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A new look at the Apollo 11 regolith and KREEP

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Abstract. Although the Apollo 11 mission landed in Mare Tranquillitatis, ~50 km from the nearest exposure of highlands, small nonmare particles are conspicuous in the regolith. The nonmare portion of the Apollo 11 regolith is compositionally similar to the Apollo 16 regolith. At both sites most of the nonmare material is from the feldspathic highlands, but some is mafic impact-melt breccia with the chemical signature known as KREEP for its high concentrations of K, rare earth elements, and P. The composition of the Apollo 11 regolith corresponds best to a mixture of 66% crystalline mare basalt, 5% orange volcanic glass, 20% material of the feldspathic highlands, 8% KREEP-bearing impact-melt breccia, and 1% meteoritic material. The volcanic-glass and KREEP-bearing melt-breccia components account for the high concentrations of Mg and Cr in the regolith. The most KREEP-rich sample known from Apollo 11, 10085,1187, is an impact-melt breccia that bears a strong textural and compositional similarity to a unique Apollo 16 melt breccia, 64815. Although not of the maria, such breccias are also not of the highlands provenance. Global data obtained from orbit show that KREEP-bearing materials are most common at low elevations in the Imbrium-Procellarum region and are rare at high elevations. Thus, as at Apollo 16, the KREEP-bearing breccias of Apollo 11 are probably ejecta from the Imbrium impact into the low-lying, Procellarum KREEP Terrane. On the basis of these observation and others, we suggest that the general acceptance of KREEP as a material of the highlands is not supported by the data and results largely from historical accident.

1. Introduction

The first two Apollo missions to land on the Moon, Apollo 11 and 12, each visited sites in the maria, Mare Tranquillitatis (11) and Oceanus Procellarum (12). Thus it came as no surprise to some that the regolith at both sites consisted largely of basalt of volcanic origin as well as breccias and glasses derived from mare basalt by meteorite impacts [*Wilhelms*, 1993]. Unexpected, however, was the nature of the nonmare lithologies that also occurred [*Marvin*, 1973]. The Apollo 11 regolith contained feldspathic particles [*Chao et al.*, 1970; *Haramura et al.*, 1970; *Keil et al.*, 1970; *King et al.*, 1970; *Short*, 1970; *Wood et al.*, 1970]. This observation led *Wood et al.* [1970] to deduce that the fragments were from the highlands, the highlands were feldspathic, and the Moon must have consequently undergone substantial melting and differentiation. The Apollo 12 regolith provided another surprise. Some glass fragments and impact breccias in the regolith contained very high concentrations of incompatible elements, again indicating extreme differentiation, at least locally [*Hubbard and Gast*, 1971]. It was these samples to which the term KREEP was first applied [*Hubbard et al.*, 1971]. The acronym effectively indicated that the samples were rich in K, rare earth elements (REE), and P. However the use and acceptance of the nonstandard term reflected that there was no word in the terrestrial geologic literature that more accurately applied [*Hubbard and Gast*, 1971] and that the petrogenesis of KREEP samples was not understood.

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In this paper we reexamine the composition of the Apollo 11 regolith and inferences about lunar geology that can be made from its composition. We provide a new mass balance model that more accurately accounts for the composition of the Apollo 11 regolith in terms of mixtures of likely lithologic components than previous models. We also reexamine the relationship between KREEP and the highlands in light of new data from the Clementine and Lunar Prospector missions.

2. Samples and Data

Unlike the subsequent missions on which numerous regolith samples were collected along multiple traverses, our knowledge of the composition of the Apollo 11 regolith is based almost entirely on one large sample, 10084 (see, however, the discussion of regolith breccias in section 4.2). Arguably the most well-studied geologic sample ever collected, 10084 is the <1-mm-grain-size fraction of the "bulk sample," which consisted of 15 kg of regolith [*Kramer et al.*, 1977]. The bulk sample was collected near the lunar module with the "large scoop," a 15-cm-high, 9-cm-wide, and 15-cm-deep open box on the end of a handle [*Allton*, 1989]. To obtain the bulk sample, astronaut Armstrong filled the scoop nine times, which in turn required 22 or 23 passes of the scoop in an area of a few tens of meters [*Kramer et al.*, 1977]. The depth to which material was collected is not recorded, but considering the height of the scoop opening (15 cm) and the inefficiency of filling it (2.5 passes/scoop), it is unlikely that more than 10% of the mass of the sample derives from more than 10 cm below the surface. The sampling and sieving techniques did not preserve any lateral and vertical variation in composition which may have existed in the regolith. Data from the few analyses of fines from the "contingency sample" (10010) col-

Table 1. Mean Concentrations of Some Mainly Lithophile Elements in the Apollo 11 Regolith[a]

Element	Mean	±	Element	Mean	±	Element	Mean	±
SiO_2	42.0	0.2	Li	13	3	Nd	38	4
TiO_2	7.54	0.08	Sc	63	2	Sm	12.7	0.5
Al_2O_3	13.55	0.18	V	67	19	Eu	1.77	0.08
FeO	15.81	0.15	Co	28.9	1.1	Gd	17	2
MnO	0.213	0.005	Ni	190	30	Tb	2.94	0.17
MgO	7.88	0.07	Rb	2.80	0.09	Dy	20	2
CaO	11.96	0.13	Sr	163	4	Ho	5.2[b]	1.0
Na_2O	0.438	0.012	Y	115	15	Er	11.5	1.5
K_2O	0.135	0.005	Zr	290	40	Yb	10.6	0.6
Cr_2O_3	0.298	0.011	Nb	18	2	Lu	1.53	0.09
P_2O_5	0.101	0.017	Cs	0.108	0.010	Hf	9.8	0.5
S	0.11	0.03	Ba	169	9	Ta	1.33	0.09
Σ	100.0		La	15.5	0.6	Th	1.94	0.18
			Ce	46.6	1.4	U	0.51	0.06

[a] <1-mm fines, largely sample 10084. Oxide values are in mass % and others in μg/g (Mean), with 95% confidence limits (±). Sources of data: *Agrell et al.* [1970], *Annell and Helz* [1970], *Boynton et al.* [1975], *Compston et al.* [1970], *Engel and Engel* [1970], *Fields et al.* [1970], *Frondel et al.* [1970], *Ganapathy et al.* [1970], *Gast et al.* [1970], *Goles et al.* [1970], *Gopalan et al.* [1970], *Haramura et al.* [1970], *Haskin et al.* [1970], *Hubbard et al.* [1972], *Kaplan et al.* [1970], *Laul and Papike* [1980], *Maxwell et al.* [1970], *Murthy et al.* [1970], *O'Kelley et al.* [1970], *Philpotts and Schnetzler* [1970], *Rhodes and Blanchard* [1981], *Rose et al.* [1970], *Silver* [1970], *Smales et al.* [1970], *Tatsumoto* [1970], *Taylor et al.* [1970], *Tera et al.* [1970], *Wakita et al.* [1970], *Wänke et al.* [1970], *Wanless et al.* [1970], *Willis et al.* [1972], and unpublished data of this laboratory.

[b] All five available Ho values are from imprecise determinations by neutron activation analysis. Based on concentrations of adjacent elements, the actual Ho concentration is more likely to be 4.3 μg/g.

lected a few meters away are indistinguishable from those for 10084.

Table 1 presents mean concentrations of a number of mainly lithophile elements in the Apollo 11 regolith based on data compiled from many sources. For the modeling discussed below, it is important to have precise, self-consistent data [*Korotev*, 2000], so the means of Table 1 are not based on all available data, but data that are likely to be most reliable and accurate. For example, Sc concentrations are based only on analysis by neutron activation, and Sr and Rb concentrations are based only on analyses by mass spectrometric isotope dilution.

3. Mass Balance Models

As noted by numerous investigators after the mission, the proportion of nonmare material in the Apollo 11 regolith is sufficiently large that its composition differs substantially from that of the local mare basalts (Figure 1). Estimates for the proportion of nonmare material in the <1-mm fines range from 20% to 30%; the range largely reflects different assumptions about the nature and composition of the nonmare components (Table 2). For example, making the simple assumption that the nonmare component is typical feldspathic material of the upper crust, as represented by the feldspathic lunar meteorites [*Korotev*, 2000], the geometry of Figures 1a and 1b leads to the conclusion that the regolith (<1-mm fines) is 77% mare basalt and 23% feldspathic material (we provide a better estimate below). As noted by *Wood et al.* [1970], the proportion of nonmare material in the <1-mm fines (20–30%; Table 2) is much greater than the proportion of "anorthositic" particles (5%) they found among the 1676 rock fragments from the 1-to-4-mm-grain-size fraction that they examined. We discuss some implications of this observation below.

One essential compositional aspect of the Apollo 11 regolith has been overlooked in previous works, although it is evident in Figure 1 of *Goles et al.* [1970]. With 7.9% MgO the regolith is substantially richer in magnesium than that mixture of mare basalt and feldspathic highland material which quantitatively accounts for other elements (Figure 1c). A similar problem occurs with Cr. Thus the Apollo 11 regolith must contain a significant proportion of some Mg- and Cr-rich component(s) that has not been explicitly considered by previous models.

