

Table 3. Minor and trace element content (parts per million) of lunar material (analyst, W. H. Champ).

Constituent	BCR-1 (USGS)	10017-29	10020-30	10084-132
Cr	<20	2200	3000	2300
Zr	<200	410	210	260
Ba	700	230	67	150
Sr	220	100	130	140
V	420	49	120	67
Ni	<20	<20	<20	190
Co	<20	<20	<20	<20
Cu	10	<5	<5	<5
Y	34	160	120	120
Yb	<10	<10	<10	<10
Sc	23	52	78	51
Li*	15	23	12	15
Zn*	120	49	26	47

* By atomic absorption spectroscopy (S. Abbey, analyst). All other determinations by optical emission spectroscopy.

solution was used to determine Si and Al by atomic absorption spectroscopy, with the nitrous oxide-acetylene flame, and K, Mn, and Cr with the air-acetylene flame. All measurements were made with a modified Techtron model AA-3 instrument. The more dilute solution was used to determine total Fe, Mg, Ca, and Na, all with the air-acetylene flame. Details of the method will be given elsewhere. Phosphorus and titanium were also determined photometrically on the main sample solution (6, 7). The results are given in Table 1.

All determinations were based on a comparison of sample solutions with solutions similarly prepared from international reference rock samples. Values assigned to the compositions of the reference samples were based on data prepared by Abbey (8) and Govindaraju (9). For some elements, it was necessary to add standard solutions of the element to the solutions of the reference samples in order to bring the elemental concentration into the same range as was present in the samples.

An additional 500 mg were decomposed by acid attack and the resulting solution, containing free sulfuric acid and some added hydrochloric acid, was analyzed for lithium and zinc (Table 3) by atomic absorption spectroscopy (10). A "standard-addition" technique was used to overcome matrix effects.

The optical emission spectrographic procedure employed a d-c arc, air-jet controlled. Sample portions were mixed with a buffer consisting of alkali salts and graphite powder, at a dilution factor of 7.5, and arced to completion. The spectra were recorded in a 3.4-m Jarrell-Ash grating spectrograph. Because of the general complexity of these spectra, internal standards were not used. Instead, intensity ratios of trace element

lines were related to selected iron lines in an "external standard" exposure on the same plate (consisting of Fe₂O₃ treated in the same manner as the samples). Concentrations (Table 3) were obtained from working curves, with cor-

rections as required to correlate with standards of similar composition which were run along with the samples.

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References and Notes

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11. We thank J. L. Bouvier for the determinations of phosphorus and titanium in the fluoborate solutions, J. G. Sen Gupta for the total sulfur and carbon determinations, and K. A. Church, D. A. Brown, Joanne Crook, and G. A. Bender for their help with the emission spectrographic work.

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Chemical Analyses of Lunar Samples 10017, 10072, and 10084

Abstract. *A crystalline rock, a vesicular rock, and a dust sample returned by Apollo 11 were chemically analyzed by several methods. The compositions of these samples are unlike that of any known rock or meteorite.*

The compositions of lunar samples 10017,20 (a crystalline rock), 10072,20 (a vesicular rock), and of 10084,102 (dust) are given in Tables 1-3. Three 1-g samples were used for each analysis. Wet chemical methods were used in de-

termining the major elements. In order to obtain correct values for some major elements, especially aluminum, it was necessary to determine some trace elements as well. In determining these trace elements, emission spectroscopy, atomic absorption spectroscopy, and neutron activation were used (1). The experimentally obtained compositions differ markedly from the composition of all hitherto analyzed rocks and meteorites.

Table 1. Chemical composition of three Apollo 11 moon samples, expressed as oxides. Sample 10017 is crystalline rock; 10072 is vesicular rock; and 10084 is dust. G, gravimetric; C, colorimetric; AA, atomic absorption; T, titration; NA, neutron activity; Q, qualitative; and F, flame.

Oxide	Sample 10017 (%)	Sample 10072 (%)	Sample 10084 (%)	Methods used
SiO ₂	40.77	40.20	42.25	G; C
TiO ₂	11.82	12.28	7.24	C
Al ₂ O ₃	7.92	7.78	13.83	G; AA
Fe ₂ O ₃	0.0	0.0	0.0	T
FeO	19.79	19.77	15.80	T
Cr ₂ O ₃	0.33	0.36	0.275	AA
MnO	0.22	0.22	0.20	C; NA
MgO	7.74	8.06	7.97	G
CaO	10.58	10.27	11.96	G
Na ₂ O	0.51	0.52	0.43	F; NA
K ₂ O	0.29	0.29	0.13	F; NA
P ₂ O ₅	0.18	0.18	0.14	C
H ₂ O	0.00	0.00	0.00	G
CO ₂	0.00	0.00	0.00	Q
Fe met.	0.0	0.0	0.0	Q
Total	100.15	99.93	100.53	

Table 2. Elemental composition of three Apollo 11 moon samples. D, by difference.

Element	Sample 10017 (%)	Sample 10072 (%)	Sample 10084 (%)	Method
Si	19.05	18.78	19.74	G; C
Ti	7.09	7.36	4.52	C
Al	4.19	4.12	7.32	G; AA
Fe	15.38	15.37	12.28	T
Cr	0.226	0.246	0.188	AA
Mn	0.17	0.17	0.155	C; NA
Mg	4.67	4.86	4.81	G
Ca	7.56	7.34	8.55	G
Na	0.38	0.385	0.32	F; NA
K	0.24	0.24	0.108	F; NA
P	0.08	0.08	0.06	C
H	0.00	0.00	0.00	G
O	(40.87)	(40.95)	(41.94)	D

Table 3. Trace elements in three Apollo 11 moon samples. ES, emission spectra.

