Chemical Composition of Crystalline Rock Fragments From Luna 16 and Luna 20 Fines

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This paper deals with the chemical composition (bulk, rare earth, and trace elements) of the Luna 16 mare regolith and Luna 20 highland regolith, as shown by 14 basaltic rock fragments (Luna 16) and 13 rock fragments of the ANT suite (Luna 20). On the basis of bulk composition, two types of basaltic rocks have been differentiated and defined in the Luna 16 regolith: mare basalts (fundamental crystalline rocks of Mare Fecunditatis) and high-alumina basalts. The bulk analyses of rock fragments of the ANT suite also enabled distinction of two rock types: anorthositic norites and troctolites and/or spinel-troctolites (the most abundant crystalline rocks of the highland region, the landing site of Luna 20), and anorthosites. The chemical composition of Luna 16 and Luna 20 regolith samples is compared. Differences in the chemistry of the Luna 16 mare regolith and that of mare basalts are discussed. The chemical affinity between the Luna 20 highland regolith and (a) anorthositic norites and (b) troctolites and/or spinel-troctolites has been ascertained.

The Soviet Luna 16 automatic station collected soil samples in the typical lunar mare region (Mare Fecunditatis) and Luna 20 in the typical highland region, between Mare Fecunditatis and Mare Crisium, near Apollonius C Crater, about 120 km north of the sample collection of Luna 16 (ref. 1). Examination of the two samples makes it possible to compare the rocks of these lunar regions of different geological character.

In Czechoslovakia, the lunar soil samples of Luna 16 and Luna 20 (both whole samples and their rock fragments) were subjected to interdepartmental studies. The fragments were handpicked from the fraction of above 100 μm and were preliminarily characterized under a stereomicroscope. The results of chemical analyses and petrographic studies of some lunar rock fragments (primary and secondary) from the Luna 16 soil have been published, for example, in Adam et al. (ref. 2), Cimbálníková et al. (ref. 3), and Cimbálníková et al. (in press, 1974) (ref. 4).

This paper presents the chemical composition of other lunar crystalline rock fragments obtained from the Luna 16 mare regolith samples—14 fragments of basaltic rocks, including four analyses of basaltic fragments (see table 1). The analyses were published in Adam et al., 1973 (ref. 1). This paper also presents analyses from the Luna 20 highland regolith (13 rock fragments of the ANT suite) (see table 2). The nondestructive neutron activation analysis (INAA) was used for the study; and the weight of the samples analyzed ranged from 0.097 to 4.764 mg.

The purpose of our study was (1) to determine the chemistry of crystalline rock types from Luna 16 and Luna 20 soils (by their bulk composition) and to compare them; (2)

Table 1.—*Chemical Composition of Soil and*

		Luna 16 Soil	Mare Basalts								
			1012 (1)	1007 (1)	1008 (1)	2005 (1)	1029	1651	1652	1653	1654
		mg	2.660	0.670	0.366	0.724	0.545	1.880	0.719	1.337	1.990
Wt. %	Si	20.0	16.5	17.2	24.3	20.6	< 33.0	22.5	21.8		27.6
	Ti	1.9	2.2	2.3	2.5	2.5	2.1	3.2	2.9	3.2	2.9
	Al	8.7	4.6	4.7	4.7	4.9	4.8	6.9	6.9	7.0	7.2
	Cr	0.20	0.21	0.20	0.24	0.18	0.14	0.19	0.17	0.25	0.18
	Fe	13.7	19.9	20.0	19.6	18.0	17.3	18.8	15.5	16.8	17.7
	Mn	0.20	0.23	0.22	0.20	0.21	0.18	0.22	0.25	0.21	0.23
	Mg	5.3	3.3	3.4	2.5	2.9	6.2	3.8	5.2	5.7	4.7
	Ca	9.2	6.5	6.2	6.2	6.7	8.8	8.6	7.4	8.3	7.8
	Na	0.32	0.42	0.50	0.47	0.40	0.30	0.33	0.30	0.35	0.35
	K	0.12	0.17		0.22	0.19	0.18	0.14	0.16		0.14
ppm	Sc	60	89	83	88	83		70	55	76	70
	V	90	55	51	68	60	65	89	81	104	89
	Co	30	22	27	27	30	30	24	60	25	22
	Sr	350	500	754	741		560	800	1100		1000
	Ba	250	280	410	243	294	330	400	400	460	400
	La	15					10	20	20	16	21
	Ce	45	59	79	66	56		65	65	58	70
	Nd	40						50	60	70	62
	Sm	7	15	19	17	14	11	15	16	15	15
	Eu	2	5	6	5	5	2	4	3.5	4	5
	Tb	1.7						2.8	2.5	2.5	3
	Dy	12	17.3	31.6	26	31.9	14	20	24	14	21
	Ho	2.2						4	4	3	5
	Tm							2.6	2.8	2.7	1.6
	Yb	6						9	9	7	10
	Lu	1						1.5	1.4	1.1	1.5
	Hf							13	10	11	14
	Th	1.1						1.1	1.2	—	1.2
	U	0.7	0.9								1
Wt. %	SiO_2	42.8	35.3	36.8	52.0	44.1		48.1	46.6		59.1
	TiO_2	3.17	3.7	3.8	4.2	4.2	3.5	5.3	4.8	5.3	4.8
	Al_2O_3	16.4	8.7	8.8	8.9	9.3	9.1	13.1	13.0	13.2	13.6
	Cr_2O_3	0.29	0.31	0.29	0.35	0.26	0.21	0.28	0.25	0.37	0.26
	FeO	17.6	25.6	25.7	25.2	23.1	22.5	24.2	19.9	21.6	22.7
	MnO	0.26	0.29	0.28	0.26	0.27	0.23	0.28	0.32	0.27	0.29
	MgO	8.8	5.5	5.6	4.2	4.8	10.3	6.3	8.6	9.5	7.8
	CaO	12.9	9.1	8.7	8.7	9.4	12.3	12.0	10.4	11.6	10.9
	Na_2O	0.43	0.56	0.66	0.62	0.53	0.40	0.44	0.40	0.46	0.46
	K_2O	0.144	0.20		0.26	0.23	0.21	0.17	0.19		0.17

NOTE: (1) Adam et al. (ref. 2).

