

GEOCHEMISTRY OF THE LUNAR HIGHLANDS*

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Abstract. The principal rock types in the highlands are highland basalt (gabbroic anorthosite) with 28% Al_2O_3 and low K Fra Mauro basalt with 18% Al_2O_3 . The chemistry of the highland soils and breccias can be represented by simple mixing models involving these rock types as major constituents. The mixing occurred during the intense highland cratering. Layering observed at the Apennine Front is interpreted as produced the Serenitatis basin collision. The plains-forming Cayley Formation and the Descartes Formation are not volcanic, but are derived from pre-existing highland crust.

Although the overall chemical composition of the Moon has been affected by pre-accretion processes (e.g. loss of volatile elements), the composition of the highlands is mainly the result of post-accretion melting and element fractionation. Thus the individual rock types show involatile element distribution patterns, relative to primitive abundances, indicative of solid-liquid equilibria, evidence of post-accretion lunar igneous activity.

The chemistry of the primitive green glass component (15426) indicates that the abundance of the involatile elements (REE, Ba, Zr, Hf, Th and U) in the source regions is at most only 2–3 times the abundances in chondrites.

1. Introduction

The highlands form the oldest exposed areas on the surface of the Moon, and are known to be chemically distinct both from the maria and the whole Moon. The samples returned from the highlands are in general intensely brecciated, so that simple stratigraphic or chemical relationships are obscured. The aim of this study is to attempt to unravel the apparently complex chemical compositions of the breccias, in order to shed light on the following questions: (1) Are the highlands simple or complex chemically; (2) was the observed chemically fractionated crust formed after accretion of the Moon; or (3) was it due to a late accretion of a chemically distinct Al-rich layer; or (4) is the present lunar crust the result of both heterogeneous accretion and later melting and chemical fractionation.

2. Sources of Evidence for Highland Compositions

The first direct information on lunar highland composition was obtained from the Luna-10 orbiting gamma ray experiment (Vinogradov *et al.*, 1966). This experiment indicated that the potassium content over the highlands was apparently lower than over the maria, contrary to expectations that the highlands might be 'granitic'.

The next data, from the soft-landing Surveyor 7 on the ejecta blanket at Tycho revealed high aluminium and low iron compositions (Turkevich *et al.*, 1968). Extensive searches were made in the maria soils returned by the Apollo 11 and 12 missions, since it was apparent that part of the regolith (estimated at 5% for the Apollo 11 site

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by Shoemaker *et al.*, 1970) would be derived as impact ejecta from highland regions. This study led to the recognition of an anorthositic component of non-mare origin (Wood *et al.*, 1970; Marvin *et al.*, 1971) and of a non-mare basalt (KREEP) enriched in potassium, rare earths and associated elements (Meyer *et al.*, 1971). Similar material was collected from the first direct sampling of the highlands by the Apollo 14 mission to the Fra Mauro Formation. This represented ejecta from the Imbrium Collision, and hence pre-Imbrium crust, probably from the upper 10 km. The high concentration of radioactive elements, rare earths etc. approached or exceeded those observed in the Earth's crust.

The Apollo 15 mission to the Hadley-Apenine region, sampled the base of the Apennine Front. Although the stratigraphic position of the samples collected cannot be related directly to depth beneath the pre-Imbrium surface (because of slumping, later cratering etc.) the possibility remains that material from deep within the crust was sampled. However it is possible that much of the front material was from the Serenitatis basin impact.

The Russian Luna-20 mission returned samples from the Apollonius highlands, between Mare Crisium and Mare Fecunditatis. This area is dominated by ejecta from the impacts forming these two basins.

The Apollo 16 mission to the Descartes region, collected the first highland material remote from the maria basins. Two of the units established by photogeological mapping techniques, were sampled. These were the Cayley Formation, the major plains forming unit of the highlands, and the associated hilly Descartes Formation. The ages of these formations are interpreted as post-Imbrium collision – pre-mare basin fill (Trask and McCauley, 1972; Wilhelms, 1971).

Both Apollo 15 and 16 missions carried out orbital XRF and gamma ray remote sensing experiments (Adler, 1972; Metzger *et al.*, 1972) providing detailed information on the distribution of Si, Al, Mg and the radioactive elements. The orbiting XRF data confirms that the highlands in general are alumina-rich and that they are broadly uniform in composition, although areal differences exist with Al/Si ratios varying from 0.51 to 0.71, and Mg/Si ratios from 0.16 to 0.28. Ground truth for these observations is well established. For example, Al/Si and Mg/Si ratios of 0.67 and 0.18 were measured at the Apollo 16 site (Adler, 1972). Values of 0.68 and 0.19 were obtained from the laboratory analysis of Apollo 16 soil 68501 (Table II, Taylor *et al.*, 1972a; LSPET, 1972).

