ELSEVIER Nuclear Instruments and Methods in Physics Research A 448 (2000) 376–383

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Particularities of rare element distribution in high-aluminium basalts from mare and highland regions of the Moon (based on SR-XFA data)

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Abstract

X-ray fluorescence analysis using synchrotron radiation (SR-XFA) has been applied for determination of rare elements (Rb, Sr, Y, Zr, Nb, Ba, La, and Ce) in lunar high aluminium (HA) and very high aluminium (VHA) basalts of Apollo 12, 14, and 15 (new multielement SR-XFA analysis of 50 lunar fragments). A comparison of all SR-XFA data for different lunar rocks (multielement SR-XRF analysis more than 300 lunar fragments) makes it possibile to suggest a common origin of HA and VHA basalts. These rocks are the result of partial melting of various basaltic magmas, but have not originated from lunar magmatic ocean. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 95.55.Pe; 32.30.Rj

Keywords: Synchrotron radiation X-ray fluorescence analysis; Rare elements in lunar regolith; Geochemistry of lunar rocks; Mare and highland lunar rocks

1. Introduction

In our previous works we have studied the rare element distribution in mare basalts [1], highland rocks [2], and ancient mare rocks [3,4] of the Moon. In this paper, we report the results of investigation of the rare element distributions in high-aluminium (HA; 15–20 wt% Al_2O_3) and very high-aluminium (VHA; 20–27 wt% Al_2O_3) lunar rocks.

2. The aim of the work

Mare and highland rocks represent two main types of rocks on the Moon. Highland rocks form the lunar crust, thickness of which is about 60 km. Mare rocks fill depressions to capacity mostly on the near side of the Moon. Highland rocks have

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PII: S0168-9002(99)00695-6

very ancient ages (4.0–4.5 Gyr). Mare rocks are a little bit younger, but they have essentially ancient ages (3.2–3.8 Gyr) also. HA basalts returned by mission of Apollo 14 have ages 4.0–4.2 Gyr [5]. Petrogenesis of lunar rocks is a very important part to our understanding of origin of the Moon and its evolution as a planet. For resolving some problems in petrogenesis of lunar rocks we used the geochemical data on the distribution and fractionation of rare elements in different types of lunar rocks, obtained by multi-element synchrotron radiation X-ray fluorescent analysis (SR-XFA) of small lunar fragments which were returned by both manned and unmanned missions to the Moon.

3. Samples and method of analysis

Samples for SR-XFA were small fragments of lunar rocks, sizes of which ranged from 0.*x* to 2–3 mm. Method of SR-XFA fulfill a need for requirements for investigation of these sample. Features of synchrotron radiation [2,6–10] open up possibilities for analysis of rare elements in small objects at very short exposure time. Our investigations were carried out on the Element Analysis Station on the storage ring VEPP-3 in G.I. Budker Institute of Nuclear Physics. The principles and features of SR-XFA on this storage ring have been described in Refs. [6–10], and the results of methodical and geochemical investigations using SR-XFA in Refs. [1–4,11–14]. BCR-1 was used as a main external standard for determination of rare element contents in lunar fragments.

4. Features of compositions of lunar rocks

Almost all of the highland rocks (Apollo 16 and Luna 20) are characterized by a very small scale of differentiation. The dominant groups of the highland rocks have low contents of rare elements (in ppm): Zr < 60, Y < 20, and Nb < 10. Mare very low titanium (VLT) basalts of Luna 24 and rare VLT basalts of Apollo 17 have similar small scales of fractionation (in ppm): Zr 10–60 and Y 4–20 (Fig. 1) [4,11,13]. Ages of these rocks are 3.25–3.54 Gyr [15]. Our SR-XFA data on Zr, Y, Nb in all fragments of aluminium (A), HA, and VHA basalts from Apollo 14 are (in ppm): 480–1370, 170–400, and 50–180, respectively (for classification groups III–VII) (see Table 1). Contents of rare elements in all A, HA, and VHA rocks from Apollo 14 are essentially higher (factor 10 and

