mineral assemblages and metastable phases so produced owe their preservation to the apparently anhydrous environment.

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Mineral Chemistry of Lunar Samples

Abstract. *Glass spherules, glass fragments, augite, ferroaugite, titanaugite, pyroxmangite, pigeonite, hypersthene, plagioclase, potassium feldspar, maskelynite, olivine, silica, ilmenite, TiO_2, "ferropseudobrookite," spinel, ulvöspinel, native iron, nickel-iron, troilite, and chlorapatite were analyzed with the electron microprobe. There are no indications of large-scale chemical differentiation, chemical weathering, or hydrous minerals. Contributions of meteoritic material to lunar surface rocks are small. Rocks with igneous textures originated from a melt that crystallized at or near the surface, and oxygen fugacities have been low. Shock features indicate that at least some surface material is impact-produced.*

Polished thin sections of loose surface fines < 1 mm in diameter (10084-97), breccias (10019-22, 10059-27, 10067-8, 10068-34), and igneous rock (10045-29) were studied by optical and electron microprobe techniques. Some of us are coinvestigators on other projects and studied breccia 10061-37 (T.E.B.) and loose surface material 10086-3 (K.K.).

Sample 10084-97 consists largely of rock fragments, feldspar, pyroxene, ilmenite, and glass spherules and glass fragments, with lesser amounts of pyroxmangite, olivine, ulvöspinel, and metallic nickel-iron. Breccias have essentially the same major phases and, in addition, accessory phases (pyroxmangite, pigeonite, hypersthene, maskelynite, olivine, silica, TiO_2, "ferropseudobrookite," spinel, native iron, metallic nickel-iron, troilite, chlorapatite, and silica-rich glass). Loose surface material and breccias contain a variety of rock fragments, many of which resemble in their mineralogy and chemistry the igneous rocks. However, there are also a variety of lithic fragments that are apparently not represented in the hand-specimen-sized samples. Fragments in sample 10059-27 consist largely of plagioclase [An_{95} (95 mole percent anorthite)] and minor amounts of olivine [Fo_{66} (66 mole percent forsterite)], augite [$Fs_{15.3}En_{45.6}Wo_{39.1}$ (15.3 mole percent ferrosilite, 45.6 mole percent enstatite, 39.1 mole percent wollastonite)], pigeonite ($Fs_{30.3}En_{61.4}Wo_{8.3}$), and ilmenite (6 percent MgO by weight) resembling terrestrial anorthositic gabbros. This occurrence, in association with Ti-rich mafic rocks, is noteworthy because terrestrial anorthositic rocks also tend to be associated with Ti-rich provinces. Fragments in sample 10019-22 consist of plagioclase (An_{95}), olivine (Fo_{81}), plagioclase glass, fine-grained lath-like feldspar and pyroxene embedded in the glass, and spinel A (Table 1). One inclusion in sample 10061-37 is largely maskelynite (An_{91}), clinopyroxene ($Fs_{16.3}En_{41.4}Wo_{42.3}$), and orthopyroxene ($Fs_{37.6}En_{58.5}Wo_{3.9}$).

Sample 10045-29 is a medium-grained ophitic igneous rock containing augite, plagioclase, and ilmenite; ferroaugite, titanaugite, pigeonite, potassium feldspar, olivine, silica, native iron, troilite, and chlorapatite are present in accessory amounts.

The following is a summary of the observed phases and their compositions in the samples studied:

Calcium-rich pyroxenes contain TiO_2 (0.67 to 9.3 percent by weight) and Al_2O_3 (0.58 to 9.7 percent). All pyroxenes with more than 2 percent TiO_2 are referred to as titanaugite (*1*). Most grains contain Cr_2O_3 (0.1 to 0.8 percent), and the amount of Cr_2O_3 increases with increasing MgO content. Manganese monoxide ranges from 0.06 to 0.54 percent; K_2O and Na_2O rarely exceed 0.10 percent each.

Pyroxenes exhibit minor to large within-grain and grain-to-grain compositional variabilities. Major elements in larger grains vary widely across grains and even broad areas (10 to 15 μm or more) do not generally show repetitions of patterns consistent with fine-scale exsolution, although well-defined exsolution of orthopyroxene or pigeonite from augite, and augite from hypersthene have been observed in a few grains. Typical patterns across large pyroxene grains show that FeO varies

Table 1. Electron microprobe analysis of less common minerals. Compositions are given in percentages by weight.