3. Rock Types in the Highlands Samples

Reid *et al.* (1972) in a survey of the Apollo soil samples, carried out numerous electron probe analyses of glass particles. By applying cluster analysis to these data, preferred groupings emerge. These are interpreted as indicating the dominant rock types being fused by meteoritic impact. This useful statistical approach has succeeded in distinguishing four types of mare basalt, three types of Fra Mauro basalt, a highland basalt and a green glass component as major constituents of lunar soils. An

advantage is that other lunar analytical data from individual samples (such as clasts from breccias) can be evaluated and interpreted against a broad picture of lunar surface compositions. In the following discussion, this approach is used to evaluate the trace element data from Apollo 14, 15 and 16 soils and breccias. By this means, it is possible to utilise these data to provide abundance estimates for many elements in common highland rock types.

A. HIGHLAND BASALT (GABBROIC ANORTHOSITE)

The most distinctive feature of this major component of the highlands is the high Al_2O_3 content (28%). This rock type has received various names, based on supposed terrestrial analogies. None of them are particularly suitable and the compromise title given above is adopted, rather than coin yet another name. The average major element composition of this rock from Reid *et al.* (1972) is given in Col. 1A, Table I. This compares closely with that of the white portion of the 'black and white' breccia (15455) given in Col. 1B, Table I. The trace element data for this sample (Col. 1, Table II) are used accordingly as approximating that of highland basalt (gabbroic anorthosite). REE patterns for this, and succeeding rock types are given in Figure 1.

TABLE I
Average major element composition of various major rock types

	Highland basalt		Low K Fra Mauro		Medium K Fra Mauro		High K Fra Mauro		Green Glass	
	(1A)	(1B)	(2A)	(2B)	(3A)	(3B)	(4A)	(4B)	(5A)	(5B)
SiO_2	44.4	44.4	46.6	47.3	49.6	47.2	53.4	53.3	45.3	45.6
TiO_2	0.43	0.07	1.25	1.35	1.43	1.75	2.08	1.50	0.42	0.29
Al_2O_3	28.0	26.2	18.8	17.1	17.6	18.2	15.6	12.7	7.72	7.67
FeO	5.05	4.2	9.67	8.79	9.52	10.5	10.3	13.0	19.6	19.7
MgO	6.86	10.9	11.0	13.3	8.94	8.89	5.77	8.3	17.5	16.6
CaO	15.6	14.3	11.6	10.6	10.8	11.5	9.57	8.4	8.34	8.72
Na_2O	0.19	0.36	0.37	0.58	0.74	0.68	1.01	1.05	0.12	0.12
K_2O	0.01	—	0.12	0.17	0.47	0.48	1.11	1.12	0.01	—
Cr_2O_3	0.08	0.06	0.20	0.26	0.17	0.15	0.12	—	0.43	0.41
Σ	100.6	100.5	99.6	99.5	99.3	99.4	99.0	99.4	99.4	99.1
Al/Si	0.71	0.67	0.46	0.41	0.40	0.44	0.33	0.27	0.19	0.19
Mg/Si	0.20	0.32	0.31	0.36	0.23	0.24	0.14	0.20	0.50	0.47

(1A) 36 analyses (Reid *et al.*, 1972, Table II)

(1B) White portion 15455 Anal. Ware

(2A) 82 analyses (Reid *et al.*, 1972, Table II)

(2B) Black portion 15455 Anal. Ware

(3A) 90 analyses (Reid *et al.*, 1972, Table II)

(3B) Apollo 14 breccia 14047 (Taylor *et al.*, 1972b)

(4A) 29 analyses (Reid *et al.*, 1972 Table II)

(4B) 12013, 10-35 (Wakita and Smith, 1970, p. 171; MgO, Hubbard *et al.*, 1970, p. 182)

(5A) 187 analyses (Reid *et al.*, 1972, Table II)

(5B) 15426 spherules. Anal. Ware

TABLE II

Average elemental abundances of various rock types. Data in ppm unless indicated as wt %. -: no data