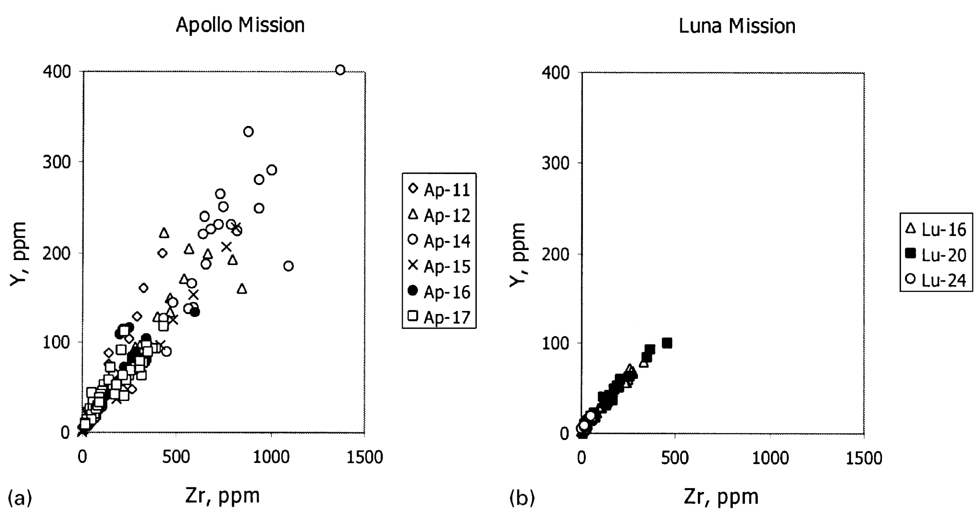

Fig. 1. Y vs. Zr diagrams for lunar rocks returned by Apollo (a) and Luna (b) missions.

Table 1
Contents of rare elements in lunar rocks of Apollo 14 on SR-XFA data (in ppm)

Number of sample	Weight (mg)	Description of sample	Rb	Sr	Y	Zr	Nb	Ba	La	Ce
Group III (A)										
14162,248-6,34	9.35	Light gray porphyritic basalt	3.5	104	264	732	70.3	823	83.8	208
14162,248-6,30	8.1	Light gray basalt	7.7	106	165	578	51.0	786	58.8	163
14162,248-6,29	13.5	Light gray basalt	6.5	136	186	1090	49.4	1425	130.1	371
Group IV (A)										
14162,248-6,31	6.0	Light gray basalt	4.5	47	89	447	27.8	796	48.7	144
14162,248-6,43	2.9	Light gray porphyritic rock	8.0	74	226	683	66.9	535	99.9	293
14162,248-6,47	9.8	Dark gray porphyritic rock	4.2	101	231	786	164.5			
14162,248-6,48	2.95	Dark gray aphanitic rock	6.6	119	402	1365	182.5	2311	172.5	385
14162,248-6,32	2.35	Gray basalt	11.5	91	240	647	73.8	757	94.4	266
Group V (A)										
14162,248-6,35	6.2	Light gray porphyritic basalt	3.5	89	140	588	70.2	742	58.4	153
14162,248-6,44	2.45	Gray porphyritic rock	4.0	127	291	999	119.6	893	93.0	239
14162,248-6,49	3.3	Dark gray porphyritic rock	1.6	113	223	819	82.8	989	95.9	234
14162,248-6,36	2.3	Gray feldspar rock	8.1	118	249	933	107.9	937	91.1	267
14162,248-6,50	3.5	Gray porphyritic rock	4.2	108	281	935	108.0	1192	105.9	276
14162,248-6,41	9.35	Dark gray porphyritic rock	3.6	53	114	216	32.6	897	42.4	128
14162,248-6,45	5.5	Dark gray porphyritic rock	19.6	110	251	748	88.5	1134	105.3	214
14162,248-6,42	5.4	Dark gray medium-grained porphyritic rock	18.6	94	232	725	75.9	1612	76.6	222
Group VI (HA)										
14162,248-6,25	8.95	Leucocratic porphyritic gabbro	1.8	131	65	163	14.7	358	28.7	76
14162,248-6,28	1.45	Shock-metamorphic gabbro	0.3	25	24	32	0.1	52	1.5	4
14162,248-6,37	13.0	Gray medium-grained rock	9.0	140	186	656	70.1	561	51.5	127
Group VII (VHA)										
14162,248-6,38	2.5	Dark gray fine-grained rock	8.1	111	145	477	55.9	530	45.0	112
14162,248-6,26	2.05	Coarse-grained gabbro	18.8	156	333	877	80.3	716	77.9	234
14162,248-6,27	1.35	Coarse-grained leucocratic gabbro	7.1	129	137	563	45.1	558	40.2	134

more) than in ordinary mare basalts from Apollo 12 and 15 (see below) (Figs. 1a–3a).

