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GEOCHEMISTRY

Compositional Variations in Kimberlites of the East European Platform as a Manifestation of Sublithospheric Geodynamic Processes

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New high-precision (ICP-MS, Sr, Nd, and Pb isotopic) data together with previously obtained data [1, 2] were used to examine compositional variations in kimberlites, including diamondiferous varieties, of the East European platform (EEP). One of the reasons for these variations is a supposed relation to an ancient megalith, which bears the remains of subducted oceanic lithosphere and has been retained beneath the EEP since ~2 Ga ago.

The discovery of the first diamondiferous kimberlite pipe north of Arkhangelsk in the early 1980s showed that the EEP is diamondiferous like most other ancient platforms. By now, kimberlites and lamproites have been found at the northern and southern margins of the EEP in the territories of Russia, Finland, and Ukraine (Fig. 1, table). No primary diamond deposits are yet known from the central part of the platform overlain by thick sedimentary cover. Economic potential was found only in kimberlites from the northern part of the structure (Zolotitsa and Verkhotina fields of the Arkhangel'sk region), although significant amounts of diamonds were also noted in the Tersky Bereg and Kaavi–Kuopio (Finland) complexes. As is known [11], the presence of thick cold ancient lithosphere is required to generate kimberliltes and preserve diamondiferous domains in the mantle. Based on heat flow data, the northern EEP is underlain by the thickest (200–300 m beneath the Karelia–Kola province) and coldest (possibly, depleted) ancient lithospheric mantle. Other cratons in the northern hemisphere also have the same characteristics, e.g., Siberian Craton (200–350 km), Western Africa (250–350 km), and the central Canadian Shield (>300 km) [12].

Geochemical and isotope–geochemical data on diamondiferous and nondiamondiferous kimberlites from 15 fields of the EEP (Fig. 1, table) obtained by the technique described in [1 and others] allowed us to distinguish the following characteristic features of the studied kimberlites. Lamproites were studied in less detail and are not considered in this paper.

Kimberlites occur in the northern and southern parts of the EEP. However, most bodies are concentrated in the northern part and have a Paleozoic age. The kimberlites with an age of 390–360 Ma extend as a W–E-trending belt from the Kandalaksha dikes through the largest occurrences in the Arkhangel'sk region to the Umba field in Middle Timan. The emplacement of economic-grade diamondiferous kimberlites is related to this period.

Based on composition, the EEP kimberlites are subdivided into three (high-Ti, moderate-Ti, and low-Ti) varieties.

Fig. 1. Main kimberlite and lamproite complexes of the East European Platform (modified after Bozhko et al., 2002). (*1–3*) Crust: (*1*) Archean, (*2*) Archean crust reworked in Neoarchean and Paleoproterozoic, (*3*) Paleoproterozoic); (*4*) Postsvecofennian unmetamorphosed sedimentary and volcanogenic complexes; (*5*) Paleoproterozoic granites; (*6*) Mesoproterozoic rapakivi granites; (*7*) Precambrian faults; (*8*) platform boundaries; (*9, 10*) kimberlite occurrences: (*9*) economic diamondiferous, (*10*) potentially diamondiferous; (*11*) lamproite occurrences; (*12*) numbers in boxes designate the age of kimberlites and lamproites, Ga. Numbers in the map: (1–11) kimberlite occurrences: (1) Kandalaksha, (2) Mela, (3) V. Grib pipe, (4) Zolotitsa field, (5) Kepa field, (6) East Azov area, (7) Umba area, (8) Tersky Bereg, (9) Kaavi-Kuopio, (10) Kimozero, (11) Kirovograd; (12–15) lamproite occurrences: (12) Por'ya Guba, (13) Kostomuksha, (14) Kuhmo–Lentiira, (15) Cherkassk.