	Highland basalt	Low K Fra Mauro	Medium K Fra Mauro	High K Fra Mauro	Green Glass	Apollo 16 Soil
	(1)	(2)	(3)	(4)	(5)	(6)
Cs	—	0.16	1.0	1.3	—	0.09
Rb	—	2.7	15	21	0.34	2.3
K %	0.008	0.13	0.40	0.93	—	0.13
Ba	42	370	730	1850	17	185
Eu	1.67	1.82	2.60	2.2	0.21	1.29
Pb	1.0	3.0	7	—	0.53	2.2
Sr	270	141	212	148	24	170
Ca %	10.2	7.55	8.21	6.0	6.23	10.8
Na %	0.27	0.43	0.50	0.78	0.089	0.27
K /Rb	—	480	267	440	—	565
Rb/Cs	—	17	15	16	—	26
Ba/Rb	—	137	49	88	50	80
Rb/Sr	—	0.019	0.071	0.14	0.014	0.014
Sr /Eu	162	78	81	67	115	132
La	3.0	32	80	37	1.4	15.7
Ce	6.7	81	214	92	3.8	41.5
Pr	0.95	11.5	26	—	0.53	5.54
Nd	3.73	47	102	47	2.2	21.6
Sm	0.88	12.8	28	14	0.76	6.32
Eu	1.67	1.82	2.60	2.2	0.21	1.29
Gd	0.95	15.5	31	—	0.91	7.57
Tb	0.14	2.41	4.7	—	0.15	1.23
Dy	0.84	16	33	22	1.10	8.35
Ho	0.17	3.76	8.0	—	0.27	1.92
Er	0.46	10.7	19	16	0.80	5.45
Tm	0.06	1.6	3.3	—	0.15	0.75
Yb	0.36	9.8	19	20	0.93	4.95
Lu	0.06	1.5	—	2.7	0.14	0.75
Σ REE	20.0	247	571	—	13.4	123
Y	4.8	93	191	240	7.2	49
Σ REE + Y	24.8	340	762	—	20.6	172
La /Yb	8.3	3.27	4.2	1.85	1.50	3.24
Gd/Eu	0.57	8.51	11.9	—	4.33	5.87
Eu/Eu*	6.4	0.43	0.25	—	0.86	0.61
Eu ^x	0.26	4.23	10.4	—	0.24	2.1
Th	0.23	5.31	12	12	0.16	2.45
U	0.05	1.37	3.2	4.6	0.04	0.63
Zr	11	480	928	2200	22	220
Hf	0.17	9.8	17	20	0.42	4.0
Sn	0.67	0.22	0.4	—	0.12	0.12
Nb	0.95	33	67	170	1.5	14.9
Ti %	0.26	0.81	1.05	0.90	0.17	0.34

Table II (Continued)

	Highland basalt (1)	LowK Fra Mauro (2)	Medium K Fra Mauro (3)	High K Fra Mauro (4)	Green Glass (5)	Apollo 16 Soil (6)
Th/U	4.2	3.9	3.75	2.6	4.0	3.87
K /U	1600	950	1250	2700	—	2060
Zr/Hf	38	49	54	110	53	55
Zr/Nb	12	14.5	14	13	15	14.8
Cr	440	1800	1220	2300	2800	1000
V	16	39	43	100	150	27
Sc	—	13	23	38	43	6
Ni	12	184	370	—	170	420
Co	10	22	34	25	72	34
Cu	1.3	3.3	—	—	3.5	4.5
Fe %	3.23	6.8	8.2	10.1	15.3	4.11
Mn	—	—	1100	1550	1600	—
Zn	—	—	—	3	—	—
Mg %	6.55	8.0	5.36	5.0	9.98	3.80
Li	—	—	—	100	—	—
Ga	2.6	3.3	4.1	6.0	4.7	4.3
Al %	13.8	9.1	9.6	6.72	4.06	14.2
Si %	20.7	22.1	22.0	24.9	21.3	21.0
V/Ni	1.3	0.21	0.12	—	0.88	0.064
Cr/V	28	46	28	23	19	37
Ni/Co	1.2	8.4	11	—	2.4	12
Fe/Ni (x10 ⁴)	2690	370	221	—	900	98
Al/Ga	5.3	2.8	2.4	1.1	0.9	3.3

(1) Highland basalt (gabbroic anorthosite) 15455 white Anal. A.N.U.

(2) Low K Fra Mauro basalt, 15455 black Anal. A.N.U.

(3) Medium K Fra Mauro basalt 14047 (Taylor *et al.*, 1972b) values adjusted for Rb, Sr, Ce, Yb, Zr and Nb following recalibration.

(4) High K Fra Mauro basalt. Data for Si, Ti, Al, Fe, Ca, Na, K, Mn, Cr, V, Sc, Hf, Th, U from Wakita and Smith (1970), for Cs, Zn, from Laul *et al.* 1970, for Rb, Ba, Sr, REE from Hubbard *et al.* (1970), for Zr, Nb, Yb, Li, Y, from LSPET (1970)

(5) Green glass from 15426. Anal. A.N.U.

(6) Apollo 16 soil 68501 (Taylor *et al.*, 1972a).

B. LOW K FRA MAURO BASALT

This is an important constituent at the Apollo 15 site, and probably over much of the highlands. It shows many of the characteristics of Fra Mauro basalts (KREEP) such as an Al₂O₃ content of about 18%, but is lower in potassium. The composition of this unit from Reid *et al.* (1972) is given in Col. 2A, Table I. This is close to that of the black portion of the 'black and white' breccia (15455) given in Col. 2B, Table I. The trace element data for this sample (Col. 2, Table II) are used as approximating to that of low K Fra Mauro basalt.

