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Abbreviations and symbols:

ppm	parts per million
mm	millimeter
cm	centimeter
g	gram
D	specific gravity

Fa	mole per cent	Fe_2SiO_4
Wo	" "	$CaSiO_3$
En	" "	$MgSiO_3$
Fs	" "	$FeSiO_3$
An	" "	$CaAl_2Si_2O_8$
Ab	" "	$NaAlSi_3O_8$
Or	" "	$KAlSi_3O_8$
Cn	" "	$BaAl_2Si_2O_8$

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Augite
Hedenbergite
Pyroxferroite
Fayalite
Quartz
Ilmenite
Nickel-iron
Zircon
Apatite
Whitlockite

Mineralogy and petrography of some Apollo 12 samples

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Abstract

Samples of the Apollo 12 fines contain fragments of crystalline rocks and breccias, mineral grains, and glassy particles. The mineral grains are mainly pyroxenes (pigeonite and augite) and olivine, with minor amounts of plagioclase and ilmenite, and rare metal grains. The compositions of the metal grains indicate that some are of meteoritic origin and some are derived from lunar rocks. A single pyroxene crystal has a pigeonite core, an augite mantle, and a rim of ferrohedenbergite, with a narrow zone of pyroxferroite along a central fissure. One rock fragment from a sample of coarse fines (12032) is a silica-rich hedenbergite granophyre, consisting of sanidine (50%), quartz (30%), hedenbergite (10%), plagioclase (7%), fayalite (3%), and accessory apatite, whitlockite, and zircon. A complete chemical analysis of 12001 fines has been made, and also a determination of the water-soluble cations, a noteworthy feature being the presence of 103 ppm water-soluble calcium.

We received the following samples from the Apollo 12 collections:

Fines (-1 mm): 12001 (3.0 g); 12003 (0.5 g); 12033 (0.5 g);

12042 (0.5 g); 12057 (2.0 g); 12070 (2.0 g)

Coarse fines: (1 mm - 1 cm): 12032 (0.5 g)

Rock sections: 12009, 12022, 12045, 12051

Each sample of the fines was sieved through 60 mesh (0.250 mm opening) and 200 mesh (0.074 mm opening) sieves. The grain-size distribution was similar in all, the weight proportions being: +60 mesh, 10-20%; 60-200 mesh, 20-30%; -200 mesh, 50-60%. The fines contained fragments of crystalline rocks and breccias, mineral grains, and glassy particles. The coarser fractions were density-separated, using methylene iodide (D = 3.32). The fraction with D > 3.32 comprised about 30%, and consisted almost entirely of grains of pyroxene (major), olivine (minor), and opaque minerals (small amount). The fraction with D < 3.32 (about 70%) consisted of rock and breccia fragments, glass spherules and fragments, and feldspar grains.

The -200 mesh fraction of 12001 was further separated with a 325 mesh sieve (0.044 mm opening), and a portion of the -325 mesh fraction analysed. The results are given in Table 1, along with two analyses of Apollo 11 fines. The compositions of the Apollo 12 and the Apollo 11 fines are rather similar, except that the Apollo 12 fines contain about half as much titanium as the Apollo 11 material; this has already been noted in earlier reports (LSPET, 1970). Our analyses also show distinctly higher potassium and chromium in Apollo 12 fines. Since microscopic examination showed minute particles of metallic iron in the glassy fraction of the fines, we attempted to determine this in the Apollo 12 fines (by dissolution in $KCuCl_3$ solution). The figure obtained, 0.33% Fe, is certainly

Table 1. Analyses and norms of Apollo 11 and Apollo 12 fines
(E. Jarosewich, analyst)

	Analyses (weight per cent) 12001 -325 mesh	10084 -325 mesh	10084 glass concentrate		Norms (weight per cent) 12001 -325 mesh	10084 -325 mesh	10084 glass concentrate
SiO_2	45.83	42.02	43.28	An	33.9	37.4	37.8
Al_2O_3	13.45	14.61	14.83	Ab	4.0	3.8	4.1
TiO_2	2.99	6.38	5.43	Or	1.5	0.9	1.1
FeO	15.78	15.59	14.91	Di	14.4	18.4	19.4
MgO	10.28	7.92	7.63	Hy	33.0	20.4	22.5
CaO	10.63	12.39	12.56	Ol	7.0	6.2	4.1
Na_2O	0.47	0.45	0.48	Il	5.7	12.1	10.3
K_2O	0.25	0.15	0.19	Cr	0.7	0.3	0.2
P_2O_5	0.22	0.27	0.17	Ap	0.5	0.6	0.4
H_2O-	0.00	0.00	0.00	Metal	0.3	-	-
MnO	0.21	0.15	0.18	FeS	0.5	-	0.4
Cr_2O_3	0.45	0.17	0.10				
Ni	0.03	0.03	0.03				
S	[illegible]	-	0.13				
[illegible]	[illegible]	-	-				
	101.09	100.13	99.92				
S = O	0.09		0.07				
	101.00		99.85				