Basaltic Fragments From Luna 16 Fines

Mare Basalts—Continued				High-Alumina Basalts				
1656	1659	Average	Range	1028	1657	1662	Average	Range
0.327	0.599			1.092	0.320	0.344		
21.5			16.5 – 27.6	40.0	24.0	18.5		18.5 – 24.0
2.5	3.8	2.7	2.1 – 3.8	1.4	2.4	1.6	1.8	1.4 – 2.4
5.0	7.2	5.8	4.6 – 7.2	8.6	7.5	9.7	8.6	7.5 – 9.7
0.12	0.20	0.19	0.12 – 0.25	0.20	0.14	0.19	0.18	0.14 – 0.20
13.7	16.1	17.6	16.1 – 20.0	12.1	11.1	10.1	11.1	10.1 – 12.1
0.21	0.23	0.20	0.18 – 0.25	0.17	0.20	0.16	0.18	0.16 – 0.20
4.2	5.3	4.3	2.5 – 6.2	5.7	5.2	5.1	5.3	5.1 – 5.7
7.5	9.8	7.6	6.2 – 9.8	9.2	8.7	9.7	9.2	8.7 – 9.7
0.40	0.35	0.38	0.30 – 0.50	0.27	0.30	0.25	0.27	0.25 – 0.30
0.15	0.14	0.17	0.14 – 0.22		0.12	0.10	0.11	0.10 – 0.12
57		75	55 – 89	50	55	45	50	45 – 55
67	107	76	51 – 107	105	105	67	92	67 – 105
	25	29	22 – 60	45	100	30	58	30 – 100
	500	744	500 – 1100	300	—	—	300	
420	400	371	243 – 460	170	360	400	310	170 – 400
22	20	18	10 – 22	11	15	12	13	11 – 15
73	60	65	59 – 79	66	50	35	50	35 – 66
65	60	61	50 – 70	27	20	30	26	20 – 30
17	15	15	11 – 19	7	12	10	10	7 – 12
4.6	4	4.4	2 – 6	2	4	2.5	2.8	2 – 4
2.5	3	2.7	2.5 – 3		2	1.3	1.6	1.3 – 2
26	22	22.5	17.3 – 31.9	11	20	12	14	11 – 20
4	4.2	4	3 – 5		3.5	2	2.8	2 – 3.5
2.4		2.4	1.6 – 2.8		1.9	1.2	1.6	1.2 – 1.9
9	9	9	7 – 10	5.5	7	6	6	5.5 – 7
1.5	1.3	1.4	1.1 – 1.5	0.7	1	0.8	0.8	0.7 – 1
13	13	12	10 – 14		8	6	7	6 – 8
1.7	1.5	1.3	1.1 – 1.7		1.1	1.7	1.4	1.1 – 1.7
		1	0.9 – 1					
46.0			35.3 – 59.1		51.4	39.6		39.6 – 51.4
4.2	6.3	4.6	3.5 – 6.3	2.3	4.0	2.7	3.0	2.3 – 4.0
9.6	13.6	11.0	8.7 – 13.6	16.25	14.2	18.3	16.2	14.2 – 18.3
0.13	0.29	0.28	0.18 – 0.37	0.29	0.21	0.28	0.26	0.21 – 0.29
17.6	20.7	22.6	17.6 – 25.7	15.6	14.3	13.0	14.3	13.0 – 15.6
0.27	0.29	0.28	0.23 – 0.32	0.22	0.26	0.20	0.23	0.20 – 0.26
7.0	8.8	7.1	4.2 – 10.3	9.5	8.6	8.5	8.9	8.5 – 9.5
10.5	13.7	10.7	8.7 – 13.7	12.9	12.2	13.6	12.9	12.2 – 13.6
0.53	0.46	0.50	0.40 – 0.66	0.36	0.40	0.33	0.36	0.33 – 0.40
0.18	0.17	0.20	0.17 – 0.26		0.14	0.12	0.13	0.12 – 0.14

