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GEOCHEMISTRY

Carbonatite Sources of the Il'meny–Vishnevogorsk Complex: Evidence from Sr and Nd Isotope Data on Carbonates

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The alkaline–carbonatite complex of the Paleozoic structure of the Urals is located in the Precambrian Sysert–Il'menogorsk block, which includes two structural levels and experienced a long-term evolution. The core of the block (lower structural level) is composed of the diaphthoritic gneiss granulites and migmatites of the Selyanka Sequence with the U–Pb zircon age of 1820 ± 70 Ma. The migmatite sample is characterized by the following values: $(^{87}Sr/^{86}Sr)_{1700}$ = 0.7067, $(^{147}Nd/^{146}Nd)_{1700}$ = 0.5099, and ε_{Nd} = –10.2 [7]. The core formation is related to the metamorphic events of the Karelian folding [3]. The framing (upper structural level) is made up of similar sequences: Il'menogorsk Sequence in the south; and Vishnevogorsk, Shumikhin, and Chernovsk sequences in the north. The sequences consist of amphibolites and less common plagiogneisses and quartzites. They have low initial Sr and Nd ratios. The Shumikhin Sequence is characterized by the following values: $(^{87}Sr/^{86}Sr)_{576}$ = 0.702–0.703, $(^{147}Nd/^{146}Nd)_{576}$ = 0.5121, and ε_{Nd} from + 3 to + 4. The U–Pb datings suggest that the aforementioned sequences are pre-Uralian paleoceanic complexes with a metamorphic age of 643 ± 46 Ma for the Il'menogorsk Sequence and 576 ± 65 Ma for the Shumikhin Sequence [4]. They were formed during the breakup of Rodinia. Based on U–Pb and Rb–Sr data, the crystallization age of the alkaline rocks and carbonatites is 440 Ma [9, 8]. Later metamorphism and granite formation in the Sysert–Il'menogorsk block were related to the Hercynian orogeny (360–320 Ma) and subsequent postcollisional extension (260–240 Ma).

According to [5], the Il'meny–Vishnevogorsk alkaline complex was formed under the influence of a strong flow of the juvenile alkaline–carbonate fluids, which provoked alkaline metasomatism and produced anatectic miaskites. The alkaline–carbonatite fluids were followed by the intrusion of carbonatites enriched in rare metals and Sr.

Another model [2, 9] based on the obtained mantle signatures of O, C, S, and Sr suggests a subordinate role of palingenesis. The formation of the alkaline complex was presumably promoted by a supply of deep-seated, possibly mantle-derived miaskite magma.

We first obtained Sr and Nd data on carbonates from calcite, calcite–dolomite, and dolomite carbonatites in the northern part of the alkaline complex, which includes the Vishnevogorsk and Buldym niobium ore fields (table).

The calcite carbonatites in the miaskites of the root and apical parts of the Vishnevogorsk Massif are represented by samples 354, 331, and 329. Sample 354 is a coarse-grained carbonatite developed as schlieren among vein miaskites in the root zone of the Vishnevogorsk miaskite massif (road cut, 6.5 km south of the town of Vishnevegorsk). Sample 331 is a coarse-grained carbonatite that grades into a brecciated one and composes a large body in the hinge of a miaskite fold within the Vishnevogorsk Massif (feldspar quarry at Mt. Dolgaya). Sample 329 was taken from a large brecciated fine-grained gray carbonatite body confined to a low-angle detachment in miaskites in the inner contact (apical) part of the massif (ore zone 147 of the Vishnevogorsk niobium deposit). Other carbonatite samples were taken from the metamorphic framing of the miaskite intrusion. Sample 3 is a coarse-grained carbonatite, which forms veins with swells at the outer contact of the miaskite massif among fenites developed after gneisses of the Vishnevogorsk sequence (ore zone 125). Calcite–dolomite (43-915 and 3311) and dolomite (10-21 and 1-54) carbonatite samples were taken from veins in the metaultramafic rocks of the Buldym Massif, which is located among gneisses of the Vishnevogorsk Sequence stratigraphically above the miaskite massif (Fig. 1).

