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Glass compositions in Apollo 16 soils 60501 and 61221

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Abstract—Major element analyses have been made of 309 glasses in two Apollo 16 soils, 60501 and 61221. Averages of preferred glass compositions are used as a guide to the nature of the major rock types contributing to these soils. The major glass groups in 60501 have the composition of Highland basalt (anorthositic gabbro), gabbroic anorthosite, low K Fra Mauro basalt (high alumina basalt), and anorthosite. Soil 61221 differs from any other soil we have studied in that 57 percent of the glasses have plagioclase compositions and may be either melted anorthosites or maskelynites. The abundances of glass groups in the two soils are similar except for the prominence of the gabbroic anorthosite group in 60501 and for the overwhelming abundance of glasses of plagioclase composition in 61221. In both soils glasses of Fra Mauro basalt (KREEP basalt) and mare basalt compositions are present but rare. The data indicate similarities in types, but differences in abundances, between the rocks of the Cayley–Descartes Highlands and those from the Apollonius Highlands, sampled by the Luna 20 mission.

INTRODUCTION

THE COMPOSITIONS of glass fragments in the 40 to 125 μm fraction of Apollo 16 soils 61221 and 60501 have been measured using an electron microprobe. Techniques are the same as used in previous soil surveys and as described by Reid *et al.* (1973a).

Soil 61221 is the < 1 mm fraction of the trench soil 61220 collected at Station 1, near the rim of Flag Crater, at a depth of 30–35 cm. It is part of a distinctive, white soil horizon underlying the darker surface soil 61241. 61220 has a median grain size of 250–300 μm and in that respect is similar to soils from Stations 11 and 13 near North Ray Crater (LSPET, 1972; Heiken *et al.*, 1973). Gibson and Moore (1972) suggest on the basis of major and trace element chemistry that 61221 is similar to North Ray ejecta. However, the ^{21}Ne exposure age of 61221 (Bogard and Nyquist, 1973) is 320 m.y. in contrast to ejecta from North Ray (Stations 11 and 13) that have ^{38}Ar exposure ages of 35–75 m.y. (Husain and Schaffer, 1973; Kirsten *et al.*, 1973). Exposure ages of 2–5 m.y. for South Ray Crater (Behrmann *et al.*, 1973) indicate that 61221 soil is not simply related to the time of formation of either North or South Ray Craters.

Soil 60501 is the < 1 mm fraction of a gray surface soil collected at the ALSEP

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site about 30 meters outside the west rim of a 150 meter diameter subdued crater (ALGIT, 1972). Heiken *et al.* (1973) have shown that 60501 soil has a relatively high agglutinate content and conclude that this is inconsistent with derivation from the South Ray cratering event. They suggest that such soils form part of a mature regolith developed on the Cayley Plains.

We have previously suggested that the recognition of preferred glass compositions in lunar soils may provide information on the composition of lunar rock types (Apollo Soil Survey, 1971; Warner *et al.*, 1972; Reid *et al.*, 1972a). Such studies may be particularly useful at the Apollo 16 site, where igneous rocks are rare in comparison to crystalline polymict breccias. A similar study of a Luna 20 soil from the Apollonius Highlands (Warner *et al.*, 1972; Reid *et al.*, 1973a) allows comparison with a second highlands site. Together with the orbital XRF data (Adler *et al.*, 1972a, b) and Surveyor data (Turkevich, 1971) such studies allow an estimate of the large scale, lateral chemical heterogeneity of the lunar highlands.

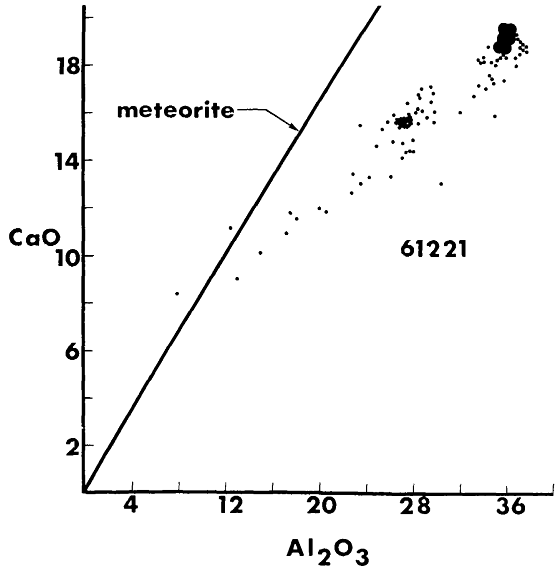
GLASS COMPOSITIONS

A total of 161 glass fragments from soil 60501, and 148 from soil 61221, were randomly selected and analyzed for Si, Ti, Al, Cr, Fe, Mg, Ca, Na, and K. The range in compositions for CaO–Al_2O_3, FeO–Al_2O_3, and FeO–MgO are shown in Figs. 1–6. Cluster analysis (Reid *et al.*, 1972a) of the 309 glasses reveals two major groupings and several minor groups (Table 1). The glass groupings are discussed individually below.

