

Diamond Resource Potential of Kimberlites from the Zimny Bereg Field, Arkhangel'sk Oblast

V. A. Kononova, Yu. Yu. Golubeva, O. A. Bogatkov, and A. V. Kargin

*Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences,
Staromonetnyi per. 35, Moscow, 119017 Russia*

Received July 14, 2007

Abstract—Kimberlites with different diamond grades from the Zolotitsa, Verkhovina, and Kepina occurrences of the Zimny Bereg field (Arkhangel'sk oblast) have been compared in order to ascertain geochemical criteria of their diamond resource potential. A new collection of 21 core samples taken within a depth interval of 207–940 m from nine boreholes drilled in the central and western portions of the high-grade diamond-bearing Grib kimberlite pipe was subjected to comprehensive petrographic and geochemical examination, including Sr, Nd, and Pb isotopes and trace elements determined with ICP-MS. The compositional variations in kimberlites are controlled by the structural types of rocks. Porphyritic kimberlite (PK) distinctly differs from autolithic kimberlite breccia (AKB). Autoliths (Av) and PK are enriched in Th, U, Nb, Ta, La, Ce, Pr, P, Nd, Sm, Eu, Ti, LREE, and MREE, whereas HREE contents are rather uniform in all types of kimberlites. No lateral zoning was observed in pipes pertaining to the same structural type. The composition of kimberlites in the Zimny Bereg field and their diamond resource potential are variable. In the series of the Zolotitsa, Verkhovina, and Kepina occurrences, the Ti content increases, the La/Yb ratio grows from 18–44 to 70–130, and the diamond grade diminishes in the Kepina occurrence. The variations in kimberlite compositions are considered in terms of the degree of partial melting in the mantle, the role of volatiles, etc. As follows from the variation in the Ce/Y ratio, kimberlites from the Zolotitsa occurrence were formed at a lower degree of partial melting in comparison with the Kepina occurrence. Products of different degrees of partial melting are recognized within the Grib pipe; Av were likely formed at a somewhat higher degree of melting than AKB. An appreciable isotopic heterogeneity of the mantle is recorded in variable Nd and Sr isotopic compositions of kimberlites. The Kepina kimberlites were derived from a source slightly depleted relative to CHUR ($\epsilon_{Nd}(t)$ reaches +4) and are close to kimberlites of group I in South Africa. Kimberlites from the Grib pipe with transitional Nd isotopic composition plotted near the Bulk Silicate Earth (BSE) value in the $\epsilon_{Nd}(t)$ – $\epsilon_{Sr}(t)$ diagram adjoin the first group. The source of kimberlites of the Zolotitsa occurrence falls in the field of enriched mantle and is considered to be a product of interaction of an asthenospheric plume with the ancient enriched lithospheric mantle. Kimberlites depleted in Ti, Zr, and Th are related to a source formed as a result of a multistage process that included mantle metasomatism with participation of fluids. Devonian kimberlites derived from sources that involve crustal material (a shift of $^{206}\text{Pb}/^{204}\text{Pb}$, minimums of Th, U, Nb, and Ta contents) are diamond-bearing both in the East European Platform (the Zolotitsa and Verkhovina occurrences) and in the Siberian Craton (the Nakyn field).

DOI: 10.1134/S1075701507060013

INTRODUCTION

Despite the fact that a few thousand pipes have been studied to date in the world, many questions concerning the nature of kimberlite magma and its modification during ascent remain ambiguous. The geological exploration of the Verkhovina occurrence in the Zimny Bereg district of Arkhangel'sk oblast resulted in the discovery of the diamond-rich Grib kimberlite pipe in 1996. This discovery belongs to the Almazny Bereg Joint Stock Company (JSC), headed by E.M. Verichev and established by Russian, Canadian, and British companies. The exploration of the deposit was completed in 2002, and its reserves were approved by the State Reserve Commission of the Russian Federation. The extensive exploration drilling (some boreholes were about a kilo-

meter in depth) allowed information to be obtained about the 3D structure of this pipe, which is situated 115 km northeast of Arkhangel'sk and 25 km northeast of the Lomonosov diamond deposit. In addition to the Grib pipe, we studied kimberlites of the Zolotitsa and Kepina occurrences (Bogatkov et al., 2001; Kononova et al., 2002) using samples kindly placed at our disposal by the Alrosa-Pomorje JSC.

The Grib pipe is peculiar in composition, but the limited data available did not allow all aspects of this peculiarity to be ascertained. The detailed geological exploration carried out recently provided an opportunity to obtain new data and undertake a more detailed examination of this pipe. It should be noted that, after discovery of the Grib pipe, the Verkhovina occurrence was classified as an economic diamond district. Because the Grib pipe and a number of subsequent dis-

Corresponding author: V.A. Kononova. E-mail: victoria@igem.ru

coveries were not included in previous publications (Vaganov, 2000; Bogatkov et al., 1999; etc.), we are filling this gap, presenting a new paper that supplements the article published by Verichev et al. (2003).

RESEARCH METHODS

We examined samples kindly placed at our disposal by the Department of Diamond Geology of the Central Institute of Geological Exploration for Base and Precious Metals and the company Arkhangel'skgeolrazvedka. The basic information on kimberlites of the Zolotitsa and Kepina occurrences is given after Bogatkov et al. (1999, 2001) and supplemented by new data (Kononova et al., 2002; Larchenko et al., 2005; etc.).

The preparation of kimberlite samples is most important for obtaining correct results. The samples were taken from unaltered kimberlites far from the contact zone and processed in the following sequence. First, thin sections were examined under a microscope to select samples fit for further analytical procedures. The sample preparation included the careful examination of coarsely crushed rocks in order to remove xenogenic material. The complex of applied analytical methods included (1) determination of major elements with XRF on a VRA-20 device (Karl Zeiss Jena) at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (IGEM RAS); (2) determination of some trace elements with XRF on a Philips PW 2400 device at the same institute; and (3) determination of Na_2O , K_2O , H_2O , CO_2 , and FeO with chemical analysis at the chemical laboratory of the Geological Institute, Russian Academy of Sciences (GIN RAS). The trace elements were determined in the least contaminated varieties with ICP-MS on an Elan 6100 DRC device (Perkin Elmer) at the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements. The Sr, Nd, and Pb isotopic compositions of the most representative samples were measured on a Finnigan MAT-261 mass spectrometer at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences.

Special attention was paid to the reliability of the analytical results. Since XRF and ICP-MS results are not always identical, especially for Cr, Rb, and Nb, additional refining measurements were carried out.

RESULTS

Geological Setting of the Zimny Bereg Kimberlite Field

All kimberlite occurrences of the Zimny Bereg field are situated at the eastern margin of the East European Platform within the Kola Geoblock, characterized by a Neoarchean age of basement cratonization (Fig. 1). As was established by interpretation of geophysical data, the Zolotitsa occurrence (with the Lomonosov deposit), the Verkhotina occurrence (with the economic diamond-bearing Grib pipe), and the Kepina occurrence are located within a physical and geological inhomogeneity $85 \times 60 \text{ km}^2$ in area (Prusakova, 2006). This inhomogeneity is interpreted as a near-vertical domain of mantle and crustal material transformed by the origination and development of a kimberlite-forming system with participation of fluids. The geophysical survey did not reveal differences between kimberlites pertaining to particular occurrences within the Zimny Bereg field.

In addition to tens of kimberlite pipes, olivine melilitites and basalts are known from this field. Some kimberlite bodies have been dated with the Rb–Sr method (mica and whole-rock samples) by Larchenko et al. (2005) and other researchers. In particular, the Rb–Sr age of porphyritic kimberlite (PK) from the Grib pipe (the Verkhotina occurrence) is $372 \pm 8 \text{ Ma}$ (Shevchenko et al., 2004); massive kimberlite from a deep level ($>940 \text{ m}$) of the Pionersky pipe (the Zolotitsa occurrence) was dated at 380.1 Ma (Pervov et al., 2005). These ages correspond to the final stage of the main phase of alkaline magmatism in the Kola Peninsula ($410\text{--}362 \text{ Ma}$) and thus testify to the common causes of the Middle Paleozoic magmatic reactivation of the northern East European Platform.

As is known, diamond-bearing kimberlites are localized in tectonic units with an ancient basement. To estimate the age of the basement in the vicinity of the Grib pipe, 28 zircon grains from kimberlite of this pipe were examined at the Center of Isotopic Studies of the All-Russia Research Institute of Geology (Lepekhina et al., 2004). The results obtained are scattered from 2850 to 1042 Ma. Three grains yielded 2850–2676 Ma. Thus, the pipe probably cuts through Archean rocks. A close Re–Os model age ($2.9\text{--}3.1 \text{ Ga}$) was obtained for sporadic sulfide grains (Malkovets et al., 2004). The ancient age of the continental lithosphere of the Arkhangel'sk diamond-bearing province is consistent with data for Yakutia and South Africa.

Fig. 1. Geological scheme of the Zimny Bereg kimberlite field, simplified after (Prusakova, 2006). (1) Neoarchean Kola Geoblock, consisting of (a) Tersky and (b) Murmansk blocks; (2) grabens of the Keret–Leshukonsky branch of the Belomorian Aulacogen; (3) Kola–Kuloi protocrustal core; (4–6) elements of deep structure related to the formation and evolution of the transcrustal heterogeneous kimberlite-forming system: (4) lower crustal transitional magma chamber, (5) region of deep transformation of the crust, (6) upper crustal domains of mafic–ultramafic magmatism (contour lines of their roof); (7) occurrences of Paleozoic magmatism: (a) kimberlite pipes, (b) diamond-bearing Lomonosov and Grib pipes, (c) kimberlite sills, and (d) melilitite bodies; (8) contours of magmatic occurrences (numerals in circles): 1, Zolotitsa; 2, Verkhotina; 3, Kepina; (9) contour of the Zimny Bereg kimberlite field deduced from geophysical data.



