

COMPARATIVE GEOCHEMISTRY OF APOLLO 16 SURFACE SOILS AND SAMPLES
FROM CORES 64002 AND 60002 THROUGH 60007

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Abstract. New data are presented for the concentrations of 23 to 27 elements in nine Apollo 16 surface soil samples, two subsplits each of 12 splits of core 60002-7, and one subsplit each of 10 splits of drive tube 64002. The surface soils are generally similar to other surface soils collected at their respective stations. All ten 64002 samples are similar to each other and to the station 4 surface soils and distinctly different from soils at other stations. High iron concentrations previously reported for these same subsplits of 60002-7 result primarily from meteoritic metal. One sample from each core is contaminated by stainless steel. The recently proposed ferroan anorthositic norites are required to explain the soil compositions. A yet uncharacterized component with high concentrations of Na, Sr, and Eu is also needed.

Introduction

Despite the large quantity of published data on the bulk composition of Apollo 16 soils, there have remained several large gaps in the data base [Korotev, 1981]. As several of these appeared to obscure understanding of the significance of the data as a whole, this project was undertaken to fill the gaps and to answer some questions raised by Korotev [1981]. New data for the concentration of 23 to 27 elements are presented here for nine surface soils. Previous data for most of these were lacking or inadequate for compositional characterization. In addition, data are presented for two subsplits each from twelve splits of the 60002 to 60007 drill core and one subsplit each from ten splits of the 64002 drive tube. Discussion of the significance of the new data relies heavily upon the data base, model, and discussion developed in Korotev [1981]. The present work is part of a continuing effort to characterize the compositionally distinct components of the Apollo 16 site.

Experimental Methods

Samples were weighed and sealed into 4 mm (outside diameter) ultrapure fused silica tubing (T21 Suprasil, Heraeus-Amersil, Sayreville, New Jersey), which was washed with hydrochloric and nitric acids solutions prior to use. For the surface soils and 'large' samples of 60002-7, nominal 40-50 mg sample masses were used. For the 64002 and 'small' 60002-7 samples, the nominal 10-20 mg sample splits originally allocated to R. V. Morris were used. The entire sample or,

if this exceeded 12 mg, an 11-12 mg portion was analyzed in order to take full advantage of the precision of the optical scale of the microgram balance used to weigh the samples. Samples and standards were initially irradiated in three separate experiments for 30-50 hours with a thermal neutron flux of $3.5 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$ in the University of Missouri-Columbia research reactor. Samples were each radioassayed twice in the tubes in which they were irradiated, once between 6-12 days and again between 27-32 days following the irradiation. The two radioassays were a nominal 8 and 12 hours in duration. Periodic checks of empty Suprasil tubes (each 0.6 to 0.8 g in mass) indicate negligible blank contributions for samples of this mass and composition. After the second radioassay some samples were transferred and weighed into polyethylene vials. In a single experiment 2-4 months following the initial activations these samples were individually reactivated for 0.5 to 1.0 minute and immediately radioassayed for short lived isotopes to yield data for Al, Ca, Mg, V, and Mn. Gamma-ray spectral data were reduced with the TEABAGS programs of Lindstrom and Korotev [1982].

The following comparator standards were used. The concentration value used is listed in parenthesis (same units as Tables 1-3). USGS basalt BCR-1: FeO (12.1), Na O (3.27), Sc (31.6), Co (36.0), Zr (218), Cs (0.94), Ba (675), La (24.6), Ce (53.7), Sm (6.80), Eu (1.92), Tb (1.10), Yb (3.37), Lu (0.526), Hf (5.2), Th (6.0), and U (1.74); USGS peridotite PCC-1: Cr (2730) and Ni (2340); Knippa basalt (in-house standard): Mn (1550), Sr (1010), and Ta (6.3); GIT-IWG anorthosite AN-G: Al O (29.8), CaO (15.9), and V (70); and synthetic diopside: MgO (17.6). For Ir, no standard was used; concentration values were calculated from the 468 keV photopeak of

Ir using the pertinent nuclear and detector efficiency parameters. Because of the uncertainty in these parameters, particularly the flux and neutron capture cross section, all Ir concentrations may be systematically high or low. The ratio of Ir concentrations determined in this manner to the Ni concentrations averages 3.0×10^{-5} for the various soils. This ratio falls comfortably within the rather wide range of Ir/Ni ratios reported by Kröhnenbühl et al. [1973] for Apollo 16 soils and separates thereof. Although the sample to sample precision for Ir is better than 0.5 ng/g, the values may be systematically high or low by an amount not expected to exceed 20%.

Samples Studied

Surface Soils

Korotev [1981] concluded that of the 42 soil samples collected from the surface of the Apollo 16 site (i.e., not core or drill soils) existing

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TABLE 1. Element Concentrations in Nine Apollo 16 Surface Soils