Element	Sample 10017 (ppm)	Sample 10072 (ppm)	Sample 10084 (ppm)	Methods used
Sc	77	77	59	ES
V	70	82	71	ES
Co	30	30	32	ES; NA
Ni	<5	<5	200	ES; NA; AA
Cu	20	21	13	ES
Zn	47	24	36	AA
Y	160	175	120	ES
Zr	430	460	380	ES
Sm	25	21	18	NA
Eu	2.1	2.0	1.8	NA
Tb	4	3	3	NA
Lu	5	5	3	NA
Yb	19	19	12	NA
Hf	12	12	8	NA
Ta	5	5	3	NA
Th	4.6	4	3	NA

As is apparent from the tables, there is hardly any resemblance with any known rock from the earth or with any meteorite. The almost complete lack of nickel in the rocks is especially peculiar. With 15 percent iron and also the other trans-

ition elements of the fourth period well represented, there should be some trace of nickel if the lunar material and the material from which the earth and the meteorites were formed had a common origin. How has the differentiation worked, if the lunar rocks are products of a differentiation, which of course is not proven at all? In any case, the rocks at the Apollo 11 site have neither a basaltic nor a eucritic composition.

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Note

1. The authors themselves performed the gravimetric, colorimetric, titrimetric, flame photometric, and atomic absorption determinations. We thank the following specialists who contributed to the work: A. Löfgren and A. Savola, who did the emission spectroscopy; P. Kauranen, P. Puumalainen, E. Häsänen, and R. Rosenberg, who did the neutron activation.

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Quantitative Chemical Analysis of Lunar Samples

Abstract. *In three lunar samples the high titanium contents previously reported were confirmed. Water and ferric oxide were absent.*

Three moon samples were analyzed by classical methods (Table 1) (1). Determinations for sulfur and chromium were made because of their possible petrologic significance (2).

We did not determine metallic iron because we doubt the reliability of published methods and therefore held this determination in abeyance pending discussion with other investigators. Material might be better used in the application of other techniques (for example Mössbauer) to the separated magnetics.

Silica. The procedure was modified to eliminate complications caused by the high concentration of titanium; too much titanium remained with the silica. The procedure (1, p. 62) was followed through step 13, the filtrate set aside, 3 g of sodium carbonate added to the silica, and the procedure repeated from step 3 through step 13. The combined filtrates were used in determination of the ammonium hydroxide group which follows.

Table 1. Analyses of moon samples. Values are percentages.

Compound	Olivine basalt 10020-23	Vesicular basalt 10072-32	Lunar fines 10084-131
SiO ₂	39.95	40.53	42.20
Al ₂ O ₃	10.19	8.52	14.07
Fe ₂ O ₃	.03	.00*	.00†
FeO	19.14	19.76	15.81
MgO	7.87	7.68	7.93
CaO	11.31	10.42	12.01
Na ₂ O	.39	.54	.46
K ₂ O	.05	.27	.12
H ₂ O ⁺	.00	.00	.05
H ₂ O ⁻	.00	.00	.00
TiO ₂	10.52	11.74	7.32
P ₂ O ₅	.07	.14	.08
MnO	.27	.24	.21
S	.18	.24	.14
Cr ₂ O ₃	.38	.35	.28
Subtotal	100.35	100.43	100.68
Less O	.09	.12	.07
Total	100.26	100.31	100.61

*Actual value obtained minus 0.14.
value obtained minus 0.12.

†Actual

Ferrous oxide. The presence of troilite (FeS) and metallic iron makes results for ferrous oxide uncertain (1, pp. 39-42). Hydrogen sulfide should not interfere greatly, because no reducible element is present and most of the hydrogen sulfide is expelled during solution of the sample. Metallic iron is counted as ferrous oxide in the analysis.

Ferric oxide. Ferric oxide is determined by difference after separate determinations of total iron oxide and ferrous oxide. The cumulative errors in both of these determinations are therefore reflected in the value for ferric oxide. The small negative and positive amounts found are probably due to such errors. Within accuracy limits of the method, the samples do not contain ferric oxide.

Combined water. The H₂O⁺ reported in sample 10084-131 is probably water adsorbed after the sample reached earth; strongly adsorbed water is not expelled when a silicate is heated at 105°C.

Titanium oxide. Titanium oxide was determined colorimetrically (1, p. 70). The precision of the method is probably no better than ±0.1 percent absolute.

Chromium oxide. It is likely that most of the chromium oxide is present in mafic minerals. Sample 10084-131 contained a little black material that might be chromite, but there was no evidence of its presence in the other two samples.

The summation on sample 10084-31 is unacceptably high. The presence of metallic iron, in amounts of about 3 percent, could account for the high total. (Metallic iron is reported as ferrous oxide.) Data from others, however, indicate that 1 percent or less of iron is present. Other factors may contribute to the high total. For example, powder segregation is troublesome in samples containing particles of high density.

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References and Notes

1. Except where otherwise noted, procedures described in *U.S. Geol. Surv. Bull. 1170* were used.
2. Methods used are described in I. M. Kolthoff and E. B. Sandell, *Textbook of Quantitative Inorganic Analysis* (Macmillan, New York, ed. 3, 1952), p. 724.

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