Calcite carbonatites in the miaskites correspond to high-temperature facies (>500°C). As compared to

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Sr and Nd isotopic compositions of carbonates

Sample no.	Sr	$^{87}Sr/^{86}Sr$	ε_{Sr_t}	Sm	Nd	$^{143}Nd/^{144}Nd$	$(^{143}Nd/^{144}Nd)_t$	ε_{Nd_t}	T_{DM}
Carbonatites in miaskites									
329¹	12340	0.70361	–5.3	7.99	46.73	0.512533	0.512235	3.2	853
331¹	21982	0.70359	–5.6	58.31	385.12	0.512507	0.512243	3.4	803
354¹	9247	0.70356	–6.0	50.89	368.29	0.512460	0.512219	2.9	809
Carbonatites in the outer contact of the miaskite massif									
3¹	21218	0.70470	10.2	52.51	509.21	0.512076	0.511896	–3.4	1081
43-915¹	10279	0.70440	5.9	39.39	292.57	0.512164	0.511929	–2.8	1135
3311¹	8373	0.70455	8.0	52.13	391.57	0.512172	0.511940	–2.6	1118
3311²				8.08	64.18	0.076109	0.511947	–2.4	1090
1-54²	9097	0.70447	6.9	24.474	181.473	0.512292	0.512057	–0.3	990
10-21²	5334	0.70450	7.3	12.631	93.215	0.512341	0.512105	0.7	936

Note: (¹) Calcite, (²) dolomite. The Nd and Sr isotope ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$ and $^{86}Sr/^{88}Sr = 0.1194$. Errors (2σ) are no more than 0.01% for $^{87}Sr/^{86}Sr$ and 0.02% for $^{143}Nd/^{144}Nd$. The initial Nd ratio was calculated at a miaskite age of 440 Ma. ε_{Nd} and ε_{Sr} were calculated relative to the CHUR; (T_{DM}) the model age calculated relative to the DM.

other carbonatite complexes, the calcite carbonatites have higher Sr and Ba contents, lower REE and Y contents, and lower Nb/Ta and Zr/Hf ratios [5, 6]. Calcite–dolomite carbonatites in the host rocks correspond to the lower-temperature facies (500–300°C) with similar Sr and Ba contents; higher Nb, REE, Y, and Pb contents; and elevated Nb/Ta and Zr/Hf ratios. Later dolomite carbonatites formed at 300–200°C are characterized by high Th and REE contents and a high La/Yb ratio.

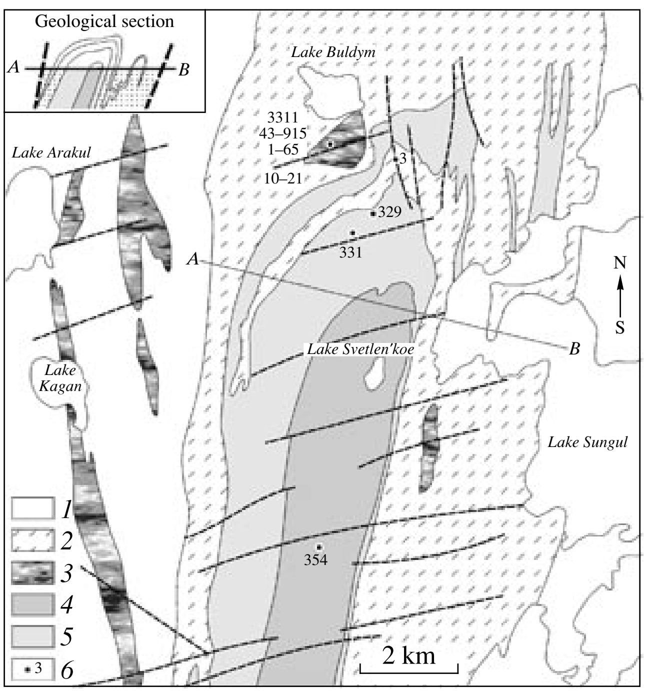

Fig. 1. Geological scheme of the northern part of the Vishnevogorsk Massif (after V. Ya. Levin and B. M. Ronenson). (*1*) Metamorphic rocks of the Igish, Saitov, Argazin, and Kyshtym sequences; (*2*) plagiogneisses and amphibolites of the Vishnevogorsk and Shumikhin sequences; (*3*) metamorphosed ultramafic rocks; (*4*) metasomatites of the central alkaline band (fenites, nepheline–feldspar migmatites, miaskites, and carbonatites); (*5*) miaskites of the Vishnevogorsk Massif; (*6*) sampling sites of the carbonatites.

