PROCEEDINGS OF THE SEVENTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 2
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. B4, PAGES E411–E431, MARCH 30, 1987

Mixing Levels, the Apennine Front Soil Component, and Compositional Trends in the Apollo 15 Soils

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Variations in concentrations of lithophile elements in samples of Apollo 15 soil can be explained in terms of only four chemical components. Three components are represented by extrusive rock types found at the Apollo 15 site: mare basalt, KREEP basalt, and the pyroclastic green glass associated with breccia 15426. The fourth component, the highlands component, can be represented by soil from the Apennine Front, particularly the soil obtained from the 55–57 cm depth interval of station 2 core 15007/8. Among samples of Apennine Front soil, this one appears to be the least contaminated by mare materials and may be our most typical sample of the Apennine Front highlands. Although soil fron the Apennine Front is itself a complex mixture of many types of highlands rocks, it behaves as a single component with respect to mixing with the other three (rock type) components. The various subcomponents of the Apennine Front soil (e.g., melt rock and anorthositic norite) that have been used in some mixing models are not required as discrete components in order to explain the compositional variation among samples of Apollo 15 soil. Most of this compositional variation results from mare-highlands mixing, i.e., Apennine Front soil with mare basalt. KREEP basalt, which probably derives from local (possibly unexposed) sources, is also a variable component of the soil and is most prevalent in the soil from stations LM, 6, and 9.

INTRODUCTION AND MIXING CONCEPTS

A major goal of compositional studies of lunar soil is to identify the various chemical components of the regolith, to estimate the relative importance of each, and to account for the variation in composition among different samples of regolith in terms of these components. This paper presents new compositional data for 29 samples of Apollo 15 soil (<1 mm grain-size fraction) as well as data on 50 individual particles from the 1–2 mm fraction of a single soil. These and other published data are discussed in terms of four techniques that have been used to determine the important components of the regolith. The constraints each of these various techniques place on our interpretation of the Apollo 15 regolith as a mixture of chemically unique components will be reviewed. The review will emphasize a distinction not always made, namely, the distinction between determining what chemical components are required to explain the systematic variations in composition observed among soil samples on the one hand, and understanding how these chemical components relate to the local rock types on the other.

To help clarify this distinction, the concept of "mixing levels" is introduced. This concept is useful in visualizing mixing relationships and is a simple formalism of the fact that, from the compositional standpoint, a sample of lunar regolith can be considered as a mixture on several different levels. In the following discussion, Figure 1 will be used to help visualize these levels and demonstrate mixing relationships among soil components. Figure 1 is a schematic representation of a two-element variation diagram for soil samples from a hypothetical landing site. It will be assumed that any mixing relationships implied by Figure 1 are not contradicted by similar plots for other elements.

Mixing Level III—Soils

The distribution of data points in Figure 1 yields an approximately linear trend. The simplest interpretation is that the soil samples are two component mixtures and that the variation in composition results from varying proportions of the two components in the various samples. Any sample plotting near the middle of the distribution of the compositional equivalent of a mixture of soils of more extreme composition and hence it could be modeled as a mixture of the samples plotting at the low-X and high-X extremes of the trend (Figure 1*a*). In this model, the two components implied by the linear trend in the soil data are soils themselves. We will call a soil of extreme composition, i.e., a soil that cannot be modeled as a mixture of other known soils, a type-III component. At level III, soils are mixtures of other soils. The light mantle soil from station 3 at Apollo 17 can be regarded as a level-III mixture. This soil is intermediate in composition to highlands soil from the South Massif (station 2) and mare soil from the valley floor (station 5) [*Rhodes et al.*, 1974]. Thus the light mantle soil is the compositional equivalent of a mixture of the two. It is, in fact, also a physical mixture as a result of avalanche of massif material onto the valley floor. Soil of intermediate composition nearly always can be modeled as a mixture of other soils of more extreme composition.

Mixing Level II—Local Rock Types

At level II, soils are mixtures of rock types observed locally. If the soils of extreme composition can be modeled as a mixture of locally observed rock types, then a soil of intermediate composition can also be modeled as a mixture of these same rock-type components. We will refer to a local rock type as a type-II component of the soil. Petrographic analysis of soil will identify type-II components as constituents. Chemical analysis can also identify type-II components. Type-II components might be igneous rocks, volcanic glass, polymict breccias, or meteorites. In Figure 1*b*, the extrapolation of the trend in the high-X direction intersects the field for a local rock type, suggesting that this rock type predominates in the high-X soil and that the linear trend in the soil data results from varying proportions of this rock type. In this case, a type-II component can be directly associated with the trend in the data. In the low-X direction, however, no particular rock type is

Paper number 6B7209.
0148-0227/87/006B-7209$05.00

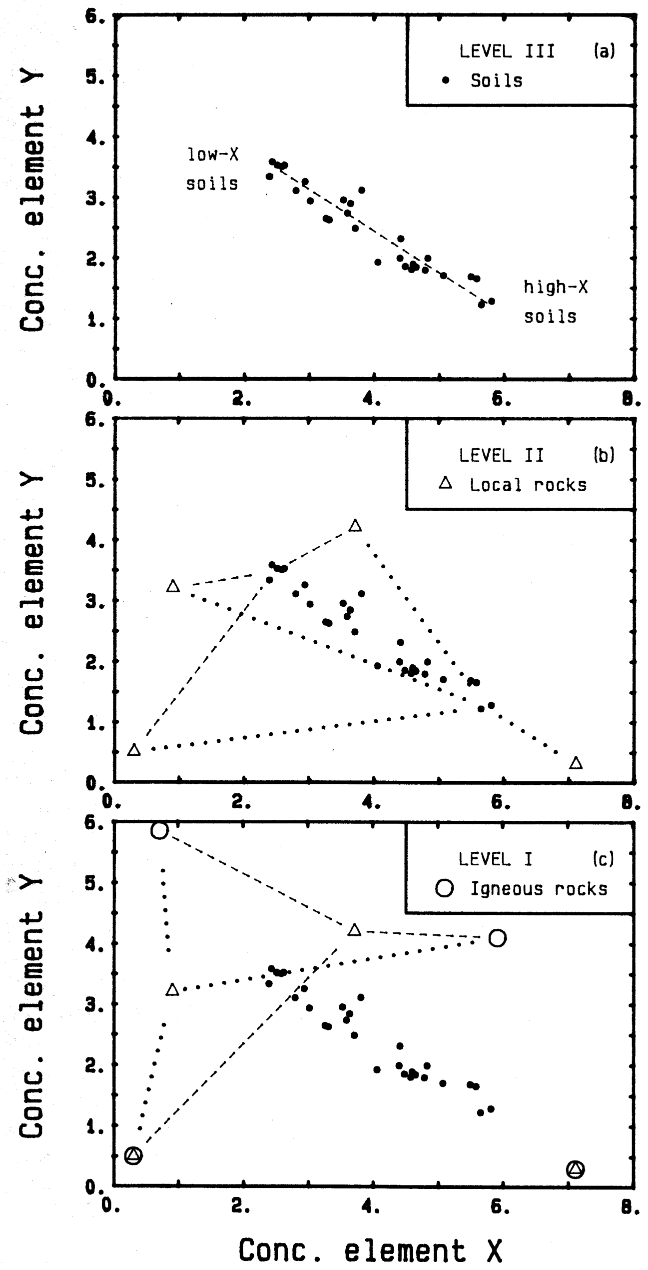

Fig. 1. Schematic mixing diagrams typical of those seen for lunar soils that illustrate the concept of mixing levels discussed in the text. (*a*) The soil samples plot along a nearly linear trend (dashed line) implying that the variation in composition results primarily from two-component mixing. The samples of intermediate composition are mixtures (or the compositional equivalents of mixtures) of the samples of more extreme composition, the low-X and high-X soils. This is an example of level-III mixing. Soils are type-III components. (*b*) The soil samples are also mixtures of four local rock types (type-II) components. The low-X soils are mixtures of three of them (represented by dashed lines). The high-X soils are dominated by the single high-X rock type but contain a small component of the other three local rock types as well (dotted lines). The soil data do not trend in the direction of any of the three low-X rocks, which indicates that these rocks are so well-mixed in the soil that the low-X soils act as a single (type-III) component. The high-X rock type is not as well mixed in the soil. Level II is mixing in terms of local rock types. (*c*) Two of the local rock types are primary igneous rocks (type-I components), but the other two are polymict breccias. These can modeled as mixtures of three of the primary rock types (dashed and dotted lines). Hence the soils, in principle, can also be modeled as mixtures of primary igneous rocks (level-I mixing). Any of these mixing levels (or combinations thereof) can represent a valid model, depending upon the purpose for which it is used.

implicated. Instead, the trend terminates at a composition intermediate to three rock types. We can reasonably expect that the low-X soil might be a mixture of these three type-II components. Because the high-X soil contains a component of the low-X soil, the high-X soil is a mixture of all four type-II components.

Quantitative modeling of regolith in terms of type-II components requires more assumptions than does a level-III model because it is usually impossible to identify all the type-II components. Any given soil sample is a mixture of many different rock types, but some may be far more important volumetrically than others. Some rock types that have been found either as clasts in breccias or as discrete samples are obvious in their compositional uniqueness or petrologic importance (e.g., the 72417 dunite at Apollo 17). However, this does not necessarily mean that they are volumetrically important components of the soil. On the other hand, an important type-II component of the soil may be overlooked because its composition is too similar to that of another component or because it is not obvious petrographically (e.g., a fine-grained component or some rock type not found as a large rock sample). At Apollo 17, the South Massif soil is dominated by noritic impact melt and anorthositic gabbro, whereas the mare soil is dominated by high-Ti mare basalt and orange glass of pyroclastic origin. These four type-II components explain most of the compositional features of the Apollo 17 soils [*Rhodes et al.*, 1974]. Although other rock types were found at Apollo 17 (e.g., dunite, very-low-Ti basalts) and are undoubtedly components of the soil, they are volumetrically minor.

The linear trend in the regolith data of Figure 1 has an important and often overlooked implication: If each individual soil sample is simply a random mixture of the various local rock types occurring at the site, then no such trend would be observed; the soil points would simply scatter within the boundaries defined by the points for the type-II components. As the soil data in Figure 1*b* do not trend in the low-X direction toward any particular rock type, none of these rock types is required to explain the trend. The low-X soil is plausibly presumed to be a well-mixed mixture of three rock types, a mixture that acts as a single, type-III component in binary mixture with the high-X soil or rock. Thus the composition of any given soil sample in Figure 1 can be modeled in several ways (levels): (1) as mixtures of four type-II components (four local rock types), (2) as a binary mixture of a type-III component (the low-X soil) and a type-II component (the high-X rock type), or (3) as a binary mixture of two type-III components (the low-X and high-X soils). The important point is that two-component models are all that are necessary to explain the linear trend in the data. The systematic variation in composition among soil samples at a given site often results from mixing of regolith with other regolith, i.e., level-III mixing. Resolution of the soil compositions into the large number of type-II components that are undoubtedly present is not required in order to explain the systematic variation.

Mixing Level I—Igneous Rock Types

Many type-II components are polymict rocks in themselves, e.g., impact melt rocks or regolith breccias. Because these rocks are physical mixtures of more primary rock types, it should be possible ultimately to model any lunar soil as a mixture of primary lunar igneous rocks. We will call such rock types type-I components (e.g., mare basalt and pristine nonmare

TABLE 1. Results of Instrumental Neutron Activation Analysis of Apollo 15 Soils

Sample	I_s/FeO[*]	Station No.	Al_2O_3 %	FeO %	MgO %	CaO %	TiO_2 %	Na_2O %	Sc µg/g	V µg/g	Cr µg/g
15007,2129[†]	36	2	20.0	10.1	10.6	11.7	1.31	0.46	18.6	64	1940
15007,2131[†]	35	2	19.9	9.9	10.2	11.4	1.16	0.46	18.7	70	2100
15007,2133[†]	32	2	20.0	9.9	10.1	11.1	1.26	0.48	18.1	62	2000
15007,89[†]	54	2	19.1	11.5	10.6	10.7	1.54	0.44	21.5	84	2270
15007,91[†]	52	2	18.2	11.6	10.4	10.6	1.31	0.41	22.6	82	2280
15007,93[†]	54	2	18.0	11.9	11.2	10.5	1.66	0.42	22.1	89	2240
15201	68.	2	17.1	11.5	10.7	10.7	1.30	0.42	22.1	76	2220
15241	45.	6	(16.5)	12.4	(10.4)	11.3	(1.55)	0.46	25.4		2410
15261	77.	6	(16.4)	12.3	(10.7)	11.0	(1.50)	0.44	24.3		2330
15271,309	63.	6	(16.5)	12.2	(10.6)	10.5	(1.47)	0.44	23.8		2260
15271,95	63.	6	(16.6)	11.9	(10.7)	10.7	(1.50)	0.48	23.5		2230
15291	63.	6	(16.4)	11.9	(10.2)	11.1	(1.44)	0.47	23.7	(85)	2190
15431	39.	7	(16.3)	12.1	(10.9)	10.0	(1.32)	0.45	23.8	80	2240
15311	–	7	16.9	12.7	11.9	10.4	1.42	0.43	24.5	89	2370
15301,307	48.	7	(14.5)	13.9	(12.1)	9.7	(1.17)	0.38	26.4		2530
15301,81	48.	7	(14.7)	13.8	(12.2)	9.7	(1.18)	0.38	26.1		2560
15411	43.	7	(15.1)	13.7	(11.7)	11.1	(1.09)	0.40	26.4		2610
15421	–	7	10.4	17.1	14.6	9.2	0.71	0.31	32.2	115	3120
15401	6.	6a	12.1	16.3	14.8	8.3	1.08	0.35	29.8	125	3070
15021	70.	LM	(14.1)	15.1	(10.5)	10.5	(1.8)	0.42	30.4		2790
15013	77.	LM	14.8	14.8	10.8	10.0	1.97	0.46	28.7	115	2780
15031	68.	8	(14.1)	15.9	(12)	9.6	(1.7)	0.41	31.6	(120)	2840
15041	94.	8	(14.2)	14.5	(11.5)	11.6	(1.7)	0.44	28.5	(110)	2710
15471	34.	4	(13.4)	16.6	(11.6)	8.9	(1.2)	0.41	32.6		3310
15501	51.	9	(12.5)	16.8	(11.0)	9.8	(1.78)	0.37	32.9		3000
15511	–	9	(12.3)	16.9	(10.9)	10.3	(1.80)	0.39	33.1	(130)	3220
15071	52.	1	(12.7)	16.8	(10.8)	9.8	(1.60)	0.35	35.6		3330
15531	27.	9a	(9.9)	20.9	(11.3)	8.0	(2.2)	0.27	40.7		3840
15601	29.	9a	(10.7)	19.9	(11.2)	8.6	(1.5)	0.30	39.7		3680
Uncertainty[‡] (±, range)			0.3–0.4	0.1–0.2	0.2–0.3	0.5–0.9	0.05–0.25	0.01–0.02	0.2–0.4	15–25	20–40
Standards[§]											
BCR-1			13.2	11.95	3.1	3.2	2.62	3.21	32.2	355	12
1633a			–	*12.07*	–	–	–	–	*38.6*	–	193
DTS-1			0.22	7.73	*49.7*	–	0.0	–	3.40	9	*4245*
AN-G			*29.8*	2.90	1.95	*15.9*	0.2	*1.64*	9.91	*70*	46