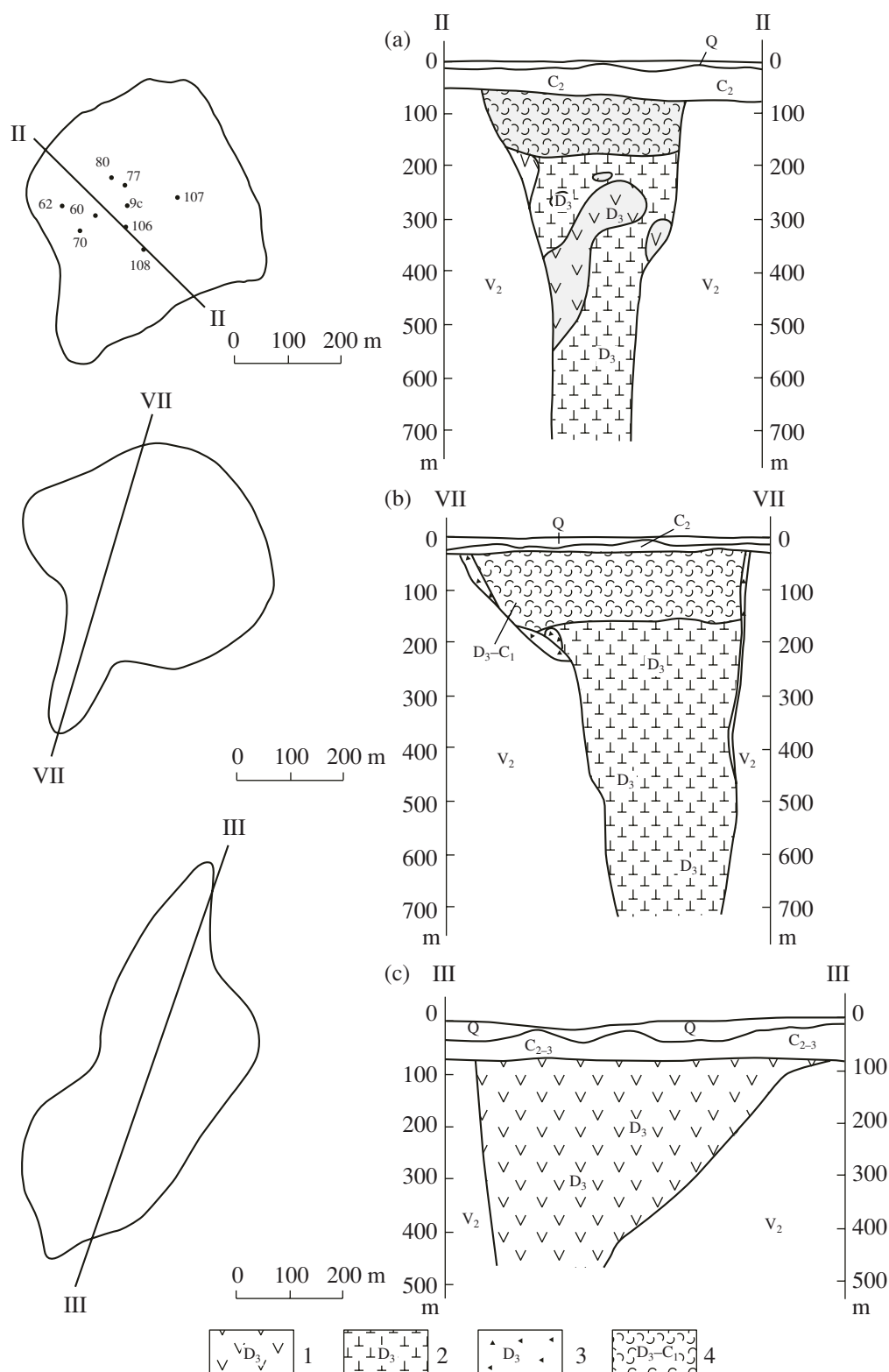


Fig. 2. Morphology and internal structure of kimberlite pipes in the Zimny Bereg field, after (Bogatikov et al., 1999) and (Burmistrov et al., 2005): (a) Grib pipe, the Verkhotina occurrence; (b) Arkhangel'sk pipe, the Zolotitsa occurrence; and (c) Anomaly 688 pipe, the Kepina occurrence. (1–3) Vent facies of kimberlite complex: (1) xenotuffaceous breccia; (2) autolithic kimberlite breccia; (3) brecciated country rocks; (4) tuffaceous sedimentary rocks of crater facies.

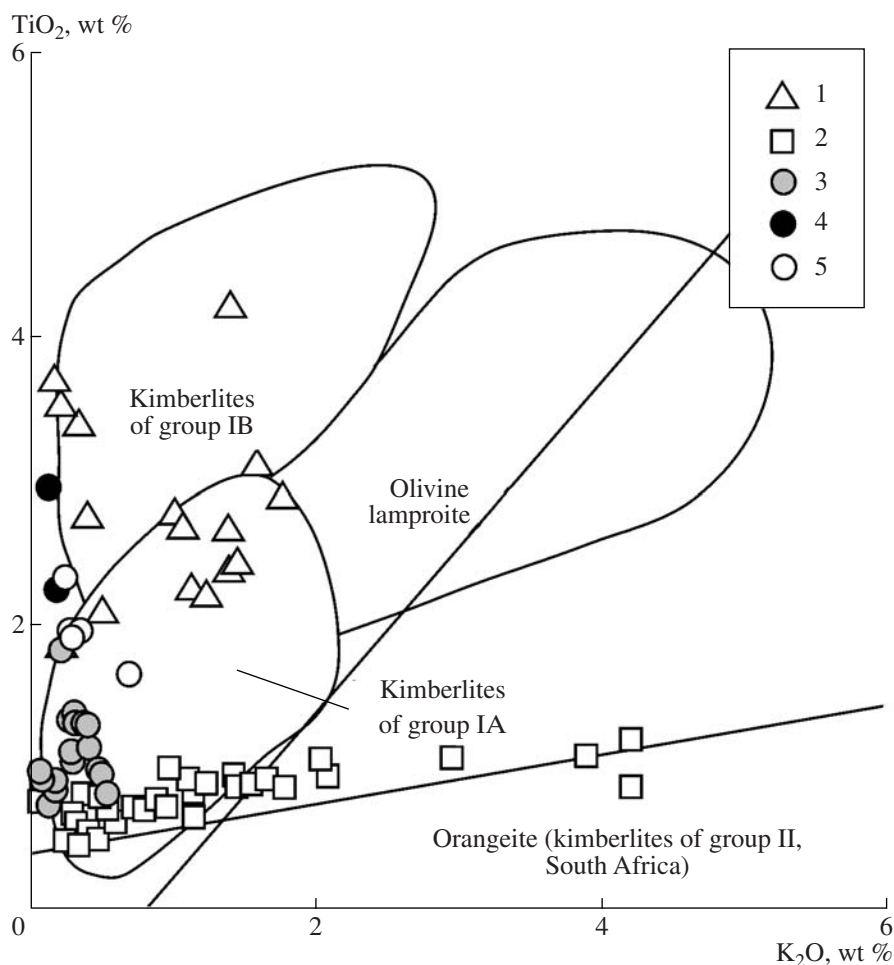


Fig. 3. Variations in TiO_2 and K_2O contents in kimberlites of the Zimny Bereg field, Arkhangel'sk oblast. The data on kimberlites from the Zolotitsa and Kepina occurrences were taken here and hereafter from (Bogatikov et al., 2001); compositional fields are given after (Taylor et al., 1994); solid lines, after (Mitchell, 1995). (1) Kimberlites of the Kepina occurrence; (2) kimberlites of the Zolotitsa occurrence; (3–5) Grib kimberlite pipe, the Verkhovina occurrence: (3) autolithic kimberlite breccia, (4) porphyritic kimberlite, (5) autoliths.

Structure and Composition of Kimberlite Pipes in the Verkhovina, Zolotitsa, and Kepina Occurrences

In the Baltic Shield, the Zimny Bereg diamond-bearing field contains the most numerous kimberlite pipes and the most diverse in geochemical and isotopic attributes (Bogatikov et al., 1999, 2001; Kononova et al., 2002). In our previous publications, we recognized the Zolotitsa and Kepina types of kimberlites. The third (Verkhovina) type, exemplified in the Grib pipe, was revealed subsequently. Examples of kimberlite pipes from various occurrences of the Zimny Bereg field are shown in Fig. 2. The pipes are rather simple in structure and consist of crater and vent portions. The crater portion is retained in the Verkhovina occurrence (Grib pipe) and the Zolotitsa occurrence (Arkhangel'sky pipe), but is eroded in the Kepina occurrence.

The geochemistry of kimberlites from different occurrences of the Zimny Bereg field is compared in Figs. 3–8. It is noteworthy that kimberlites of the Grib

pipe are characterized by transitional mineralogical and geochemical attributes, including isotopic marks.

Kimberlites from pipes of the *Kepina occurrence* vary from moderate-Ti (2.0–2.5 wt % TiO_2) to high-Ti (>2.5 wt % TiO_2) varieties (Fig. 3). They are enriched in LREE, with $(\text{La}/\text{Yb})_N = 70\text{--}130$. $\epsilon_{\text{Nd}}(t)$ is steadily positive within the range from +2.8 to +1.2; high Pb/Pb ratios are also typical ($^{206}\text{Pb}/^{204}\text{Pb} = 18.46\text{--}19.03$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.53\text{--}15.65$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.43\text{--}38.77$) (Figs. 4–8). According to geochemical parameters, including Nd, Sr, and O isotopic compositions, these rocks correspond to kimberlites of group I in South Africa.