Two categories of Mg-rich lithologies occur in the Apollo 11 regolith, picritic volcanic glasses and mafic, nonmare rocklets. Two kinds of picritic glasses have been identified, an orange and a green variety [*Keil et al.*, 1970; *Delano*, 1986; *Shearer and Papike*, 1993]. These glasses are compositionally similar to the well studied Apollo 17 orange and Apollo 15 green glasses [e.g., *Taylor et al.*, 1991]. The few Mg-rich nonmare lithologies include a norite with 17.5% MgO, a mafic, KREEP-bearing impact-melt breccia with 12.0% MgO, and several "poikilitic rocks" which, with 9.0–10.5% MgO, are not substantially richer in Mg than the basalts (7.5–8.0% MgO; Figure 1c) [*Laul et al.*, 1983]. The mafic melt breccia, sample 10085,1187, is 40 mg in mass and described as a granulitic breccia [*Simon et al.*, 1983]. It bears a strong compositional and textural similarity to sample 64815, a 21-g metapoikilitic impact-melt breccia that is unique among Apollo 16 rocks [*Ryder and Norman*, 1980; *Korotev*, 1994, 2000].

In order to identify the carrier of the excess Mg in the regolith, we have modeled, using least squares mass balance techniques, the average composition of the Apollo 11 soil as a mixture of four classes of components (Table 3): (1) mare basalt, (2) feldspathic material, (3) various Mg-rich components discussed above, and (4) a CI chondrite component. The CI component is needed to account for the higher concentrations of Ni, Co, and other siderophile elements in the regolith than in the mixture of lithologic components of which the regolith is composed. It represents meteoritic material in excess of that carried by any brecciated lithologic components (section 5.2). The model differs from previous models (Table 2) in that (1) it is based on a greater number of elements (24; Table 3) than all but that of *Laul and Papike* [1980], (2) it uses all three major compositional types of Apollo 11 mare basalt, types A, B, and D [*Beatty and Albee*, 1980; *Jerde et al.*, 1994], as separate components instead of using a single, average component, (3) the KREEP component represents a lithology that actually occurs in the Apollo 11 regolith, not an Apollo 14-type KREEP component [e.g., *Schonfeld and Meyer* [1972], and (4) the feldspathic component represents typical material of the upper crust of the highlands (28% Al_2O_3; Table 3), not highly feldspathic ferroan anorthosite (e.g., 34% Al_2O_3 [*Goles et al.*, 1971, *Laul and Papike*, 1980]). None of the other models combine all these features. The modeling is of the type described elsewhere [*Korotev and Kremser*, 1992; *Korotev*, 1997, 2000] in that we tried various combinations of multiple components to see which gave the best fit (smallest reduced chi-square). We do not present the modeling details here because, despite the differences in assumptions about the identity and nature of the components (e.g., the compositions of the feldspathic and KREEP compo-

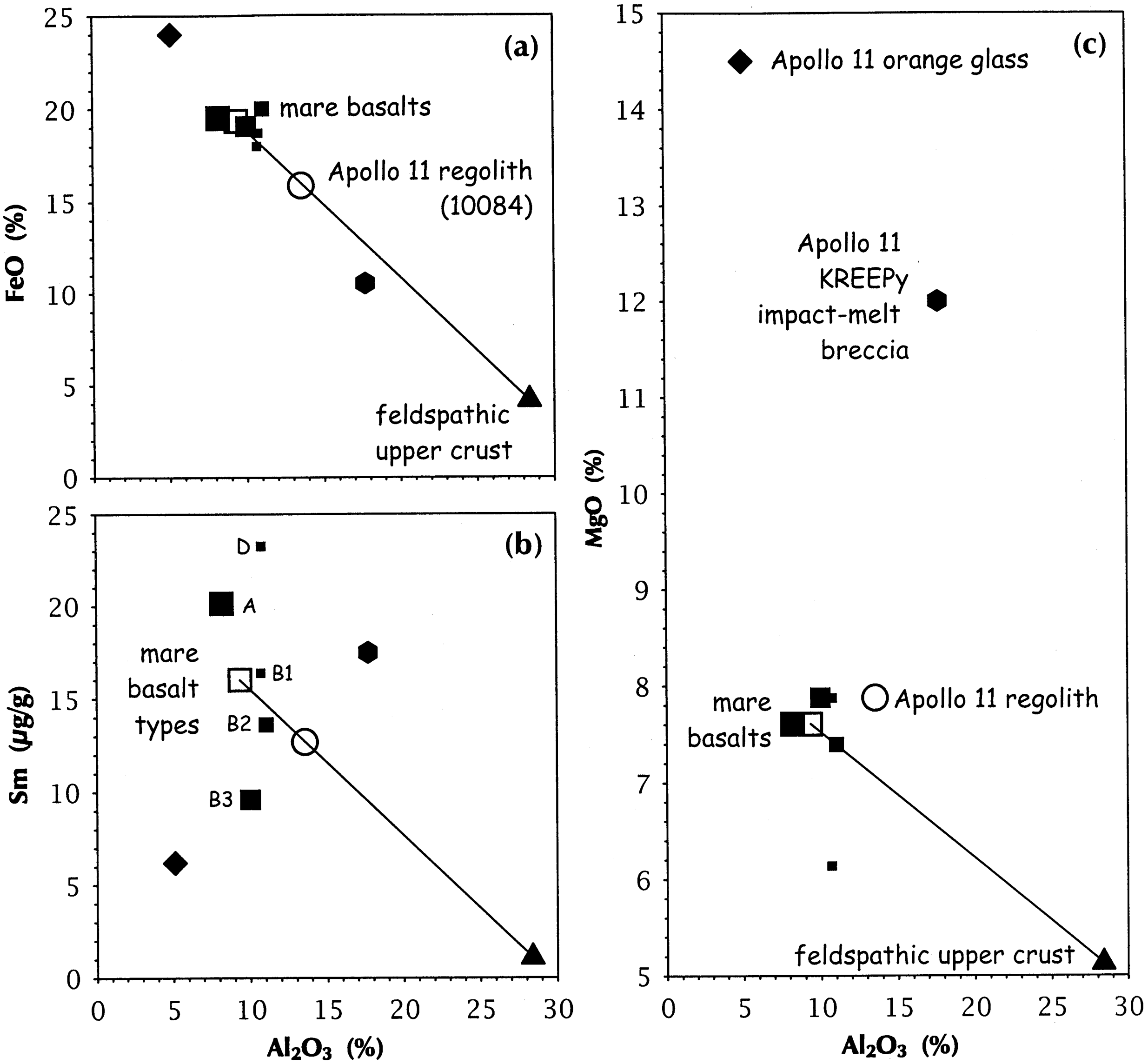

Figure 1. Mean concentrations of Al_2O_3, FeO, MgO, and Sm in the Apollo 11 regolith (circle), the various types of Apollo 11 mare basalts (squares), Apollo 11 orange volcanic glass (diagonal square), Apollo 11 KREEPy impact-melt breccia (hexagon; sample 10085,1175 of Laul et al. [1983]), and the feldspathic upper crust component of the model (triangle [Korotev, 2000]). For the mare basalt types the area of the squares correlates with the relative abundance of the basalt type in the regolith. The open square represents the average mare-basalt component of the regolith weighted by the approximate relative abundances of the basalt types. (For the model, a single type-B basalt component was used, representing a 9:29:62 mixture of types B1:B2:B3; these are the relative proportions among samples [Beatty and Albee, 1980].) In each plot the diagonal line is defined by the feldspathic crust and mean basalt points. (a) and (b) In terms of FeO, Al_2O_3, and Sm only, the regolith corresponds to a mixture of 77% mare basalt and 23% feldspathic upper crust. (c) However, such a mixture does not account for the high concentration of MgO in the regolith; some Mg-rich component(s) must also be present. On the basis of other elements, orange volcanic glass and KREEPy impact-melt breccia are also likely components of the regolith and are the main carriers of the excess Mg.

nents), the quantitative results are similar to those obtained by other models (Table 2), except that we model a portion of the mare basalt component as picritic glass component.

4. Model Results

4.1. Sample 10084

Model results (Table 4) suggest that the excess Mg and Cr is carried by two components: (1) orange volcanic glass (5% of the soil by mass) and (2) KREEP-bearing impact-melt breccia such as samples 10085,1187 or 64815 (7–9 mass %). Together, these two components account for the composition of the soil considerably better than does either alone. The orange-glass and melt-breccia components carry 10% and 12% of the Mg and 11% and 6% of the Cr in the soil, respectively (Table 5). Orange glass provides a better fit than green glass because it accounts better for Cr and heavy REE. No significant improvement in model fit is obtained by including the

Table 2. Results of Compositional Mass Balance Models for the Apollo 11 Regolith[a]

Source[b]	Mare Basalt	Orange Glass	Anorthosite[d]	KREEP[c]	Meteorite	Σ
W70	80		20			100
S&M72	78		19	5	2	104
G71	76		19	4	1	100
L71	74		14	12		100
L&P80	72		14	13		99
H&G71	70		20	10		100
This work[d]	66	5	20	8	1	101

[a] Mass percent of component for <1-mm fines (Table 1).

[b] W70, *Wood et al.* [1970]; H&G 71, *Hubbard and Gast* [1971]; G71, *Goles et al.* [1970]; L71, *Lindsay* [1971]; S&M72, *Schonfeld and Meyer* [1972]; and L&P80, *Laul and Papike* [1980].

[c] The various models use significantly different compositions to represent the anorthosite and KREEP components.

[d] Details are in Table 4.