Sample	Mn µg/g	Co µg/g	Ni µg/g	Sr µg/g	Zr µg/g	Cs µg/g	Ba µg/g	La µg/g	Ce µg/g	Nd µg/g	Sm µg/g	Eu µg/g
15007,2129[†]	1130	30.5	165	150	350	0.24	235	22.0	57	33	10.4	1.34
15007,2131[†]	1120	29.8	155	140	330	0.24	235	21.2	55	31	10.1	1.33
15007,2133[†]	1090	30.2	165	145	410	0.29	298	25.5	65	39	11.9	1.40
15007,89[†]	1225	39.0	240	95	260	0.22	239	21.2	55	33	10.1	1.33
15007,91[†]	1240	37.3	235	110	260	0.19	226	19.7	52	33	9.3	1.25
15007,93[†]	1300	38.2	240	135	310	0.20	214	21.0	56	32	10.1	1.28
15201	1215	37.7	225	140	320	0.24	218	20.4	53	30	9.48	1.27
15241	(1165)	38.8	212	155	390	0.27	262	25.5	67	38	12.2	1.41
15261	(1230)	40.9	247	150	330	0.29	251	25.4	66	38	11.9	1.39
15271,309	(1200)	41.0	281	135	380	0.27	250	24.5	64	36	11.5	1.39
15271,95	(1220)	39.3	246	145	370	0.28	297	27.6	72	37	12.9	1.47
15291	(1300)	37.6	228	155	360	0.26	266	26.0	67	41	12.1	1.44
15431	1305	37.8	167	140	330	0.26	244	22.7	59	33	10.5	1.30
15311	1345	45.9	215	110	260	0.19	190	17.1	45	28	8.16	1.15
15301,307	(1500)	54.7	253	110	260	0.15	182	17.3	45	26	8.07	1.08
15301,88	(1390)	49.6	236	110	260	0.20	172	17.6	46	26	8.29	1.115
15411	(1230)	49.6	215	105	250	0.17	189	17.4	46	25	8.28	1.09
15421	1730	64.5	204	<100	130	<0.1	90	7.83	21	11	3.77	0.653
15401	1750	58.5	160	100	300	0.16	227	18.2	49	28	8.68	0.923
15021	(1420)	44.6	232	130	380	0.27	263	25.0	67	38	12.0	1.325
15013	1580	76.5[‖]	278	140	410	0.27	290	27.2	70	40	13.2	1.455
15031	(1450)	46.4	203	115	430	0.27	271	26.4	70	41	12.6	1.36
15041	(1450)	46.3	252	150	370	0.27	259	26.1	68	36	12.4	1.40
15471	(1560)	50.5	172	115	220	0.10	153	13.4	36	21	6.63	1.055
15501	(1640)	48.5	201	120	330	0.24	195	19.9	50	30	9.56	1.17
15511	(1720)	48.1	215	105	300	0.20	211	21.6	57	35	10.4	1.23

TABLE 1. (continued)

Sample	Mn μg/g	Co μg/g	Ni μg/g	Sr μg/g	Zr μg/g	Cs μg/g	Ba μg/g	La μg/g	Ce μg/g	Nd μg/g	Sm μg/g	Eu μg/g
15071	(1680)	46.7	183	100	200	0.13	149	13.6	37	21	6.82	1.095
15531	(1960)	55.1	127	60	140	0.12	95	9.11	25	15	5.04	0.849
15601		53.2	142	90	250	0.13	105	10.8	29	16	5.74	0.953
Uncertainty[‡] (±, range)	10– 20	0.3– 0.6	15– 25	15– 40	15– 40%	0.02 0.04	8 15	1– 2%	2– 4%	3– 6%	1– 2%	1– 2%
Standards[§]												
BCR-1	1410	37.3	<40	350	210	0.98	650	25.4	53	27	6.68	1.95
1633a	–	*44.1*	–	*835*	*240*	*10.42*	*1320*	*79.1*	*168*	*76*	*16.83*	*3.58*
DTS-1	945	138.6	*2405*	–	–	–	–	–	–	–	–	–
AN-G	340	24.7	27	68	<50	0.04	29	2.20	4.7	2.3	0.71	0.36

Sample	Tb μg/g	Yb μg/g	Lu μg/g	Hf μg/g	Ta μg/g	Ir ng/g	Au ng/g	Th μg/g	U μg/g	Mass mg
15007,2129[†]	1.96	7.3	1.00	8.4	0.97	4.3	2.1	3.8	1.18	32.41
15007,2131[†]	1.92	7.3	0.99	8.0	0.92	3.8	1.6	3.3	1.20	34.13
15007,2133[†]	2.19	8.4	1.13	9.6	1.10	5.0	2.0	4.3	1.33	31.62
15007,89[†]	1.97	7.1	0.99	8.2	0.96	7.2	2.6	3.4	0.89	29.07
15007,91[†]	1.79	6.6	0.91	7.3	0.89	7.4	3.4	3.3	0.90	29.55
15007,93[†]	1.91	7.1	0.97	7.6	0.95	6.9	3.8	3.4	0.81	30.00
15201	1.78	6.6	0.99	7.6	0.90	7.6	2.2	4.3	0.86	45.74
15241	2.38	8.1	1.23	9.6	1.16	8.1	2.7	4.2	1.02	46.21
15261	2.33	8.1	1.20	9.2	1.13	7.5	107. [‖]	4.2	1.13	47.03
15271,309	2.22	7.8	1.17	9.4	1.11	7.1	2.3	4.3	1.18	47.51
15271,95	2.52	9.1	1.29	10.4	1.26	8.3	3.9	4.6	1.40	47.21
15291	2.41	8.7	1.23	9.7	1.15	6.6	3.2	4.6	1.06	49.14
15431	2.15	7.8	1.14	8.9	1.03	2.0	<2.	3.9	0.97	43.47
15311	1.60	6.0	0.81	6.9	0.80	4.8	4.5	2.8	0.86	31.51
15301,307	1.62	5.9	0.86	6.6	0.81	4.6	2.1	2.9	0.82	44.91
15301,88	1.59	5.9	0.86	6.4	0.81	5.6	2.9	3.2	0.6	49.35
15411	1.68	6.0	0.84	6.7	0.84	3.7	2.7	2.7	0.77	49.41
15421	0.81	3.02	0.449	3.11	0.40	<3.	24.9[‖]	1.11	0.31	44.68
15401	1.75	6.5	0.88	6.9	0.93	<3.	<3.	3.4	0.93	29.13
15021	2.39	8.8	1.22	9.9	1.18	8.2	3.8	4.3	1.09	41.94
15013	2.43	8.2	1.23	10.0	1.34	7.9	2.6	5.2	1.10	26.51
15031	2.49	8.8	1.32	11.8	1.24	4.9	<4.	4.8	1.10	44.50
15041	2.50	8.3	1.25	9.8	1.18	9.3	3.9	4.3	1.18	43.90
15471	1.37	4.74	0.71	5.4	0.69	3.3	1.8	2.0	0.61	43.53
15501	1.93	6.7	0.99	8.1	0.98	5.7	1.3	3.4	0.89	46.35
15511	1.95	7.2	0.98	8.1	1.05	6.4	<3.	3.1	0.81	48.88
15071	1.42	5.0	0.75	5.6	0.65	6.4	1.5	1.8	0.52	41.85
15531	1.05	3.61	0.534	4.1	0.57	<2.	1.0	1.19	0.29	41.69
15601	1.27	4.11	0.614	4.6	0.63	<2.	<2.	1.31	0.43	43.26
Uncertainty[‡] (±, range)	3– 5%	2– 4%	2– 4%	2– 4%	2– 4%	0.8– 1.5	0.6– 2.0	2– 6%	7– 15%	
Standards[§]										
BCR-1	0.98	3.31	0.477	5.15	0.78	<2.	<2.	5.84	1.66	31.66
1633a	*2.38*	*7.50*	*1.075*	*7.29*	*1.93*	–	–	*24.0*	*10.3*	58.57
DTS-1	–	–	–	–	–	–	–	–	–	47.01
AN-G	0.16	0.79	0.118	0.38	0.16			<0.1	<0.1	40.05

Samples are arranged by station number in approximate order of increasing mare component. Concentration values in parentheses are from the following sources: 15021: *Wänke et al.* [1973]; 15031: *Laul and Schmitt* [1973]; 15041: *Laul and Schmitt* [1973]; 15071: *Duncan et al.* [1975]; 15241: *Palme et al.* [1978]; 15261: *Duncan et al.* [1975]; 15271: *LSPET* [1972] and *Duncan et al.* [1975]; 15291: *Cuttitta et al.* [1973]; 15301: *LSPET* [1972]; 15301: *Duncan et al.* [1975]; 15411: *Willis et al.* [1972]; 15431: *Rose et al.* [1975]; 15471: *Wänke et al.* [1973]; 15501: *Duncan et al.* [1975]; 15511: *Chou et al.* [1975] and *Duncan et al.* [1975]; 15531: *Wänke et al.* [1973].

[*] I_s/FeO values are from *Morris* [1978] and *Bogard et al.* [1982].

[†] Depth below surface for core samples: 15007,2133,2203: 55.1–55.6 cm; 15007,2131,2204: 55.6–56.1 cm; 15007,2133,2205: 56.1–56.8 cm; 15007,89,363: 42.1–42.6 cm; 15007,91,354: 42.6–43.1 cm; 15007,93,365: 43.1–43.6 cm.

[‡] Uncertainties are one standard deviation estimates of precision. For most incompatible trace elements the uncertainty is expressed as a percentage of the concentration value. Absolute uncertainties are listed for other elements. Within the range listed, the smaller absolute uncertainties and larger relative uncertainties usually apply to lowest concentrations and conversely.

[§] Multielement standards include N.B.S. SRM 1633a (coal flyash), U.S.G.S. DTS-1 (dunite), and GIT-IWG AN-G (Greenland anorthosite) [*Korotev*, 1987*a*]. Chemical standards were used for Ti, Mn, Ir, and Au. Italicized values are those against which all other values for that element were determined. USGS basalt BCR-1 was treated as an unknown.

[‖] Contamination suspected because the ratio to Ni or Ir is outside the range for meteorites.

rocks). The use of the composition of terrestrial sedimentary rocks to infer the nature of the early igneous rocks of the earth's crust [e.g., *Taylor et al.*, 1986] is an example of modeling the sediments as level-I mixtures. Unlike on earth, however, the only important nonigneous process affecting the distribution of lithophile elements on the moon has been physical mixing, mainly by meteorite impact. Thus it is in principle easier to account for chemical mass balance during crustal evolution on the moon than on the earth because fewer processes have acted to complicate it.

In Figure 1*c*, four type-I components are plotted. We see that two of the type-II components are polymict rocks that can each be modeled as mixtures of three of the type-I components. The other two type-II components are also type-I components, i.e., they are igneous rocks that are observed locally. It is possible that such a component may also be a type-III component if it occurs as fine-grained material in pure form. The orange glass at Apollo 17 is a material that can be regarded as any of the three types of components.

The mixing levels discussed here have been designated numerically I, II, and III to imply that there are even higher (but more degenerate) levels. Mixing level IV might be regarded as the mixing of the different mineral phases of which the rocks and soils are formed. Resolving the major element composition of a rock into its normative mineral composition is an example of a level-IV mixing model. At some level, say level V, rocks and soils are simply mixtures of chemical elements. These levels will not be discussed here; they are mentioned only to demonstrate that any given soil can be modeled in terms of a number of sets of components. Two models that use different sets of components are not necessarily contradictory; they may merely reflect different modeling levels and may be intended to answer different questions. Note that the mixing levels do not necessarily relate to possible paths by which a particular soil sample evolved; they merely indicate that, when modeled as a mixture, different sets of components can account for the composition. A total of eight type-I, -II, and -III components (six rocks and two soils) are implied by Figure 1. The composition of any given soil sample can be explained by many possible combinations of these eight components; however, many of these combinations are less useful than others for understanding the geology of the site.

Most attempts at modeling lunar soils as mixtures have been directed at level II, i.e., accounting for the soil compositions in terms of locally observed rock types. Some of these models have deliberately used polymict, type-II components such as regolith breccias [*Schonfield*, 1975] and agglutinate particles [*Taylor et al.*, 1978], but most have preferentially used type-II components that are also type-I components and, except perhaps for impact melt breccias, have avoided local rock types that are polymict. Few models have used components that are primarily of type-III [e.g., *Korotev*, 1981, Table 7] and only a few models have been directed principally at level I. The model of *Ryder* [1979] attempts to account for the composition of highlands breccias in terms of rock types recognized as "pristine" (anorthosite, KREEP, and norite). The models of *Wasson et al.* [1977] and *Korotev et al.* [1980] are both level-I models in their intent. Each attempts to account for compositions of highlands breccias or soils on the global, not local, basis in terms of fundamental rock types. However each uses a hypothetical igneous component ("SCCRV" and "HON") to represent the mafic component, in part to demonstrate that observed samples of type-I mafic rocks are not adequate to account for the compositions of the highlands soils and breccias. Because of our insufficient sampling of the moon, modeling of lunar polymict materials using only known type-I components is usually less precise and provides less certain geologic constraints.

