrowth of feldspar and pyroxene. Although these textures appear to be of a subsolidus nature, substantial oxidation would be required for their formation. It is likely therefore that the simultaneous crystallization of the cubic and rhombohedral phases has taken place. These complex crystals are associated with troilite and are surrounded by a well-defined reaction rim in the enclosing pyroxene which appears generally lighter in polished section than the main mass of pyroxene. The ilmenites in the above mentioned rock types are generally untwinned although occasional needlelike twins are observed.

In breccia specimen 48.42 ilmenite occurs as single relict grains or enclosed within rock fragments. The coarse fines, sample 85.4.16, contain chips of rocks of the two primary igneous varieties having ilmenite textures similar to those described above. One fragment of type A rock lacks the second mode of subangular crystals described above; in this case the first mode of acicular crystals is very well developed. Another fragment of type A rocks shows a fine-grained equigranular texture with subangular ilmenites.

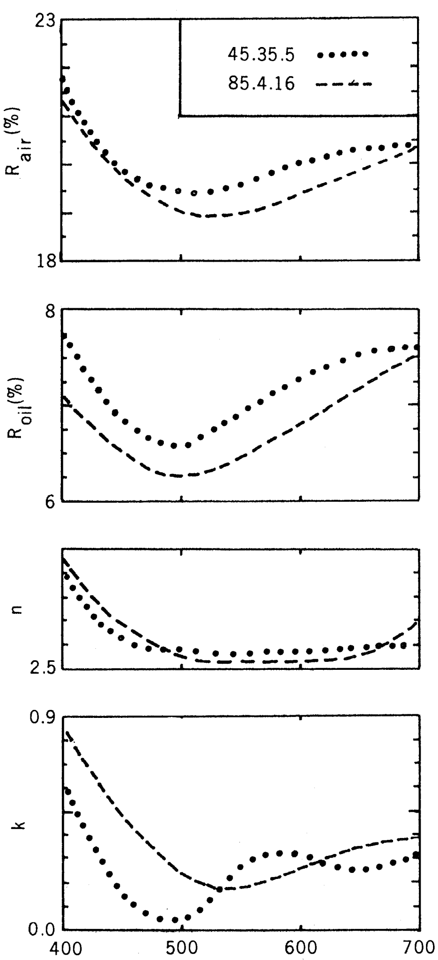

Fig. 1. The reflectance, *R*, in air and oil, refractive index, *n*, and absorption coefficient, *k*, in the visible spectrum for the ordinary vibration direction of ilmenite from samples 45.35.5 and 85.4.16. The immersion oil used is Cargille type "A" at 22.5°C.

Table 2. Analyses of metals and alloys. Sample 10045·35 is a type A rock in which iron occurs intergrown with troilite. Sample 10048·42 is a breccia; in this rock iron with a high nickel content occurs alone and may have a meteoritic origin, whereas the iron with high cobalt content is associated with troilite and is more likely to be derived from the igneous rock types.

Metal	Sample			
	10045·35	10045·35	10048·42	10048·42
Fe	99.19	99.50	89.10	98.12
Co	0.65	0.50	0.58	1.23
Ni	0.00	0.00	10.32	0.64
Total	99.84	100.00	100.00	99.99

In a glassy fragment from coarse fines, sample 85.4.14, ilmenite occurs as skeletal crystals; troilite and native iron are the only other crystalline phases in this glass. One rock fragment from coarse fines, sample 85.4.16, carries an ilmenite grain with multiple curved twin lamellas which coincide with actual displacements in the grain. This ilmenite crystal is on the margin of the rock fragment. Other ilmenites within the fragment appear normal, but optical studies (Fig. 1) of one of these crystals indicate that they too may be affected by shock metamorphism. Oxide distribution in the fine fines, sample 84.5, is very similar to that in the breccia described above.

Troilite is present as an accessory phase in all the different types of material. It is usually observed intergrown with native iron. In the case of one relatively large droplet in sample 72.46, the iron has migrated to form a continuous rim on one side of the sulfide droplet. An unidentified flamelike exsolution of possible pentlandite is observed within troilite at the contact with iron. In the same rock another relatively large troilite droplet devoid of iron has a rim of spinel where the troilite is molded on an early ilmenite lath. In general, in this rock the troilite occurs intergrown with hexagonal grains of iron which together form ragged patches enclosed within silicates or alternatively have smooth contacts molded on ilmenite. Composite iron/troilite ovoid droplets occur enclosed within ilmenite. Where this occurs calculations indicate that the composition of the liquid from which the droplet crystallized contained 68 percent Fe, which corresponds closely to the composition of the eutectic at 988°C in the system Fe-S at 1 bar (*1*). The oxygen fugacity for a liquid of this composition would be less than $10^{-15.5}$ and the sulfur fugacity would be 10^{-6} at 1050°C (*2*). However, the absence of iron and the presence of spinel in association with troilite in the large droplet described above indicate local variation in the oxygen and sulfur fugacities of the sulfide liquid. The oxygen and sulfur fugacities at 1050°C for magnetite, pyrrhotite and liquid are $10^{-10.04}$ and 1 bar respectively (*2*). The smaller of the sulfide liquid droplets are more likely to be buffered by the host silicate magma. The fine-grained iron/troilite droplets therefore probably indicate the very low fugacities of oxygen and sulfur for the silicate magma.