Plagioclase glass 1. This glass group has the composition of calcic plagioclase. The average composition is An_{95} with a small standard deviation for all elements. This glass type is present in both soils, but is the most abundant group in 61221 (Fig. 7). Several of these glasses occur within lithic fragments associated with ferromagnesian mineral grains, and hence are maskelynites and not glasses derived by melting of pure anorthosite. Many homogeneous glass grains of anorthitic plagioclase composition are not associated with shocked lithic fragments, and thus can either be maskelynites or melted anorthosites.

Anorthositic gabbro glass. The largest glass group in 60501 and a large, but not dominant, group in 61221 have anorthositic gabbro compositions (Table 1). This group is chemically similar to Highland basalt glasses (Reid *et al.*, 1972b) that occur as a major glass component in all lunar soils. This glass type has essentially the same composition in both soils (Table 2), and is higher in Al_2O_3, CaO, and lower in FeO and MgO than average Highland basalt from other Apollo and Luna sites (Table 2). There is a small variation in Mg/Mg+Fe ratio in this type in the individual soils, but the average ratio (0.72) is identical to that for Highland basalt glasses from other lunar soils (Table 2).

Highland basalt glasses have a remarkably uniform average composition, if Apollos 11, 12, 14, 15, Luna 16, and Luna 20 are considered. Addition of data from Apollos 16 and 17 (Table 2) increases the variability a small amount. However, all



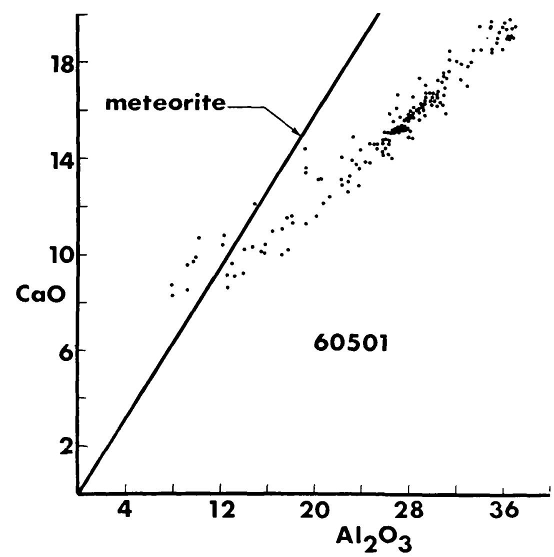


Fig. 1. CaO–Al_2O_3 wt.% plot for glasses in soil 61221. The large filled circles represent 98 analyses of plagioclase glass (also Figs. 3, 5). The meteorite line is from Ahrens and von Michaelis (1969).

Fig. 2. CaO–Al_2O_3 wt.% plot for glasses in soil 60501. Note the much smaller plagioclase glass group than in 61221 soil.

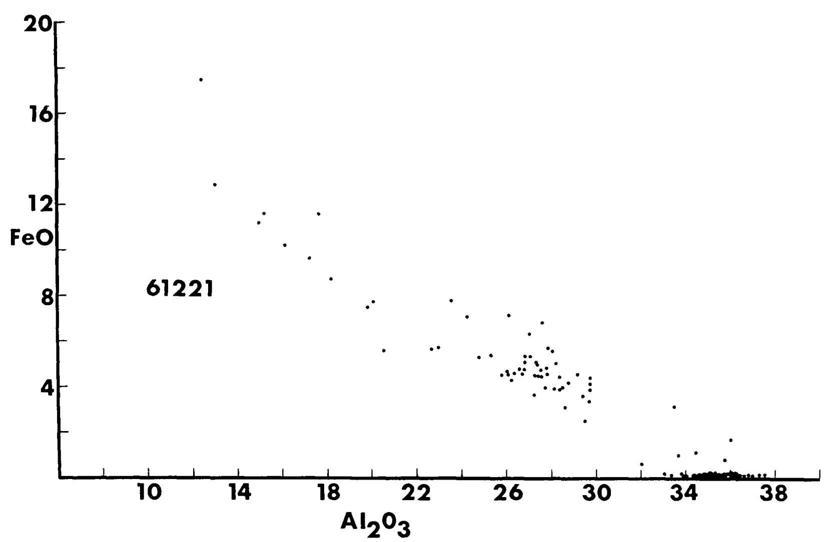


Fig. 3. FeO–Al_2O_3 wt.% plot for glasses in soil 61221.

these average glass compositions fall within the standard deviations (for nearly all elements) for any one average Highland basalt composition (Table 2).