Table 3. Compositions of Components Used in the Mass Balance Model[a]

	Mare				Nonmare				
						MIMB			
	A	B	D	OVG	FUpCr	A11	A16	CI	WF
	1	2	3	4	6	7	8	9	10
SiO_2	40.6	39.8	42.0	37.8	45.0	(45.4)	45.3	31.0	1.0
TiO_2	11.4	10.3	8.5	10.0	0.23	1.8	1.6	0.10	1.0
Al_2O_3	8.20	10.37	10.77	5.10	28.3	17.7	19.0	2.23	1.0
Cr_2O_3	0.333	0.307	0.329	0.634	0.094	0.218	0.243	0.529	1.7
FeO	19.5	19.2	18.7	24.0	4.10	10.5	9.2	33.3	1.0
MgO	7.61	7.58	7.88	14.5	5.10	12.	12.0	22.3	1.0
CaO	10.5	11.3	11.5	7.40	16.5	11.2	11.9	1.77	1.0
Na_2O	0.50	0.38	0.38	0.28	0.35	0.51	0.525	0.92	1.3
K_2O	0.294	0.059	0.087	0.020	0.026	0.250	0.270	0.092	1.8
Σ	98.9	99.3	100.1	99.7	99.7	99.6	100.1	92.2	
Sc	82	86	78	58	8.3	20	22	7.9	1.6
Co	27	16	17	64	10	70	47	693	1.8
Ni	2	2	2	30	5	900	630	14960	7.8
Sr	173	150	146	164	153	160	150	10.6	1.8
Zr	451	281	483	204	36	(476)	489	5.4	5.4
Ba	289	103	203	55	34	420	367	0.3	2.5
La	25.8	10.0	33.1	4.4	2.4	40	34.2	0.32	1.8
Ce	78	33	93	13.7	6.2	100	91	0.82	1.3
Sm	20.1	11.4	23.3	6.20	1.11	17.5	15.8	0.20	1.8
Eu	2.20	1.81	1.93	1.57	0.80	1.8	1.71	0.08	2.1
Yb	17.6	10.3	16.8	4.85	0.93	14	11.9	0.22	2.6
Lu	2.50	1.55	2.39	(0.70)	0.13	2.1	1.67	0.03	2.1
Hf	16.7	8.7	12.6	(6.2)	0.82	11.9	11.8	0.14	2.2
Th	3.25	0.91	2.50	(0.45)	0.37	7.1	5.40	0.04	4.1
U	0.82	0.25	0.62	(0.13)	0.13	1.7	1.44	0.01	5.3

[a] Oxide values are in %, others are in µg/g; values in parentheses were estimated. Numbers in the table headings are as follows: (1–3) mean compositions of Apollo 11 basalt types A, B, and D based on data from many literature sources, (4) mean composition of Apollo 11 orange volcanic glass [*Shearer and Papike*, 1993; *Delano*, 1986], (5) mean composition of the feldspathic upper crust; estimate based on lunar meteorites [*Korotev*, 2000], (7 and 8) KREEP-bearing, mafic impact-melt breccias: Apollo 11 sample 10085,1187 [*Laul et al.*, 1983] and Apollo 16 sample 64815 [*Korotev*, 1994], (9) volatile-free CI chondrite component [*Korotev*, 2000], and (10) relative weighting factors used in modeling (r_i of *Korotev* [2000]); the values are the greater of 1% or the relative standard deviation (%) of the values used to obtain the means of Table 1.

green glass in addition to the orange glass, but mass balance arguments are not sufficiently constrained to exclude the possibility that there is as much as a few percent green glass in the Apollo 11 regolith.

Although several previous models have assumed the presence of a KREEP component in the Apollo 11 regolith (Table 2), no strong justification has been given for why such a component is necessary. The need for a KREEP-bearing component is not evident in Figure 1b in that it appears from the figure that mare basalt can supply the required incompatible elements. However, from the studies of *Simon et al.* [1983] and *Laul et al.* [1983], which postdate all of the models of Table 2 except the one presented here, we know that KREEP-bearing, nonmare lithologies actually occur in the Apollo 11 regolith. Also, as noted above, inclusion of a KREEP-bearing melt-breccia component considerably improves the fit, especially for incompatible elements. In particular, without the KREEP component the concentrations of Th and U are underestimated by 6–8% because the soil has greater Th/REE and U/REE ratios than the mare basalts that supply most (~70%, Table 5) of the Th and U (Figure 2). To represent the KREEP component, we tested both melt-breccia samples 10085,1187 (from Apollo 11) and 64815 (from Apollo 16) because 64815 may well be a sample of the same lithology as 10085,1187 and more data representing a greater mass of material are available for 64815 [*Korotev*, 1994]. Perhaps as a consequence, 64815 provides a slightly better fit than does 10085, 1187. Results from both components are presented in Table 4; subsequent discussion and Tables 2, 5, 6, and 7 are based on average results for the two types of melt breccia component.

Quantitatively, the model results (the best fit proportions of components) are similar to those of previous models, particularly that of *Hubbard and Gast* [1971], except that 7% (5/[66+5]; Table 2) of the nominal mare component is picritic glass instead of crystalline mare basalt. The total proportion of orange-glass component, 5 ± 2% (Table 4), is consistent with petrographic data. *Simon et al.* [1981] report that the 90-to-1000-µm-grain-size fraction of 10084 contains 2.7% grains of "orange/black" glass and 0.8% grains of "yellow/green" glass. (The black "glass" is orange glass liquid from which ilmenite and olivine have crystallized [*Weitz et al.*, 1999].) However, 59.5% of the particles are agglutinates and dark matrix breccias, which are glassy breccias constructed from soil, so the "chemical" proportion of the picritic glasses in the soil is likely to be ~6.7% (2.7/[1–0.595]) orange/black and 2.0% yellow/green, consistent with the model results. It is noteworthy that 6% is the lower limit for the proportion of Apollo 17 orange-glass component among the most basaltic

Table 4. Results of New Compositional Mass Balance Model for the Apollo 11 Regolith[a]

	%	±	%	±
Mare basalt, type A	*30*	*3*	*28*	*3*
Mare basalt, type B	*32*	*5*	*34*	*5*
Mare basalt, type D	*4*	*3*	*4*	*2*
Total mare basalt	66.0	1.0	66.6	1.0
Orange volcanic glass	5.7	1.7	4.8	1.6
Feldspathic upper crust	21.3	1.3	19.7	1.6
KREEPy MIMB 10085,1187[b]	6.9	2.3	–	
KREEPy MIMB 64815[b]	–		8.7	2.4
CI chondrite	0.74	0.17	0.89	0.13
Total	100.7	7.6	100.6	7.3

[a] Values are mass percent of components on the basis of the compositions of Tables 1 and 3 and the model described in the text.

[b] Mafic impact-melt breccia [*Korotev*, 2000]; two different components were tested (see text).

Table 5. Percent of Element Carried by Each Model Component[a]

	MB	OVG	FUpCr	MIMB	CI	Σ
Si	64	5	22	8	1	99
Ti	94	7	1	2	0	103
Al	46	2	43	11	0	102
Fe	81	8	5	5	2	101
Mg	64	10	13	12	2	101
Ca	61	3	28	8	0	100
Na	65	3	16	9	2	96
K	81	1	4	15	1	101
Sc	88	5	3	3	0	98
Cr	70	11	6	6	1	95
Co	48	12	7	15	19	101
Ni	1	1	1	30	62	94
Sr	65	5	19	7	0	97
Zr	83	4	3	13	0	102
Ba	75	2	4	18	0	99
La	79	1	3	18	0	102
Ce	81	2	3	16	0	101
Sm	83	3	2	10	0	98
Eu	74	5	9	8	0	96
Yb	87	2	2	9	0	100
Lu	87	2	2	9	0	100
Hf	84	3	2	9	0	99
Th	70	1	4	25	0	99
U	68	1	5	24	0	98

[a] Values are based on average results of Table 4. MB, mare basalt (total); OVG, orange volcanic glass; FUpCr, feldspathic upper crust; MIMB, KREEP-bearing, mafic impact-melt breccia; CI, volatile-free CI chondrite (Table 3).

soils from Apollo 17 [*Korotev and Kremser*, 1992]. By analogy with Apollo 17, there may have been pyroclastic eruptions from source vents near the Apollo 11 site which now are buried.

Taken at face value, the model results suggest that the relative abundances of basalt types A, B, and D in the <1-mm fines are (44 ± 4):(50 ± 8):(6 ± 4) (A:B:D; Table 4). These values compare well with the proportions 47:49:4, which are those of the 70 classified basalts (rocks and pebbles) of *Beatty and Albee* [1980] (three samples are unclassified). The agreement suggests that the distribution of basalt types in the <1-mm-grain-size fraction of the regolith is not significantly different from that of the >4-mm fraction.

Only 80% of the Fe in the Apollo 11 regolith derives from crystalline mare basalt; 8% of the Fe and 7% of the Ti derive from the volcanic glass component (Table 5). These estimates may be useful for interpretation of the spectral reflectance properties of the Apollo 11 regolith.