Kimberlites from the *Grib pipe (the Verkhovina occurrence)* vary in composition depending on their structure and, in general, correspond to moderate-Ti varieties. Autolithic kimberlite breccia (AKB) shifts toward low-Ti kimberlites, whereas PK is high-Ti; all analyzed samples are moderate-Ti (Fig. 3). They are

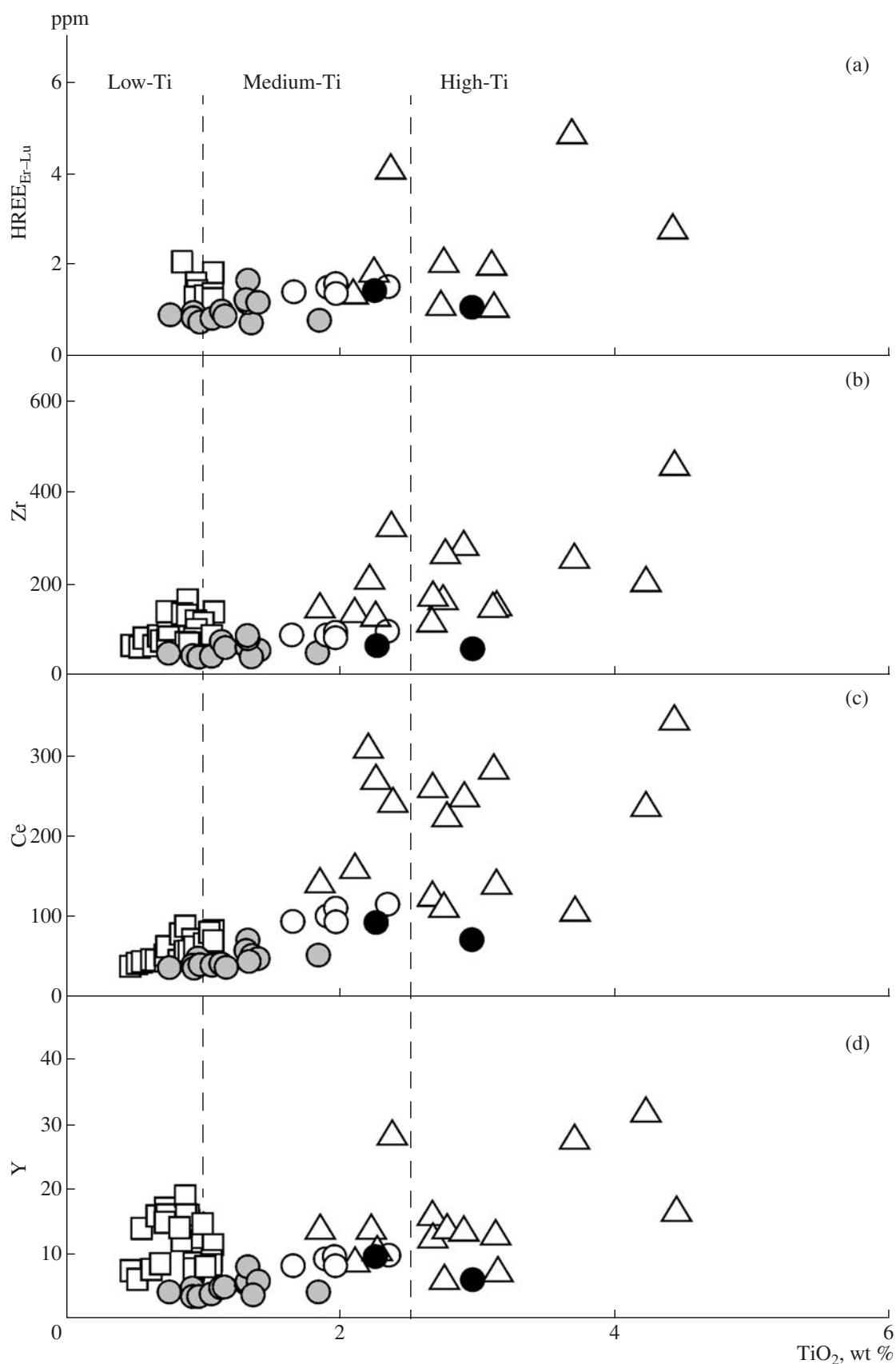


Fig. 4. HREE, Zr, Ce, and Y versus TiO_2 in kimberlites of the Zimny Bereg field, Arkhangel'sk oblast. See Fig. 3 for legend.

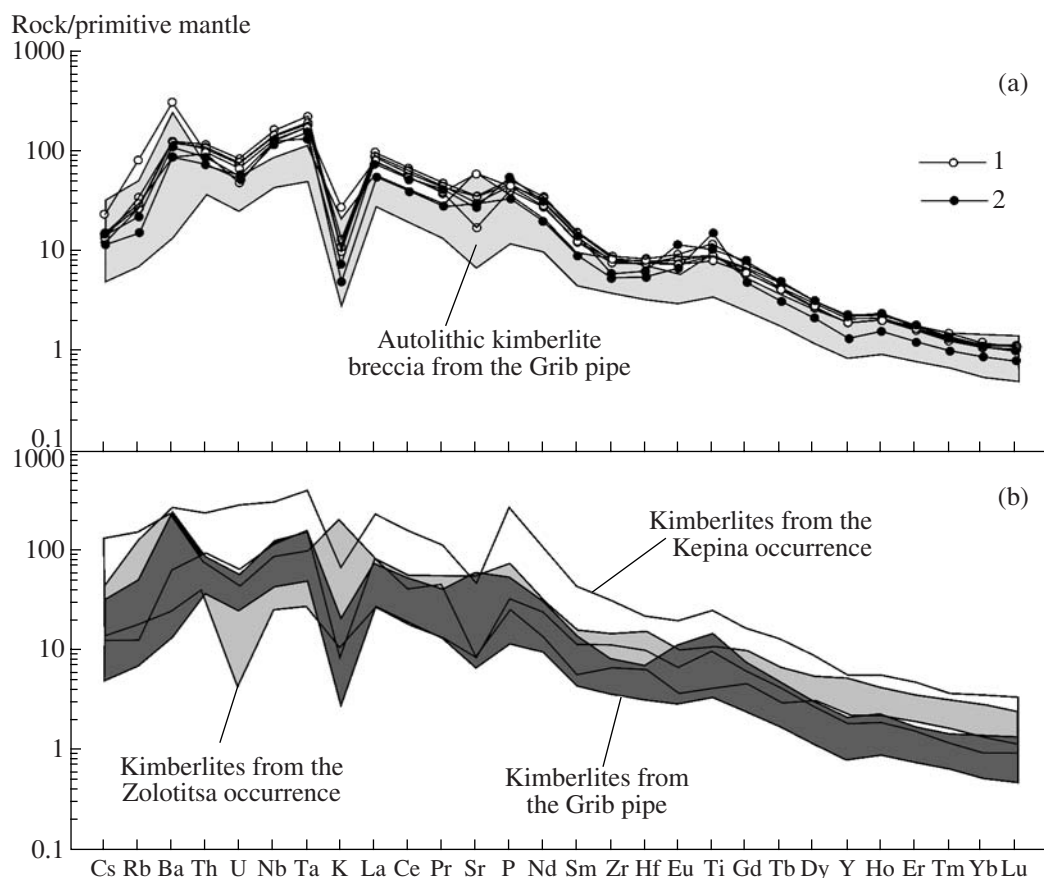


Fig. 5. Spidergrams of trace elements: (a) kimberlites and autoliths from the Grib pipe and (b) kimberlites from the Zolotitsa and Kepina occurrences. Kimberlites from the Zolotitsa occurrence and the Grib pipe are characterized by negative Th, U, Nb, and Ta anomalies. The primitive mantle composition was taken from (McDonough and Sun, 1995). (1) Autoliths and (2) porphyritic kimberlite.

close to the Bulk Silicate Earth (BSE) in the Nd isotopic composition, ranging from slightly negative $\epsilon_{Nd}(t)$ (–1.0) to moderately positive (+1.5) values (Fig. 6). At the same time, in the initial Pb isotopic composition ($^{206}\text{Pb}/^{204}\text{Pb} = 18.03\text{--}18.08$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.49\text{--}15.52$, $^{208}\text{Pb}/^{204}\text{Pb} = 37.89\text{--}38.02$), they approach the Zolotitsa kimberlites. The rocks have $(\text{La}/\text{Yb})N = 38\text{--}87$, transitional between the Kepina and Zolotitsa kimberlites.

Kimberlites of the *Zolotitsa occurrence* correspond to the low-Ti variety and are slightly enriched in LREE, with $(\text{La}/\text{Yb})N = 18\text{--}44$. In contrast to the kimberlites from the Kepina occurrence, they are characterized by negative $\epsilon_{Nd}(t)$, from –2.2 to –5.3; not high $\epsilon_{Sr}(t)$, mainly from –4.5 to +29 (Fig. 6); and a less radiogenic Pb isotopic composition ($^{206}\text{Pb}/^{204}\text{Pb} = 18.13\text{--}18.27$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.50\text{--}15.60$, $^{208}\text{Pb}/^{204}\text{Pb} = 37.69\text{--}38.14$) (Fig. 8). These geochemical parameters may indicate a significant contribution of ancient enriched mantle of EM1 type to the composition of these rocks.