Table 2.—*Chemical Composition of Soil and Rock*

		Luna 20 Soil	Anorthosites						
			20001	20002	20010	20012	20013/15	Average	Range
		mg	0.518	0.622	0.410	0.213	0.233		
Wt. %	Si	20.0	23.0	14.8	20.0	24.0	21.0		14.8 – 24.0
	Ti	0.28	—	—	—	—	—	—	
	Al	12.5	18.8	20.9	20.1	17.5	19.7	19.5	17.5 – 20.9
	Cr	0.11	180 (1)	50 (1)	18 (1)	10 (1)	38 (1)	29 (1)	10 (1) – 50 (1)
	Fe	5.1	1.90	0.30	0.14	0.17	0.25	0.22	0.14 – 0.30
	Mn	83 (1)	400 (1)	84 (1)	50 (1)	100 (1)	80 (1)	78 (1)	50 (1) – 100 (1)
	Mg	5.7	1.9	1.3	1.2	1.2	1.7	1.4	1.2 – 1.7
	Ca	10.3	14.0	14.7	16.2	13.7	13.5	14.5	13.5 – 16.2
	Na	0.26	0.35	0.37	0.20	0.22	0.30	0.27	0.20 – 0.37
	K	0.05	—	560 (1)	300 (1)	<800 (1)	610 (1)	490 (1)	300 (1) – 610 (1)
ppm	Sc	15	5	1.5	0.2	0.3	0.6	0.7	0.2 – 1.5
	V	43							
	Co	28	45	31	47	90	90	64	31 – 90
	Sr	<120	435	400	300	<450	360	353	300 – 400
	Cs	240							
	Ba	170	80	10	200	140	150	125	10 – 200
	La	8	1.1	0.6	1.7	2	2	1.6	0.6 – 2
	Ce	18	2.7	2.1	4	4	5	3.8	2.1 – 5
	Nd	20							
	Sm	3.5	0.5	0.33	0.5	1	0.5	0.6	0.3 – 1
	Eu	1	0.7		1.8	0.8	1.5	1.4	0.8 – 1.8
	Tb	0.6		0.1					
	Dy	5	1	0.9	0.8	1	0.5	0.8	0.5 – 1
	Ho	1.3							
	Yb	2.5	0.5	0.3				0.3	
	Lu	0.4	0.05	0.05				0.05	
	Hf	0.3	0.3	0.3					
	Th	0.9	0.17						
	U	0.75							
Wt. %	SiO_2	42.8	49.2	31.7	42.8	51.4	45.0		31.7 – 51.4
	TiO_2	0.47	—	—	—	—	—	—	—
	Al_2O_3	23.6	35.5	39.5	38.0	33.1	37.2	36.95	33.1 – 39.5
	Cr_2O_3	0.16	260 (1)	73 (1)	26 (1)	14 (1)	55 (1)	42 (1)	14 (1) – 73 (1)
	FeO	6.6	2.4	0.38	0.18	0.22	0.32	0.28	0.18 – 0.38
	MnO	0.10	520 (1)	108 (1)	65 (1)	130 (1)	103 (1)	101 (1)	65 (1) – 130 (1)
	MgO	9.5	3.15	2.16	1.99	1.99	2.80	2.24	1.99 – 2.80
	CaO	14.4	19.6	20.6	22.7	19.2	18.9	20.4	18.9 22.7
	Na_2O	0.35	0.47	0.50	0.27	0.29	0.40	0.36	0.27 – 0.50
	K_2O	0.06		670 (1)	360 (1)		735 (1)	590 (1)	360 (1) – 735 (1)

NOTE: (1) In parts per million.

Fragments of the ANT Suite From Luna 20 Fines

Anorthositic Norites and Troctolites and/or Spinel-Troctolites									
20003	20004	20005	20023	20026/28	20032	20142	20143	Average	Range
2.829	0.483	0.258	0.097	0.227	0.140	4.764	0.773		
20.7	23.0		18.0	13.7	20.0	24.0	24.0		13.7 - 24.0
0.09	0.16	0.17	0.25		0.18	0.27	0.28	0.20	0.09 - 0.28
11.9	14.0	12.1	15.3	13.3	10.9	12.7	14.8	13.1	10.9 - 15.3
0.10	0.11	0.18	0.18	900[1]	990[1]	0.12	0.12	0.12	0.09 - 0.18
5.0	4.5	3.4	6.0	3.8	4.2	5.9	5.3	4.8	3.4 - 6.0
650[1]	650[1]	500[1]	0.1	515[1]	600[1]	850[1]	850[1]	700[1]	0.05 - 0.1
10.5	11.7	8.6	10.3	7.3	9.5	6.2	5.3	8.7	5.3 - 11.7
9.2	10.7	9.1	12.8	10.4	8.6	10.8	12.3	10.5	8.6 - 12.8
0.25	0.37	0.40	0.20	0.47	0.15	0.30	0.25	0.30	0.15 - 0.47
						0.10	550[1]	780[1]	550[1] - 0.1
6	7.5	4.3	12	5.8		13	15	9.1	4.3 - 15
34	31	51	90	27		34	56	46	27 - 90
29	50	90	250	90	150	22	45	91	29 - 250
<140						190	320	255	190 - 320
< 10		31							
100	100	220	290	300	160	200	150	190	100 - 300
1.3	1.5	3.4	1.5	2.9	3	19	8.5	5.1	1.2 - 19
4.2	6	8	5.6	8	7	40	20	12.3	4.2 - 40
0.6	0.65	1.4	0.9	1.1	1.2	8	4	2.2	0.6 - 8
0.8	0.6	0.8	0.7	1.2	1	1.5	1.4	1.0	0.6 - 1.5
		0.25				1.4	0.5		
1.2	1.3	2.7	4	1.6	2.8	10	6.4	3.7	1.2 - 10
			0.14			2	1.5		
0.6	0.8	1	0.7	1.4	1.6	6	2.8	1.9	0.6 - 2.8
0.08	0.07	0.16	0.10	0.12	0.20	0.90	0.40	0.25	0.07 - 0.90
						5.5	2.5		
						2.5	1		
						0.8			
44.3	49.2		38.5	29.3	42.8	51.4	51.4		29.3 - 51.4
0.15	0.26	0.28	0.41		0.30	0.45	0.47	0.33	0.15 - 0.47
22.5	26.5	22.8	28.9	25.1	20.6	24.0	28.0	24.8	20.6 - 28.9
0.14	0.16	0.26	0.26	0.13	0.14	0.18	0.18	0.18	0.13 - 0.26
6.4	5.8	4.3	7.7	4.9	5.4	7.6	6.8	6.1	4.3 - 7.7
840[1]	840[1]	645[1]	0.13	665[1]	775[1]	0.11	0.11	0.09	645[1] - 0.11
17.40	19.40	14.27	17.10	12.11	15.77	10.29	8.80	14.40	8.8 - 19.40
12.9	15.0	12.7	17.9	14.6	12.0	15.1	17.2	14.7	12.0 - 17.9
0.34	0.50	0.54	0.27	0.63	0.20	0.40	0.33	0.40	0.20 - 0.63
						0.12	0.06		