SAMPLE SELECTION AND ANALYSIS

Samples of 29 Apollo 15 soils were analyzed by instrumental neutron activation analysis (INAA) using the general techniques described by *Korotev* [1987*a*]. Results are reported in Table 1. Concentrations of Al, Mg, Ti, V, and Mn were determined only for those samples for which literature data were unavailable or ambiguous. For samples for which literature data are available, Table 1 includes these data (in parentheses) for completeness. Most of the samples were analyzed concurrently with samples of Apollo 15 regolith breccias. These results are reported briefly in *Korotev* [1985, 1986]. For this analysis samples were irradiated for 48 hours in a thermal neutron flux of 4×10^{13} $cm^{-2}s^{-1}$ in the University of Missouri Research Reactor. Soil samples were selected to represent the range of soil compositions at the Apollo 15 site. Several samples were selected because there were incomplete or no compositional data previously available for them, according to the catalog of *Morris et al.* [1983]. These include 15013, 15201, 15311, 15401, and 15431. Two splits each of samples 15271 and 15301 were analyzed. Also analyzed were samples from six depth intervals of 15007, the bottom half of the double drive tube at station 2 on the Apennine Front. Specific samples were selected on the basis of the FeO profile of *Bogard et al.* [1982] to represent the range in composition of the core. Of particular importance are the three samples between 55–57 cm at the very bottom of the core. *Bogard et al.* [1982] noted that these samples have lower FeO concentrations than do any other Apollo 15 soil, are immature, and have probably not been involved in downslope mixing on the front. In addition to <1 mm fines samples (e.g., 15271), 52 samples composing an entire 226 mg allocation of 15272, the 1–2 mm grain-size fraction of 15270 (station 6), were analyzed for 25 elements.

RESULTS AND DISCUSSION

The following discussion is based upon results obtained in this work as well as on results of the large amount of previously published work on compositions of Apollo 15 soil, particularly those of *Fruchter et al.* [1973], *Schonfeld* [1975], *Chou et al.* [1975], *Duncan et al.* [1975], and *Walker and Papike* [1981]. Many of the conclusions of previous work will be repeated in an effort to discuss systematically the constraints on site geology imposed by the regolith data. It is intended that the discussion will benefit from the new data obtained here, the wider data base employed, and the new information on the geology and rock types of the Apollo 15 site obtained as a result of the recent Workshop on the Geology and Petrology of the Apollo 15 Landing Site [*Spudis and Ryder*, 1986]. This discussion is an expansion of one presented in an extended abstract to that workshop [*Korotev*, 1986].

Organization of the discussion will be based on four techniques that have been used to understand the chemical composition of the soil: graphical techniques, factor analysis, chemical analysis of individual soil particles, and mixing models.

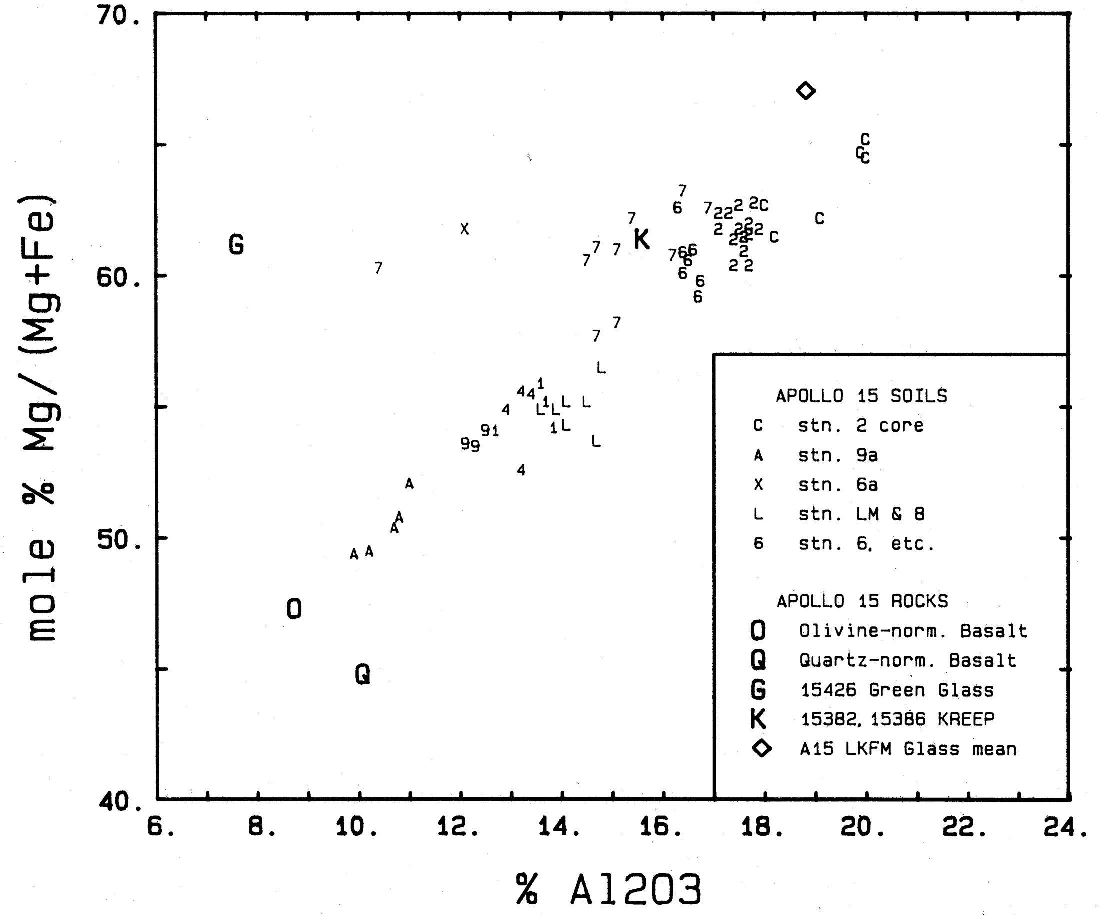

Fig. 2. Bulk mg′ versus Al_2O_3 concentration for Apollo 15 soil. Samples are keyed according to the station number at which they were collected. Soil data are from Table 1 and various literature sources referenced in *Morris et al.* [1983]. All analyses in which Al, Fe, and Mg were determined on the same sample are plotted. Consequently, more than one point is plotted for many five-digit (15XX1) soil samples. Mare basalt data are from *Rhodes and Hubbard* [1973], *Helmke et al.* [1973*a*], *Lindstrom et al.* [1977], and *Ma et al.* [1978]; green glass data are from *Taylor et al.* [1973] and *Ma et al.* [1981]. Data for Apollo 15 LKFM glass mean are from *Reid et al.* [1977]. Note that average mg′ of the minerals composing the soil might actually be greater than the values plotted because of the effect of metallic Fe [*Korotev*, 1987*c*]. However, the difference is small and probably nearly constant from soil to soil because Ni concentrations in Apollo 15 soils are not highly variable.

Graphical Techniques

Four components. Figure 2 is a plot of mg′ (mol % Mg/[Mg + Fe], based on bulk chemical analysis) versus alumina content for samples of Apollo 15 soil and some types of rock. This plot shows the essential features of the variation in bulk composition of the soils. With increasing Al concentration, concentrations of both Fe and Mg decrease, but Fe decreases relatively more than does Mg (see Table 1), so mg′ increases. Most of the samples lie on a trend between samples from station 9a on the rim of Hadley Rille (low-mg′, low-Al) and samples from station 2 on the Apennine Front (high-mg′, high-Al). The three most aluminous samples are those from the 55–57 cm interval at the bottom of the 15007 drive tube from station 2. The least aluminous samples are nearly as mafic as the mare basalts. Compositions of most other samples are intermediate. The data are correlated with sampling station: The soil becomes more mafic as the distance from the front increases (except for 15401 from station 6a, the highest sampling station on the Apennine Front). All samples with over 15% Al_2O_3 are from the Apennine Front (stations 2, 6, and 7). Observations such as these led previous workers to conclude that most of the variation in composition of Apollo 15 soils results from mixing of mafic, ferroan rocks from the mare with more aluminous, magnesian materials of the Apennine Front [*LSPET*, 1972; *Fruchter et al.*, 1973; *Rhodes*, 1977; *Walker and Papike*, 1981].

Some samples plot on a second trend between the surface soil from station 2 and the emerald green glass found at station 7. All samples plotting on this trend are from station 7 on the rim of Spur crater or from station 6a, 150 m to the east of Spur crater. The "soil" sample plotting closest to the green glass in Figure 2 is 15421, which is not a true soil, but the fines abraded from the friable green glass clods 15425/6 [*Ryder*, 1985]. Hence the samples from station 7 appear to be like those from station 2 but with addition of variable amounts of green glass. Heiken and McKay observed that the 0.125–0.25 mm grain-size fraction of 15421 contains 82% green glass droplets [unpublished data quoted in *Morris et al.*, 1983].

Although Figure 2 is useful for understanding mixing relationships based on bulk composition, it provides no information on lithophile trace elements. For example, KREEP basalt, a major rock type at Apollo 15 [e.g., *Spudis and Ryder*, 1985; *Warren and Wasson*, 1979*b*], plots with the station 7 soil in Figure 2, although it has considerably greater concentrations

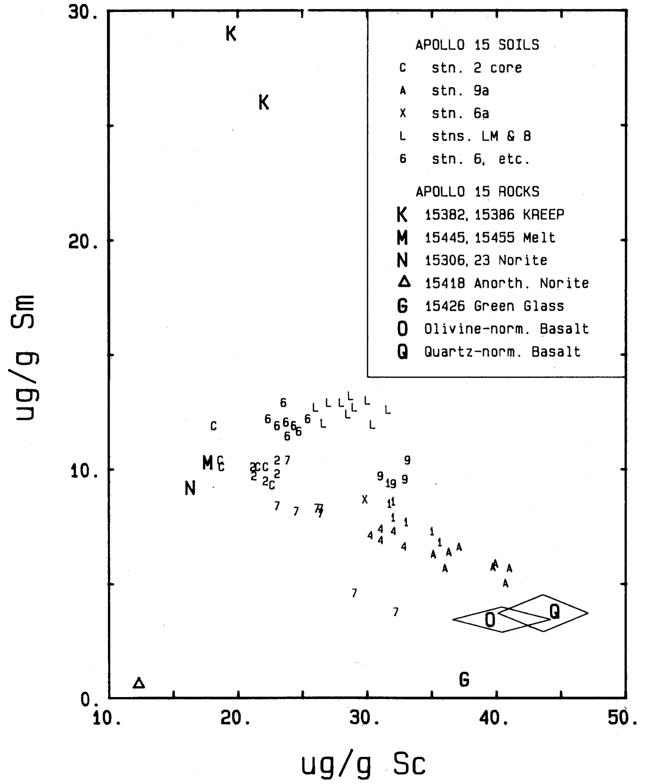

Fig. 3. Samarium and Sc concentrations in Apollo 15 soils. Data are from Table 1 and various literature sources referenced in *Morris et al.* [1983]. Samples are keyed according to station number and all analyses for which Sc and Sm were determined on the same sample are plotted, as in Figure 2. Data for some rock types are from sources referenced in Figures 2 and 4. The two points for KREEP are based on analyses of 15382 [*Murali et al.*, 1977] and 15386 [*Warren and Wasson*, 1978]. Other samples of Apollo 15 KREEP basalt tend to have even greater concentrations of Sm (see Figure 5). Fields for mare basalts represent one standard deviation limits about the mean based on data of *Helmke et al.* [1973*a*], *Laul and Schmitt* [1973], *Fruchter et al.* [1973], *Lindstrom et al.* [1977], and *Ma et al.* [1978]. The spread in Sc concentrations for mare basalts results primarily from interlaboratory bias. Taken at face value the data indicate that the difference in the mean Sc concentrations in the two basalt types is significant at the 99% confidence level. However, the olivine-basalt mean (40.4 μg/g, n = 49) is dominated by the data of *Laul and Schmitt* [1973] and *Ma et al.* [1978], which are low compared to data from the other labs, while the quartz-basalt mean (43.6 μg/g, n = 16) is dominated by the data of *Fruchter et al.* [1973] and *Helmke et al.* [1973*a*]. There may be no significant difference in Sc and Sm concentrations between olivine- and quartz-normative basalts.

of incompatible trace elements (ITEs). A useful two-element plot for examining the constraints imposed by the ITEs is that of Sm against Sc [e.g., *Korotev*, 1982; *McKay et al.*, 1986; *Lindstrom and Lindstrom*, 1986]. Scandium is a compatible trace element associated with mafic mineral phases, particularly clinopyroxene. Among lunar rock types, mare basalts have the greatest Sc concentrations. Samarium is an ITE associated with KREEP; any of a number of other KREEP-related elements would do as well, but both Sm and Sc are precisely determined by INAA.

Figure 3 is a plot of Sm and Sc concentrations in samples of Apollo 15 soil. It is evident in both Figures 2 and 3 that the compositions of samples from a given station are generally similar to each other and overlap little with those from other stations. This observation was previously noted by *Duncan et al.* [1975]. Both mixing trends seen in Figure 2 are also evident in Figure 3: Samples from stations 2, 4, 9a, and some from station 7 plot along the main mixing trend between mare basalt and the aluminous soil from the bottom of the 15007 core, while samples from station 7 plot along a trend between the station 2 soil and the green glass. However, it is evident in Figure 3 but not in Figure 2 that samples from stations 6, 9, and LM/8 cannot be simple mixtures of mare and Apennine Front soil. In Figure 3 they appear to be "pulled off" the main two-component mixing line by a third component that is rich in Sm.

