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GEOCHEMISTRY

Timing and Duration of Kimberlitic Magmatism in the Zimnii Bereg Diamondiferous Province: Evidence from Rb–Sr Age Data on Kimberlite Sills along the Mela River

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Determination of the age boundaries of magmatic activity and elucidation of the sequence of magmatic eruptions in certain magmatic provinces allow correlation of magmatic events over wide areas. This is of great importance for understanding the reasons and manner of evolution of deep magmatic processes.

Kimberlites and lamproites were emplaced in the East European Craton (in particular, in the Baltic Shield and adjacent areas) in several stages. The Devonian stage was marked by the wide occurrence of alkali–ultramafic rocks (including kimberlites) in the Baltic Shield (Kola Peninsula and Karelia), Arkhangelsk district, Middle Timan, and Ukrainian Shield (eastern Azov region).

The alkali–ultramafic rocks in the Baltic Shield compose central-type massifs and complex dike system. Isotopic dating of alkali rocks made it possible to constrain the timing of the most active magmatism at 410–360 Ma [1, 2, 8].

The Zimnii Bereg diamondiferous province incorporates numerous Paleozoic ultramafic and mafic rocks (different types of kimberlites, alkali picrites, melilitites, and basalts), which could be formed over a long period. Plant remains in the rocks of crater and diatreme facies of kimberlite pipes indicate Late Devonian age [5]. However, particular dates can be obtained for kimberlite bodies only with isotopic methods, which allow one to determine the timing and duration of magmatism in the area.

In addition to pipes, kimberlites of the Zimnii Bereg district also include sills, ages of which cannot be strictly constrained on the basis of geological data, e.g., sills in the Mela River valley found in 1975. They represent the earliest kimberlite finding in the Zimnii Bereg district [3]. The sills are located among rocks of the Upper Vendian Mezen Formation away from the main fields of kimberlites and other ultramafic alkali rocks in the Zimnii Bereg district (Fig. 1). Thus, the

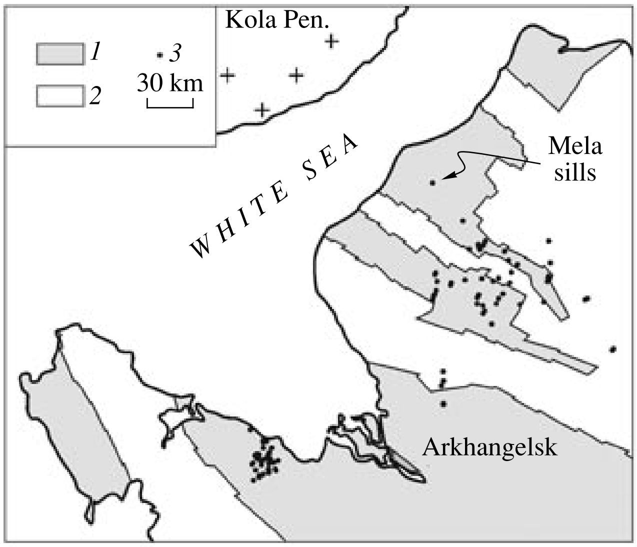

Fig. 1. Location of the Mela sills. (*1*) Basement uplifts, (*2*) basement depressions, (*3*) Paleozoic magmatic bodies.

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Mela sills could be older than other Zimnii Bereg kimberlites. Isotopic methods were required to determine their age. However, isotopic dating of the rocks was hampered until recently because of strong secondary alterations of the rocks (in particular, almost universal partial or complete chloritization of phlogopite) in the exposures and boreholes. In connection with prospecting for new kimberlite bodies in the Tovsk area, the Alrosa Closed Joint-Stock Co. carried out works on further study of ultramafic rocks along the Mela River and recovered weakly altered kimberlite sills. Fresh kimberlites suitable for dating are very rare in the Zimnii Bereg district. They are only found in some sills and pipes at great depths (for example, Pionerskaya Pipe [4]). Therefore, the kimberlite sills mentioned above represent a unique material for the determination of age and duration of magmatism in the area, as well as the sequence of formation of different rock types.