Basalts from Apollo 12 and 15 are subdivided into two groups: (i) ordinary LT mare basalts, and (ii) HA and VHA basalts. LT basalts are characterized by low contents or rare elements (Figs. 1a–3a, Table 2): for LT basalts from Apollo 12 and 15 the contents of Zr, Y, and Nb are (in ppm): 20–90 and 20–60, 10–40 and 7–30, 2–10 and 1–5 [1]. In Figs. 1a–3a all points, corresponding to the LT basalts, occupy fields near the origin of coordinates. This suggests that LT basalts are formed from silicate magma with a small factor of differentiation. The HA and VHA basalts are characterized by high contents of rare elements. For Apollo 12, contents of Zr, Y, and Nb are (in ppm): 150–840 (rare up to 2100), 80–200 (rare up to 640), and 35–90 (rare up to 380), respectively; for Apollo 15 the contents of these elements are (in ppm): 410–1700, 100–350, and 40–70 (rare up to 150). The high contents of rare elements in these basalts suggest that HA and VHA rocks are products of high differentiation magmas, similar to Apollo 14 magma.

Fields of HA and VHA basalts on the diagrams Y vs. Zr, Zr vs. Sr, and Nb vs. Zr (Figs. 1–3) lie as thin parallel or partly overlapped bands. Similarity in evolution trends for different diagrams (Zr vs. Sr, Y vs. Zr, and Nb vs. Zr) is the main feature of HA and VHA basalts from Apollo 12, 14, and 15. Very small dispersion in Sr contents and large variations

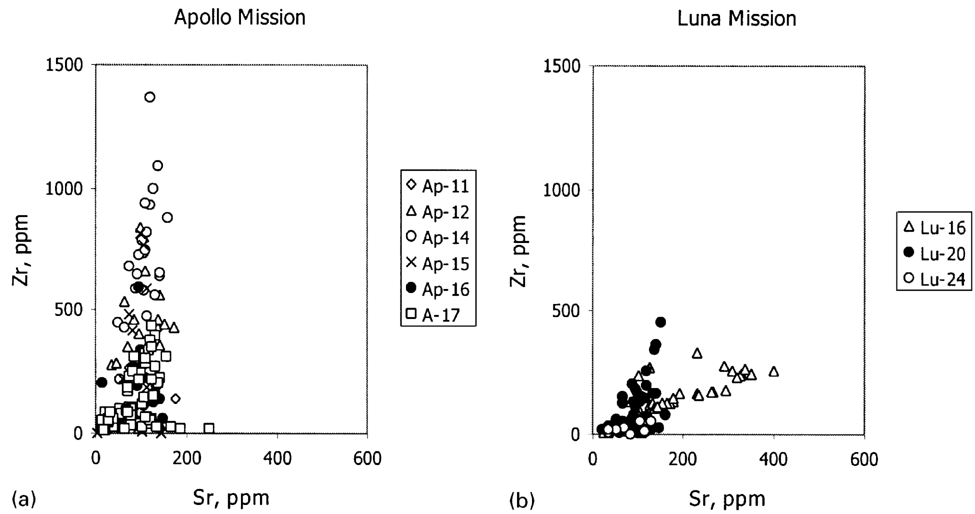

Fig. 2. Zr vs. Sr diagrams for lunar rocks returned by Apollo (a) and Luna (b) missions.