In summary, Figures 2 and 3 imply that for the elements plotted, only four components are required to explain the compositional variation in Apollo 15 soils. That these four components account for the other lithophile elements as well is argued later. Most of the variation in concentrations of elements associated with major mineral phases results from mare-highlands mixing, i.e., the geographically correlated variation in the proportions of mare basalt and material from the Apennine Front. At stations 6a and 7 on the Apennine Front the green glass is a compositionally distinct and volumetrically important component. The ITEs like Sm indicate that some soil also contains an ITE-rich component, presumably KREEP basalt. This component is most important at stations 6, LM/8, and 9 and is not so obviously correlated with site geography.

Of the four components implied by Figures 2 and 3, three are type-II components in that they are each clearly represented by a major, local rock type: mare basalt, KREEP basalt, and green glass. The green glass does not occur as a crystalline rock (although the peridotitic mare basalts found in regolith breccia 15459 [*Lindstrom*, 1986] may be related), but as small glass droplets of apparent pyroclastic origin [e.g., *Delano*, 1979]. Breccia 15426 is composed predominantly of green glass spheres. Two principal types of mare basalt occur at Apollo 15, olivine-normative and quartz-normative (= pyroxene phyric; see *Rhodes and Hubbard* [1973] and review in *Spudis and Ryder* [1985]). Differences in bulk composition between the two basalt types are indicated on Figure 2. The figure implies strongly that the olivine basalts are the more important component of the soil, at least at stations 9a and 9. This is consistent with the predominance of olivine basalts among rake samples at station 9a (Hadley Rille) [*Spudis and Ryder*, 1985]. At face value Figure 3 implies, however, that the quartz-normative basalts are more important because the soil data trend toward the field labelled "Q." Close examination of the data indicates that the implication is erroneous or unfounded. It is not clear whether any significant difference really exists in trace element concentrations, particularly Sc, between these two basalt types (see Figure 3 caption). Also, even a small component of KREEP basalt in the station 9a soil would raise the Sm concentrations in the soil to values plotting to the high-Sm side of the main mixing line between the olivine basalts and the station 2 soil. Apollo 15 KREEP basalt is generally regarded as an igneous rock [see *Spudis and Ryder*, 1985, and *Warren and Wasson*, 1979*b*]. Thus three of the four components implied by Figures 2 and 3 are not only type-II components, but are also type-I components because they are primary, igneous products of lunar differentiation.

The Apennine Front soil component. The fourth component is not easily associated with any specific rock type. Its presence is merely implied by the mixing diagrams. It is clearly associated with the Apennine Front and is most prevalent in the soil from

TABLE 2. Comparison of Mean Composition of Apollo 15 LKFM Glasses to That of the Most Aluminous Soils Collected at Apollo 15

	AF soil	LKFM glass	
		Mean	±
SiO_2	(46.2)*	46.6	1.8
TiO_2	1.24	1.25	0.4
Al_2O_3	20.0	18.8	1.8
Cr_2O_3	0.29	0.20	0.05
Fe	10.0	9.7	1.9
MnO	0.14	n.a.	
MgO	10.3	11.0	1.6
CaO	11.4	11.6	0.9
Na_2O	0.47	0.37	0.14
K_2O	(0.18)†	0.12	0.07
mg′	64.7	67.1	5.4

Values are in mass percent. Apollo 15 LKFM glasses: mean of *Reid et al.* [1977] with one standard deviation. Most aluminous soils collected at Apollo 15: mean of three soils from 55–57 cm depth interval of Apennine Front core 15007 (Table 1).

*By difference.

†Not analyzed, but estimated based on mean Sm concentration and regression of K_2O against Sm for soils for which both elements have been analyzed: $(\%\ K_2O) = (\mu g/g\ Sm)0.0172 - 0.005$.

station 2, particularly the soil at 55–57 cm depth in the core. It appears to be what would remain after removal of mare basalt, green glass, and KREEP basalt from the Apennine Front soil. For convenience, and so as not to suggest biases immediately by associating it with known rock types, this component will be called by a new name, the Apennine Front soil component [*Korotev*, 1986]. We define it as the average composition of the intrinsically highlands portion of Apennine Front soil in the vicinity of the Apollo 15 site. Such a definition is risky because we do not know whether we actually have a sample of such material or whether Apennine Front soil is really of uniform composition farther away from the mare surface. It also implicitly assumes that mare basalt, KREEP basalt, and green glass are contaminants and farther up the slope of the front these materials may be less common. With these caveats and for operational convenience, we will regard the samples from the 55–57 cm depth interval of 15007 (Table 1, 15007,2129, 2131, and 2133) as the type specimens of the Apennine Front soil component. As will be argued, the Apennine Front soil component is a mixture of many rock types. The name is intended to imply, in light of the concepts discussed in the introduction, that it may be treated as a single type-III, chemical component with respect to mixing because there is no evidence that the various subcomponents of the Apennine Front soil component behave as individual components.

Relationship of the Apennine Front soil component to LKFM. The similarity in composition between the soil from the Apennine Front and the composition known as low-K Fra Mauro basalt (LKFM) has been noted by many workers [*Taylor et al.*, 1973; *Carr and Meyer*, 1974; *Duncan et al.*, 1975]. The LKFM composition was originally defined in terms of a diffuse cluster in the bulk composition of glasses in soil from Apollo 15 [*Reid et al.*, 1972, 1977. In Figure 2, the trend in the soil data in the highlands (high-Al_2O_3) direction approaches the mean LKFM composition. In fact, the most aluminous soil is more similar in bulk composition to the LKFM glass particles found in the soil (Table 2) than in any specific rock type found at Apollo 15. This similarity may mean either that the Apennine Front soil has a large component of LKFM glass or that the glass itself is a bulk-soil melt.

Taylor et al. [1973] noted that the bulk composition of the dark melt-rock portion of "black and white" breccia 15455 was also similar to the LKFM composition, and since that comparison, "15455 dark" has been regarded as one of the type specimens of LKFM [*Taylor*, 1975]. The minor and trace element composition of noritic melt rocks such as 15455 has become associated with the LKFM composition [*Taylor*, 1975] even though concentrations of ITEs, except K, were not measured on the original LKFM glasses. The potassium data indicate that the LKFM glasses and the melt rocks are not the same type of material: The mean K_2O concentrations in LKFM glasses from various landing sites [*Reid et al.*, 1977] are a factor of 4–5 less than that of melt rocks identified as LKFM (e.g., 14310, 15455, 65015, 77135 [*Reid et al.*, 1977; *Vaniman and Papike*, 1980]). Hence LKFM melt rocks are not really "low K" in the original sense of "low-K Fra Mauro basalt." Also, the noritic melt rocks of LKFM composition at a given site are usually more magnesian (greater mean mg′ of silicate minerals) than are LKFM glasses found in the soil. (For Apollo 16 melt rocks, this comparison requires a substantial correction for meteoritic Fe-Ni metal when based on bulk analyses [*Korotev*, 1987*b*].) This difference in mg′ is demonstrated for Apollo 15 in Figure 4, which is like Figure 2, but with various rock types associated with the Apennine Front also plotted, including the melt (dark) portions of 15455 and similar 15445.

The LKFM composition is not plotted on Figure 3 because Sc and Sm were not determined in the original LKFM glasses. However, the proximity of the points for the aluminous (low-Sc) soil samples from the station 2 core (15007) and the 15455 melt rock suggests that even if melt rock such as this is not exactly like LKFM (as originally defined), it may still be an important component of the Apennine Front soil. Note also that a "probably pristine" norite clast, 15306,23 [*Warren and Wasson*, 1980], is very similar in composition to the melt portions of 15445 and 15455 (Figures 3 and 4). If it is a pristine, plutonic norite and if the 15455 melt is regarded as an LKFM rock, then the 15306 norite is our only sample of pristine LKFM. This would be important because it has been noted that despite the commonness of glasses and melt rocks of LKFM composition, no igneous samples have been found [*Reid et al.*, 1977; *Hess et al.*, 1977; *Warren and Wasson*, 1979*a*]. On the other hand, the norite clast 15306,23 may simply be a fragment of a coarse-grained melt rock like that in 15455.

Together, the arguments made thus far indicate that the Apennine Front soil component may be closely linked with the LKFM composition, that the melt rock portions of 15445 and 15455 (and compositionally similar norite clast 15306,23) are different in composition from the Apollo 15 LKFM glasses, but that melt rocks similar to that in 15455 might still be an important component of the Apennine Front soil. That other types of Apollo 15 melt rock may actually be more important than the 15445/55 type is argued later.

Rock components of the Apennine Front soil component. There is little direct evidence of what type-I and type-II components are mixed to form the Apennine Front soil component. The identification of these components is nevertheless important to our understanding of the geology of the Imbrium basin. It is instructive to consider the constraints the soil data impose on modeling the Apennine Front soil in terms of locally sampled rock types. Figure 4 contains a mixing line (dashed) between the soil samples richest and poorest in mare basalt. The composition of the Apennine Front soil

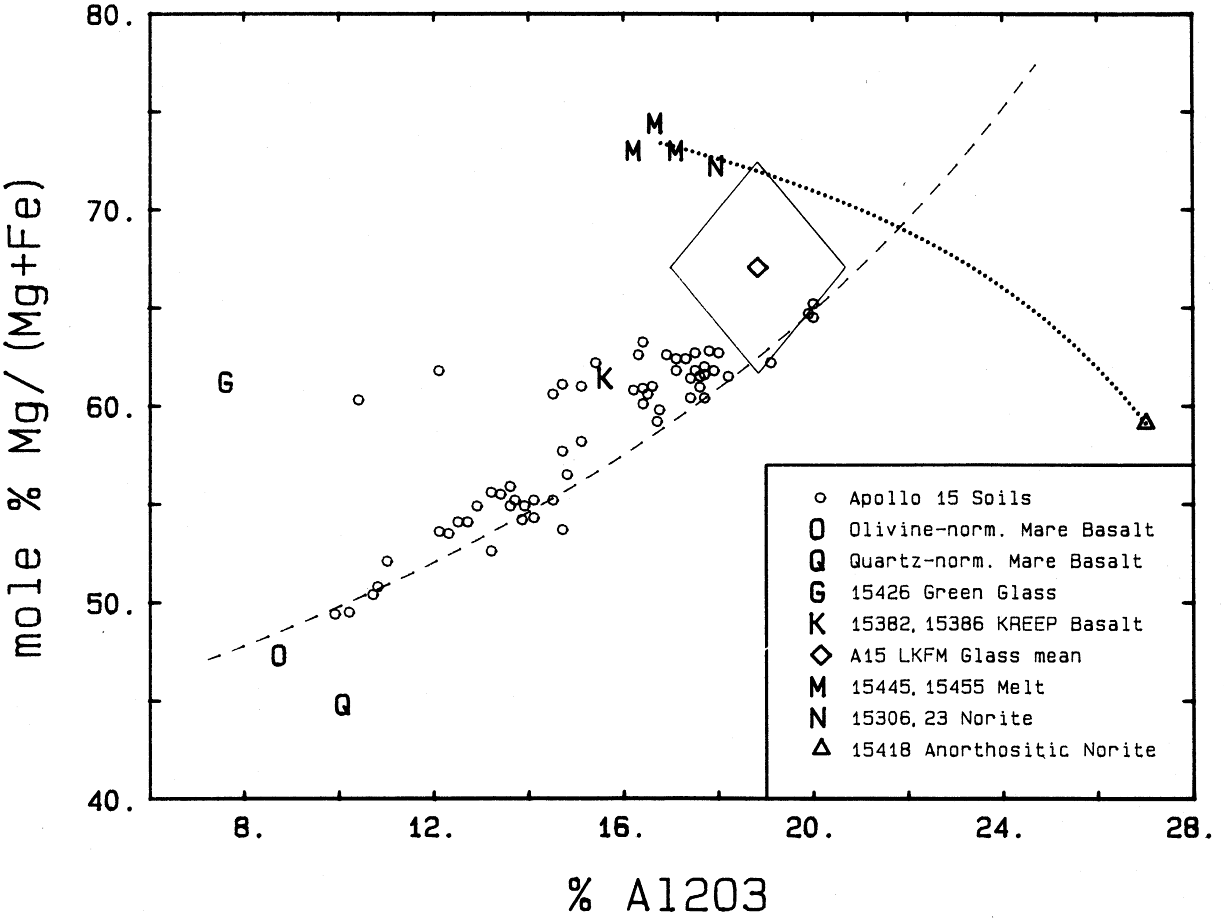

Fig. 4. Like Figure 2, but with points for Apennine Front rock types added. See Figures 2 and 3 for sources of data. Additional data are from *Warren and Wasson* [1980] (15306,23); *Lindstrom and Lindstrom* [1986] (15418); *Ridley et al.* [1973] and *Blanchard et al.* [1976] (15445); and *Taylor et al.* [1973] and *Lindstrom* [1986, and unpublished data] (15455). The one standard deviation range about the mean composition of Apollo 15 LKFM glasses is shown [*Reid et al.*, 1977]. The dashed line is the mixing line between (and extending beyond) the mean composition of the five analyses with lowest Al_2O_3 (the station 9a soil on the edge of Hadley Rille) and the three analyses with highest Al_2O_3 (the soil between 55–57 cm depth in the station 2 core on the Apennine Front). The dotted line is the mixing line between the 15445/55 melt composition and the 15418 anorthositic norite. Because the concentrations of three elements are represented on this diagram, mixing lines between pairs of components are usually curved.

component (as defined above) must correspond to a point on this line at an alumina concentration equal to or greater than that of the most aluminous soil samples. The curve does not intersect the region of the 15455 melt rock. Thus if melt rock as magnesian (high mg′) as the 15455 sample is an important type-II component of the Apennine Front soil, the soil must also contain a significant portion of a more ferroan (low mg′) component that plots below the dashed line and at the same time contains concentrations of Fe and Mg sufficiently great to lower the mg′ of the mixture. This component is not mare basalt; the effect of adding or subtracting mare basalt to the Apennine Front soil is defined by the dashed line. The component is also not primarily KREEP basalt because adding enough KREEP basalt to account for the low mg′ of the soil would result in concentrations of ITEs very much higher than observed in the soil. Addition of troctolite such as 15455,106 [*Warren and Wasson*, 1979*a*] as a component only aggravates the problem because these troctolites are even more magnesian (mg′ > 80). The implied missing component is also not an anorthosite such as sample 15415. Although sufficiently ferroan, anorthosite does not contain enough Fe and Mg to alter the mg′ of the mixture.

