
Crystalline igneous rock samples 14053, 14310, 15058, 15076, 15415, 15475, 15495, 15555; breccia samples 14303, 14305, 14319, 14321, 15405; and soil samples 14162 and 14163 from the Apollo missions, and soil samples 301, 303, 304, 311, 315, 318, and 320 (Smithsonian Astrophysical Observatory numbers) from the Luna 16 mission were examined by microscope and electron microprobe. They exhibit many features seen in Apollo 11 and 12 samples, and some novel ones as well. Our main goal was not to make standard petrographic descriptions and analyses of the major minerals, but rather to obtain crystallization and differentiation trend data from silicate melt inclusions. Coincidental with this examination for minute inclusions various other small-scale features were observed, including some that are not easily interpreted but are reported because they may be significant to other workers.

Silicate melt inclusions in olivine are abundant and occasionally large (300μm) in some clasts in 14321. Olivine in 15555 has many small melt inclusions, mostly <10μm. After trapping, many inclusions in olivine formed blebs of sulfide and daughter crystals of ilmenite and plagioclase (both epitaxial), and pyroxene. Nucleation and growth (epitaxial or random) of these phases varies with inclusion size, gross composition, and probably with cooling history. Solid inclusions in olivine consist of relatively large chrome spinel euhedra, and in part of the olivine crystals rows of very minute chromium-rich crystals have decorated what are apparently dislocations, otherwise invisible. The decorations could have formed during metamorphism of these breccias. The inclusions in olivine of the Luna sample are very similar in appearance, but these olivines also have external epitaxially-arrayed ilmenite plates growing in the groundmass, a feature not seen in Apollo 11 or 12. The gross composition of melt inclusions in olivine varies from about 48 to 62 percent silica.

Melt inclusions in coarse anorthosite rock 15415 are scarce and small (<1μm). Most occur along healed fractures within individual plagioclase grains, indicating the presence of at least a small amount of melt at the time of fracturing.

Actual melt inclusions in ilmenite (as opposed to the apparent inclusions of matrix phases so common in these skeletal crystals) range in composition from the anomalous low-silica, high-potassium type reported in Apollo 11 to those that are essentially identical with the late-stage, high-silica residual melts. In several samples, melt inclusions in ilmenites suggest trapping at successive stages in a differentiation sequence; these show a systematic distribution of MgO between the inclusions and the host ilmenite.

Melt inclusions related to the onset of immiscibility are common in all the samples. Although somewhat variable, these two immiscible melts are essentially like those in Apollo 11 and 12 — potassic rhyolite and ferropy-
roxenite in composition. These are best seen as interstitial inclusions of late-stage residual melt (mesostasis) in 14310, where there are many excellent examples of menisci between spherical blebs of colorless high-silica melt (now containing a few minute acicular crystals, presumably feldspar), protruding into almost opaque, high-iron melt (now a very fine grained crystalline aggregate) which fills the interstices between late plagioclase crystals. Some of the later plagioclase and many of the later pyroxene crystals contain melt inclusions in their outer zones, generally of high-silica melt. A few of the melt inclusions within late plagioclase exhibit both immiscible melts and a vapor (shrinkage) bubble, although none of these are as large, clear and abundant as those recently found in 12035,24.

Most of the high-iron melt has crystallized, as in the Apollo 11 and 12 samples. In slowly cooled rocks this now consists of single crystals of fayalite (or pyroxferroite?) containing intergrown, wormy inclusions of high-silica melt. In addition, some of this late-stage material contains blebs of iron metal and (or) troilite, euhedral crystals of apatite (low in rare earths and yttrium), potassium feldspar, tridymite, and cristobalite, plus minor amounts of tranquillityite and other, unidentified phases. The mesostasis in 14053 has some unusual textures, which may indicate the simultaneous occurrence of four immiscible melts: the two silicate melts, plus iron-rich metal and iron sulfide melts.

The two immiscible silicate melts at the several sites have similar compositions for the major components, except for some very significant differences in the alkali ratios. There is an inverse relationship between the $K_2O/Na_2O$ ratio in the bulk rock and its residual high-silica melt.