Soil Split	60051 91	61181 28	Stn.1 Mean	62231 13	64811 45	65501 71	65511 12	Stn.5 Mean	66031 47	67511 4	67960 34	σ %
Al ₂ O ₃	27.8	25.2	26.6	26.5	27.0	25.6	25.3	26.2	26.7	28.6	n.a.	3
FeO	4.50	5.54	5.4	5.60	5.56	6.02	5.82	5.85	5.80	4.10	4.56	1
MgO	5.6	5.9	6.0	6.4	6.1	7.0	6.7	6.25	6.8	4.0	n.a.	12
CaO	15.7	14.4	15.6	14.5	14.6	14.2	14.2	15.0	14.6	15.7	16.1	5
Na ₂ O	0.446	0.463	0.495	0.444	0.462	0.473	0.474	0.45	0.440	0.390	0.527	1
Sc	7.83	9.26	9.2	9.28	9.27	10.18	10.59	10.1	9.95	8.18	7.76	1
V	19.	21.	20.	22.	21.	20.	24.	25.	22.	<20.	n.a.	25
Cr	612.	760.	720.	731.	733.	830.	847.	780.	777.	500.	624.	1
Mn	476.	535.	540.	566.	567.	581.	610.	580.	582.	493.	n.a.	3
Co	21.3	31.5	25.5	35.3	35.5	36.4	26.3	31.	34.2	7.18	16.2	1
Ni	250.	435.	340.	485.	465.	515.	370.	430.	480.	55.	215.	5
Sr	165.	180.	160.	165.	165.	155.	165.	162.	155.	155.	175.	6
Zr	165.	185.	161.	165.	225.	215.	240.	205.	210.	61.	175.	8
Cs	0.10	0.18	---	0.14	0.17	0.16	0.17	---	0.12	0.08	0.13	20
Ba	108.	139.	123.	129.	159.	175.	172.	130.	144.	45.	127.	4
La	10.06	12.43	12.1	11.00	14.21	14.71	15.90	14.4	13.65	3.42	10.14	1
Ce	27.0	33.9	32.	29.7	38.3	39.5	42.7	37.5	36.8	9.24	27.6	2
Sm	4.88	5.92	5.6	5.29	6.82	7.03	7.56	6.7	6.50	1.71	4.77	2
Eu	1.119	1.185	1.19	1.129	1.185	1.211	1.233	1.24	1.192	0.968	1.248	2
Tb	1.04	1.28	1.15	1.13	1.44	1.49	1.59	1.44	1.37	0.39	1.04	4
Yb	3.42	4.17	4.0	3.70	4.83	4.99	5.35	4.9	4.55	1.34	3.53	2
Lu	0.501	0.593	0.58	0.518	0.684	0.704	0.751	0.71	0.642	0.191	0.519	3
Hf	3.89	4.69	4.0	4.17	5.67	5.48	6.15	5.1	5.01	1.24	3.77	2
Ta	0.526	0.654	0.49	0.527	0.758	0.740	0.834	0.54	0.685	0.192	0.532	3
Ir	7.6	15.9	---	14.8	14.8	14.1	10.5	---	15.4	1.7	5.3	(5)
Th	1.76	2.09	1.8	1.98	2.68	2.77	2.84	2.2	2.49	0.51	1.88	5
U	0.46	0.54	0.54	0.48	0.70	0.70	0.74	0.67	0.70	0.158	0.51	8
Mass(mg)	44.30	43.19		47.66	47.63	43.85	50.31		40.50	68.05	55.11	

Element concentrations in $\mu\text{g/g}$, except ng/g for Ir and cg/g (%) for oxides (total element as oxide). One standard deviation (percent) estimates of analytical precision are included. Also included for comparison are the stations 1 and 5 means of Korotev [1981].

compositional data for seven samples was inadequate for accurate chemical characterization. Hence these seven samples were analyzed for this work: 61181, 62231, 64811, 65511, 66031, 67411, and 67960. (This conclusion, however, was based on the inadvertent oversight of the data of Taylor et al. [1973] for several soils, including 61181. 67031, which is not a true soil but a disaggregated portion of rock 67035, is not included in this count.) 67960 has not been sieved. Prior to analysis of the 55 mg subsplit used here several $>1\text{mm}$ particles were removed. In addition to these seven, samples of 60051 and 65501 were analyzed. Although some data were available for these soils additional data was needed to confirm their special significance.

Drill core 60002-60007

In their study of the 60002-7 drill core Gose and Morris [1977] reported twelve splits (of 212) with total FeO concentrations ranging from 7.0 to 8.7%. (The recalibration of Morris et al. [1978] would lower these values only 'negligibly'.) No Apollo 16 surface soil exceeds 6.1% FeO. Although the likely explanation was the presence of metallic iron in the small (10-20 mg) samples analyzed, the interesting possibility existed

that some of these soils were truly more enriched in elements associated with mafic minerals (i.e., Fe, Mg, Ti, Sc, Cr, and Mn). This could be important to the understanding of the 'mafic component(s)' of the Apollo 16 soils and breccias [e.g., Korotev, 1981]. In order to evaluate the cause of the high iron analyses of Gose and Morris [1977], two subsplits of each of the twelve high-Fe sample splits were analyzed. One was the returned sample of Gose and Morris [1977]; the other was a separate 40-50 mg subsplit.

Drive tube 64002

Although the distinction is subtle, the four surface soils collected at station 4 have a composition different from those collected at the other Apollo 16 sampling stations. The major element composition of these soils is similar to that of the North Ray Crater soils of station 13 and some from station 11, but they are more enriched in LIL (large ion lithophile) elements. There is also a greater variability in composition among the four soils at station 4 than among those collected at any other station except 11. Korotev [1981] interpreted their compositions as mixtures of anorthosite with material

such as the stations 5 and 6 soils and postulated South Ray Crater as the source of the anorthosite. These distinctions plus the considerable difference in composition between the station 4 and station 5 soils (both collected in Stone Mountain about 0.5 km apart) make the station 4 drive tube potentially very interesting. The ten samples analyzed from 64002 were selected, on the basis of the FMR studies of Morris and Lauer [1982], to yield the range of compositions expected within the core. The subsplit analyzed was the same subsplit analyzed by Morris and Lauer [1982].