a minimum value, since the procedure would only dissolve those metal particles exposed on the surface of the glass fragments, and not those totally enclosed. The high summation of the analysis of the Apollo 12 fines probably results from the reporting of some metallic iron as FeO, and possibly some trivalent titanium as TiO_2.

The calculated mineral compositions (norms) of these analyses show about 40% feldspar of anorthitic composition and about 45% pyroxene. The compositions are slightly undersaturated in SiO_2, giving small amounts of olivine. The Apollo 12 fines contain the equivalent of about 5% ilmenite, compared to about 10% in the Apollo 11 material. After subtracting the ilmenite, the FeO/FeO+MgO molecular percentage is remarkably similar in all these analyses (42 for the Apollo 12, 41 and 43 for the Apollo 11 analyses).

We also determined the water-extractable cations in both Apollo 11 and Apollo 12 fines. A control experiment without sample yielded less than 1 ppm of the cations determined. A sample of the Allende meteorite was extracted for comparison. The results are as follows (in ppm):

	Na	K	Mg	Ca	Fe	Ni
12001	14	<5	31	103	<5	<5
10084	21	<5	16	325	<5	<5
Allende	238	<5	25	20	<5	<5

The notable feature is the comparatively high amount of extractable calcium, considerably less, however, in 12001 than in 10084. The extractable cations are not present in the fines as halides, since Reed and Jovanovic (1970) report less than 2 ppm water-soluble halogens in 10084. The high surface area and reactivity of the fresh lunar glass may be responsible. The water-extractable calcium perhaps explains the reported stimulating effect of lunar dust on plant growth.

Thirty grains of olivine in the Apollo 12 fines were analysed with the microprobe. The range in composition, in mole per cent Fe_2SiO_4 (Fa), is Fa_{26-60}, with no marked compositional preference; the mean is Fa_{41}. Minor elements detected with the microprobe were Ca (average 0.28%), Mn (0.24%), Cr (0.14%) and Ti (0.08%). The contents of calcium and chromium are notably high for olivine; in meteoritic olivines which we have measured Ca is usually 0.01-0.02%, and Cr 0.02-0.04%. This probably reflects a high temperature of crystallization for the lunar olivine, and rapid chilling preventing readjustment at lower temperatures.

Some sixty pyroxene grains in the Apollo 12 fines were also analysed. They showed two compositional clusters, one for pigeonite and the other for augite-subcalcic augite. The mean composition of the pigeonite cluster is $Wo_{11}En_{55}Fs_{33}$, of the augite-subcalcic augite cluster $Wo_{33}En_{40}Fs_{27}$. The principal minor elements are aluminum and titanium. The pigeonite grains average 1.4% Al_2O_3 and 0.9% TiO_2, the augite and subcalcic augite 2.3% Al_2O_3 and 1.3% TiO_2.

The range of compositions shown by the isolated pyroxene grains are essentially duplicated in a single pyroxene crystal fragment picked from 12057. This crystal fragment, 1.1 mm by 0.7 mm, has a central core of pigeonite of rather uniform composition ($Wo_{10}En_{57}Fs_{32}$) with a mantle of subcalcic augite ($Wo_{37}En_{37}Fs_{26}$), and on one edge a narrow rim of ferrohedenbergite ($Wo_{30}En_7Fs_{63}$). A narrow rift in the central core is lined with a thin zone of pyroxferroite. The individual minerals are clearly distinguished in crossed polars by the increase in birefrigence in passing from pyroxferroite to pigeonite to augite to ferrohedenbergite. The compositional variation across this grain is given in Fig. 1 in terms of the pyroxene end members. A similar pyroxene crystal from Apollo 12 material has been described by Bence et al. (1970).

Plagioclase grains from the Apollo 12 fines show a range of composition from An_{82} to An_{96}, with a mean of An_{90}. The plagioclase contains detectable iron (average 0.4% FeO), potassium (average 0.1% K_2O), and titanium (average 0.08% TiO_2).