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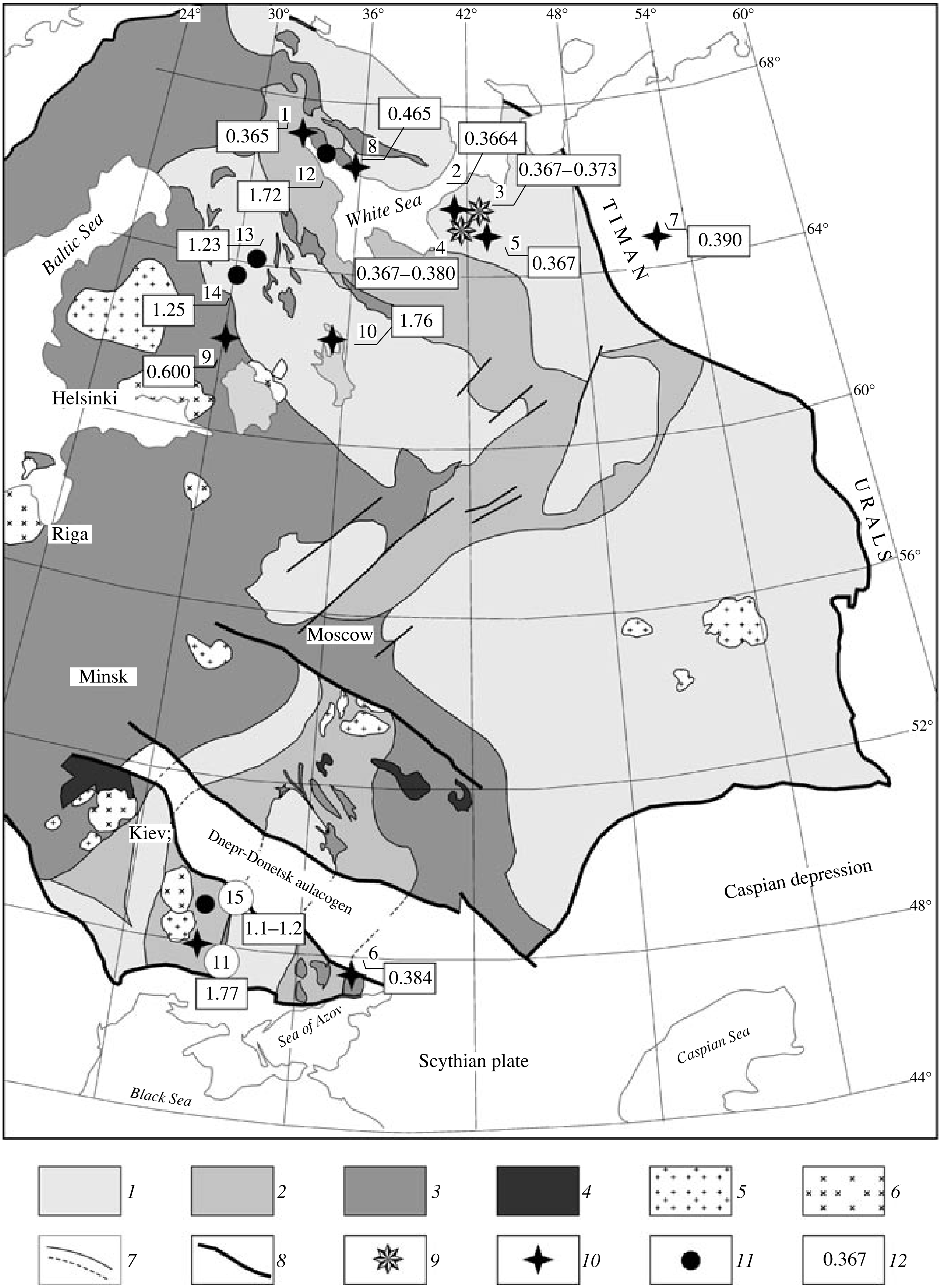
24°
30°
36°
42°
48°
54°
60°
68°
64°
60°
56°
52°
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44°
1
0.365
0.465
8
12
1.72
0.3664
2
0.367–0.373
3
White Sea
Baltic Sea
13
1.23
4
0.367–0.380
5
0.367
7
0.390
TIMAN
14
1.25
10
1.76
9
0.600
Helsinki
Riga
URALS
Moscow
Minsk
Kiev;
Dnepr-Donetsk aulacogen
15
1.1–1.2
11
1.77
6
0.384
Caspian depression
Sea of Azov
Scythian plate
Caspian Sea
Black Sea
1
2
3
4
5
6
7
8
9
10
11
0.367
12