Plagioclase glass 2. A small group of plagioclase glasses, with an average composition of An_{84} and relatively large standard deviations (Table 2) occurs in 61221, but such glasses are not represented in our sample of 60501 (Fig. 7). Lunar anorthosite fragments have feldspar compositions more calcic than An_{84}, and plagioclase glasses in the Luna 20 highland soil (Reid *et al.*, 1973a) are significantly more

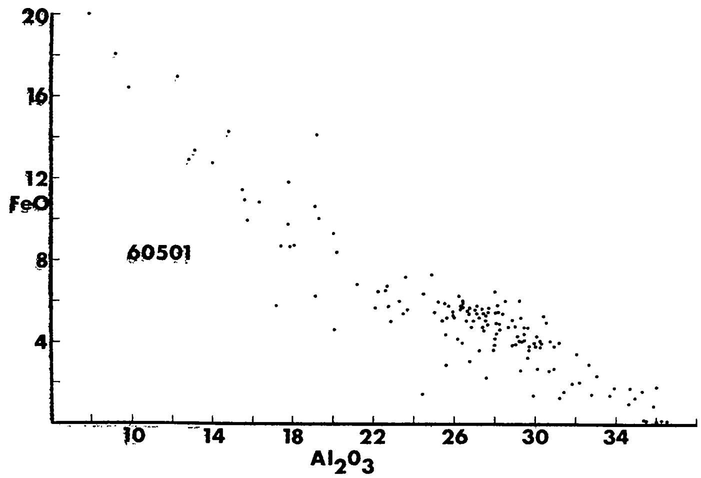


Fig. 4. FeO–Al_2O_3 wt.% plot for glasses in soil 60501.

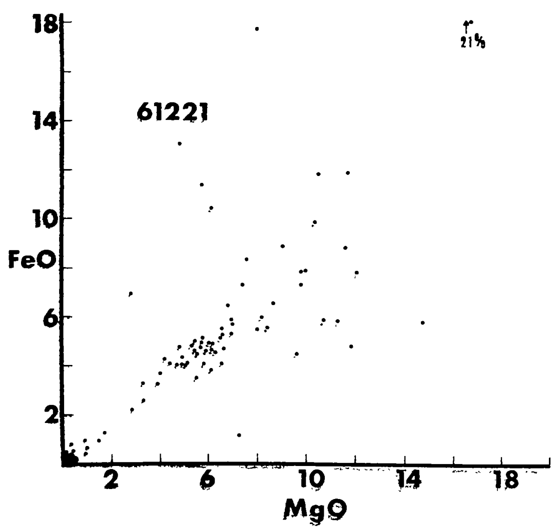


Fig. 5. MgO–FeO wt.% plot for glasses in soil 61221.

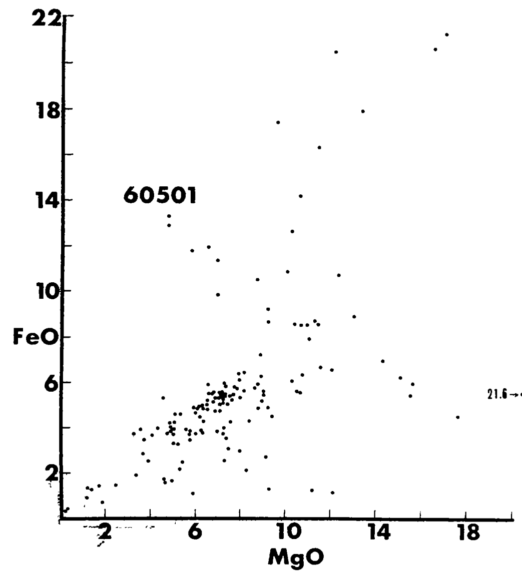


Fig. 6. MgO–FeO wt.% plot for glasses in soil 60501.

calcic than An_{84}. The compositional variability within this glass group affects only the plagioclase components indicating that this group consists of maskelynites of variable An content and not anorthosites. As the majority of highland plagioclases (Reid *et al.*, 1973a) are more calcic than plagioclase 2 glasses, it follows that many of the more calcic plagioclase 1 glasses are probably also maskelynites.

