Reports

Lunar Anorthosites: Rare-Earth and Other Elemental Abundances

Abstract. *Elemental abundances of major (Ti, Al, Fe, and Ca), minor (Na, Mn, and Cr), and trace elements [14 rare-earth elements (REE), Y, In, Cd, Rb, Cs, Ba, Co, and Sc] in lunar anorthosites separated from Apollo 11 sample 10085 coarse fines have been determined by means of instrumental and radiochemical neutron activation analysis. The REE distribution pattern of lunar anorthosites, relative to ordinary chondrites, has a positive Eu anomaly. On the assumption that (i) the lunar composition is similar to that of ordinary chondritic meteorites low in total Fe (~ 13 percent); (ii) lunar anorthosites are derived from highland cratering events and are representative of the highlands; and (iii) the moon differentiated into olivine, hypersthene, and basaltic and anorthositic phases, and plagioclase crystallization began after ~ 93 percent solidification, then mass balance calculations yield ~ 30-kilometer and ~ 10-kilometer thicknesses for the lunar highlands for the melting and chemical differentiation of the entire moon and of the upper 200 kilometers, respectively. Corresponding thicknesses of the basaltic basement rocks were ~ 5 kilometers and ~ 2 kilometers, respectively. Alternatively, if the anorthosites of this study are representative of the highlands and the onset of plagioclase crystallization occurred after ~ 50 percent solidification of the initially melted moon, calculations with REE and Ba partition coefficients suggest that the REE and Ba abundances in the primeval moon were similar to those observed in basaltic achondrites.*

One of the most striking features reported in the recent Apollo 11 and Apollo 12 lunar sample analyses is a negative europium anomaly, that is, the depletion of Eu relative to the Eu abundance in chondritic meteorites. An idea, proposed by Wood *et al.* (*1–3*) and Anderson and his co-workers (*4, 5*), for the formation of the anorthositic highlands provides an attractive explanation of the Eu anomaly. Since these anorthositic fragments, comprising about 4 percent of Apollo 11 soil, are different from the dark Ti-rich basalts in composition, density, and texture, and since there is no apparent close genetic relationship between these anorthosites and the basaltic type A and type B rocks, it has been postulated (*1–6*) that these anorthosites are the ejecta from cratering events on the lunar highlands. Since the REE distribution patterns in terrestrial anorthosites (*7, 8*) and in plagioclase separated from lunar rocks (*9*) show a positive Eu anomaly, the primary aims of this investigation were to determine the existence of a positive Eu anomaly in lunar anorthosites and to attempt mass balance calculations, consistent with postulates of complete and partial melting of the moon. Although the gabbroic anorthosites represent ~ 20 percent of the anorthositic materials found in Apollo 11 bulk samples (*3*), the close similarity between the bulk composition of the fragments of our study and both the average composition of six anorthosites and ten anorthositic glasses *and* the composition of lunar material at the Surveyor 7 landing site on the ejecta blanket of the Tycho crater strongly suggests that the elemental composition of our analyzed fragments is very closely related to that of the anorthositic highlands.

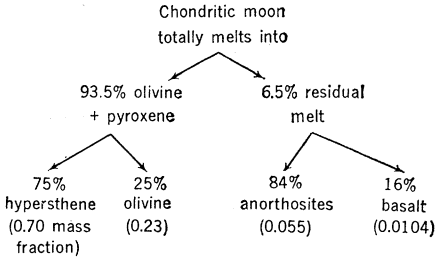
In this study anorthositic material, very similar in composition (Table 1) to gabbroic anorthosite (*1–3*) and separated from the Apollo 11 coarse fines (*10*), has been analyzed by means of both instrumental and radiochemical neutron activation analysis for elemental abundances of major, minor, and trace elements (Table 1). Analytical procedures used have been described elsewhere (*11*). Abundances for the major elements, Ti, Al, Fe, and Ca, are in agreement with those obtained by Wood *et al.* (*2*). On the basis of data for the Na and Ca, the plagioclase composition is about 3 mole percent albite and 97 mole percent anorthite.