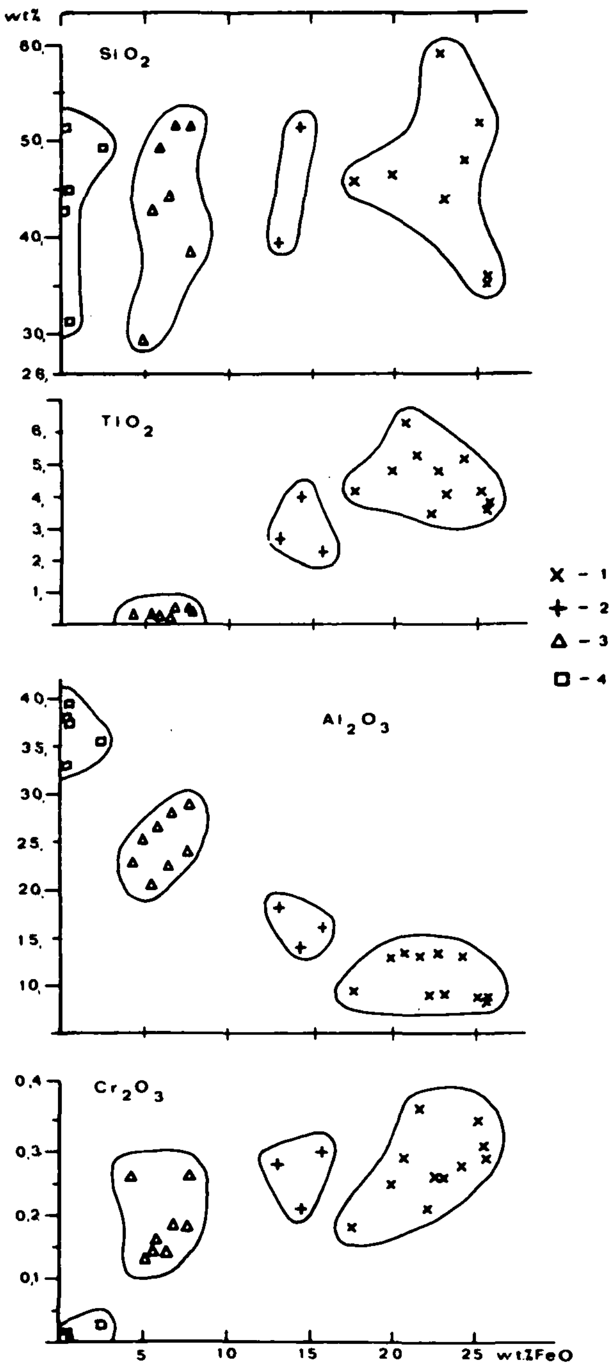

Figure 1.—*Plots of SiO_2, TiO_2, Al_2O_3, and Cr_2O_3 versus FeO in mare basalts and high-alumina basalts from Luna 16 soil and in rocks of the ANT suite from Luna 20 soil (1—mare basalts; 2—high-alumina basalts; 3—anorthositic norites and troctolites, and/or spinel-troctolites; and 4—anorthosites).*

in extending the number of analyzed fragments of lunar crystalline rocks, to contribute to a wider chemical basis for the statistical treatment of the data obtained, and thus to a more detailed and .unbiased description of characteristics of the lunar rock types, and to the recognition of their genetic relations; and (3) to assess the differences in the chemistry of Luna 16 and Luna 20 soils and in that of the major and most abundant types of their crystalline rocks.

The fragments of crystalline rocks separated from the regolith samples are a more objective source of information on the nature of lunar rocks than the study of several more or less randomly collected samples. The study of local rock types typical of mare and highland lunar regions makes it possible to characterize these units of different geological nature. In contrast, the admixture of exotic rock types that are invariably present in the regolith and are derived from greater depths or distant places enables description of an overall characteristic of lunar rocks. The regolith can thus be regarded as a representative of the Moon rocks.

Experimental Studies

The preparation of samples for analysis, the irradiation method used in the nondestructive neutron activation analysis, and the evaluation of chemical composition have been described by Adam et al. (ref. 2). In this procedure the lower limits for quantitative determination are as follows:

Short-time irradiation:

Si	10 %
Ca, Ni	1 %
Ti, Pd, K, Rb, Mo	0.1%
Cl, Cu, Sr, Sn, Al, Ba, Te	100 ppm
Na, V, Sb, Co, Ga, As, Br, I, Cs, La, W	10 ppm
Mn, Sm, Re, Au, U	1 ppm
In, Eu, Dy	0.1 ppm

Long-time irradiation:

Fe, Ni, Zr	0.1%
K, Zn, Rb, Sn, Ce, Pr	100 ppm
Na, Cr, Mo, Ag, Te, La, Gd	10 ppm
Ca, Ga, As, Br, I, Ba, Tb, Mo,	

Tm, Yb, Hf, Ta, W, Re, Th, U	1	ppm
Se, Sb, Nd, Sn, Lu	0.1	ppm
Ir, Au	0.01	ppm

Results

Chemical compositions of analyzed crystalline rock fragments from Luna 16 and Luna 20 soils are summarized in tables 1 and 2. Figures 1 and 2 show the plots of the FeO content versus some other major elements.

Tables 1 and 2 and figures 1 and 2 show that the crystalline rock fragments from Luna 16 and Luna 20 soils form four groups, markedly differing in chemistry, which correspond to the following rock types:

1. Rocks of the ANT suite (anorthosite-norite-troctolitic suite) comprising (a) anorthosites and (b) anorthositic norities and troctolites and/or spinel-troctolites
2. Basaltic rocks involving two subgroups: (a) mare basalts and (b) high-alumina basalts.

For the designation of rocks, the nomenclature and chemical classification proposed by Prinz et al. (ref. 5) have been used.

All fragments of basaltic rocks were obtained from the Luna 16 mare regolith; rock fragments of the ANT suite were collected from Luna 20 highland regolith. Fragments of anorthositic rocks also occur in Luna 16 regolith as they do in all lunar maria sampled so far, but they were not analyzed by the INAA method, since they are rare, very brittle and light. Analogously, the Luna 20 highland regolith contained sporadic rock fragments identical with mare basalts.