4.2. Regolith Breccias, and Clementine-Derived FeO Concentration Estimates

Our knowledge of the properties of the Apollo 11 regolith is based almost entirely on 10084, a single large sample of surface soil collected near the lunar module (section 2). The model results of Tables 4 and 5 apply strictly to that one sample only. A number of the Apollo 11 rocks, however, are regolith breccias, and some of these, at least, represent regoliths more distant from the landing site than the location of sample 10084. Some may also have been lithified long ago and thus represent ancient regoliths [*McKay et al.*, 1986]. *Rhodes and Blanchard* [1981] studied a suite of 16 Apollo 11 regolith breccias, all of which appear to be of local derivation in that they consist mainly of Apollo 11-type mare basalt; none appear to be highly exotic to the site (the extreme examples being the several lunar regolith breccias found as meteorites on Earth [e.g., *Warren*, 1994]). FeO concentrations of the breccias range from 15.4% to 18.6%. In terms of the model of Table 2 the proportion of nonmare material in the breccias ranges from 8% (sample 10056,23) to 31% (10075,12) and averages 23%. These breccias suggest that had the astronauts made an extensive traverse of the site, as was done at other sites on later missions, they might have encountered a considerable range of surface regolith compositions.

If we assume that the breccias are a better sampling of surface regoliths around the landing site than sample 10084, then they provide weak evidence that regionally (scale?) the FeO concentration of the local regolith (breccia mean: 16.4%) may be greater than at the Apollo 11 lunar module (15.8%). The mean FeO concentration of the breccias is still not sufficiently large, however, to account for the high FeO concentration estimated for the landing site (18.2%) from the Clementine spectral reflectance data (Plate 1). The large discrepancy between the Clementine-derived estimate and the actual soil composition probably reflects error or uncertainty in the estimation technique [*Lucey et al.*, 2000], but it might instead be an indication that the landing site is highly anomalous. In the subsequent discussion we assume that the FeO concentration scale depicted in Plate 1 accurately reflects relative concentrations but not necessarily absolute concentrations.

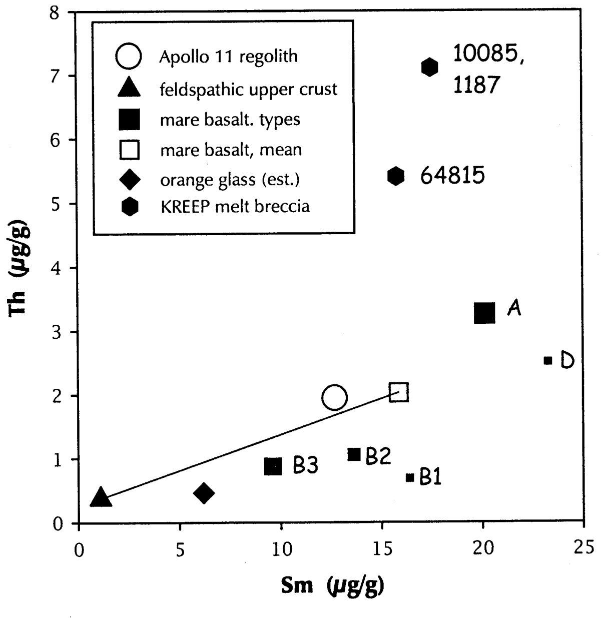

Figure 2. Th and Sm concentrations in the Apollo 11 regolith and regolith components (see Figure 1). The regolith has a slightly greater Th/Sm (and U/Sm) ratio than can be accommodated by the mixture of mare basalt and feldspathic highlands material that accounts best for all other elements modeled. KREEP-bearing, mafic impact-melt breccias have greater Th/Sm ratios than do all known types of mare basalts, and inclusion of a small proportion of mafic melt breccia in the model considerably improves the fit for Th and U (also Ba, Eu, and light REE). The concentration of Th has not been determined for the Apollo 11 orange volcanic glass; for this plot (and for the model) the concentration was estimated on the basis of the Apollo 17 orange volcanic glass and Yb concentrations in both glasses.

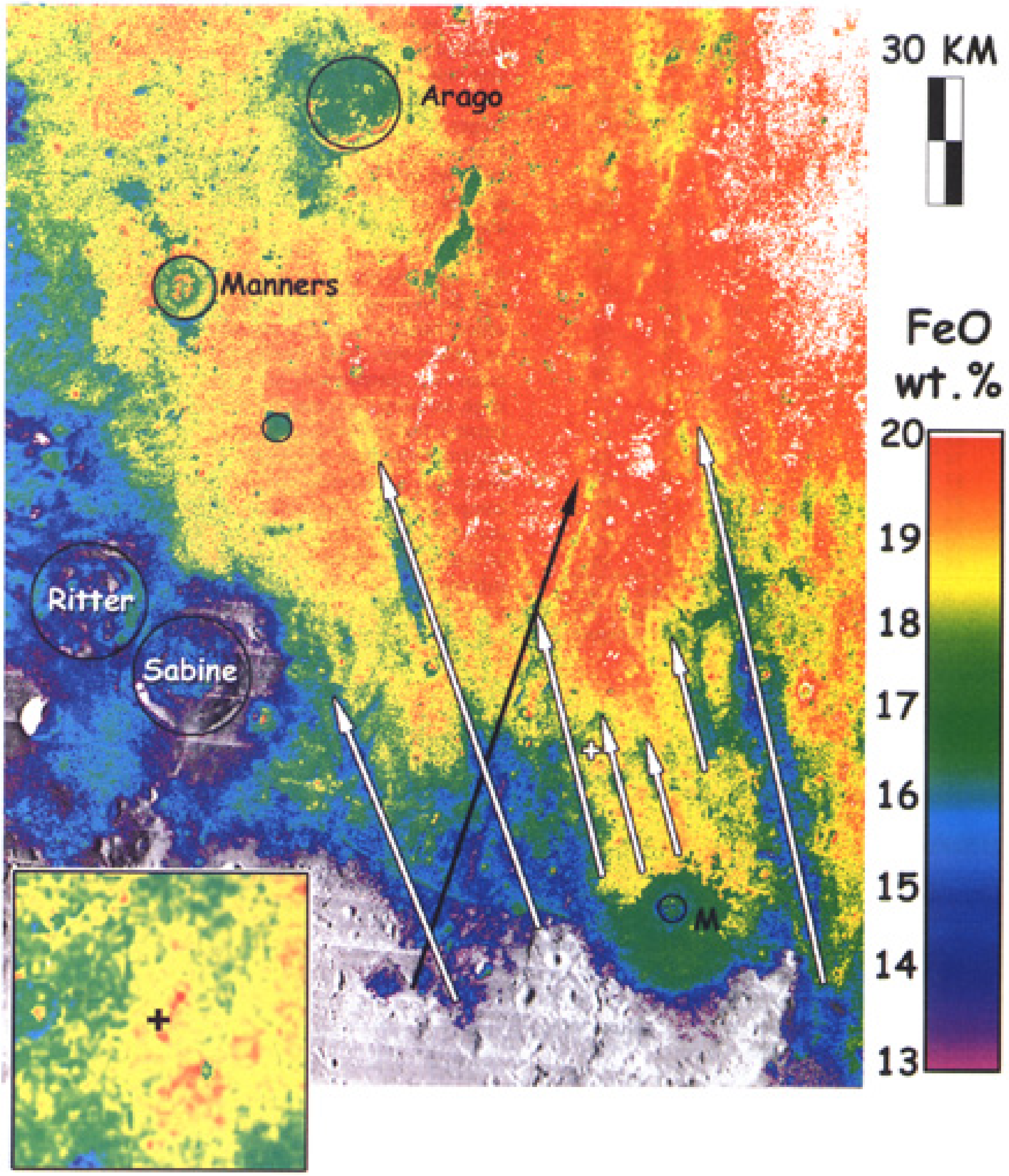

Plate 1. Image illustrating surface concentrations of FeO in southwest Mare Tranquillitatis in the vicinity of the Apollo 11 landing site (cross); the uncolored region in the southern part of the image is highlands with <13 wt.% FeO (merged Lunar Orbiter image). The inset is a 5× enlargement of the area of the site. The white arrows illustrate crater rays from Theophilus, 380 km to the south-southeast of the site (arrows point away from crater), and the black arrow depicts a ray of the crater Tycho. The high-albedo crater rays of Figure 3 appear as low-iron streaks, some as low as 13–14 wt% FeO and others around 17–18 wt% FeO, thus the rays are compositional rays, not rays resulting from regolith immaturity [*Staid et al.*, 1996; *Hawke et al.*, 2000]. The Apollo 11 landing site is straddled by some of these low-FeO crater rays. The crater Moltke (6-km diameter; Figure 3), south-southeast of the landing site (M), appears as a low-iron feature, indicating that is has excavated nonmare material from beneath the basalt. The basalt must be <600 m thick at this point, based on the 0.1 depth-of-excavation to crater-diameter relation [*Croft*, 1980]. FeO concentrations were determined using the Clementine 750- and 950-nm images and the method developed by *Lucey et al.* [2000]. There is a significant difference between the actual FeO concentration of the Apollo 11 soil (15.8%; Table 1) and the apparent regional concentration implied by the plate (18.2% FeO for the pixel containing the site, 18.5% for the 3×3 block centered on the site). We do not understand the cause or significance of the difference, but the Apollo 11 point is clearly one of the most anomalous in the calibration of *Lucey et al.* [2000] (the rightmost triangular point of their Figure 1b).

Table 6. Comparison of the Fraction of Nonmare Lunar Material in Regoliths from Mare Landing Sites Based on Compositional Mass Balance for the <1-mm-Grain-Size Fraction.