Several metal-rich particles were extracted from the Apollo 12 fines by means of a hand magnet. The total amount in any sample is small, making up much less than 1%. Two types of metal were distinguished; one type is finely granular and shows deformation structures, the other is coarse-grained and undeformed. Microprobe analyses of the deformed grains give figures for nickel and cobalt comparable with those for meteoritic nickel-iron, suggesting that these grains have been derived from meteorite impacts on the lunar surface. The coarse-grained undeformed metal usually has lower nickel concentrations than meteoritic nickel-iron, and sometimes more cobalt than nickel; these fragments are presumably indigenous to the Moon, probably formed by localized reduction of basaltic material. One such fragment is essentially pure iron, with no detectable amounts of other elements; it is extremely soft, comparable with the purest strain-free iron we have been able to obtain. This metal fragment contains inclusions of olivine and ilmenite similar to these minerals in the lunar basalts, from which it was presumably derived.

Our 0.5 g sample of coarse fines (12032, from the rim of Bench Crater) was washed with acetone to remove dust, and then density-fractionated in methylene iodide-acetone mixtures. The density fractions were hand-sorted under a binocular microscope into breccia fragments and crystalline rock fragments. The results are set out in Table 2. The average weight of individual fragments is 3.5 mg, and the percentages of breccia and crystalline rocks are 82 and 18 respectively.

Several crystalline rock fragments were selected for detailed examination. The most remarkable one was a lone white fragment in the D $<$ 2.70 fraction, which otherwise consisted of highly vesiculated black breccia fragments. This crystalline fragment, 3 mm long, proved to consist largely of sanidine, with minor amounts of quartz, plagioclase, fayalite, and hedenbergite, and accessory zircon, apatite, and whitlockite. The composition of the individual minerals, determined by the microprobe, is given in Table 3, along with the calculated bulk composition.

Table 2. Fractionation of 0.5 g coarse fines from the rim of Bench Crater (12052, 46).

Density	Weight per cent	Number of fragments Breccia	Crystalline rocks
2.70	8	11	1
2.70-2.90	33	43	3
2.90-3.10	44	58	6
3.10-3.32	12	5	12
3.32	3	-	4
Totals	100	117	26

Table 3. Analyses (microprobe) of minerals in hedenbergite granophyre (12032, 46-2)

	1	2	3	4	5	6
SiO_2	65.4	57.0	99.7 (diff.)	48.8	29.8	72.0
TiO_2	-	-		0.75	0.21	0.1
Al_2O_3	18.6	26.8	0.28	0.45	0.04	11.1
Cr_2O_3	-	-	-	0.06	0.13	-
FeO	0.82	1.10	n.d.	28.0	67.8	5.3
MnO	n.d.	n.d.	n.d.	0.39	0.95	0.1
MgO	n.d.	n.d.	n.d.	1.55	1.22	0.2
CaO	0.31	8.74	n.d.	19.3	0.67	2.7
Na_2O	2.96	6.85	n.d.	0.10	n.d.	2.1
K_2O	11.6	0.15	-	-	-	5.8
SrO	n.d.	n.d.	-	-	-	-
BaO	1.21	n.d.	-	-	-	0.6
	100.9	100.6	(100.0)	99.4	100.8	100.0

n.d. = not detected ($<$ 0.05%)

1. Sanidine ($Or_{69}Ab_{28}Cn_2An_1$); 50%
2. Plagioclase feldspar ($Ab_{58}An_{41}Or_1$); 7%
3. Quartz; 30%
4. Hedenbergite ($Wo_{45}En_5Fs_{50}$); 10%
5. Fayalite (Fa_{95}); 3%
6. Bulk composition (calculated)

The hedenbergite and fayalite are present as phenocrysts, up to 1 mm long, in a fine-grained groundmass of quartz and feldspar, much of it in micrographic intergrowth. The percentages of sanidine and quartz in this intergrowth are approximately 65 : 35, a composition close to the temperature minimum on the liquidus in the system $KAlSi_3O_8$ - $NaAlSi_3O_8$ - SiO_2. The rock is comparable to some terrestrial granophyres, specifically the hedenbergite granophyres of the Skaergaard intrusion. One of these (EG 3021) has essentially identical mineralogy, consisting of hedenbergite ($Wo_{44}En_6Fs_{50}$), fayalite (Fa_{95}), plagioclase (An_{40}), potash feldspar, and quartz and tridymite. Lindsley et al. (1969) estimate temperatures of 950°-$980^\circ C$ and an oxygen fugacity ranging from $10^{-13.0}$ to $10^{-13.6}$ atm for the crystallization of the Skaergaard rock, and these figures should be equally applicable to the lunar granophyre.