Sills along the Mela River make up a band 2.5 × 0.8 km in size at several (at least three) levels of stratigraphic sequences with absolute marks ranging from –4 to +38 m. However, each borehole recovered only 1–2 levels of sills, with occasional splitting of stratal bodies into several thin layers. Rocks at these levels compose monolithic bodies up to 4.3 m thick, or series of layer injections. Kimberlites that compose sills vary in contents of altered olivine, phlogopite, and carbonates, as well as in rock textures. A brief description of dated rocks is given below.

The upper sill (up to 0.7 m thick) in the northern area consists of the weakly differentiated kimberlites with numerous phenocrysts of olivine (replaced by calcite and serpentine), subordinate small phenocrysts of phlogopite, numerous microphenocrysts of Cr-spinel, and weakly crystallized groundmass consisting of chloritized mica and carbonates (Sample Me-21/1).

Sills from the lower level in the northern area is made up of more differentiated kimberlites, with a lesser amount of olivine phenocrysts (completely replaced by calcite) and more abundant (partially chloritized) mica phenocrysts (Me-28).

In the southern area (Borehole M35), well-crystallized kimberlite (Me-46) composes the majority of the 1.3-m-thick sill. The sill contains numerous phlogopite phenocrysts 0.5–1.5 mm in size. Phlogopite crystals are squeezed between olivines and intensely deformed. Spinels are only represented by Al–Mg–Ti-magnetite. The groundmass consists of serpentine, dolomite, and mica. Rocks in the upper part of the sill are strongly differentiated. Olivine is virtually absent, whereas carbonates are abundant in these rocks. The sill also includes taxitic phlogopite–carbonate rocks and rocks with large sectorial crystals of carbonate (0.5–1 mm) in a fine-grained chlorite–carbonate interstitial groundmass with smaller mica and carbonate phenocrysts (0.2 mm).

Taxitic phlogopite–dolomite rocks with subordinate pseudomorphs of olivine (Sample Me-49) were taken approximately at the same level in neighboring Borehole M36, at a distance of 250 m from Borehole M35. The rocks have a banded structure owing to the uneven distribution of dolomite and phlogopite. The rocks also contain accessory Mg–Al–Ti-magnetite and apatite. Phlogopite and dolomite plates are parallel to the bands. Dolomitic bands are enriched in apatite (up to 10 wt %).

Rocks with carbonate spinifex occur in several areas. In the northern area, such textures were found in the groundmass of porphyritic kimberlites. We also found thin (5–10 mm) bands of spinifex-textured carbonate-rich rocks with thin carbonate plates perpendicular to the sharp contact with host porphyritic kimberlites.

Thus, in addition to typical massive porphyritic kimberlites, the sills also contain weakly altered carbonate-rich rocks. In these rocks, carbonates (dolomite and, partially, calcite) are primary minerals, which presumably crystallized from magmas or highly concentrated residual solutions-melts enriched in carbonates, alkalis, and phosphorous.

The Rb and Sr contents in rocks and minerals were determined by double isotope dilution. The Rb and Sr isotopic composition was analyzed on a Finnigan MAT-261 mass spectrometer (Institute of Precambrian Geology and Geochronology) and a Finnigan MAT Triton (Center of Isotopic Research of the Karpinskii All-Russia Research Institute of Geology) in a static regime. Measured ratios were corrected for Sr isotopic fractionation by normalizing to $^{88}Sr/^{86}Sr = 8.37521$. The Rb and Sr contents were measured accurate to 0.5%. Procedure blanks were 30 pg for Rb and 30 pg for Sr. Rb–Sr isochron ages, and initial $(^{87}Sr/^{86}Sr)_t$ ratios were calculated with the ISOPLOT program using decay constant $\lambda_{87Rb} = 1.42 \cdot 10^{-11}$ yr^{-1}. The isotopic ratios were measured accurate to 0.5% for $^{87}Rb/^{86}Sr$ and to 0.03% for $^{87}Sr/^{86}Sr$.

Rb–Sr isotope data were obtained for bulk samples and minerals from olivine-rich porphyritic kimberlites and taxitic phlogopite–carbonate rocks. To determine variations in Sr isotopic composition in the sills and their possible changes caused by secondary processes, we also studied bulk samples of the main kimberlite varieties and carbonate-rich rocks, as well as carbonates of different generations.