Data Presentation

Analytical results are listed in Tables 1, 2, and 3 along with core sample depths and the one standard deviation estimate of analytical precision. These percentages apply to typical concentrations but must be increased by a factor of two or even three for the lowest concentrations reported (e.g., 67960). These estimates are primarily 'counting statistics' but include contributions from other well-evaluated sources of random uncertainty. They do not include any systematic error due to uncertainty in the standard values. No standard material useful for establishing the overall analytical accuracy was included in the analyses. However, the mean composition of soils from stations 1 and 5 from the compilation from many sources by Korotev [1981] are included in Table 1. These can be compared with the results reported here for 61181 and similar 62231 and with results for 65501, 65511, and similar 66031.

Apollo 16 soils are all quite similar in composition, which complicates data presentation. Two visual methods are used here which are intended to be complimentary: a simple variation diagram and a 3-component mixing diagram.

In Figure 1 concentrations of Sm are plotted against those of Sc for all Apollo 16 surface soils and the core samples of Tables 2 and 3. Each surface soil is represented by its station number; those analyzed for this work are underlined. This variation diagram is useful because it compares a typical LIL element with one that correlates well with mafic mineral content but is unaffected by meteoritic or terrestrial metal contamination. As there is a strong negative correlation of Sc with Al in Apollo 16 soils, the approximate ($\pm 0.5\%$ Al 0) concentration of Al 0 is also indicated on the plot for reference.

Despite the utility of such a variation diagram, it can only show the concentrations of two or three elements at once. Korotev [1981] has argued that because at least three general components are necessary to account for the compositions of the lunar highland soils, a more useful tool than any single variation diagram for comparing the bulk composition of highland soils is the plotted results of the FAN-KREEP-HON mixing model [Korotev et al., 1980]. The model takes into account the concentrations of up to 30 elements, thus minimizing that part of the scatter in a diagram such as Figure 1 which is due to analytical imprecision. Apollo 16 soils (as well as soils from other highland sites) are well modeled as mixtures of ferroan anorthosite (FAN), KREEP [Warren and Wasson, 1979], highlands

olivine norite [HON, Korotev et al., 1980], and a minor meteoritic component. Mixing model results for the three major components can be plotted on a triangular diagram (or a portion thereof, Figure 2). The mixing diagram is a visual device for comparing the bulk composition of the soils. It is in many respects analogous to resolving a rock into its normative mineral components or plotting a pyroxene composition on a pyroxene quadrilateral: treatment of the data in this manner does not necessarily imply that the soil, rock, or pyroxene is a physical mixture of the end member components, only that the composition can be expressed as a mixture. Indiscriminant reliance upon mixing models such as this, however, can obscure subtle but significant compositional characteristics if these are not capable of being expressed by the model components. In this regard the FAN-KREEP-HON model does not account for the higher Mg/Fe ratio and/or high Na, Sr, and Eu concentrations of some Apollo 16 soils.

Figure 2b is an updated version of Figure 4 of Korotev [1981]. It includes results for the data of Table 1 combined with any other relevant analytical data available for these soils [see references under 'Data Base,' Korotev, 1981]. Figure 2b contains one point for each Apollo 16 surface soil. Each soil has been 'graded' A, B, or C by the criteria of Korotev [1981] to reflect the quantity and quality of available analytical data. These grades are indicated by the size of the points. Several soils have been 'promoted' a grade based on the additional data.

Results

Surface Soils

Of the seven surface soils analyzed for which there were few or no previous data, two, 67511 and 65511, are distinctive in having respectively lower and higher LIL element concentrations than any of the previously characterized soils (discounting 67711 which is compositionally anomalous; see Korotev, [1981]). Both, however, are only 'slightly' distinctive in this regard and are generally similar to the other soils collected at their respective stations. 65511 has REE (rare earth element) concentrations 7-8% higher than 65501, which was regarded by Korotev [1981] as the most 'mafic' and LIL-element rich surface soil. With inclusion of the new data for 65501, the ratio of mafic components to anorthositic components (e.g., HON + KREEP to FAN) for this soil is similar to that for 65511 and 66081. Hence these three soils are the best representatives among the surface soils of the 'Cayley' soil component discussed by Korotev [1981].

LIL element concentrations in 64811 are 25% greater than in 64801 and 64421, two other station 4 soils with similar Al 0 concentrations. Korotev [1981] argued that the station 4 (and station 8) soils were compositionally equivalent to mixtures of the Cayley soil component (above) with anorthosite (Figures 1 and 2). Although 64811 plots high on the FAN-KREEP-HON mixing diagram (Figure 2b) compared to other soils on the station 5-8-4 mixing trend, its composition is well duplicated by a 89-11 mixture of 65511 and anorthosite (FAN). The additional

TABLE 2. Element Concentrations in Two Subsplits Each of Twelve Splits from Apollo 16 Core 60002-7