In any given cogenetic rock series the early melt inclusions in olivine, the later melt inclusions in plagioclase, ilmenite and ulvospinel, and the late-stage immiscible melt inclusions should form a continuous series, delineating the liquid line of descent (with its split into two lines at the onset of immiscibility). The limited number of samples studied and the small volumes available for analysis have frustrated efforts to obtain a complete series of successive melts representing the liquid line of descent for any given magma. However, when the compositions of all silicate melt inclusions that we have analyzed, from all hosts and all five sites, are plotted on a silica variation diagram the results are surprisingly consistent, showing a generally similar liquid line of descent for most of these samples.

Many of the above features are present in the breccias and soil samples, but less suitable for study. These latter also exhibit many petrologically important features seen poorly or not at all in the crystalline igneous rocks. Individual pyroxene crystal fragments show a variety of exsolution textures, including oriented platelets of ilmenite, as in some terrestrial rocks. In some of the metamorphosed breccias, olivine grains are surrounded with a reaction rim of pyroxene. Shock damage to plagioclase or anorthosite, followed by later recrystallization, has yielded some novel textures.

Many grains of a reddish-purple spinel were found in several samples of soil and breccia from the Apollo 14 site. Two major composition groups have been found by electron microprobe, one approximately $(Mg_{0.53}Fe_{0.47})(Al_{0.91}Cr_{0.09})_2O_4$, and the other $(Mg_{0.58}Fe_{0.42})(Al_{0.98}Cr_{0.02})_2O_4$. With only minor
amounts of other ions. These differ greatly from all previously recorded lunar spinels, and no spinels of intermediate composition were found. A darker rim on some of these spinels, and a narrow zone of almost pure plagioclase, free of pyroxene and opaques, in the breccia matrix at the contact indicate reaction between the spinel and the breccia matrix. One crystalline rock fragment was found in which relatively coarse grained spinel occurs in a possibly cumulus texture with olivine and plagioclase, which suggests that such a rock may be the source of the spinel. Several others have spinel embedded in single plagioclase crystals. Another clast, itself a breccia, in the Apollo 14 breccias contains many grains of this spinel, along with olivine and plagioclase but no pyroxene, implying the existence of a spinel-rich regolith somewhere. As only a few grains of this spinel have been recognized in all the work on the Apollo 11, 12, 15 and Luna 16 samples, despite its striking appearance, and as it is abundant in the Apollo 14 samples, it seems reasonable to assume that exposure(s) of this spinel-rich rock must be very restricted on the Moon, and must be near to the source of the Apollo 14 materials. These data are also in agreement with the concept of essentially local origin for most soil fragments, i.e., relatively little lateral mixing.

Glass fragments and spherules in the lunar fines from all three sites show a range of crystallization textures which vary with the individual cooling history and composition. Using the microscope crushing stage (Roedder, 1970, Schéiz, Min. Pet. Mitt., v. 50, p. 41-58), the bubbles in some of these glasses are now found to contain $10^9-10^{10}$ molecules of (unidentified) noncondensable gas (pressure <0.01 atm); presumably these are mainly solar wind gases from the soil that entered (or formed?) the bubbles during the fusion to form the glass.

A very small fraction of the glass spheres, and nearly 10% of the glass dumbbells in lunar soil 14163 show two immiscible glasses, one light and the other dark red brown in color. The latter was apparently higher in density as a melt, as those dumbbells that have dark glass in one end only are asymmetrical, with that end smaller, as would be expected during rotation while in free fall. More significant, however, is the occurrence of several areas and fragments of glass of potassic rhyolite composition in the Apollo 14 breccias. These glasses have slightly lower CaO and FeO, and appreciably higher K$_2$O than the high silica immiscible melt. We believe, however, that these represent fragments of a rhyolitic phase that separated as a result of liquid immiscibility and was concentrated somewhere at the surface of the Moon relatively near to the source of the materials for the Apollo 14 site.