

THE DISTRIBUTION OF SULFUR IN LUNAR ROCKS AND ITS RELATIONSHIP TO CARBON CONTENT*

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Abstract. A summary of total sulfur abundances representative of the Apollo Missions is presented. Lunar crystalline rocks range from 0 to $3100 \mu\text{g S g}^{-1}$. Lunar soils range from 310 to $1300 \mu\text{g S g}^{-1}$. Rock mixing models evaluate the distribution of sulfur and define indigenous rock components and extralunar contributions of sulfur in lunar soils. Extralunar sulfur shows a positive correlation with a CC-1 like meteoritic component and solar wind derived total carbon content in the Apollo 16 and 17 lunar soils.

1. Introduction

Carbon, nitrogen and sulfur abundances have been measured on large numbers of lunar samples by investigators in different laboratories. In the case of carbon and nitrogen the analyses were usually made specifically for these elements, but in the case of sulfur some analyses have been reported as part of whole rock analyses. Extensive carbon analyses have been reported by Epstein and Taylor (1975), Chang *et al.* (1974), Moore *et al.* (1974), Des Marais *et al.* (1973), Cadogan *et al.* (1973), and Kaplan and Petrowski (1971). For each of these investigators or laboratories only a late paper in the Lunar Science Proceedings is listed in order to keep the references to a minimum. These recent papers usually list earlier reports by the same authors. Reported carbon analyses show a high degree of consistency between laboratories and it thus may be concluded that the reported numbers are creditable. Investigators who have reported sulfur values include: Kerridge *et al.* (1975), Rees and Thode (1974), Moore *et al.* (1974), Wanke *et al.* (1975), Gibson *et al.* (1975), Rhodes *et al.* (1975), and all LSPET reports. This list is not complete in that it includes only those investigators who have specifically analyzed for sulfur and selected whole rock analyses. Sulfur values determined in different laboratories show consistent trends but there are absolute differences of up to 15% of the total sulfur reported between some laboratories. Such differences may be due to the method of opening the sample. Laboratories using acid hydrolysis of sulfides tend to report lower numbers. The analyses performed in our laboratory, done by combustion and iodometric titration, usually are among the higher results reported and compare favorably with X-ray fluorescence analyses.

Nitrogen analyses reported by four laboratories have not agreed. At this time it is thus difficult to use the available nitrogen data for synthesis purposes.

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In order to quantify and understand the distribution of carbon, nitrogen and sulfur in lunar samples, it is necessary to classify the samples and run suitable analyses on representative samples. It has been shown that carbon and nitrogen are low in lunar rocks, but have accumulated in the lunar fines due to solar wind bombardment while sulfur is higher in indigenous lunar rocks than similar terrestrial rocks and that extralunar meteoritic and solar wind additions account for a small percentage of the total found. Bulk sulfur concentrations may be accounted for by rock mixing models with minor extralunar additions (Cripe and Moore, 1976).

A major question in understanding the distribution of volatiles in lunar samples is to determine the original content, any volatiles added during large fragmenting impacts early in the Moon's history and volatiles added by solar wind or smaller meteoroid bombardment. In this paper we will attempt to estimate the distribution of sulfur in different rock units, added sulfur and its relationship to carbon.

A histogram of data from our investigations and selected literature values (XRF and combustion-IR techniques) is shown in Figure 1. Lunar fines for Apollo 11, 12, 15, and 17 are depleted in their total sulfur content relative to the mare basalts found at each collection site. Lunar highland soils from Apollo 15, 16, and 17 have the lowest sulfur values in soils ranging from 310 to 840 $\mu\text{g S g}^{-1}$. Apollo 11 and 17 lunar mare soils were relatively high with a range of 680 to 1300 $\mu\text{g g}^{-1}$ sulfur. The median total sulfur content of lunar soils collectively is 820 $\mu\text{g S g}^{-1}$ (153 samples) with a range of 310 to 1300 $\mu\text{g S g}^{-1}$.

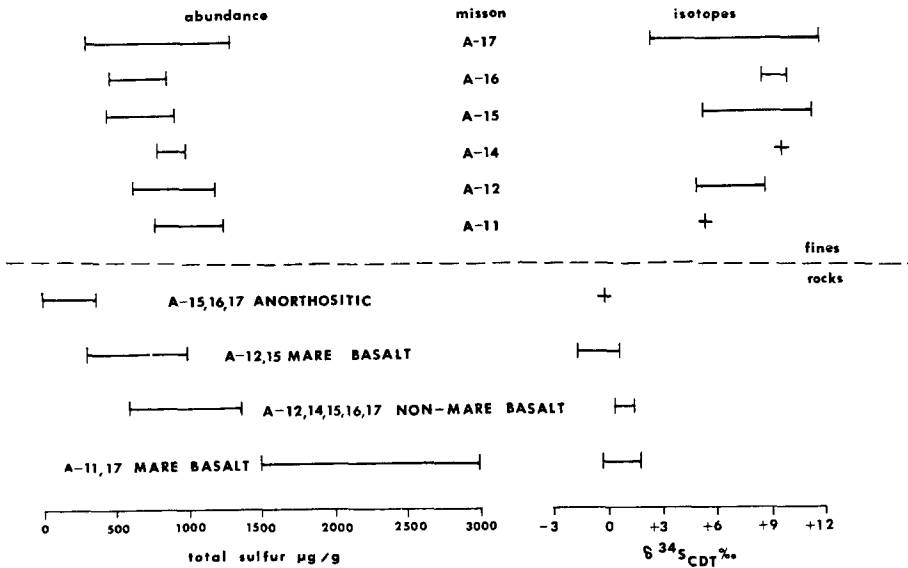


Fig. 1. Histogram of total sulfur abundances and isotope data for Apollo rock and soils. References: Moore *et al.* (1972, 1973), Cripe (1973), Cripe and Moore (1974, 1975), Compston *et al.* (1970, 1971), Kaplan *et al.* (1970), Kaplan and Petrowski (1971), Rees and Thode (1972, 1974), Hubbard *et al.* (1972), Thode and Rees (1972), Gibson and Moore (1973, 1974), LSPET (1972, 1973a, b), Petrowski *et al.* (1974), Chang *et al.* (1974, 1975), Gibson *et al.* (1975), Heiken *et al.* (1974), and Sakai *et al.* (1972).