The REE distribution pattern in anorthosites has been compared with the average REE abundance pattern in 29 chondritic meteorites (*12–14*); the pattern in chondrites is assumed to represent the REE distribution in the primordial solar nebula. Comparing the REE distribution pattern of lunar anorthosites with those of terrestrial anorthosites (*7, 8*), we note that the absolute abundances of light REE and the degree of Eu enrichment are almost identical. The slope of the REE distribution patterns is much steeper for terrestrial anorthosites than for lunar anorthosites. The positive and negative Eu anomalies for the lunar anorthosites and Apollo 11 and Apollo 12 soils (Fig. 1) suggest a genetic relationship between lunar anorthosites and soils. This observation lends credence to the postulate (*1–5*) that anorthosites and basalts crystallized from the residual magma after crystallization and gravity-settling of olivine and pyroxene and other high-temperature minerals. The fragmentation or disintegration of the basaltic crystalline rocks would result in the formation of lunar soil. (It is not implied that the mare soil was derived directly from fragmentation of the specific crystalline rock types of Apollo 11 and Apollo 12, but it was probably derived from rocks with generally similar composition.) Goles *et al.* (*15*) and Haskin *et al.* (*16*) have suggested other mechanisms for the Eu anomaly that do not require large-scale separation of plagioclase.

Consonant with previous suggestions (*1–5*), we propose that the total moon accreted from matter similar to that of ordinary chondritic meteorites. Many combinations of a large variety of chondritic material could be assumed for the primitive material. Anders (*17*) has suggested that an appropriate raw material might consist of chondrules from carbonaceous meteorites that are significantly depleted in alkalies and are deficient in metal and have a small amount of petrologic type-6 matrix. Because of the lack of sufficient data on the abundances of REE and other elements in chondrules, we have approximated the primeval matter with ordinary chondritic matter. Kaula (*18*) and O'Keefe (*19*) have estimated the uncompressed mean density of the moon to be 3.36 and 3.34 g/cm^3, respectively—values that are considerably less than the mean densities of 3.57 and 3.76 g/cm^3 for the two main chondritic groups. If about half of this chondritic iron of the moon were selectively accreted by the earth (*20*) during a simultaneous formation of the earth-moon system (*21*), then the mean lunar density and the material balance calculations for iron (see below) would be satisfactory.

We assume that in its early history the moon was completely melted. Upon cooling and after formation of a small Fe core, fractional crystallization of the high-temperature minerals, olivine and orthopyroxene, took place. Continued slow cooling, crystallization, and gravity-sinking of olivine and pyroxene minerals and floating of a lighter residual magma would produce a layered structure. As has been suggested (*1–5*), the anorthosites and basalts of such a residual magma separated from each other, the lighter anorthositic layer floating over the heavier basaltic layer.

During this fractional crystallization process differentiation of the lithophilic elements, the REE, the alkali elements, and the chalcophilic and siderophilic elements took place. The absolute abundances of REE in olivine (in meteoritic pallasites) and pyroxene (hypersthene achondrites) are so low (*12, 13, 22*) that the REE concentration in the residual magma increases with crystallization of olivine and pyroxene minerals (Fig. 2). In this model we explicitly assume that chemical fractionation of a melted chondritic moon into olivine, orthopyroxene, and residual matter is closely approximated by the assumed derivation of meteoritic hypersthene achondrites and pallasitic olivines from a chondritic magma. After 90 to 95 percent of the olivine and pyroxene minerals has crystallized, the REE distribution pattern in the residual melt appears almost flat with a small depletion in heavier REE. From the positive and negative Eu anomalies in anorthosites and in the average Apollo 11 and Apollo 12 lunar soil (Fig. 1) and the REE distribution pattern of the hypothetical residual melt, the mass ratio of anorthosites to basalts may be obtained. For such a simple lunar model, we calculated that ~93 percent of mixed olivine plus hypersthene minerals crystallized from the initial melt and that the other ~7 percent remained as a residual melt with a thickness of ~35 km. From this residual melt ~84 percent separated as anorthosites and ~16 percent remained as basalts. The flow chart below illustrates the proposed process.



The results of our material balance calculations for 17 elements are listed in Table 2.

Table 1. Elemental abundance of major, minor, and trace elements in lunar anorthosites.

