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GEOCHEMISTRY

Geochemistry of Rare Earth Metals in the Ultrabasic–Alkaline–Carbonatite Complex of Kugda (Polar Siberia)

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Abstract—The distribution patterns of rare earth metals (REM) in the rocks of the Kugda massif (Polar Siberia) are assessed. The REM content decreases from early olivinite rocks, containing, on average, 1938 ppm, to the end products of syenite differentiation and increases again in carbonatites. The difference in the distribution coefficients of light and heavy rare earth metals is the reason for the noticeable fractionation of these elements during the evolution of the magmatic system of the Kugda massif. The ratio of light REM to heavy Ce/Yb drops by almost an order of magnitude in later differentiation products. The main process of the Kugda massif formation was continuous crystallization differentiation, characterized by a wide crystallization field of perovskite. An interesting feature of the process is the very early crystallization of perovskite, associated with the high potential of carbon dioxide.

Keywords: Kugda massif, rare metal deposits, Polar Siberia, rare earth metals

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INTRODUCTION

Rare earth metals (REMs) belong to the group of strategic materials. Their consumption is constantly growing in the high-tech industry. Superlarge rare earth deposits in Russia, Brazil, and China are associated with ultrabasic–alkaline–carbonatite formations. Due to the sharp expansion of rare earth metals in industry, their prices have increased significantly in recent decades. In this regard, expert work to identify the patterns of concentration of these metals in alkaline rock complexes is essential for the growth of the ore potential of Russia.

This work aimed to study the patterns of concentration and dispersion of REMs in the Kugda ultrabasic–alkaline–carbonatite complex (Polar Siberia) (Table 1).

A feature of the Kugda massif is the sharply undersaturated with silica and high-calcium composition of the original magma. This led to the widespread development of olivinites and larnite–normative melilite varieties. The process of a deeply differentiated complex is completed by the intrusion of carbonatites, represented mainly by forsteritites. Although the development of the Kugda complex is marked by the classical magmatic evolution of ultrabasic–alkaline–carbonatite massifs, the primary magma of this complex was significantly enriched in magnesium and calcium and depleted in silicon. The second feature of the Kugda massif is the early crystallization of perovskite, which becomes a liquidus phase during the earliest formation of olivinite rocks.

GEOLOGY OF KUGDA MASSIF

The world's largest ultrabasic–alkaline Maimecha-Kotui province covers an area of about 74 300 km^2 and is located northeast of basalts of the Siberian plateau. It includes 32 ultrabasic–alkaline intrusions, a large volume of alkaline lavas and dikes, and several carbonatite bodies [1].

The Kugda massif is an isometric funnel-shaped body with an area of 16 km^2. The host rocks are represented by horizontally lying Middle Cambrian dolomites. The Central type of the massif structure is emphasized by the roughly concentric arrangement of the intrusive phases of the massif. Six intrusive phases are distinguished in the development of the Kugda complex [1]:

(1) stock of olivinites (olivinites, ore olivinites, perovskite magnetite, and magnetite). This intrusion is characterized by magmatic layering in places turning into rhythmic layering;

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Table 1. Mean REM concentration in the Kugda massif rocks (ppm)

Elements	Olivinite	Melilitholite	Melteigite	Ijolithe	Nepheline syenite	Syenite	Forsterite	Dike
La	704	250	123	77	126	13.43	467	189
Ce	1589	388	261	131	204	23.17	1104	312
Pr	233	40.62	44.22	17.60	23.00	2.70	51.93	34.61
Nd	669	108	118	58.40	69.70	9.10	134	119
Sm	78.51	15.16	18.62	8.90	6.40	1.12	19.85	15.12
Eu	14.04	3.38	4.02	2.20	1.47	0.21	4.40	3.75
Gd	33.84	9.14	10.58	5.20	4.15	0.75	12.71	10.19
Tb	3.09	1.00	1.22	0.68	0.49	0.10	1.24	1.09
Dy	9.75	4.13	5.39	3.10	2.12	0.49	5.06	5.44
Ho	1.24	0.62	0.85	0.51	0.37	0.09	0.72	0.86
Er	2.29	1.31	1.95	1.20	0.93	0.28	1.49	2.11
Tm	0.19	0.13	0.23	0.12	0.14	0.05	0.15	0.25
Yb	0.93	0.67	1.37	0.81	0.99	0.40	0.69	1.59
Lu	0.10	0.08	0.19	0.12	0.17	0.08	0.07	0.21
Ce/Yb	1101	579	190	162	206	57.92	1592	196
Total	1938	822	591	307	441	51.96	1803	696

(2) ring intrusion of melilitholites, also with the manifestation of magmatic layering and alternation of turyaites, uncompagrites, and okaites;

(3) a thick ring body of melanocratic foidolites and foidolites (melteigites, yakupirangites, melanephelinites, olivine melanephelinites, and nepheline picrites);

(4) small stock-like bodies of ijolithes; the larger part of these rocks mass is probably consolidated below the level of the modern section;

(5) small stocks and veins of alkaline and rarely nepheline syenites;

(6) a thick semicircular body of forsteritites, which, in our opinion, are cumulates of olivine from the phoscorite intrusion since phoscorites predominate in certain zones of this phase. This complex includes thin calcite veins intersecting forsteritites.