Parent Subsplit Depth (cm)	60002,84		60002,40		60003,21		60003,162		60003,202		60004,198	
	633	513	632	504	1749	387	1748	418	1747	421	546	503
	194.2		187.7		180.4		150.4		147.1		137.3	
FeO (G&M)†	8.7		7.0		7.1		7.5		7.2		7.3	
FeO	5.56	9.73	6.70	6.63	5.86	5.85	5.97	5.40	5.75	5.89*	5.94	5.76
CaO	15.8	13.7	14.9	14.0	15.3	14.4	15.4	14.1	15.0	15.8	15.4	15.0
Na ₂ O	0.507	0.472	0.458	0.475	0.485	0.471	0.471	0.448	0.466	0.476	0.477	0.457
Sc	9.34	9.52	10.09	10.04	10.23	9.95	10.42	9.84	10.06	10.30	11.22	10.31
Cr	736.	796.	908.	869.	818.	807.	833.	834.	791.	1084.*	828.	827.
Co	31.6	157.1	49.1	48.5	30.0	30.9	33.5	26.0	29.1	32.0*	24.3	24.1
Ni	415.	2230.	915.	825.	480.	495.	475.	385.	415.	710.*	330.	355.
Sr	190.	190.	200.	170.	170.	175.	165.	165.	185.	180.	170.	175.
Zr	210.	205.	215.	195.	245.	200.	310.	190.	230.	240.	240.	190.
Cs	0.16	0.17	0.11	0.14	0.18	0.11	0.16	0.17	0.15	0.14	0.17	0.11
Ba	145.	162.	149.	146.	164.	157.	161.	149.	155.	185.	155.	156.
La	12.5	13.2	12.6	12.8	13.2	12.5	14.4	12.8	13.4	14.5	13.7	12.8
Ce	34.3	37.4	34.5	35.6	36.8	34.8	38.9	37.2	37.4	43.4	37.7	35.8
Sm	5.93	6.42	5.96	6.45	6.37	6.08	6.80	6.21	6.42	7.18	6.71	6.49
Eu	1.20	1.17	1.16	1.16	1.19	1.18	1.23	1.16	1.21	1.21	1.22	1.23
Tb	1.27	1.46	1.25	1.38	1.34	1.31	1.49	1.36	1.35	1.60	1.45	1.33
Yb	4.21	4.37	4.39	4.59	4.70	4.31	4.89	4.28	4.70	5.07	4.80	4.60
Lu	0.619	0.668	0.643	0.678	0.688	0.655	0.721	0.644	0.682	0.779	0.719	0.698
Hf	4.54	4.86	4.70	5.06	5.10	4.86	6.67	4.69	4.95	6.21	5.17	4.91
Ta	0.66	0.69	0.70	0.67	0.72	0.62	0.74	0.60	0.74	0.68	0.75	0.68
Ir	12.7	106.	28.	25.	13.7	14.9	11.9	11.1	11.9	19.	10.9	9.7
Th	2.25	2.75	2.6	2.7	2.8	2.2	2.45	2.25	2.6	2.5	2.7	2.9
U	0.55	0.61	0.61	0.65	0.65	0.55	0.60	0.55	0.60	0.72	0.60	0.66
Mass(mg)	43.22	11.19	47.55	9.41	40.56	10.75	37.06	10.92	44.33	5.35	41.08	10.85

Parent Subsplit Depth (cm)	60004,223		60004,232		60004,246		60005,92		60007,49		60007,53	
	545	508	544	510	543	513	144	141	412	356	411	358
	131.5		129.5		126.5		94.5		10.2		9.2	
FeO (G&M)†	7.0		7.9		7.1		7.3		8.2		7.5	
FeO	5.49	5.71	5.81	5.71	5.84	5.89	5.78	5.94	5.10	7.27	5.40	6.29
CaO	15.5	14.6	15.3	14.5	15.4	14.7	15.1	14.6	16.0	16.2	15.6	14.8
Na ₂ O	0.475	0.480	0.472	0.478	0.466	0.490	0.477	0.492	0.453	0.476	0.464	0.455
Sc	9.86	10.30	10.26	10.26	10.21	10.45	10.63	11.36	8.75	8.95	9.07	9.08
Cr	769.	858.	815.	828.	796.	838.	797.	849.	706.	734.	729.	728.
Co	24.0	23.9	28.3	24.0	31.1	27.9	24.5	23.1	24.2	91.8	29.1	59.6
Ni	330.	3.45	425.	355.	440.	405.	330.	330.	370.	1390.	420.	900.
Sr	180.	130.	165.	155.	175.	195.	170.	150.	165.	220.	180.	165.
Zr	205.	175.	255.	210.	245.	200.	225.	225.	200.	145.	210.	170.
Cs	0.12	0.22	0.12	0.16	0.09	0.19	0.12	0.13	0.13	0.09	0.10	<0.2
Ba	159.	169.	189.	160.	162.	165.	158.	201.	131.	165.	146.	147.
La	13.0	13.3	15.5	13.3	13.6	14.0	13.4	17.4	11.7	13.1	12.9	11.9
Ce	35.7	36.2	42.6	36.5	36.6	37.7	36.2	49.0	32.0	35.6	35.1	32.0
Sm	6.20	6.72	7.40	6.69	6.50	6.96	6.48	8.64	5.52	6.68	6.17	5.93
Eu	1.20	1.21	1.25	1.22	1.19	1.23	1.22	1.26	1.14	1.23	1.19	1.16
Tb	1.31	1.38	1.57	1.42	1.38	1.49	1.38	1.87	1.18	1.45	1.32	1.26
Yb	4.56	4.74	5.29	4.66	4.64	4.88	4.63	5.96	3.94	4.38	4.34	4.08
Lu	0.664	0.703	0.781	0.70	0.689	0.721	0.691	0.887	0.586	0.668	0.649	0.629
Hf	4.76	5.11	5.86	5.45	4.98	5.01	5.07	6.39	4.27	4.48	4.76	4.49
Ta	0.67	0.74	0.83	0.69	0.71	0.69	0.74	0.94	0.60	0.66	0.67	0.60
Ir	10.8	8.9	11.0	9.5	13.8	11.2	9.7	11.7	10.6	34.	12.5	29.
Th	2.35	2.4	2.7	2.45	2.55	3.05	2.45	3.35	2.0	2.35	2.4	2.5
U	0.59	0.57	0.68	0.66	0.65	0.67	0.59	0.92	0.47	0.67	0.65	0.45
Mass(mg)	31.39	10.10	41.25	11.86	42.32	10.30	39.50	7.90	47.81	7.42	41.00	11.24

Element concentrations in µg/g, except ng/g for Ir and cg/g (%) for oxides (total element as oxide).

Sample mass: 11-12 mg each.

*Anomolously high due to contamination by stainless steel.

