lized. Compositionally these spheres are quite unlike chondrules, but they do illustrate a mechanism whereby chondrule-like bodies can develop. The glass beads probably formed by melting different proportions of minerals from a preexisting rock. Thus the bulk composition may vary considerably, but certain element ratios (reflecting phase compositions in the parent rock) will be preserved. This suggests a possible explanation of one of the puzzling characteristics of ordinary chondrites, where chondrules vary in bulk composition but contain olivine and pyroxene of fixed compositions.

There are many similarities between the Apollo 11 samples and basaltic achondrites, despite the obvious differences in bulk composition and the nature of the pyroxenes. Textures are remarkably similar, as are the development of zoning and degree of exsolution, apparent cooling rates, depth of burial and oxygen fugacities, the range of textures for similar bulk compositions, and the common occurrence of monomict breccias. The lunar surface may not have the appropriate composition to generate basaltic achondrites, but the necessary environments and processes probably did exist.

In the terminal stages of lunar accretion the material being added had a very distinctive chemical composition. Local melting formed a shallow liquid silicate pool that cooled rapidly. Impacts destroyed the uppermost surface and formed a soil layer over the igneous rocks very early in lunar history. There has been no major exchange of material between the surface and the deep interior, and the moon retains its accretionary stratigraphy. Later impacts and radiation effects have modified but not destroyed the imprint of these early processes.

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References and Notes

1. The term soil is used here for unconsolidated material of less than 1 cm diameter.
2. Lunar Sample Preliminary Examination Team, *Science* 165, 1211 (1969).
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Mineralogy, Petrology, and Surface Features of Lunar Samples 10062,35, 10067,9, 10069,30, and 10085,16

Abstract. *The primary rocks are a sequence of titanium-rich basic volcanics, composed of clinopyroxene, plagioclase, and ilmenite with minor olivine, troilite, and native iron. The soil and microbreccias are respectively loose and compacted mixtures of fragments and aggregates of similar rocks, minerals, and glassy fragments and spheres. Impact events are reflected by the presence of shock metamorphosed rock fragments, breccias, and glasses and their resulting compaction to form complex breccias, glass-spattered surfaces, and numerous glass-lined craters. Chemistry of the glasses formed by the impact events is highly variable, and the high iron and nickel content of a few moundlike features suggests that at least some of the projectiles are iron and nickel-rich meteorites.*

Samples 10062,35; 10067,9; 10069,30; and 10085,16 have been analyzed. Samples 10062,35 and 10069,30 are thin sections of rocks; sample 10067,9 is a thin section of a microbreccia, and sample 10085,16 is a 10-g portion of lunar soil.

Sample 10062,35 is composed of radiating lathlike and acicular calcic-plagioclase crystals that enclose irregular grains of clinopyroxene and olivine. Skeletal crystals up to 1.5 mm of ilmenite occur throughout the section, and irregular patches of troilite with rounded exsolution blebs of iron are common. The plagioclase and clinopyroxene have a patchy extinction. The ilmenite has two types of exsolution features; the first occurs as bluish-gray elongated blebs, probably a spinel, and the second as fine whitish-gray lamellas of rutile. The overall texture of the section is very similar to a rapidly quenched silicate liquid of low viscosity. The mineralogy indicates that the liquid had the composition of a titanium-rich olivine basalt.

Sample 10069,30 is composed of euhedral to subhedral clinopyroxene and stubby subhedral to lathlike ilmenite in a matrix of poikilitic calcic-plagioclase. Small amounts of troilite with small exsolved blebs of native iron occur in irregular and rounded patches. The clinopyroxene crystals are either zoned or show a patchy extinction, suggesting compositional variation. In many crystals the cores contain numerous inclusions that are less than 1 μm in diameter. The plagioclase crystals