Lunar breccias are highly variable in sulfur content representing a complex history and sampling problems encountered with fragmental rocks. Breccia sulfur values range from <36 to $2140 \mu\text{g S g}^{-1}$.

All lunar crystalline rocks together range from nondetectable amounts of sulfur ($<20 \mu\text{g g}^{-1}$) to $3140 \mu\text{g S g}^{-1}$ with a median of $990 \mu\text{g g}^{-1}$ sulfur for 86 samples. The Apollo 11 and 17 mare basalts have the highest range in sulfur values (1500 to $3140 \mu\text{g S g}^{-1}$) with a median of $1920 \mu\text{g S g}^{-1}$ for 24 samples. Intermediate value Apollo 12, 14, 15, 16, and 17 non-mare basalts range from 580 to $1400 \mu\text{g S g}^{-1}$ with a median of 880 for 20 samples. Intermediate Apollo 12 and 15 mare basalts have a median sulfur value of $660 \mu\text{g S g}^{-1}$ (28 samples) with a range from 300 to $1000 \mu\text{g g}^{-1}$ sulfur. The lowest values are anorthositic rocks with a median value of $190 \mu\text{g g}^{-1}$ sulfur (14 samples) ranging from nondetectable amounts of sulfur ($<20 \mu\text{g g}^{-1}$) to $410 \mu\text{g g}^{-1}$ sulfur from Apollo 15, 16, and 17 sites. Pure anorthosite end members have sulfur values of less than $36 \mu\text{g S g}^{-1}$.

A major feature of the abundance data in Figure 1 is the steady rise in average sulfur concentrations in the series anorthositic rocks – Apollo 12 and 15 mare basalts – non-mare basaltic rocks and the two to three fold increase concentration of Apollo 11 and 17 mare basalts. A wide but systematic range in sulfur concentration is evident in lunar crystalline rocks.

In contrast sulfur isotope values from the literature for lunar rocks (Figure 1) reflect a small range from $\delta^{34}\text{S} -2.7$ to $+1.7$ over the entire compositional range. The Apollo lunar soils show a marked enrichment in $\delta^{34}\text{S}$ from $+2.7$ to $+11.7$. The representative highland site, Apollo 16, shows a narrow enrichment centering around $\delta^{34}\text{S} +10$. In contrast Apollo sites with mare basalt dilution show wider ranges and contain less heavily enriched values down to $+2.7$. No correlative $\delta^{34}\text{S}$ isotope data is evident between rock types or compositions. The isotopic enrichment of soil data over rock data evident in Figure 1 will be discussed in a later section.

2. Sources of Sulfur on the Moon

2.1. LUNAR PROCESSES

The lunar highlands show a crater density which is approximately one order of magnitude higher than the mare regions (Shoemaker *et al.*, 1970). Lunar craters for the most part are clearly of impact origin implying the highlands formed before the mare. The differences of approximately a factor of ten in crater density between lunar maria and highlands does not correspond to an age factor of ten. To explain the density difference the flux of impacting bodies must have been higher in the early days of the solar system and decreased as time went on. Age determinations on lunar rocks from Tranquillitatis, Imbrium, Oceanus Foecunditatis are between 3.9 and 3.3 aeons ago while highland estimates are about 4.4 aeons ago.

There is a paradox in the cratered lunar highland areas of the moon. The rocks are of a brecciated nature suggesting impact related mixing processes, but the bulk chemical data is compatible with chemical processes representing magmatic differentiation of the rocks (Short and Forman, 1972; Hubbard and Rhodes, 1975). Perhaps no other element demonstrates this paradox more dramatically than sulfur.

The abundance and distribution of sulfur in the highland soils appears to follow mixing models of igneous components which make up the sample (Moore *et al.*, 1972, 1973; Cripe, 1973) while isotope values in the same soils seem to reflect exposure age and impact related events (Rees and Thode, 1974; Kerridge *et al.*, 1975). Isotopic date in correlative with carbon, nitrogen, helium, hydrogen, and metallic iron abundances which are strongly influenced by lunar surface processes (Petrowski *et al.*, 1974). These changes reflect surface exposure age or maturity as gardening of the lunar regolith takes place from influxes of large and small meteorites providing a well-stirred and homogeneous regolith with time. Impacts can form agglutinates-glass bonded aggregates; glass, rock, and mineral fragments welded together by glass (McKay *et al.*, 1972). Sieved fraction analyses of soils for isotope data also reflects isotope enrichment with decreasing grain size correlative with a surface process (Rees and Thode, 1974). The enriched isotope values for sulfur in lunar soils over lunar rocks occur in direct correlation with the factors which show increased soil maturity or surface exposure age. Three probable major sources which contribute sulfur to the lunar surface are magmatic sulfur in the igneous rocks, meteoritic sulfur, and a solar wind contribution.

2.2. INDIGENOUS SULFUR

First, indigenous or magmatic sulfur trapped during the crystallization of the igneous rocks will be a source of sulfur. The dominant form of sulfur in lunar materials is troilite, FeS, although trace quantities of other metal sulfides have also been found (El Goresey *et al.*, 1971). In basalts the troilite associated with metallic iron Skinner (1970) attributed to a homogeneous sulfide liquid which separated immiscibly from a parent magma.