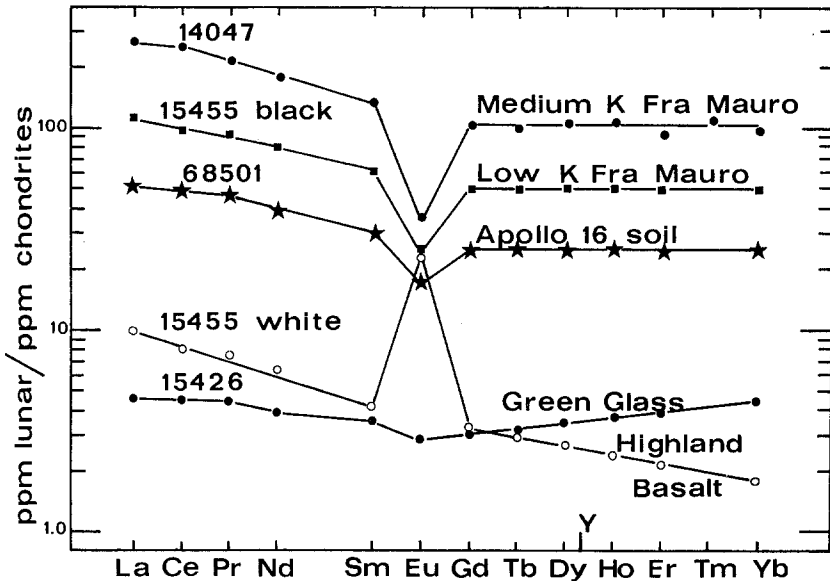


Fig. 1. Rare Earth abundance patterns for the various rock types, and for the Apollo 16 soil.

C. MEDIUM K FRA MAURO BASALT

This is another variant on the KREEP component, first identified in the Apollo 12 soils, and sampled in abundance at Fra Mauro. Many of the soils and breccias at the Apollo 14 site showed rather uniform composition (Taylor *et al.*, 1972b), close to that of the major glass type identified by Reid *et al.* (1972) as Medium K Fra Mauro basalt. This composition, distinguished by 18% Al_2O_3 and about 0.5% K_2O , is given in Col. 3A, Table I. This compares closely with that for sample 14047 (Col. 3B, Table I) and the trace element data (Col. 3, Table II) for this Apollo 14 sample are used as representative of the rock type.

D. HIGH K FRA MAURO BASALT

This rock type shows much variation in chemistry. The mean major element composition is given in Col. 4A, Table I from Reid *et al.* (1972). Some difficulties arise in selecting trace element data. No samples with such high K values have been analysed in this laboratory. Many data exist for sample 12013, but the average silica content (60%) is higher than the average of 53% established by Reid *et al.* (1972) as the median value. A tentative correlation is made with split 10-35 of rock 12013 for which the major element match (Col. 4B, Table I) is fair. A selection of trace element data from various sources for 12013, 10-35, is given in Col. 4, Table II.

E. OTHER COMPONENTS

Other components present in minor amount include high K ($\sim 5\%$) low (Mg < 1%) granitic fragments. These do not appear to be major components. Likewise, fragments

of mare basalts appear in the Apollo 14 breccias, (e.g. 14321, Taylor *et al.*, 1972b) indicating that some mare basalts predated the Imbrium collision. The extent of such pre-Imbrium mare basalt activity remains to be evaluated.

F. METEORITIC COMPONENT

This comprises all chondritic, iron meteoritic and cometary material, and provides much important genetic information on highland history. For example, if the smooth highland plains (e.g. Cayley Formation) are the result of volcanic constructional processes (Trask and McCauley, 1972) then the meteoritic component should be low. If this material is derived from pre-existing highlands by impact, then a high meteoritic component, derived from the intense cratering, should be present.

G. GREEN GLASS

This primitive component is abundant in the Apollo 15 soils. The composition established by Reid *et al.* (1972) is given in Col. 5A, Table I, and compared with our analysis given in Col. 5B, Table I. The trace element data are listed in Col. 5, Table II. The major element data closely resembles that of howarditic meteorites, and some Apollo 12 basalts (e.g. 12040, Green and Ringwood, 1972). The REE data (Figure 1) exhibit only a slight Eu depletion and resemble those of howardites, as do the Th, U, Zr and Ba contents. Cr, V, Sc and Co are significantly higher, and are closer to lunar values. The δO^{18} values are lunar, not meteoritic (Clayton, personal communication) and accordingly, the green glass is considered lunar. It appears to be definitely associated with the Apennine Front, rather than with the mare. It is the most primitive lunar composition yet identified, with abundances of REE, Th, U etc. only 4-5 times the chondritic abundances. It is interpreted as derived by a high degree of partial melting from source rocks similar to those of the Apollo 12 mare basalts. The age relationships remain to be established.

4. Overall Composition of the Highlands

In Figure 2, the composition of several Apollo 15 breccias and soils is shown in terms of mixing of two end members. These are the highland basalt (gabbroic anorthosite) and the low K Fra Mauro basalt. The fit for the elements shown is very good. Such a simplified model accounts for variations in REE, Th, U, Zr, Hf, Nb, Ba and associated elements. For the Apollo 15 samples an additional more basic component is needed to supply extra Cr, V and Sc. Ni (and Co) are of course variable due to the meteoritic component. In addition an extra feldspathic constituent is needed to account for Sr and Eu.