†FeO value from Gose and Morris [1977].

TABLE 3. Element Concentrations in Ten Subsplits from Apollo 16 Core 64002

Parent Subsplit Depth (cm)	14 207 1.25	20 210 2.75	50 224 9.75	56 227 11.25	76 236 15.75	80 238 16.75	84 240 17.75	99 246 20.25	107 250 22.25	111 252 23.25	σ %
Al ₂ O ₃	27.1	27.4	27.4	26.4	26.5	27.9	28.2	26.6	26.4	27.2	3
FeO	5.28	4.94	4.76	5.16*	5.41	4.76	4.09	5.09	6.16	4.77	1
MgO	5.9	5.0	5.4	5.7	5.6	5.5	5.0	5.9	6.5	4.6	20
CaO	15.8	16.6	15.8	15.9	15.8	16.0	15.9	15.7	15.4	15.9	5
Na ₂ O	0.459	0.452	0.462	0.447	0.583	0.464	0.476	0.455	0.459	0.461	1.5
Sc	8.68	9.27	8.54	7.77	10.40	7.18	7.71	9.25	9.54	8.23	1
V	21.	19.	19.	27.	23.	19.	14.	28.	28.	17.	30
Cr	711.	707.	691.	1226.*	681.	557.	590.	723.	715.	624.	1
Mn	545.	530.	520.	515.	560.	450.	465.	560.	555.	495.	4
Co	33.6	21.3	22.1	45.6*	29.5	43.3	15.2	23.4	57.6	28.7	1
Ni	465.	320.	330.	1190*	460.	580.	220.	315.	790.	450.	5
Sr	190.	195.	165.	180.	190.	185.	170.	175.	190.	165.	8
Zr	170.	170.	155.	150.	180.	155.	170.	170.	215.	165.	16
Cs	0.14	0.11	0.13	0.13	0.25	0.11	0.09	0.10	0.10	0.11	40
Ba	150.	140.	143.	136.	237.	130.	146.	150.	158.	136.	5
La	13.4	11.7	12.3	11.8	15.3	11.5	12.3	12.3	12.8	11.4	1.5
Ce	35.8	32.3	32.7	30.6	40.6	30.2	32.4	33.1	34.0	29.9	2
Sm	6.42	5.89	5.88	5.60	7.28	5.50	5.85	5.89	6.04	5.38	2
Eu	1.16	1.15	1.15	1.08	1.29	1.11	1.13	1.16	1.15	1.17	2
Tb	1.28	1.25	1.21	1.15	1.56	1.14	1.21	1.23	1.26	1.12	4
Yb	4.35	4.30	4.08	3.80	6.51	3.81	3.99	4.18	4.39	3.75	2
Lu	0.635	0.642	0.594	0.557	0.985	0.553	0.580	0.608	0.646	0.543	3
Hf	5.05	4.51	4.32	4.19	4.85	4.38	4.41	4.71	5.99	4.17	2
Ta	0.72	0.87	0.62	0.59	1.06	0.61	0.60	0.69	0.95	0.63	4
Ir	13.6	8.6	9.2	14.8	13.3	16.9	5.7	11.2	25.5	7.6	(5)
Th	2.65	4.9	2.5	2.5	3.05	2.2	2.15	2.5	2.55	2.15	10
U	0.56	1.54	0.51	0.47	0.71	0.58	0.54	0.60	0.67	0.57	8

Element concentrations in $\mu\text{g/g}$, except ng/g for Ir and cg/g (%) for oxides (total element as oxide). Sample mass: 11-12 mg each.

* Anomalously high due to contamination by stainless steel.

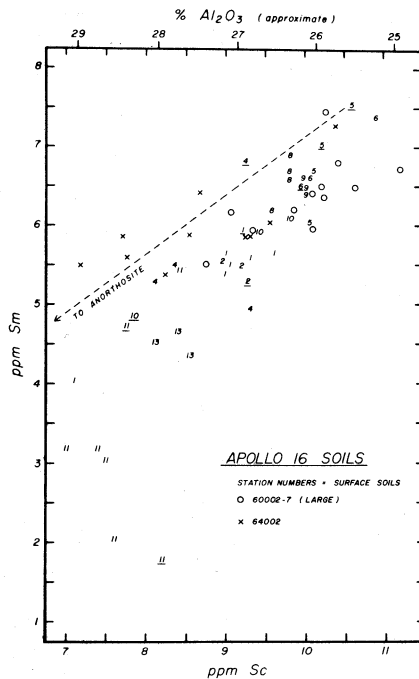


Fig. 1. Sm versus Sc concentrations in Apollo 16 soils. Surface soils are indicated by their station number. References for the data are given in Korotev [1981]. For surface soil samples analyzed for this work the station numbers are underlined. The core samples analyzed here are also plotted. The 'to anorthosite' line connects the most Sc and Sm enriched surface soil with the point corresponding to the concentrations of these elements in anorthosite (approximately 0.5 $\mu\text{g/g}$ Sc, 0.05 $\mu\text{g/g}$ Sm).

data for 60051 confirm its similarity to 64501, the most anorthositic of the station 4 soils. Soils 61181, 62231, and 66031 are indistinguishably similar in composition to other soils at their respective stations.