Gabbroic anorthosite glass. This group is well defined in 60501, forming over 17 percent of all analyzed glasses, but is insignificant in 61221. It is chemically intermediate between Highland basalt (anorthositic gabbro) and pure anorthosite of plagioclase glass 1 composition. The Mg/Mg+Fe ratio is higher than that of Highland basalt, high-K or low-K Fra Mauro basalt. The abundance of this glass type in 60501 is higher than in any other lunar soil we have examined. Glass

Table 1. Mean compositions and norms of glass groups in soils 61221 and 60501.

	Plagioclase Glass 1	Highland basalt (Anorthositic gabbro)	Plagioclase Glass 2	Gabbroic Anorthosite Glass	Low-K Fra Mauro Basalt Glass	High-K Fra Mauro basalt (KREEP) Glass	High-Mg Glass	Mare 1 Glass	Mare 2 Glass	Green Glass
SiO_2	44.89 (0.60)	45.35 (0.91)	48.83 (2.06)	41.95(1.41)	46.69 (2.07)	50.76 (1.55)	45.36	46.21 (1.43)	41.98	44.14 (0.48)
TiO_2	0.04 (0.08)	0.43 (0.22)	0.08 (0.05)	0.35 (0.22)	0.75 (0.45)	2.54 (1.07)	0.19	1.76 (1.53)	7.92	0.37 (0.06)
Al_2O_3	35.76 (0.84)	27.63 (1.49)	33.36 (1.70)	30.94 (2.73)	21.53 (2.47)	15.63 (2.55)	15.41	14.34 (3.88)	9.98	7.81 (0.02)
Cr_2O_3	—	0.07 (0.04)	—	0.04 (0.03)	0.11 (0.06)	0.15 (0.04)	0.25	0.29 (0.10)	0.42	0.33 (0.07)
FeO	0.18 (0.27)	4.62 (0.97)	0.22 (0.19)	3.46 (1.84)	6.89 (1.85)	11.05 (2.13)	8.46	14.86 (3.35)	16.98	21.05 (0.36)
MgO	0.12 (0.30)	6.13 (1.40)	0.05 (0.08)	6.24 (2.53)	10.36 (1.73)	7.13 (2.12)	21.10	10.31 (1.84)	10.43	16.72 (0.24)
CaO	19.03 (0.49)	15.64 (0.82)	16.27 (1.53)	17.26 (1.56)	12.86 (0.98)	10.22 (1.09)	9.55	11.00 (1.43)	10.14	8.41 (0.23)
Na_2O	0.55 (0.21)	0.42 (0.23)	1.82 (0.62)	0.12 (0.13)	0.31 (0.23)	0.85 (0.25)	0.17	0.36 (0.21)	0.39	0.13 (0.07)
K_2O	0.03 (0.03)	0.05 (0.05)	0.11 (0.07)	0.01 (0.02)	0.08 (0.09)	0.65 (0.42)	0.01	0.10 (0.09)	0.10	0.03 (0.03)
QZ	0.50	—	2.76	—	—	6.51	—	—	—	—
OR	0.18	0.30	0.65	—	0.47	3.84	0.06	0.59	0.59	0.18
AB	4.65	3.55	15.40	—	2.62	7.19	1.44	3.05	3.30	1.10
AN	94.41	73.36	80.72	83.86	57.12	36.91	41.26	37.22	25.19	20.64
DI	—	3.43	—	—	5.39	11.37	4.89	14.33	20.54	17.39
HY	0.56	12.09	0.40	—	26.84	28.11	19.02	33.47	31.19	24.38
OL	—	6.70	—	15.32	5.55	—	33.11	6.80	2.07	34.12
CH	—	0.10	—	0.06	0.16	0.22	0.37	0.43	—	0.49
IL	0.08	0.82	0.15	0.56	1.42	4.82	0.36	3.34	15.04	0.70
Mg/Mg + Fe in normative silicates	—	72	—	78	75	59	82	58	65	59
No. of Samples	103	111	7	30	29	13	2	9	2	3
Rel. abund. 60501	11.8	44.7	0	16.8	13.0	5.6	1.2	4.3	1.2	1.2
Rel. abund. 61221	56.8	26.4	4.7	2.0	5.4	2.7	0	1.4	0	0.7

Numbers in parentheses are one standard deviation.