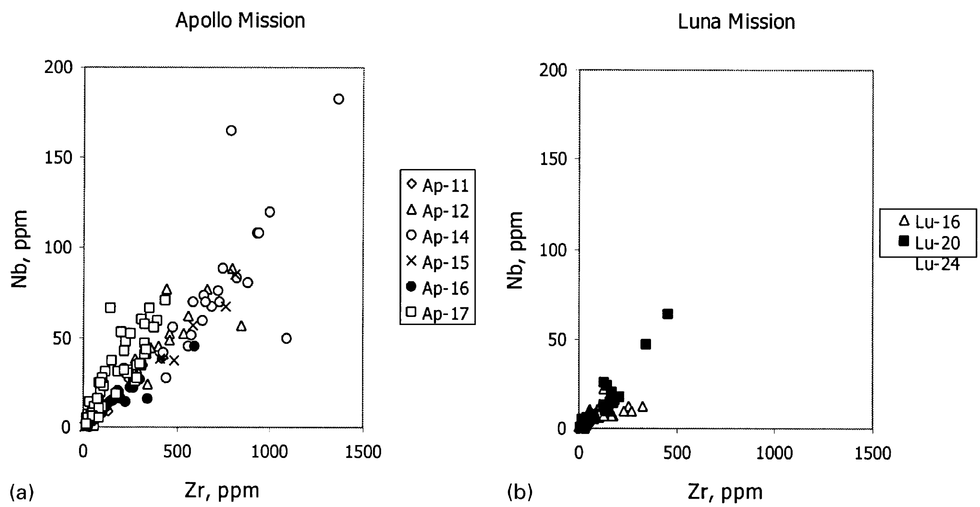

Fig. 3. Nb vs. Zr diagrams for lunar rocks returned by Apollo (a) and Luna (b) missions.

of Zr in lunar basalts are reflected by thin near-vertical fields on the Zr vs. Sr diagram (Fig. 2). Although ages of basalts from Apollo 12, 14, and 15 are different, the general tendency of composition trend within the boundaries of Zr–Sr area is common to the three different regions of the Moon. This suggests the similar character of geochemical differentiation of parent lunar magmas. The same is true for Y vs. Zr (Fig. 1) and Nb vs. Zr (Fig. 3) diagrams. Slopes of areas on each diagram are kept nearly constant. The last suggest that geochemical situation at the crystallization of magmatic liquids has been retained with no (or very small) changes.

The last two groups of lunar rocks are high-titanium (HT) basalts of Apollo 11 [1], Apollo 17 [14], and aluminium-rich titanium (T) basalts of Luna 16 [4]. HT basalts begin the time sequence of mare basalts and have ages 3.6–3.8 Gyr [5].

Table 2
Contents of rare elements in lunar rocks of Apollo 11, 12, and 15 on SR-XFA data (in ppm)

Number of sample	Wt.(mg)	Description of sample	Rb	Sr	Y	Zr	Nb	Ba	La	Ce
Apollo 11. Group II (VHA)										
10085,169-5,128	0.45	Leucocratic gabbro	0.5	176	88	138	9.3	77	7.7	29
Apollo 12. Group I (VHA)										
12033,22-5,223	0.45	Dark gray aphanitic rock	4.7	94	129	402	45.0	488	40.4	136
12033,22-5,224	0.2	Plagioclase-porphyritic rock with black aphanitic matrix	5.7	99	160	842	56.9	433	35.6	101
12033,22-5,221	0.65	Dark gray aphanitic rock	7.3	109	200	664	76.6	834	74.6	191
12033,22-5,227	0.9	Dark gray fine-grained rock	5.5	141	204	562	61.9	635	53.7	242
12033,22-6,179	1.15	Plagioclase-porphyritic fine-grained rock	3.5	136	149	463	49.0	735	38.4	165
12033,22-5,183	0.8	Plagioclase-porphyritic rock with black aphanitic matrix	3.3	83	96	308	36.3	435	30.8	151
12033,22-5,222	0.5	Dark gray aphanitic rock	4.8	84	134	464	52.3	550	50.8	133
12033,22-5,225	1.0	Dark gray aphanitic rock	2.2	35	83	278	38.5	719	76.6	211
12033,22-5,182	0.55	Plagioclase-porphyritic rock with black aphanitic matrix	2.3	142	61	358	44.3	331	22.0	62
Apollo 12. Group VII (VHA)										
12033,22-5,219	0.3	Light gray medium-grained basalt	5.1	90	87	282	33.1	486	14.9	47
12033,22-5,184	0.3	Plagioclase-porphyritic rock with fine-grained matrix	40.0	105	193	797	88.5	1955	79.1	160
12033,22-5,185	0.45	Black aphiritic rock	3.2	45	95	285	29.5	627	69.0	159
12033,22-5,191	0.25	Dark gray fine-grained rock	35.5	142	640	2108	378.7	2063	113.7	290
12033,22-5,220		Light gray rock	5.5	62	171	535	51.8	457	68.8	162
12033,22-5,216	0.55	Light gray rock with spinel	2.5	16	129	148	9.6	73	6.1	17
12033,22-5,187	0.1	Coarse- to medium-grained basalt	0.7	17	22	43	4.1	26	6.4	9
Apollo 15. Group III (A)										
15272,26-6,20	2.55	Coarse-grained gabbro	13.7	97	227	816	85.2	1081	110.4	268
15272,26-6,21	1.8	Leucocratic porphyry-like rock	5.9	82	96	415	38.2	377	36.3	107
15272,26-6,24	14.0	Fine-grained basalt	7.1	105	206	766	67.3	803	76.1	235
15272,26-6,18	8.4	Dark gray medium-grained rock	5.5	75	126	482	37.3	419	39.1	141
15272,26-6,19	3.05	Coarse-grained leicocratic gabbro	22.1	132	347	1673	155.9	1544	151.5	417
Apollo 15. Group IV (A)										
15272,26-6,16	5.85	Dark gray feldspar rock	6.6	113	154	588	56.5	507	53.1	161
Apollo 15. Group VI (HA)										
15272,26-6,17	12.05	Gray olivine-porphir rock		58	52	219	30.6	202	28.4	88