Soil 67960 is of special significance. It is the reference soil for 67940, which was collected from the split in 'House Rock' near the edge of North Ray Crater. Korotev [1981] noted that 67941 was unlike other station 11 soils and more similar to the station 13 soils in being more enriched in elements associated with the Cayley component (Fe, Mg, REE, etc.). 67941 is also unusual in having a high value of mg' (molar concentration ratio of Mg to Mg + Fe), 0.71, compared to the range of 0.63 to 0.68 for other Apollo 16 soils. 67960 is similar to 67941 but has slightly lower concentrations of most elements analyzed except Ca and Sr. Although the important elements Al and Mg were not analyzed for 67960, the mixing model translates these differences into a higher proportion of FAN component in 67960. The bulk composition of 67960 is, in fact, more similar to 60051 and 64501 than it is to the other station 11 soils. This makes 67960 unique in being the only North Ray Crater soil that plots more nearly on the Cayley-FAN mixing trend in Figure 2b than on the Cayley-NRC trend, with the possible exception of 67941 which does not plot unambiguously on either trend.

The North Ray Crater soils are compositionally the most variable of any station. There is, however, a geographical trend in the variation. Soils 67511, 67461, and 67481 were all collected from the southwestern extreme of the sampling area, 60-70 m west-southwest of the LRV [Sutton, 1981]. Samarium concentrations range from 1.7 to 3.0 $\mu\text{g/g}$ and mg' values are 0.63 for each. 67601 and 67701 were collected about 20 m west and 45 m northeast of the LRV. Samarium concentrations and mg' values for each are 3.2 $\mu\text{g/g}$ and 0.67-0.68. The two House Rock soils, 67940 and 67960 were collected 170 m northeast of the LRV. Samarium concentrations are 5.4 and 4.8 $\mu\text{g/g}$. The high mg' value of 0.71 for 67941 has already been discussed. Hence LIL element concentrations and mg' values increase from southwest to northeast around the rim. Muehlberger et al. [1980] note that dark matrix breccias increase in proportion to light matrix breccias in this same direction. However, 'darkness' in melt rocks does not necessarily correlate with LIL element abundances and there is no obvious corresponding trend in rock

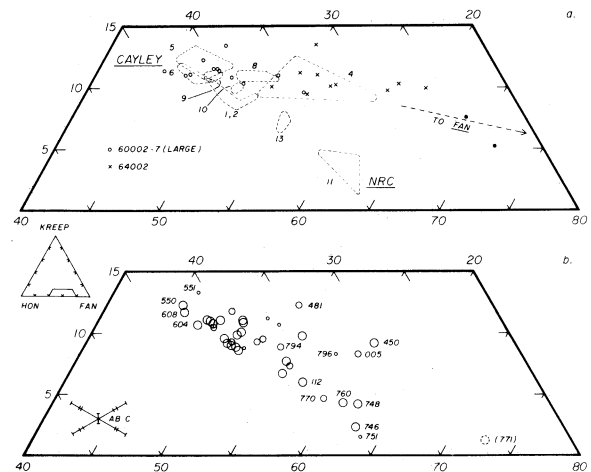


Fig. 2. A portion of the FAN-KREEP-HON mixing triangle showing the compositions of Apollo 16 soils. The model and methods are discussed in Korotev [1981] and Korotev et al. [1980]. (a) Results for the core samples analyzed here (points) compared with fields for the surface soils (dashed lines with station number labels). The two filled circles are for 60007, 114 and 60009, 454, two of the few other core samples with enough good data to model [see Korotev, 1981]. The anorthosite rich samples from the bottom of the 60009 drive tube would plot generally along the 'to FAN' line with many of these lying off the diagram. The dashed lines indicate the fields obtained by enclosing all 'surface' soil points from a given station (below) except certain anomalous soils discussed in the text and Korotev [1981] (60051, 61121, 67711, 67941, and 67961). (b) Each circle represents an Apollo 16 surface soil. All 42 are plotted. Some are labeled with the middle three digits (6XXX1) of their sample number. The three circle sizes (large, medium, small) key to the 'quality and quantity' of data grade (A, B, C) discussed in the text. These affect the mixing model uncertainty, as so indicated. Sample 67711 is not well fit by the model unless Na, K, Rb, Sr, and Eu are excluded, hence the dashed circle.

compositions [e.g., Lindstrom and Salpas, 1982]. Soil sampling was not extensive and systematic enough to determine whether there is any significance to this trend.

Deep Drill 60002-60007

For seven of the 'small' subsplits of 60002-7 the FeO concentrations obtained here are typical of those for Cayley-type surface soils (i.e., 5.4 to 6.0% FeO). All but one of the large subsplits (60002,632) are also typical. The FeO concentrations obtained here for the small subsplits are considerably lower (by 0.4 to 2.2% FeO) than the values obtained by Gose and Morris [1977] for the same subsplit, except for 60002,513, for which the value obtained here is considerably higher. Some, if not all, of this discrepancy might be because the subsplit analyzed here was not always the entire sample analyzed by Gose and Morris [1977]. See 'Experimental Methods'.

Except for one sample discussed below, all samples with anomalously high iron concentrations also have correspondingly high concentrations of Ni, Ir, and Co, but do not have unusual concentrations of other elements associated with mafic mineral phases (e.g., Sc and Cr). Hence the cause of the high FeO values is not the unusually high content of mafic phases, but the presence of larger than normal amounts of meteoritic metal in the small samples. This is convincingly demonstrated in Figure 3, a plot of Co versus Ni. The high Fe samples plot on the extension of the trend defined by the surface soils. For the split with the highest concentrations of Fe, Ni, Ir, and Co (60002,84) the mixing model predicts the equivalent of an 18% CCl component, compared to 3-4% for most Apollo 16 soils.