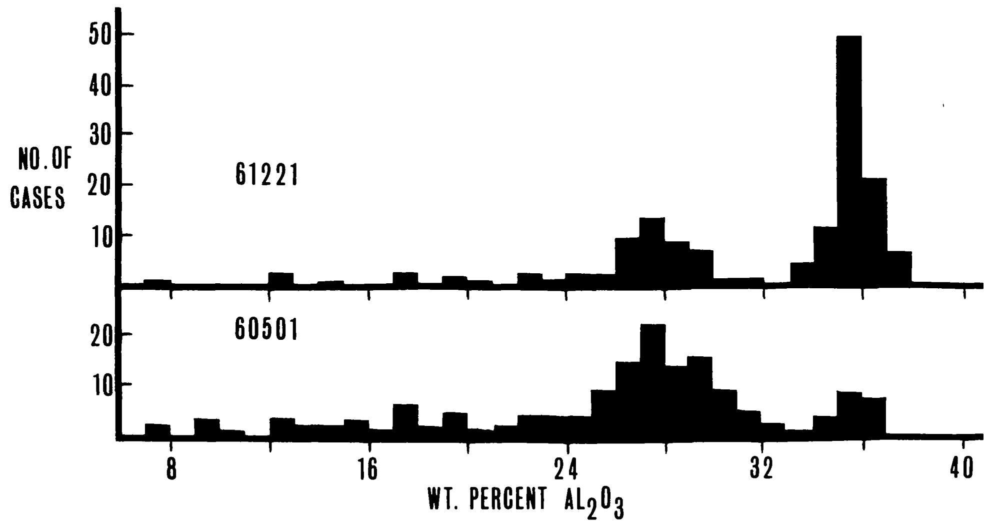


Fig. 7. Histogram of Al_2O_3 contents of 61221 and 60501 glasses.

Table 2. Major element composition of Highland basalt glasses in 60501 and 61221, and some comparisons.

	60501	61221	74240	H.B. average	78155
SiO_2	45.24 (0.93)	45.54 (0.86)	45.46 (1.10)	44.81	45.57
TiO_2	0.44 (0.25)	0.42 (0.17)	0.46 (0.20)	0.37	0.27
Al_2O_3	27.61 (1.62)	27.68 (1.23)	25.13 (1.81)	25.83	25.94
Cr_2O_3	0.06 (0.04)	0.07 (0.03)	0.12 (0.03)	0.10	—
FeO	4.63 (1.04)	4.60 (0.83)	5.72 (1.47)	5.61	5.82
MgO	6.40 (1.40)	5.62 (1.25)	9.25 (1.12)	8.01	6.33
CaO	15.59(0.85)	15.73 (0.75)	14.05 (0.88)	14.79	15.18
Na_2O	0.37 (0.23)	0.49 (0.20)	0.25 (0.12)	0.22	0.33
K_2O	0.05 (0.05)	0.05 (0.03)	0.05 (0.03)	0.03	0.08
OR	0.30	0.30	0.30	0.2	0.5
AB	3.13	4.15	2.12	1.9	2.8
AN	73.53	73.18	67.30	69.4	69.1
DI	3.08	3.94	1.93	3.2	5.1
HY	12.22	12.27	17.89	14.5	16.4
OL	7.21	5.49	10.00	9.8	5.2
CH	0.09	—	0.18	0.2	—
IL	0.84	0.80	0.87	0.7	0.5
Mg/Mg + Fe in normative silicates	0.73	0.70	0.75	0.73	0.67

Standard deviations are in brackets. Data from this work and Reid *et al.* 1973b (Apollo 17). H.B. average is the average of median Highland basalt compositions from glasses in Apollo 11, 12, 14, 15, Luna 16, and 20 soils. 78155 is one of the highly aluminous rocks from the Apollo 17 mission (LSPET, 1973).

groups intermediate between Highland basalt and anorthosite, and spanning a range of 28–33 wt.% Al_2O_3, have been recognized in Apollo 11, 12, and 14 soils, but are always subordinate to the less aluminous glass groups.

Low-K Fra Mauro basalt glass (LKFM). This group of aluminous basaltic glasses are distinguished by their general similarity to KREEP basalt compositions, but they have lower K_2O, TiO_2, and higher Al_2O_3, MgO contents and Mg/Mg + Fe ratio than KREEP (Table 2). LKFM is also significantly more silica undersaturated than KREEP basalt (Table 3).

Both soils contain LKFM, although more glasses of this type occur in 60501 (Table 1). Compared to Apollo 15 LKFM (Reid *et al.*, 1972c), the Apollo 16 glass group is lower in TiO_2, FeO and higher in Al_2O_3, CaO and Mg/Mg + Fe ratio. LKFM in the Luna 20 soil (Warner *et al.*, 1972) is very similar to Apollo 16 LKFM except for the slightly lower FeO content of the latter.