Al_2O_3 is representative of a refractory major element which represents igneous trends and is widely used for chemical classifications. In Figure 2 data for total S versus Al_2O_3 shows the wide variance between discrete populations of sulfur in lunar rocks and soils. The subdivisions of Hubbard and Rhodes (1975), based on major element chemical classifications (see Table I) are well defined for sulfur. The trend in Figure 2 is not a straight line, suggesting the components are from distinct igneous sources and not merely combinations formed by igneous mixing processes. Most importantly with regard to sulfur chemistry is the close proximity of the soil data to the rock values. This proximity demonstrates a small volatile loss of sulfur in regolith forming processes or a balanced gain in sulfur loss in regolith forming processes. The same relative positioning, clustering, and trends are shown for refractory TiO_2 versus Al_2O_3 . The agreement is very striking with the same three to four fold concentration from Apollo 12 and 15 mare basalts to Apollo 11 and 17 mare basalts. It appears the abundance of TiO_2 and total sulfur are covariant in lunar rocks and soils. The correspondence to the refractory TiO_2 content of rock and soil data further supports small volatile loss in lunar regolith processes.

The sulfur content for igneous rocks will be representative of a classification grouping only if no loss has occurred during a flow emplacement.

In subaerial terrestrial basalts from Hawaii some 90% of the total sulfur content has been outgassed as shown by Moore and Fabbi (1971) and Cripe (1973). Cripe (1973) demonstrated that subaerial basalts range from 17 to 460 $\mu\text{g S g}^{-1}$ with a

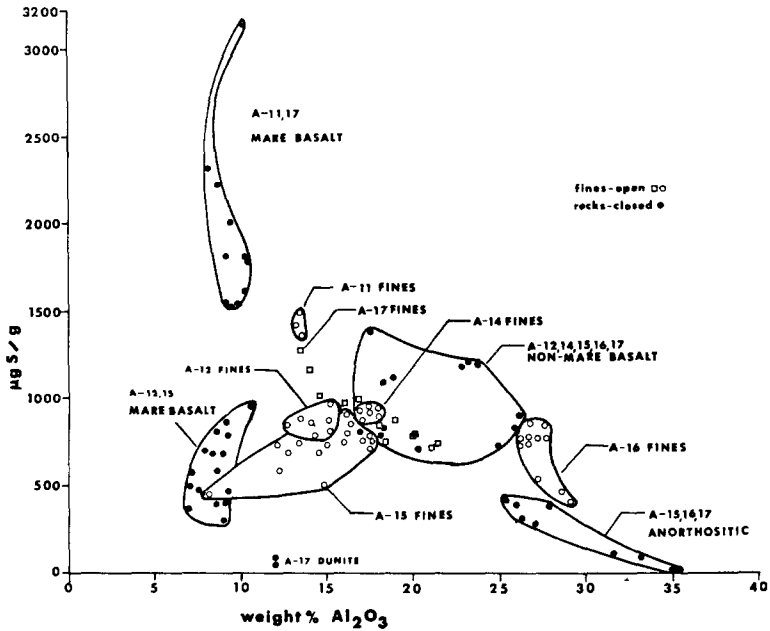


Fig. 2. Total S versus Al_2O_3 for lunar rocks and fines. Data are from the same sources as for Figure 1.

median $240 \mu\text{g S g}^{-1}$ content. Submarine basalts from Hawaii have the greatest sulfur content of terrestrial basalts ranging from 420 to $1300 \mu\text{g S g}^{-1}$ with a median $860 \mu\text{g S g}^{-1}$ content. Columbia River Plateau flood basalts were intermediate ranging from 30 to $500 \mu\text{g S g}^{-1}$ with a $440 \mu\text{g S g}^{-1}$ median value. A histogram of data for the 217 terrestrial basalt analyses is shown in Figure 3. Terrestrial loss seems

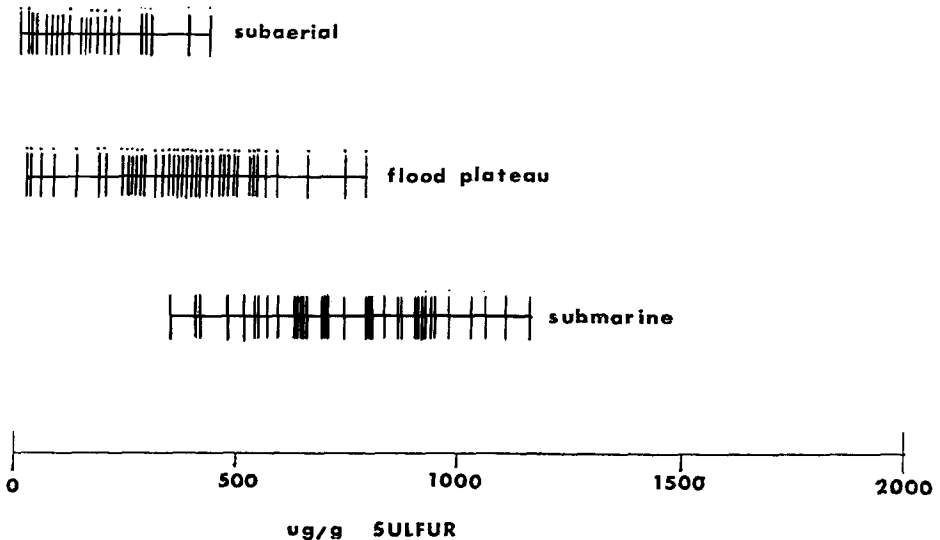


Fig. 3. Histogram of terrestrial basalts and total sulfur content (data from Cripe, 1973).

TABLE I
Apollo 15 mixing models for lunar soil

Rock type	Sulfur observed	Station 2 St. George Site			LM Site			Station 9A Rille Site	
		Relative abundance	Sulfur contrib.	$\mu\text{g g}^{-1}$	Relative abundance	Sulfur contrib.	$\mu\text{g g}^{-1}$	Relative abundance	Sulfur contrib.
Green glass	350	39%	137	12%	42	51%	179		
Mare-derived	1200	19	228	27	324	21	252		
Highland basalt	300	8	24	8	24	4	12		
Fra-Mauro	1000	14	140	36	360	16	176		
Low K-High Al basalt	1100	20	220	17	187	9	99		
Granite	—	—	—	0.6	—	0.6	—		
Total calculated soil			750		940		720		
Observed soil			750-850		850-900		800		

to follow an oxidation mechanism which occurs as subaerial flows are implaced. Submarine basalts retain their sulfur due to hydrostatic pressure and the lack of exposure to an oxidizing atmosphere.