The ICP-MS method was used to study 45 samples of all varieties of the Kugda massif rocks for the REM content (Table 1). The average contents of the studied elements noticeably exceed the concentrations of these elements in other formations (Table 1, Fig. 1). A decrease in the total REM content from early rocks (olivinites, melelitholites) to later differentiation products, except for the rocks of the carbonatite complex, is noted (Table 1). This pattern is not typical, and the geochemistry of the Kugda complex REMs differs from other massifs of Polar Siberia and many alkaline–carbonatite complexes of the Kola Peninsula. However, the differentiation of several Devonian alkaline–carbonatite intrusions of the Kola Peninsula (Lesnaya Varaka, Afrikanda) is also associated with the rare-metal mineralization of precisely the early rocks, olivinites and pyroxenites containing perovskite, which are the main mineral concentrating rare earth elements. The REM content in some Kugda complex ore olivinites reaches 9479 ppm. Thus, ore olivinites are valuable REM raw materials. The concentration of REMs in ore olivinites is slightly higher than in the carbonatite complex (Table 1), in which the highest REM content is 6846 ppm. Our studies have shown that the Kugda massif perovskite is significantly enriched in the REMs (Table 2). Some crystals in olivinites contain up to 23 778 ppm of total REMs.

Table 2. REM content in the perovskites of olivinites of the Kugda massif

Elements	A08	A09	A13	A16	A17	Mean
ΣREE	23497	20724	20743	18497	14834	19659
Ce/Yb	1990	1765	1846	2320	1793	1943

In all the Kugda complex rocks, the Ce/Yb ratio is tenfold higher (Table 1) than the chondritic one (Ce/Yb is about 4.2). That is due to the predominant concentration of the REM in perovskite. In some perovskite grains from olivinites, the Ce/Yb ratio reaches 2320 (Table 2). According to experimental data, perovskites have an increased REM distribution coefficient in equilibria with melts similar in composition to melilite nephelinites [3, 4], and for the light REMs (value about 20) it is much higher than for the heavy REM (Kd a few digits).

This difference is the reason for the noticeable fractionation of rare earth metals during the evolution of the magmatic system of the Kugda massif. In later dif-

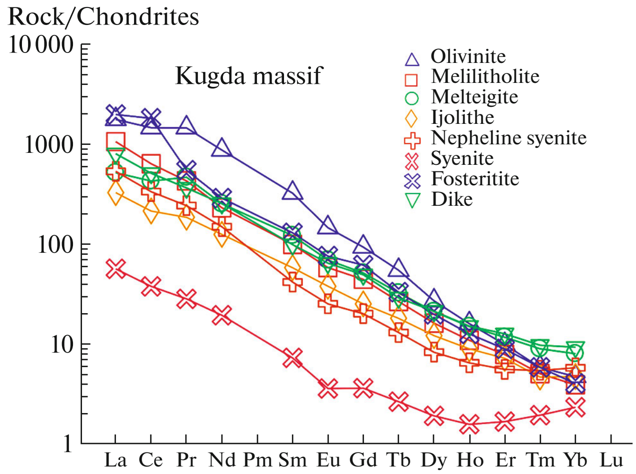

Fig. 1. REM distribution in the Kugda massif rocks.

ferentiation products, the ratio of light REM to heavy Ce/Yb drops by almost an order of magnitude (Table 1). However, in the Kugda carbonatite complex, this ratio again sharply increases since the perovskite content in the carbonatite complex is relatively high. In addition, according to our petrographic studies, pyrochlore, calcirtite, and apatite are noted in forsteritites, which are also enriched in the light REMs.

The evolution of the ultrabasic–alkaline magmatic system of the Kugda complex was determined by the processes of crystallization differentiation, coupled with the phenomena of magmatic layering.

It should be noted that some varieties of rocks of the Kugda massif are not melts, but are cumulative, i.e., accumulation of individual minerals, which can affect the established patterns.

Thus, our studies have convincingly shown that the main process of the Kugda massif formation was continuous crystallization differentiation, characterized by a wide crystallization field of perovskite, and an interesting feature is the very early crystallization of perovskite, associated with the high potential of carbon dioxide. According to our experimental data [5], olivine and perovskite are early liquidus phases during the melilite-containing nephelinite crystallization under conditions of increased carbon dioxide pressure. During the evolution of the Kugda magmatic system, a significant fractionation of the heavy and light REMs was established. Due to the higher distribution coefficient of the light REMs in perovskites, the Ce/Yb ratio in the final differentiation products decreases significantly.

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CONFLICT OF INTEREST

The author declares that she has no conflicts of interest.

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