In sample 45.35.5 native copper occurs in association with troilite and iron as a small segregation in troilite at a troilite/ilmenite contact. This is further evidence of the low oxygen and sulfur fugacities since the native copper appears to have crystallized as a primary phase.

In sample 72.46 the ragged boundaries of the troilite/iron composite droplets enclosed within silicates contrast strongly with the smooth contacts against ilmenite. A fine-grained disseminated bright phase in silicates bordering troilite globules may represent an iron residuum from the breakdown of troilite. This sulfur loss may be related to the process responsible for natural cracks in the rock. In one case iron has migrated along a crack and cut a composite iron/troilite droplet enclosed within ilmenite. In another case possible troilite is present in a crack crosscutting ilmenite. These features may best be explained by a metamorphic event which resulted in loss of sulphur after the rock had solidified and which occurred while it was hot.

In the glasses of sample 85.4.14, grain 12, troilite and iron occur intergrown in spherical globules (*3*). The variety of textures observed may be accounted for by the phase relations in system Fe-S below 1600°C (*1*). Liquids range in composition from pure iron to troilite. This implies (*1*) temperatures over 1535°C at one atmosphere for the iron sulfide liquids in this sample. In general the smaller the globule the greater the probability that it consists entirely of iron. A diffusion of very fine globules showing a flow pattern occurs in glass in sizes down to the resolution limit of the microscope. Each iron/sulfide globule tends to act as a complete system not in equilibrium with adjoining globules from which it may differ radically in bulk composition. Iron globules give evidence of shearing in glass where iron forms infilling in a zone of dilation, thereby indicating that some glass suffered mechanical deformation shortly after solidifying. A strongly anisotropic phase is noted forming fine spots and bands within troilite in a troilite/iron globule in a chondrule-like body from sample 85.4.14, grain 7. This phase is tentatively identified as mackinawite.

Modal analyses for the principal opaque phases in rocks are given in Table 1. The primary igneous rocks (types A and B) have comparable amounts of ilmenite, troilite, and iron, whereas the breccia (type C) exhibits depletion of ilmenite and troilite relative to the primary igneous rocks. Iron modes for the breccia are comparable with those of primary igneous rocks. However, the presence of nickel in amounts ranging from 0.6 precent up to 10.3 percent in the iron in the breccia suggests that this iron has a diverse origin.

The low modal amounts of ilmenite and troilite in breccia relative to primary rock types suggest that ilmenite and troilite of the primary igneous rocks are destroyed in the glass-forming process. The presence of skeletal ilmenite crystals and composite iron/troilite globules in glass from coarse fines, sample 85.4, supports this conclusion. The glass-forming process may also involve some loss of sulfur. Ilmenite, troilite, and iron are unlikely to be preferentially preserved or destroyed in this process. However, material of iron or iron-nickel composition is enriched relative to ilmenite and troilite in the breccia by a factor of 4 as compared with the abundance of iron in the primary igneous rocks. It would appear, therefore, that approximately 75 percent of the iron or iron-nickel alloy in the breccia could have a meteoritic origin.

Reflectance measurements (*4*) in air and oil have been made on selected ilmenites to determine the reflectance, R, absorption coefficient, k, and refractive index, n, in the wavelength range 400 to 700 nm (Fig. 1). The shocked ilmenite described above in sample 85.4.16 exhibits simple absorption of the ordinary ray, whereas the unshocked ilmenite from sample 45.35,5 displays a curve with a maximum at about 590 nm, which may be indicative of more complex bonding.

The following phases were analyzed by electron probe: ilmenite, chrome-titanium spinel, ulvöspinel, native iron, native copper, iron-nickel alloys and troilite. All data are corrected by computer programs written by Aucott (*5*). The nickel content of iron in breccia varies between 0.6 and 10.3 percent, whereas nickel is low, or lacking, in iron in the igneous rocks. Cobalt is often present up to 0.65 percent in these cases. Table 2 presents analyses for some phases. Ilmenites in all rock types are unzoned and carry appreciable but variable amounts of Mg, Al, Si, Ca, Cr, and Mn.

Primary igneous rocks studied have a simple mineralogy as far as opaque minerals are concerned. The opaque mineral assemblages have crystallized under conditions of very low oxygen and sulfur fugacities. Similar opaque mineral assemblages are present in glasses, but in this case equilibrium has not been established. Optical data indicate that ilmenites in the fines are affected by shock metamorphism. The fines contain some metal of meteoritic origin.

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Lunar Troilite: Crystallography

Abstract. *Fine, euhedral crystals of troilite from lunar sample 10050 show a hexagonal habit consistent with the high-temperature NiAs-type structure. Complete three-dimensional counter intensity data have been measured and used to confirm and refine Bertaut's proposed low-temperature crystal structure.*

The rare mineral troilite is formed under strongly reducing conditions and has previously been found in nature only in serpentinized rocks and meteorites. Troilite was early recognized as a very minor but generally occurring constituent of the material returned by Apollo 11 from the Sea of Tranquillity.