The chemical, mineralogical, and textural features of this rock strongly suggest that it represents the last liquid differentiate from the fractional crystallization of a large body of lunar basaltic magma (or possibly an initial product of partial melting). Its composition is similar to that of the high-silica glassy mesostasis of many of the Apollo 11 igneous rocks, described by Roedder and Weiblen (1970). It is also comparable with the light-colored, silica-rich parts of the unique rock 12013. Whether it was formed at or near the locale of the Apollo 12 landing, or whether it is an exotic fragment, possibly from a Copernicus ray, remains an open question.

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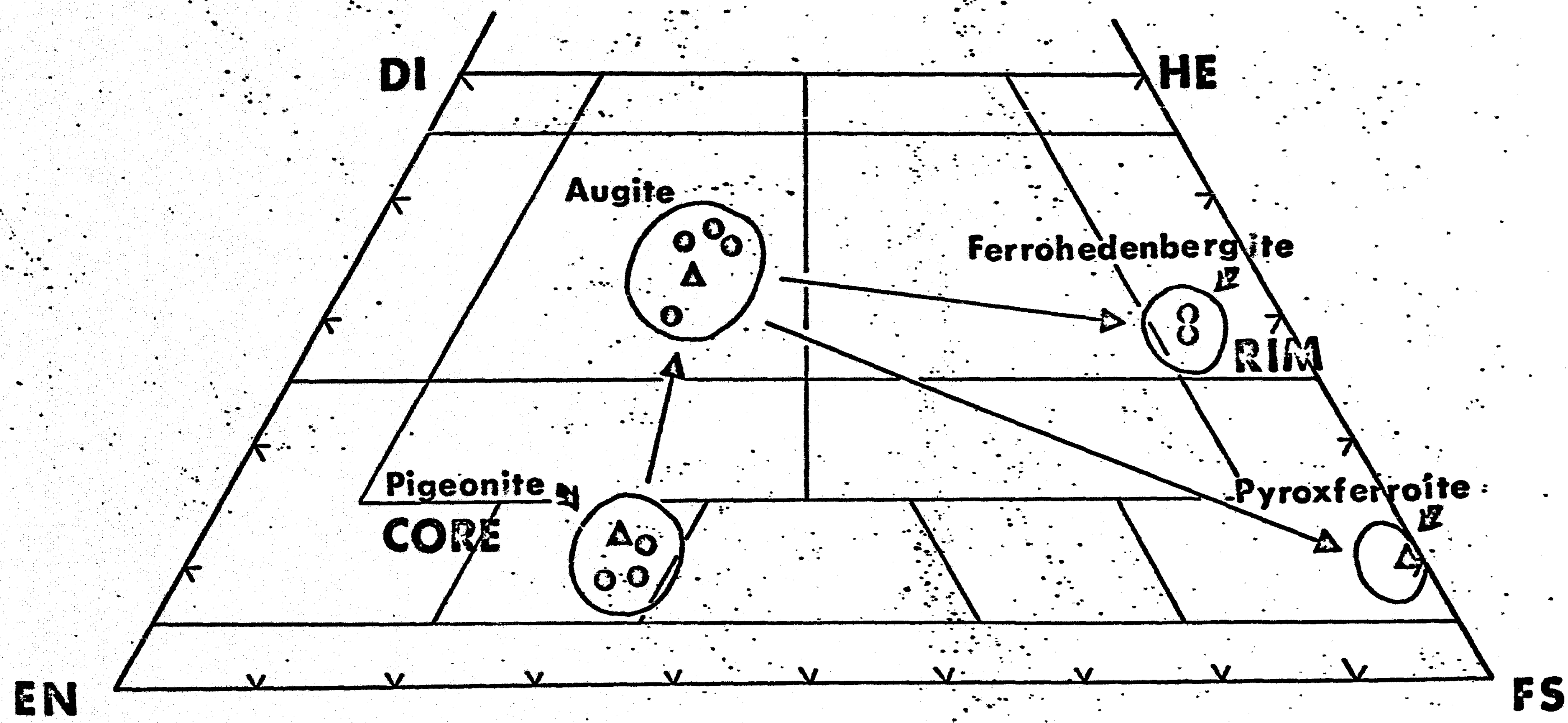

Figure 1. Compositional zoning across a single pyroxene crystal from sample 12057, projected in the system enstatite (En), ferrosilite (Fs), wollastonite (Wo); arrows indicate crystallization sequence from core (pigeonite) through mantle (augite) to rim (ferrohedenbergite); a thin zone of pyroxferroite occurs along the central fissure.