The comparative analysis showed that Ti is the most indicative rock-forming element in kimberlites of the Zimny Bereg field. The low-Ti kimberlites from the Zolotitsa occurrence and the high-Ti kimberlites from

the Kepina occurrence are clearly distinguished in the $\text{TiO}_2\text{--K}_2\text{O}$ (Fig. 3) and $\text{TiO}_2\text{--HREE}$ (Zr, Ce, Y) (Fig. 4) diagrams. The AKB from the Grib pipe approaches the rocks of the Zolotitsa occurrence, whereas autoliths and PKs are enriched in titanium and partly overlap kimberlites from the Kepina occurrence.

New Geochemical Data for the Grib Kimberlite Pipe

The Grib pipe was penetrated by many boreholes to a depth of ~1 km. The drilling results allow us to consider its internal structure in detail, supplementing the previous publication (Verichev et al., 2003) and emphasizing some important features. As follows from the results of seismic surveying by Arkhangel'skgeolrazvedka, the roof of the crystalline basement in the proximity of the pipe is about 1200 m. The pipe cuts through poorly lithified Upper Riphean and Upper Vendian sedimentary rocks and is, in turn, overlapped by Middle Carboniferous terrigenous and carbonate rocks and Quaternary loose sediments. The thickness of the overlying sequence is 67 m. The average thickness of crater fill is 110 m. The vent portion of the pipe is filled with tuffaceous and xenotuffaceous breccias. Products of the

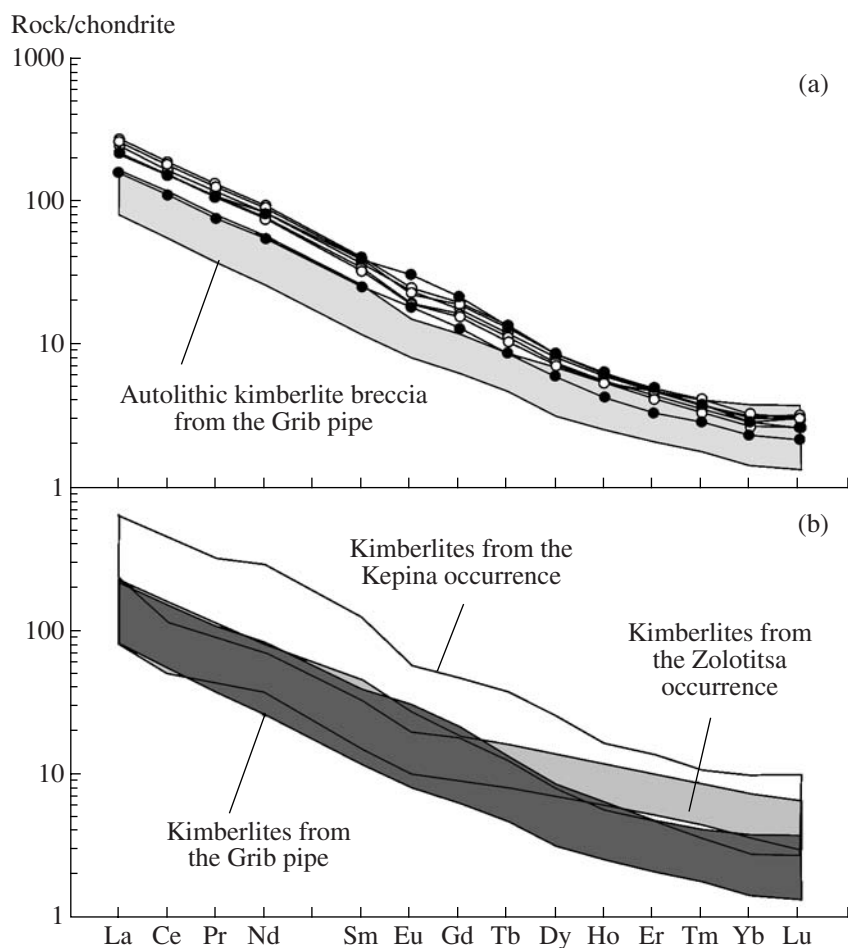


Fig. 6. Chondrite-normalized REE patterns: (a) kimberlites from the Grib pipe and (b) kimberlites from the Zolotitsa and Kepina occurrences. The chondrite composition was taken from (McDonough and Sun, 1995). See Fig. 5a for legend.

first phase of eruption occupy 28% of the vent volume, while the remainder is filled with kimberlite of the second phase. The breccias of crater facies are varicolored. Brown and red colors are predominant owing to the considerable amount of Vendian sedimentary rocks. The content of xenoliths reaches 40–50 vol %; the prevalent mudstone and siltstone xenoliths are combined with fragments of gneisses, gabbroids, granulites, and eclogite-like rocks. In comparison with kimberlites, the tuffaceous and xenotuffaceous breccias underwent more intense secondary alteration. The marginal zone of the pipe is contaminated by altered fragments of the country rocks, including siltstones, mudstones, and sandstones of the Ust'-Pinezh, Mezen, and Padun formations.

Kimberlites of the second phase of eruption are heterogeneous. Autolithic breccia occurs in the upper part of the pipe. The main volume is occupied by ataxitic, porphyritic, and transitional ataxitic–porphyritic kimberlite varieties (APK). AKB has an autolithic structure and a crystal–lithoclastic texture. The greater part of rocks is composed of saponite and serpentine that replace olivine; serpentinization and chloritization are

the most abundant secondary alterations. Fragments of crustal rocks and autoliths are predominant in AKB. Xenocrysts of ilmenite, garnet, and phlogopite are noted. The disseminated ore mineral is largely contained in autoliths. Olivines 1 and 2 are almost completely replaced by secondary minerals. Autoliths are composed of serpentine pseudomorphs after olivine and phlogopite. The transitional, actually porphyritic kimberlites and ataxitic kimberlites enriched in fragments are greenish gray and dark gray with a greenish hue. The clastic fraction (10–70 vol %) is largely composed of magmatic material; the content of xenogenic particles does not exceed 5 vol %. The magmatic material is mainly composed of pseudomorphs after olivine xenocrysts of two generations. The irregularly smoothed or oval grains of olivine 1 (30–50 vol %) are 1–4 mm (up to 10–25 mm) in size. The subhedral olivine 2 grains (1–5 vol %) are small (0.2–0.8 mm). Pseudomorphs consist of a thin-sheeted and flaky aggregate of serpentine with an admixture of finely crystalline carbonate. Relict grains of olivine 1 and less frequently olivine 2 appear at a depth below 240 m. Crystalloclasts of orange garnet, pyrope, picroilmenite,

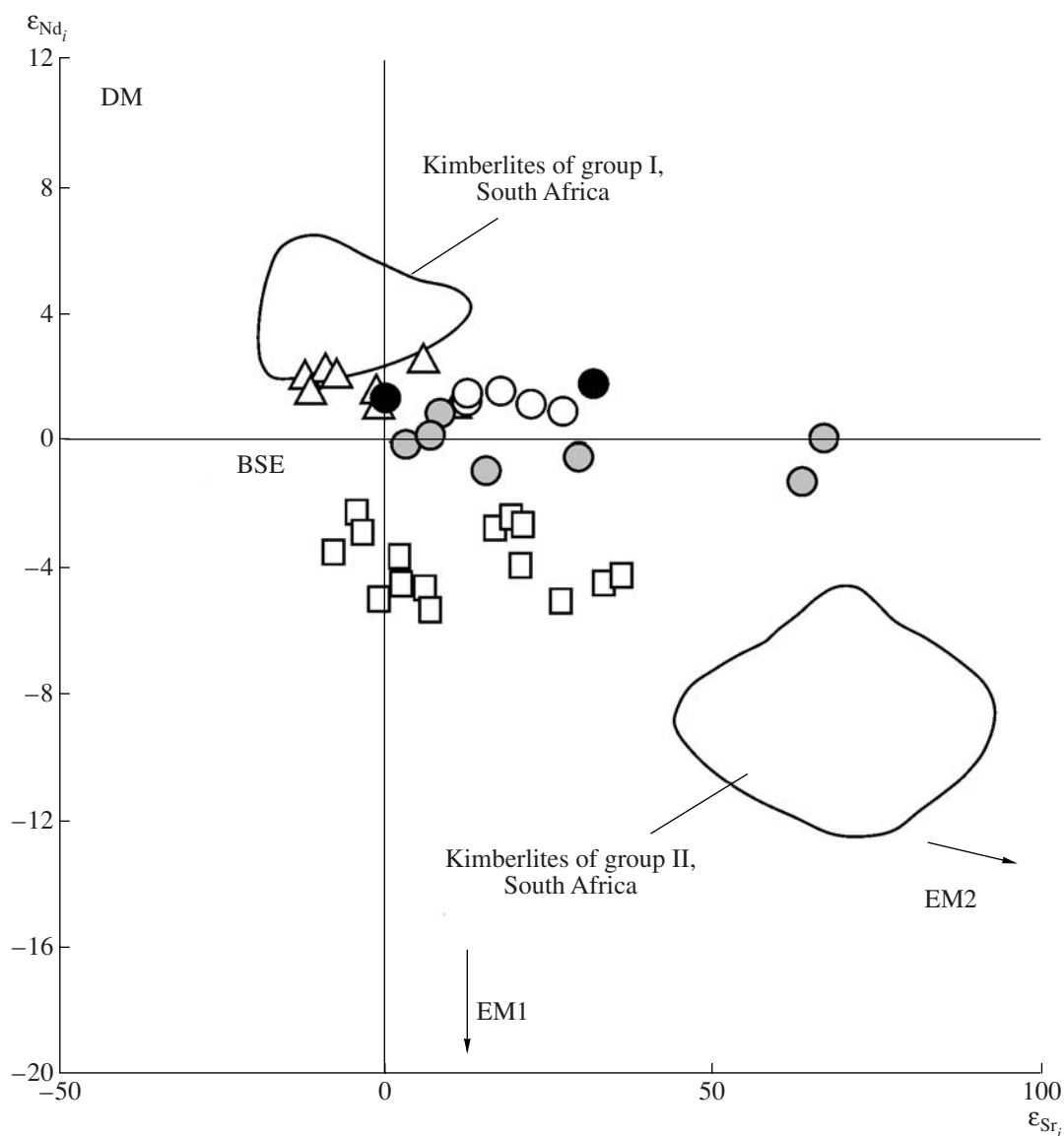


Fig. 7. ϵ_{Nd_i} versus ϵ_{Sr_i} for kimberlites from the Grib pipe and the Zolotitsa and Kepina occurrences. Compositional fields are shown after (Mitchell, 1986). See Fig. 3 for legend.

phlogopite, and less abundant Cr-diopside occupy approximately 2 vol % of kimberlite. Xenogenic material consists of siltstone, mudstone, and sandstone. Carbonation, silification, saponitization, and limonitization are typical secondary alterations.