An example of sulfur loss, from a terrestrial lava flow is demonstrated in the May, 1971 Mauna Ulu, Hawaii flow which was sampled at intervals for approximately 10 km of its length from the vent. The glassy samples were collected in March, 1972 from the complex pahoehoe lava flow which flowed a total of 12 km from the vent to the ocean. Samples at the vent averaged $320 \mu\text{g S g}^{-1}$ while 10 km from the vent the sulfur abundance averaged $120 \mu\text{g S g}^{-1}$. During flowage the lava outgassed such that the initial sulfur content was decreased by a factor of 2.7 in 10 km of outgassing. Swanson and Fabbi (1973) noted similar loss during fountaining and flowage at Kilauea Volcano and Gibson *et al.* (1975) found a 2.5 loss factor over 7.5 km along a January 9, 1973 Mauna Ulu basalt flow.

The lack of a well developed atmosphere with oxygen negates the possibility of oxidation of flows by this process on the lunar surface. Lunar loss of sulfur during flow emplacement has been reported for mare basalts. Lunar loss by iron reduction, postulated by Sato and Helz (1971) is less dramatic than 90% terrestrial loss with from 0 to 30% loss during outgassing (Brett, 1974; Gibson and Moore, 1974, 1975). An inverse correlation between metallic iron abundance and total sulfur content for Apollo mare basalt samples suggests the metallic iron present in mare basalts results from the desulfuration of FeS. Gibson and Moore (1975) using the assumption that all the metallic iron results from desulfuration calculated minimum sulfur abundances for mare basalt source magmas. Apollo 11 and 17 mare basalts were 2540 and 2760 $\mu\text{g S g}^{-1}$ respectively with Apollo 12 and 15 basalts having 1185 and 1110 $\mu\text{g S g}^{-1}$ values. Brett (1975) points out that the source magmas for Apollo 11 and 17 were saturated with sulfur while the Apollo 12 and 15 magmas were undersaturated.

The source regions for the lunar basalts are enriched two to three fold over terrestrial basalts. No reduction mechanism has been demonstrated for non-mare basaltic or anorthositic rock compositions. With regards to the lunar surface the sulfur content for these rocks should be representative of sulfur from this source. Mare basalts may fluctuate up to 30% due to flow reduction.

2.3. METEORITIC SULFUR

The flux of meteorites and micrometeorites impacting on the lunar surface might be expected to contribute sulfur in some form to the lunar surface. Moore *et al.*, (1972) pointed out the seemingly minor role of meteoritic and solar wind contributions of sulfur to Apollo soils. A meteoritic component of lunar soils is estimated to range from 1 to 1.5% based on the abundance of siderophile elements for type I carbonaceous chondrites (Ganathapy *et al.*, 1974). Type I carbonaceous chondrites (CC-I) contain approximately 6% sulfur. A 1 to 1.5% CC-I content will contribute 600 to 900 $\mu\text{g S g}^{-1}$ to the lunar soils. This value is greater than the total sulfur content of some lunar soils. A large loss or exchange mechanism must be operating with formation of the regolith.

Morgan *et al.* (1974) summarized three types of meteoritic materials found on the Moon; micrometeorites, ancient planetesimal debris from the 'early intense

bombardment', and debris of recent crater forming projectiles. The micrometeorite component is most clearly seen in the mare soils, but is uniformly distributed over the lunar surface. It has a primitive CC-I like composition and comprises 1 to 1.5% of mature soils, representing cometary debris.

The ancient component is seen in the highland breccia soils which are 3.9 aeons old. Six varieties have been suggested which have siderophile abundance patterns unlike known meteorite classes. They represent debris of an extinct population of bodies that produced the mare basins during the first 700 m.y. of the Moon's history.

The crater forming component has remained elusive with only ejecta from Apollo 15 Dune Crater and Apollo 12 keep glass being possible representatives (Morgan *et al.*, 1974).

2.4. SOLAR WIND

A contribution is likely from implantation by solar wind ions. When the Moon is outside the Earth's magnetosheath these species are implanted into unshielded surfaces. Rare-gas enrichment in lunar soils and breccias is thought to be due totally to solar wind (LSPET, 1969). The enrichment in finer materials was due to the increased surface area and therefore greater exposure of the finer material to solar wind. Moore *et al.* (1970b) performed mass calculations which give estimated values for sulfur in the lunar soils. Solar wind contributes from 15 to 20 $\mu\text{g S}$ to the Apollo lunar soils and thus constitutes the contribution of a small percent are of the total sulfur content. This contribution is smaller than the sampling precision of analyses (approximately 10%) and is not resolved by present analytical techniques.

3. Sulfur Mixing Models for the Lunar Regolith

3.1. APOLLO 11, 12, 14, 15, AND 16 COMPOSITE MIXING MODELS FOR STATION SITES

A first attempt to interpret the abundance pattern of sulfur in the lunar soils was computed by Moore *et al.* (1970b). The calculated and experimental concentrations of volatile elements in the lunar fines suggested that meteoritic impact atomized and severely shocked material with a resulting loss of volatile elements. Assuming the lunar soils to be made up mostly of Apollo 11 type A mare basalts, calculations and comparison of the volatile elements was made assuming a one-half loss represented by a one-half glass content of the soils. The model explained the lower sulfur content in the Apollo soils versus Apollo 11 basalts. Later Apollo 12 and 14 soils data were often found to be higher than associated basalts, thus requiring a reconsideration of the model.