ROCKS OF THE ANT SUITE

These constitute the dominant crystalline rock type of the Luna 20 highland regolith. Under a stereomicroscope they are white—milky- or icy-white; yellow olivines and pinkish-brown spinels are discernible in some specimens. The milky-white fragments of the ANT suite are either coarser grained (of

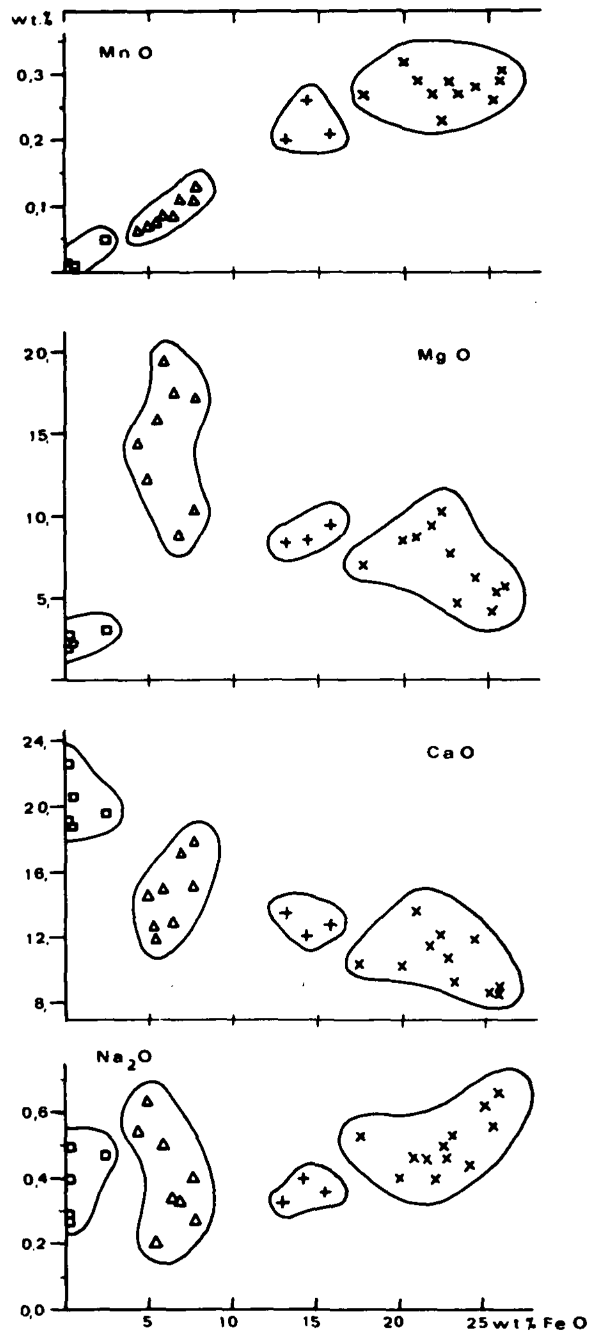

Figure 2.—*Plots of MnO, MgO, CaO, and Na_2O versus FeO in mare basalts and high-alumina basalts from Luna 16 soil and in rocks of the ANT suite from Luna 20 soil.*

depth derivation or recrystallized) or very fine grained (effusive or affected by shock or other alterations).

The rocks of the ANT suite are chemically characterized by a high Al_2O_3 content and low FeO and TiO_2. The Al_2O_3 invariably exceeds 22 weight percent.

From table 2 and figures 1 and 2 it is apparent that the rock fragments of the ANT suite do not constitute a compositionally continuous rock series ranging from anorthosites through noritic and troctolitic anorthosites (such a continuous series was determined by Prinz et al. (ref. 5) from the analyses of a much larger number of fragments (157) from Luna 20), but rather two separate groups. The rocks of the first group correspond in their chemical composition to anorthosites; the second group corresponds to anorthositic norites and troctolites and/or spinel troctolites.

Anorthosites (5 fragments) are virtually monomineral feldspathic rocks (> 90 percent plagioclases (refs. 6 and 5)). For their chemical composition, see table 2. They are characterized by average contents of Al_2O_3 (36.9 wt.%), FeO (0.3 wt.%), and MgO (2.2 wt.%). They are also characterized by ratios of CaO/Al_2O_3 (0.6), Fe/Al (0.01), and Fe/Mg (0.2).

Anorthosites differ from anorthositic norites and troctolites or spinel-troctolites in having higher Al and Ca and Eu (of microelements) and appreciably lower Cr, Fe, Mn, and Mg (7–10 times) and the following microelements: Sc, Co, Ce, Sm, Dy, Yb, Lu (2–4 times), and La. The differences in the content of elements of the two groups in the ANT suite are apparent from figure 3 (macroelements) and figure 4 (microelements). The values obtained for fragment 20001 have not been involved in the computation of average contents (Table 2), because it has somewhat higher Fe, Cr, and Mn relative to other anorthosites. Owing to this, it could be assigned more readily to noritic and troctolitic anorthosites, but its content of Al and Ca is too high for these rocks.