Element	Lunar anorthosite		Normalized REE values†		
	This work (140 mg)	Wood *et al.**	Lunar anorthosite/ chondrite (this work)	Terrestrial anorthosite/chondrite: Philpotts *et al.* (*7*)	Terrestrial anorthosite/chondrite: Green *et al.* (*8*)
	Abundances in percentage by weight				
Ti	0.22 ± 0.09	0.18			
Al	17.9 ± 0.4	17.9			
Fe	2.3 ± 0.2	2.2			
Ca	14 ± 1	12.5			
	Abundances in parts per million				
Na	2820 ± 60	3000			
Mn	290 ± 6	800			
Cr	400 ± 20				
Ba	33 ± 10				
Co	6.4 ± 0.3				
Sc	5.5 ± 0.2				
In	0.0027 ± 0.0001				
Cd	0.083 ± 0.006‡				
Rb	< 1.0 §				
Cs	0.05 ± 0.01				
La	1.58 ± 0.08		4.9		11.8
Ce	3.54 ± 0.18		4.1	5.0	7.6
Pr	0.53 ± 0.02		4.8		
Nd	2.55 ± 0.15		4.3	3.7	6.1
Sm	0.69 ± 0.04		3.5	1.8	2.7
Eu	0.89 ± 0.04		12.5	9.1	7.6
Gd	0.84 ± 0.04		3.4	1.2	4.3
Tb	0.15 ± 0.01		3.1		2.0
Dy	0.80 ± 0.04		2.5	0.51	
Ho	0.22 ± 0.01		3.1		
Er	0.51 ± 0.02		2.6		
Tm	0.084 ± 0.008		2.7		
Yb	0.47 ± 0.02		2.4	0.12	1.0
Lu	0.074 ± 0.03		2.2		0.33
Y	5.2 ± 0.2		2.7		

* Electron microprobe analysis of a gabbroic anorthosite (*2*). † Average REE abundances of 29 chondrites were taken from references (*12–14*) and are given in a footnote to figure 1 of reference (*31*). ‡ Analyzed by Dr. P. Rey. § Less than 1 ppm for .99 probability.

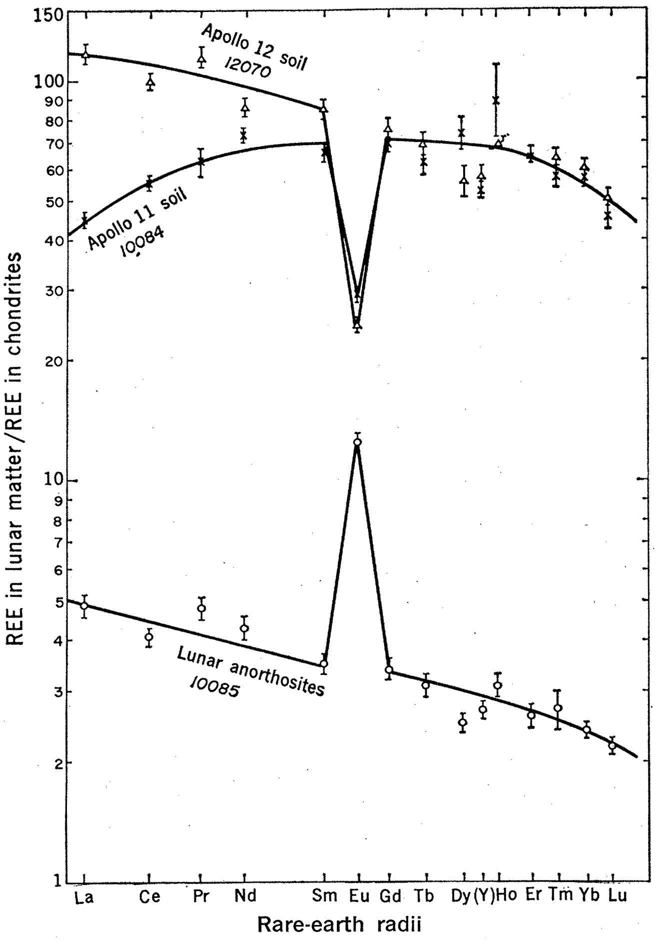
Rare-earth elements and yttrium. As noted, above, the abundances of these elements have been used in estimating the mass ratio of anorthosites to basalts from the residual melt after crystallization and settling of olivine and pyroxene minerals. The REE values (*12, 22*), of the Shalka and Brenham meteorites (olivine phase) were assumed to be representative for hypersthene achondritic and olivine materials. Of the eight stone meteorites that comprise the hypersthene group (*23*), the REE have been determined in only two of them, namely, the Shalka and Johnstown meteorites (*12*). The absolute REE abundances in the pallasitic olivine phase are still not well known (*13, 22*); however, the extremely low REE abundances will not significantly change the calculated mass ratios. Results of calculations based on the REE distributions in another hypersthene achondrite, Johnstown (*12*), were inconsistent with the model; that is, because the abundances of the heavy REE approximated those observed in ordinary chondrites, crystallization of ~70 percent hypersthene-like minerals, similar to those of the Johnstown meteorite, from a melt would remove too large a fraction of the heavy REE. Moreover, the partition coefficients of the REE in terrestrial orthopyroxenes (~0.02) (*16, 24–26*) approximate the partition coefficients of orthopyroxenes in Shalka, that is, the ratio of REE in

Shalka to REE in ordinary chondrites. [Partition coefficients for REE in olivines have similar values of ~ 0.01 (*25, 26*).] Perhaps the difference between REE contents in Shalka and Johnstown may be ascribed to enhanced accessory mineral content or enhanced REE abundances in accessory minerals in the Johnstown meteorite, such as the presence of 0.7 percent plagioclase (*23*). The high CaO content (*23*) of 1.39 percent in Johnstown pyroxenes may also be conducive to enhanced REE acceptance.