Reid *et al.* (1972) used over 2000 electron microprobe analyses of glass phases in the lunar soils as a guide to the composition and abundance of lunar rock types. Based on natural breaks or minima in overlapping populations of random surveys a classification scheme was devised. A similar model based on bulk chemistry was derived by Goles (1972) using computer analysis of the data compiled by NASA on all Apollo 11 and 12 lunar samples. Major and trace elements were incorporated in the computer model developed by Goles while Reid concentrated on only major

element and normative mineral compositions for his model. The number of components for Apollo 11 and 12 lunar regolith samples was independently derived by the two groups.

The Apollo 11 regolith is dominated by four types of glass. Reid *et al.* (1972) determined the average chemical composition and normative mineral compositions. The Apollo 11 Tranquility A and B components were found to be high Fe, Ti, and low Al, K. The highland basalt was a feldspathic basalt and identical to a highland component in both Apollo 12 and 14 fines.

Procellarum mare basalt, at Apollo 12, resembled the Tranquility mare basalt except for higher Si and lower Ti and correspondingly lower sulfur content (rock 12002, S = 680 $\mu\text{g S g}^{-1}$). Higher K, Al basaltic glasses at 12 and 14 sites were called Fra Mauro type basalts (later generalized as krep basalt) and are major components.

Anorthosite and granitic material have been reported and make up minor proportions of the regolith. Experimental mean total sulfur abundances for all the rock component rock types, except for krep basalt were derived from direct analyses. The value for krep basalt was determined by mixing diagrams (Moore *et al.*, 1972; Cripe, 1973) and later by experimental determination.

An estimation for the total sulfur content in the krep basalt component of the lunar regolith can be made by application of sulfur data for soils and breccias in this study to the mixing diagrams of Wänke *et al.* (1971). Wänke divided Apollo 12 soils into two chemically well defined groups. The groups were end-member Procellarum and krep (Fra Mauro) basalt which correspond to high and low Mg rocks. The approximately 10% feldspathic rocks of highland origin were not considered in this model. Wänke computed the best fit to 21 element lines for each of light soil samples with the assumption these samples represent a mixture of only two components with different and unknown mixing ratios.

The concentration of the Procellarum basalt in specific soil samples was reported to be: 12037 (25%), 12042 (42%), and 12033 (74%). A plot of the total sulfur values obtained for these soils and breccias gave a linear plot with less than 6% deviation for the least squares best fit line. A projection of the best fit line to the Fra Mauro end-member gave an approximate sulfur abundance of 1000 $\mu\text{g S g}^{-1}$. An experimental value for rock 60 315 is in good agreement with a value of 1100 $\mu\text{g S g}^{-1}$ as determined by Apollo 16 LSPET (1973a) and 60015 (890 $\mu\text{g S g}^{-1}$).

With sulfur values for the rock components and relative abundances of the components in the regolith sample, multiplication gave the contribution for each rock type. A total of the calculation contributions should equal the experimentally observed values for the fines if no volatilization of sulfur occurred.

The petrologic make up for Apollo 14 and 15 was determined in a similar fashion by Reid *et al.* (1972). Individual components found in the soils at a particular station were derived from glass compositions of the soils at that station. Tables I, and II illustrate the total sulfur balance for three Apollo 15 stations and Apollo 16, station 1. The total sulfur value of 340 $\mu\text{g S g}^{-1}$ for the green glass is from rock 15426. The mare-derived and low-K, high Al basalt values were taken from analyses by Compston *et al.* (1971) and Hubbard and Gast (1972). The highland basalt value is from sample 15418, LSPET (1972) and 15058. The anorthositic values are from 15415; 60015 and 67455.

TABLE II
Apollo 16 mixing model for lunar soils

Rock type	Sulfur observed	Station 1 Rim of plum crater	
		Relative abundance	Sulfur contribution
Highland basalt	300 $\mu\text{g g}^{-1}$	68%	204 $\mu\text{g g}^{-1}$
Low K high Al basalt	1100	14	154
Fra Mauro	1000	7	70
Mare-derived	1200	7	84
Anorthosite	40	4	2
Total calculated soil			510
Observed soil			500

The simple mixing models for Apollo 11 through 16 demonstrate the domination of sulfur concentration covariant with sulfur addition from individual rock components in the soils at that site.

A comparison for these models is given in Table III. The comparison of calculated component contribution is equal to that observed for Goles Apollo 11 model and station 2, Apollo 15 model. Experimental variation does not exceed a difference of plus 12% or minus 19% from calculated rock contributions independent of meteoritic component considerations. These models are generalizations for modeling sites in that values from the same sample sites or stations were used for comparisons, not specific sample comparisons.

Data from the component modeling by Reid and Goles did not overlap with sulfur abundance data on a sample for sample basis in the above models. With sparse data available, station comparisons versus specific sample modeling was

TABLE III
Comparison of simple sulfur mixing models

Mission	Model	Calculated $\mu\text{g S g}^{-1}$	Experimental $\mu\text{g S g}^{-1}$	Difference %
Apollo 11	Reid	1600	1300	-19
	Goles	1300	1300	0
Apollo 12	Reid	800	850	+6
	Goles	800	850	+6
Apollo 14	Reid	800	850	+6
Apollo 15	Reid			
	Station 2	750	750-850	0, +12
	LM Site	940	850-900	-10, -4
	Station 9A	720	800	+10
Apollo 16	Reid			
	Station 1	510	500	+2

interpreted. Abundance patterns of S in soils have been interpreted in terms of the simple mixing models presented above involving the contribution from various identifiable major rock types within a soils sample (Moore *et al.*, 1972, 1973; Cripe, 1973; Cripe and Moore, 1974, 1975; Gibson and Moore, 1974). The analysis of sieved samples suggest that some surface correlated S may be present as well as the influence of the volume related rock component documented in the above models (Moore *et al.*, 1974; Rees and Thode, 1974). This is demonstrated by the increase of sulfur with decreasing grain size.

