THE MAGNESIUM MYSTERY OF THE APOLLO 11 REGOLITH. Randy L. Korotev, Department of Earth and Planetary Sciences, Campus Box 1169, Washington University, Saint Louis, MO 63130 (rlk@levee.wustl.edu)

One of the first-order observations made about the Moon upon study of the Apollo 11 samples was that although the mission landed on a mare surface, the regolith did not consist entirely of mare basalt. The soil also contained feldspathic lithologies [1–4], and it was correctly inferred that such lithologies derived from the highlands and that the lunar crust must, therefore, consist largely of anorthosite [4].

The proportion of nonmare material in the Apollo 11 regolith is sufficiently large to yield a regolith (<1-mm fines) that is substantially different in composition from the local mare basalts (Fig. 1). Simple consideration of the geometry of Figs. 1a and 1b, for example, leads to the conclusion that the regolith is a 77:23 mixture of mare basalt and feldspathic material from the highlands. Multi-element mass-balance models for the Apollo 11 regolith, however, have usually also included a KREEP component (Table 1). It is not clear why such a component is required by mass balance, however, as the basalts themselves clearly contain sufficiently high concentrations of incompatible elements to account for the composition of the soil (Fig. 1b).

Table 1. Results of mass-balance models for Apollo 11 soil.

	mare basalt	"anor-thosite"	KREEP	Mg rich	CI	Σ
H&G 71 [5]	70	20	10			100
G 71 [6]	76	19	4		1	100
L 71 [7]	74	14	12			100
S&M 72 [8]	78	19	5		2	104
L&P 80 [9]	73	14	13			100
This work*	69	22	=0	8	1	100

The various models use different compositions to represent the anorthosite and KREEP components. * From column 9 of Table 2.

All previous work has overlooked an essential constraint: The Apollo 11 regolith is substantially richer in Mg and Cr than any mixture of mare basalt and feldspathic highland material that accounts for other elements (Fig. 1c). The regolith must therefore contain a significant proportion of some unidentified Mg-rich lithology. Various Mg-rich lithologies occur on the Moon, but none has been identified as being common at the Apollo 11 site. Picritic volcanic glass, for example, occurs in the Apollo 11 regolith [e.g., 10],

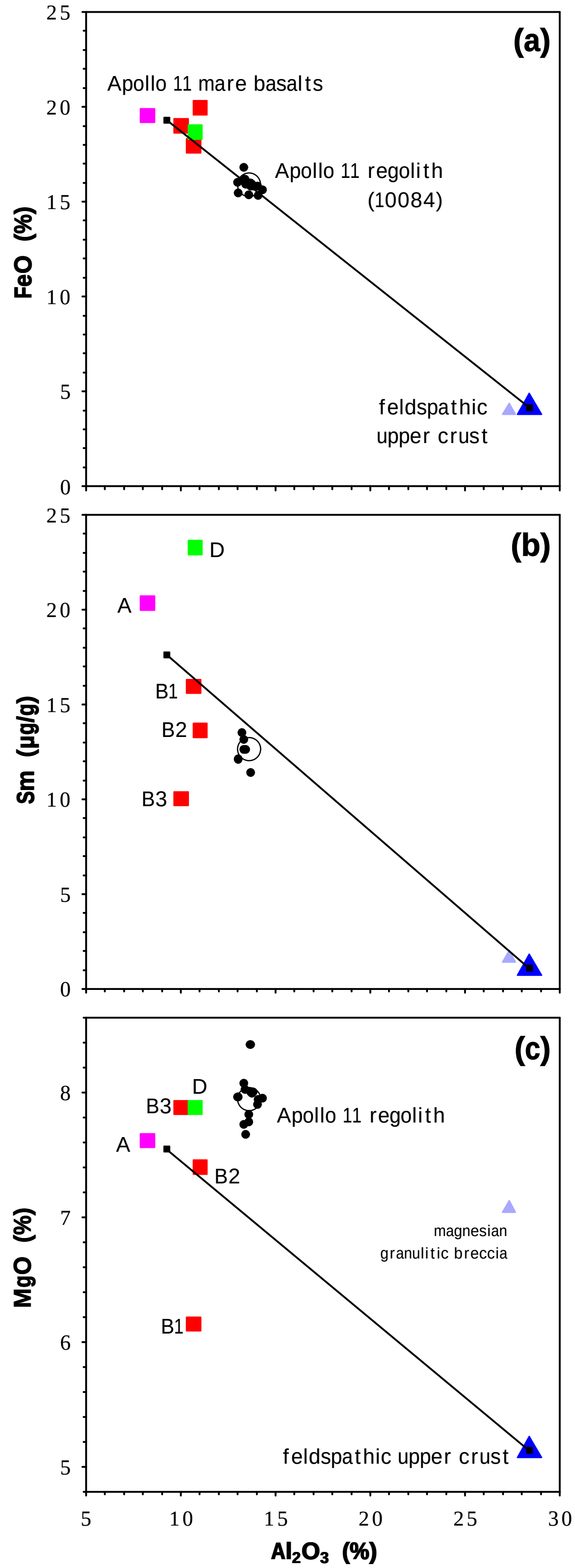

Figure 1. Concentrations of Al_2O_3, FeO, MgO, and Sm in Apollo 11 regolith sample 10084 (large unfilled circle = mean; small circles = individual analyses) and comparison to types of Apollo 11 mare basalt (squares) and typical feldspathic upper crust (large triangle [14]). Mean compositions of the various types of Apollo 11 mare basalts [15] are plotted. The diagonal lines are mixing lines between the upper crust point and a point corresponding to the mean of the mare basalts weighted according to their approximate proportions among rock samples (A:B1:B2:B3:D = 55:08:11:18:08; N = 38). The actual proportions of the various basalt types in the regolith is not known, however. Clearly, if the proportions of type A or D are lower in the regolith than among rock samples, the line of (b) would pass through the soil points, but not the line of (c).