Site	% Nonmare	Source[a]
Luna 24	<10	1
Apollo 17, most basaltic (station 5)[b]	12	2
Apollo 15, most basaltic (station 9a)[b]	14	3
Luna 16	~20	1
Apollo 11	28	4
Apollo 12, typical (e.g., 12070)	~40	5

[a] Sources: (1) based on Ti, Al, and Fe only, assuming the nonmare material has the FUpCr composition of Table 3 (i.e., negligible KREEP component); (2) *Korotev and Kremser* [1992]; (3) *Korotev* [1987]; (4) this work (Table 4); (5) *Korotev et al.* [2000].

[b] Soils from highlands stations of Apollo 15 and 17 contain >90% nonmare material.

5. Nonmare Materials of the Apollo 11 Regolith

5.1. Lunar Materials

In concurrence with previous models (Table 2), our modeling indicates that 29% of the Apollo 11 regolith (<1-mm-grain-size fraction) is of nonmare origin, 1% in meteoritic material and 28% in lunar material (Table 4). The proportion of nonmare material in the Apollo 11 regolith is high compared to soils from other mare sites (Table 6). A significant proportion of the nonmare material, 29% (8/28), is KREEP-bearing impact-melt breccia (Table 4). Thus we must disagree with *Basu et al.* [2001, p. 177] that the Apollo 11 and Luna 24 sites are "the two sites on mare basalt provinces with least contamination from highland and KREEPy rocks."

5.1.1. Lateral versus vertical mixing. Historically, the discussion of the origin of the nonmare component of mare regoliths has focused on lateral versus vertical impact mixing [*Rhodes*, 1976; *Hörz*, 1978; *Simon et al.*, 1983; *Staid et al.*, 1996; *Mustard et al.*, 1998]. The distinction between "lateral" and "vertical" mixing is not well defined. All mixing discussed in this section is lateral in the literal sense in that, on average, the net horizontal component of movement of the ejected material far exceeds the net vertical component. Vertical impact mixing, however, usually implies movement of material from a lower stratigraphic level to a higher level, one that is dominated by a different type of material.

A small proportion of the nonmare material of the Apollo 11 site may derive from impacts into the nearby highlands. Prior to the mission, E. M. Shoemaker had predicted that 4% of the particles at the Apollo 11 site should be such ejecta (unreferenced anecdote given by *Marvin* [1973]). Other works have argued to the inefficiency of lateral mixing at such distances (50+ km) [*Rhodes*, 1976; *Hörz*, 1978; *Simon et al.*, 1983]. However, southern Mare Tranquillitatis has obviously been influenced by at least one special case of lateral mixing, rays from the crater Theophilus (100-km diameter) centered 380 km to the south (Figure 3). *Wood et al.* [1970] suggested the Theophilus rays as a possible source of the anorthositic fragments they found in the Apollo 11 soil, and *Staid et al.* [1996] attributed most of the nonmare material at the Apollo 11 site to Theophilus rays. *Staid et al.* [1996] noted that the iron concentration of the rays is less than that of the interray material and that craters thought to be secondaries from Theophilus occur within a few kilometers of the site [*Grolier*, 1970; *Wilhelms*, 1987, Figure 11-10]. Thus lateral mixing has, in fact, happened in the vicinity of the Apollo 11 site, and Fe-poor Theophilus material clearly occurs there (Plate 1). In the next three paragraphs, however, we argue that the amount of nonmare material at the Apollo 11 site is too great for it all to have come from Theophilus.

On the basis of ejecta scaling laws, we should expect an average thickness of Theophilus ejecta of ~1 m at a distance of 380 km from the crater center, the distance of the Apollo 11 site [*Housen et al.*, 1983, equation (40) and Figure 8, $\alpha = 0.65$; *Haskin et al.*, 2001, and personal communication, 2001]. At the time of deposition, the ejecta would have mixed with the preexisting regolith to form a deposit, a mixing layer, that was thicker than the equivalent thickness (e.g., 1 m) of the primary ejecta [*Morrison and Oberbeck*, 1975]. (We do not estimate a deposit thickness, as do *Morrison and Oberbeck* [1975] and *Haskin* [2001], because their equations were derived for continuous ejecta deposits near a crater or basin, not far-field ejecta delivered as rays.)

Wilhelms [1987] classifies Theophilus as a late Eratosthenian or early Copernican crater, making it ~1 Gyr old. In the last billion years, many local impacts [e.g., *Wilhelms*, 1987, Figures 11.10 and 11.11] would have mixed any Theophilus ejecta deposited on Mare Tranquillitatis to an even greater depth than the original deposit. We have no direct information about the variation in composition or the relative abundance of nonmare material with depth at the Apollo 11 site, but we can infer some information from the sample data. Although the results of the mixing model (Table 4) apply strictly to the upper 10 cm of regolith only (section 2), the Apollo 11 surface regolith is mature [*Morris*, 1978]. At other sites where core or drive tubes were taken at locations where the surface regolith was mature, the composition of the regolith at the top 10 cm of a core closely approximates the average composition of the whole core [*Korotev*, 1998]. Thus, we can reasonably assume that the upper few meters, at least, of regolith near the Apollo 11 lunar module contain ~28% nonmare material, and this approximate proportion may actually extend to a considerably greater depth. If (1) all of the nonmare material in the Apollo 11 regolith is from Theophilus, (2) Theophilus ejecta contain minimal mare material, and (3) the Apollo 11 site has the average amount of Theophilus ejecta expected from the scaling laws (1 m), then Theophilus ejecta must be mixed to a depth of no more than 3–4 m in order to account for the 28% nonmare material in the present regolith.

We would expect, however, that the Apollo 11 site would contain less than the average amount of ejecta predicted by the scaling laws because the site lies between rays (Plate 1). Taken at face value, the range of Clementine-derived FeO concentrations in Mare Tranquillitatis within 50 km of the landing site (13–20%, Plate 1) corresponds to a range of 0–47% nonmare material, assuming a mean FeO concentration of 5.7% for the nonmare component (Table 7, column 4). Among the lowest of the FeO concentrations depicted in Plate 1 (i.e., ≥47% nonmare material) is a deposit of Theophilus ray material ~30 km east-northeast of the site. Regardless of the cause of the discrepancy between the Clementine-derived FeO concentrations and the concentrations measured on Apollo 11 soil samples (section 5.1), the Apollo 11 site is on the high-Fe side of the range of Plate 1 (18.2% FeO), suggesting that it is minimally affected by Theophilus rays. These various con-

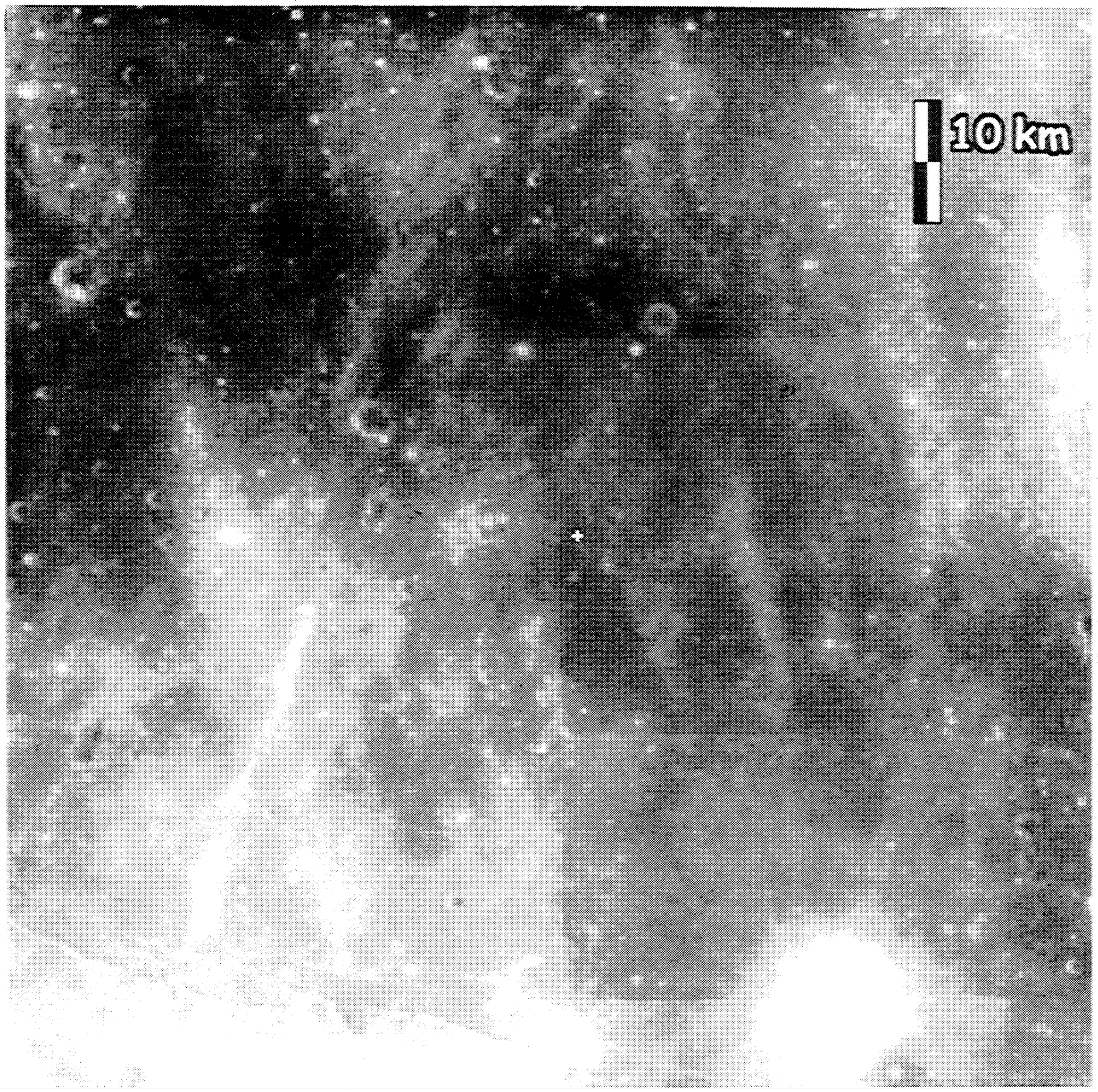

Figure 3. Clementine 750-nm mosaic of the Apollo 11 landing site (white cross at center) and surrounding Mare Tranquillitatis. The bright crater in the bottom right of the image is Moltke (6-km diameter). Also visible in the image are bright northeast trending rays from Tycho (43.4°S, 11°W, 102-km diameter, ~900-km distance), northwest trending rays from Theophilus (11.4°S, 26.5°E, 100-km diameter, 380-km distance), and the crater Moltke (bottom right). The nearest exposure of highlands occurs 50 km south of the site, ~20 km from the bottom of the figure (Plate 3).