T basalts are slightly younger (3.4–3.6 Gyr) [16]. The two dominant rock types in Apollo 17 are titanium-rich (HT) and aluminium-rich (HA and VHA) basalts. Group of HT basalts are characterized by moderate high contents of rare elements (in ppm): Zr 50–150, Y 30–70, and Nb 20–50. T basalts (with contents of Zr, Y, and Nb, respectively (in ppm): 140–220, 60–110, 50–70) are an extension of the HT basalt trend (Figs. 1–3). The overall variations of Zr, Y, and Nb in HA and VHA basalts of Apollo 17 are respectively (in ppm): 170–430, 40–120, and 30–75. The contents of these elements in HT basalts of Apollo 11 are 250–420, 100–200, and 25–30 ppm, respectively. By this means similar characters of differentiation rocks and fractionation of rare elements were established for all basalts of groups HT, HA, and VHA. At Luna 16, three groups of basalts have been defined (Figs. 1b–3b):

VLT-LT (Zr 35–70, Y 10–20, Nb 3–11 ppm); T(1) (Zr 80–150, Y 20–40, Nb 6–15 ppm); T(2) (Zr 160–260, Y 40–70, Nb 7–13 ppm). VLT-LT group of Luna 16 overlap with VLT group of Luna 24 in diagrams Zr vs. Sr, Y vs. Zr, and Nb vs. Zr. The points of T(1) and T(2) groups in these diagrams formed a comparatively flat trend, which is the result of a small scale of geochemical differentiation of parent lunar magmas.

5. The main types of lunar basaltic magmas

As is evident from the above discussion there are three main types of lunar basaltic magmas. The first type has very small scale of differentiation. It was parent magma for LT basalts Apollo 12 and 15. The second type has moderate scale of differentiation and it formed HT, some T basalts, VHA and HA basalts of Apollo 11, 17, and T basalts of Luna 16. The third type of basaltic magma is extremely enriched with aluminium. It formed HA and VHA basalts. However, abundances of rare elements in various types of HA and VHA basalts are essentially distinct. In moderate differentiation of HA and VHA basalts of Apollo 11, 17, and Luna 16 the contents of rare elements are not more than 440 ppm Zr, 115 ppm Y, and 75 ppm of Nb. HA and VHA basalts of Apollo 12 and 15, which are complementary rocks of LT basalts, have very high contents of rare elements (up to 800–1600 ppm). The same is true for basalts of Apollo 14.

6. Geochemical features of rare element distribution in lunar rocks

Let us consider whole body of knowledge about rare element distribution in lunar rocks. For this purpose one must draw on spectra (Fig. 4). For rocks of Apollo 12 and 15 (Fig. 4a) two types of spectra were established: the first (Type I) — for mare LT basalts with clearly defined maximum of Sr and small concentrations (usually less than 80 ppm) of other elements, and the second (Type II) – with high concentration of rare elements (up to 1000 ppm) without Sr maximum. Type II spectra are characterized by higher contents of Rb (2–8 ppm, up to 40 ppm for KREEP-like rocks of Apollo 12) than spectra of Type I (< 0.1–1.0 ppm Rb). Type II spectra are inherent to the rocks collection of Apollo 14. The contents of Rb in rocks of Apollo 14 range from 3 to 19 ppm. The contents of Ce are higher than La (by factor 3–5) for all rocks of Apollo 12, 14, and 15 (Fig. 4a). Hence, VHA and HA basalts of Apollo 12 and 15 even