On the assumption that REE and Ba partition coefficients in terrestrial hydrous magma (*16, 25, 26*) are applicable to anhydrous lunar melts [for example, K(La) ~ 0.1 to 0.3, K(Yb) ~ 0.01 to 0.3, and K(Ba) ~ 0.1 to 0.6 for concentrations in plagioclase solid to concentration in magma], from REE and Ba abundances in lunar anorthosites (Table 1) it can be shown that the minimum amounts of La and Yb (representative light and heavy REE) and Ba present in the magma at the onset of plagioclase crystallization are ~ 5, ~ 1.5, and ~ 55 parts per million (ppm), respectively. For a chondritic lunar composition, these calculated abundances preclude plagioclase crystallization until ~ 93 percent of the magma has crystallized into olivine and pyroxene minerals. Smith *et al.* (*5*), assuming a modified (low-Fe) chondritic composition for the moon, suggested that plagioclase crystallization began after ~ 50 percent of the magma had solidified. Initiation of plagioclase crystallization at such a relatively early stage of chemical differentiation would yield REE and Ba abundances in lunar anorthosites that are ~ 0.1 of the observed abundances. Perhaps the anorthosites of our study originated elsewhere than from the lunar highlands, or the absolute abundances of the heavy elements such as the REE and Ba in the primeval moon were more closely approximated by those observed in basaltic achondrites [for example, see figure 3 in (*26*)] with REE and Ba abundances ~ 7 times greater than values for the chondrites. However, on the basis of density considerations, Ringwood and Essene (*27*) conclude that the average bulk chemical composition of the moon cannot resemble that of basaltic achondrites.

Scandium. The Sc abundances for hypersthene and olivine were obtained from the results of an examination of the Shalka meteorite and the Brenham olivine phase (*12, 13*), respectively. The Sc abundance in hypersthene achondritic-like materials, relative to that of ordinary chondrites, is ~ 20 times higher than the REE abundances (see Table 2). From the material balance calculation for Sc, we deduced the necessary olivine dilution in the high-temperature mineral phase; that is, the relative olivine-to-orthopyroxene masses are about 1 to 3.