Since all rocks have a very low Rb/Sr ratio, the isotopic composition of bulk samples is close to the initial ratio (table, Fig. 2). Most studied samples are grouped into a compact cluster with the $(^{87}Sr/^{86}Sr)_{366.4\ Ma}$ ratio varying from 0.7038337 to 0.704350. This group includes olivine-rich porphyritic kimberlites (samples Me-21/1, Me-46, and Me-28), phlogopite–carbonate rocks without pseudomorphs after olivine (Me-49/1) and dolomitic interbed with carbonate laths (Me-49/2), and spinifex-textured calcitic rocks (Me-8). Data points of calcite and dolomite from kimberlite Me-46 also plot in this group. The most differentiated barite–apatite–calcite rock (Sample Me-5) has a slightly higher

Sr isotopic composition of rocks and minerals of the Mela sills

Sample	Rock	Material	Rb, ppm	Sr, ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	$(^{87}\text{Sr}/^{86}\text{Sr})_t$
Me-5 (105-2/1.5)	Barite–apatite–calcite	bulk	0.182	3204	0.00016	0.705287 ± 11	0.705286
Me-8 (106-2A)	Calcitic spinifex with trace apatite	bulk	1.42	988.5	0.000415	0.704274 ± 14	0.704272
Me-21/1 (M7/10.7)	Kimberlite	bulk	19.25	677.6	0.0822	0.704672 ± 19	0.704243
Me-28 (M6/35.7-1)	Kimberlite	bulk	24.48	1050	0.0674	0.704469 ± 14	0.704117
		mica	283.4	167.3	4.9136	0.733159 ± 14	–
		calcite, complete pseudomorphs after olivine	0.152	185.5	0.0024	0.708607 ± 22	0.708594
Me-49/1 (M36/44.8)	Taxitic phlogopite–carbonate rock	bulk	44.89	1127	0.1152	0.704457 ± 18	0.703856
		mica	339.1	77.66	12.71	0.771032 ± 16	–
		carbonate	2.723	549.8	0.0143	0.704326 ± 17	0.704251
Me-49/2 (M36/44.8)	Carbonate interbed in the taxitic phlogopite–carbonate rock	bulk	6.09	2119	0.0083	0.703880 ± 21	0.703837
Me-46 (M35/25.8–26.3)	Kimberlite	bulk	24.7	636.6	0.1122	0.704543 ± 22	0.703957
		mica	353.2	59.91	17.181	0.793580 ± 7	–
		lighter carbonate fraction	3.503	690	0.0147	0.704427 ± 22	0.704350
		heavier carbonate fraction	4.135	2134	0.0056	0.704353 ± 15	0.704324
Me-42 (M32/18.8)	Silty sandstone, Vendian Mela Formation	whole-rock	97.43	42.48	6.687	0.786845 ± 28	0.751941

Note: Borehole number and sampling depth are shown in parentheses, with the exception of the first two samples taken from the exposures. Initial isotopic ratio $(^{87}\text{Sr}/^{86}\text{Sr})_t$ was calculated for 366.4 Ma.

$(^{87}\text{Sr}/^{86}\text{Sr})_{366.4\ \text{Ma}}$ value (0.705286). Calcite forming complete pseudomorphs after olivine in Sample Me-28 shows the most significant deviations of the $(^{87}\text{Sr}/^{86}\text{Sr})_{366.4\ \text{Ma}}$ ratio (0.708607). Such an increase in isotopic ratios could be caused by Sr introduction from host rocks during interaction of residual carbonate-rich liquids with host rocks or during kimberlite alteration (formation of calcite pseudomorphs after olivine). The possibility of such processes is confirmed by a high $(^{87}\text{Sr}/^{86}\text{Sr})_{366.4\ \text{Ma}}$ ratio (0.751941) in Vendian sandstones taken near the contact with kimberlites. Contamination by such material should shift the isotopic composition of magmatic rocks. Thus, sills have steady Sr isotopic composition. Contamination by the Vendian host rocks was presumably insignificant and this process had a minor influence on the isotopic composition of kimberlites.