For one of these subsplits (60003,202) and for one subsplit from the station 4 drive tube (60004,227) the cause of the high FeO is probably not meteoritic metal, but contamination with stainless steel. The two splits do not plot on the trend in Figure 3 (i.e., non-meteoritic Co/Ni ratio) and do not have correspondingly high con-

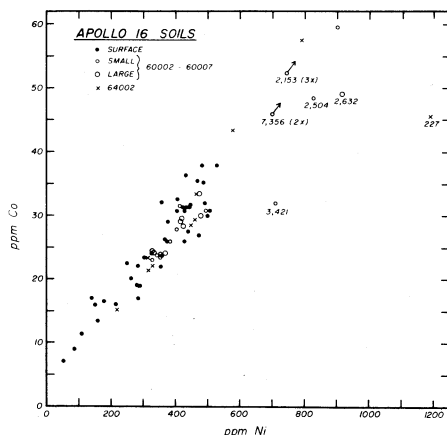


Fig. 3. Co versus Ni concentrations in Apollo 16 soils. Filled circles represent surface soils. Two points, as indicated, plot off the diagram at 2x and 3x the concentrations plotted here. Samples 60003,421 and 60004,227 are contaminated by stainless steel.

TABLE 4. Homogeneity in Large and Small Subsplits from Twelve Samples from 60002-7.

element	s/\bar{x} , %	
	(1)	(2)
Na	4.1	3.0
Sc	4.1	6.8
Ba	13.3	8.9
La	12.0	7.2
Sm	12.7	7.6
Eu	3.5	2.5

For six high precision elements, the relative standard deviation (s/x in %, $n = 12$) is given in (1) the ratios of the concentration in the small subsplit to that in the large subsplit compared to that of (2) the ratios of the concentration in the large subsplit to the mean concentration of the large splits for the 60002-7 samples of Table 2.

centrations of Ir. They do, however, have anomalously high concentrations of Cr.

It is interesting to compare the concentrations of elements not affected by the preceding problems in the two subsplits of the 60002-7 samples. The largest difference occurs for the LIL elements in 60005,92: REE concentrations in the small split are 32% greater than those in the large split. If we assume the large subsplit is more representative of the split as a whole then we can use the ratio of the small to large subsplit concentrations as a measure of how well the small subsplit represents the whole split. We can then compare these to the variation among the large splits. In Table 4 such a comparison is made. Although the experiment was not done in a manner to prove that the following contention is true, the data suggest that the variance among several 10 mg subsplits of any one of the major depth splits is as great as the variance among representative samples of the twelve major depth splits analyzed here. It should be clear that 10 mg subsplits are not sufficient to characterize the composition of a split to much better than 5-10% for many elements and worse than this for LIL elements. This may be adequate for many purposes.

Mixing model results for the large subsplits of 60002-7 are plotted in Figure 2a and Sc and Sm concentrations plotted in Figure 1 for comparison with the surface soils. Most of these samples (which were systematically selected to be among the most iron-rich samples) are similar to the station 10 surface soils. The composition of none is dissimilar to the range observed for the stations 5, 6, 8, 9, and 10 surface soils.

Drive Tube 64002

The ten samples chosen for analysis were intended to show the range of compositions within the core. Although there are some subtle variations among the subsplits analyzed, based on the preceding discussion it would be hard to argue that these represent corresponding variations among the splits as a whole. Subsplit 236 (15.75 cm) is anomalously high in Na, Sc, and LIL ele-

ments compared to the others and is even 13% enriched in Eu (perhaps the most invariant element among Apollo 16 soils) compared to the mean of the others. Nearby subsplits 238 and 240 (16.75 and 17.75 cm) are the most different from the preceding by being the most anorthositic (low Fe and Sc; high Al and Ca). These three samples are the most immature of those analyzed [Morris and Lauer, 1982] and are toward the top of the lower of the two compositional units identified by Houck [1982] in the drive tube. It cannot be argued on the basis of these data, however, that there is an overall compositional difference between these two units. Subsplit 210 (2.75 cm) has an unusual Th and U anomaly (2X and 3X typical concentrations) which is difficult to explain even as a sampling problem in that the REE are not anomalous. Subsplit 250 (22.25 cm), as noted by Morris and Lauer [1982], is anomalously high in Fe. The cause in this case is certainly meteoritic metal since the point plots along the meteoritic line in Figure 3 and the sample has appropriately high Ir and appropriately typical Cr concentrations. Subsplit 227 (11.25 cm), as mentioned previously, is contaminated by stainless steel. However, no anomaly was noted for this subsplit by Morris and Lauer [1982].

The ratio of the FeO concentration obtained by Morris and Lauer [1982, as read to the nearest 0.1% FeO from their Figure 2] to the values obtained here average (with one standard deviation) 1.03 ± 0.08 . This is excellent agreement.

For comparison to the station 4 surface soils Sc and Sm concentrations for the ten subsplits are plotted in Figure 1 and mixing model results are plotted in Figure 2a. These samples have a distinct station 4 affinity; six of the ten plot within the field of the four surface soils in Figure 2a and the others plot nearby. Of the remaining four, three are slightly more anorthositic than 64501 and one, as mentioned, is unusually LIL-element rich.

The 64002 core data argue against the suggestion of Korotev [1981] that South Ray Crater is the source of the excess anorthosite component in the station 4 soils compared to the station 5 soils. If this were true, the ejecta have been worked into the soil relatively uniformly to a depth of at least 23 cm, which is probably not reasonable or consistent with the modal petrologic data of Houck [1982]. A more likely explanation is that the anorthosite is of more local origin, probably underlying the site. Houck [1982] suggest crater Cinco a as the source of the core material.

