gregated in boiling water and centrifuged several times to separate the water-soluble components from the insoluble residue. The residue is dissolved in hydrochloric acid and passed through a column (15 cm long by 3 cm in diameter) containing Dowex-1 resin (50–100 mesh) in chloride form. Two column volumes each of the following acid solutions were passed and collected sequentially: $12N$ HCl carries the rare earths, Ag; $8N$ HCl carries Ti, Zr, Hf; $4N$ HCl carries Co; $0.1N$ HNO_3 carries Hg. Other elements, of course, are also removed from the column with the sought elements. From the appropriate fraction the following elements are separated, purified if necessary, and counted: Silver is separated and counted with the NaI detector, chemical yield is determined and compared with a silver standard; the remaining solution containing Sc and the rare earths is evaporated to dryness on a planchet and counted on the Ge(Li) detector. The Ce/Sc count ratio combined with the previously determined Sc concentration gives the Ce concentration, as compared with the standard pot, without the necessity of yield determination or further purification. The cobalt fraction containing ^{60}Co and ^{58}Co from n,p on ^{58}Ni is purified and counted on the NaI detector, the count ratio ^{58}Co/^{60}Co is compared with the standard pot, and the previously determined cobalt concentration gives the results for nickel. The Zr- and Hf-bearing fraction is evaporated to dryness and counted on the Ge(Li) detector, and the Zr/Hf count ratio combined with the previously determined Hf concentration gives the Zr concentration as compared with the standard pot without yield determination or further purification.

Selenium is separated from the water-soluble fraction by passing SO_2 through the acidified solution. Counting is done on the Ge(Li) detector.

The results of our analyses to date are listed in Table 1. Because of probable weighing problems in the irradiation A suite between samples and standards (suspected first by the low Ti results), all the numbers obtained from this irradiation sequence were corrected by the use of data from irradiation B. All values from irradiation A are normalized to the europium determined carefully together with the other short-lived nuclides in irradiation B.

Duplicate results indicate an error of about 5 to 10 percent (coefficient of variations determined from the ranges of a pooled sample). We think that most of this error is due to heterogeneities or sample handling since the counting errors in most cases are lower.

Many of the distinctive chemical properties of the Apollo 11 materials were outlined in the published preliminary results (*3*). We confirm the high rare earth, Ti, Zr, and Cr contents and the low Mn, Co, and Ni contents. In addition, the results given in Table 1 show a deficiency of europium relative to other rare earths as compared with chondrites. Tantalum and hafnium are considerably higher in Apollo 11 site materials than in terrestrial basalts.

The elemental abundances vary among the several Apollo 11 site materials we have examined. Roughly, it appears that three coherent groups exist. One group varying together is Mn, Sc, Ta, Hf, and the rare earths; a second group appears to be Fe, Ti, Co, and Cr; and a third group is Na and U. If we conceive of Apollo 11 material as being composites of different proportions of three dominant phases, pyroxene, ilmenite, and plagioclase, the trace element groupings may be crudely explained as strong associations with these phases. Separated portions must be analyzed before this point can be made explicit.

Although it is premature to present a quantitative model for the chemical makeup of Apollo 11 site materials, several constraints are imposed by the data. The low cobalt and nickel concentrations relative to chromium and scandium, and the low abundance of metallic iron, implies that these components were either not accumulated or were separated out by a secondary process. The high abundances of Ti, Cr, Sc, Ta, Hf, and rare earths imply that the raw material for Apollo 11 material could be a condensate from the solar nebula at temperatures between the higher temperature for the condensation of metallic iron and nickel and the lower temperature for the condensation of sulfides and proton-rich materials, a general model suggested by several people (*4*). The phases and their variations now observed may be due to the redistribution of the elements at the time of impact or as the result of some other magma-producing process.

The analytical procedure we have described is being modified to include an initial x-ray fluorescence scan of the pellet in the type 2 planchet before irradiation. Hence, on the same 20-mg sample we should obtain useful data for Ca, Fe, Ti, Sr, Y, and Zr on the specific sample to be analyzed by neutron activation. Our method is most suitable for small samples and, in particular, may be valuable for the analysis of separated mineral phases and glass beads. Results on a sample as small as 5 mg may be adequate for many problems.