Assuming the validity of the frac-



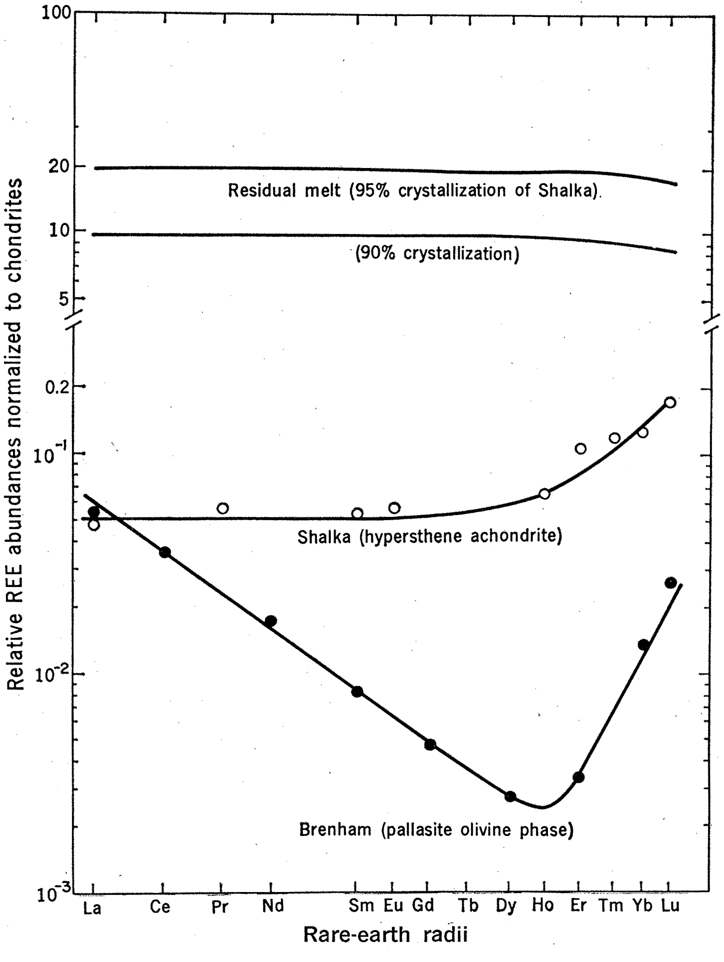


Fig. 1 (left). Ratios of REE abundances in Apollo 11 (10084) and Apollo 12 (12070) lunar soil (top) and in lunar anorthosites (10085) (bottom) relative to the REE abundances in 29 chondrites (*12–14*). Fig. 2 (right). Ratios of REE abundances in Shalka, a hypersthene achondrite (*12*), and in Brenham, a pallasitic olivine (*22*), relative to the REE abundances in 29 chondrites (*12–14*). Top curves indicate the degree of REE enrichment, derived only from REE material balance calculations, after 90 and 95 percent crystallization of hypersthene achondritic-like minerals.

tional values for the four phases of a differentiated moon, based on the REE and Sc abundances, we have calculated as a test of this model the mass balances of nine other elements for which data are available in all four phases.

Chromium. The Cr abundance (5700 ppm) reported by Urey and Craig (*28*) was selected for the hypersthene material. The average abundance of Cr in pallasitic olivine was 320 ± 110 ppm, ranging from 180 to 570 ppm for five meteorites (*29*). An abundance ratio for Cr of 1.14 in the model moon to that in chondrites is reasonably satisfactory.

Indium. The abundance for In of 0.34 part per billion (ppb) found in the Johnstown meteorite (*30*) was chosen for the hypersthene phase. Since $\sim$ 1.55 percent has been reported in Johnstown (*28*) and the chalcophilic element In will be incorporated into the troilite phase, the Johnstown abundance of In may be considerably too high in the hypersthene phase. No data are available for the pallasitic olivines. The terrestrial dunites seem to have higher concentrations. The value of In in DTS-1 (U.S. Geological Survey standard dunite rock) (2.2 ppb) was selected for olivine (*11*). The value for ordinary equilibrated chondrites is $\sim$ 0.3 ppb (*30*). Analyses of Apollo 11 and Apollo 12 lunar soil showed extremely high concentrations of In, which may be attributable to contamination. For the "true" soil value, we have adopted a value for In of $\sim$ 1 ppb, the lowest abundance reported in any Apollo 11 rocks (*31*). Mass balance calculations for In yield $\sim$ 3 times more In in the model moon than in ordinary chondrites. If we assume carbonaceous chondritic matter for the original material, the model moon-to-chondrite ratios are $\sim$ 0.01, 0.02, and 0.04 if carbonaceous chondrites of types I, II, and III, respectively (*30*), are assumed. If a small fraction of $\sim$ 5 to 10 percent of unequilibrated chondritic matter, such as L3 or L4 chondrites (*30*), or $\sim$ 1 to 2 percent of carbonaceous chondritic meteorites, which are both enriched in In and other trace elements as compared to ordinary chondrites, were added to the original lunar composition, the average initial In abundance would be about 1 ppb. The model moon-to-chondrite ratio would then be approximately unity. The addition of a small percentage of carbonaceous or unequilibrated chondrites appears consistent with recent ideas of Ganapathy *et al.* (*21*).

Cadmium. Abundances for Cd of 0.33 and 0.13 ppm, respectively, were found in the Johnstown achondrite and the olivine phase of Brenham; the average Cd abundance of six ordinary chondrites is about 0.06 ppm, with the value ranging from 0.02 to 0.12 ppm (*32*). Since $\sim$ 1.55 and $\sim$ 0.39 percent FeS have been found in Johnstown and Shalka, respectively, and CdS also follows FeS, the Cd abundances in the hypersthene phases may also be too high. Our model requires 4.5 times more Cd than the amount reported in ordinary chondrites. However, it seems reasonable that $\sim$ 5 to 20 percent of carbonaceous or unequilibrated chondrites were added to ordinary chondritic matter. The paucity of abundance data on hypersthene, olivine, lunar anorthosites, and soil precludes more precise comparisons.

Titanium. A markedly high Ti enrichment in Apollo 11 lunar samples is one of the significant observations of the lunar sample investigations. A lower Ti abundance was found in Apollo 12 rocks and soil (*33, 34*). The average Ti abundance in Apollo 11 and Apollo 12 lunar soils is $\sim$ 3.2 percent. Data on the abundances of Ti for hypersthene achondrites and pallasitic olivines are quite scarce. The value of 0.02 percent Ti for hypersthene achondritic material was obtained from Shalka and the value of $\leq$ 0.02 percent Ti from Brenham

Table 2. Material balances between model moon and ordinary chondrites. The composition of these rock types is represented by the meteoritic and lunar mass fraction data given in parentheses in column headings 2 through 5. If we assume an initial chondritic composition for the moon, these fractional values represent the mass fractions of the four principal differentiation phases of the moon. These values were obtained from material balance calculations of the abundances of only the REE plus Sc. To avoid redundancy, ratios for only representative light, medium, and heavy REE were calculated.