The PKs of deep levels are characterized by large (up to 5–7 cm in diameter) olivine phenocrysts, occasionally slightly serpentinized and incorporated into the phaneritic groundmass, composed of small olivine 2 crystals, serpentine, and ore mineral. The diamond content of kimberlites pertaining to the second phase is approximately three times higher than that of xenotuffaceous breccia. The highest diamond grade is achieved in AKB, which commonly occurs in the central zone of the pipe.

We will focus on some details of specific samples that are accurately tied to a certain place within the kimberlite pipe. The typical features of porphyritic and autolithic kimberlites are given in Table 1. The location of boreholes within the pipe is shown in Fig. 2a. The boreholes are often inclined, and the depth of a sample indicated in the core documentation may deviate from the vertical depth within the pipe. Sample 77/940 of PK is an example of such a discrepancy. Judging by the geological plan (Fig. 2a), the depth of the pipe in this place does not exceed 400 m, although cores were carried up from a depth of 940 m. Microphotographs of some kimberlite samples are shown in Fig. 9.

Porphyritic kimberlite is rich in phenocrysts (Figs. 9a, 9b); largely, they are rounded or irregularly

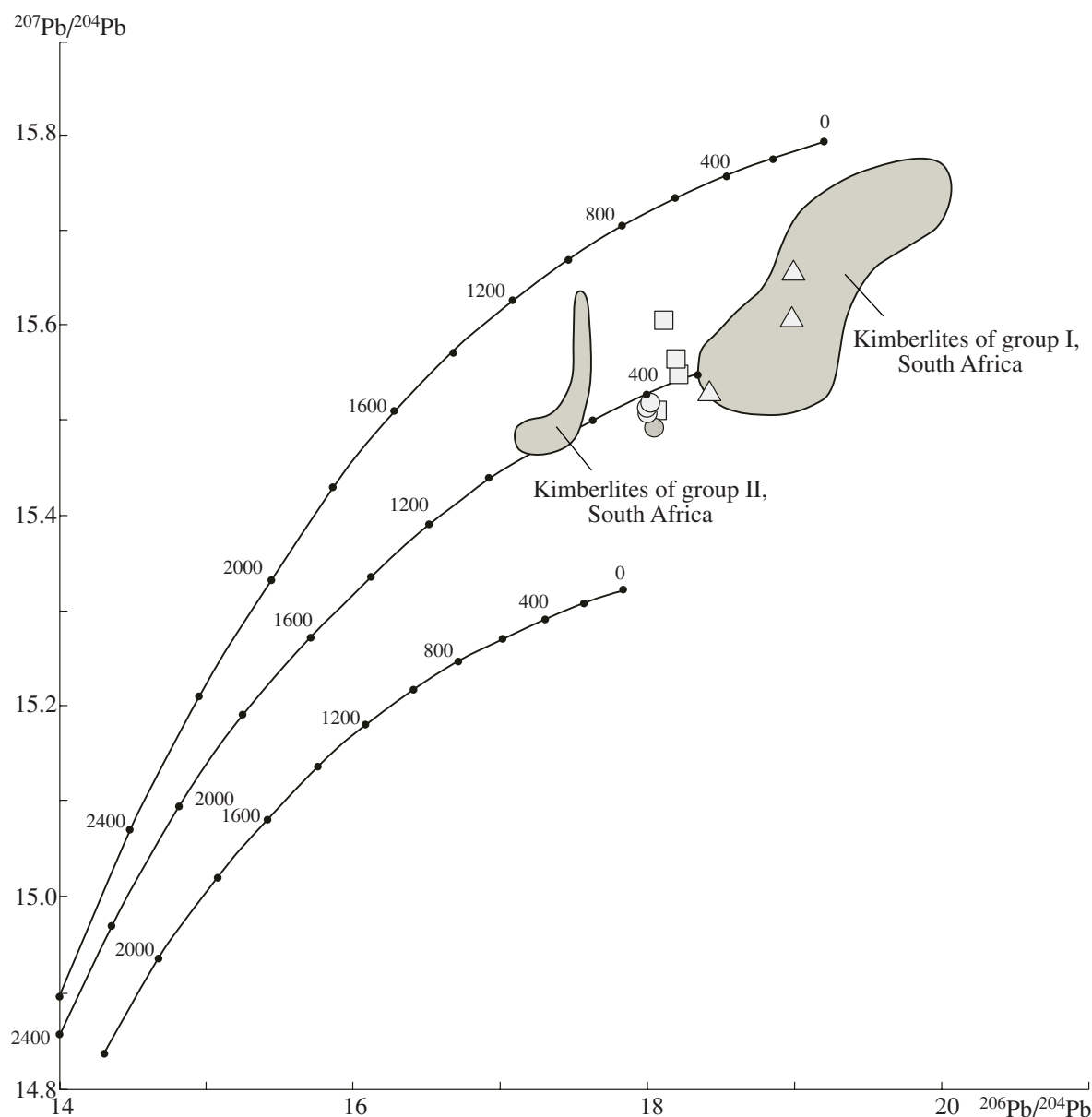


Fig. 8. $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for kimberlites of the Zimny Bereg field, Arkhangel'sk oblast. Model curves of Pb evolution of the mantle (M), lower crust (LC), and upper crust (UC). Numerals on lines are time, Ma. Compositional fields are shown after (Fraser et al., 1985), (Smith, 1983), and (Nelson, 1992). See Fig. 3 for legend.

shaped serpentine or saponite pseudomorphs after olivine grains varying from a few millimeters to 1 cm in size (the first generation); sporadic euhedral olivine phenocrysts are noted. Some pseudomorphs are rimmed with calcite (sample 9c/484). Mica phenocrysts partly replaced by chlorite are extremely rare. Large ilmenite phenocrysts are worthy of note. The groundmass largely consists of serpentine, chlorite, calcite (sample 77/940), and ore minerals. In addition, calcite veinlets are present; carbonated xenoliths or ones consisting of primary calcite country rock fragments were detected in sample 9c/484. Examination of thin sections and chemical analysis of samples clearly indi-

cate that the latter are actually PKs from the Grib pipe. However, according to the results of geological exploration, PKs do not occur at such a depth. Probably, the analyzed PKs were either xenoliths entrained by AKB or large autoliths.

Autolithic kimberlite breccia. The rocks, which have an autolithic structure and a crystal–lithoclastic texture, were described in detail by Burmistrov et al. (2005) and Golubeva et al. (2006). The content, size, and morphology of autoliths and the thickness of outer shells are variable even within a particular thin section (Figs. 9c, 9d). The autolith core is commonly composed of serpentine, chlorite, or saponite pseudomorphs after olivine (sam-

Table 1. Brief petrographic description of the studied samples from the Grib kimberlite pipe

Sample	Variety	Brief description
9c/484*	PK	Phenocrysts are composed of olivine 1 (up to 1 cm) and olivine 2 replaced by serpentine. A calcite rim often develops around olivine 1 (Fig. 9a). Olivine 2 is occasionally euhedral. Calcite veinlets and carbonated xenoliths are noted. Finely dispersed ore mineral occurs in the groundmass; ilmenite is identified.
77/940	PK	Phenocrysts are composed of olivine (up to 1 cm) replaced by serpentine (Fig. 9b). The groundmass consists of chlorite, calcite, and serpentine pseudomorphs after olivine grains 0.5 mm in size, occasionally euhedral. Fine-grained calcite aggregate rims large olivine phenocrysts.
9c/584–586	AKB	Film autoliths (thin autolithic shells) are predominant; an autolith-in-autolith structure (Fig. 9c) is noted. Ore minerals are observed mainly in autolithic shells; contents of ore minerals in rock are low. Olivine is replaced by serpentine and chlorite. Carbonate content is extremely low.
106/590	AKB	Very dark autoliths enriched in perovskite. The matrix consists largely of serpentinite. Pyroxenes are noted as fragments in the groundmass and autolith cores.
60/445	AKB	Thickness of autolithic shells varies widely, down to complete absence. Xenoliths of metamorphic rocks occasionally occur as autolithic cores. Large mica flakes are incorporated into the groundmass. Ore mineral content is medium.
60/546	AKB	Olivine in the groundmass is replaced by calcite and serpentine. Calcite veinlets and mica flakes are noted.
60/955.1	AKB	The sample is enriched in perovskite (Fig. 9d). Large euhedral perovskite grains occur in the groundmass and autolithic shells. Fragments of serpentine pseudomorphs after olivine and xenoliths of Vendian rocks form autolithic cores.
62/355	AKB	Rock consists of vaguely outlined pseudomorphs after olivine. The rock is limonitized and brown in color.
70/190	AKB	This rock resembles sample 62/355. Autoliths are mainly clastic in appearance. Pseudomorphs after olivine are vaguely outlined.
77/478	AKB	Autoliths are sporadic, mainly clastic in appearance, and coreless. The groundmass consists of serpentine. Xenoliths of Vendian rocks are abundant. The content of ore minerals in the groundmass is low.
77/700	AKB	Autoliths often are larger than 1 cm; an autolith-in-autolith structure is noted. Autoliths are much darker than the groundmass due to the secondary minerals replacing perovskite. The ore mineral content in the rock itself is low. Chlorite occurs in autolithic shells.
80/265	AKB	The rock is of porphyritic appearance and consists of serpentinite and chlorite. Rare autoliths occupy interstices between serpentine blocks.
108/650	AKB	Autoliths contain cores and are devoid of cores; film autoliths are noted. Autoliths vary in shape from spherical to angular fragments. Autoliths are darker than the groundmass due to enrichment in ore minerals and mica. Olivine is replaced by serpentine and calcite. The matrix consists of serpentine and chlorite.