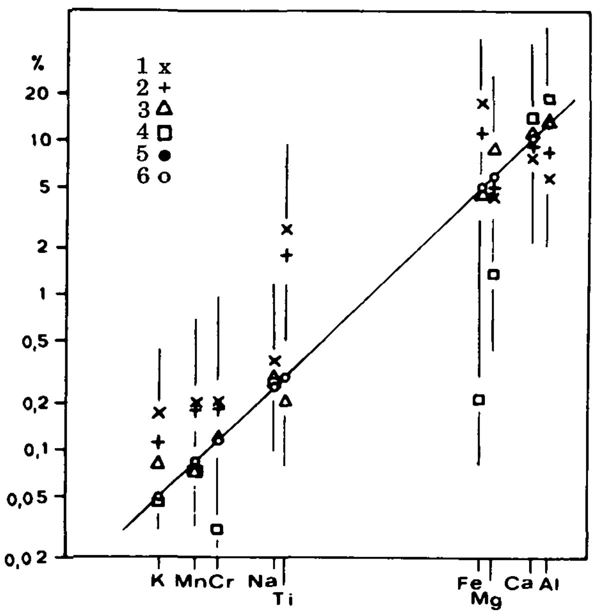

Figure 3.—*Plots of macroelement content in Luna 20 soil (on the straight line (6)) in mare basalts (1), high-alumina basalts from Luna 16 (2), in anorthositic norites and troctolites and/or spinel-troctolites (3), and in anorthosites from Luna 20 soil (4).*

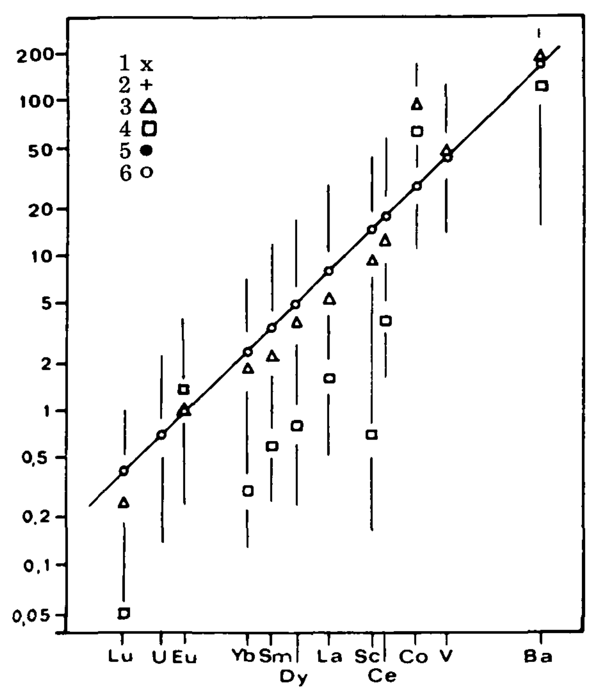

Figure 4.—*Plots of microelement content in Luna 20 soil (on the straight line) and in rocks of the ANT suite from Luna 20.*

Anorthositic norites and troctolites and/or spinel-troctolites (8 fragments) have a higher proportion of mafic minerals, which distinguish them chemically from the anorthosites.

The study of the lunar highland samples has shown that anorthositic norites and troctolites are the most abundant rocks of lunar highlands (refs. 7, 8, 9, 10, 1, and others). Prinz et al. (ref. 5) also identified rocks of spinel-troctolite type in the Luna 20 highland regolith and consider them to be the major highland rock type.

Most of the rock fragments of the ANT suite that we analyzed are compositionally equivalent to anorthositic norite and troctolite types.

Their average contents are as follows:

	Wt.%
Al_2O_3	24.8
FeO	6.1
MgO	14.4
Cr_2O_3	0.2
CaO	14.7

The mean ratios are $CaO/Al_2O_3 = 0.6$; $Fe/Al = 0.4$, and $Fe/Mg = 0.6$.

The average contents of macroelements are near the values given by Prinz et al. (ref. 5) for anorthositic norites and troctolites, except for MgO, which is higher and practically identical with that given by Prinz for spinel-troctolites. On the basis of bulk composition (table 2), fragments 20142, 20143, and probably also 20005 and 20026/28 may be regarded rather as anorthositic norites or troctolites, whereas fragments 20003, 20004, 20023, and 20032 are more likely to be regarded as troctolites. The former have a high TiO_2 content and comparatively lower MgO, while the latter show a strikingly high MgO. The contents of Al_2O_3, CaO, Cr_2O_3, FeO, and MnO do not allow an unequivocal differentiation of the two types in individual fragments. A more precise discrimination of the fragments of this group will be possible only by conducting a petrographical study of their thin sections.

Fragments with Al_2O_3 content corresponding to noritic and troctolitic anorthosites have so far not been found among our materials (except for fragment 20001, whose assignment is unclear). A compositional hiatus thus appears within the group of ANT suite rocks (figs. 1 and 2), which results in the existence of two separate subgroups (anorthosites and anorthositic norites and troctolites and/or spinel-troctolites). The fact that we have not safely established rocks of noritic and troctolitic anorthosite type may be caused by a small number of analyzed fragments, but it provides indirect evidence of the predominance of anorthositic norites and troctolites in the highland region sampled by Luna 20.

BASALTIC ROCKS

These are the major and most abundant crystalline rocks of the Luna 16 mare regolith. In a stereomicroscope, coarser grained microgabbro and fine-grained basalt are easily distinguishable (refs. 11 and 12). Chemically, the rocks have higher FeO and TiO_2 and lower Al_2O_3 than the highland rocks of the ANT suite. Table 1 and figures 1 and 2 show that basalts of two compositionally different types, i.e., mare basalts and high-alumina basalts, are represented in the 14 fragments of Luna 16 mare soils.

Mare basalts (11 fragments) are major crystalline rocks of Luna 16 soil. Like all basalts from the lunar mare terrains so far sampled, they are distinguished by high FeO —invariably above 20 wt.% (22.6 wt.% on the average, except for fragment 1656)—and a low Al_2O_3 content (11.0 wt.% on the average, with a maximum of 13.6 wt.%). The TiO_2 content is also high, averaging 4.6 wt.%. The average ratios are as follows: $CaO/Al_2O_3 = 1.0$; $Fe/Al = 3.0$; $Fe/Mg = 4.1$; and $TiO_2/Al_2O_3 = 0.4$. The chemical compositions of mare basalt fragments are presented in table 1. In regard to chemical composition, the chemistry of Luna 16 mare basalts and its relation to some secondary rocks of this regolith were discussed in more detail by Adam et al. (ref. 2).

