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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Trace element distribution in lunar rocks of various titanium content by SR-XFA data

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Abstract

The distribution of trace elements (Rb, Sr, Y, Zr, Nb) in various types of lunar mare basalts has been investigated by SR-XFA. The new data of Apollo 11, Apollo 12, and Apollo 15 and also our earlier published data of other mare basalts have been discussed. Geochemical groups and trends for rocks of various titanium content were distinguished on the basis of diagrams of Zr vs. Sr and of Y vs. Zr. The problem regarding the magmatic sources of various types of lunar basalts has been considered.

1. Introduction

The aim of this work is a systematic investigation of the trace element distributions in mare basalts of the Moon. There are basalts of various titanium content: very low titanium (VLT), low titanium (LT), titanium (T), and high titanium (HT). In this connection we investigated the distribution of incompatible elements (Rb, Sr, Y, Zr, Nb) in small (0.4–3.0 mm) individual fragments of these rocks by an X-ray fluorescent method using synchrotron radiation (SR-XFA) [1–7]. In this work we studied about 30 LT samples (Apollo 12 and Apollo 15) and HT samples (Apollo 11) of basalts by SR-XFA (Tables 1 and 2). We also used our data on VLT and similar rocks (Luna 24, Luna 20, and Luna 16) and Luna 16 titanium rocks presented in a companion report [8] and HT of Apollo 17 published early [4]. Thus trace element abundances in all groups of lunar mare basalt with different titanium contents (total 106 samples) were studied and discussed.

2. Analytical techniques

Our investigations were carried out on the element analysis station on the storage ring VEPP-3 in G.I. Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences. The techniques and equipment used have been described in refs. [2–4,6,7]. On this station a single-crystal monochromator was used. As the crystal-monochromator we applied flat pyrolithic graphite. The crystal had a volume of $50 \times 50 \times 3$ mm^3 and a reflection coefficient of 20%. Cu-foils of various thicknesses were applied between the monochromator and the sample for control of the counting rate of the detector (from 0.7 to 1.2 kHz). Moving the crystal monochromator was performed also. A Si(Li)-detector at low energy (20–30 keV) was used as well as an Al-filter to decrease the influence of Fe peaks. The exposure time per sample was 200 s. Samples of BCR-1 and W-1 were used as external and control standards. A correction was done for the influence of K_α Y, K_α Zr, K_α Nb on K_β Rb, K_β Sr, and K_β Y, respectively. The estimated errors of SR-XFA are less than 10–15%. In this report we consider the distribution of Zr, Sr and Y as more geochemical informative elements in mare lunar basalts.

3. Chemical grouping of mare lunar basalts

Mare lunar basalts are usually divided into several groups: very low titanium basalts (VLT), low titanium basalts (LT), an intermediate subgroup VLT-LT, titanium basalts (T), and high titanium basalts (HT).

3.1. VLT and VLT-LT basalts

VLT and VLT-LT basalts provide important constraints on the composition and evolution history of the lunar upper mantle. A detailed trace element abundance characterization of this type of basalts is present in a companion article [8]. The new subgroup of intermediate VLT-LT

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Table 1
Contents of trace elements in Apollo 11 and Apollo 12 mare basalts by SR-XFA (in ppm)

Sample number	Sample description	Weight (mg)	Rb	Sr	Y	Zr	Nb
Apollo 12 basalts							
Group 1 (LA-HT)							
12028.228.237	medium-grained melanocratic basalt	6.30	0.32	15.0	35.3	44.6	7.7
Group 2 HA-(LT-T)							
12033.22-5.181	porphyritic black basalt	0.55	1.49	65.4	38.5	88.1	10.8
12033.22-5.218	medium-grained basalt	0.15	0.40	50.2	20.8	53.4	5.6
12033.22-5.190	dark fine-grained basalt	0.30	0.76	26.9	19.8	55.4	5.2
12033.22-5.226	dark-gray aphanitic rock	0.20	1.77	44.1	21.2	51.7	4.7
Group 3 (A-LT)							
12009.99.235	gray-black fine-grained basalt	2.35	0.71	68.8	32.9	79.0	8.5
12009.99.236	gray-black fine-grained basalt	0.65	0.12	49.0	24.2	57.8	5.0
Group 4 (LT)							
12038.229.231	ilmenitic medium-grained basalt	5.40	0.66	121.9	15.7	45.4	2.4
12033.22-6.180	gray fine-grained rock	1.35	2.46	69.5	102.1	347.7	23.9
12002.294-0.89	olivine basalt	4.15	0.61	40.1	21.2	40.8	2.9
Group 5 (HA)							
12033.22-5.217	ilmenitic basalt	0.20	0.67	20.5	12.2	21.8	2.0
Apollo 11 basalts							
Group 6 HT-(LT-T)							
10085.169-6.162	ilmenitic gabbro	2.50	0.51	111.3	76.2	142.9	15.2
Group 7 HT							
10085.169-6.163	ilmenitic fine-grained basalt	2.25	n.d.	73.5	47.5	263.0	n.d.
10085.169-6.165	ilmenitic fine-grained basalt	4.15	1.11	136.3	198.4	422.5	37.7
10085.169-6.161	ilmenitic medium-grained gabbro	2.35	3.37	86.0	104.8	245.0	26.3
10085.169-5.130	black fine-grained basalt	0.45	3.46	104.1	159.7	322.3	34.1
10085.169-5.129	black fine-grained basalt	0.50	2.32	87.4	129.3	286.5	27.7