Carbonatites are composed of low-Mg calcites (up to 2% MgO) and dolomites. The carbonates contain traces of MnO (0.4–2.5%), SrO (0.8–3.2%), and LREE (up to 0.35%).

Based on an isotope study, the carbonates are subdivided into two groups distinguished by initial Sr compositions (Table 1). The first group with low $(^{87}Sr/^{86}Sr)_t = 0.7035–0.7036$ is represented by calcite in carbonatites developed in the miaskites. The second group with elevated initial $(^{87}Sr/^{86}Sr)_t = 0.7044–0.7047$ is represented by calcite and dolomite in carbonatites developed in the framing of the miaskite massif.

We compared the new isotope results with the previously published data on Sr and Nd isotopic compositions of the miaskites and host rocks of the Sysert–Il'menogorsk block [7, 9–11]. For geochemical modeling, all the Sr and Nd ratios in the host rocks were adjusted to the miaskite crystallization age of 440 Ma.

Carbonatites define two parallel lines (Fig. 2a). The trend of carbonates of group I incorporates the majority of miaskites, as well as oceanic plagiogneisses and amphibolites. Another trend is defined by the carbonates of group II. Both groups show wide variations in Sr content and a nearly constant isotope ratio, which can be explained by fractional crystallization of the carbonatites. The wide variations in Sr isotope composition of the miaskites can be related to several reasons, e.g.,

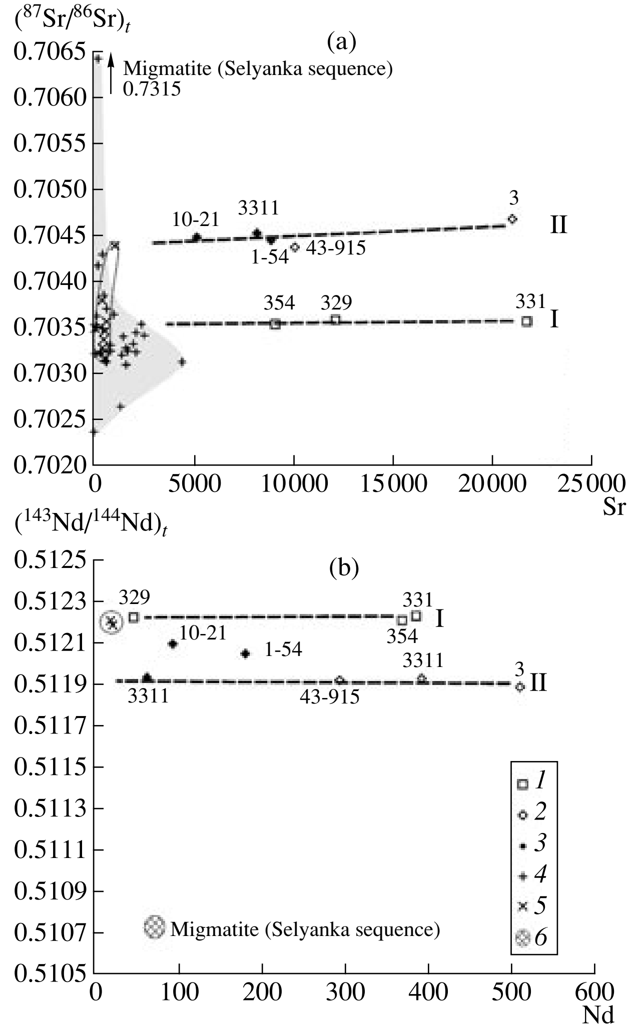

Fig. 2. (a) Sr–($^{87}Sr/^{86}Sr)_t$ and (b) Nd–($^{143}Nd/^{144}Nd)_t$ diagrams for rocks of the Il'meny–Vishnevogorsk alkaline–carbonatite complex and host rocks. (*1*) Calcite (carbonatites in miaskites); (*2, 3*) calcite and dolomite, respectively (carbonatites in fenites and metaultramafic rocks of the Buldym Massif); (*4*) miaskites [9]; (*5*) plagiogneisses and amphibolites of the Il'menogorsk, Shumikhin, and Chernovsk sequences [10, 11]; (*6*) migmatite of the Selyanka block [7].

contamination of the miaskite magma by the host rocks.