Mineral	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	Cr_2O_3	TiO_2	MnO	MgO	ZrO_2	Total
Silicates												
Potassium feldspar	64.6	19.9	0.60	0.72	0.33	13.1						99.25
Silica	96.9	1.03	0.35	0.52	0.05	0.25						99.10
Oxides												
Ulvöspinel		1.88	62.2	0.03			3.5	32.7	0.22	0.04		100.57
Spinel A		68.0	3.33				2.16			25.9		99.39
Spinel B		6.0	46.3				19.3	23.0		4.3		98.9
"Ferropseudobrookite"		1.48	14.7	0.32			1.94	71.4	0.07	8.7	0.05	98.66

Table 2. Electron microprobe analyses of glass spherules in percentage by weight. Analyses of angular glasses are similar in composition and are not given. Parenthetical numbers indicate the number of spherules analyzed.

Oxide	Clear (15)	Green (10)	Orange to brown (20)	Red to black (22)
SiO_2	45.5	44.2	40.1	37.2
Al_2O_3	27.0	21.0	14.8	5.2
Cr_2O_3	0.12	0.17	0.32	0.61
TiO_2	0.45	1.81	7.6	10.7
FeO	3.8	7.9	15.3	24.7
MgO	6.9	8.6	8.4	13.1
MnO	0.8	0.15	0.22	0.30
CaO	15.0	14.7	12.9	7.7
Na_2O	0.24	0.41	0.14	0.27
K_2O	0.02	0.39	0.05	0.04
ZrO_2	0.02	0.04	0.07	0.06
P_2O_5	0.04	0.14	0.04	0.05
Total	99.17	99.51	99.94	99.93

sympathetically with MgO and that FeO and MgO vary antipathetically with CaO; TiO_2 varies sympathetically with Al_2O_3, and TiO_2 and Al_2O_3 vary antipathetically with SiO_2. However, patterns have been observed where (i) CaO varies sympathetically with FeO and MgO; (ii) CaO varies antipathetically with FeO, but MgO shows no relation to either; (iii) FeO varies sympathetically with MgO, but CaO shows no relation to either; and (iv) CaO, FeO, and MgO show variations unrelated to one another, and TiO_2 always varies sympathetically with Al_2O_3.

Analyzed pyroxenes range from augite to ferroaugite to ferrohedenbergite (or pyroxmangite); a few grains conform to subcalcic augite and ferroaugite compositions. Figure 1 appears to define a compositional trend similar to that of the diopside-ferropigeonite series (*2*). However, these pyroxenes may have originated in nonrelated parent rocks and the compositional trend may be fortuitous.

Calcium-poor pyroxenes are pigeonite that is always in association with augite or titanaugite in lithic fragments, and hypersthene that is always in association with exsolved augite. Both are low in Al_2O_3, Cr_2O_3, and TiO_2 by comparison with calcium-rich pyroxenes, but they contain higher amounts of MnO.

Plagioclase (anorthite or bytownite, sometimes labradorite) is usually somewhat zoned, and within one rock or fragment type it may range in composition by about ± 20 percent An. In five lithic fragments of sample 10059-27, it ranges from An_{64} to An_{90}. The most common plagioclase in the surface fines and breccias is An_{93}. Potassium feldspar was found in small patches in sample 10045-29 (Table 1). Maskelynite of An_{91} occurs in sample 10061-27. Other maskelynite grains are also similar to unshocked plagioclase in composition, and no particular depletion of alkalis was noted.

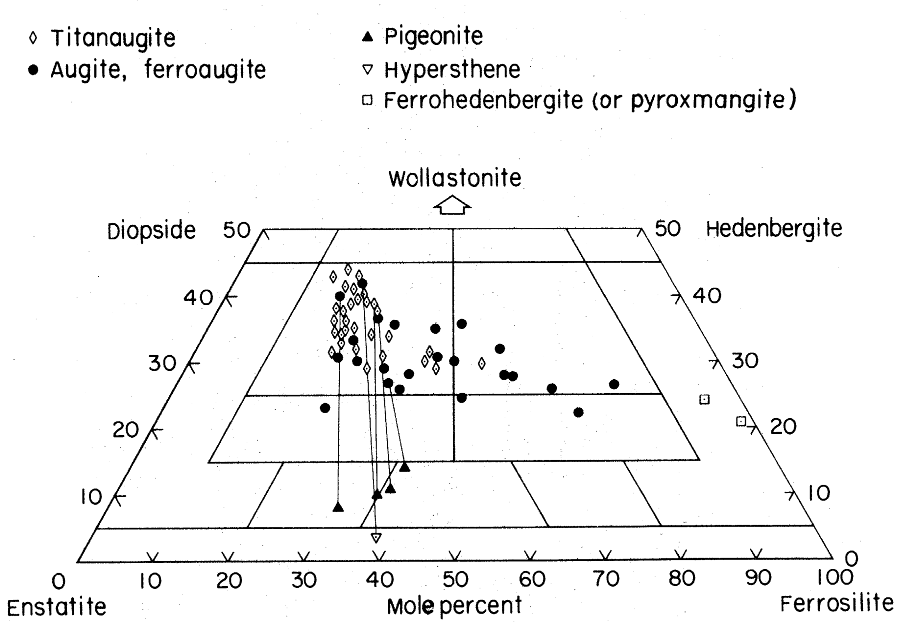

Fig. 1. Composition of 54 fairly homogeneous pyroxenes from breccias plotted in the ferrosilite-enstatite-wollastonite diagram (in mole percent).