basalts as well as VLT basalts are depleted by Rb, Sr, Y, Zr, and Nb with respect to other mare lunar basalts. The basalts of this type are more abundant in soil returned by Luna 24 and Luna 20; these basalts are less common in Luna 16 soils and are rare in samples returned by Apollo 17 (Fig. 1).

3.2. LT basalts

This type of mare basalt is more abundant among the rocks of the Apollo 12 and Apollo 15 missions. The contents of trace elements (mentioned above) in Apollo 15 LT basalts (Table 2) are low also (very similar to some of

Table 2
Contents of trace elements in Apollo 15 low titanium mare basalts by SR-XFA (in ppm)

Sample number	Sample description	Weight (mg)	Rb	Sr	Y	Zr	Nb
Group 1: low aluminium and low titanium rocks (LA-LT)							
15602.19-6.1	gabbro	13.70	0.06	70.3	15.1	46.2	4.6
15602.19-6.7	olivine gabbro	4.50	0.43	41.5	7.5	19.1	1.6
15602.19-6.2	olivine gabbro	8.50	0.70	81.0	30.6	63.5	5.2
15602.19-6.5	olivine gabbro	8.15	n.d.	64.0	16.3	40.9	n.d.
15602.19-6.12	brown porphyritic basalt	3.75	0.06	37.6	10.6	28.3	2.1
15602.19-6.4	gabbro	10.10	0.55	53.0	14.7	41.6	4.1
15602.19-6.8	gabbro	4.35	0.66	37.0	9.7	25.7	1.1
15380.14-0.94	medium-grained feldspar basalt	11.25	0.94	40.1	13.7	31.5	3.0
Group 2: aluminium and low titanium rocks (LT)							
15602.19-6.9	brownish-gray porphyritic basalt	9.20	0.90	73.9	24.3	60.5	4.9
15602.19-6.11	brown basalt	6.05	0.62	80.8	21.7	55.7	5.3
15602.19-6.10	brown middle-grained basalt	4.20	n.d.	59.5	17.3	46.1	3.6
15016.82.4.213	middle-grained basalt	13.55	0.56	75.8	11.7	28.7	2.5
15602.19-5.15	black fine-grained basalt	0.45	n.d.	31.6	8.8	26.3	3.2

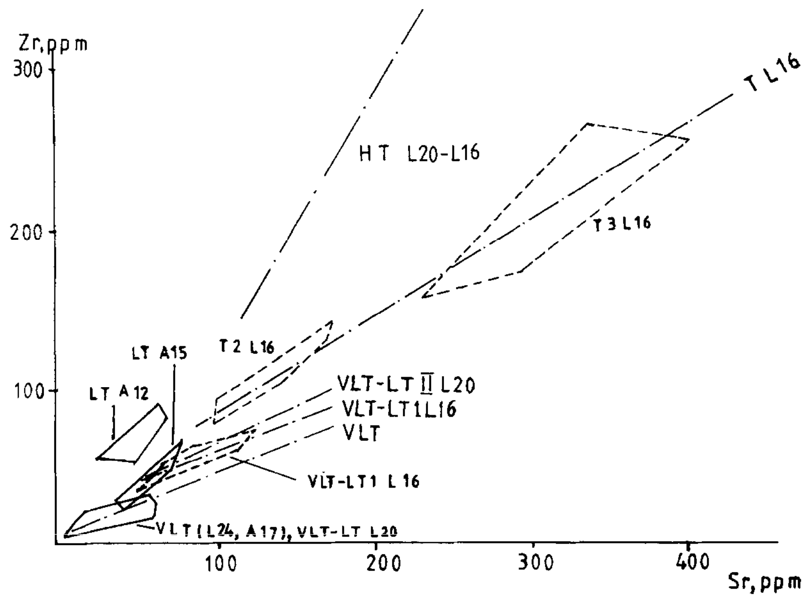

Fig. 1. Groups of VLT, LT, and T basalts in a Zr vs. SR diagram.

