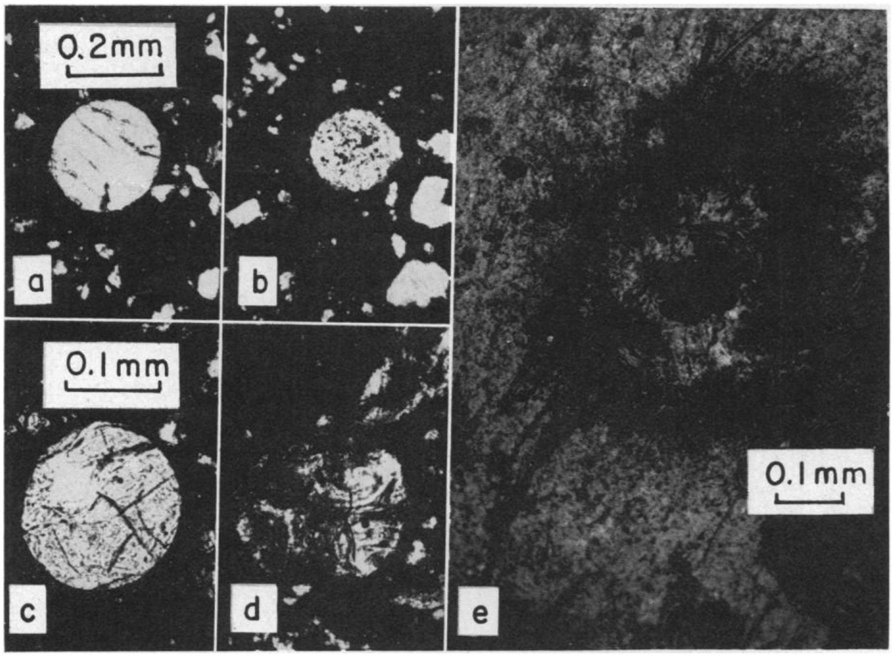

Fig. 3. (a) Homogeneous glass spherule, yellow to slightly greenish-yellow, fractured, holohyaline with no mineral inclusions or devitrification (10065). (b) Slightly irregular orange glass spherule with abundant mineral inclusions (10065), scale same as in (a). (c) Yellowish-brown glass spherule with 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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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.

4 January 1970

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 examined in the present study. The mineralogical compositions are similar in all three; 10050 and 10072 contain predominantly pyroxene, calcic plagioclase, and ilmenite with minor amounts of cristobalite; 10062 has the same major minerals, but instead of cristobalite contains a minor amount of olivine. Each of the rocks contains in addition small amounts of both pyrrhotite (variety troilite, FeS) and native iron. It is with the petrological significance of these last two phases that this paper is concerned.

X-ray powder diffraction of a fragment of pyrrhotite from rock 10050 yielded a pattern identical with that of troilite from Del Norte County, California (*2*). Electron-microprobe analyses of pyrrhotites in both 10050 and 10072, using carefully prepared synthetic FeS as a standard, gave an identical composition of FeS. The pyrrhotite has the ideally stoichiometric composition FeS and is therefore the variety troilite. A search for other minor elements such as Cu, Ni, Co, and Mn did not reveal any above the detection limits of approximately 0.1 percent.

Metallic iron was identified as a phase by optical examination on polished surfaces, by x-ray powder diffraction, and by microprobe analysis. The iron in rocks 10050 and 10072 contains detectable amounts of both Co and Ni in solid solution, with Co more abundant than Ni. Lacking reliable analysis standards, it is possible only to specify that the Co content is approximately 1 percent.

The polished surfaces available for textural examination differed considerably. A 1-in.^{2} (6.45-cm^2) polished section of 10072 was available, whereas for 10062 and 10050 only 0.25- and 0.15-in.^{2} surfaces, respectively, were examined.

Troilite is present in the vesicles of rock 10072, where it occurs as rare euhedral to subhedral crystals. The vesicular troilites overgrow minerals of the rock matrix forming the vesicle walls and clearly formed later than the body of the rock. They presumably involve vapor-phase movement into the vesicles.

Within the matrix of the rocks, the troilite is never euhedral and does not occur as individual grains but is invariably intergrown with iron. Where apparently separate grains of either iron or troilite were observed, further grinding and polishing showed them to be the partly exposed projections of larger two-phase intergrowths. Iron is always the minor phase of the two, and is present in rounded to subrounded grains scattered through the troilite. Some grains have 4- or 6-sided shapes suggestive of sections through single crystals (see Fig. 1A). Although it is not clear whether or not all the iron grains in a given intergrowth have a single orientation, it was observed that the troilites were monocrystalline aggregates that extinguished as a single unit under crossed nicols.