Among the well-known and compositionally extreme rock types found at Apollo 15, only the 15418 anorthositic norite [see, e.g., *LSPET*, 1972, and *Lindstrom and Lindstrom*, 1986] is a suitable component both in the sense of being an observed rock type as well as balancing the composition of 15455. Points for 15418 are plotted on Figures 2, 3, and 4, and a mixing line between the 15455 melt and 15418 is shown as a dotted line on Figure 4. The intersection of the two mixing lines corresponds to a composition both more aluminous and more magnesian than that for any of the soil samples. This may mean that even the most aluminous soil is contaminated with mare basalt and/or green glass and that the true composition of the Apennine Front soil component plots at the intersection point of the two mixing lines. It is clear from Figure 3, however, that if the Apennine Front soil component is to be modeled principally as a mixture of 15455-type melt rock and 15418-type anorthositic norite, then a small component of KREEP basalt is also needed to account for the high concentrations of ITEs in the station 2 soils. This would minimize the need for such a large proportion of mare material. The KREEP basalt is a type-I component. Whether the 15418 anorthositic norite represents a type-I component is controversial [*Lindstrom and Lindstrom*, 1986].

TABLE 3. Mass Balance Data on 1–2 mm Particles from Station 6 Soil 15272

Compositional group	No. of particles	Total mass (mg)	Mass fraction (%)
Mare basalts	3	12.40	5.5
Like station 9a soil	1	2.47	1.1
Like station 6 soil, regolith breccias	21	65.10	28.8
Intermediate to station 6 soils and KREEP	3	16.44	7.3
Like Apollo 15 KREEP	15	62.77	27.8
Like station 2 soil	1	6.00	2.7
Noritic and troctolitic anorthosites	6	15.11	6.7
Remaining small fragments	–	27.23	12.1
Fines (< 100 mesh)	–	18.34	8.1
Total	50	225.86	100.

All mixing models (see later discussion) for Apollo 15 soils have used some type of noritic component like the 15455 melt rock (or other similar material identified as LKFM) because among type-I and type-II components, 15455 melt rock most closely resembles the composition of the Apennine Front soil. Each has also used (explicitly or implicitly) at least two of the following three different types of components: 15418-type anorthositic norite, 15415-type anorthosite, and KREEP. The preceding discussion illustrates, using graphical methods, why these additional components have been required. The choice of type-I and type-II components to model the Apennine Front has been severely limited by the lack of rock samples returned from the Apennine Front (there were not very many to be found) and, to a lesser extent, by a lack of data on the rocks that do exist. Most rock samples collected on the Apennine Front are regolith breccias and these are intrinsically less informative as mixing components. The rock types plotted in Figures 3 and 4, along with anorthosite and troctolite, cover the entire range of rock types recognized (through 1985) as the "fundamental" rock types associated with the Apennine Front. Most of these are represented by at most one or two large samples; the rest are clasts in regolith breccias.

Factor Analysis

A disadvantage of two- or three-element plots such as Figures 2, 3, and 4 is that mixing relationships implied by one such plot may be contradicted by another that uses different elements. The elements used in these particular plots were selected among several considered to show best all the constraints. Techniques such as factor analysis and principal component analysis are available that use data for all elements simultaneously to imply end-member components. Despite their potential utility, these techniques have seldom been applied to lunar soil data. One such application was of R-mode factor analysis to major and trace element data for Apollo 15 soils by *Duncan et al.* [1975]. From the results of their analysis, they concluded that the soil samples lay mainly along a basalt-LKFM mixing line and that samples from stations LM, 6, and 9 had an additional component of KREEP, consistent with the observations made above based on Figures 2 and 3. They did not observe the trend toward green glass in the station 7 samples because only the mean composition of samples from each station was used and the "soil" richest in green glass (15421) was not included in the station 7 mean. Although the 15418 anorthositic norite was included in the analysis, no trend toward this component was observed in the results. This again argues that if such a rock type is an important component of the soil, then it does not act as a discrete component, but only as a well-mixed subcomponent of the Apennine Front soil component.

Individual Soil Particles and Grain Size

1–2 mm particles from 15272. One possible way to determine the rock-type components of the Apennine Front regolith is to examine individual particles of soil. *Lindstrom et al.* [1977] studied the petrography and chemistry of individual fragments from the Apollo 15 deep drill core on the mare surface. For the present study, all material in a quarter-gram allocation of station 6 soil 15272 was analyzed. The 50 largest particles were analyzed individually and examined with a binocular microscope. The remaining material was seived through a 100 mesh sieve (0.15 mm) and the two splits obtained were analyzed in their entirety. The fine material was produced presumably by abrasion during shipping of the 1–2 mm particles to the lab. The mass balance information is presented in Table 3 and selected analytical results are presented in Table 4. Samarium and Sc concentrations in the 15272 samples are plotted in Figure 5.

Twenty-one of the 50 particles (31% by mass of the allocated sample) are regolith breccias with compositions similar to that of the <1 mm fraction of the soil from station 6; three others are similar, but have slightly greater concentrations of ITEs. The large number of breccia particles with bulk soil compositions may be a peculiarity of station 6; many similar breccias were found among the rocks collected at this station [*Korotev*, 1985, 1986]. Only 4 of the 50 particles are of mare affinity. One (no. 46, Table 4) appears to be a breccia and has a composition like that of the soil from stations 1 and 9a. The remaining three are crystalline basalts. One of these (no. 29) is dissimilar to any large sample of Apollo 15 basalt in being ITE-rich and very mafic; the Sc concentration is far greater than that of large samples of Apollo 15 basalts (Figure 5). It is coarse-grained and may not be a representative sample of the rock from which it came. Fifteen of the particles (28% of the total mass) are of KREEP composition. These range from lithic fragments, to glass-coated lithic fragments, to pure glass. The remaining seven particles (9% of the mass) appear to be of highlands origin. One (no. 18) is somewhat similar to station 2 soil in composition. Two others are crystalline fragments with compositions of troctolitic anorthosite, and the last four, while different from each other, are of noritic anorthosite composition. No particles with compositions like the 15415 anorthosite or the melt portion of 15455 were found. Particle no. 15 remotely resembles the 15418 anorthositic norite. No particle rich in a green glass component was found.

The few highlands particles found are neither sufficient in mass fraction nor in mean composition to represent the total highlands component of the soil. Thus most of the Apennine Front component of the soil must be carried by the numerous regolith breccia particles, although these must also contain components of both KREEP and mare basalt to account for their bulk composition. The regolith breccia particles are a type-II component (because they are a rock type) that acts as a type-III component (because they have soil compositions). For the purpose of identifying those rock types associated with the Apennine Front that are more primary than regolith breccias (i.e., type-I components or other type-II components such as impact melt breccias), it may be better to examine particles from station 2, where regolith breccias are less common.

TABLE 4. Selected Results of INAA on Samples from Soil 15272, Station 6, Apollo 15

	Note	Mass (mg)	Na_2O %	Sc μg/g	Cr μg/g	FeO %	Co μg/g	Ni μg/g	Ba μg/g
Bulk and Means									
15271 (<1 mm)	(a)	94.72	0.46	23.6	2240	12.0	40.1	265	280
15272 total	(b)	225.86	0.52	23.3	2160	11.7	35.0	193	340
Remaining	(c)	27.23	0.45	25.3	2540	13.1	42.7	220	260
Fines	(d)	18.34	045	24.5	2360	12.5	39.4	260	280
Soil-like	(e)	65.10	0.46	23.1	2250	11.9	41.1	250	270
KREEP	(f)	62.77	0.72	19.8	1960	9.96	24.1	123	590
Individual Particles									
Mare Basalts									
39		3.82	0.30	45.1	4540	20.3	47.4	50	42
23		3.46	0.28	46.0	3580	22.5	47.6	60	66
29		5.12	0.12	66.8	1950	28.3	50.4	110	200
Other									
46		2.47	0.39	35.9	3730	18.5	55.0	230	160
Troctolitic Anorthosite									
11		3.76	0.42	0.80	77	4.37	20.3	39	42
12		1.91	0.36	5.33	362	3.09	9.0	105	11
Noritic Anorthosite									
15		2.69	0.49	11.6	822	6.24	14.6	80	58
25		2.90	0.47	10.9	924	5.29	19.4	200	130
56		1.87	0.68	18.1	1140	8.79	21.4	80	140
14		1.98	0.28	16.9	1580	8.91	31.4	200	175
Other									
18		6.00	0.48	20.3	1970	10.6	34.1	140	230
High-Sm KREEP									
24		6.04	0.84	21.0	2250	10.1	20.5	50	720
38		3.44	0.77	23.8	2140	11.0	24.4	60	700
57		1.54	0.90	22.1	2060	10.2	18.8	<80	810

	La μg/g	Ce μg/g	Sm μg/g	Eu μg/g	Tb μg/g	Yb μg/g	Lu μg/g	Hf μg/g	Th μg/g
Bulk and Means									
15271 (< 1mm)	26.0	68.	12.2	1.43	2.37	8.4	1.23	9.9	4.4
15272 total	32.4	85.	15.7	1.61	2.92	10.5	1.45	12.1	5.5
Remaining	24.0	63.	11.5	1.37	2.22	8.2	1.11	9.0	3.9
Fines	25.5	67.	13.1	1.37	2.35	8.8	1.19	9.8	4.0
Soil-like	25.7	68.	12.6	1.41	2.35	8.2	1.16	9.5	4.5
KREEP	57.0	148.	26.7	2.17	4.88	17.7	2.43	21.0	10.0
Individual Particles									
Mare Basalts									
39	4.3	10.	2.7	0.81	0.62	1.83	0.265	2.02	0.2
23	6.0	17.	4.2	1.01	0.88	2.43	0.344	3.2	0.34
29	18.4	50.	11.9	1.73	2.56	7.4	1.02	8.8	1.84
Other									
46	13.0	37.	7.0	1.14	1.40	4.7	0.65	5.1	1.6
Troctolitic Anorthosite									
11	0.54	1.6	0.26	1.46	0.03	0.18	0.024	0.14	0.08
12	1.90	2.1	0.35	0.75	0.07	0.28	0.043	0.21	0.08
Noritic Anorthosite									
15	5.2	13.	2.42	1.18	0.54	2.08	0.305	2.1	0.67
25	11.1	29.	5.4	1.17	1.06	3.54	0.52	4.1	1.8
56	8.85	22.	4.7	1.62	0.87	3.9	0.58	4.3	1.9
14	15.7	42.	7.6	1.13	1.47	5.0	0.72	5.7	2.9
Other									
18	21.7	57.	10.3	1.34	2.07	7.1	0.99	7.8	3.5
High-Sm KREEP									
24	69.	180.	32.4	2.63	5.8	21.2	2.88	25.4	11.4
38	73.	194.	33.6	2.50	6.4	21.9	3.04	27.8	12.6
57	79.	206.	37.5	2.71	6.6	24.5	3.3	29.1	14.7

Notes: (a) Mean of two analyses of 15271 from Table 1; (b) mass-weighted mean of 50 individual particles, remaining small particles, and fines, i.e., entire allocation of 15272,21; (c) all material except 50 largest particles and fines, mostly <1 mg particles; (d) all material passing 100 mesh sieve; (e) mass-weighted mean of the 21 particles with composition of bulk soil; (f) mass-weighted mean of the 15 particles with KREEP-like compositions.