The Apollo 16 soil composition (68501, Table II, Col. 6, Table III) is shown on the same diagram (Figure 2) where it can be represented as a 60/40 mix of highland basalt (gabbroic anorthosite) and low K Fra Mauro basalt for *all* elements except Sr and Eu. Figure 3 shows this comparison. The identity in composition is striking since the Apollo 15 and 16 sites are 900 km apart.

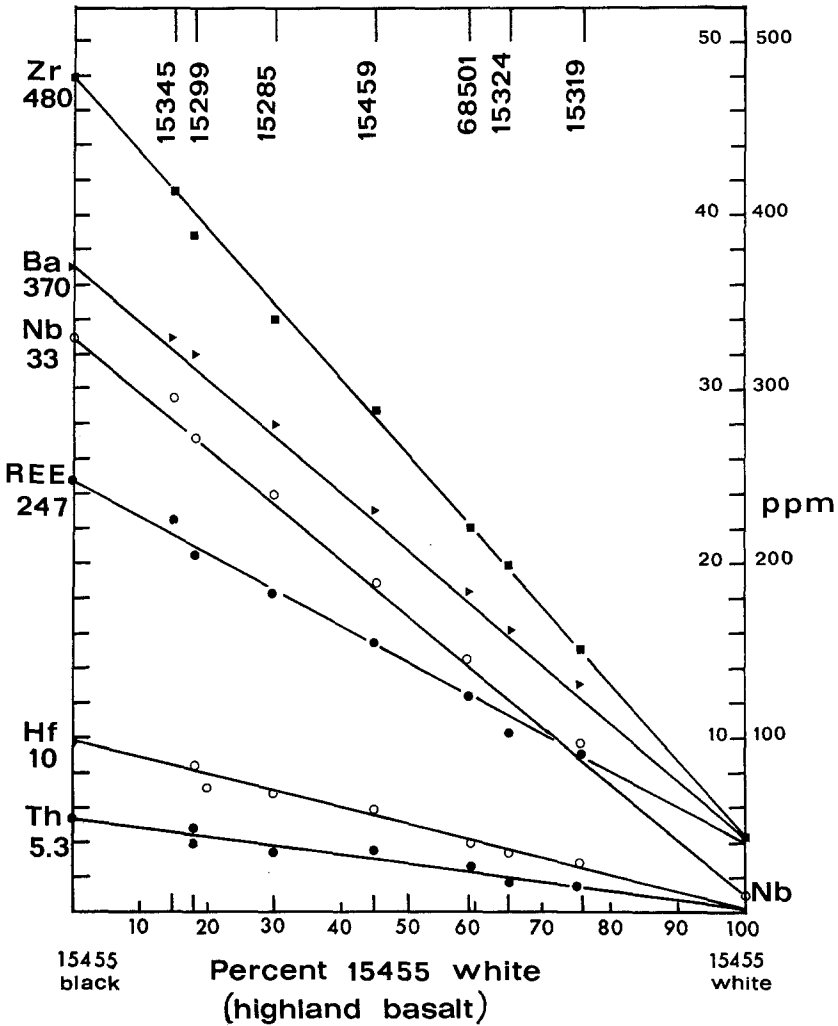


Fig. 2. Two component mixing model. Element abundances in Apollo 15 breccias and Apollo 16 soil match percentage mixes of highland basalt (gabbroic anorthosite) and low K Fra Mauro (15455 black) basalt.

The overall average Al/Si ratio as measured by the Apollo 15 and 16 orbiting XRF experiments (Adler, 1972) is 0.60. This corresponds, for an SiO₂ content of 45%, to 24% Al₂O₃. Such a composition is close to a 50/50 mixture of highland basalt (gabbroic anorthosite) and low K Fra Mauro basalt. Such a composition is given in Table III, together with several other highland compositions.

The main conclusion which emerges is that the various breccia and soil compositions can be represented as mixtures of a few end member components, the principal contributors being highland basalt (gabbroic anorthosite) and low K Fra Mauro basalt. The orbiting XRF data, the similarities between Apollo 15 and 16 chemistry,

TABLE III
Major element analyses of highland material

	(1)	(2)	(3)	(4)
SiO ₂	44.9	42.3	46.1	45.5
TiO ₂	0.56	1.7	—	0.84
Al ₂ O ₃	26.9	22.7	22.3	23.4
FeO	5.3	8.0	5.5	7.36
MgO	6.3	8.4	7.0	8.93
CaO	15.1	17	18.3	13.3
Na ₂ O	0.36	0.32	0.7	0.28
K ₂ O	0.16	0.12	—	0.07
Cr ₂ O ₃	0.17	0.13	—	0.14
Σ	99.77	100.7	99.9	99.82
Al/Si	0.68	0.61	0.55	0.58
Mg/Si	0.18	0.26	0.20	0.25

(1) Apollo 16 soil 68501 Anal. Ware.

(2) Luna-20 soil (M. Duke, pers. comm.).

(3) Surveyor 7, Tycho (Turkevich *et al.*, 1968).

(4) 50/50 mix of highland basalt (gabbroic anorthosite) and low K Fra Mauro basalt.

(Data from Table I.)