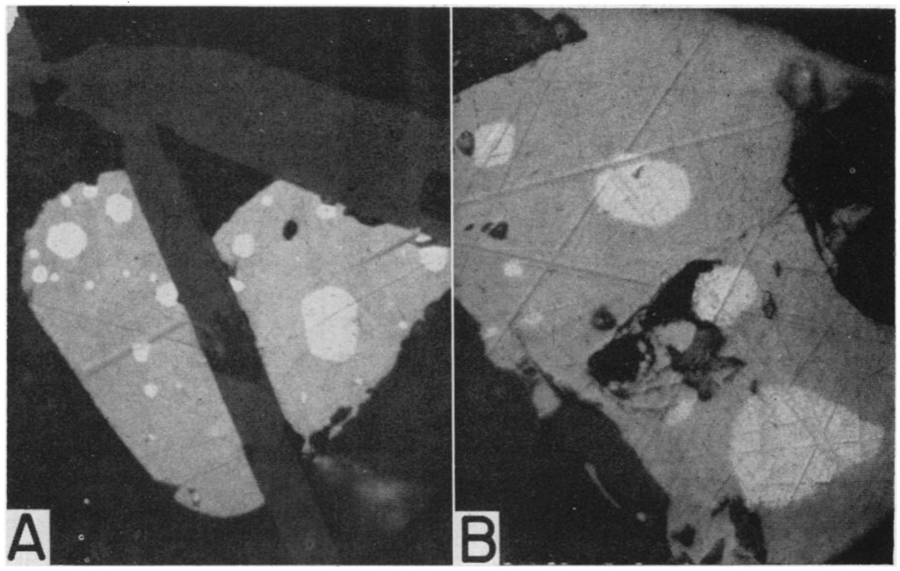

Fig. 1. (A) Rock 10072. Intergrowth of troilite (light gray) and iron (white) enclosing a branching arm of a skeletal ilmenite crystal (dark gray). Notice the rough, six-sided shapes of some iron grains. The troilite is a mono crystal. Width of field of view, 0.01 mm. (B) Rock 10050. Intergrowth of troilite and iron. Lines are scratches remaining from polishing. Width of field of view, 0.02 mm.

The troilite-and-iron intergrowths were apparently one of the last features to form in the rocks. They often enclose the branching limbs of the skeletal crystals of ilmenite (Fig. 1A) or are intergrown with bladed pyroxene crystals (in 10072) in such a way as to suggest formation after the pyroxene had grown. Though such textural criteria are rarely unambiguous, the troilite-and-iron intergrowths give every indication of having crystallized late in the cooling and crystallization of the silicate magma.

Visual examination of the polished surfaces suggests a constant composition for the intergrowths. Because the intergrowths rarely exceed 200 μm in diameter, it was not possible to analyze the volumetric content of iron directly. The polished surfaces of individual grains were therefore photographed and the exposed areas of iron and troilite were measured planimetrically. In the absence of specific evidence of the third dimension, it was assumed that the surface measurements yielded a reasonable estimate of the volume percentages. For rock 10072, 24 intergrowths were measured, and for 10062, 11. The observed range in 10072 is 3.3 to 14.6 percent iron by volume; in 10062 from 4.4 to 13.3 percent iron by volume. The average of 24 measurements in 10072 is 8.4 percent iron by volume with a standard deviation of 2.3 percent, and the average of 11 measurements in 10062 is 8.3 percent with a standard deviation of 3.3 percent. If iron contents are grouped in 2 percent brackets and their frequency is plotted (Fig. 2), a narrow distribution pattern emerges for 10072. The distribution of values from 10062 does not show a clear pattern, but one might hardly be expected on the basis of 11 measurements.

Too few intergrowths were measured in rock 10050 to yield either a meaningful average composition or a meaningful distribution. It is clear from a visual examination, however, that the iron content differs little from those in 10062 and 10072 (see Fig. 1B).

The ubiquitous intergrowth of troilite and iron in a constant ratio precludes the possibility of their having co-crystallized from the magma, or of the iron's having been formed by post-magmatic desulfuration of pyrrhotite grains. Loss of sulfur would lead to a concentration of iron grains along the rims of the troilite grains and would probably give inhomogeneous intergrowth compositions. Had the troilite and iron grown

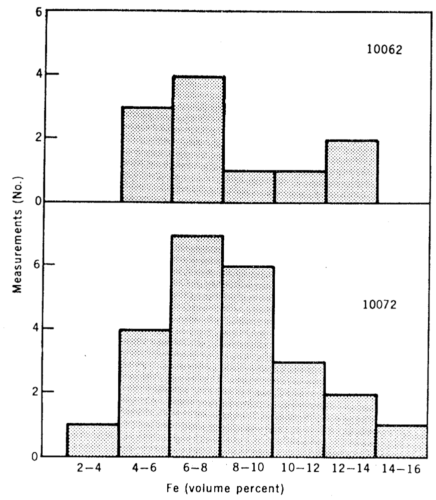

Fig. 2. Frequency distribution of measured iron contents for troilite-and-iron intergrowths in rocks 10062 (top) and 10072 (bottom).

as separate crystalline phases from the magma, we should expect to sometimes find them as independent phases—or if as intergrowths because of unknown nucleation effects, to observe a wider spread in intergrowth compositions.