Fra Mauro basalt glass (KREEP). Reid *et al.* (1972c) distinguish medium- and high-K Fra Mauro basalt glass in the Apollo 15 soils, but such glasses are not common in the two Apollo 16 soils and no subdivision can be made. The Apollo 16 K-rich glasses most closely resemble the high-K variety (Table 1) and are

Table 3. Major element composition of Apollo 16 low-K Fra Mauro basalt and some comparisons.

	Apollo 16	Luna-20	Apollo 15	Luna-16	Apollo 17
SiO_2	46.69 (2.07)	46.09 (2.10)	46.56 (1.78)	46.0	47.08 (2.25)
TiO_2	0.75 (0.45)	0.79 (0.56)	1.25 (0.45)	1.0	1.08 (0.92)
Al_2O_3	21.53 (2.47)	20.11 (3.14)	18.83 (1.85)	20.7	19.29 (2.65)
Cr_2O_3	0.11 (0.06)	0.19 (0.06)	0.20 (0.05)	—	0.23 (0.07)
FeO	6.89 (1.85)	9.36 (3.01)	9.67 (1.88)	9.8	8.76 (2.25)
MgO	10.36 (1.73)	10.27 (2.00)	11.04 (1.61)	8.8	11.50 (1.91)
CaO	12.86 (0.98)	12.60 (1.13)	11.60 (0.93)	13.0	11.76 (1.14)
Na_2O	0.31 (0.23)	0.37 (0.21)	0.37 (0.14)	0.4	0.27 (0.16)
K_2O	0.08 (0.09)	0.08 (0.07)	0.12 (0.07)	0.12	0.04 (0.04)
OR	0.5	0.47	0.7	0.7	0.2
AB	2.6	3.1	3.2	3.4	2.3
AN	57.1	53.0	49.3	54.3	51.3
DI	5.4	7.8	6.7	8.3	5.7
HY	26.8	23.6	30.1	23.0	33.1
OL	5.6	10.1	7.0	8.2	4.9
CH	0.2	0.3	0.3	—	0.3
IL	1.4	1.5	2.4	1.9	2.1
Mg/Mg + Fe in normative silicates	0.75	0.68	0.67	0.64	0.73

Standard deviations, where available, are in brackets. Data from this work; Reid *et al.*, 1973a (Luna 20); Reid *et al.*, 1972c (Apollo 15); Reid *et al.*, 1973a (Luna 16); Reid *et al.*, 1973b (Apollo 17).

characterized by high K_2O, TiO_2, and relatively low Mg/Mg + Fe ratio. There is a strong positive correlation between K_2O and TiO_2, both of which are negatively correlated with the Mg/Mg + Fe ratio. These glasses are less abundant than LKFM glasses, as was also observed in the Apollo 15 Front soils (Reid *et al.*, 1972c), where high-K Fra Mauro basalt is noticeably subordinate to moderate- and to low-K Fra Mauro basalt. In the Luna 20 soil the high-K variety is virtually absent (Warner *et al.*, 1972).

High-Mg glasses Two glasses were found that are very rich in Mg and Al but quite low in Fe (Table 1, high-Mg glass). The Mg/Fe ratio in these glasses is very high, resembling the ratios found for lunar troctolite fragments but the overall chemistry is outside the range of (spinel) troctolites as defined by Prinz *et al.* (1973a).

Mare basalt glass. Glasses that are iron-rich, and alumina poor, and hence probably derived from mare regions, are rare in both 60501 and 61221 (Table 2). Mare 1 glass (Table 1) is very similar to the mare basalt glass component in the Luna 20 soil (Warner *et al.*, 1972) and Mare 2 glass resembles the high Ti mare-type glasses found in nearly all lunar soils (Reid *et al.*, 1972a; Reid *et al.*, 1973b). These mare-type glasses, including the green glass, make up 5 percent of the total glass population.

Green glass. These rare glasses are distinctive both in their color and chemistry. They are very high in FeO, MgO, and low in TiO_2 and Al_2O_3 compared to any other glass group in the soils (Table 1) and are identical to the green glasses, found in great abundance in some Apollo 15 soils (LSPET, 1972a), that represent one of the most chemically invariant glass groups in the lunar soil. Taken in this broader context, the rare green glasses examined from the Apollo 16 site are treated as a separate group.