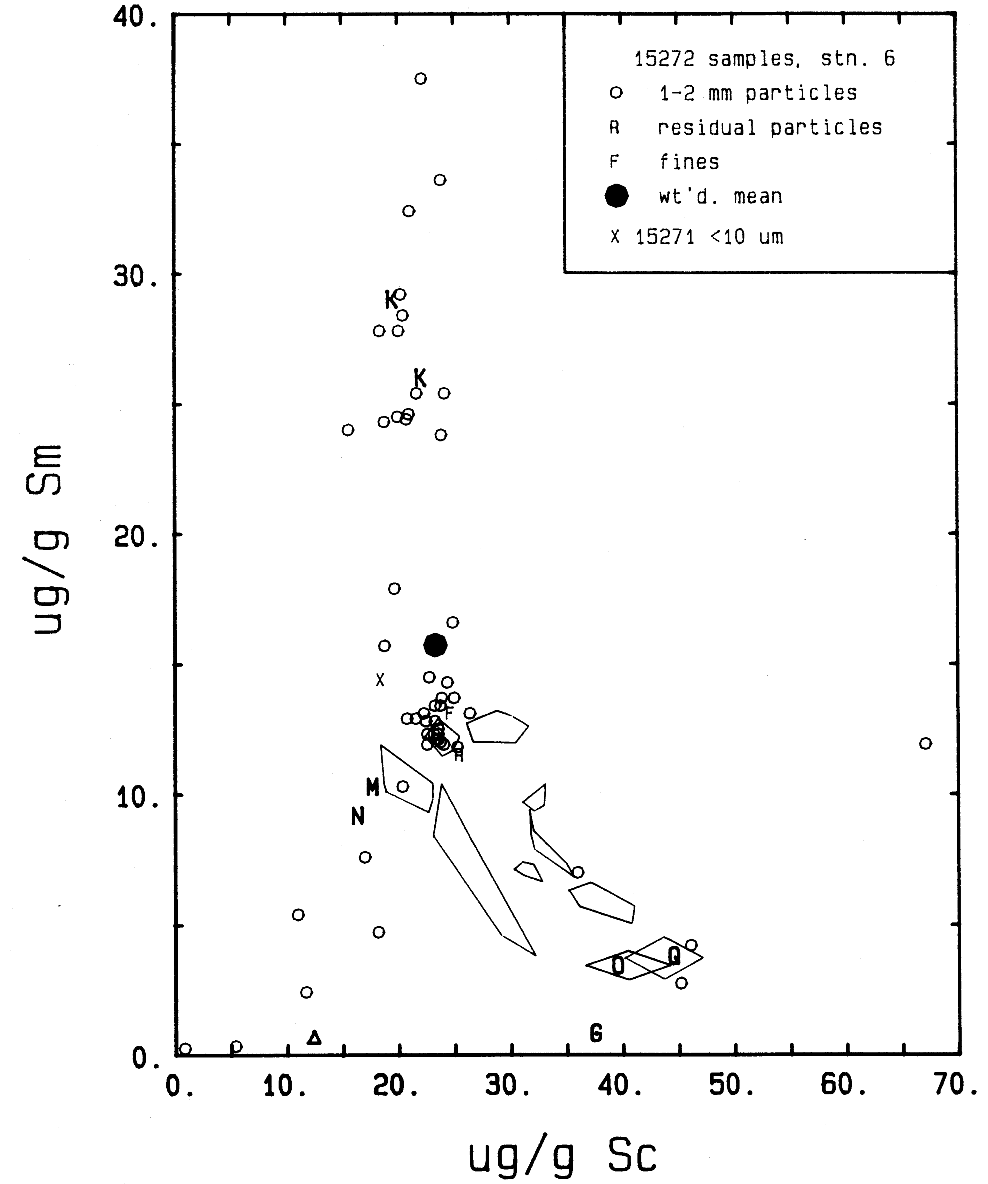

Fig. 5. Like Figure 3, but with points for 1–2 mm particles from station 6 soil 15272 added. Fields enclose all samples of <1 mm soil from a given station (see Figure 3). The cluster of points in the middle overlaps the field for <1 mm soil from station 6. Most of the 15272 particles appear to be regolith breccias. The 1–2 mm grain-size fraction is distinctly enriched in Sm and other incompatible trace elements compared to the <1 mm fraction as a result of the large number of KREEP particles. The <10 mm fraction [*Laul and Papike*, 1980] appears to contain less mare basalt than the <1 mm material.

Grain-size fractions and coarse-grained KREEP basalt. The most interesting aspect of the results of this experiment is that the bulk composition of the 1–2 mm grain-size fraction of Apollo 15 soil 15270 is 20–30% enriched in ITEs compared to the <1 mm fraction (Table 4, Figure 5). This corresponds to about a factor of 2 greater component of KREEP basalt in the coarser fraction in terms of the mixing model to be discussed in the next section. The model also indicates that the KREEP excess in the coarser fraction is at the expense of the Apennine Front soil component. This result combined with the observation of a large number of discrete particles of KREEP basalt in the 1–2 mm fraction indicates that the KREEP basalt component of the soil has a coarser grain-size distribution than does either the bulk soil or the Apennine Front component of the soil. The observation of KREEP enrichment of the coarser fraction is similar to that *Chou and Pierce* [1979] for grain-size fractions from soil from the Apollo 15 deep drill core. Among grain-size fractions of <1 mm material, the KREEP was concentrated in the coarser fractions. These are examples of variation in composition with grain size resulting from mixing of compositionally distinct, type-III components of different grain-size distribution [*Korotev*, 1976]. Soil 15270 appears to be a mixture of fine-grained, presumably mature Apennine Front soil and a coarser-grained regolith rich in KREEP basalt.

Relevant to a discussion of variation in composition with grain size are the data of *Laul and Papike* [1980], who have analyzed grain-size fractions of 15271, as well as station 2 soil 15221. Curiously, for 15271 they do not observe any significant variation in concentration of ITEs among size fractions between 0.01 and 1.0 mm. The composition of the finest fraction, however,

TABLE 5. Apollo 15 Breccia and Soil Mixing Models

	Mare		Highland				Met.
	MB*	GG	A	AG	LKFM	KREEP	CC1
Breccias							
Taylor et al. [1973]	0	0	1	1	1	0	0
			(4)	(9)	(100)		
Lindstrom et al. [1977]	1	0	0	1	1	1	0
KREEP-rich				(1–15)	(100)	(250)	
Soils							
Fruchter et al. [1973]	1	0	0	15418	15455	15059	1
				(4)	(100)	(230)	X
Carr and Meyer [1974]	2	1	0	1	1	1	0
Major elements only							
Duncan et al. [1975]	2	1	0	15418	1	1	1
				(4)	(100)	(300)	
Chou et al. [1975]	2	1	1	0	15455	1	1
			(0.4)		(100)	(330)	
Schonfeld [1975]	2	1	0	1	1	1	1
				(5)	(100)	(250)	
Korotev et al. [1980]	2	0	1	0	HON	1	1
Stn. 2 (AF) only			(0.2)		(16)	(330)	
Laul and Papike [1981]	1	1	1	0	62295	15386	0
Walker and Papike [1980]			(0.4)		(60)	(250)	

The table summarizes components used by various mixing models and compositions used to represent the component. 1 = Component of this type is used; 0 = not used. Values in parentheses are chondrite-normalized La concentration (in ppm) of component.

*Component key with synonyms: MB: Mare basalt. 1 = one mare basalt component was used, 2 = both an olivine- and quartz-normative basalt component were used; GG: green glass (e.g., from 15426); A: anorthosite (35% alumina, e.g., 15415); AG: anorthositic gabbro or norite, highland basalt (26–28% alumina, e.g., 15418); LKFM: low-K Fra Mauro basalt, noritic melt rock (17–19% alumina, e.g., melt portion of 15455); KREEP: intermediate-K Fra Mauro, medium-K KREEP, Apollo 15 KREEP basalt (e.g., 15382, 15386), or high-K KREEP (Apollo 14 KREEP); Met.: meteoritic component, extralunar component.

(<0.010 mm fraction, Figure 5) differs from the bulk in being more felsic, less mafic, and slightly richer in ITEs. According to the results of the mixing model of *Laul and Papike* [1980], this difference in composition results from a greater proportion of anorthosite (such as 15415) and KREEP in the very finest fraction. In contrast, the model to be presented in the next section explains a large portion of this difference in composition of the finest fraction to a greater proportion of the Apennine Front soil component and a lesser proportion of mare basalt. It should be noted, however, that although both models account reasonably well for the composition of the coarser fractions, the finest fraction is not well fit by either model. Poor fits for the finest fraction are often observed in modeling grain-size fractions of lunar soil as mixtures of rock-type components (e.g., see chi-square values of *Laul and Papike* [1980]). This was one of the major reasons why *Korotev* [1976] concluded that differential comminution of mineral phases was an important secondary process contributing to variation in chemical composition with grain size of lunar soil. As there is no reason to expect a particular rock-type component to be uniform in composition when the grain size of the comminuted rock approaches the intrinsic grain size of the minerals of which it is composed, precise modeling of grain-size fractions of soil may require using type-IV components, i.e., individual mineral phases and mesostasis [*Korotev*, 1976].

Multielement Mixing Models

Once a likely set of components are selected, the ability of those components to account for the soil composition can be tested mathematically using multielement mixing models. These models are mass balance calculations that seek to obtain the mass fraction of each of the various components that best accounts for the composition of a soil [*Schonfeld*, 1974; *Boynton et al.*, 1975]. The number of chemical elements used (typically 15–30) usually exceeds the number of components (typically 3–6); hence no unique solution can be calculated. Instead, a least-squares solution is obtained. Often residuals for each element are weighted differently so that some elements have more effect on the results than do others. Models usually attempt to account for both the major and trace element concentrations of each soil.

Mixing models are popular in lunar soil studies. When applied and interpreted properly they can be powerful tools. However, it is important to understand their limits and to distinguish between what are input assumptions to the models and what are legitimate constraints and conclusions. The least-squares solutions merely provide a mathematical measurement of how well the components selected account for the composition of the soil. These and various other criteria (mostly subjective) must be used to judge whether an acceptable fit has been obtained and whether the results are meaningful. Mixing models cannot "prove" that the components being tested are, in fact, the "true" components of the soil; at best the models can only demonstrate that a particular set of components adequately accounts for the soil composition or that it does not. Mixing model solutions are not unique; various sets of components may provide equally good fits, depending upon what level of mixing is being tested (see Introduction). A geologically absurd set of components may provide a good fit to the data. In poorly constrained models,

TABLE 6. Mixing Model Predictions: Mean Percent Mare Component (Basalt Plus Green Glass) and LKFM-Like Noritic Component in Surface Soils From the Apennine Front (Station 2)

	Total mare (%)	LKFM-like (%)	Composition of LKFM-like component
This work	14	84	deep core soils
Carr and Meyer [1974]	20	44	LKFM glass
Schonfeld [1974]	(25)	(32)	glass/15455 ?
Fruchter et al. [1973]	26	34	15455
Duncan et al. [1975]	26	59	glass/15455
Korotev et al. [1980]	27	50	HON
Walker and Papike [1981]	32	29	62295

the least-squares solution may be only insignificantly better than one based on very different proportions of the end-member components. When two or more components of similar composition are included (e.g., two different kinds of basalt) or when one component might be equivalent to a mixture of others, results are unpredictable and often unrealistic. Models can only distinguish between components that have substantial mutual differences in concentrations of at least some elements. It is important to keep in mind that the components used to model a soil and the particular compositions used to represent those components are input parameters to the models, not output results or predictions.

Previous models. Table 5 summarizes input parameters for mixing models that have been applied to Apollo 15 breccias and soils. No two are the same with respect to which components are used and what compositions are used to represent the components. Each model apparently provided a sufficiently good fit to the data that its authors were satisfied with the results. It is impossible to compare rigorously the goodness-of-fit of the various models because different elements and weighting factors were used in each, different compositions were used to represent components that are nominally the same, and sufficient information about how the results were obtained is not always provided. Also, two models that provide equally good fits in the mathematical sense may not be equivalent in the geochemical sense based on other criteria. Table 6 summarizes model predictions for station 2 surface soil, i.e., those samples of Apennine Front surface soil with the least mare basalt. (Models in Table 5 that are not in Table 6 did not include station 2 soil.) The differences in the model predictions in Table 6 are a direct result of differences in model input assumptions and parameters listed in Table 5.

Most of these models are level-II models in that they attempt to account for the soil compositions in terms of components that can be identified with rock types found at the Apollo 15 site. (However, in many cases the actual composition used to represent a particular component does not correspond to that of any rock type actually observed in the regolith.) The model of *Taylor et al.* [1973] was for Apennine Front breccias, not soil, hence no mare components are included. *Lindstrom et al.* [1977] modeled only KREEP-rich polymict breccias from the 15002 core; several different "ANT suite" components (anorthosite, anorthositic gabbro) were tested. *Schonfeld* [1975] used as a type-II component "brown glass matrix breccia," i.e., the common regolith breccia found at station 6, because "it is the most abundant highlands component even though it appears to be a mixture of other rock types." This component itself was resolved into the more fundamental type-II and type-I components listed in Table 5. The renormalized values are listed in Table 6 in parentheses. The model of *Korotev et al.* [1980] is dissimilar to the others in not being so much an attempt to model Apollo 15 soils as a mixture of local rock types as an attempt to use the Apennine Front soil to deduce the important type-I components of the lunar highlands in general. It used a hypothetical noritic component (HON) with a composition somewhat similar to that of LKFM.

Despite the differences in detail, the various models in Table 5 have some similarities. Nearly all include green glass as a component. All the soil models include one or two components of mare basalt. All except the breccia model of *Taylor et al.* [1973] also contain some type of KREEP component. The models of *Duncan et al.* [1975] and *Chou et al.* [1975] use a KREEP component with higher concentrations of ITEs than the typical KREEP basalts found at Apollo 15, i.e., an Apollo 14 type of KREEP. Because KREEP is a volumetrically less important component of most soil and the relative ITE concentrations are similar in all types, the goodness-of-fit of the models is not too sensitive to which type of KREEP is used, although the predicted proportion of KREEP is.

The most significant differences among the models are in what components are used to represent the highlands or Apennine Front material. All nine models contain either anorthosite (like 15415) or anorthositic gabbro (like 15418) or both, despite the fact that no such component is directly indicated by trends in the raw data (Figures 3 and 4) or by the factor analysis of *Duncan et al.* [1975]. All nine models also contain some type of noritic component usually identified as LKFM. Most models use the composition of the 15455 "dark" melt rock to represent LKFM, although *Duncan et al.* [1975] use the major element composition of the LKFM glasses (Table 2) and the trace-element concentrations of the 15455 melt [*Taylor et al.*, 1973]. In a novel approach, *Walker and Papike* [1981] [also *Laul and Papike*, 1980] use an Apollo 16 melt rock with an unusually high Mg concentration, 62295, as the LKFM component of Apollo 15 soil. Accounting for the intermediate mg′ of the station 2 soil (about 62) in terms of a mixture of mare basalt (mg′ = 47) and the magnesian melt rock (mg′ = 80) leads to the extreme proportions of these two components predicted by this model (Table 6).

A new model. Earlier it was argued on the basis of variation diagrams that only four components are needed to explain the variation in concentrations of lithophile elements in Apollo 15 soils. To test this assertion, a model using mare basalt, green glass, KREEP basalt, and an Apennine Front soil component was applied to the data in Table 1. A meteoritic component was also included to account for any excess Ni (a predominantly siderophile element). Components of both olivine- and quartz-normative basalt were included. Compositions of the components are listed in Table 7 and the model results are listed in Table 8. The model calculations are those described by *Korotev et al.* [1980]. A comparison is given in Table 9 between the observed composition and typical results for the best-fit composition obtained from the model for samples of soil from three different stations. The results obtained here are at least as good as those from any model using only rock types as components.