The constant intergrowth composition clearly suggests the breakdown of an initial homogeneous phase. Despite extensive work in the system Fe-S (*3*), no solid phases have ever been found between FeS and Fe, nor does troilite or iron reach the intergrowth composition by solid solution. The homogeneous parent phase must therefore have been an iron sulfide liquid which separated immiscibly from the silicate magma.

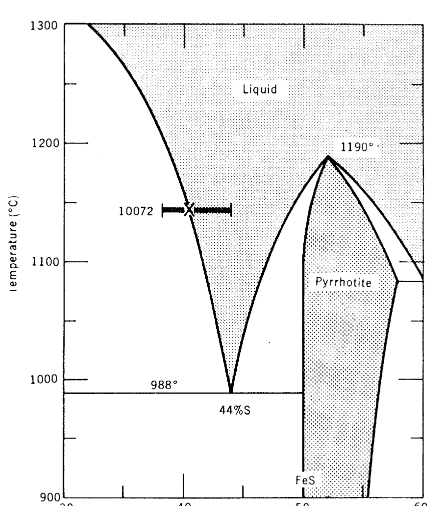

Fig. 3. Portion of the phase diagram for Fe-S after Hansen and Anderko (*3*). The composition of the troilite-and-iron intergrowth in 10072 (X) falls at 1140°C on the liquidus. The bar graph shows the standard deviation of measurement of the intergrowth.

If volumes are converted to weights on the basis of a density of 7.87 g/cm^3 for iron and 4.79 g/cm^3 for troilite, the minimum temperature at which the intergrowth composition could be a homogeneous liquid is 1140°C (Fig. 3). The first solid to separate below 1140°C would be iron, in agreement with the observation that some of the iron grains have crystal outlines.

The density of a sulfide liquid with the composition of the intergrowth would be approximately 5 g/cm^3. The density of a silicate magma with the bulk composition of rocks 10062 or 10072 would not have exceeded 3.5 g/cm^3. The immiscible sulfide liquid should therefore have separated gravitatively. That it did not do so, but instead remained evenly dispersed through the rock, means either that the magma was so rapidly quenched there was insufficient time for settling or that the sulfide liquid did not separate until the magma was already sufficiently crystallized to prevent settling. Rapid quenching is probable for the fine-grained vesicular rocks, 10062 and 10072, but not for the coarser-grained type B rock, 10050. The second circumstance must therefore be the applicable one. This is in accord with the previously mentioned textural evidence, that the troilite-and-iron intergrowths formed late in the crystallization history, after ilmenite and pyroxene had started crystallizing. Most of the crystallization relations of magmas with the composition of Tranquillity Base rocks must therefore be above 1140°C.

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Morphology and Related Chemistry of Small Lunar Particles from Tranquillity Base

Abstract. *Glass spherules show multiple high-velocity impact craters and are coated with small particles including glass, plagioclase, clinopyroxene, ilmenite, olivine, chromite, rock fragments, and frozen droplets of iron, nickel-iron, and troilite. These spherules passed through an impact cloud of hot fragmental material, condensing iron-rich vapor and high-velocity projectiles. Breccia contains concentric, accretionary lapilli units and appears to be a sintered deposit from a hot lunar base surge generated by impact.*

Lunar fines and breccias were examined by optical microscope, scanning electron microscope with nondispersive x-ray detector, and electron microprobe. Prior to this detailed examination all chip-sized (4 to 10 mm) material from the bulk fines was examined in order to determine rock types and their relative proportions prior to distribution to the principal investigators. Of 122.3 g of chips, 35.2 percent are breccia, 36.4 percent are fine-grained crystalline rock, 15.4 percent are medium coarse-grained crystalline rock, 0.8 percent are anorthosite, and 12.2 percent are glass and glass-coated rock. The amount of actual glass is estimated to be about 6 percent. Crystalline rock fragments therefore constitute about 60 percent of the nonglass fragments, and breccia constitutes the remaining 40 percent. Because of the large number of chips and the lack of apparent sampling bias, we consider this to be a relatively unbiased estimate of the overall proportion of these two rock types at the Tranquillity Base site.

Our examination of the fines and breccia confirmed the general description provided by the Preliminary Examination Team (*1*). The majority of the fines result from mechanical disaggregation and from the production of glass by meteorite impact. The composition of the fines is generally similar to that of the breccia and will be discussed in detail in a later paper.

Small glass spherules, which occur in the fines and breccia, provide a record of some of the processes associated with lunar surface impact. Many of the spherules are dark, nearly opaque glass and are covered with smaller particles. A typical spherule of this type is shown in Fig. 1A (insert). This spherule is a titanium- and iron-rich glass and is covered with several different types of material. The microstratigraphy of the spherule indicates a history of melting,