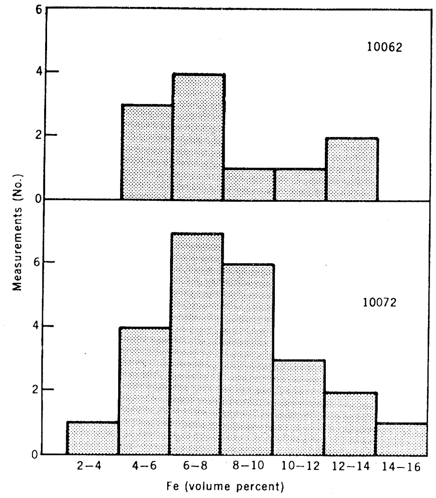

Fig. 2. Frequency distribution of measured iron contents for troilite-and-iron intergrowths in rocks 10062 (top) and 10072 (bottom).

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.

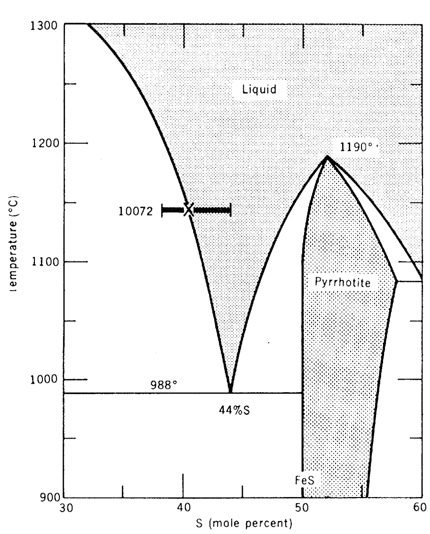

Fig. 3. Portion of the phase diagram for Fe-S after Hansen and Anderko (*3*). The composition of the troilite-and-iron intergrowth in 10072 (X) falls at 1140°C on the liquidus. The bar graph shows the standard deviation of measurement of the intergrowth.

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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4 January 1970

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, capture, and accumulation. The innermost material on the glassy skin of the spherule is a partial coating of micrometer- and submicrometer-sized frozen droplets of iron, nickel-iron, and troilite. The nickel-iron droplets (Fig. 1, A and C) contain 5 to 6 percent nickel. Most droplets contain detectable amounts of nickel but a few contain less than the limit of detection for our nondispersive x-ray system, which is about 2 percent for nickel in iron. The droplets range in size from about 0.05 to about 30 μm. The average size is about 1 μm. In one region on the spherule the droplets are so numerous that they form a coating over the glass skin. Smooth indentations made in the glass by the droplets indicate that the glass was still molten or soft during the capture of the droplets. The glass was also vesiculating during this period, and many vesicle openings ranging from 0.1 to 10 μm in diameter were preserved as the glass cooled. Troilite droplets are relatively rare and are mixed with nickel-iron droplets. Figure 1B is a mixture in which the troilite forms a partial coating over and a matrix between a complex of nickel-iron droplets. There is apparently no mixing between the two phases.

After the deposition of the droplets had occurred on the large spherule, many small chips of glass and mineral fragments were also captured. Some of this captured material was partially imbedded in the molten glass as shown by the ilmenite grain (Fig.1C). The lower left portion of the grain is completely covered with glass. The contact between the glass and ilmenite clearly shows that the impact of the ilmenite caused some of the molten silicate to splash out. Hundreds of tiny (0.1 μm) glass spherules sprayed out by the impact can be seen on the ilmenite.

Figure 1A shows a glass spherule about 20 μm in diameter which is necking out from the larger spherule as a rebound from an impact of a particle into this molten spherule. Also visible in this picture are numerous partly coalesced nickel-iron droplets.

As this large glass spherule cooled, it continued to capture a variety of material which became partly imbedded in the surface. These particles were welded to the glass spherule and to each other and could not be removed by ultrasonic cleaning. Glass fragments predominate, but grains of plagioclase, clinopyroxene, olivine, and chromite were also identified. Many captured glass spherules show a capture and accumulation sequence on their own surfaces. Some of

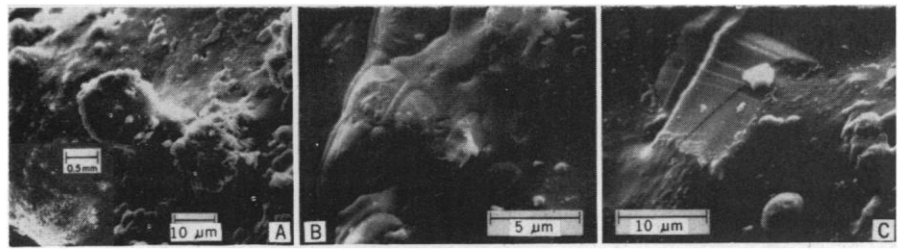

Fig. 1. Scanning electron microscope photographs of coated glass spherule. (A) (insert) Overall view; (A) nickel-iron droplets (right) and large glass splash droplet (center); (B) troilite coating and matrix surrounding nickel-iron droplets; (C) partly buried ilmenite grain, tiny glass splash droplets (on ilmenite), and larger nickel-iron droplets (bottom).