Discussion

All new data are consistent with the observation made by Korotev [1981] that three compositional extremes exist among the Apollo 16 soils (both surface and cores) and that the composition of all soils can be expressed as mixtures of these three end-member components. The three components are ferroan anorthosite (FAN), a North Ray Crater (NRC station 11) soil component, and a Cayley (station 5 and 6) soil component. (The exceptions are those fines samples which derive the bulk of their material from a single rock, e.g., 67711 and 67031.) The Cayley soil component is best represented among the surface soils

by 65501, 65511, and 66081. These soils are the most enriched in LIL elements and elements associated with mafic minerals and least enriched in Al and Ca. The component is identified with the Cayley formation because of the similarity of the composition of these soils to the composition of the Cayley plains west of the landing site as deduced by the orbital X ray and gamma-ray data [see Korotev, 1981]. The NRC soil component is represented in its extreme by soils 67511 and 67461. These are low in LIL elements and are noritic anorthosite in bulk composition. The ferroan anorthosite component is most prevalent in the anorthositic samples from the 60009 drive tube [e.g., Blanchard et al., 1976; McKay et al., 1976] but among the surface soils is most important at station 4. Most of the Apollo 16 soils correspond to binary mixtures of either the Cayley and NRC components or the Cayley and FAN components. This produces the two mixing trends of Figure 2 (also vaguely discernible in Figure 1). The convergence of both trends at stations 5 and 6 coupled with the absence of a rock type corresponding to this composition argues that the soil itself is the component important to the mixing trends.

The goal of studies such as this is to use the composition of the regolith and variations therein to extrapolate information about the composition of the underlying bedrock and/or other constituents. The assumption is that although we have many samples of rock, the soils provide a better average of the bulk composition of the site. This is both an advantage and a disadvantage. For detailed understanding of the petrogenesis of rocks we must study rocks. However, the compositional variations within the soils are much less than within the rocks. So from soil studies used in conjunction with results from rock studies we should be able to determine the volumetric importance of the various compositionally distinct rock types found at a site. We might also be able to deduce the existence of components which have not been recognized in the rocks.

The problem of deducing something about the site bedrock from the soils is particularly difficult at Apollo 16 as the soil data are not easily reconciled with the rock data. Two of the three components discussed above are not rocks, but soils, which are presumably mixtures of comminuted rocks. Some of the considerations involved with explaining the Apollo 16 soil components as mixtures of rock types have been discussed, but the problem was left unresolved [Korotev, 1981]. A thorough treatment must again be deferred until we have a better understanding of the rock types themselves. The problem is exemplified by the NRC soil component. In the recent study of North Ray Crater rock composition by Lindstrom and Salpas [1982], four compositionally distinct types were identified: ferroan anorthosite, ferroan anorthositic norite, a magnesian melt rock of the very high alumina (VHA) basalt type [e.g., Hubbard et al., 1973], and a magnesian granulite. Each of these components is compositionally distinct in the sense that none can be a mixture of the others. Even considering the observed variation in composition among different samples of each of these rock types, no mixture of these four components can adequately

reproduce the composition of the station 11 soils. The specific problems involve fitting the ratio of Fe to Mg and supplying the high concentrations of Na, Sr, and Eu observed in some of the soils (67481, 67601, 67701, and particularly 67711). The latter problem also applies to certain North Ray Crater rocks (feldspathic melt rocks, some bulk breccias) which in other regards appear to be mixtures of the four compositionally distinct components. Thus despite detailed analysis of the rocks, the soil data indicate the presence of a component not yet identified in the rocks. This component must be either volumetrically important (> 10%) and moderately enriched in Na, Sr, and Eu or minor and extremely enriched in Na, Sr, and Eu.

The problems involved in modeling the Cayley soil component and Apollo 16 soils in general as mixtures of observed rock types has been discussed by Korotev [1981]. It was argued that, among the observed rock types, the basaltic impact melts of VHA composition and anorthosite were certainly necessary, but combinations of them were insufficient because the Mg/Fe ratio in the VHA melt rocks is too high to explain the soil value. It was postulated that another component must be present with similarly high concentrations of Fe, Mg, and related elements but with a mg' value lower than that of the soils. Such a component has now been found, namely, the ferroan anorthositic norites recently identified in North Ray Crater breccias by Lindstrom and Salpas [1982]. Inclusion of this component in the soil mixing models greatly improves the fits for Fe and Mg. Because of the low LIL-element concentrations in the ferroan anorthositic norites, however, an additional LIL-element rich component is probably required (depending upon the LIL-element concentrations in the VHA component used; these are quite variable from sample to sample). The LIL-element rich poikilitic impact melts are the logical choice. These have the same mg' values as the soils and hence do not affect the Mg/Fe ratio in the soils, but are too LIL-element rich to account alone both for the Fe and Mg concentrations and LIL element concentrations in the soils. These four components (plus a minor meteoritic component) can explain most of the characteristics of the Cayley soil compositions. One problem remains. Like some of the North Ray Crater soils, some Cayley soils are also richer in Eu and to a lesser extent Na and Sr than that combination of the four components needed to fit the other elements. The soil data again indicate the presence of a Eu-rich component yet unidentified in the rocks.

No attempt will be made here to model the Apollo 16 soils quantitatively as mixtures of the six components just discussed (ferroan anorthosite, ferroan anorthositic norite, magnesian basaltic impact melt, poikilitic impact melt, a high Na, Sr, and Eu component, and a meteorite component). Preliminary models, using the 67711 soil as the high Na, Sr, and Eu component, suggest that such a model would work as well as any yet suggested. Serious modeling of this kind must await further information of two kinds. First, the high Na, Sr, and Eu component must be identified and characterized. Second, the reason for the compositional variation within the VHA type melt rocks must be understood. Of the various

rock types discussed these are the most variable in composition, which may preclude 'fine tuning' of any model. Finally, a challenge to any such effort, particularly one which attempts to include (as is apparently required) both a ferroan and a magnesian Fe and Mg rich component, is to account for the relative invariance in the ratio of Mg to Fe among the soils while accounting for the range of Al, Ca, and LIL element concentrations.

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