siderations suggest that there is too much nonmare material in the Apollo 11 regolith for it all to be Theophilus ejecta. If it is from Theophilus, then either (1) the immediate landing site area is anomalously enriched in Theophilus ejecta, presumably from a small Theophilus secondary, at a scale below the Clementine resolution (200 m) or (2) the scaling laws for crater ejecta are inadequate for the purpose of evaluating average thicknesses of far-field ejecta from rayed craters.

Thus some to much of the nonmare material in the Apollo 11 region must derive from vertical mixing [*Rhodes*, 1976]; *Hörz*, 1978; and *Simon et al.*, 1983]. *De Hon* [1974] shows that at the vicinity of the site, the basalt flows are ~500 m thick and they thin to the south and west. *Hörz* [1978] argues that the flows are half as thick as *De Hon* [1974] estimates. Thus any local impact into the mare that has formed a crater a few kilometers in diameter or larger will excavate nonmare material and deposit it on the surface. In the vicinity of the site, FeO concentrations decrease overall in the direction of the highlands to the south, and the nearby crater Moltke (6 km in diameter) clearly excavated low-Fe material and deposited it several crater radii away (Figure 3 and Plate 1) [see also *Staid et al.*, 1996]. In the 3.6 Gyr since the last Apollo 11 basalts were formed, many such impacts, the older ones of which may not still be evident in Plate 1, have caused the surface regolith of the mare to become more feldspathic. Also, the basalt flows were not emplaced in one event but were erupted in series of flows that may have each acquired a layer of nonmare ejecta. These interbedded horizons of nonmare

Table 7. Comparison of Mean Composition of Nonmare Particles from the Apollo 11 Regolith of *Laul et al.* [1983], Model Components, and Apollo 16 Soil[a]

	Feldspathic		All Nonmare		Apollo 16	
	Laul 1	Model 2	Laul 3	Model 4	Obs. 5	−MB 6
TiO_2	0.36	0.23	0.58	0.65	0.59	0.48
Al_2O_3	27.4	28.3	25.2	25.5	26.7	27.8
FeO	4.3	4.1	5.3	5.7	5.5	4.6
MgO	5.2	5.1	6.4	7.1	6.1	5.7
CaO	16.2	16.5	14.9	15.1	15.4	15.7
Na_2O	0.46	0.35	0.48	0.40	0.46	0.47
K_2O	0.043	0.026	0.19	0.09	0.12	0.12
Mg'	68	69	68	69	67	69
Sc	7.7	8.3	10.0	11.9	9.6	7.1
Cr	540	640	754	906	775	634
Sm	1.11	1.11	4.5	5.5	6.2	6.3
Eu	1.04	0.80	1.21	1.07	1.20	1.20
Th	0.31	0.37	2.4	2.0	2.2	2.3

[a] Oxide concentrations in mass %, *Mg'* (Mg/[Mg+Fe]) in mole %, other values in μg/g. (1) Mass-weighted mean of the 29 particles of *Laul et al.* [1983] with ≤2.3 μg/g Sm. For this calculation, values for TiO_2, MgO and Th were estimated for the "less than" values reported by *Laul et al.* [1983]. (2) The feldspathic upper crust component of the model (Table 3). (3) Mass-weighted mean of all 38 nonmare particles of *Laul et al.* [1983]. (4) Mass-fraction-weighted mean composition of the nonmare lunar components of the model of Table 4. (5) Mean composition of mature soils from Apollo 16 [*Korotev*, 1997]. (6) Column 5 minus 6% mare basalt [*Korotev*, 1997].

material may be tapped by even small craters. The surface of southwestern Mare Tranquillitatis contains abundant nonmare material that is not obviously related to Theophilus rays [*Staid et al.*, 1996] (see also Plate 1), and much of that material is likely to have derived from vertical mixing.

5.1.2. The Imbrium connection. In the preceding analysis we showed that both lateral and vertical mixing are likely to have contributed nonmare material to the Apollo 11 site. Can we determine whether one process is more important than the other? The nature of the nonmare material provides some clues but cannot be used to favor one source or the other because in either case the nonmare material is likely to be derived from an Imbrium ejecta deposit.

Although the work of *Wood et al.* [1970] is noted (among others) for the discovery of lunar anorthosite, of the ~84 anorthositic particles they studied from the Apollo 11 regolith, only 15% were true anorthosites, that is, crystalline rocks with >90% plagioclase [*Stöffler et al.*, 1980]. The rest were classified as gabbroic anorthosites, anorthositic gabbros, glassy fragments of anorthositic composition, and anorthositic breccias. A similar diversity was obtained in the study of *Simon et al.* [1983] and *Laul et al.* [1983] (both papers describe the same suite of samples). Some of the mafic particles of the Simon-Laul study are KREEP-bearing, polymict breccias or glasses. Most, however, are KREEP-poor lithologies typical of the feldspathic highlands. As a consequence, of the 38 nonmare particles studied, the mean composition of the 29 particles with the lowest concentrations of Sm (those with the lowest proportion of KREEP) is very similar to the feldspathic upper crust component of the our model (Table 7), a component which, normatively, contains only ~82% plagioclase by volume. It is significant that the mass-weighted mean composition of all 38 particles of the Simon-Laul study (Table 7, column 3) is very similar to the composition of the nonmare portion of the regolith inferred from the mass balance model presented here (column 4). This similarity argues that although the proportion of nonmare material in the <1-mm fines is greater than the proportion in the >1-mm fines (section 5.1.3), the nonmare material is essentially the same material in both grain-size fractions, a material somewhat more mafic on average than "anorthosite."

Simon et al. [1983] note that the nonmare lithologies of the Apollo 11 regolith are similar to those of Apollo 16. They assumed vertical mixing and concluded that the basalts of southwestern Mare Tranquillitatis covered highlands material similar to that found at the Apollo 16 site. At the Apollo 16 site the Cayley Plains are believed to be an Imbrium ejecta deposit overlying Nectaris ejecta [*Spudis*, 1984; *Wilhelms*, 1987, Figure 10.39], although *Haskin* [2001] argues that Serenitatis ejecta may be considerably more important than Nectaris ejecta at the site. In addition to the lithologic similarity between the nonmare material of the Apollo 11 and 16 sites, the mean composition of the Apollo 11 particles of the Simon-Laul study is also similar to (but slightly less feldspathic than) the composition of the regolith of the Cayley Plains at the Apollo 16 site (Table 7, columns 3 and 5). The distance between the two sites is 379 km (based on data of *Davies and Colvin* [2000]). More important, however, both sites are about the same distance from the center of the Imbrium basin (35°N, 17°W [*Spudis*, 1993]), 1545 km for Apollo 11 and 1625 km for Apollo 16. This means that the proportion of primary Imbrium ejecta in the nonmare regolith beneath the Apollo 11 basalt flows should be the same as that of the Apollo 16 regolith, 13–18% [*Morrison and Oberbeck*, 1975] or 20–40% [*Haskin*, 1998].

We have suggested that the KREEP component of the Apollo 16 regolith, which occurs as mafic impact-melt breccias and rebrecciated products (e.g., regolith breccias), derived from the Procellarum KREEP Terrane [*Jolliff et al.*, 2000] as Imbrium basin ejecta, not as ejecta from Nectaris, which is closer but older [*Korotev*, 1997; *Haskin et al.*, 1998]. The argument is based in large part on the observation that there is no evidence in the orbital gamma-ray data [*Metzger et al.*, 1981; *Lawrence et al.*, 1999] that Th-rich material was encountered by the Nectaris impactor. If (1) the KREEP-bearing melt breccias of the Apollo 11 and 16 sites are Imbrium ejecta, as suggested by *Haskin et al.* [1998], and (2) the nonmare component of the Apollo 11 regolith derives mainly from vertical mixing, then we would expect the nonmare materials of the Apollo 11 and 16 sites to have about the same proportion of KREEP material, which is what we observe. If the nonmare material of the Apollo 11 site instead derives mainly from Theophilus, then we must conclude that the Theophilus target area is also dominated by Imbrium ejecta, a conclusion consistent, for example, with the inferred stratigraphy of the Theophilus region [*Wilhelms*, 1987, Figure 11.9]. Thus the composition and lithologic makeup of the nonmare material of the Apollo 11 regolith are consistent with both vertical mixing and lateral mixing in the form of rays from Theophilus. The similarity in the proportion of KREEP-bearing materials between Apollo 11 and Apollo 16, however, somewhat favors vertical mixing as we would expect the Theophilus area, at 1880 km from the center of Imbrium, to contain less primary Imbrium ejecta (less KREEP) than the Apollo 11 site (1545 km).