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Elemental Composition of Lunar Surface Material

Abstract. *Elemental abundances, so far obtained, derived from the analysis of Apollo 11 lunar material are reported. Similarities and differences exist between lunar material, the eucritic achondrites, and the augite achondrite Angra dos Reis, the analysis of which is also reported.*

We present here the results of our initial analytical work on (i) lunar fines (sample 10084), (ii) lunar rock (sample 10060,26), (iii) glassy spheres (sample 10085/30/5) received, respectively, on 19 September, 23 October, and 19 November 1969. We also give some data on the elemental abundances in the augite achondrite Angra dos Reis, of which we were able to get 240 mg (BM 63233). In order to give approximate results in an initial survey of as many elements as possible, we used the following methods: spark source mass spectrography (SSM), emission spectrography (E), and x-ray fluorescence spectrometry (XRF). To give more accurate results for a smaller number of elements, we used activation analysis (AA; instrumental, neutron, activation analysis, INAA; radiochemical, neutron activation analysis, RNAA; radiochemical, high-energy gamma, activation analysis, RGAA) and mass spectrometric isotope dilution analysis (MSID). Not all methods were used on the glassy spheres or the meteorite because of the limited amount of sample available.

In the SSM method we used an A.E.I. MS702 instrument. Powdered samples were mixed with graphite previously doped with rhenium as an internal standard and were pressed into electrodes. The electrode surfaces were cleaned by presparking (~ 100 nc), and the analysis was carried out over a wide exposure range (300 to 0.003 nc) at intervals of × 1.5 to × 3. The photographic plates were examined by microdensitometry for the rare earths and by inspection for other elements, results being obtained by the "just detectable line" method. Results recorded for "standard" rocks W-1 and BCR-1 were used to provide empirical corrections for ionization efficiency factors in a number of cases. The accuracy of the method is believed to be within a factor of 3 of the stated values. The cleaved glassy spherule was examined directly by mounting it in an indium support and sparking against a carbon counter electrode. Plates were analyzed visually, and the relative ion exposures were verified by densitometry for several multiisotopic elements. Values for Ti, Mn, and Dy from separate neutron activation analysis were used as internal standards.

In the ES method we used the technique of Webb and Wordingham (*1*); synthetic standards and "standard" rocks (G-1, W-1, AGV-1, BCR-1, DTS-1, T-1, and syenite rock-1) were used for calibration, the spectra being assessed visually and by microphotometry. Coefficient of variation for a single determination was between 5 and 10 percent at concentrations between 20 and 100 parts per million. Accuracy is estimated as ± 20 percent.

In the XRF method we used for major elements a fusion mix consisting of lithium tetraborate, lithium carbonate, and lanthanum oxide (Spectroflux 105) to which had been added 0.8 percent lithium nitrate, the general method being that of Norrish and Hutton (*2*). We measured the minor and trace elements using lithium tetraborate only. Synthetic standards were used in both cases. Comparison of results by these methods was made with published figures on "standard" rocks AGV-1, BCR-1, G-1, and DTS-1, and from this the estimated accuracy is, for major elements (>1 percent) ± 3 percent, minor elements (0.1 to 1 percent) ± 5 percent, trace elements (<0.1 percent) ± 15 percent.

Table 1. Elements determined by activation analysis* or mass spectrometric isotope dilution, or both.

Atomic number	Element	Concentration of elements			
		Lunar fines	Lunar rock	Lunar glassy spheres	Meteorite Angra dos Reis
		Percentages			
11	Na	0.32	0.38	0.14	0.03
12	Mg		6	4	
13	Al	7.0	5.2	7.0	5.7
19	K	0.12‖	0.17‖		
20	Ca	~8†	~ 11†	~ 10†	~ 17†
22	Ti	4.7	5.2	4.9	1.7
26	Fe	12.5	14.2	12.3	6.5
		Parts per million			
9	F	74§			
21	Sc	66	70	57	57
23	V		~ 90†	~ 120†	
24	Cr	2300	2800	2300	1700
25	Mn	1630	1620	1610	700
27	Co	~25†	~ 30†	~ 30†	~ 10†
29	Cu		9.1‡		
31	Ga	3.8‡	4.7‡		
32	Ge	0.5‡	0.4‡		
33	As	0.03‡	0.01‡		
37	Rb	3.0‖	4.2‖		
38	Sr	177‖	180‖		
46	Pd		0.006‡		
49	In	2.0¶,0.5¶	0.004‡		
55	Cs	0.12‖	0.19‖		
56	Ba	174‖	212‖		
57	La	19	25	27	10
58	Ce	46‖	56‖		
60	Nd	37‖	45‖		
62	Sm	13‖,14	16‖,16	13	8
63	Eu	1.8‖,2.0	1.9‖,2.6	2.1	2.0
65	Tb	4	6	5	2
66	Dy	23	24	21	12
67	Ho	5	7	5	3.5
70	Yb	12	14	12	6
71	Lu	1.5	1.8	1.4	0.7
72	Hf	11	12	11	3

*Accuracy by INAA, ± 5 percent for all results, except where noted. †Accuracy by INAA, ± 10 percent. ‡Accuracy by RNAA ± 5 percent. §Accuracy by RGAA, ± 10 percent. ‖Accuracy by MSID, ± 5 percent. ¶Contamination of samples suspected.