The isochron correlations obtained are defined by isotopic compositions of micas (Fig. 2). The mica from Sample Me-28 is partially chloritized, and its bulk sample is depleted in K (6.08 wt % K_2O). As mentioned above, calcite from this rock is also characterized by elevated (i.e., disturbed) $(^{87}\text{Sr}/^{86}\text{Sr})_{366.4\ \text{Ma}}$ ratios relative to other analyzed kimberlite samples and carbonate-rich rocks. However, the Sr content in this calcite is lower (185.5 ppm) than that in the bulk sample (1050 ppm). The replacement of olivine by such a carbonate had an insignificant influence on the bulk composition of kimberlite Me-28, which has the same low $(^{87}\text{Sr}/^{86}\text{Sr})_{366.4\ \text{Ma}}$ ratio as most other samples. Mica Me-28 has reduced Rb content and low ^{87}Rb/^{86}Sr ratio. The Rb–Sr age calculated for this rock (based on bulk sample and mica) is 415.7 Ma. By contrast, micas taken from weakly altered rocks have higher ^{87}Rb/^{86}Sr ratios. These micas define ages of 371.3 Ma (Me-49/1) and 366.4 Ma (Me-46) (Fig. 2). The ^{87}Rb/^{86}Sr ratio in mica is correlated with the calculated age of the rocks. The highest Rb content, lowest Sr content and highest ^{87}Rb/^{86}Sr ratio are typical of mica Me-46. This mica is presumably least altered. This is consistent with the minimal alteration of the whole rock. It is possible that not all altered (chloritized and oxidized) micas were removed during hand picking of micas from Sample Me-49/1.

Based on data presented above, we believe that the age obtained for Sample Me-46 (366.4 Ma) is the closest to the true kimberlite age. The analytical error is ±1.8 Ma.

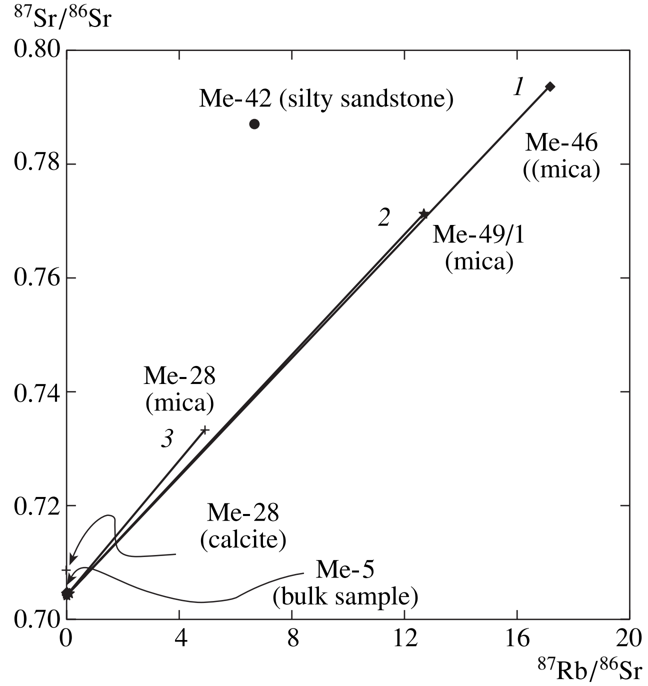

Fig. 2. Rb–Sr isotopic data on kimberlites and carbonate-rich rocks of the Mela sills. (*1–3*) Two-point "isochrons" (corresponding to the bulk sample–mica pairs): (*1*) Me-46 (t = 366.4 Ma), (*2*) Me-49/1 (t = 371.3 Ma), (*3*) Me-28 (t = 415.7 Ma). (t) Calculated age.

Thus, taking into consideration datings of kimberlites from the Pionerskaya Pipe (380.1 Ma [4]) and V. Grib Pipe (372 Ma [6]), we assume that the Zimnii Bereg kimberlites formed 380–366 Ma ago. This age interval corresponds to the main phase of alkali magmatism at the Kola Peninsula (410–362 Ma [1]), indicating common causes of the Late Paleozoic magmatism in the northern East European Platform.

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