In terms of the model presented here (Table 4) and terrane concept of *Jolliff et al.* [2000], the Apollo 11 regolith contains

29% nonmare material: 20% from the Feldspathic Highlands Terrane, 8% from the Procellarum KREEP Terrane, and 1% from meteorites (section 5.4). Thus, 29% (8/[20+8]) of the nonmare lunar material of the Apollo 11 site is KREEP-bearing, mafic impact-melt breccia from the Procellarum KREEP Terrane. In terms of the hypothesis of *Haskin* [1998] and *Haskin et al.* [1998], that material would be primary Imbrium ejecta. Using comparable techniques, *Korotev* [1997] estimated that the same proportion, 29%, of the Apollo 16 regolith is KREEP-bearing, mafic impact-melt breccia. The similarity is a necessary consequence of the similarity in the composition of the Apollo 16 regolith and the nonmare component of the Apollo 11 regolith (Table 7). If the KREEP-bearing, mafic impact-melt breccias of Apollo 11 and Apollo 16 do not derive mainly from the Procellarum KREEP Terrane or are ejecta from a basin other than Imbrium (e.g., Nectaris [*Spudis*, 1984, 1992]), then some other explanation must be sought for why the proportion of such material is so similar in the nonmare portion of the regoliths of these two sites.

5.1.3. Grain size. The proportion of nonmare material increases with decreasing grain size in the Apollo 11 regolith. No nonmare samples occur among the rocks (>2 g), although 20 basalts and 29 basaltic breccias were collected. In the 1-to-4-mm-grain-size fraction of the regolith, 5% of the particles are of nonmare origin [*Wood et al.*, 1970]. If we (1) use the same argument used in section 4 with respect to orange volcanic glass and (2) assume that as much as 60% of the 1-to-4-mm particles of *Wood et al.* [1970] are agglutinates and glassy soil breccias that were not included among their nonmare particle count, then the 1-to-4-mm-grain-size fraction may contain as much as 12.5% (=5%/[1–0.6]) chemical component of nonmare material. This proportion is still much less than the 28% in the <1-mm grain-size fraction. Clearly, the nonmare component of the regolith has a significantly finer grain-size distribution than the mare component. If this difference extends to the finest grain sizes, then it may contribute to the observed enrichment in feldspar of the <10-μm-grain-size fraction of sample 10084 compared to coarser fractions [*Laul and Papike*, 1980; *Taylor et al.*, 2000]. Although the enrichment in feldspar of the finest fraction of mare soils is often attributed largely to "differential comminution" of basalt [e.g., *Laul et al.*, 1988; *McKay et al.*, 1991], the simple effect of mixing coarser-grained mare basalt with finer-grained feldspathic material from the highlands cannot be ruled out and should not be overlooked [*Korotev*, 1976, 1989].

Unfortunately, the observation that the nonmare component of the Apollo 11 regolith is finer grained than the mare component is also consistent with either lateral and vertical mixing. As noted above, the Apollo 11 lavas likely erupted onto a regolith surface, one composed of basin ejecta. At the time of the Imbrium impact, fine-grained regolith existed in the highlands [*McKay et al.*, 1986; *Korotev*, 1997]. Vertical mixing by impacts large enough to penetrate the basalt flows of Mare Tranquillitatis would have brought the ancient, fine-grained, nonmare regolith to the surface. With regard to lateral mixing, the grain-size distribution of the ray material deposited by the Theophilus impact is not known. It may have arrived as fine-grained material [*Wood et al.*, 1970], but even if it was deposited mainly as blocks [e.g., *Simon et al.*, 1983; *Korotev et al.*, 1997], the mean grain size will have decreased during the ~1 Gyr since its deposition [*McKay et al.*, 1974]. During this period, impacts large enough to penetrate the regolith, but not the basalt flows, continually replenished the surface with fresh basalt blocks. For example, *Beatty and Albee* [1980] argue that most of the basalt rocks collected at the site were ejecta from relatively fresh West Crater. Thus, regardless of the source of the nonmare component, if it is not replenished and the thickness of the basalt flows exceeds the regolith thickness, it must remain finer grained than the mare component.

5.2. Extralunar Materials

Early studies used the concentrations of siderophile elements in lunar regolith to estimate the integrated flux of meteoritic material striking the lunar surface [*Ganapathy et al.*, 1970; *Baedecker et al.*, 1972; *Wasson et al.*, 1975]. For some regoliths from the Apollo sites, this technique overestimates the flux of meteorites involved with regolith formation because a significant fraction of the siderophile elements presently in the regolith are carried by impact-melt breccias, which in turn were created in one or a few basin-forming impacts. For example, at the Apollo 16 site, KREEP-bearing, mafic impact-melt breccias contain high concentrations of siderophile elements derived from the impactor(s), probably an iron, that formed the breccias [*Korotev*, 1997, 2000]. Because these breccias constitute 29% of the regolith, only a third of the Ni in the Apollo 16 regolith derives from meteorites involved with regolith formation (the CI chondrite component of Table 8 of *Korotev* [1997]). Similarly, even though only 8% of the Apollo 11 regolith is KREEP-bearing impact-melt breccia such as samples 10085,1187 or 64815 (Table 4), about one third of the Ni in the Apollo 11 regolith is carried by the melt-breccia component (Table 5) and two thirds derive from regolith-forming meteorites (the CI component of Table 4). This distinction is essentially the same as that between the short-lived (basin-forming impactors) and long-lived (micrometeorites and macrometeorites) components of *Wasson et al.* [1975].

6. KREEP and the Highlands

Is all the nonmare material of the Apollo 11 regolith originally from the highlands? We reason here that the answer is "no" despite the fact that nearly any general or introductory treatise on the Moon explains that, on the basis of albedo and surface morphology, the Moon consists of two terrains, the maria and the highlands (terra). Pervasive in the lunar literature is the notion that the provenance of lunar igneous rocks or regolith components is similarly black and white, that is, they are either "mare" or "highlands." Thus the nonmare components of the Apollo 11 and 17 regoliths, for example, have been assumed to be from the highlands [e.g., *Wood et al.*, 1970; *Korotev*, 1976; *Laul et al.*, 1983; *Simon et al.*, 1983] as there are no alternatives in the simple mare-highlands classification system. The dichotomous taxonomy has persisted despite more than 25 years of evidence that a system based on surface albedo and morphology is inadequate geochemically. Polymict samples from the Apollo sites as well as orbital geochemical data require at least three chemical components, a mare component, a feldspathic component, and a KREEP component, to account for the first-order compositional features [*Metzger et al.*, 1973; *Schonfeld*, 1974; *Taylor*