For activation analysis both neutrons (from DIDO, flux 1.3 × 10^{13} neutron cm^{-2} sec^{-1}) and high-energy gamma photons (bremsstrahlung produced from the Harwell electron linear accelerator) were used. For INAA, irradiation and decay periods were 12 seconds and 7 minutes, followed by 5 minutes and 14 hours, respectively, for one set of samples; we used irradiation and decay periods of 2¼ days and 3½ days, respectively, for a different set of samples. Counting was done with two Ge(Li) detectors, a small planar, high-resolution detector (1 kev at 120 kev) for identification of photopeaks, and a larger 30-cm^3 coaxial detector (resolution, 5 kev at 1.32 Mev) for general counting. The associated PDP-8 gamma spectrometer has been described by Pierce *et al.* (*3*); we processed data from this instrument on the main Harwell computer (IBM 360/65), using a specially developed least-squares fitting program which applies corrections for both decay and dead-time. Estimated accuracy is ± 10 percent except where stated. For RNAA we used a flux of 5 × 10^{12} neutron cm^{-2} sec^{-1} generally, but for short-lived radionuclides the higher flux (1.3 × 10^{13}) was used as a pneumatic "rabbit" tube into that flux position. Radiochemical methods used have been described elsewhere (*4*). Estimated accuracy is ± 5 percent. For the fluorine determination by RGAA, samples and standards were irradiated in Al-foil containers for 30 minutes in the bremsstrahlung produced in a tungsten converter ⅛ inch thick from a 10-μa beam of 24- to 28-Mev electrons. Radiochemical separation was achieved by distillation of H_2SiF_6; counting of the 0.51-Mev annihilation radiation (after gamma spectrometry to establish absence of other gamma emitters) was then used for measurement of ^{18}F. Decay of this nuclide was followed for four half-lives as further confirmation of radiochemical purity. "Standard" rocks G-1 and W-1 were also analyzed, and the estimated accuracy is ± 10 percent.

In the MSID methods we used enriched isotopes of the elements concerned, Rb, Cs, Ba, Sr, Ce, Nd, and Sm being determined in the same sample, K being determined in a separate sample. Cation exchange was used to separate the alkali, alkaline earths, and rare earths as three groups, for subsequent mass analysis on a laboratory-constructed instrument with a radius

Table 2. Major elements in lunar fines, expressed as oxides.

Oxide	By XRF (%)	By INAA (%)	By MISD (%)
Na_2O		0.43	
MgO	7.6		
Al_2O_3	13.0	13.2	
SiO_2	43.0		
K_2O	0.15		0.14
CaO	12.2		
TiO_2	7.7	7.8	
Cr_2O_3	0.3	0.34	
MnO	0.2	0.21	
FeO	15.6	16.1	

of 6 inches and a sector of 60° for the two former groups and on an A.E.I. MS5 instrument for the latter group. Details are given elsewhere (*5*). Estimated accuracy is ± 5 percent.

Results obtained by AA and MSID are reported in Table 1; results obtained for the major elements by XRF, MSID, and AA are given in Table 2, and data from some supplementary analyses by SSM, E, and XRF are presented in Table 3. Table 4 lists conservative upper limits for several other elements derived from SSM measurements; some of these, for example, P, S, and Pb, were detected but not measured.

By comparison with the work of the Preliminary Examination Team (PET) (*6*), who used mainly emission spectrography for elemental analysis, and where results for 23 elements and upper limits (for that method) for 30 more were given, we list results so far for 35 elements in Tables 1 and 2, less firm results for 11 more in Table 3, and upper limits (generally at lower levels) for 25 elements in Table 4. Of those we undertook to determine in our original proposal, we have not yet any result for seven elements; on the other hand, we quote results for 18 elements which we did not include in our original proposal. We have not as yet done all the cross-checking of results by our several methods that we would wish to do. (This may explain the conservative accuracy estimates quoted.)