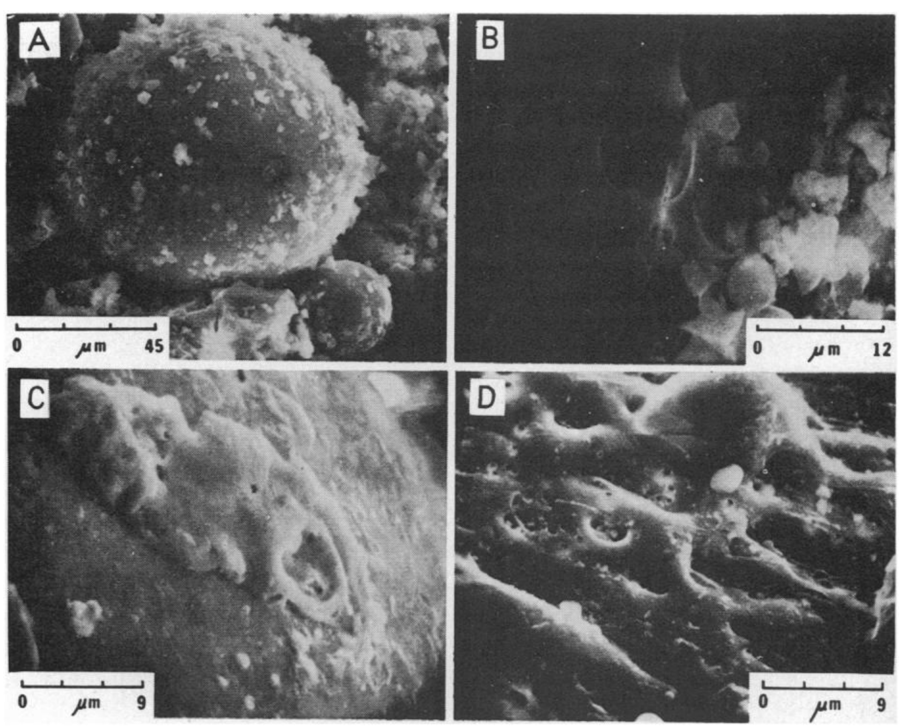

Fig. 1. Scanning electron micrographs (*2*). (A) Sphere with adhering dust fragments in a typical angular microbreccia matrix; (B) vesicular glassy fragment in microbreccia; (C) irregular glass bleb on glass sphere; and (D) ropy glass spatter on glass.

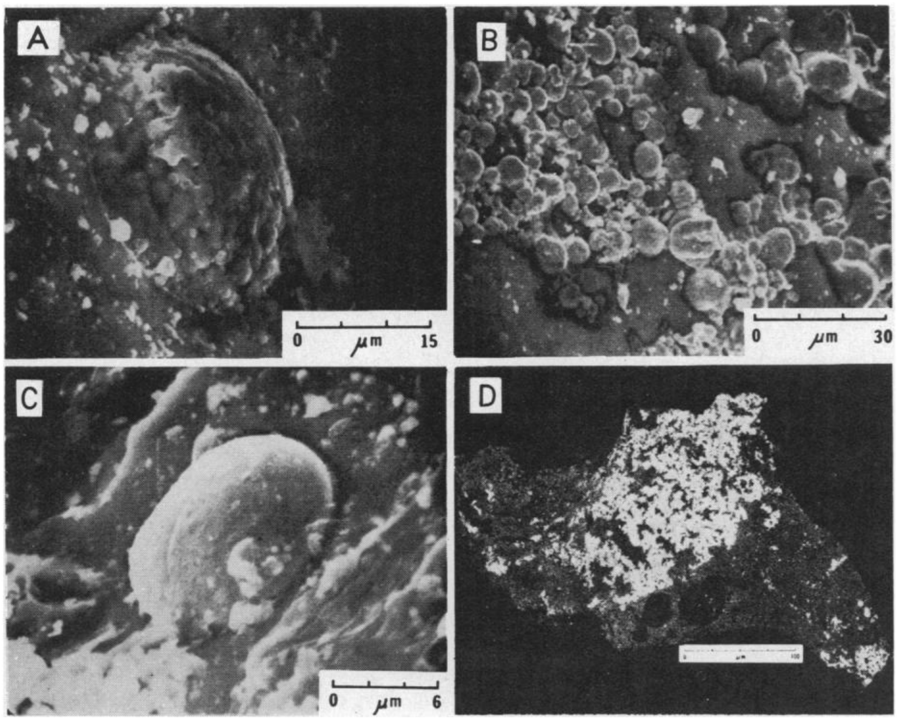

Fig. 2. Scanning electron micrographs (*2*). (A) Textured mound on glass sphere. (B) Magnetic iron-nickel mounds on glass fragment. (C) Magnetic iron-nickel mound surrounded by depressed rim on glass sphere. Note distortion of scanning picture by magnetic mound. (D) Electron microprobe iron scan of glass fragment shown in (B).

occur both as poikilitic crystals that enclose clinopyroxene and ilmenite grains or as radiating laths; their birefringence is very low, and the undulatory extinction is suggestive of mild shock metamorphism. The mineralogy, texture, and a few large vesicles indicate that this rock is a fine-grained vesicular basalt. The textures indicate that both clinopyroxene and ilmenite occur as primary minerals in a plagioclase-rich liquid. Patches of radiating "quench" plagioclase suggest rapid chilling, and minor shock effects indicate a later bombardment by meteoritic material.