Kimberlites (1) and lamproites (2) of the East European Platform (Late Proterozoic–Devonian)

No.	Area, complex, sample		TiO_2, wt %	ε_{Nd}	ε_{Sr}	Emplacement time (Ma), method	Model age T(Nd)DM, Ga
	Late Paleoproterozoic						
1	Kimozero (1)		0.6–1.5			1760, Sm–Nd [4]	
2	Por'ya Guba (2)		1–2	–9.3	+5.7	1720, Rb–Sr [1]	2.9
3	Kirovograd (1)		2–4.6	+1.1, +1.19	+19.7	1770, Rb–Sr [5]	2.04, 2.11
	Mesoproterozoic (Early–Middle Riphean)						
4	Cherkassk (2)		3.43	–12, –14		1100–1200, Rb–Sr [5]	
5	Kostomuksha (2)		3.7–3.3	–9.5 to –7.9	+6 to +35	1230, Rb–Sr [1]	2.1
6	Kuhmo-Lentiira (2)			–9	+50	1250, U–Pb perovskite [6]	
	Neoproterozoic (Vendian)						
7	Kaavi–Kuopio (1)		2–3	From +1 to 0	From –6.8 to 1.0	600, U–Pb [6]	
	Paleozoic (Middle Ordovician)						
8	Tersky Bereg (Ermakov 7) (1)		1–1.2	From –1.4 to +3.2	From –9.4 to +1.2	465, Sm–Nd, Rb–Sr [7]	1.0
	Paleozoic (Devonian)						
9	Kandalaksha (1) Dikes					365, K–Ar [1]	
10	Kepa field (1)	49-AP	2.77	1.7	–11.6	360, Rb–Sr [1]	0.8
11		64-AP	3.12	1.2	–1.2	360, Rb–Sr [1]	0.8
12	Verkhotina field (V. Grib pipe) (1)		1.15	–0.4	28.7	360, Rb–Sr [1]	0.97
13	Zolotitsa field (1)	58AP	1.06	–2.2	–4.5	380, Rb–Sr [1, 8]	1.1
14		47AP	0.73	–5.0	26.2	380 [1, 8]	1.3
15	Mela field (1)		0.8–1.1	–6.1 to –4.6	–4.1 to +2.9	366.4, Rb–Sr [9]	
16	Umba field (1)	436/231	2.79	3.0	15.8	390, Rb–Sr [1]	0.80
17		427/157		2.8	31.2	390, Rb–Sr [1]	0.80
18	Eastern Azov area (1)	293/11	3.98	1.7	0.73	384, Rb–Sr [10]	0.84
19		396/4b		–0.1	28.9	384, Rb–Sr [10]	0.96
20		1459a		1.9	25.6	384, Rb–Sr [10]	0.84