* Borehole, depth, m; here and in Tables 2–4, AKB is autolithic kimberlite breccia and PK is porphyritic kimberlite.

ples 106/590, 60/546, and 77/478) and scarce pyroxenes (sample 106/590), garnet, ilmenite, and mica. The pseudomorphs after olivine are rounded and frequently clastic in shape. Ore minerals (magnetite, perovskite, etc.) concentrate in the outer shells and their contents vary from one sample to another. Calcite, phlogopite laths, and an autolith-in-autolith structure occur in the fairly thick outer rims. The rounded and angular (clastic) coreless autoliths are observed in rocks. The most abundant xenoliths are composed of Vendian country rocks and metamorphic basement rocks. They occur as autolith cores and merely as phenocrysts without autolithic shells. The groundmass that fills interstices between autoliths consists of serpentine or saponite, chlorite, and ore minerals occurring in variable amounts.

Compositional variations in kimberlites within the Grib pipe were established from examination of 16 core samples taken from a depth of 207–940 m in the central and western portions of the pipe (Tables 2, 3). The compositional differences are related more to the structural type of kimberlites rather than to the location of samples. The most distinct difference was established between PK and AKB (Fig. 3–8). Autoliths (Av) commonly are transitional in composition between PK and AKB. The behavior of some indicative components is noted below:

TiO₂ (wt %) decreases in the series 2.96 (PK) – 1.6–2.3 (Av) – 0.75 (AKB) (Table 2, Fig. 3);

MgO (wt %) is 9–31 in PK and Av, is 33 in one Av sample, and increases up to 31–36 in AKB (Table 2);

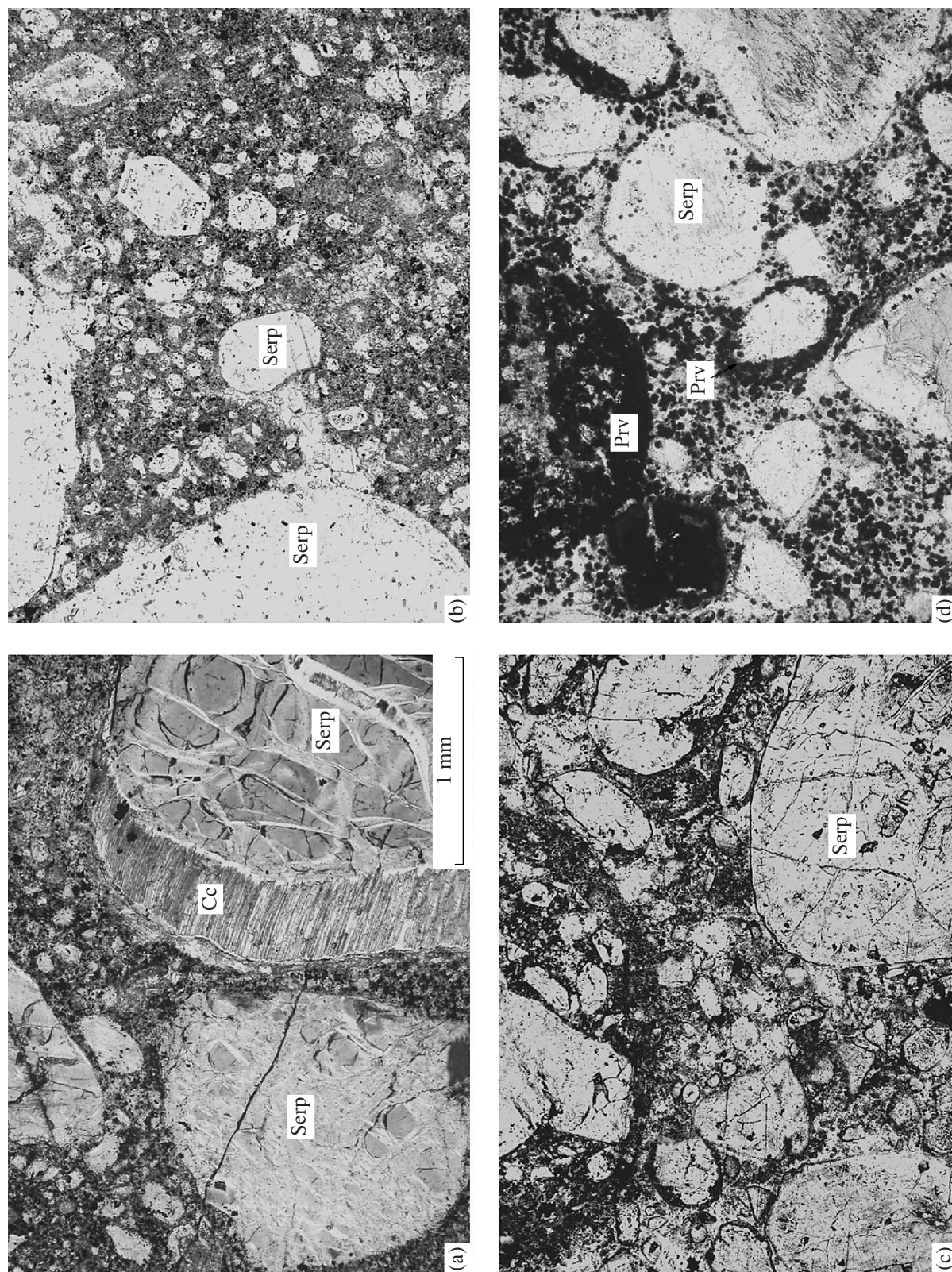


Fig. 9. Varieties of rocks from the Grib kimberlite pipe: (a) porphyritic kimberlite, sample 9c/484; (b) porphyritic kimberlite, sample 77-940; (c) autolithic kimberlite breccia, sample 9c/584-586; (d) autolithic kimberlite breccia, sample 60/955.1. Magn. 10. (Serp) serpentine, (Prv) perovskite, (Cc) calcite.

Table 2. Major oxide composition of kimberlites and autoliths from the Grib pipe, wt

Oxide	9c/484	77/940	9c/584–586		106/606	106/590	107/302	60/445	60/546	60/955.1	62/355
SiO ₂	33.34	31.22	36.71		40.81	36.51	40.31	39.34	36.54	35.65	41.83
TiO ₂	2.26	2.96	0.96		1.39	0.97	1.15	1.31	1.83	1.35	1.32
Al ₂ O ₃	1.51	1.21	1.77		1.72	1.30	1.51	1.96	1.47	1.64	1.57
Fe ₂ O ₃	5.65	4.88	5.14		4.16	6.02	3.13	5.67	4.94	6.19	5.39
FeO	2.15	3.46	2.90		3.06	1.93	4.2	2.00	2.59	1.60	2.39
MnO	0.57	0.12	0.12		0.15	0.12	0.14	0.11	0.13	0.13	0.12
MgO	29.84	31.19	35.82		31.83	36.35	33.07	34.83	35.76	36.14	30.83
CaO	6.74	7.15	1.07		3.70	3.25	2.49	0.67	2.06	2.06	1.72
Na ₂ O	0.20	0.10	0.04		0.38	0.10	0.17	0.21	0.06	0.13	0.44
K ₂ O	0.18	0.12	0.50		0.31	0.07	0.41	0.40	0.22	0.27	0.37
P ₂ O ₅	0.51	0.32	0.22		0.22	0.16	0.11	0.14	0.24	0.19	0.17
LOI	15.65	15.59	13.40		12.45	11.96	12.76	12.13	12.66	13.41	12.54
Total	98.60	98.33	98.64		100.18	98.74	99.45	98.77	98.51	98.76	98.69
CO ₂	5.19	5.28	0.65		0.54	0.56	1.1	0.47	2.17	0.83	0.81
H ₂ O ⁻	1.09	1.01	1.39		11.91	0.91	1.53	1.65	0.56	1.31	3.30
H ₂ O ⁺	9.95	9.57	11.76			10.97	10.90	9.88	10.39	11.64	8.63
C.I.	1.16	1.03	1.05		1.32	1.04	1.24	1.17	1.05	1.02	1.39
#mg	0.79	0.79	0.82		0.82	0.82	0.82	0.82	0.83	0.82	0.80
Variety	PK	PK	AKB		AKB	AKB	AKB	AKB	AKB	AKB	AKB
Oxide	70/190	77/478	77/700	80/265	108/207	108/650	106/612A	106/627A	106/628A	106/630A	106/690A
SiO ₂	38.97	37.00	38.57	40.42	37.79	41.04	33.78	33.52	32.88	33.81	35.07
TiO ₂	1.06	0.75	0.93	1.12	0.92	1.32	1.90	1.65	2.33	1.96	1.95
Al ₂ O ₃	1.42	1.57	1.49	2.50	1.59	2.16	1.84	1.96	2.18	2.58	1.69
Fe ₂ O ₃	5.04	3.76	4.29	4.19	4.56	4.33	4.05	4.21	4.96	4.54	4.11
FeO	2.37	2.85	3.30	2.95	3.13	3.18	3.75	3.25	3.25	3.67	3.82
MnO	0.11	0.16	0.12	0.11	0.13	0.15	0.14	0.15	0.15	0.15	0.16
MgO	32.56	36.79	34.43	32.04	33.51	31.09	31.45	29.46	30.49	29.70	33.11
CaO	2.06	0.88	3.02	1.68	2.70	2.62	6.84	8.37	7.14	6.63	4.45
Na ₂ O	0.13	0.04	0.12	0.26	0.10	0.39	0.13	0.19	0.16	0.15	0.15
K ₂ O	0.29	0.13	0.08	0.28	0.17	0.32	0.27	0.68	0.24	0.33	0.27
P ₂ O ₅	0.14	0.15	0.15	0.16	0.16	0.33	0.43	0.41	0.47	0.42	0.37
LOI	14.74	14.23	12.20	12.99	13.93	11.62	15.03	15.61	15.59	15.04	12.82
Total	98.89	98.31	98.70	98.70	98.70	98.55	99.61	99.46	99.85	98.98	97.97
CO ₂	1.64	0.96	0.51	0.96	1.71	0.81	3.91	4.94	4.14	3.77	2.45
H ₂ O ⁻	2.48	1.52	1.20	2.01	1.93	1.60	11.12	10.67	11.45	11.27	10.37
H ₂ O ⁺	10.81	12.24	9.81	10.01	10.58	9.81					
C.I.	1.22	1.04	1.16	1.32	1.17	1.37	1.12	1.16	1.14	1.20	1.10
#mg	0.81	0.85	0.82	0.82	0.81	0.81	0.80	0.80	0.79	0.78	0.81
Variety	AKB	AKB	AKB	AKB	AKB	AKB	Autoliths				