Element	Moon				Model moon	Ordinary chondrites[b]	Model moon/ chondrites
	Orthopyroxene (hypersthene achondritic-like material) (0.70)	Olivine (pallasitic olivine-like material) (0.23)	Anorthosite (lunar anorthosites) (this work) (0.055)	Basalt (lunar soil)[a] (0.0104)			
La (ppm)	0.015[c]	0.018 (*22*)	1.58	23[d]	0.34	0.32 (*12–14*)	1.06
Sm (ppm)	0.0103[c]	0.0016 (*22*)	0.69	14.7[d]	0.198	0.196 (*12–14*)	1.01
Eu (ppm)	0.004[c]	(0.004)[e]	0.89	1.90[d]	0.072	0.072 (*12–14*)	1.01
Yb (ppm)	0.0024[c]	0.0026 (*22*)	0.74	11.4[d]	0.16	0.19 (*12–14*)	0.84
Lu (ppm)	0.0058[c]	0.0008 (*22*)	0.074	1.82[d]	0.027	0.033 (*12–14*)	0.82
Y (ppm)	0.22[c]	1.6 (*13*)	5.2	106[d]	1.9	1.9 (*12–14*)	1.00
Sc (ppm)	9.8[c]	0.79 (*13*)	5.5	60[f]	8.0	8.0 (*47*)	1.00
Cr (ppm)	5700 (*27*)	320 (*29*)	400	1800[f]	4110	3600 (*47*)	1.14
In (ppb)	0.34 (*30*)	(2.2)[h]	2.7	(1)[g]	0.90	0.3 (*30*)	3.0
Cd (ppm)	0.33 (*32*)	0.13 (*32*)	0.08	0.05[f]	0.27	0.06 (*32*)	4.5
Ti (%)	0.02 (*35*)	$\leq$0.02 (*35*)	0.22	3.2[d]	$\leq$0.064	0.065 (*27*)	$\leq$0.99
Al (%)	0.48	0.01 (*37*)	17.9	7.0[d]	1.39	1.09 (*37*)	1.28
Fe (%)	14.0 (*27*)	10.4 (*29*)	2.3	12.5 (*33*)[f]	12.5	24.7 (*27*)	0.51
Ca (%)	0.64 (*27*)	0.13 (*35*)	14.1	7.9[d]	1.33	1.32 (*27*)	1.01
Na (ppm)	120	70 (*29*)	2820	3250[d]	290	6100 (*47*)	0.05
Mn (ppm)	4230	1970 (*29*)	290	1600[d]	3450	2300 (*47*)	1.50
Ba (ppm)	(0.05)[i]	(0.04)[i]	33	170[j]	3.6	3.7 (*49*)	0.97

[a] It is assumed that fine lunar soil has been derived from the fragmentation of a variety of lunar crystalline rocks. [b] Ordinary chondrites include the equilibrated H-group and L-group. [c] Abundances in the Ca-poor achondrite Shalka (*12*). [d] Estimated abundance based on our results for sample 10084 (Apollo 11) and sample 12070 (Apollo 12) (*31, 34*). [e] Estimated value from adjacent REE values in Fig. 2. [f] Our results for sample 10084 (*31*). [g] In general, soil samples show high In abundances of $\sim$500 ppb that have been attributed to contamination. The average In value was calculated from the observed lowest In abundance $\sim$1 ppb reported for Apollo 11 rocks (*31*) and of $\sim$2 ppb reported for Apollo 12 rocks (*34*). [h] Estimated value from dunite DTS-1 (*11*). [i] Calculated from Ba partition coefficients in terrestrial andesites (*25, 26*). [j] Average Ba in Apollo 11 soil, for example, see (*48*).

(*35*). The value for ordinary chondrites was chosen from the compilation of Mason (*36*). A value of 0.99 for the model moon-to-chondrite ratio is indeed very gratifying.