The *high-Ti kimberlites* (TiO_2 ~ 3 wt %) are isotopically and geochemically similar to the Group I kimberlites of South Africa. They occur both in the northern (Kandalaksha, Kepa, Umba, and others) and in the southern (Kirovograd, Eastern Azov area) areas of the EEP, spanning the entire (Late Paleoproterozoic–Devonian) interval of the kimberlite formation. The Kepa kimberlites are enriched in Ti (TiO_2 ~ 3 wt %) and LREE ($(La/Yb)_n$ ~ 70–130). The distribution of trace elements, including the indicator Th–U–Nb–Ta elements, show a smooth pattern in spidergrams (Fig. 2). The isotopic composition of the Kepa kimberlites (ε_{Nd} (+1.7; +1.2); ε_{Sr} (–11.6; –1.2); $^{206}Pb/^{204}Pb$ 18.5, $^{207}Pb/^{204}Pb$ 15.5, $^{208}Pb/^{204}Pb$ 38.4) indicates that they were derived from depleted mantle, like Group I kimberlites of South Africa (Fig. 3). The Umba kimberlites (Middle Timan) were obtained from even more depleted source (ε_{Nd} from + 3 to + 4).

The *moderate-Ti kimberlites* (TiO_2 ~ 1 wt %) from the V. Grib breccia pipe have high mg# value (89). The V. Grib pipe and pipes from the Zolotitsa field are characterized by low LREE contents (19 ppm) and deficiency in Nb, Ta, and Th (38, 4, 3, respectively) (Fig. 2). The Nd isotopic composition of the V. Grib pipe resembles the BSE pattern (ε_{Nd} from –0.4 to + 1.0) (Fig. 3), while its Pb isotope ratios ($^{206}Pb/^{204}Pb$ 18.1, $^{207}Pb/^{204}Pb$ 15.5, $^{208}Pb/^{204}Pb$ 38.04) approximately coincide with those typical of the Zolotitsa kimberlites. The kimberlites from the V. Grib pipe contain diverse diamond-associated minerals (mainly, picroilmenite, garnet, and Cr-diopside) mantle xenoliths. Similar varieties occur in the Tersky Bereg (Ermakov 7 pipe) and Kaavi–Kuopio complexes. These complexes contain Vendian kimberlites (Kaavi–Kuopio), in addition to Paleozoic (Grib pipe and Tersky Bereg pipes).

The *low-Ti kimberlites* (TiO_2 < 1 wt %) prevail in the Devonian. They are most abundant in the Zolotitsa field. The rocks are characterized by elevated mg# values (75–85), low contents of HFSE (Nb, Zr, Ta, Hf, Th, and U) and LREE (La 9–40 ppm, Ce 21–70 ppm) as

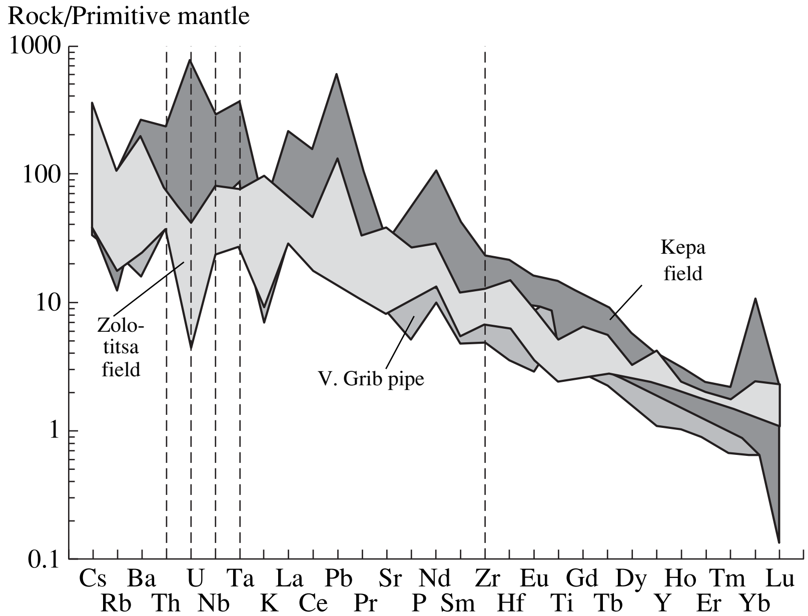

Fig. 2. PM [13]-normalized trace element distribution. Kimberlites of the Zolotitsa field and V. Grib pipe demonstrate negative anomalies of Th, U, Nb, and Ta.