the VLT-LT rocks; see Fig. 1). However, petrochemical features, REE contents, and rare earth patterns are different than those of VLT and VLT-LT basalts. Apollo 12 basalts are enriched in trace elements (Table 1 and Fig. 1) with respect to Apollo 15 basalts and a diagram of Zr vs. Sr (Fig. 1) clearly shows these differences.

3.3. T basalts

Titanium basalts are very abundant in Mare Fecunditatis (Luna 16) [8]. The contents of Zr, Sr, and Zr/Sr-ratios in these basalts are very different from those in VLT and LT basalt groups. This is illustrated in Fig. 1, where T basalts show a much higher concentration of Zr and Sr than VLT and LT rocks. The ranges of the trace element contents are large enough (100–400 ppm for Sr and 70–250 ppm for Zr; see Fig. 1). Both groups of titanium basalts form a single trend in the Zr vs. Sr diagram (Fig. 1).

3.4. HT basalts

This type of basalt is the most abundant among the samples returned by Apollo 11 and Apollo 17. In Luna 16 and Luna 20 soils the HT basalts are rare. In the diagrams of Zr vs. Sr (Fig. 2) and Y vs. Zr (Fig. 3) HT basalts form compact clusters. As Figs. 3 and 4 illustrate, trends for HT basalts rise more steeply than those for Luna 16 titanium basalts. The points for several samples form a cluster of melanocratic basalts – a specific group with low a content of aluminum (LA–HT). We suggest that this type of basalt originates from an early cumulation of high-titanium magmas. LA–HT basalts have low contents of trace elements and are characterized by a trend which rises steeply and is very different from the others (Figs. 2 and 3). Several points of Apollo 17 titanium basalts follow the trend of Apollo 17 HT basalts, but at high contents of Zr they follow a different trend; the slopes rise steeply also. The

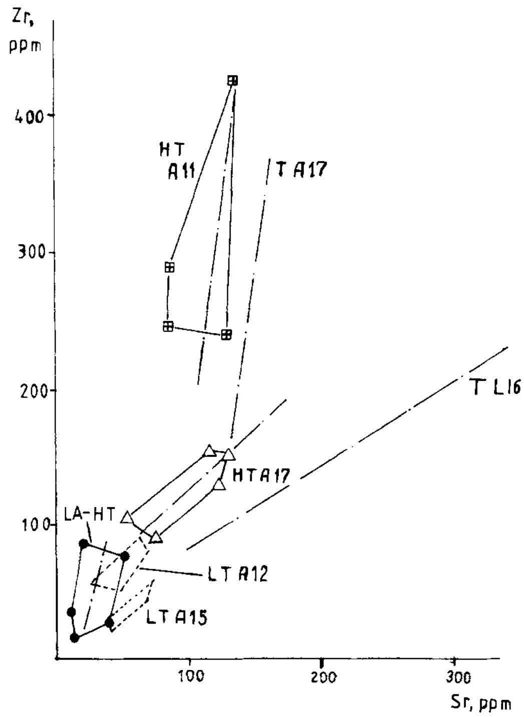

Fig. 2. Groups of T and HT basalts in a Zr vs. Sr diagram.

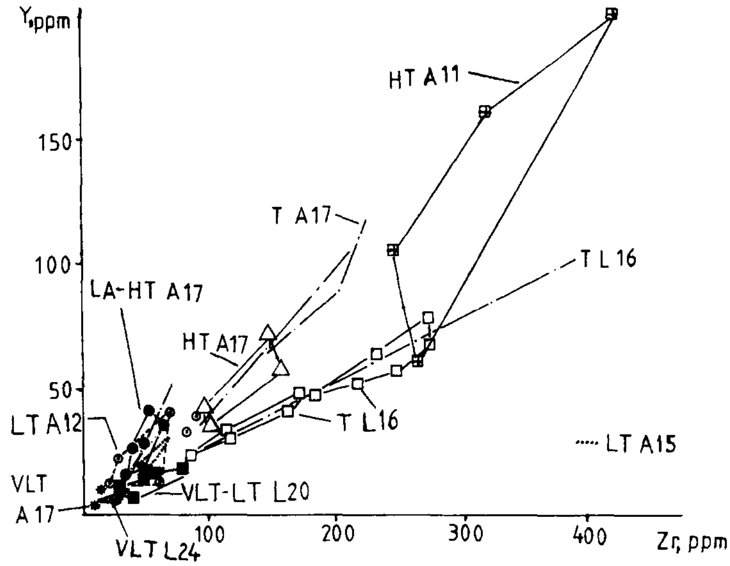

Fig. 3. Different groups of basalts in a Y vs. Zr diagram.