DISCUSSION

Significance of glass groups

Our data and those of several workers has shown that, provided a large enough number of glasses are analyzed, preferred compositional groupings can be discerned. We use a cluster analysis technique (Reid *et al.*, 1972a) to determine these groupings because this technique eliminates subjective grouping of the data. The major clusters are recognizable when two elements are compared, in plots such as Figs. 1–6, but these are poor representations of the total 9-element matrix that is considered by the cluster analysis program. Using this technique we have arrived at the glass groups described above. Along with several workers in the field we believe these can be used as a guide to the nature of lunar rocks contributing to these soils (Apollo Soil Survey, 1973). As evidence supporting this conclusion we note that: (1) with the exception of the feldspathic glasses, there are no monomineralic glasses; (2) the same glass groupings can be recognized in soils of different bulk compositions and from different selenographic locations; (3) there is a good correspondence between glass compositional groupings and lithic fragments from soils and breccias (*see* summary in Reid, 1973); and (4) large rocks equivalent in composition to the major highland glass groups have been returned from the moon (LSPET, 1972a, b, 1973). For these reasons we use rock names, based on selenographic location or on normative mineralogy, for the glass groups.

Proportions of glass groups

The disparity between the proportions of glass groups in 60501 and 61221 primarily reflects the high abundance of plagioclase glass in 61221. The true abundance of glass derived from anorthosite is, however, unknown as the proportion of these glasses that are maskelynites is unknown. LSPET (1972b) and Taylor *et al.* (1973) have shown that the Apollo 16 rocks, including the soils, are extremely aluminous and that the site must contain a high proportion of anorthosite. Both 60501 and 61221 soils have glass groupings consistent with these conclusions. Gibson and Moore (1973) contend that the high volatile element content of 61221 results from cometary-impact production of this soil. We note that this soil is also unique in its unusually high content of plagioclase glass.

Glasses with the composition of anorthosite, gabbroic anorthosite, Highland basalt, and low-K Fra Mauro basalt are the most abundant glass types in soils 60501 and 61221. We deduce that the crystalline equivalents of these glasses are the dominant rock types in the area of the Apollo 16 site. Taylor *et al.* (1973), using a mixing model approach, conclude that Highland basalt and low-K Fra Mauro basalt predominate in a spectrum of Apollo 16 samples and the proportion of these two components is approximately the same as estimated in this study.

Comparison of Cayley–Descartes Region with the Apollonius Highlands.

The major highland rock types recognized in the Luna 20 glasses (Warner *et al.*, 1972) have also been recognized in Apollo 16 soils 61221 and 60501. However, the differences in major element chemistry between the Luna 20 soil (e.g., Vinogradov, 1972) and all the Apollo 16 soils clearly indicate that the proportions of highland rock types are different at the two sites. The glass data indicate that the mare component is more prominent at the Luna 20 site than at the Apollo 16 site, as a consequence of the close proximity of the Apollonius region to large mare areas.

The Luna 20 glasses are dominated by Highland basalt glass; anorthosite comprises less than 10 percent of the glasses and gabbroic anorthosite was not recognized as a separate glass group. The Luna 20 anorthosites are slightly less calcic than those found at the Apollo 16 site, but all are characterized by normative plagioclase with a composition more calcic than An_{90}.

In both regions low-K Fra Mauro basalt (LKFM) is a major glass component. At the Luna 20 site this rock type has also been recognized as lithic fragments (low alkali high alumina basalt, Prinz *et al.*, 1973a). In the nearby Mare Fecunditatis soil at the Luna 16 site (Table 3; Reid *et al.*, 1972a) LKFM glasses have also been recognized. The composition of LKFM basalt as determined from the glasses is slightly variable from site to site (Table 3). LKFM basalt at the Apollo 16 site has a higher Mg/Mg+Fe ratio than at the Luna 20 site (Table 3) but otherwise is very similar to the Luna 20 composition. Several elements (K_2O, TiO_2, SiO_2, MgO, FeO) combine to distinguish LKFM from KREEP basalt, and it cannot be considered as KREEP basalt that has undergone alkali loss (see also Prinz *et al.*, 1973b) or as a mixture of KREEP basalt and Highland basalt (Warner *et al.*, 1972).

High-K Fra Mauro basalt (KREEP) is not abundant at the Apollo 16 or the Luna 20 site, and preliminary data (Reid *et al.*, 1973c) suggest that this is also true for the Apollo 17 site. Orbital gamma-ray data (Metzger *et al.*, 1972; Arnold *et al.*, 1972) initially indicated the distinct provinciality of KREEP basalt, and it is clear from the soil data that the highlands east of Oceanus Procellarum contain a relatively small amount of KREEP.

Comparison of Apollo 16 and Luna 20 glasses demonstrate that the detailed evolution of these two highland areas has been different. At the Apollo 16 site the shallow crust contains much more anorthositic material than at the Luna 20 site. The individual glass types present at the Apollo 16 site are slightly more aluminous than at the Luna 20 site, but our techniques are not refined enough to evaluate such small differences in chemistry.