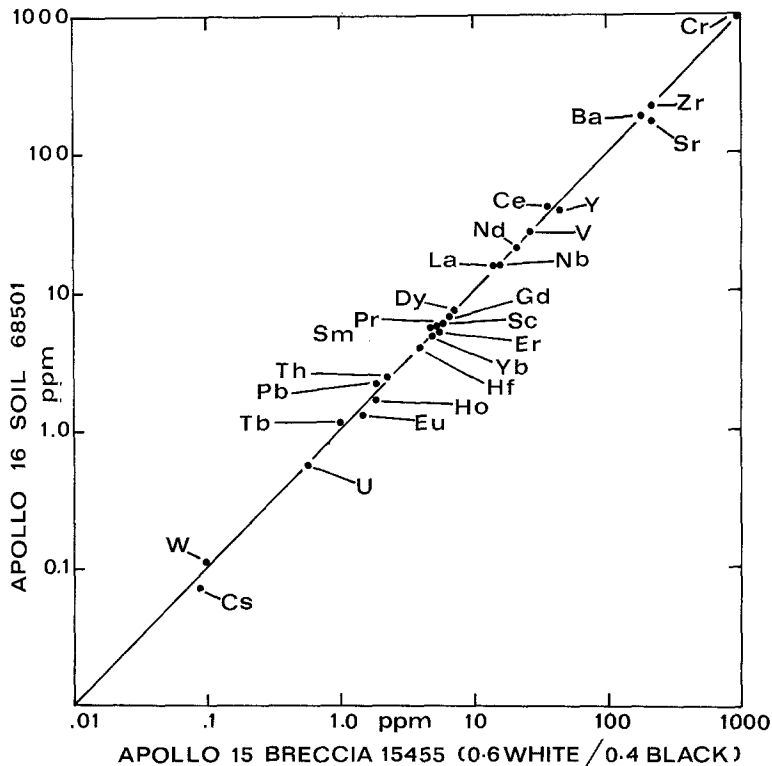


Fig. 3. The Apollo 16 soil 68501 trace element content compared with the composition of a 60/40 mix of highland basalt (15455 white) and low K Fra Mauro basalt (15455 black). The compositions are identical for all elements shown. The sample sites are 900 km apart.

the similar compositions observed in the Apollonius highlands (Luna-20, Table III) and at Tycho (Table III) by Surveyor 7, argue for a broad uniformity in composition across the highlands.

5. Relation of Composition to Highlands Terrain

The composition of the highlands, as discussed above, can be interpreted as resulting from thorough mixing a few discrete and widespread units. Such mixing is consistent with the observed intense pre-Imbrium cratering of the highlands, and the seismic evidence of a brecciated layer about 20 km thick (Latham *et al.*, 1972; Toksöz *et al.*, 1972). Many generations of impact debris are involved. In addition to the large craters, at least eleven large mare-forming events can be detected on the visible hemisphere, and their ejecta blankets overlap in a complex manner (Wilshire and Jackson, 1972).

Two other features of highland terrain call for explanation. These are the observed layering in the Apennine Front, and the plains forming units (Cayley Formation and equivalents). Astronaut observations and photographs at the Apollo 15 Hadley-Apennines site revealed a layered structure, particularly well exposed at Silver Spur, dipping away from the Imbrium basin (Swann, 1972). The survival of such well developed primary crustal layering is unlikely because of the intense pre-Imbrium cratering. A preferred explanation is that the layering was formed relatively late in the evolution of the highlands, as ejecta from mare-basin forming impacts. The Apennine Front is close to the Serenitatis basin outer rim. The layering observed is considered as forming during the Serenitatis impact, being uplifted and exposed in the Apennines by the Imbrium impact. The survival of the layering is due to the decline in frequency of large crater-forming impacts, after the Imbrium collision (witness the survival of the Apennine ridge).

The smooth plains observed widely across the highlands (Mutch, 1970; Wilhelms, 1971) and mapped as Cayley Formation, or equivalents, have been interpreted as late volcanic constructional units (Trask and McCauley, 1972). The absence of volcanic rocks and the abundance of breccias at the Apollo 16 site (LSPET, 1972) militate against this interpretation. The chemical composition of the plains forming Cayley Formations, and the adjacent hilly Descartes Formation is very similar and can be interpreted as due to mixing of highland basalt (gabbroic anorthosite) and Fra Mauro basalt components (Taylor *et al.*, 1972c). Such similarity does not accord with the interpretation that these terrain distinctions are due to lava viscosity differences. The composition, as noted above, can be represented as a mixture of highland basalt (gabbroic anorthosite) and low-K Fra Mauro basalt, consistent with derivation with pre-existing highland crust, perhaps as base surge deposits.