The model results are in qualitative agreement with the compositional trends already discussed. They suggest that the proportion of green glass in the station 2 soil is small and that the proportion of mare basalt in the station 2 surface soil is

TABLE 7. Mixing Model Components

	AFSC*	A-15 Mare Basalt		A-15 Green Glass	A-15 KREEP Basalt	Met.
		Ol.	Qz.			
SiO_2	46.2 †	45.0	48.6	45.3	51.3	22.0
Al_2O_3	20.0	8.67	9.47	7.6	15.3	1.61
FeO	9.97	22.4	19.8	19.9	10.0	23.7
MgO	10.3	10.9	8.9	17.1	9.0	15.9
CaO	11.4	9.56	10.44	8.5	10.6	1.48
TiO_2	1.24	2.34	1.78	0.32	2.0	0.07
Na_2O	0.47	0.26	0.31	0.14	0.72	0.060
Sc	18.5	40.0	44.	38.	19.8	5.1
Cr	2010.	4390.	3740.	3750.	1960.	2400.
Mn	1110.	2200.	2160.	1990.	1180.	1900.
Co	30.2	55.	44.	77.	24.0	510.
Ni	162.	50.	10.	160.	85.	11000.
Sr	145.	90.	104.	30.	159.	7.4
Ba	256.	40.	61.	17.	589.	2.4
La	22.9	4.9	5.8	1.22	57.	0.25
Ce	59.	13.8	15.6	3.8	148.	0.64
Sm	10.8	3.3	3.7	0.80	26.7	0.154
Eu	1.36	0.85	0.99	0.24	2.17	0.058
Tb	2.02	0.75	0.87	0.19	4.88	0.037
Yb	7.7	2.2	2.7	0.94	17.7	0.165
Lu	1.04	0.31	0.35	0.15	2.43	0.025
Hf	8.7	2.6	2.8	0.64	21.	0.12
Ta	1.00	0.42	0.50	0.1	2.37	0.02
Th	3.8	0.60	0.59	0.3	9.95	0.032
U	1.24	0.15	0.13	0.1	2.58	0.009

Oxide values in percent, others in μg/g.

*Source of data: AFSC—(Apennine Front soil component) mean of three soil samples between 55 and 57 cm in Apennine Front core 15007 (Table 1); Apollo 15 Mare Basalts—*Korotev et al.* [1980]; Apollo 15 Green Glass—*Ma et al.* [1981] and *Taylor et al.* [1973]; Apollo 15 KREEP Basalt—from data in Table 4, *Rhodes and Hubbard* [1973], *Warren and Wasson* [1978], and *Murali et al.* [1977]; Meteorite—*Korotev et al.* [1980].

†By difference.

much smaller than predicted by other models (Table 6). It is possible that the samples used to represent the Apennine Front soil component contain some green glass and mare basalt, in which case the amounts of these two components might actually be higher in other samples of Apennine Front soil than predicted by the model, but because of the extreme composition of the deep soil from the 15007 core, the quantity is probably minor. *Bogard et al.* [1982] report that about 5% green glass is observed petrographically in a soil from the 55–57 cm interval of the core. This new model is the first to account for the unusual composition of the only soil from station 6a, 15401. Unlike other soil sample, it contains a high proportion of components of both green glass and KREEP basalt. It is the only soil for which the ratio of KREEP component to mare basalt component is significantly greater than unity.

KREEP. The new model indicates that the soils from stations 6, 8/LM, and 9 contain 20–30% KREEP component, but that those from stations 2, 4, and some from station 7 contain very little. The models of *Schonfeld* [1975] and *Duncan et al.* [1975] also predict essentially no component of KREEP in the station 2 soil. This is in contrast to the models of *Fruchter et al.* [1973] and *Walker and Papike* [1981], which predict 13% and 23% KREEP in surface soil from station 2. The latter value is nearly equal to what *Walker and Papike* [1981] predict for soils from stations LM and 8 (25% and 25%). These differences do not reflect model uncertainty, for among all the components (except perhaps the meteoritic component) the fraction of KREEP component predicted by any model is the most accurate because the KREEP composition is the most extreme. The differences result because (1) each model contains two primary carriers of ITEs, KREEP with high ITE concentrations and an LKFM-like component with intermediate ITE concentrations, and (2) different compositions were used in each model to represent these components. Thus the differences in the model results reflect different levels of modeling and, to some extent, a semantic problem about what is meant by KREEP.

In the new model, the LKFM component is represented by the Apennine Front soil component. The KREEP component accounts for all ITEs in excess of that portion carried by the Apennine Front soil component; hence the station 2 soil contains no KREEP component by definition. If, in fact, the station 2 soil contains little or no discrete (type-II) component of KREEP basalt, then the results in Table 8 should be a good estimate of the KREEP component of the soils that is not associated with the highlands component of the soil; i.e., the KREEP component in this model represents the quantity of igneous KREEP basalt in the soils (some of which might be carried by regolith breccias).

In previous models, the KREEP component represents concentrations of ITEs in excess of those carried by the LKFM component. Earlier, reasons were discussed why any model using 15455 (or other melt rock with a similarly magnesian composition) to represent LKFM also requires a component of KREEP to account for the composition of station 2 soil. (In this regard, the model of *Walker and Papike* [1981], which uses the most magnesian LKFM component, predicts the most KREEP at station 2 and the model of *Fruchter et al.* [1973], which uses the least magnesian LKFM component, predicts the

TABLE 8. Results of Mixing Model

Station	Sample	AFSC	Mare basalt	Green glass	KREEP basalt	Met.
2	55–57 cm	100	(by definition)			
2	42–44 cm	84	16	−1	1	1.0
2	15201/221	84	8	6	1	1.1
6	n = 6	58	16	4	20	1.2
7	15311	72	16	10	0	1.1
7	15431	65	11	11	13	0.3
7	15301/411	55	12	25	7	1.3
7	15421	24	12	61	1	0.7
6a	15401	18	8	51	24	0.4
LM	15021/013	29	37	3	31	1.5
8	15031/041	25	29	11	34	1.3
4	15471	37	35	25	5	0.6
9	15501/511	17	48	10	25	1.1
1	15071	29	56	9	7	0.8
9a	15531/601	5	70	17*	9	0.6
unc.	(±1 s.d.)	4	4	4	2	0.3

Soil compositions from Table 1 and *Laul and Papike* [1980] (15221 and 15271). Mixing components from Table 7. Mean results are given for soils of similar composition from the same station.

*The model does not fit station 9a soils well. The high proportion of green glass predicted here probably does not represent green glass, but mare basalt of some composition different than that of mare basalt components used, possibly a peridotitic basalt (see text).

least KREEP.) If the LKFM component, as represented by a melt rock, used by other models adequately represents the melt rock component(s) of the Apennine Front soil with respect to ITE concentrations and if no other important carriers of ITEs occur, then the high levels of KREEP some of these models predict for the station 2 soil may actually indicate that this soil contains a significant amount of igneous KREEP basalt, in contrast to the results of the model presented here. However, as will be argued later, the 15455 melt rock (and certainly the 62295 melt rock used by *Walker and Papike* [1981]) may not be representative of the melt-rock component of the Apennine Front soil. Hence it cannot be established with just mixing models how much type-II component of KREEP is in the station 2 soil (i.e., discrete particles of KREEP basalt or regolith breccias containing KREEP basalt) and therefore in any other soil, because a large portion of the ITEs in the station 2 soil is carried by melt rocks and these are not all characterized well enough to be used as mixing components.

It is generally assumed that the relatively high concentrations of ITEs in melt rocks of LKFM composition result because the melt rocks contain a component of KREEP in the type-I sense. For the purpose of understanding the Apennine Front, it is important to distinguish between any discrete component of KREEP basalt, such as found at station 6, and a KREEP subcomponent (type-I) of the melt rocks. The former represents total melting and mixing of surface and deep material, possibly involving ur-KREEP [*Warren and Wasson*, 1979*b*], during basin-forming impacts. The latter involves more recent mixing of material derived from KREEP basalt flows or near surface intrusives.

KREEP basalt occurs in both mare and highlands soil at Apollo 15. Some have argued that it is more prevalent on the eastern side of the landing site [*Duncan et al.*, 1975], in support of the contention of *Reid et al.* [1972] that it is ray material from craters Aristillus or Autolycus. However, if the results given in Table 8 reflect, as intended, the component of KREEP basalt in the type-II sense, then the soil data do not support any geographic trend. Considerably different amounts of KREEP are found in soil from stations located close to each other, e.g., 9 and 9a or 6 and 7 (Table 8), whereas the KREEP content of the deep drill core is nearly constant through its 2.4-m length [*Helmke et al.*, 1973*b*]. It seems more likely that the source of the KREEP basalt is local and possibly underlies part of the site [*Spudis and Ryder*, 1985].

Olivine- versus quartz-normative mare basalt. Several mixing models have attempted to distinguish between the predominance of olivine- and quartz-normative basalts in the soil. Models including both basalt types generally concur that the abundance of the olivine variety exceeds that of the quartz variety by a factor of 5–10 in basalt-rich soil. Models of *Schonfeld* [1975], *Duncan et al.* [1975], and *Chou et al.* [1975] indicate that a significant component of quartz-normative basalt occurs only in the soil from stations 1 and possibly 4. *Chou et al.* [1975] suggest that the quartz-normative basalts were ejecta from deep in Elbow crater at station 1. These are particularly model-dependent results that are only valid if the models account well for the other mafic components in the soil. It may be a safe conclusion that olivine-normative basalts predominate in the soil from stations 9a and 9, which contain little highlands component (see previous discussion of Figures 2 and 3). Mixing models for soil from the LM area or any of the Apennine Front stations cannot be relied upon to indicate whether olivine- or quartz-normative basalts are more important in these soils because (1) the composition of the two types of mare basalt are too similar to each other, (2) the mafic components of the Apennine Front are not well known, and (3) the KREEP basalt and green glass components carry a large portion of the elements characteristic of mare basalt.

The new model presented here cannot distinguish between olivine- and quartz-normative mare basalt even in samples rich in mare basalt, and this is likely to be the case in most of the other models as well. The major compositional feature distinguishing the two types of basalt is the silica content. Silica was not determined here, but calcuated by difference, and this is probably not sufficiently accurate. Also, major element concentrations were obtained from a variety of sources. In the present model, both basalt types were included, but ratios of one to the other, as predicted by the model, are highly variable,

TABLE 9. Comparison of Observed Composition (Table 1) and Best-Fit Composition From Mixing Model (Tables 7 and 8) for Three Apollo 15 Soils

	15291 Stn. 6		15041 Stn. 8		15501 Stn. 9	
	obs.	calc.	obs.	calc.	obs.	calc.
SiO_2	48.0*	47.2	45.5*	47.0	47.1*	47.2
Al_2O_3	16.4	16.8	14.2	13.9	12.5	12.3
FeO	11.9	11.9	14.5	14.4	16.8	16.4
MgO	10.2	10.0	11.5	10.5	11.0	10.7
CaO	11.1	10.9	11.6	10.2	9.8	10.1
TiO_2	1.44	1.44	1.70	1.67	1.78	1.69
Na_2O	0.47	0.48	0.44	0.45	0.370	0.40
Sc	23.7	23.2	28.5	26.6	32.9	31.5
Cr	2190.	2322.	2710.	2790.	3000.	3161.
Mn	1300.	1321.	1450.	1524.	1640.	1725.
Co	37.6	37.3	46.3	45.7	48.5	48.4
Ni	228.	236.	252.	266.	201.	202.
Sr	155.	137.	150.	122.	120.	112.
Ba	266.	281.	259.	273.	195.	207.
La	26.0	26.0	26.1	26.0	19.9	19.9
Ce	67.	67.	68.	68.	50.	52.
Sm	12.1	12.4	12.4	12.5	9.56	9.81
Eu	1.44	1.42	1.40	1.35	1.17	1.20
Tb	2.41	2.32	2.50	2.35	1.93	1.88
Yb	8.7	8.6	8.3	8.5	6.7	6.7
Lu	1.23	1.17	1.25	1.17	0.99	0.92
Hf	9.7	9.9	9.8	9.9	8.1	7.7
Ta	1.15	1.15	1.18	1.17	0.98	0.95
Th	4.6	4.4	4.3	4.4	3.4	3.3
U	1.06	1.28	1.18	1.22	0.89	0.90

*By difference.

even among samples from the same station. Hence only the sum of the fraction of the two mare basalt components is given in Table 8. For example, results for 15421 are typical: -11 ± 7% ONB and 25 ± 9% QNB. When negative values occurred, the model calculations were repeated with the negative component excluded and the results of the single mare basalt component were reported. This value was always within error of the sum of the positive and negative values obtained when both basalt types were included, e.g., 12 ± 3% in the example above. The uncertainty is much smaller when only one basalt component is included. This reflects the inability of the model to distinguish between the two different basalt types [*Chou et al.*, 1975].

Station 9a. Results of the new model for the soil from station 9a on the edge of Hadley Rille are not as good as those for other stations and indicate a high proportion of green glass (17%) compared to other models (8–10%, *Duncan et al.* [1975], *Walker and Papike* [1981]). In their studies of the petrography of the two soil samples from station 9a, *Basu et al.* [1980, 1981] report less than 2% green glass. The high (and probably erroneous) proportion of green glass predicted by each of these mixing models results from either a minor missing component or from an inadequacy of the composition of the basaltic components used to actually account for the mare basalt component of the station 9a soil. An understanding of the nature of the missing component or of the inadequacy can be obtained by repeating the model calculations excluding the green glass and noting the misfit between the observed and best-fit composition. Both 15531 and 15601 contain less Ca, Sr, and Eu (all elements associated with plagioclase) and more Mg than the best-fit composition (which requires 81% and 88% mare basalt components). The soil is more magnesian (mg′ = 50) then either the best-fit composition (mg′ = 48) or the mare basalts (mg′ = 45–47, see Figure 4). Much of this discrepancy can be explained by the presence of a component like green glass (mg′ = 60, low Ca) in the soil, as suggested by the mixing models. If green glass is the cause, however, it must be concentrated in the finer grain-size fractions or in agglutinates where it is not observed petrographically. Alternatively, there may be a significant component in the station 9a soil of some similar mafic component that is more magnesian than the typical mare basalts. One possibility is the peridotitic basalt found in station 7 breccias 15459 and 15426 [*Lindstrom*, 1986]. Such a component substitutes well for green glass in the model and yields results similar to those in Table 8 for the station 9a soil, although the fits are still not as good as should be expected. It should also be considered that the mineral proportions of the basalt component of <1 mm regolith material might not be identical to that of the larger samples of basalt upon which the composition of the components is based (Table 7), i.e., that differential comminution effects [*Korotev*, 1976; *Hörz et al.*, 1984] might be important for <1 mm material as well as for the ultrafine fractions (<10 μm fraction, e.g., *Laul and Papike* [1980]). This is likely to be most obvious in a soil that is composed primarily of a single rock type, such as the station 9a soil.