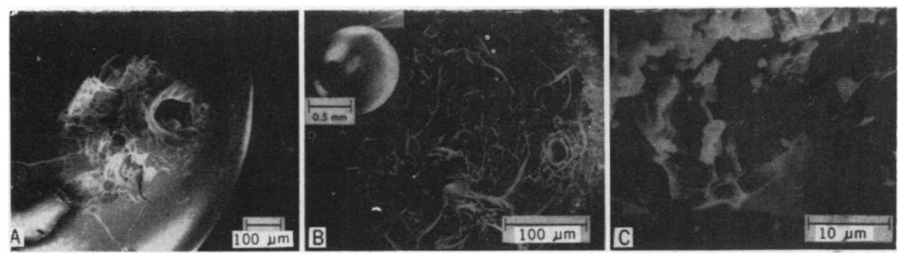

Fig. 2. Scanning electron microscope photographs. (A) Detail of hypervelocity impact crater; (B) (insert) overall view of pitted spherule; (B) detail of spalled zone showing cone of percussion (lower center) and subsequent small hypervelocity impact (right); (C) broken vesicle surface in glass fragment coated with potassium-rich material, possibly vapor condensate.

the large fragments on the surface of the spherule consist of microbreccia and contain a wide variety of particles which were accumulated and partly welded together before the fragment was captured by the large spherule. The material forming these microbreccia fragments has a softened or sintered appearance.

The microstratigraphy, as preserved on this and many similar spherules, indicates that they passed in a molten state through an impact plume or cloud and encountered and captured a wide assortment of ejecta material during that passage. The part of the cloud encountered first contained molten nickel-iron, iron, and troilite droplets having a mean diameter on the order of 1 μm. Some of the iron droplets may represent a condensation aerosol from an iron-rich vapor generated by the impact of an iron meteorite. Similar droplets are found in terrestrial impact-produced glass (*2*).

Another type of glass spherule is characterized by a surface relatively free from captured material. This surface typically shows small impact craters which reflect a wide range of impact velocities up to and including hypervelocity. Figure 2, A and B, shows a variety of features associated with this type of glass spherule. Figure 2A shows a hypervelocity impact which has melted a central region and radially and concentrically fractured a larger region. The impact vented into a vesicle beneath the surface and displaced a large segment of glass outward. Circular structures in the fracture zone are vesicles exposed by the spallation of the spherule skin. Figure 2B is an overall view (insert) and a closeup of another glass spherule showing a large circular spalled area resulting from impact. A small cone of percussion is visible in the lower part of the picture. At some later time a hypervelocity impact occurred and melted a small crater near the edge of the larger crater. Other craters ranging from those caused by multiple hypervelocity impact to those caused by simple lower velocity impact are present on this spherule.

These and similar spherules indicate an environment of numerous high-velocity particles. It is possible, although it does not seem likely, that these spherules remained exposed directly at the lunar surface long enough to allow all of the impact craters to be formed by a random rain of micrometeoroids. Alternatively, it might be more likely that all of the impact pits on any one glass spherule were closely associated in time and were in fact part of the same major event. Gault *et al.* (*3*) have shown that the velocity of secondary material may exceed that of the primary impacting object. It is possible that the impact pits on a glass spherule are all caused by the secondary (or tertiary, or so on) projectiles from a single impact of a large meteorite on the lunar surface. These projectiles could be expected to exhibit a wide range of velocities including hypervelocities, and this is reflected in the variation in the types of pits. By inference some or all of the pits on lunar rocks also may result from impacts in one or more impact plumes, and therefore the relative densities of pits on rocks may not be a satisfactory indicator of length of exposure on the lunar surface.

Gradations between the completely covered and smooth spherules were also found. In several cases the two types were welded together, and both may have been formed in the same event. Nickel-iron droplets were found on both types of spherules.