6. Comparison with Mare Compositions

The highlands components show the same distinctive features of lunar geochemistry

as the mare basalts. These include low K/U ratios (about 10^3 , compared to terrestrial values of 10^4 and meteoritic ratios of 10^5), high Cr/V ratios, and Eu anomalies. The most distinctive differences between highland and maria chemistry are outlined in Table IV. Although there are considerable differences among both individual mare basalts and between the highland rock types, several elements exhibit differences outside the range of internal variations. Those elements enriched in the highlands

TABLE IV
Comparison of highland and mare basalt compositions

Enriched in highlands	Ni	Al	Ca				
Depleted in highlands	Fe	Ti	Cr	V	Sc	Co	Cu
Elements showing no discernible trend	Cs	Rb	K	Ba	Eu	Sr	Pb
	REE	Y	Th	U	Zr	Hf	Nb
	Si						

are Ni, Al and Ca. The nickel concentration is attributed to a higher meteoritic component, a result of the much higher cratering frequency. In contrast, Fe, Cr, V, Sc and Cu are depleted relative to the mare basalts. It should be recalled that some mare basalt formation occurred before the Imbrium collision, as attested by the presence of mare basalt clasts in Apollo 14 breccias (e.g. 14321, Taylor *et al.*, 1972b). Such activity appears to have been small in the light of the observed chemical differences between maria and highlands.

7. Comparison with Primitive Solar-Nebula Abundances

Various workers have suggested that the highland material was directly accreted and represents the last stage of accumulation of a heterogeneous Moon. This involves pre-accretion fractionation of the elements. In order to establish the degree of chemical fractionation, the element concentrations for the highland components are compared with those in type 1 carbonaceous chondrites, used as a first approximation (Anders, 1971) to abundances in the solar nebula prior to condensation of the Sun and planets.

In Tables V, VI and VII, the chondritic abundances are compared with those for highland basalt (gabbroic anorthosite) low K Fra Mauro basalt, and the green glass. In each case there is a first order difference based on volatility, and siderophile character. This is the same type of relationship common to all lunar samples first observed by LSPET (1969) and attributed to depletion at or before accretion (Wetherill, 1971).

When the *involatile* elements are looked at in more detail, a second relationship, illustrated in Figures 4 and 5 emerges. In these diagrams the elements are arranged in order of ionic radius and valency. The assumption is made that there is no relative fractionation of the *involatile* elements between the Moon and the primitive abundances. For example, they are assumed to have the same relative abundances for the rare earth elements. Some direct evidence for this comes from the rare earth abundances in the green glass, which, although enriched 4–5 times over the primitive abun-

TABLE V

Comparison of highland basalt with that of type 1 carbonaceous chondrites

	Concentration relative to chondrites	Elements
Enriched	>20	Eu Sr
	10-20	Ba Al La
	2-10	REE (-La, Eu) Th U Zr
	1-2	Si Hf Nb
Depleted	0.5-1	Mg
	0.1-0.5	Cr V Fe Ga
	<0.1	Ni Co Cu

TABLE VI

Comparison of low K Fra Mauro basalt with that of type 1 carbonaceous chondrites

	Concentration relative to chondrites	Element
Enrichment	100-150	Ba La Th U
	50-100	REE (-La, Eu) Zr Hf Nb
	20-50	Al
	3-20	Ca Sc
	1-3	Rb K Pb Si
Depletion	0.5-1	Na Cr V Mg
	0.1-0.5	Sr Fe Ga
	<0.1	Ni Co Cu

TABLE VII

Comparison of green glass composition with that in type 1 carbonaceous chondrites

	Concentration relative to CCI	Elements
Enrichment	5-7	Ba Ca Al
	3-5	REE Th U Y Ti Hf Nb V
	2-3	Si Zr Sr Eu
	~ 1	Cr Mg Mn Fe
Depletion	0.5	Ga
	~ 0.2	Na Rb Pb Co
	0.08	Sn
	0.03	Cu
	0.01	Ni

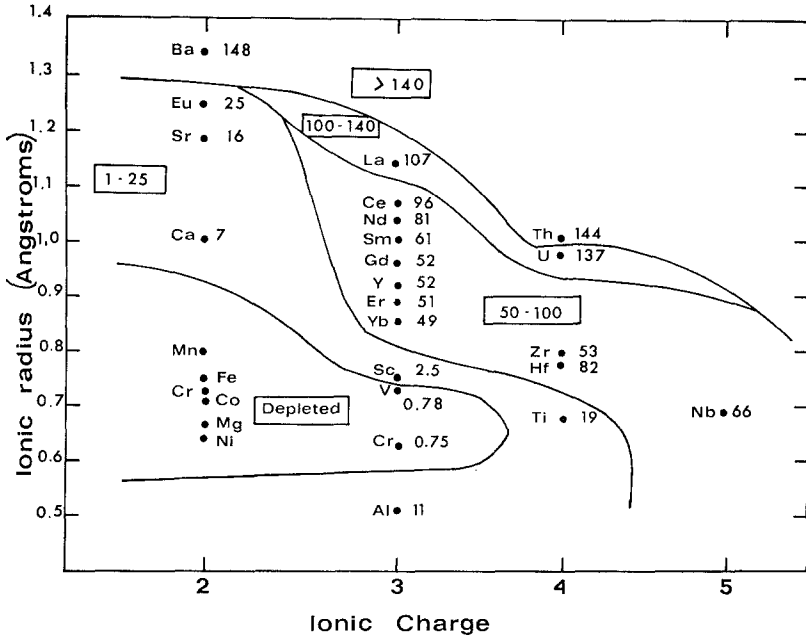


Fig. 4. Involatiles element abundances in low K Fra Mauro basalt, normalised to those in type 1 carbonaceous chondrites and plotted according to ionic radius and valency. The numbers beside the element symbols are the normalised values. The contour lines separate relative degrees of enrichment in the lunar samples.