3.2. APOLLO 16 AND 17 MIXING MODELS FOR SPECIFIC SOIL SAMPLES

A large number of chemical mixing models were determined by Duncan *et al.* (1973) and Schonfeld (1974), for Apollo 16 and 17 lunar soils in which sulfur content has been determined in this study. Duncan *et al.* (1973), compiled data for 19 Apollo 16 soil samples for which there was good analytical agreement among the literature sources used. The analyses of 14 chemical elements were used according to the weighted least squares method of Gauss. To determine rock components compositional mixing models were calculated by Duncan using the techniques of Lindstrom *et al.* (1972).

The minimum viable set of components was determined by Duncan to be anorthosite, krep, granite, CC-1 meteorites, and high Mg group Apollo 12 basalts. Granite contribution was 1.0% or less and estimates in previous studies (Moore *et al.*, 1972, 1973; Cripe, 1973) suggested the granite component has a sulfur value

TABLE IV
Apollo 16 mixing models for sulfur in specific lunar soil samples

Sample	Anorthosite		Krep		Basalt		Calculated soil $\mu\text{g S g}^{-1}$	Experimental soil $\mu\text{g S g}^{-1}$	Excess $\mu\text{g S g}^{-1}$
	%	$\mu\text{g S}$	%	$\mu\text{g S}$	%	$\mu\text{g S}$			
60600	73.2	29.3	10.6	106	12.1	72.6	208	660	452
61220	80.5	32.2	7.1	71	10.5	63.0	166	500	437
61241	75.9	30.4	9.9	99	12.1	72.6	202	700	498
61501	73.3	29.3	9.5	95	11.9	71.4	196	740	544
64421	75.9	30.4	11.0	110	9.1	54.6	195	790	595
64801	74.5	29.8	10.9	109	8.1	48.6	187	810	623
65701	70.9	28.4	12.3	123	12.4	74.4	226	880	654
66041	70.7	28.3	10.8	108	13.9	83.4	220	900	680
66081	70.6	28.2	11.9	119	13.1	78.6	226	900	674
67481	85.5	34.2	5.2	52	8.0	48.0	134	430	296
67600	84.4	33.8	4.4	44	9.5	57.0	135	400	265
67701	83.3	33.3	5.6	56	7.5	45.0	134	460	326
68501	69.6	27.8	15.1	151	7.9	47.4	226	800	574
68841	71.8	28.7	11.5	115	12.0	72.0	216	780	564
Rock values	100.0	40.0	100.0	1000	100.0	600.0	-	-	-

Relative abundances of rock components from Duncan *et al.* (1973).

Experimental soil data from Table 18.

Rock values from Table 21-26.

TABLE V
Apollo 17 mixing models for sulfur in lunar fines

Sample	Anorthositic Gabbro		KREEP		Mare Basalt		Orange Glass		Dunitite		Calculated fines $\mu\text{g S g}^{-1}$	Experimental fines $\mu\text{g S g}^{-1}$	Median Excess $\mu\text{g S g}^{-1}$	Low Mare Excess $\mu\text{g S g}^{-1}$	High Mare Excess $\mu\text{g S g}^{-1}$
	%	$\mu\text{g S}$	%	$\mu\text{g S}$	%	$\mu\text{g S}$	%	$\mu\text{g S}$	%	$\mu\text{g S}$					
72141	40	16	20	200	20	400	20	130	0	0	766	950	184	304	64
72161	30	12	16	160	20	420	30	195	1.7	5	987	990	3	123	-17
72441	39	15	55	550	3.1	65	4	26	0	0	657	750	93	111	74
72701	44	18	49	490	0.7	16	6	39	0	0	562	790	228	232	224
73121	49	20	42	420	1	21	7	46	1.5	5	555	710	149	155	143
73141	52	21	42	420	0.8	17	4	26	1.7	5	484	730	241	246	236
74121	44	18	38	380	9.7	204	6	39	1.0	3	586	890	246	304	188
76260	42	17	28	280	15	315	11	72	3.4	10	604	880	186	276	96
76321	44	18	32	320	11	231	8	52	3.8	11	566	770	138	204	72
78221	46	18	18	180	18	378	12	78	4.7	14	561	950	281	389	173
79221	30	12	10	100	35	735	22	143	1.9	6	786	1280	318	494	74
79261	32	13	15	150	32	672	19	124	1.2	4	770	1330	362	560	176
Rock values	100	40	100	1000	100	2100	100	650	100	300	---	---	---	---	---

Relative abundances of rock components from Schonfeld (1974).

Experimental fines from Crife and Moore (1974), Gibson and Moore (1974), LSPEI (1973).

Rock values from Moore *et al.* (1972), Crife (1973), Crife and Moore (1974), Gibson and Moore (1974).

near 0; the granite contribution in the sulfur mixing models was set at zero. Values for anorthosite, krep, and high-Mg component Apollo 12 basalts shown in Tables IV and V are estimates from Moore *et al.* (1972). A 6% sulfur value for the CC-I component is from Moore (1971). The column of calculated soils in Table IV represents the sulfur contribution of individual rock components as determined from the chemical mixing model by Duncan *et al.* (1973). In each case the experimental soils have higher sulfur content than the calculated rock component contributions. The excess sulfur, experimental minus calculated, is shown in a separate column.

Table V gives similar determinations for twelve Apollo 17 samples. Schonfeld *et al.* (1974) used a linear mixing model of chemical elements similar to that of Duncan *et al.* (1973).

Cripe and Moore (1976) have estimated the meteoritic component in Apollo 16 and 17 soils. The sulfur ranges from 250 to 650 $\mu\text{g g}^{-1}$ for Apollo 16 and 17 soils. The enrichment of sulfur shows a positive correlation with a CC-I like meteoritic component and $\delta^{34}\text{S}$ isotope enrichment. The implantation of sulfur by meteoritic processes provides a source for sulfur during regolith maturation and a mechanism for exposure related enrichment in $\delta^{34}\text{S}$.