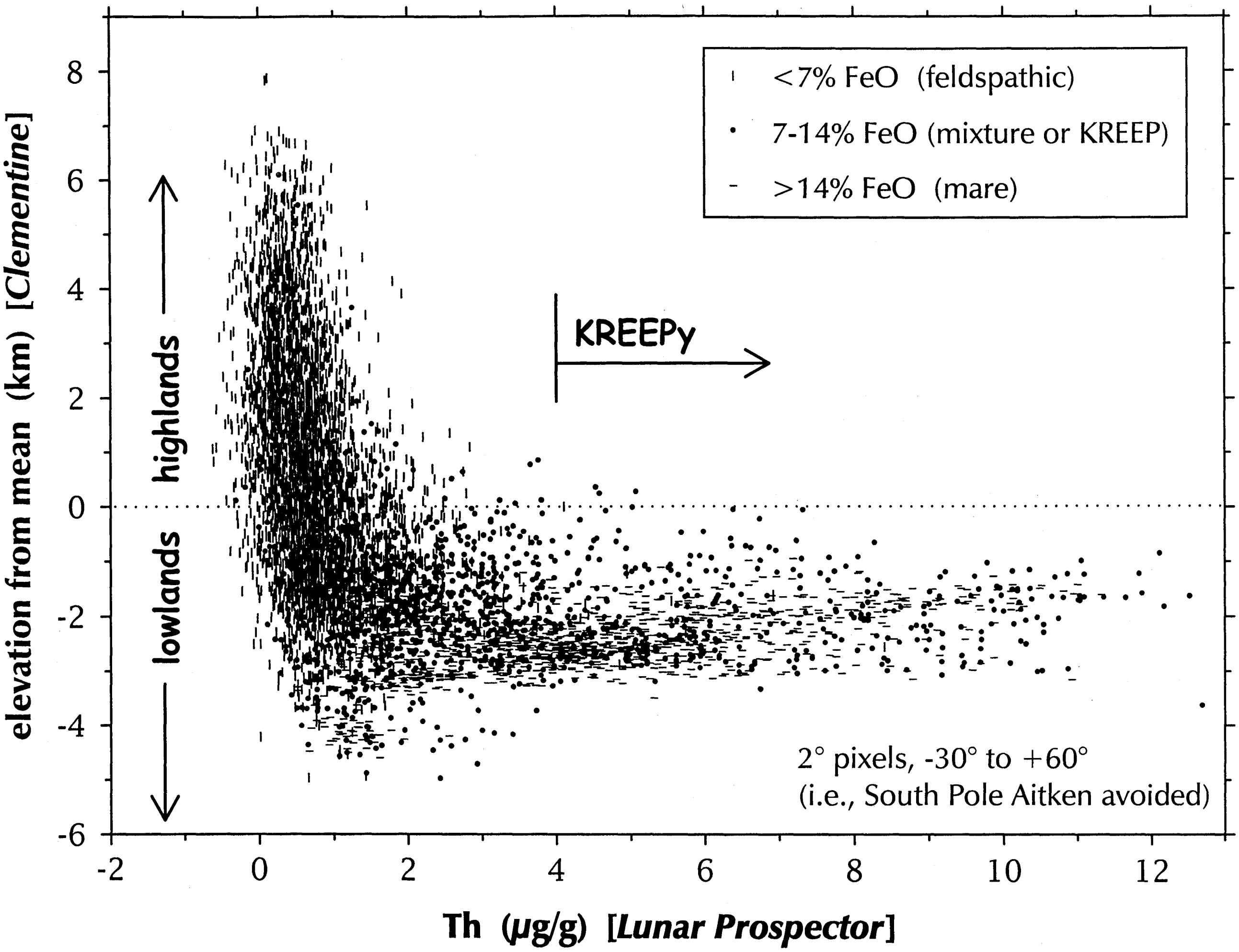

Figure 4. Elevation from the mean lunar radius based on center of figure (Clementine laser altimeter [*Smith et al.*, 1997]) as a function of Th concentration (Lunar Prospector gamma-ray spectrometer [*Lawrence et al.*, 1999], with calibration of *Gillis et al.* [2000]). Each point represents a 2° x 2° area of the lunar surface. The region south of 30°S latitude is excluded in order to avoid the anomalous South Pole–Aitken region. Each point is keyed according to its FeO concentration as determined by Clementine spectral reflectance [*Lucey et al.*, 1995, 2000]. Areas with <7% FeO are largely feldspathic. The plot shows that most areas at high elevation ("highlands") are feldspathic and KREEP (Th) poor. Areas with >14% FeO consist largely of mare basalt. Expectedly, these are at low elevation. Some to many of the pixels with intermediate FeO concentration represent mixtures of mare and feldspathic materials. However, Apollo samples rich in KREEP (e.g., KREEP basalt and KREEP-rich impact-melt breccias) are also in this range, typically having 10 ± 2% FeO. Thus areas with both 7–14% FeO (circles) and high concentrations of Th consist largely of KREEP. KREEPy areas do not plot at high elevations, thus, in the literal sense, KREEP is not a highlands lithology. The essential aspects of this observation were made at the time of the Apollo missions on the basis of Apollo 15 and 16 orbiting gamma-ray spectrometers and laser altimeters [*Trombka* et al., 1973; *Metzger et al.*, 1973, 1977; *Schonfeld*, 1974].

and Jakeš, 1974; *Boynton et al.*, 1975; *Hawke and Head*, 1978; *Spudis and Davis*, 1986; *Jolliff et al.*, 2000; *Haskin et al.*, 2000].

Some have cautiously and accurately used the term "nonmare" in reference to KREEP and related rocks [e.g., *Warren and Wasson*, 1978, 1979]. More commonly, however, "nonmare" is used as a synonym for "highlands." The misperception is more consequential than one of semantics in that it has been an actual impediment to progress in the understanding of lunar geology. In particular, the practice of regarding KREEP rocks and those plutonic rocks that appear to derive from KREEP magmas as "highland rocks" assumes and implies a degree of proximal relationship between KREEP magma and the feldspathic highlands crust that may never have existed. The faith in the dichotomy has driven the science. Models that locate urKREEP, the hypothetical residual liquid of crust formation [*Warren and Wasson*, 1979], globally in a layer beneath the feldspathic crust have assumed the mare-highlands dichotomy, despite long-existing evidence for the asymmetric lateral distribution of KREEP on the Moon's surface [*Metzger et al.*, 1973] and the absence of KREEP in the ejecta of basins outside the Procellarum region (e.g., low Th concentrations for likely Nectaris basin deposits [*Metzger et al.*, 1981]).

In retrospect, the acceptance of KREEP-bearing rocks as rocks indigenous to feldspathic highlands is an accident of landing site location, order of discovery, and confusing nomenclature. We did not know at the time of Apollo site selection that much of the accessible area of the Moon was in a unique, geochemically anomalous area revealed by the Lunar Prospector gamma-ray spectrometer [*Lawrence et al.*, 1999] (i.e., the Procellarum KREEP Terrane). If, prior to the Apollo missions, we had (1) collected and studied the suite of presently known lunar meteorites and (2) obtained a map of the distribution of radioactivity on the lunar surface, it would probably not ever have occurred to us to model KREEP as a material that is or had been globally sandwiched between the lower crust and mantle. Even without the lunar meteorites, the Th-rich rocks of the Apollo 11 regolith [*Laul et al.*, 1983] would never have been regarded as highlands rocks because the need for a more complicated classification system would have been self-evident from the orbital gamma-ray data. Global chemistry combined with geomorphology and geophysics would have alerted us that the crust of the Procellarum KREEP Terrane must have formed very differently from that of the Feldspathic Highlands Terrane [*Haskin*, 1998; *Haskin et al.*, 1998, 2000; *Jolliff et al.*, 2000; *Wieczorek and Phillips*, 2000]. Comparison of maps of radioactivity and albedo might instead have led to the conclusion that KREEP was associated more closely with the maria than the feldspathic highlands [*Wieczorek and Phillips*, 2000]. Clearly, if high concentrations of Th indicate the presence of KREEP, the combination of orbital radioactivity and elevation data alone [*Trombka et al.*, 1973; *Metzger et al.*, 1973, 1977; *Spudis and Davis*, 1986] demonstrate that KREEP is not a substance of the highlands, but one associated with low elevations and the nearside maria (Figure 4).

Wilhelms [1987, p. 258] noted that the existence of "highland basalt" was anticipated at the time of the Apollo 14 mission. Impact-melt breccias were a lithology largely unknown to terrestrial geologists. Consequently, because the KREEP-bearing melt rocks and breccias found at the Apollo 14 site were basaltic in mineralogy and texture but were apparently unrelated to the maria geochemically and petrologically, they were designated highland basalts, as there was no alternative in the dichotomous classification system. The highlands tie was unfortunately strengthened when KREEP-bearing breccias were found to be abundant at the Apollo 16 site, the Apollo site expected (based on albedo and geomorphology) to be the most typical of the highlands. The highland basalt designation persisted well after the "basalts" were recognized to be of impact origin [e.g., *Basaltic Volcanism Study Project*, 1981]. It occurred only to a few that all KREEP-bearing materials in the Apollo collection might be ejecta from impacts into an anomalous terrain [*Evensen et al.*, 1974; *Metzger et al.*, 1974, *Tera et al.*, 1974], but the idea was not taken seriously.

7. Summary and Conclusions

In terms of components known to occur in the Apollo 11 regolith, the composition of the regolith (<1-mm fines) can be modeled well as a mixture of 66 ± 1% mare basalt, 5 ± 2% picritic (orange) volcanic glass, 20 ± 2% material typical of the Feldspathic Highlands Terrane, 8 ± 2% material of the Procellarum KREEP Terrane in the form of mafic, KREEP-bearing, impact-melt breccias, and 0.8 ± 0.2% chondritic material (volatile-free CI chondrite). The components are consistent with and the proportions are in good agreement with petrographic studies of the regolith and the nonmare materials of the regolith [*Simon et al.*, 1981, 1983; *Laul et al.*, 1983]. The picritic glass and melt breccia are essential components needed to account for the high abundance of Mg and Cr in the regolith. The picritic-glass component carries 8% of the FeO and 7% of the TiO_2 in the regolith, values which may be high enough to affect spectral reflectance properties.

The nonmare material of the Apollo 11 regolith derives mainly from two sources, from beneath the basalt flows of Mare Tranquillitatis and as ray material from Theophilus. The nonmare component is similar in composition to the nonmare component of the regolith of the Cayley Plains at Apollo 16 but is less feldspathic (25% Al_2O_3 at Apollo 11 versus 28% at Apollo 16). Compositionally, 29% of the nonmare material at both sites is "KREEP" in the form of KREEP-bearing, impact-melt breccias. A KREEP-rich impact melt breccia found in the Apollo 11 regolith, sample 10085,1187, bears a strong compositional and textural similarity [*Laul et al.*, 1983; *Simon et al.*, 1983] to a unique Apollo 16 melt breccia, 64815 [*Ryder and Norman*, 1980; *Korotev*, 1994]. As at the Apollo 16, the nonmare material of the Apollo 11 site was part of the Imbrium ejecta deposit.

Although KREEP in its various forms has long been regarded as a material of the highlands, there is little rationale for this association. KREEP occurs largely in low-lying areas, often in association with mare basalt. In the feldspathic highlands, KREEP occurs mainly as ejecta from impacts into the Procellarum KREEP Terrane, which is geologically and geochemically distinct from the Feldspathic Highlands Terrane [*Jolliff et al.*, 2000].

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