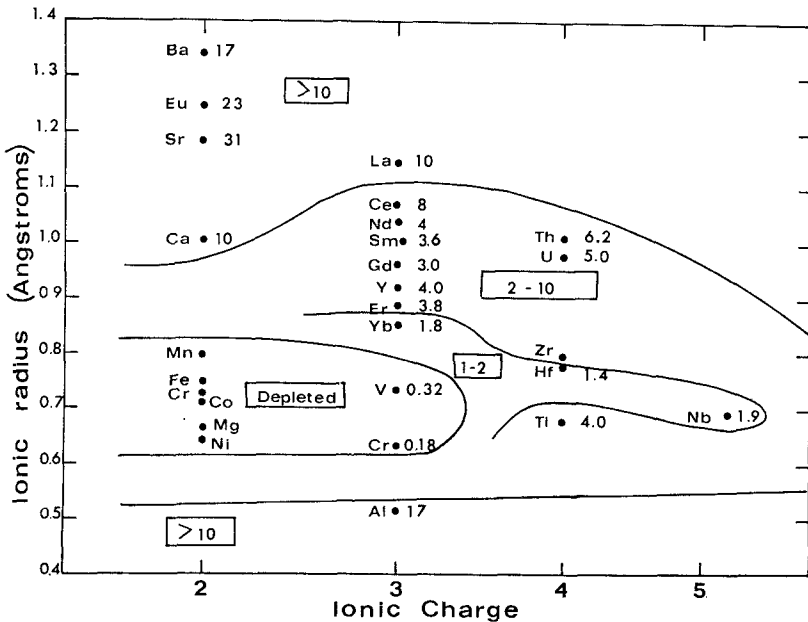


Fig. 5. Involatiles element abundances in highland basalt (gabbroic anorthosite) normalised to those in type 1 carbonaceous chondrites. The numbers beside the element symbols are the normalised values. Contour lines separate relative degrees of enrichment.

dances, are parallel to the chondritic REE patterns. If this assumption is correct, then the involatile elements in the highlands components have been fractionated to a degree which depends on the differences in ionic radii and/or valency from those of Fe^{2+} and Mg^{2+} . Similar observations have been interpreted by Taylor *et al.* (1972b) as evidence for fractionation based on crystal-liquid equilibria, and hence imply large scale partial melting in the outer layers of the Moon. The type and levels of enrichment are analogous to those observed in terrestrial crustal rocks, and show no dependence on volatility (e.g. fractionation is observed within the REE group). From this evidence it is concluded that the chemically distinct rock types in the highlands are derived by partial melting in post accretion processes. Pre-accretion processes are responsible for loss of volatile and probably the siderophile elements. Post-accretive processes of melting and fractionation are responsible for the production of the surface rocks.

8. A Heterogenous Moon?

Several authors (e.g. Hubbard *et al.*, 1972; Ringwood, 1972) have suggested that the outer Ca-Al rich lunar crust is derived directly or indirectly from late accretion of material enriched in involatile constituents. In addition to radial chemical zonation, lateral variations may be present. The high concentrations of gamma-ray emitters (K, U, Th) over Southern Mare Imbrium and Northern Oceanus Procellarum (Metzger *et al.*, 1972) appear to be independent of geological structure (LSAPT, 1972). This non-uniform distribution of radioactivity may be due to sampling of a deeper layer, for example, by the Copernican impact. The identification of medium K Fra Mauro compositions at the Apollo 16 site (65015, Taylor *et al.*, in prep.) indicates that the apparent lateral heterogeneity may be due to depth of sampling. The conclusions in this paper indicate formation of the various highland components by partial melting. Whether the source regions are enriched in involatile components and whether there are real lateral variations in composition are problems for future study.

In conclusion, it should be noted that the green glass composition places some restraints on whole Moon composition. It is similar in major element composition to some Apollo 12 mare basalts (e.g. 12040) and Green and Ringwood (1972) conclude that it is derived by 50% partial melting of the same pyroxomitic source material which gave rise to the Apollo 12 basalts. Table VII shows the concentration of elements relative to type 1 carbonaceous chondrites. If all elements such as the rare earths are partitioned into the melt, then the source material (and possibly the whole Moon) can contain only 2-3 times chondritic abundances at most for the involatile elements (REE, Ba, Zr, Hf, Th, U, Nb). This implies that pre-accretion processes, which depleted the lunar material in volatile elements, did not concentrate the involatile elements by large factors.

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