Note: C.I. is contamination index, after (Taylor et al., 1994); #mg is magnesian number MgO/(MgO + FeO_{tot}).

Table 3. Trace element composition of kimberlites and autoliths from the Grib pipe, ppm (ICP-MS data)

Element	9c/484	77/940	9c/584–586	106/606	106/590	107/302	60/445	60/546	60/955.1	62/355
Be	2.49	1.97	1.58	1.00	1.46	–	1.53	1.75	1.70	1.83
Sc	5.5	0.2	7.2	4.5	7.4	6.4	9.1	9.3	6.7	20.6
V	172	188	81	91	75	63	103	110	75	97
Cr	1452	1731	1101	1256	907	1100	1063	1400	1170	949
Co	72	96	88	77	88	70	78	85	90	82
Ni	1125	1041	1258	1679	1346	1450	1129	1180	1382	1247
Cu	126	78	22	99	133	–	35	40	23	29
Zn	57	85	56	98	56	–	57	65	60	58
Ga	5.3	4.9	4.1	3.2	3.0	–	4.4	4.0	4.0	3.9
Rb	13.7	9.6	31.2	15.2	4.2	20.3	19.1	14.4	15.1	18.0
Sr	536	632	136	215	407	179	210	480	183	221
Y	9.6	6.0	3.7	5.8	3.6	5.0	5.9	4.3	3.7	5.6
Zr	64	58	40	54	40	59	59	50	40	88
Nb	85	79	36	43	34	38	36	52	42	37
Mo	2.69	1.33	1.28	0.48	2.68	–	0.89	3.27	1.39	1.55
Cd	0.31	0.43	0.18	–	0.26	–	0.22	0.34	0.23	0.33
Cs	0.30	0.26	0.64	0.38	0.11	0.73	0.44	0.21	0.45	0.53
Ba	728	613	189	196	351	111	295	990	193	353
La	49.8	38.1	26.1	24.8	21.6	19.4	32.7	28.1	27.8	23.8
Ce	92.1	69.8	46.5	45.2	38.3	35.5	56.1	50.4	49.5	42.7
Pr	10.49	7.39	4.81	4.82	4.01	3.64	5.88	5.31	5.13	4.50
Nd	38.86	26.02	16.81	16.77	13.93	13.67	20.44	18.39	17.82	15.80
Sm	5.96	3.91	2.36	2.63	1.96	2.09	3.06	2.62	2.47	2.42
Eu	1.775	1.085	0.647	0.679	0.547	0.480	0.770	0.733	0.652	0.656
Gd	4.388	2.702	1.637	1.862	1.367	1.380	2.081	1.727	1.630	1.772
Tb	0.494	0.322	0.207	0.240	0.177	0.213	0.262	0.222	0.191	0.241
Dy	2.147	1.495	0.902	1.214	0.811	1.130	1.297	0.982	0.845	1.148
Ho	0.354	0.240	0.151	0.215	0.141	0.170	0.230	0.165	0.144	0.211
Er	0.791	0.552	0.354	0.541	0.339	0.410	0.562	0.378	0.347	0.535
Tm	0.094	0.071	0.045	0.073	0.046	0.050	0.083	0.052	0.046	0.075
Yb	0.478	0.386	0.266	0.437	0.283	0.320	0.466	0.279	0.242	0.445
Lu	0.065	0.055	0.036	0.064	0.039	0.050	0.064	0.041	0.034	0.066
Hf	1.74	1.59	1.06	1.51	0.99	1.09	1.44	1.18	0.95	2.07
Ta	5.08	6.15	2.50	4.03	2.70	3.55	2.25	4.08	3.05	2.66
Th	7.06	6.24	3.74	3.76	3.07	3.18	4.26	4.03	3.44	3.27
U	1.17	1.11	0.70	0.73	0.58	0.54	0.83	0.74	0.64	0.67

Table 3. (Contd.)

Element	70/190	77/478	77/700	80/265	108/207	108/650	106/612A	106/627A	106/628A	106/630A	106/690A
Be	1.89	1.70	1.90	1.55	1.77	1.99	1.42	3.22	1.95	2.16	1.92
Sc	11.5	4.5	14.2	24.2	18.6	23.6	9.6	8.2	11.3	10	8.7
V	92	76	89	93	89	122	138	170	165	142	130
Cr	1111	964	1065	1064	1015	1080	1635	1673	2233	1889	1850
Co	88	77	92	84	93	81	74	71	68	76	76
Ni	1325	1060	1342	1228	1403	1222	1391	1361	1420	1447	1562
Cu	103	21	28	22	25	55	568	460	760	458	83
Zn	57	50	58	55	57	66	65	57	70	67	59
Ga	3.4	3.5	3.8	4.9	4.3	5.9	4.4	4.8	5.6	5.1	4.2
Rb	20.2	8.3	6.5	16.1	12.8	19.6	16.3	49	16.4	21.8	17.8
Sr	160	1211	155	223	184	541	708	1201	709	617	345
Y	3.9	4.3	3.6	4.8	4.8	8.1	9.3	8.3	9.8	9.8	8.3
Zr	43	47	43	73	42	81	87	87	94	91	80
Nb	33	30	29	33	31	57	93	86	110	99	85
Mo	1.40	1.77	1.50	1.49	1.24	2.18	0.53	1.19	1.35	1.32	1.32
Cd	0.23	0.83	0.22	0.25	0.23	0.43	—	—	—	—	—
Cs	0.50	0.33	0.18	0.40	0.25	0.40	0.31	0.50	0.26	0.30	0.31
Ba	383	1673	90	412	137	808	848	2072	873	826	585
La	20.4	20.0	19.8	20.8	20.3	38.2	57.6	52.6	65.9	62.5	52.7
Ce	37.1	34.8	35.1	39.2	37.3	69.4	100.7	93.5	116.3	110.6	93.4
Pr	3.88	3.60	3.66	4.13	4.01	7.43	11.09	10.05	12.54	12.00	10.08
Nd	13.43	13.02	12.78	14.59	14.21	25.85	39.52	36.19	44.79	42.44	35.38
Sm	2.05	2.10	1.84	2.17	2.22	3.86	5.62	5.17	6.25	6.10	5.05
Eu	0.506	0.606	0.497	0.532	0.603	0.883	1.366	1.118	1.459	1.319	1.131
Gd	1.300	1.634	1.392	1.360	1.588	2.406	3.685	3.37	4.107	3.925	3.309
Tb	0.176	0.207	0.179	0.190	0.212	0.314	0.442	0.413	0.501	0.480	0.400
Dy	0.907	0.988	0.819	0.960	0.990	1.727	2.072	1.887	2.163	2.166	1.843
Ho	0.159	0.172	0.146	0.170	0.173	0.304	0.335	0.31	0.346	0.358	0.310
Er	0.376	0.412	0.375	0.439	0.438	0.770	0.772	0.727	0.785	0.815	0.710
Tm	0.055	0.056	0.049	0.063	0.059	0.104	0.095	0.089	0.095	0.105	0.087
Yb	0.293	0.325	0.301	0.383	0.354	0.643	0.522	0.487	0.511	0.547	0.466
Lu	0.047	0.053	0.046	0.056	0.051	0.095	0.08	0.079	0.076	0.078	0.069
Hf	1.18	1.20	1.21	1.71	0.99	1.99	2.17	2.27	2.40	2.30	2.15
Ta	2.55	2.13	2.56	2.44	1.98	3.79	6.93	6.71	8.47	7.44	6.63
Th	3.22	3.08	3.13	3.19	3.18	5.63	8.54	7.84	9.48	9.22	7.79
U	0.62	0.57	0.61	0.65	0.65	1.14	1.53	1.38	1.69	1.57	0.99

Note: Dash denotes not analyzed.