Olivine is sometimes zoned and ranges in composition from Fo_{48} to Fo_{80}. It is remarkable because of its consistently high CaO content (~ 0.5 percent) and minor amounts of TiO_2 and Cr_2O_3.

Silica occurs in small (<10 μm) grains not suitable for precise quantitative microprobe analysis. However, one grain about 25 μm in diameter was found in sample 10045-29 and analyzed (Table 1); the analysis indicated large amounts of elements other than Si and O. Identification of the phase by optical or x-ray diffraction methods was not possible; the composition suggests that it is not quartz, but probably tridymite.

Ilmenite analyses show the presence of Al_2O_3 (0.1 to 0.3 percent), MnO (0.5 to 0.6 percent), MgO (0.8 to 6.2 percent), CaO (<0.02 to 0.3 percent), Cr_2O_3 (0.5 to 1.3 percent), and V_2O_3 (up to 0.2 percent) besides the major oxides FeO and TiO_2.

Titanium dioxide occurs as small grains (<20 μm) in ilmenite and appears to be pure TiO_2; accurate quantitative analysis was prevented because of the small grain size.

"*Ferropseudobrookite*," (Mg,Fe)Ti_2O_5, is a new mineral which was discovered in samples 10059-27 and 10067-8. It occurs in small grains (<20 μm) in contact with and enclosed by ilmenite. The chemical composition (Table 1) is intermediate between that of the theoretical compounds $FeTi_2O_5$ and $MgTi_2O_5$. Insufficient amounts of the phase in the sections at hand have thus far prevented x-ray diffraction studies. A survey of other sections is presently being made in an attempt to locate a grain large enough for x-ray work.

Spinel A is nearly pure $MgAl_2O_4$ and occurs in a lithic fragment in sample 10019-22 that consists largely of plagioclase, plagioclase glass, olivine, and pyroxene (Table 1). An unusual spinel B containing large amounts of Cr_2O_3 and TiO_2 was found in sample 10059-28 (Table 1). It resembles a spinel from the meteorite Cachari which was probably produced by shock melting of ilmenite and chromite, followed by rapid cooling (*3*).

Ulvöspinel was found in two 30-μm grains in sample 10084-97 (Table 1).

Native iron is usually intergrown as blebs or droplets in troilite and is essentially pure Fe. One grain in sample 10045-29, however, has about 0.1 percent Ni.

Metallic nickel-iron commonly occurs

as small (<20 μm) droplets in glass spherules and glass fragments or as small grains in the fine-grained breccia matrix. Nickel contents range from 0.5 to 19.8 percent; Co ranges from 0.35 to 0.94 percent.

Troilite occurs as an intergrowth with native iron or as a separate phase. Minor amounts of Mn (0.4 percent) and Cr (0.03 percent) are common.

Chlorapatite was identified with the electron microprobe; however, the grain size is too small (<10 μm) to allow accurate quantitative microprobe analysis.

Glass spherules and fragments are similar in composition for any given color (Table 2). The amounts of SiO_2, Al_2O_3, and CaO decrease as the color of the spherules darkens, whereas the amounts of Cr_2O_3, TiO_2, FeO, and MgO increase; other oxides show no definite trends.

Igneous glass occurs in minute patches <30 μm in diameter of silica-rich glass which range in SiO_2 from about 72 to 84 percent. A typical analysis is: SiO_2, 78.1 percent; TiO_2, 1.11 percent; Al_2O_3, 10.6 percent; FeO, 0.96 percent; MnO, 0.04 percent; MgO, 0.07 percent; CaO, 5.1 percent; Na_2O, 1.24 percent; K_2O, 3.4 percent; P_2O_5, 0.19 percent; Cr_2O_3, 0.05 percent; ZrO_2, 0.04 percent; total, 100.90 percent.