compared to the Group I (La 90–125 ppm, Ce 140–220 ppm) and Group II kimberlites (La 200 ppm, Ce 350 ppm) of South Africa (see [14]). The Nd isotopic composition is significantly shifted towards negative values (ε_{Nd} from –2 to –6), suggesting enriched mantle source (EM1) of these kimberlites (Fig. 3). The kimberlites of the Zolotitsa field are significantly depleted in radiogenic Pb and have the following initial isotope ratios: $^{206}Pb/^{204}Pb$ 18.1–18.3, $^{207}Pb/^{204}Pb$ 15.5–15.6, and $^{208}Pb/^{204}Pb$ 37.7–38.1.

The kimberlites of different compositions are spatially separated from each other. In particular, low-Ti (Zolotitsa and Mela) and moderate-Ti (V. Grib, Ermakov, and Kaavi–Kuopio pipes) kimberlites form two small areas confined to the boundaries of intraplatformal structures (Archean cratons with Lower Proterozoic mobile belts). The high-Ti kimberlites (Kandalaksha, Kepa, and Umba fields in the north; East Azov fields in the south) are restricted to the platformal margins. The moderate- and low-Ti kimberlites were derived from mantle with BSE or EMI characteristics. Diamond deposits, including economic deposits in the EEP, are related to these rocks. The depleted mantle served as the source for high-Ti kimberlites; i.e., they were derived from a rather primitive OIB-type source. The Nd model ages indicate that events of mantle enrichment and kimberlite emplacement were separated by an interval shorter than that for low-Ti kimberlites (table). This provided more favorable conditions for enrichment in fluids and/or the crustal component.

The Zolotitsa and, to a lesser extent, V. Grib kimberlites are depleted in Nb, Ta, Th, and some other HFSE (Fig. 2), indicating generation from lithospheric melts with traces of crustal contamination. The lithosphere could be preliminarily metasomatized by fluids, which were liberated from crustal blocks subsided in mantle during ancient subduction and/or terrane collision. Recent seismic tomography data show that the buried remains of oceanic lithosphere (megaliths) underlay whole continents [11 and others]. They possibly consist

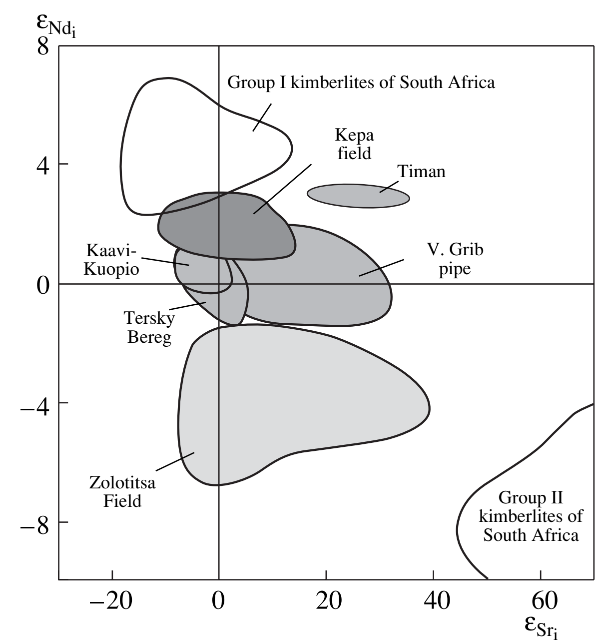

Fig. 3. Isotopic composition of kimberlites of the EEP in the ε_{Sr}–ε_{Nd} diagram. Field of South African kimberlites is shown after [14].

of a mixture of residuals from partial melting and subducted material, which continues to release volatiles during subsidence in transitional zones [11 and others].