trace element contents in Apollo 11 HT basalts are very different from Apollo 17 basalts; for example, Apollo 17 rocks are enriched in Zr and Y by a factor of 3–4. In the diagrams Zr vs. Sr (Fig. 2) and Y vs. Zr (Fig. 3) the slopes for Apollo 11 samples are steep.

4. Results and discussion

All trends for mare basalts with different titanium contents, mentioned above, are shown in Fig. 4. The

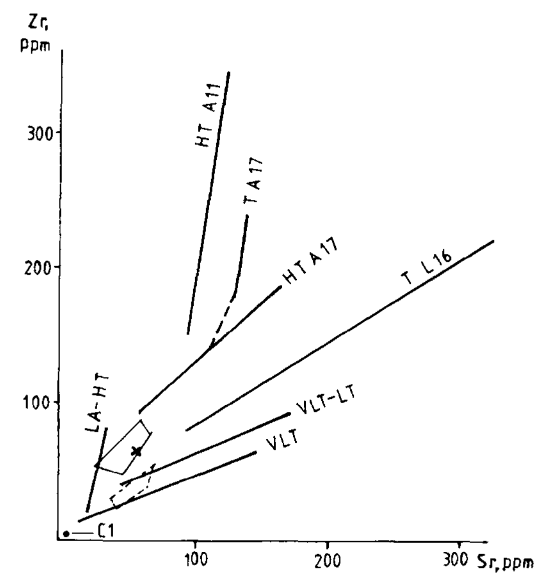

Fig. 4. Fields and trends of different groups of mare lunar basalts in a Zr vs. Sr diagram.

positions of points and ranges of the trace element contents suggest a different degree of the geochemical differentiation of parent lunar magmas. Note that the different types of basalts have different radiogenic ages (see Fig. 4).

1) All of types of mare lunar basalts are characterized by individual fields in the Zr vs. Sr diagram; the slopes for VLT and VLT-LT groups are comparatively flat; the slopes for high titanium basalt rise steeply.

2) Three groups of the trends were established:
(i) flat short trends (< 30°) for VLT and VLT-LT rocks;
(ii) slopes rise steeply (35–40°) for large fields of Luna 16 T and Apollo 17 HT basalts;
(iii) slopes rise steeply for Apollo 11 HT and Apollo 17 T basalts.

3) Apollo 12 and Apollo 15 LT basalts have a very small degree of geochemical differentiation and form compact clusters in the diagrams mentioned above. Our basic conclusion from these studies of trace element contents in the small lunar particles is that the LT basalts have geochemical features very similar to those of their precursor. Evidence for this conclusion is provided also by data obtained by Ganapathy and Anders [9] for Bulk Moon Composition (BMC) (Fig. 4): the point of BMC (×) is placed in the field of LT basalts. The bulk composition of such a source is not primary, because it is different enough from CI carbonaceous chondrites [10].

4) Apollo 17 LA-HT basalts have a small degree of differentiation also. This is a result of the regression character of the differentiation processes, which were connected with the early cumulation events when these components were removed from the high titanium magmas.

5) We suggest that VLT-LT basalts are the restites from the partial melting of precursor magmas which were related with primary magmas by a differentiation pro-

cesses. This is an individual genetic type of mare lunar basalts which is not related with any others.

6) The difference between Apollo 11 and Apollo 17 HT basalts and Luna 16 titanium basalts suggests that sources and evolution history of lunar magmas from different regions of the Moon are not the same. The positions of the fields of Apollo 11 and Apollo 17 HT basalts in the Zr vs. Sr diagram suggest that, unlike Luna 16 magmas, Apollo 11 and Apollo 17 HT basalts were formed by differentiation processes which took place at changes of distribution coefficients for Zr, Sr, and, possible, for Y; as a result of these processes the melts were enriched in zirconium and yttrium.

7) It is possible that the more ancient magmas (HT and T; see Fig. 4) are more fractionated than younger ones.

8) The new micro-SR-XFA method, briefly described above, can produce excellent analyses of geochemically important trace elements in very small individual particles of lunar rocks and minerals.

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