Our results broadly confirm those of the PET, the only significant difference being that for ytterbium (PET reports 1.3 to 7 parts per million; our value is 12 to 14 ppm). We do not know at present whether our samples are taken from those analyzed by the PET or whether they are different. If the samples are different, then our ytterbium figures may simply indicate a larger range for that element in the lunar material rather than an analytical disagreement. The PET comment that "samples are apparently free from inorganic contamination . . . from . . . indium, which forms the seal of the rock box . . ." may no longer hold on the basis of methods of higher sensitivity. Our evidence is not strong but we believe that the disagreement between duplicate indium determinations for lunar fines, coupled with the comparatively high values, indicates contamination. The value for the lunar rock of 0.004 ppm was obtained by irradiating a piece of rock, then leaching it after irradiation with boiling HNO_3-HF, and thereafter proceeding with radiochemical separation on the leach liquor and on the remaining rock as separate samples. The leach liquor contained the equivalent of an additional 0.004 ppm of indium; this result possibly implies that even here some readily removable indium (that is, contamination) was present.

Table 3. Supplementary results by spark source mass spectography, emission spectrography, and x-ray fluorescence spectrometry.

Atomic number	Element	Lunar fines (ppm)			Lunar rock (ppm)		Lunar spheres SSM (ppm)	Meteorite Angra dos Reis (ppm)	
		SSM	E	XRF	SSM	E		SSM	E
19	K							50	
23	V	50	50			45	40	160	150
28	Ni	170	180		100	150	80	30	50
29	Cu	10			10		10	10	
30	Zn	50			40		20	10	
31	Ga							6	
37	Rb	3					3	1	
38	Sr	200	170	170	200	170	200	100	150
39	Y	100	120	100	100	120	60	40	30
40	Zr		330	320	300	340	200	100	100
41	Nb	10			10		5	5	
56	Ba	200		180	200		150	30	30
58	Ce						40	20	
59	Pr	20			20		20	10	
60	Nd						40	20	
64	Gd	15			20		20	10	
68	Er	10			10		10	5	
69	Tm	2			2		2	1	
90	Th	1			1			1	
92	U	0.4			0.4			0.4	

Table 4. Upper limits by our spark source mass spectrographic method for elements not quantified in lunar fines and rocks.

Atomic number	Element	Upper limit (ppm)
5	B	2
15	P	1500
16	S	500
17	Cl	70
34	Se	20
35	Br	3
42	Mo	10
44	Ru	1
45	Rh	1
47	Ag	1
48	Cd	1
50	Sn	10
51	Sb	1
52	Te	1
53	I	1
73	Ta	3
74	W	1
76	Os	1
77	Ir	1
78	Pt	1
79	Au	1
80	Hg	1
81	Tl	1
82	Pb	10
83	Bi	1

The results for rare earths and barium on the Angra dos Reis meteorite compare quite reasonably with those of Schnetzler and Philpotts (*7*), and our approximate values for potassium, thorium, and uranium are not dissimilar to published values (*8*). Our results for the major elements are in broad agreement with those of Ludwig and Tschermak (*9*), but not unexpectedly our data for sodium and potassium differ markedly from theirs [as also do the results of Muller and Zahringer (*8*) for potassium].

We had some 10 mg of the glassy spheres; one-half sphere we analyzed by SSM; the other whole sphere, after grinding, was analyzed by AA. On grinding the color changed from black to yellow-brown. The analysis shows the spheres to be quite similar to the lunar fines and rocks, except for the sodium content which is distinctly lower in the spheres. The result is very similar to that of Fredriksson and Kraut (*10*) for the analysis of Cachari eucrite glass. The analogy with the arguments about tektites and their probably terrestrial parent material is also obvious.

Several attempts have been made to compare the chemical composition of Apollo 11 lunar meterial with that of known terrestrial and meteoritic silicates. Only the suggestion of terrestrial anorthositic gabbro (*11*) seems to meet the requirements for the major elements, but it fails on the alkali metals and carbon. Several authors have suggested similarities with the basaltic achondrites, especially the eucrites. Turkevich *et al.* (*12*) say, however, that in the lunar material "the high value for titanium and the relatively low value for iron are at variance with the content of these elements in eucrites and other calcium-rich achondrites." The statement about titanium is true, but that about iron is incorrect. Moore County, a eucrite containing 12.4 percent of FeO, comes well within the accuracy range of Turkevich's value of 12.1 percent. Our values for FeO (15.6 and 16.1 percent) on Apollo lunar fines are higher than the latter value and fit well into the eucrite range (*13*).