A considerable variation existed in the composition of the glass particles in the fines and breccia. Some single glass spherules were homogeneous; others contained zones or flow bands of different compositions. This is not surprising in view of the number of different ways in which glass spherules were formed and the possible variations in temperatures and mixing. At least six mechanisms produce lunar spherules. These include (i) expansion and tearing apart of large masses of molten glass formed toward the center of major impacts, (ii) the breakup of impact-produced liquid jets into droplet trains, (iii) splash and rebound from objects hitting molten glass, (iv) drag of splattered glass over hard nonwetted surfaces, (v) condensation from a vapor, and (vi) vesiculation of impact-produced or volcanic magma. The production of glass spherules by vesiculation may be a major lunar mechanism and occurs when segments of broken bubble walls are pulled together by surface tension (*4*).

A typical homogeneous spherule in breccia 10068,32 contains 41.8 percent SiO_2, 14.7 percent Al_2O_3, 7.0 percent TiO_2, 12.2 percent CaO, 8.5 percent MgO, 14.0 percent FeO, 0.07 percent K_2O, and 0.17 percent Na_2O. This breccia contains two unusual glass fragments which are similar in texture and contain about 30 percent euhedral to subhedral mostly equant olivine crystals averaging 20 to 50 μm in diameter. The glass matrix contains 45.2 percent SiO_2, 15.5 percent Al_2O_3, 0.3 percent TiO_2, 9.9 percent CaO, 13.5 percent MgO, 13.6 percent FeO, 0.2 percent K_2O, and 1.4 percent Na_2O. The normally zoned olivine ranges from 85 to 92 (mean, 88) mole percent forsterite. The fragment may be a partly quenched glass resulting from the impact melting of pyroxene and plagioclase, or it may contain chondritic material.

A chrome titanium spinel of unusual composition was analyzed in a small fragment of crystalline rock in breccia 10068,32. This opaque phase contains 41.5 percent FeO (total iron), 24.5 percent TiO_2, 21.4 percent Cr_2O_3, 4.6 percent MgO, 6.5 percent Al_2O_3, and 0.3 percent SiO_2. Several small (15 to 30 μm) grains of this phase are present and are homogeneous at the scale of the electron beam (1 μm).

A slightly botryoidal coating (Fig. 2C) on the wall of a broken vesicle in a breccia glass fragment has a very high concentration of silica and contains about 5 percent K_2O. This coating may constitute a condensate from a silicate vapor formed when the glass was heated by impact. Condensed silicate vapor has been observed during volcanic eruptions (*5*), has been produced experimentally (*4, 5*), and has been produced in nuclear explosions (*6*). Material formed in this way may have complex and variable composition and morphology, and our search for such material in the lunar fines is continuing.

Fisher and Waters (*7*) have discussed the possible characteristics of lunar base surges. The lunar breccias show many features which could be explained if they were the deposit from a hot base surge produced from a large impact event. Turbulence in the base surge could build the observed accretionary rims (*8*) on nuclei of glass spheres and crystal fragments by rolling and tumbling action. Coarse layering in some of the breccias (*1*) corresponds to the bedding which is often characteristic of base surge deposits. After the flow had stopped, sintering of the finest glass fractions in the still hot deposit lithified the matrix which bonded the accretionary lapilli to each other. Partial devitrification of some glass fragments took place during cooling. Additional heat or thicker deposits could produce a more densely welded rock with a dense crystal-bearing glass as the final product in a sequence analogous to the formation of terrestrial welded ash flow tuffs. Sintering of lunar base surge deposits may proceed at temperatures which produce no sintering in the earth's atmosphere. Air interacts with gold particles (*9*) and MgO particles (*10*) to inhibit sintering by comparison with that which takes place in a vacuum. A similar vacuum enhancement of lunar glass sintering might be expected.

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4 January 1970

Mineralogy and Petrography of Lunar Samples

Abstract. *The lunar samples consist largely of augite, calcic plagioclase, and ilmenite. Olivine is a minor constituent of some rocks, as is cristobalite. Other minerals present in small amounts include tridymite, chromite, kamacite, taenite, and troilite. The principal rock types can be broadly grouped into ilmenite basalts and breccias. Except for their high ilmenite content, the lunar rocks resemble the calcium-rich achondritic meteorites (eucrites and howardites) in composition and structure. Evidence of a meteoritic increment in the lunar soil is provided by the presence of nickel-iron particles in glass and breccia, and the occurrence of metal-troilite spheroids; the breccias contain occasional silicate aggregates that resemble meteoritic chondrules. The lunar fines contain 325 parts of water-soluble calcium per million.*

We have confirmed the presence of plagioclase, pyroxene, ilmenite, olivine, cristobalite, tridymite, chromite, kamacite, taenite, and troilite in the lunar samples. Microprobe analyses show a range of plagioclase compositions from An_{70} to An_{100}, individual grains being zoned with increasing An content to-