Aluminum. Two hypersthene achondrites, Shalka and Johnstown, were analyzed for Al abundances; average Al values are 0.48 and 0.84 percent, respectively. Aluminum abundances for pallasitic olivine and ordinary chondrites were obtained by Loveland *et al.* (*37*). The value of 7.0 percent Al in lunar soil is obtained from studies of Apollo 11 samples (*31, 33*) and our studies of Apollo 12 samples (*34*). A model moon-to-chondrite ratio of 1.28 seems satisfactory.

Iron. The value of 14.0 percent Fe in Shalka was selected for hypersthene achondritic-like material (*28*). For pallasitic olivine material, the value of 10.4 ± 2.4 percent Fe was obtained from the average value of five pallasitic olivines (*29*). A comparison of our model with ordinary chondrites reveals that the Fe in the moon has been depleted by approximately half. This, in turn, suggests a possible Fe core for the moon or selective Fe loss before accretion, as discussed earlier. A simple calculation reveals that about 12 percent iron (by weight) corresponds to about 5 percent of the volume for the total moon. Nakamura and Latham (*38*) noted that geophysical data do not preclude an iron core of $\sim$ 6 percent of the total lunar mass. From recent estimates of the moon's moment of inertia of 0.401 ± 0.002 Mr^2 (where M is the lunar mass and r is the average lunar radius), O'Keefe has suggested (*39*) that an iron core of 1 percent in the moon may be the upper limit. Smith *et al.* (*5*) have also suggested that, relative to the composition of chondritic meteorites, some Fe was lost before accretion. Urey and MacDonald (*40*) have arrived at the same conclusion from detailed arguments of lunar and meteoritic densities and suggest that $\sim$ 16 percent FeO (or $\sim$ 12 percent Fe equivalent) was the initial Fe content of the primitive moon. Such an iron content is in good agreement with our moon model (see below).

Calcium. The Ca values of a hypersthene anchondrite and pallasitic olivine were obtained from Shalka (*28, 36*) and Brenham (*35*). The value of 7.9 percent Ca for crystalline rock is the average value for the Apollo 11 and Apollo 12 soil samples (8.3 and 7.5 percent, respectively) (*31, 33, 34*). The Ca value for ordinary chondrites was obtained from the table by Mason (*36*). A Ca ratio of 1.01 for the model moon to chondrites is quite satisfactory.

Table 3. Calculated lunar highlands thicknesses (in kilometers).

Complete melting of chondritic composition*	Anorthositic highlands	Basaltic basement	Olivine-pyroxene interior†
Whole moon	$\sim$30	$\sim$5	$\sim$1703
Upper 300 km	$\sim$14	$\sim$3	
Upper 200 km	$\sim$10	$\sim$2	
Upper 100 km	$\sim$ 5	$\sim$1	

* The iron content may be about half that observed in ordinary chondrites (*40*). † This thickness may include a small Fe core of $\sim$ 1 to 5 percent of the total lunar mass.

Sodium. Sodium presents a serious dilemma for this model. It appears that the model moon, the result of assumed differentiation of ordinary chondritic matter, has retained only $\sim$ 5 percent of its original Na content. As suggested by O'Hara *et al.* (*41*) and others, the alkali elements may have been lost preferentially during or subsequent to the lunar accretion stage. The average Na values of duplicate analyses of the hypersthene achondrites, Shalka and Johnstown, were found to be 120 and 250 ppm, respectively. The Na value for pallasitic olivine is the average value for five different pallasites (*29*). The amount of Na in lunar soil (3250 ppm) is based on the results of analyses of Apollo 11 and Apollo 12 soil samples (*31, 34*).

The first plagioclase feldspars to separate from terrestrial silicate melts are quite deficient in albite; with decreasing temperature and continued crystallization, the plagioclase feldspar becomes more sodic and less calcic. Therefore, for a completely melted moon or a moon whose outside shell (100 to 500 km deep) is the only part melted (*42, 43*), late-crystallizing albitic plagioclase would be deposited at the bottom of the highlands. The highly calcic anorthosite specimens of this study were probably derived from shallow cratering events in the highlands (*1–3*). Even if the average albitic fraction of the highlands were 0.30 instead of 0.03, the model moon would still be deficient in Na by factors of 3 to 4, relative to that of chondrites. The fact that Na and Fe abundances in chondrules (*44*) from type II carbonaceous chondrites are low by about a factor of $\sim$ 8 and $\sim$ 3, respectively, relative to that of ordinary chondrites, lends support to the hypothesis by Anders (*17*) that metal-free chondrules may represent a major share of the primitive lunar matter.