The following tentative conclusions may be drawn from the data presented herein: (i) There are no indications of chemical weathering or the presence of hydrous minerals. (ii) The presence of troilite, native iron, and the less oxidized end members ulvöspinel (Fe_2TiO_4), rather than magnetite (Fe_3O_4), in the magnetite-ulvöspinel series; ilmenite ($FeTiO_3$), rather than hematite (Fe_2O_3), in the hematite-ilmenite series; "ferropseudobrookite" ($FeTi_2O_5$), rather than pseudobrookite (Fe_2TiO_5), in the "ferropseudobrookite"-pseudobrookite series indicates that the oxygen fugacities of the lunar rocks are low relative to those of terrestrial rocks. (iii) Contributions (by weight) of meteoritic material to lunar surface rocks appear to be small. (iv) The texture of sample 10045-29 and many lithic fragments is typical of rapidly cooled rocks and is analogous to terrestrial volcanic or hypabyssal rocks. (v) The ilmenite content of all samples is higher (~ 15 to 20 percent by weight) than that of most terrestrial rocks and is similar in bulk composition to that of meteoritic ilmenite. (vi) Shock features indicate that at least some of the loose surface material and breccias are impact-produced. (vii) Metallic nickel-iron present in glass spherules and glass fragments is interpreted as being of meteoritic origin.

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Petrographic, Mineralogic, and X-Ray Fluorescence Analysis of Lunar Igneous-Type Rocks and Spherules

Abstract. *Three lunar rocks show almost identical mineralogy but grain sizes that vary from basaltic to gabbroic. Clinopyroxene is zoned from augite to subcalcic ferroaugite compositions and is accompanied by decrease in Cr, Al, and Ti. Plagioclase is zoned from 93 to 78 percent anorthite. Olivine (68 percent forsterite) is present in one rock and apatite is rare. Cristobalite, ilmenite with Ti-rich lamellae, ulvöspinel (often Cr-rich), troilite, and kamacite are low in trace elements. Glassy spherules are of basaltic or feldspathic (92 percent anorthite) composition but contain abundant iron spheres of taenite composition (13 percent Ni). Four rock analyses by x-ray fluorescence show affinity with terrestrial basalts but with anomalous amounts of Ti, Na, Cr, Zr, Y, Rb, Nb, Ni, Cu, and Zn.*

Three polished thin-rock sections (17/50, 45/35, 58/23) were provided for nondestructive optical and electron microprobe analysis, and three 2-g samples of rock powders (44/39, 45/24, 60/25) for nondestructive x-ray fluorescence analysis of minor elements. A 5-g sample of 1-mm to 1-cm heterogeneous fragments (85/3) yielded different rock types, which were prepared for microprobe analysis, and 2 g of 1- to 3-mm size was powdered and analyzed for major and minor elements by x-ray fluorescence.

The three main rock types are very similar in mineralogy and have no terrestrial or meteoritic analogs. They are closest to terrestrial tholeiite basalt and meteoritic eucrite, but the high titanium and reduced state of each lunar rock make such comparisons superficial. The textures and mineral assemblage

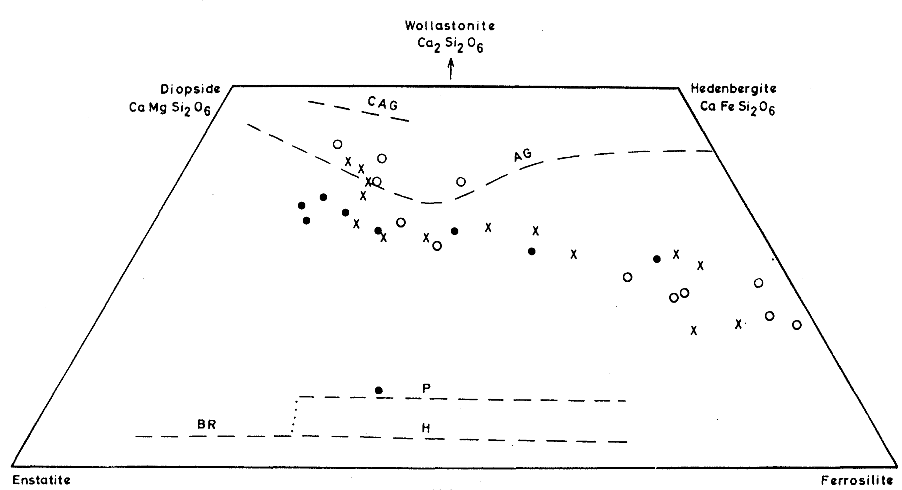

Fig. 1. Pyroxene compositions in relation to the trends (2) for terrestrial igneous pyroxenes (broken lines: CAG, calcic augite; AG, augite; BR, bronzite; H, hypersthene; P, pigeonite series). Symbols refer to the three igneous-type rocks (Table 1): closed circles, A; crosses, B; open circles, C. The pale yellow phase (crystallographically a pyroxenoid according to S. O. Agrell *et al.*, this issue) is present as the most iron-rich compositions in B and C. Only one pigeonite composition was obtained, but more measurements are needed.