Like the Sr isotopic composition, the Nd isotopic composition is also distinguished in carbonates of both groups. Group I carbonates have the highest initial ratio $(^{143}Nd/^{144}Nd)_t$ = 0.51223 and positive ε_{Nd} ranging from + 2.9 to + 3.4. Group II carbonates have the lower Nd ratio $(^{143}Nd/^{144}Nd)_t$ = 0.51193 and, correspondingly, negative ε_{Nd} ranging from –2.4 to –3.4. Thus, the carbonates form two parallel lines (Fig. 2b). The wide Nd variations in carbonates are related to the fractionation of this element during crystallization of the major and accessory minerals of the carbonatites. At the same

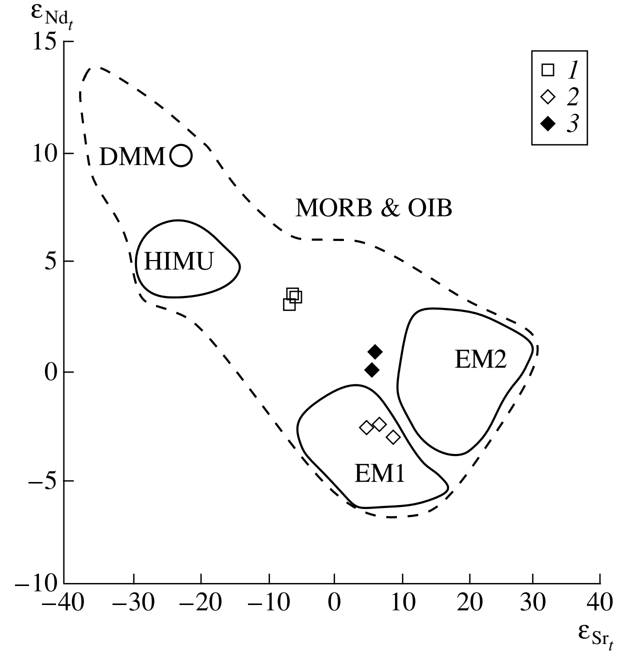

Fig. 3. Initial Nd and Sr ratios in the carbonatites of the Il'meny–Vishnevogorsk alkaline–carbonatite complex. Legend as in Fig. 2. MORB, OIB, and mantle reservoirs (DMM, PRIMA, HIMU, EM1, and EM2) are plotted after [13, 14].

time, the compositions of the late (purely dolomitic) carbonatites occupy an intermediate position between the two lines, presumably reflecting the disturbance of the Sm–Nd system owing to contamination by host ultramafic rocks.

In the ε_{Nd}–ε_{Sr} diagram, the data points of carbonatites are plotted in the DMM–EM1 line (Fig. 3). The carbonatites from the host metamorphic rocks are plotted in the EM1 field with a model Sm–Nd age of T_{DM} = 1000–1500 Ma, whereas miaskite carbonatites were derived from the LREE- and LILE-depleted source with a model age of T_{DM} = 800–1000 Ma. The depletion could be caused by crustal extension and generation of tholeiitic basalts. The EM1 source can be related to the partial decarbonation of the Precambrian marine carbonates and melting of the subducted oceanic crust, which generated the CO_2-rich fluid (melt) that metasomatized the subcontinental lithosphere [12].

The isotope data on carbonatites at the northern termination of the Il'menogorsk–Vishnevogorsk complex suggest the following conclusions. Carbonatites are represented by two types. Carbonatites I are related to miaskites, whereas carbonatites II (Buldym type) are located among the host metamorphic rocks in the framing of the alkaline rock complex. The existence of these types was shown in [5] based on their geological positions, as well as mineralogical and metallogenic characteristics.

The stability of Sr and Nd isotope ratios in both carbonatite types is inconsistent with the notion of their contamination by the host rocks. This is also suggested by the mantle signatures of O, C, and S isotopes in the carbonatites [1, 2]. At the same time, these data do not rule out the possible contamination of silicate rocks of the complex (miaskites and syenites).

The carbonatites were formed from two different sources. The carbonatites of the Buldym Massif were presumably formed from the older EM1-type source enriched in radiogenic Sr and nonradiogenic Nd, whereas carbonatites from the miaskites and host amphibolites were derived from the more depleted source.

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