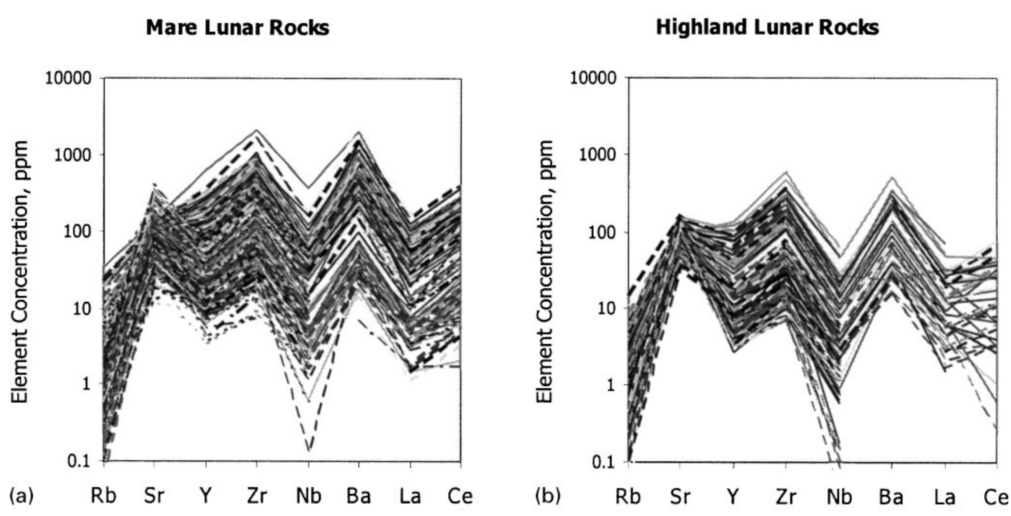

Fig. 4. Rare element spectra in main types of lunar mare (a) and highland (b) rocks.

though much younger to basalts of Apollo 14, have very similar geochemical features. This suggests analogous mechanism of genesis of these rocks.

Spectra of HT basalts of Apollo 17 as well as VHA and HA basalts from this region are among Type I. Spectra of the most part of T-basalts from Luna 16 belong to Type I. The concentration range for Sr fall within the content variation for other rare elements (Fig. 4a). Finally, the last type of mare basalts are presented by basalts from Luna 24. All of these rocks have spectra with high Sr maximum, small variation in Sr contents (from 50 to 100 ppm) and very small contents of other rare elements (Figs. 2b and 4b).

The highland rocks of Apollo 16 and Luna 20 have very similar spectra; distinctions between them show as different Zr concentration levels (up to 600 ppm Zr for Apollo 16 rocks). In both, Apollo 16 and Luna 20, rocks are characterized by nearly constant concentration of Sr and very large variations in other rare element contents.

7. Conclusions

(1) Practically all of VHA highland lunar rocks have low contents of Zr (< 100 ppm) and Y (< 30 ppm). The concentration ranges for these elements are too small. This suggests the small scale of differentiation of parent magmas. (2) HA and VHA basaltic rocks from mare regions of the Moon are characterized by essentially higher concentrations of Zr (up to 1300 ppm), Y (up to 400 ppm), and Ba (up to 2000 ppm). The concentration levels of these elements are higher than those for highland lunar rocks (factor 10 and more). (3) VHA and HA basalts of Apollo 12 and 15, and VHA basalts of Apollo 14 have very similar geochemical characteristics. Similarity is manifested as the lack of Sr maximum on rare element spectra, high concentration levels of all rare elements, and the presence of KREEP-like material in all of these regions of the Moon. (4) The lack of Sr maximum suggests that the origin of basalts is related to partial melting and is not the result of stores of Sr in plagioclase at cumulate processes in lunar magmatic ocean. (5) By this means, our SR-XFA analytical data on rare element abundance in high-aluminium lunar basaltic fragments (HA and VHA), which enriched by rare elements, are genetically related with differentiation process of mare basaltic magmas (like VHA basalts from Apollo 14 rocks), but not lunar magmatic ocean. (6) The exception is HA and VHA basalts from highland regions. These basalts are characterized by very low concentration levels of rare elements, and they were formed at the evolutionary Moon-stage of forming of highland rocks.

Acknowledgements

We express our appreciation to G.N. Kulipanov who generously allowed us to use his laboratory. This work was supported by RFBR grant 96-05-65144 and Program Russian Universities – Fundamental Research grant 5305.

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