Sample 10067,9 is a microbreccia. It is a compacted composite of rock, mineral, and glass fragments and fine lunar dust. The rock fragments may be divided into three types. Most common are fragments of basaltic rocks of varying grain size made up of mixtures of clinopyroxene, calcic-plagioclase, and ilmenite. Also abundant are aggregates of calcic-plagioclase, clinopyroxene, and ilmenite with characteristic feathery or herringbone textures reminiscent of quench products. In addition fragments of breccia occur. Mineral fragments of calcic-plagioclase, clinopyroxene, and ilmenite are common, while smaller amounts of troilite and native iron are present. Small glass spheres and fragments of glass varying in color from colorless to brownish orange are scattered throughout the slide. In many cases small fragments of rocks and minerals are imbedded in the spheres and glasses. The very fine-grained matrix was not identifiable in thin section, but x-ray diffraction data confirmed the presence of plagioclase, ilmenite, clinopyroxene, and abundant glass. A number of rocks and mineral fragments indicate varying degrees of shock from shattered fragments to irregular glassy patches. Scanning microscopy shows local welding of fragments by silicate glasses, which result either from shock metamorphism or from admixed droplets in the breccia.

Sample 10085,16 is a portion of the lunar soil. The soil is composed of a mixture of rock, mineral, and glass fragments and glass spheres (see Fig. 1, A and B) much like the microbreccia (sample 10067,9). Aggregates of rocks, minerals, and glasses are common. The rock fragments are microbreccias, vesicular basalts, gabbros, and microgabbros. The lithology, texture, and mineralogy of the microbreccias are similar to those of sample 10067,9. The igneous rocks are composed of varying proportions of calcic-plagioclase, clinopyroxene, and ilmenite. The coarser-grained rocks vary from anorthosites to gabbros, while the finer-grained rocks are basaltic in their mineralogy. Mineral fragments are abundant and are composed of the three primary minerals calcic-plagioclase, clinopyroxene, and ilmenite. Minor amounts of olivine, troilite, and native iron are present. The glass spheres and fragments occur in many forms, and range from hollow to vesicular to solid. The glass spheres varied in color from colorless through green, brown, and wine-red to opaque which suggests variation in chemical composition. Semiquantitative electron-microprobe analysis of glass spheres showed that they are chemically heterogeneous; approximate weight percentage ranges are: SiO_2, 40 to 50; Al_2O_3, 2 to 18; TiO_2, 3 to 15; Cr_2O_3, 0.00 to 0.08; total iron as FeO, 3 to 18; MgO, 2 to 9; CaO, 1 to 12; Na_2O, 0.1 to 0.7; MnO, 0.03 to 0.1; and NiO, 0.00 to 0.3.

An important aspect of the interpretation of the petrogenesis of the Apollo 11 material has been the examination of surface textures of the rocks and glasses with a scanning electron microscope. The fine-grained igneous rocks, breccias, and mineral fragments often are covered with thin films of glass, or may have a fine frosted surface (Fig. 1D). The frosted surface was shown to be either the result of intense fracturing or a glass coating. In addition, small craters from 20 to 2000 μm, often glass-lined, occur on the surface of many of the tiny rock fragments. The craters are often surrounded or underlain by a whitish margin which is composed of fractured particles of the host. In contrast, the vesicules of the rocks contain highly reflective euhedral mineral faces.

The glass-covered surfaces and spheres have three major types of features: vesicules (Figs. 1B, 1D, and 2D), craters (Fig. 3), and mounds (Figs. 1C and 2). The vesicules are usually spherical or subspherical in shape and often coalesce into irregular networks (Fig. 1D). Occasionally perfectly hemispherical vesicules are seen. The vesicules probably formed by the expansion of gas bubbles from the silicate glass, and thin fragile shells of the original bubbles may be seen in a number of cases.

There appear to be three types of craters: a hole surrounded by a flared lip (Fig. 3A); a raised "crown" of glass surrounded by a circular ring with radiating sets of conchoidal fractures (Fig. 3B); and a deep glass-lined hole with a "splashed" rim surrounded by radiating sets of fractures (Fig. 3, C and D), and, at greater distances, very fine radiating rays of splashed glass. It is inferred that the different crater features result from variations in the plasticity of the target with the target becoming increasingly brittle in the sequence described. It is probable that some of the impact phenomena occur in the particulate cloud that results from the impact event.

The glass surfaces and spheres are often covered with small moundlike features which sometimes are small droplets of glass and sometimes highly magnetic features (Figs. 1C and 2, A–C). They may have smooth or rough surfaces and in some cases are surrounded by a narrow depression or moat (Fig. 2, A and C).

These small moundlike features coat many surfaces, giving them a finely dusted appearance. In addition, some surfaces are splashed with irregular blebs or stringers of ropy glass (Fig. 1D). These and the moundlike glass features are often of a different color than the substrate.

Semiquantitative electron-microprobe analyses of the cratered and moundlike features indicate that the glass within and surrounding the cratered features is essentially isochemical, which suggests that the impacting particle has been expelled and that the raised lips and crowns are essentially a remelted glass of the area surrounding the impact. However, the moundlike features and ropy glasses have a distinctly different chemistry from the underlying substrate. For example, Fig. 2D shows the distribution of iron on a glass fragment spattered with the small moundlike magnetic features shown in Fig. 2B. In these moundlike features, iron is the major element, nickel is minor with cobalt, magnesium, aluminum, phosphorus, and silicon in lesser amounts.