TABLE VI

Sulfur content for primary rock components

Rock type	Sample selected	Sulfur $\mu\text{g g}^{-1}$	Carbon $\mu\text{g g}^{-1}$
Tranquility A basalt	10049	2300	68
Tranquility B basalt	10050	1600	64
Procellarum mare basalt	12002	600	16
Fra Mauro - Krep basalt	60315	890	20
	60015	1100	6
Highland basalt	15418	200	11
	15058	400	10
Anorthosite	15415	<36	15
	60015	27	20
	67455	<20	8
A - 15 green glass	15426	340	21
A - 17 orange glass	74220	650	5

The success of the sulfur mixing models to explain total sulfur content measured provides circumstantial evidence for the validity of the sulfur contents selected for each component. A summary of these values is given in Table VI.

Since S and C in the lunar samples comes primarily from different sources, a direct relationship between them in individual samples does not exist. However, a plot of excess or meteoritic sulfur and total carbon content in Apollo 16 soils shows a direct relationship (Figure 4). Again, the excess sulfur and carbon are from different sources but both are related to soil maturity or exposure and hence show a direct correlation.

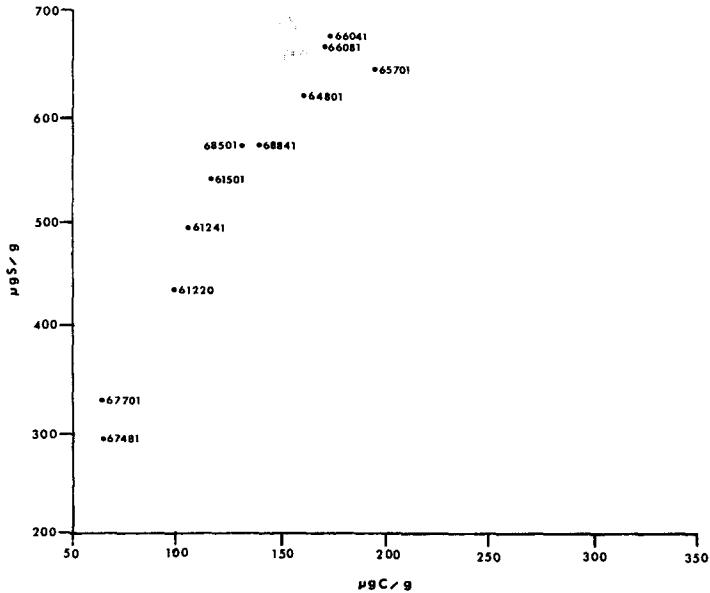


Fig. 4. Extralunar sulfur versus total carbon content for Apollo 16 soils.

References

- Brett, R.: 1974, *Geochim. Cosmochim. Acta* **39**, 1135–1141.
- Brett, R.: 1975, *Lunar Science-VI*, pp. 89–91, Lunar Science Institute, Houston.
- Cadogan, P. H., Eglinton, G., Gowar, A. P., Jull, A. J. T., Maxwell, J. R., and Pillinger, C. T.: 1973, *Proc. 4th Lunar Sci. Conf.*, 1493–1508.
- Chang, S., Lennon, K., and Walberg, G.: 1975, *Lunar Science-V*, pp. 131–133, Lunar Science Institute, Houston.
- Chang, S., Lawless, J., Romiez, R., Kaplan, I. R., Petrowski, C., Sakai, H., and Smith, J. W.: 1974, *Geochim. Cosmochim. Acta* **38**, 853–872.
- Compston, W., Chappell, B. W., Arriens, P. A., and Vernon, M. J.: 1970 *Proc. Apollo 11 Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 1*, **2**, 1007–1027.
- Compston, W., Berry, H., Vernon, M. J., Chappell, B. W., and Kay, M. J.: 1971, *Proc. 2nd Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 2*, **2**, 1471–1485.
- Cripe, J. D.: 1973, *The Total Sulfur Content of Lunar Samples and Terrestrial Basalts*, Thesis, Arizona State University, Tempe, Arizona, 75 pp.
- Cripe, J. D. and Moore, C. B.: 1974, *Lunar Science-V*, pp. 523–525, Lunar Science Institute, Houston.
- Cripe, J. D. and Moore, C. B.: 1975, *Lunar Science-VI*, pp. 168–170, Lunar Science Institute, Houston.
- Cripe, J. D. and Moore, C. B.: 1976, *Proc. 7th Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 7*, **2**, (in press).
- Des Marais, D. J., Hayes, J. M., and Meinschein, W. G.: 1973, *Proc. 4th Lunar Sci. Conf.*, 1543–1558.
- Duncan, A. R., Erlank, A. J., Willis, J. P., and Ahrens, L. H.: 1973, *Proc. 4th Lunar Sci. Conf. Geochim. Cosmochim. Acta Suppl. 4*, **2**, 1097–1113.
- El Goresy, A., Ramdohr, P., and Taylor, L. A.: 1971, *Proc. 2nd Lunar Sci. Conf. Geochim. Cosmochim. Acta Suppl. 2*, **1**, 219–235.
- Epstein, S. and Taylor, Jr., H. P.: 1975, *Proc. 6th Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 6*, **2**, 1771–1798.
- Ganapathy, R., Morgan, J. W., Higuchi, H., Anders, E., and Anderson, A. T.: 1974, *Proc. 5th Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 5*, **2**, 1659–1683.
- Gibson, E. K., Jr. and Moore, G. W.: 1973, *Proc. 4th Lunar Sci. Conf.*, *Geochim. Cosmochim. Acta Suppl. 4*, **2**, 1577–1586.