In relation to other mare basalt fragments, sample 1012 has a strikingly low FeO (table 1, figs. 1 and 2), only 17.6 wt.%. Its position in the graphs (figs. 1 and 2) at the mare basalt and high-alumina basalt boundary did not show clearly in which groups it should be placed. Since, however, the ratios of Fe/Al = 3.0, TiO_2/Al_2O_3 = 0.4, and CaO/Al_2O_3 = 1.0 are invariably higher than those of high-alumnia basalts, the fragment fits well into the group of mare basalts.

High-alumina basalts (3 fragments) were safely determined in the Luna 20 highland soils by Prinz et al. (ref. 5), who defined them as rocks transitional to anorthositic norites and troctolites. Compared with other rocks of the ANT suite, they have higher TiO_2, Cr_2O_3, FeO, MnO, K_2O, and P_2O_5, and lower Al_2O_3 and CaO. In relation to alkalic high-alumina basalts (KREEP), they are poorer in alkalies and REE. The authors named above believe these high-alumina basalts to be an important group of highland rocks that are genetically related to the rocks of the ANT suite.

Table 1 and figures 1 and 2 clearly show that the chemical composition of basaltic rock fragments 1028, 1657, and 1662 from mare regolith is near to that of high-alumina basalts described by Prinz et al. (ref. 5). The fragments we have studied have the following average contents:

	Wt.%
Al_2O_3	16.2
MgO	8.9
CaO	12.9
TiO_2	3.0

The average ratios are Ca/Al_2O_3 = 0.8, Fe/Al = 1.3, and Fe/Mg = 2.1.

The fragments are richer in Al_2O_3, MgO, and CaO, and poorer in FeO, Na_2O, and K_2O than the mare basalts (fig. 5). Of microelements, Sc, Sm, Dy, and particularly Sr occur in smaller amounts, whereas the V content is somewhat higher (fig. 6). The ratios of Fe/Mg, Fe/Al, TiO_2/Al_2O_3, and CaO/Al_2O_3 are lower than the ratios of mare basalts.

Basalts of KREEP type have not been found in the Luna 16 rock samples.

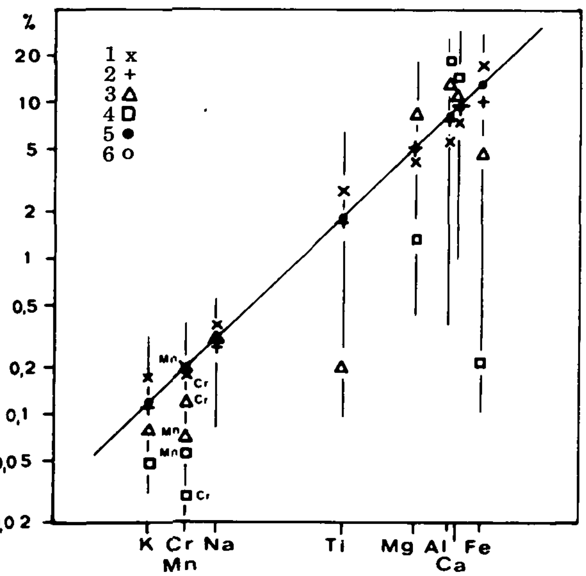

Figure 5.—*Plots of macroelement content in Luna 16 soil (on the straight line (5)), in mare basalts and high-alumina basalts from Luna 16, in anorthositic norites and troctolites and/or spinel-troctolites, and in anorthosites from Luna 20 soil.*

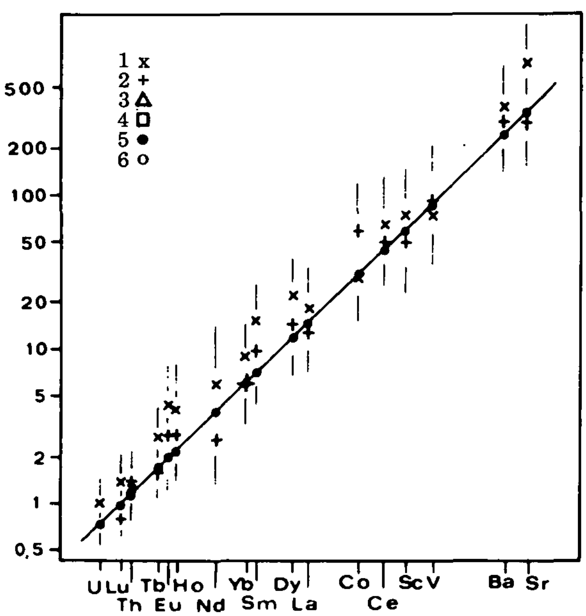

Figure 6.—*Plots of microelement content in Luna 16 soil (on the straight line) and in mare basalts and high-alumina basalts from Luna 16.*

CHEMICAL DIFFERENCES BETWEEN LUNA 16 AND LUNA 20 SOILS AND BETWEEN THEIR MAJOR OR MOST ABUNDANT CRYSTALLINE ROCK TYPES

Mare regolith—mare basalts

Compositional differences between the Luna 16 mare regolith and its basaltic rock fragments are shown in figure 5 (macroelements) and figure 6 (microelements). Compared with its major crystalline rocks, i.e., mare basalts, the Luna 16 regolith has lower Ti, Fe, Na, and K, and higher Al, Mg, and Ca; of microelements, Th, REE (La, Ce, Nd, Sm, Eu, Dy, Ho, Yb, and Lu), Sc, Ba, and Sr occur in smaller amounts, and V content is larger. The contents of Mn, Cr, and Co are very similar.

These differences are caused by an admixture of highland rocks. Figure 5 demonstrates that the deviations in the chemistry of the mare regolith, in relation to those of mare basalts, are more affected by anorthositic norites and troctolites than by anorthosites. This is exemplified especially by Mg (fig. 5), the content of which is higher in anorthositic norites and troctolites and lower in anorthosites than in mare basalts. The Mg amount in the regolith is still higher than in mare basalts and thus nearer to that in anorthositic norites and troctolites. As a result of deviations in the composition of the regolith caused by a proportion of anorthositic norites and troctolites, the chemistry of the Luna 16 mare regolith is closer to the composition of high-alumina basalts than to that of the mare basalts (fig. 5).