Schnetzler and Philpotts (*25*) have shown that the Eu anomaly increases with increasing albitic content of terrestrial feldspars. If the Eu anomaly varies similarly for feldspar crystallization from chondritic magma and if the average albitic content of the feldspars were known, then more accurate values could be calculated for the volumes of the four principal lunar layers. For example, if the average Eu anomaly in lunar anorthosites were increased by a factor of 2, the combined volume of olivine and orthopyroxene minerals would increase by only $\sim$ 3 percent.

An approximate abundance of $\sim$ 170 ppm was obtained for K in this work. Assuming a K abundance of $\sim$ 15 ppm in Brenham pallasitic olivine (*45*) and in hypersthene minerals and $\sim$ 1200 ppm in lunar soil (*33*), we calculate a total K abundance of $\sim$ 37 ppm in the primitive moon. Therefore, the model moon-to-chondrite ratio for K is $\sim$ 0.05, which is in agreement with the corresponding ratio for Na. The calculations suggest an alkali depletion by a factor of $\sim$ 20 relative to that of chondritic meteorites. Crude calculations indicate that Cs and Rb have also been depleted by a factor of $\sim$ 2 and $\sim$ 8, respectively, relative to chondritic meteorites. These relative depletion values are consistent with a diffusion-limited volatilization of alkali elements from magmas below 1180°C (*46*).

Manganese. Manganese abundances of 4230 and 3830 ppm were determined in hypersthene achondrites, Shalka and Johnstown, respectively. The Mn abundances for pallasitic olivine and ordinary chondrites were obtained from the average value of five determinations by Schmitt and Smith (*29*) and by Schmitt *et al.* (*47*), respectively. The abundance of Mn (1600 ppm) is averaged from the results of Apollo 11 and Apollo 12 soil analyses (*31, 34*). Considering the scarcity of data, about 50 percent discordance in the model moon-to-chondrite ratio may or may not be satisfactory.

Barium. Barium abundances have not been directly measured in pallasitic olivines and in hypersthene achondrites. On the assumption that the partition coefficients for Ba in olivines ($\sim$ 0.01) and orthopyroxenes ($\sim$ 0.013) from andesites (*26*) are applicable to a melted chondritic magma, and that the average Ba abundance in Apollo 11 soil is $\approx$ 170 ppm [for example, see (*48*)], we calculate a model moon-to-chondrite ratio for Ba of $\sim$ 1.0.

In general, the agreement between

our moon model and ordinary chondrites for most elements appears satisfactory. On the basis of this model, the thickness of the residual melt after crystallization of olivine and pyroxene minerals and settling is calculated at ~ 35 km. After anorthosite flotation, the thickness of the highland crust is calculated to be ~ 30 km, which compares favorably with a thickness of ~ 25 km proposed by Wood *et al.* (*1–3*) on the basis of isostatic calculations. The corresponding thickness of the basaltic basement is calculated to be ~ 5 km.

Implicit in these calculations is the assumption that the impacting planetesimals (*1–5*) punctured the anorthositic crust in areas that were small relative to the areas of the present lunar maria ($\sim \frac{1}{5}$ of the lunar surface) and that basaltic magma flowed over vast areas.

As noted by Urey and MacDonald (*43*), complete melting of the total moon may not seem possible; however, our material balance argument is valid in any fraction of the moon, on the assumption that complete melting of chondritic material and fractional crystallization into the four assumed rock phases occurred. For example, if we assume that the upper 200 km was completely melted, the thickness of the highland crust is calculated at ~ 10 km and that of the basaltic basement at ~ 2 km (see Table 3).

Urey and MacDonald (*40*) have recently reported some mass balance calculations of the major elements Si, Ti, Al, Fe, Mg, and Ca for differentiation of the average silicate phases of the ordinary chondritic meteorites into three principal components, namely, lunar anorthosites, titaniferous Apollo 11 and Apollo 12 rocks, and a dunitic phase. Although no specific thicknesses were calculated for the melting and differentiation of varying depths of the lunar exterior matter, the conclusions of Urey and MacDonald seem to be consistent with those of this work.

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Natural Oil Seepage at Coal Oil Point, Santa Barbara, California

Abstract. *Aerial, surface, and underwater investigations reveal that natural seeps off Coal Oil Point, California, introduce about 50 to 70 barrels (approximately 8,000 to 11,000 liters) of oil per day into the Santa Barbara Channel. The resulting slicks are several hundred meters wide and are of the order of 10^{-5} centimeters thick; tarry masses within these slicks frequently wash ashore.*

During the controversy surrounding federal oil leases in the Santa Barbara Channel, there has been periodic reference to the fact that these waters have long been polluted by natural submarine oil seeps. Although their existence is well known, the amount of pollutant oil that flows from these seeps has never been documented. Thus, meaningful evaluation of the sources and