The *T*(Nd)DM model ages suggest that the sources of the Devonian kimberlites of the EEP are different in age. The earliest model age was obtained for the sources of the low- and moderate-Ti kimberlites of the Zolotitsa and Verkhotina fields (~1 Ga), whereas the source of the high-Ti kimberlites of the Kepa and some other objects (table) was presumably younger (~0.8 Ga). It should be noted that only Proterozoic lamproites are known from EEP. They were derived from enriched mantle EMI (ε_{Nd} from –9 to –14) with an enrichment age (model age) of ~2 Ga (Kostomuksha and Kirovograd) and even up to 2.9 Ga (Por'ya Guba). A giant (up to 1 Ga) gap between source enrichment and emplacement of low-Ti kimberlites (table) provided favorable conditions for the enrichment of the source in fluid and/or crustal components.

While discussing the formation conditions of kimberlites, Helmsteadt and Gurney [11] emphasized that known models of the origin of Groups I and II kimberlites of South Africa are inconsistent with both hot spot and plume hypotheses. In particular, the intracratonic structure, including hotspot trajectories, localize kimberlites, but they destroy "mantle root," leading to a loss of diamond potential. These authors suggest that kimberlites were formed under the influence of a megalith consisting of the remains of subducted oceanic lithosphere. We considered a similar mechanism for the kimberlites of the Zolotitsa field in the Arkhangel'sk province [2]. We assumed that collision and/or subduction (with participation of mantle metasomatism) took place at the boundary between the Belomorian and Kola blocks. The kimberlites of the Zolotitsa and Verkhotina fields derived from variably enriched EMI source were formed there, whereas the kimberlites of the Kepa field were derived from depleted mantle. New data obtained for the entire EEP demonstrated a wider abundance of high-Ti kimberlites, which testifies to the mainly depleted composition of the underlying mantle. However, one more area of low- and moderate-Ti kimberlites was found at the boundary of the Karelian and Svecofennian blocks, where mantle was also metasomatized by fluid/melts supplied from a megalith.

The appearance of the deepest intracratonic (kimberlitic) magmatism in the EEP is correlated with global tectonic events, marking the formation and breakup of supercontinents. The formation of kimberlites and lamproites of the eastern Baltic Shield and central Ukrainian Shield (Kimozero, Por'ya Guba, and Kirovograd occurrences) coincided with the Late Paleoproterozoic stage (1.7–1.8 Ga) of intense crustal growth, which was responsible for the formation of the Columbia (Hudsonian) supercontinent. The breakup of this continent 1.2–1.3 Ga ago was marked by the appearance of lamproites in the western part of the Karelian block of the EEP (Kostomuksha and Kuhmo–Lentiira), which was simultaneous with lamproite magmatism in the Ukrainian Shield (Cherkassk occurrence). The diamondiferous kimberlites were also formed in the western Karelian Craton (Kaavi-Kuopio in Finland) during the breakup of the Neoproterozoic Rodinia (~0.6 Ga ago). Active orogenic events in the Paleozoic led to the collision between the EEP (Baltica continent) and Laurentia and the formation of Laurasia (~0.4 Ga ago) and, finally, Pangea. The Devonian kimberlites were emplaced in the north and south of the EEP (390–365 Ma). As is seen, the main stages of kimberlite formation in the EEP coincide with the breakup and/or formation of supercontinents (Meso- and Neoproterozoic stages). According to the alternative scenario, the kimberlites could postdate large-scale accretionary processes (Paleoproterozoic and Paleozoic stages). Thus, the above speculations indicate ambiguous relations between kimberlite magmatism and ascending mantle flows (upwelling) that provoke the breakup of supercontinents and large-scale plume (superplume) activity, which can occur also during growth of continental crust, i.e., can be initiated by subduction processes [15].

As shown in [11], the relation found between epochs of kimberlite formation and global rearrangement of plates in the EEP presumably indicates that the ancient diamond-bearing mantle roots were contaminated with material of the subducted oceanic lithosphere (possibly megalith), which was entrained in recycling with participation of ascending mantle plumes.

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