- Gibson, E. K., Jr. and Moore, G. W.: 1974a, *Proc. 5th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 5, 2, 1823-1837.
- Gibson, E. K., Jr. and Moore, G. W.: 1974b, *Trans. Am. Geophys. Union* 55, 333.
- Gibson, E. K., Jr., Chang, S., Lennon, K., Moore, G. W., and Pearce, G. W.: 1975, *Proc. 6th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 6, 2, 1287-1301.
- Goles, G. C., Duncan, A. R., Lindstrom, D. I., Martin, M. R., Beyer, R. L., Osawa, M., Rnadle, K., Meek, L.T., Steinborn, T. L., and McKay, S. M.: 1971, *Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 2, 2, 1063-1081.
- Heiken, G.: 1974, *A Catalog of Lunar Soils*, Lunar Science Institute, Houston, 221 pp.
- Hubbard, N. J. and Rhodes, J. M.: 1975, *Proc. Conf. Geochem. of the Moon and Planets*, preprint, 20 pp.
- Hubbard, N. J., Gast, P. W., Rhodes, J. M., Bansal, B. M., Weismann, H., and Church, S. E.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 2, 1161-1179.
- Kaplan, I. R. and Petrowski, C.: 1971, *Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 2, 2, 1397-1406.
- Kaplan, I. R. and Smith, J. W.: 1970, *Science* 167, 541.
- Kaplan, I. R., Smith, J. W., and Ruth, E.: 1970, *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 1, 2, 1317-1329.
- Kerridge, J. F., Kaplan, I. R., and Petrowski, C.: 1975, *Proc. 6th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 6, 2, 2151-2169.
- Lindstrom, M. M., Duncan, A. R., Fruchter, S. M., McKay, J. W., Stoesser, Goles, G. G., and Lindstrom, D. J.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 2, 1201-1214.
- LSPET (Lunar Sample Preliminary Examination Team): 1969, *Science* 165, 1211-1227.
- LSPET (Lunar Sample Preliminary Examination Team): 1970, *Science* 167, 1325-1339.
- LSPET (Lunar Sample Preliminary Examination Team): 1971, *Science* 173, 681-693.
- LSPET (Lunar Sample Preliminary Examination Team): 1972, *Science* 175, 363-375.
- LSPET (Lunar Sample Preliminary Examination Team): 1973a, *Science* 179, 23-24.
- LSPET (Lunar Sample Preliminary Examination Team): 1973b, *Science* 182, 659-674.
- McKay, D. S., Heiken, G. H., Taylor, R. M., Clanton, U. S., Morrison, D. A., and Ladle, G. H.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 1, 983-994.
- Moore, J. G. and Fabbri, B. P.: 1971, *Contr. Mineral. Petrol.* 33, 118-127.
- Moore, C. B., Lewis, C. F., and Cripe, J. D.: 1974, *Proc. 5th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 5, 1897-1906.
- Moore, C. B., Lewis, C. F., and Gibson, E. K. Jr.: 1973, *Proc. 4th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 4, 2, 1613-1623.
- Moore, C. B., Lewis, C. F., Cripe, J. D., and Volk, M.: 1974, *Lunar Science-V*, 520-522, Lunar Science Institute, Houston.
- Moore, C. B., Gibson, E. K. Jr., Larimer, J. W., Lewis, C. F., and Nichiporuk, W.: 1970, *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 1, 2, 1375-1382.
- Moore, C. B., Lewis, C. F., Cripe, J. D., Delles, F. M., and Kelly, W. R.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 2, 1613-1623.
- Moore, C. B., Lewis, C. F., Larimer, J. W., Delles, F. M., Gooley, R., and Nichiporuk, W.: 1971, *Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 2, 2, 1343-1350.
- Morgan, J. W., Ganapathy, R., Higuchi, H., and Anders, E.: 1974, *Proc. Soviet-American Conf. Cosmochemistry of the Moon and Planets (Moscow)*, in press, Lunar Science Institute, Houston.
- Petrowski, C., Kerridge, J. F., and Kaplan, I. R.: 1974, *Proc. 5th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 5, 2, 1963-1973.
- Rees, C. E. and Thode, H. G.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 2, 1479-1485.
- Rees, C. E. and Thode, H. G.: 1974, *Proc. 5th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 5, 2, 1963-1973.
- Reid, A. M., Warner, J., Ridley, W. I., Johnston, D. A., Harmon, R. S., Jakes, P., and Brown, R. W.: 1972, *Proc. 3rd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 3, 1, 363-378.
- Rhodes, J. M., Adams, J. B., Blanchard, D. P., Charette, M. P., Rodgers, K. V., Jacobs, J. W., Brannon, J. C., and Haskin, L. A.: 1975, *Proc. 6th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 6, 2, 2291-2307.
- Sakai, H., Petrowski, C., Goldhaber, M. B., and Kaplan, I. R.: 1972, *Lunar Science-III*, 672-674, Lunar Science Institute, Houston.
- Sato, M. and Helz, R. T.: 1971, *Second Lunar Sci. Conf.*, unpublished proceedings.
- Schonfeld, E.: 1974, *Proc. 5th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 5, 2, 1269-1286.
- Shoemaker, E. M., Batson, A. L., Bean, A. L., Conrad, C., Dahlem, D. H., Goddard, E. N., and Waters, A. C.: 1970, *Proc. Apollo XX Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl.* 1, 1, 2399-2421.

- Skinner, B. J.: 1970, *Proc. Apollo 11 Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 1*, **1**, 891–895.
- Swanson, D. A. and Fabbi, B.: 1973, *J. Res. U.S. Geol. Survey*, **1**, 649–658.
- Thode, H. G. and Rees, C. E.: 1972, in J. W. Chamberlain and C. Watkins (eds.), *The Apollo 15 Lunar Samples*, pp. 402–404, Lunar Science Institute, Houston.
- Wänke, H., Palme, H., Baddenhausen, H., Dreibus, G., Jagoutz, E., Kruse, H., Palme, C., Spettel, B., Teschke, F., and Thacker, R.: 1975, *Proc. 6th Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 6*, **2**, 1313–1340.
- Wänke, H., Wlotzka, F., Baddenhausen, A., Balacescu, B., Spettel, B., Teschke, F., Jagoutz, E., Kruse, H., Quijano-Rico, M., and Reider, R.: 1971, *Proc. 2nd Lunar Sci. Conf., Geochim. Cosmochim. Acta Suppl. 2*, **2**, 1187–1208.