Highlands regolith—rocks of the ANT suite

The compositional relationships between the Luna 20 regolith and the ANT suite rocks are shown in figure 3 (macroelements) and figure 4 (microelements). In general, the composition of the Luna 20 highlands regolith shows a close affinity to anorthositic norites and troctolites, whereas it differs from the composition of anorthosites. Small deviations in the composition of the regolith and of anorthositic norites and troctolites are due rather to the presence of basaltic rock fragments than to that of anorthosites. Owing to basalt admixture, the Luna 20 highlands regolith has higher contents of Mn, Ti, and Fe, and lower amounts of Mg, Ca, and Al. On the whole, the Cr content remains unchanged. This chemical affinity between the Luna 20 highlands regolith and anorthositic norites and troctolites provides additional indirect evidence for the predominance of anorthositic norites and troctolites in the highland regolith.

Mare regolith—highlands regolith

The chemical data we have obtained for the Luna 16 and Luna 20 regolith samples (tables 1 and 2, respectively) are on the whole in agreement with the data given for both regoliths by Vinogradov (ref. 1).

For easier correlation, the relationships between the contents of elements from Luna 20 highland soils and Luna 16 mare soils are plotted in figure 7 (macroelements) and figure 8 (microelements). The latter have higher contents of K, Mn, Cr, Na, and especially Ti and Fe, and lower amounts of Mg, Ca, and Al than the former.

Conclusions

1. On the basis of bulk composition, two types have been differentiated in basaltic rock fragments from the Luna 16 mare soil: mare basalts and high-alumina basalts.

In relation to mare basalts, the high-alumina basalts have higher contents of Al_2O_3 (an average value of 16.2 versus 11.0 wt. %), MgO, and CaO, and lower content of FeO (an average value of 14.3 versus 22.6 wt.%), TiO_2, MnO, Na_2O, and K_2O.

2. Two rock groups have been distinguished in the rock fragments of the ANT

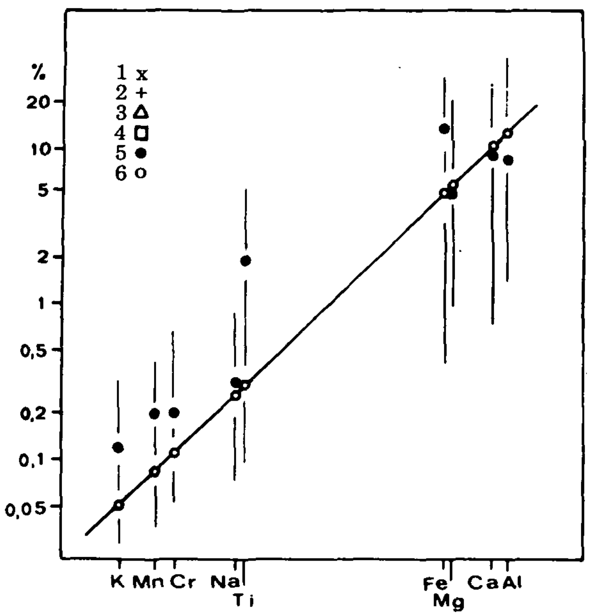

Figure 7.—*Plots of macroelement content in Luna 20 soil (on the straight line) and in Luna 16 soil.*

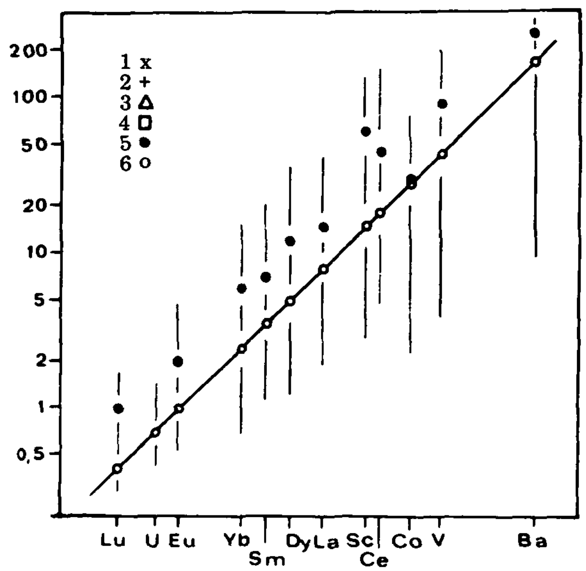

Figure 8.—*Plots of microelement content in Luna 20 soil (on the straight line) and in Luna 16 soil.*

suite from Luna 20 highlands regolith: anorthositic norites and troctolites and/or spinel-troctolites, and anorthosites.

Anorthositic norites and troctolites possess larger amounts of MgO (an average value of 14.4 versus 2.2 wt.%), TiO_2, Cr_2O_3, FeO, and MnO, and less Al_2O_3 (an average value of 24.8 versus 36.9 wt.%) and CaO, in comparison with anorthosites.

3. In relation to the major crystalline rocks, i.e., mare basalts, the Luna 16 mare regolith has lower contents of Ti, Fe, Na, and K; lower contents of microelements Th, REE, Sc, Ba, and Sr; and higher contents of Al, Mg, Ca, and V (of microelements). These compositional deviations are due to the admixture of fragments of anorthositic norite and troctolite rock types. The predominance of anorthositic norites and troctolites even in highland fragments of Luna 16 mare regolith is thus confirmed. The finding is in keeping with the view that anorthositic norites and troctolites are the most abundant rock types of lunar highlands.

4. The chemical composition of the Luna 20 highlands regolith is very close to that of anorthositic norites and troctolites. Deviations are accounted for by the admixture of basaltic rocks; their small size suggests a slight contamination.

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