Our data support the conclusions of the Preliminary Examination Team (*1*) that the primary rock types at the Apollo 11 landing site are basic volcanic rocks. The textures indicate crystallization in a low pressure environment where crystallization has been rapid, and in those cases where quench textures are observed, almost instantaneous. The main phase assemblage is fairly simple, being composed primarily of clinopyroxene, calcic-plagioclase, and ilmenite with minor amounts of olivine, troilite, and native iron in a few rocks. No secondary or hydrous minerals were noted. Superimposed on their primary history, later events are reflected by the presence of shock-metamorphed minerals; fragmentation of the rocks and the resulting compaction to form breccia; the presence of glass-spattered surfaces and the presence of numerous craters, often glass-lined, on their surface. The breccias and soil contain similar rocks and minerals degraded by the secondary processes following their formation.

These data suggest that the main process responsible for the degradation of the igneous rocks is the rain of fragments, both from primary and secondary impact events. All of the surface features observed for the Apollo 11 samples are compatible with phenomena associated with meteoritic events. The numerous small glassy spheres, shells, and the glass mounds are probably relicts of the spattered molten beads that are ejected during the impacting event. The chemical data also indicate that in the cratered features the impacting particle was probably completely ejected while the moundlike glassy features and irregular glassy surface blebs are the result of foreign droplets of liquid that have splashed onto the surfaces. The range of cratered features, moatlike surrounds of the mounds, and fragments adhering to glassy surfaces indicate collisions between particles while some were still plastic. The local melting resulting from the impact event is probably responsible for most of the splattered glass. The presence of the moundlike features that are rich in iron and nickel suggests further that iron-nickel meteorites played a role in the formation of the Apollo 11 samples.

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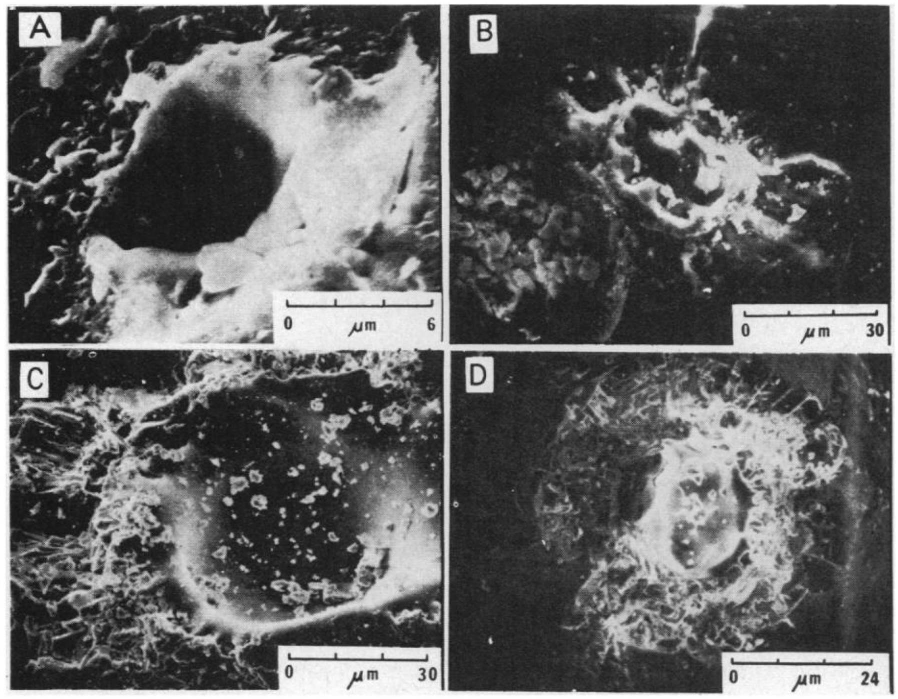

Fig. 3. Scanning electron micrographs of impact structures (*2*). (A) Glass-lined crater with flared lip on glass sphere. (B) Glass-lined crater with raised "crown" of glass surrounded by a circular ring with radiating sets of conchoidal fractures on glass sphere. Note hemispherical pit lower left. Small particles welded to surface of pit. (C) Glass-lined hole with "splashed" rim surrounded by radiating sets of fractures on glass fragment. (D) Glass-lined hole with "splashed" rim surrounded by radiating sets of fractures on glass-spattered surface.

References and Notes

1. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
2. Uncoated surfaces.
3. Supported by NASA contract NAS 9-8766. We thank W. Brown, T. Lyon, D. Martin, J. Pangborn, J. Toney, and R. Wittkopp for technical assistance. Contribution No. 127, geosciences division.

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