*Highland basalt and low-*K *Fra Mauro basalt*

The origin of Highland basalt remains controversial. Origins by physical mixing of aluminous rocks (e.g., Bansal *et al.*, 1973) or by true igneous processes either as a magma or as an igneous cumulate (e.g., Reid *et al.*, 1972b) have been suggested.

Derivation of glasses of this composition by melting of well mixed highland regolith seems unlikely since Highland basalt occurs as a significant glass component in both the Luna 20 soil, Apollo 16 soil, and Apollo 17 soil, all of which have different major element bulk compositions. Similar diversity characterizes the highlands on a regional scale (Adler *et al.*, 1972a, b) and there is no reason to assume that melting of such diverse regoliths would produce Highland basalt glass. Reid *et al.* (1972b) suggested that material of Highland basalt composition is a dominant rock type in the lunar highlands. Variations in abundance of this rock type in the highlands are to be expected and can be demonstrated from Apollo 16 and Luna 20 data.

Mixing of highland materials, e.g., VHA basalt with more anorthositic material as suggested by Bansal *et al.* (1973) to form Highland basalt is also unlikely. If one end-member of this process is anorthosite, then severe restrictions are placed on the Mg/Mg+Fe ratio of the other end member to give the Mg/Mg+Fe ratio of Highland basalt at 0.72. Variations in major element compositions of published analyses of VHA basalt are substantial and do not allow a more detailed treatment of the model in terms of major elements. To produce the rather limited compositional range of Highland basalt a more specific major element composition than VHA basalt, as presently defined, would be required as an end member.

Reid *et al.* (1972b) have stressed the widespread occurrence and chemical uniformity of Highland basalt, and have postulated that igneous processes acting on a regional scale have produced Highland basalt. Prinz *et al.* (1973a) and Walker *et al.* (1973) have shown that the major highland rocks can be related to each other in terms of crystal-liquid processes without recourse to physical mixing at the lunar surface. Highland basalt must play a role in any model that invokes crystal-liquid processes to derive the observed spectrum of aluminous highland rocks.

The Apollo 16 soil data indicate that low-K Fra Mauro basalt is as regionally ubiquitous in the lunar highlands as Highland basalt. This compositional type was initially recognized as a glass grouping in the Luna 16 and Apollo 15 soils (Reid *et al.*, 1972a, 1972c), and its importance at the Luna 20 site has been stressed by Reid *et al.* (1973a) and Prinz *et al.* (1973a). Its further discovery at the Apollo 16 and Apollo 17 sites (Reid *et al.*, 1973c) emphasizes its wide-spread distribution in the lunar highlands.

The low K_2O content of LKFM basalt suggests that the incompatible trace elements (REE, Rb, Zr, Nb, etc.) will also be significantly lower than in KREEP basalts. Data from Prinz *et al.* (1973b), Taylor *et al.* (1973) and Laul and Schmitt (1973) suggest values for REE etc. at least one-third the concentrations in KREEP basalts. Some VHA basalts (Bansal *et al.*, 1973) also have major element concentrations similar to LKFM basalt, and have distinctive REE abundances. Walker *et al.* (1973) note the difficulty of segregating KREEP liquids by partial melting of an aluminous source region because the degree of melting would be very small. Similar generation of LKFM basalt would involve a higher degree of partial melting, and magma could be more easily segregated. The LKFM basalt composition lies very close to a peritectic piercing point in the pseudoternary system, silica–olivine–plagioclase, and hence has a composition that would be generated as an early liquid during melting of a source region composed of feldspar, olivine, and pyroxene, ± spinel (Walker *et al.*, 1973). Walker *et al.* (1973) suggest that rocks of the anorthosite–norite suite provide a suitable source material for Fra Mauro basalts whereas Prinz *et al.* (1973a) consider a melt of LKFM basalt (high-alumina basalt) composition to be a primary magma type from which the more anorthositic rocks and the troctolites may be derived as cumulates. Both Highland basalt and LKFM basalt are apparently ubiquitous in the highlands. The problem remains however of distinguishing possible parental material from cumulate material since partial melting processes that have produced highland magmas and accumulation processes that produce highland cumulates, all have progressed in a low-pressure environment and involve a restricted number of minerals. The inferred abundances of Highland basalt and LKFM basalt would be consistent with Highland basalt being the source material from which LKFM basalt was derived by partial melting. Major element chemistry and abundance data seem insufficient to unequivocally resolve this situation, and trace element and isotopic studies will have to be integrated with major element data, in deriving crustal models.

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