but there is no petrographic evidence to suggest that it is common, as it is at the Apollo 17 site. The only high-Mg crystalline lithology reported in the Apollo 11 samples of which I am aware is a "norite" (10085,1175 with 17.5% MgO) described by [11].

In an attempt to identify the Mg-rich lithology, I have modeled (weighted least-squares, e.g. [12,13]) the mean composition of Apollo 11 regolith sample 10084 as various mixtures of the components of Fig. 1 and components representing each of seven likely and not-so-likely mafic, Mg-rich lithologies (Table 2). Without a Mg-rich component, the fit is poor (χ^2/ν = 1.72; Table 2, column 1) and Mg and Cr concentrations are underestimated by 9% and 12% of their values. Any of the Mg-rich components (columns 2–8) tested provides a substantially better fit (χ^2/ν = 0.23–0.50). Considering the magnitude of the uncertainties in the compositions of soil and model components, the various models are probably all statistically equivalent and mass balance cannot be used to identify the actual Mg-rich lithology. However, it is clear that whatever that lithology is, it must be present in a significant proportion, 3–12% (Table 2). Mathematically, the best fit is obtained with 8% of the Apollo 11 "norite" of [11] although Apollo 11 green glass is nearly as good.

The requirement for such a high proportion of mafic, Mg-rich component can be relieved, but not eliminated, if the feldspathic component of the soil is more magnesian than the feldspathic component of the model. At one extreme, for example, replacing the "feldspathic upper crust component" (based on 6 feldspathic lunar meteorites [14]) with a magnesian, feldspathic granulitic breccia (Fig. 1; [13]) in model 7 reduces the proportion of Mg-rich component from 7% to 4% while the proportion of feldspathic material remains about the same (from 20% to 22%). This model is unrealistic, however, in that it assumes that the none of the feldspathic material of the regolith is closely related to ferroan anorthosite.

No KREEP component was included in the models, except that in model 7 the Mg-rich component is a KREEP-bearing material. The fact that good fits can be obtained without a KREEP component suggests that KREEPy lithologies are not important in the Apollo 11 regolith. Thus, although some KREEP-bearing lithologies are known to occur in the Apollo 11 regolith [11], it is unlikely that their total abundance is as high as suggested by some of the other models of Table 1.

Conclusions: The Apollo 11 regolith (<1-mm fines) contains a substantial proportion (8 ± 3 %) of some unidentified Mg-rich component, possibly of nonmare origin. The proportion of feldspathic highlands material in the regolith is 22 ± 3 %.

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Table 2. Results of mass-balance models (this work) testing various Mg-rich components.

	Mg-rich component								columns 2–8		
	1	2	3	4	5	6	7	8	9	10	11
	none	A16 spinel troct. anorth.	A17 tracto-lite	A11 orange glass	A11 green glass	A11 red-black glass	A16 melt breccia 1M	A11 norite	mean	s.d.	±
MB-A	*30*	*35*	*34*	*35*	*38*	*33*	*13*	*34*	*32*	*8*	*3*
MB-B	*30*	*29*	*29*	*16*	*24*	*15*	*58*	*30*	*29*	*14*	*3*
MB-D	*14*	*9*	*10*	*13*	*7*	*14*	*0*	*8*	*9*	*4*	*3*
MB Σ	74	73	73	63	70	62	71	71	69	4	
FUpCr	24	23	20	27	23	27	17	20	22	3	1
Mg-rich	0	3	6	10	6	11	12	7	8	3	1
CI	1.64	1.24	1.41	1.02	1.15	1.12	0.83	1.33	1.17	0.19	0.11
Σ	100.5	100.5	100.4	100.5	100.6	100.7	100.2	100.3	100.4	0.2	4.9
χ^2/ν	1.72	0.50	0.41	0.34	0.29	0.50	0.54	0.23	0.40		

Abbreviations: MB = mare basalt, FUpCr = feldspathic upper crust [14], CI = CI chondrite [13], χ^2/ν = reduced chi-square [12,13]. χ^2/ν is a function of the weighting factor assigned for each element. The standard deviation of the concentration values averaged for each element in 10084 were used as weighting factors [12,13]. For example, the weighting factors for FeO and Sm were 2% and 5% of the mean concentration, respectively.
Mg-rich components: Column 2 = 67435,77 spinel troctolitic anorthosite [16]; 3 = 76535 troctolite [17]; 4, 5, & 6 = Apollo 11 picritic glasses [10]; 7 = Apollo 16 group 1M (e.g., 60315) KREEP bearing, mafic melt breccia [18]; 8 = norite 10085,1175 [11].
Column statistics: 9 = mean of columns 2–8; 10 = sample standard deviation of columns 2–8; 11 = average model uncertainty (s.d.) of columns 2–8.