Metoritic component. A meteoritic component was included in the model to account for any Ni and, to a lesser extent, Co in excess of that contributed by the other components. The fact that all values for the fraction of meteoritic component are positive (Table 8) results primarily from the fact that the Ni concentrations in the deep (55–57 cm) soil from the 15007 core (i.e., the soils used to represent the Apennine Front soil component) have lower than average Ni concentrations. This soil is less mature than other soil in the core and station 2 surface soil [*Bogard et al.*, 1982]. The results of this and other studies [*Schonfeld*, 1975; *Chou et al.*, 1975; *Duncan et al.*, 1975;

Walker and Papike, 1981] indicate that there is little systematic variation in the amount of meteoritic material among soil samples from different stations. Soil from stations 1 and 9a may have a little less and those from stations LM and 8 may have a little more than the average. Soil from station 1 on the mare surface has a quantity of extralunar Ni similar to that of soil from the Apennine Front. The concentration of extralunar siderophile elements is a factor of 2–3 less in the Apennine Front soil than in soil from Apollo 16 [e.g., *Korotev*, 1987*c*].

Mixing model summary. The model presented here is superior to other mixing models for Apollo 15 soil with respect to accounting for the trends in the compositional data because it relies on a broader base of data than was available for most of the previous models and because no assumption is made about what rock types compose the Apennine Front regolith. It only assumes that the relative proportions of the various rock types of the Apennine Front that are not explicitly included in the model (e.g., anorthositic norite) remain constant among the soils from differing parts of the site. There is no indication in the compositional data that the assumption is not valid. Thus the model accounts for level-III mixing. As three of the four major components are represented by rock types found at the site, the problem of modeling the Apollo 15 soil in terms of level-II components reduces to accounting for the Apennine Front soil component in terms of local rock types.

Rock Components of the Apennine Front Regolith

As summarized in Table 5, previous studies have usually modeled the Apennine Front soil as a mixture of the melt ("black") portion of breccia 15455 (or other LKFM melt rock), KREEP basalt 15386, and either or both anorthosite 15415 and anorthositic norite (gabbro) 15418. Compositional constraints that led to this choice were discussed earlier. A more cogent reason for using these rocks as components is that very few large rocks of any kind were found on the Apennine Front and these four were among the most obvious in being large samples and compositional extremes; i.e., they were the only samples available. To test the reasonableness of these components, I have attempted to model the Apennine Front soil component (Table 7) as various mixtures of 15455 melt rock, 15415, 15418, KREEP basalt, green glass, mare basalt, and even troctolite such as 15455,106 [*Warren and Wasson*, 1979*a*]. Mean compositions of these various rock types were compiled and included new compositional data for 15418 [*Lindstrom and Lindstrom*, 1986] and 15455 [*Lindstrom*, 1986 and unpublished data]. As is usually the case, satisfactory mathematical solutions can be obtained if enough components are included. All mathematically acceptable models require about 20% mare basalt and/or green glass as well as 30% KREEP basalt, a result that may not be geologically acceptable.

Detailed results of the modeling are not presented here because they are probably meaningless in light of our poor knowledge of the rocks associated with the Apennine Front. All evidence points to the conclusion that the Apennine Front soil is a complex mixture of many components, some of which may not be represented by rocks that have been studied. Each of the three highlands components most often used to model the Apennine Front is represented by only one or two large rocks (15445/55, 15418, 15415). Any of these rocks may in turn be sampling flukes and may not represent a volumetrically significant component of the Apennine Front. The analysis of individual particles from 15272 (Tables 3 and 4) do not indicate that rock types like any of these three samples were important, discrete components of the soil. *Ryder and Spudis* [1986] and *Lindstrom* [1986] have recently found several other types of noritic melt rock in Apennine Front samples. *Ryder and Spudis* [1986] conclude, in fact, that the 15455-type melt may be rare. Most of the new types of melt rocks have higher concentrations of ITEs, which would minimize the need for the large proportion of KREEP basalt in the mixing models just discussed. Anorthositic norite 15418 is unique among the large rock samples and may not represent a primary rock type despite its extreme composition (see review in *Lindstrom and Lindstrom* [1986]; *Lindstrom* [1986] has found small clasts of similar composition in Apennine Front breccias, however). Anorthosite sample 15415 is also unique and may not represent an important component of the Apennine Front soil, at least as a type-II component.

From the view of bulk composition, the major challenge to explaining the composition of the Apennine Front soil is that made above in the discussion of Figure 4. The normative composition of the soil corresponds to a point near the boundary between norite and anorthositic norite [*Stöffler et al.*, 1980]. If noritic melt rocks, which typically have mg′ values of about 75, are called upon to be the principal carriers of Fe and Mg in the soil, then the soil must also contain a relatively mafic component with a low (<60) mg′ value. This component appears not to be mare basalt or KREEP basalt, but may be related to the 15418 anorthositic norite. This is virtually the same dilemma as faced at Apollo 16, where the melt rocks are all more magnesian than the soils and ferroan counterparts are not common among the large rock samples [*Korotev*, 1981, 1982]. Among the melt rocks newly recognized by *Lindstrom* [1986 and unpublished data] as clasts in Apennine Front breccias are some more ferroan varieties. These may be useful mixing model components. A quantitative accounting of the composition of the Apennine Front soil must await a better understanding of the rock types of which they are composed.

"LKFM" and "KREEP"

The use of the term LKFM (low-K Fra Mauro basalt) is pervasive in the lunar literature. In many contexts, it is difficult to determine whether the term refers to glass fragments in the soil, a rock type, a specific rock sample, or a composition. The term was originally applied to the composition of a loose cluster of glass fragments in soil [*Reid et al.*, 1972]; however, it has come to be associated with noritic melt rocks of generally similar composition found at various lunar sites [e.g., *Reid et al.*, 1977; *Vaniman and Papike*, 1980]. The term has also been associated with specific rocks (e.g., 15455, as discussed above), the composition of bulk soil (Table 2; also *Hess et al.* [1977]), intercumulus residual liquid from crystallization of anorthosite [*Hess et al.*, 1977], and a "probably pristine" [*Warren and Wasson*, 1980] norite clast in 15306,23 [*Korotev*, 1986]. In light of the difference discussed earlier in mg′ and K_2O content between the original Apollo 15 LKFM glasses and melt rocks such as 15455, it is likely that these two are not even related materials. Because of the possible confusion in just what is meant by LKFM in a particular context, the author urges that the use of the term "LKFM," particularly when used as a noun, be avoided if less ambiguous terms are available. Even as a modifier (e.g., "LKFM melt rock"), the term is not well defined.

Similarly, KREEP (in the most generic sense of the term) manifests itself in different ways at Apollo 15. There are crystalline fragments of KREEP basalt as well as glasses of identical composition that may be melts from meteorite impact into KREEP basalt flows. There are also regolith breccias such as those at station 6 that appear to be lithified local soil with a component of KREEP, probably KREEP basalt. There are regolith breccias that are unlike local soil in having concentrations of KREEP-related elements much higher than those in any returned soil sample, concentrations nearly as high as those in igneous KREEP basalt (e.g., 15205, *Korotev* [1985, 1986]). There are noritic impact melt rocks with relatively high concentrations of KREEP-related elements [*Ryder and Spudis*, 1986; *Lindstrom,* 1986] that, like melt rocks of LKFM composition from other sites, are often described as "KREEPy" or "KREEP-rich," even though their relationship (if any) to igneous KREEP basalt is unclear. Some of these melt rocks have higher concentrations of incompatible trace elements than do samples of KREEP basalt from Apollo 15. To say a rock is "KREEPy" when, in fact, it merely has high concentrations of incompatible trace elements can only impede the goal of establishing genetic relationships among different rock types by implying a relationship that may not exist. Progress in understanding lunar differentiation processes can only come by exploring differences among "KREEPy" samples, not by lumping all of them as a single kind of stuff.

SUMMARY AND CONCLUSIONS

Among soil samples returned from the Apollo 15 mission, those with the strongest highlands affinity (i.e., those least contaminated by mare basalt) are those from the very bottom (55–57 cm) of the double drive tube at station 2 on the Apennine Front (core 15007/8). The soil from the bottom of this core may be our best sample of typical Apennine Front material. The major element composition of this core soil is very similar to the mean composition of LKFM glasses found in Apollo 15 soil by *Reid et al.* [1972, 1977]. The composition cannot be explained by any mixture of the nonmare rock types found at Apollo 15 that have been used "traditionally" to account for the composition of Apennine Front soils and breccias [anorthosite, troctolite, 15418-type anorthositic norite, 15455-type melt rock (= "LKFM"), and KREEP basalt]. Chemical mixing models that also include mare components such as basalt and green glass yield better mathematical fits to the composition of the Apennine Front soil, but the goodness of fit is at best marginally acceptable and the results require unreasonable proportions of some components. Few rocks were returned from the Apennine Front, and many of those are compositionally unique. New rock types are still being discovered as clasts in the Apennine Front breccias. Hence it may be premature to model the Apennine Front soil quantitatively in terms of the few rock types we now recognize. Apennine Front soil is a mixture of many components, some of which may not have been sampled as large rocks.

The various highlands components of the Apennine Front soil are well mixed and, as represented by the soil at the bottom of the station 2 core, behave as a single component with respect to mixing with other components at the site. The variation in the concentration of major elements among samples of Apollo 15 soil results primarily from mixing of mare basalt and highlands materials with the composition of the soil from the bottom of the station 2 core. The soil samples with the strongest mare affinity are those from station 9a at the edge of Hadley Rille followed by those from stations 9, 1, 8/LM, and 4. The soil samples with the strongest highlands affinity are those from station 2, followed by those from stations 7, 6, and 6a, all on the Apennine Front. In addition to the main mare-highlands mixing trend, there is a second trend among soil samples from stations 6a and 7. These samples are generally like those at station 2, but with variable amounts of green glass such as that found in sample 15426. Concentrations of incompatible lithophile elements indicate the presence of KREEP basalt in most of the soils, particularly in those from stations 6, 9, 8, and LM. This component of KREEP basalt is in addition to any that may be associated with the Apennine Front component. From the chemical point of view, it is difficult to evaluate how much KREEP basalt is contained in the deep core soil from stations 2 because of the uncertainty in the nature of the other components, some of which are melt rocks with relatively high concentrations of KREEP-related elements. Thus only four components are required to account for the variation in concentrations of lithophile elements in samples of Apollo 15 soil: mare basalt, KREEP basalt, green glass, and Apennine Front soil such as that at the bottom of the station 2 core. The various highlands subcomponents of the Apennine Front soil do not act as discrete components. The deep core soil may contain some mare basalt and green glass, but the quantity is probably small.

KREEP basalt occurs in variable quantities from nearly 0% up to 30% in soil from both mare and highlands stations. There is little geographic pattern in the distribution. In soils from both the mare (15002, *Chou and Pierce* [1979]) and station 6 on the Apennine Front, KREEP basalt is more prevalent in coarser grain-size fractions. KREEP is not just a near-surface component. The data of *Helmke et al.* [1973*b*] show that the KREEP content of soil from the deep drill core on the mare is nearly invariant with depth through its 2.4-m length. The soil from station 6 on the Apennine Front has a large component of KREEP basalt, and this soil may be in large part ejecta from a 12-m-diameter crater. Hence KREEP basalt is a volumetrically important component of the soil at Apollo 15, although it is not the predominant component at any station. Grain-size data suggest that the KREEP component is a more recent component of the soil than is the mare basalt or Apennine Front material. The observed distribution suggests that it is not associated with a particular local geologic feature, yet the high proportion at some stations implies a local source. The various observations slightly favor a local, unexposed source of KREEP basalt that has been occasionally excavated by meteorite impact.

The emerald green glass found in breccia 15426 is an important component of soil from stations 6a and 7. Both mixing models and petrographic studies show that it is a minor component of soil from other stations as well. The peridotitic mare basalts found in breccias 15426 and 15459 [*Lindstrom*, 1986] are compositionally more similar to the green glass than to the typical mare basalts at Apollo 15. These may be an important component of the soil at some stations and are not readily distinguished from green glass by mixing models.

Unless the other mafic components of the soil are well known, mixing models cannot be relied upon to determine whether olivine-normative basalt predominates over quartz-normative basalt in soil containing significant amounts of highlands material. Olivine-normative basalts are probably more prevalent in the soil near Hadley Rille, but mixing models for this soil do not fit the data as well as would be expected for a soil that is dominated by mare basalt. There may be a cryptic component in the station 9a soil.

Acknowledgments. Many thanks to R. V. Morris for pointing out the unusual soil at the bottom of the station 2 core. The assistance of M. M. Lindstrom and P. A. Salpas during sample analysis is much appreciated. The paper has benefited greatly from discussions with L. A. Haskin, M. M. Lindstrom, and D. J. Lindstrom and reviews by P. D. Spudis and G. Ryder. This work was supported by the National Aeronautics and Space Administration through grant NSG 9-56 to L. A. Haskin.

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(Received April 23, 1986;
revised December 9, 1986;
accepted December 9, 1986.)