As a result of these considerations we felt that it would be worthwhile to examine Angra dos Reis, a unique calcium-rich achondrite, which is reported to have the highest titanium content of any meteorite so far analyzed. We analyzed a small sample by SSM and by AA and found that there are some quite interesting similarities to Apollo 11 lunar material. Concentrations of the rare earths, especially, are within a factor of 2 of those in lunar samples, closer than values for any other meteorite. The concentration of europium, which seems very low in lunar material by comparison with the other rare earths, is in this meteorite almost exactly the same as that in the lunar material. (Incidentally, the "normalized to ytterbium" figure for europium in lunar material is lower than for any meteoritic material.) The uranium and thorium abundances in the two materials are also quite similar.

Dissimilarities exist in that for Angra dos Reis, the titanium content is lower [Turkevich *et al.* comment that Sinus Medii material may have lower titanium content than Mare Tranquillitatis material (*12*)], the sodium and potassium content is much lower, and the calcium content is higher than in lunar material. Also the points on the plot of CaO content as a function of Fe/(Fe + Mg) (*14*) are in quite different positions (that for lunar material fitting well with eucrites).

We agree with Turkevich *et al.* (*12*) that "there appears to be no common material (available) on earth that matches in all respects the chemical composition of lunar surface material at Mare Tranquillitatis."

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Abundances of 30 Elements in Lunar Rocks, Soil, and Core Samples

Abstract. *Abundances of 30 elements in seven lunar rocks and soil were determined by instrumental and radiochemical activation analysis. Seven major and minor elements in chips from 27 rocks were determined by instrumental activation analysis. Abundances of ten bulk elements overlap for the breccia rocks and soil samples. All lunar rare earth elements distribution patterns resemble those found in terrestrial abyssal subalkaline basalt, but with Eu depleted by about 60 percent in all lunar samples compared to the adjacent rare earth elements. Precipitation of plagioclase and hypersthene achondritic-like minerals from a melt could account for Eu depletion and the observed distribution of rare earth elements. Abundances of Ti, Al, Ca, Na, and Mn determined by instrumental activation analysis in five core-tube soil samples indicate uniformity for Al and Mn and apparent differences (10 to 20 percent) for Ti, Ca, and Na at 7.8 and 10.5 centimeters as compared to 0 to 5.2 centimeter depths.*

Elemental abundances of ten bulk elements were determined by instrumental activation analysis (IAA) in specimens (about 0.3 to 1 g) of chips, powders, or fine material from five type-B rocks (10017, 44, 45, 47, and 50), two type-C rocks (10019 and 59), and lunar soil (10084), returned from Tranquillity Base (*1*). In collaboration with other investigators (*2*), abundances of seven major, minor, and trace elements were obtained by IAA in chips (about 0.5 to 2 g) from 27 rocks—that is, in two type-A, seven type-B, and 18 type-C rocks. Experiments are in progress for determination of 15 additional minor and trace elements by IAA in these 27 specimens (*2*). The analytical method has been described elsewhere (*3*). Gamma-ray spectroscopy measurements were taken with Ge(Li) and NaI(Tl) detectors.

After IAA, chips (about 0.5 to 1 g) of two type-B rocks (10017 and 50), one type-C rock (10019), and fine soil material (10084) were further subjected to RNAA (radiochemical neutron activation analysis) for determination (*4*) of the 14 rare earth elements (REE), plus Y, Cd, In, K, Rb, and Cs. Abundances of Rb and Cs will be reported elsewhere (*5*). Core-tube specimens of soil were also subjected to IAA for abundance measurements of Ti, Al, Ca, Na, and Mn. Five samples (73 to 146 mg each) were taken at 2.6-cm depth intervals. Further IAA of these core samples are currently in progress for the determination of Cr, Fe, Sc, Co, Ba, La, Sm, Eu, Yb, Lu, Zr, Hf, and Th (*5*).

Chips from rocks 10017, 45, 50, 19, and 59 were split into two smaller chips. Powders from rocks 10044 and 47 were sieved through 100 nylon mesh into a coarse fraction ($>$ 100 mesh) and a fine fraction ($<$ 100 mesh). For 10044, the coarse and fine fraction weights were 0.85 and 1.03 g and for 10047, 0.35 and 0.56 g, respectively. From a total of 5.3 g of lunar soil, three aliquants were split into two unsieved 1-g samples and the third sample of 3.1 g was sieved