Table 4. Nd and Sr isotopic data for autoliths, porphyritic kimberlites, and autolithic kimberlite breccia from the Grib pipe

Sample	Rb, ppm	Sr, ppm	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_t$	$\epsilon_{\text{Sr}(t)}$
106/612A	16.86	717.0	0.0680	0.705969 ± 10	0.705608	+22
106/627A	50.70	1259.0	0.1165	0.706563 ± 19	0.705944	+27
106/628A	16.15	690.7	0.0676	0.705656 ± 7	0.705297	+18
106/630A	22.27	631.9	0.1019	0.705475 ± 12	0.704934	+12
106/690A	16.02	339.7	0.1364	0.705640 ± 17	0.704915	+12
9c/484	14.26	587.1	0.0702	0.704618 ± 7	0.704245	−0.1
77/940	9.25	633.0	0.0422	0.706699 ± 8	0.706475	+32
9c/584–586	30.33	126.6	0.6929	0.712638 ± 6	0.708956	+67
106/606	15.48	211.6	0.2116	0.706251 ± 14	0.705127	+15
70/190	18.38	154.9	0.3428	0.706546 ± 6	0.704724	+7
77/478	7.69	1240.0	0.0179	0.708815 ± 7	0.708720	+63

Sample	Sm, ppm	Nd, ppm	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$(^{143}\text{Nd}/^{144}\text{Nd})_t$	$\epsilon_{\text{Nd}(t)}$	$t\text{Nd}(\text{DM}), \text{Ga}$
106/612A	5.16	36.77	0.0848	0.512422 ± 8	0.512215	+1.1	0.9
106/627A	4.56	32.36	0.0851	0.512413 ± 10	0.512205	+0.9	0.9
106/628A	5.61	40.2	0.0843	0.512441 ± 9	0.512235	+1.5	0.8
106/630A	5.59	39.81	0.0848	0.512440 ± 6	0.512233	+1.5	0.8
106/690A	4.63	33.07	0.0846	0.512426 ± 10	0.512219	+1.2	0.9
9c/484	6.50	42.53	0.0924	0.512449 ± 8	0.512223	+1.3	0.9
77/940	3.72	25.64	0.0878	0.512463 ± 7	0.512248	+1.8	0.8
9c/584–586	2.29	16.25	0.0853	0.512368 ± 7	0.512160	0.0	0.9
106/606	2.39	16.06	0.0898	0.512328 ± 11	0.512109	−1.0	1.0
70/190	1.95	13.28	0.0886	0.512380 ± 10	0.512163	+0.1	0.9
77/478	1.94	12.28	0.0953	0.512321 ± 7	0.512088	−1.4	1.1

Note: Initial isotope ratios, $\epsilon_{\text{Sr}(t)}$, and $\epsilon_{\text{Nd}(t)}$ are calculated for $t = 373$ Ma relative to UR and CHUR, respectively, with present-day parameters $^{87}\text{Rb}/^{86}\text{Sr} = 0.825$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$ for UR and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ for CHUR.

CaO (wt %) is the lowest (1–3) in AKB and increases up to 6–8 in Av and ~7 in PK (Table 2);

CO₂ (wt %) is elevated in PK (5) and Av (~4) and decreased in AKB (<1 in most samples and up to 2 in single samples (Table 2)); the impression is given that separation of autoliths results in dilution of melt in CaO and CO₂;

H₂O (wt %) is elevated in AKB (12–13) and somewhat lower in PK (10–11) and autoliths (10.5–11.0).

As concerns the trace elements, the difference of autoliths from PK and AKB (especially from the latter) is noteworthy (Table 3, (partly) Fig. 4):

Cr (ppm) shows elevated concentrations in Av (1635–2233) relative to PK (1450–1730) and AKB (~1000);

Ni (ppm) is slightly variable (1000–1400) in PK and AKB and two orders of magnitude lower in Av (~70).

As can be seen from Fig. 4, PK is enriched in Y, Ce, Zr, and HREE. The contents of these elements decrease in Av and especially in AKB.

AKB is markedly depleted in almost all trace elements (Fig. 5a). As follows from Table 3, Av and PK are enriched in Th, U, Nb, Ta, La, Ce, Pr, P, Nd, Sm, Eu, and Ti. The enrichment of Av and PK in LREE and MREE is combined with rather similar contents of HREE in all structural varieties of kimberlites (Fig. 6a).

The Sr and Nd isotopic composition varies near zero values of $\epsilon_{\text{Sr}(t)}$ and $\epsilon_{\text{Nd}(t)}$ (Table 4; Fig. 7). $\epsilon_{\text{Nd}(t)}$ of Av and PK ranges from +0.9 to +1.5 and +1.3 to +1.8, respectively, whereas $\epsilon_{\text{Nd}(t)}$ of AKB is equal to zero or negative. In other words, the kimberlite sources vary from slightly depleted (PK and Av) to slightly enriched (AKB), probably, indicating participation of crustal material.

The diamond grade of the Grib pipe is higher than that of any other pipe at the Lomonosov deposit. The recovery of heavy fraction minerals is 10 times (350 times for garnet) higher than at the Lomonosov deposit. Most samples from the Grib pipe from the Verkhotina occurrence and all pipes of the Zolotitsa occurrence are comparable in Y/Be and Ni/Be indicator ratios with kimberlites of the highly diamondiferous

Nakyn field in Yakutia (Fig. 10b). Thus, in terms of geochemical indicators, the above occurrences may be classified as potentially diamond-bearing objects.

DISCUSSION

The diamond-bearing kimberlites of the Verkhotina occurrence (Grib pipe) and the Zolotitsa occurrence differ in geochemistry from kimberlites of the Kepina occurrence. The causes of this difference should be sought in the specific features of kimberlite pipe formation.

The degree of partial melting. It is assumed that the CO₂-rich ultramafic kimberlite melt ascended from a depth of at least 200 km. As judged from the absence of graphitization of diamond (Anderson, 1979) and good preservation of xenoliths, the ascent must have been rapid (10–30 m/s). Vaganov (2000) suggested that partial melting concurrently developed throughout the upper mantle, giving rise to the formation of many isolated batches of kimberlite magma different in composition in dependence on *PT* parameters and degree of melting, which is recorded in some geochemical ratios. In particular, variations in the Ce/Y and Zr/Nb ratios in kimberlites of the Zimny Bereg field (Fig. 10a) demonstrate a changeable degree of partial melting. By analogy with ocean island basalts (OIB), a decrease in the Ce/Y ratio in combination with an increasing Zr/Nb ratio indicates that the degree of partial melting in the mantle magma source is decreasing (Smedley, 1988). It is suggested that an increasing Ce/Y ratio testifies to the enrichment of the source in garnet, which holds back the supply of Y to the melt. Thus, it may be inferred that kimberlites of the Zolotitsa field were formed at a lower degree of partial melting than their counterparts from the Kepina field. Kimberlite from the Grib pipe occupies an intermediate position, as was established for other parameters.

The source composition and the time of source activation. Judging from the zircon age (Lepekhina et al., 2003), a fragment of the Archean mantle is retained beneath the Verkhotina occurrence (the Grib pipe). The mantle is likely composed of garnet–spinel lherzolite with a high garnet content, typical of cratons (Verichev et al., 2003; Melkovets et al., 2003). According to the mineral equilibria in peridotite nodules, the mantle temperature was lower than 1000°C and the heat flow is estimated at 37–38 mW/m², whereas the high-temperature mantle is characterized by a heat flow of 42 mW/m². The fluids that provided metasomatic reworking of the mantle source were derived from the sublithospheric mantle related to the ascent of a mantle plume (Le Roex, 2003) that initiated ultramafic alkaline magmatism with carbonatites.

The Nd and Sr isotopic compositions (Fig. 7). The source of the Kepina kimberlites is slightly depleted relative to CHUR ($\epsilon_{\text{Nd}}(t)$ is +3 to +4) and they are close to kimberlites of group I from South Africa. Kimberlites from the Grib pipe (the Verkhotina occurrence) are

close to BSE in Nd and Sr isotopic compositions. As a rule, these kimberlites have lower $\epsilon_{\text{Nd}}(t)$ values than the South African kimberlites of group I. The $\epsilon_{\text{Nd}}(t)$ value of AKB is close to zero, while the $\epsilon_{\text{Nd}}(t)$ values of Av and PK are slightly positive. The sources of kimberlites from the Zolotitsa occurrence fall into the field of enriched mantle in coordinates $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Sr}}(t)$ and may be explained by interaction of an asthenospheric plume with ancient enriched lithospheric mantle. The isotopic and geochemical signatures of the Zolotitsa kimberlites could have been related to the interaction of materials supplied from asthenospheric and lithospheric sources during the formation of kimberlite pipes. If the Zolotitsa kimberlites were derived from the ancient lithospheric mantle, their intermediate isotopic composition might be controlled by the gain of deep-seated asthenospheric material (LREE, in particular) immediately before melting and melt ascent.

The Pb isotopic composition is not always steadily correlated with the Nd isotopic composition. The slightly variable ratios of Pb isotopes in rocks of the Zimny Bereg field remain within ranges typical of a relatively young mantle (Fig. 8). The lithospheric source likely had a U/Pb ratio close to that of the depleted mantle, which was enriched in the process of metasomatic alteration. The Pb isotopic compositions of kimberlites from the Zolotitsa and Verkhotina occurrences appreciably shift to the less radiogenic lead. The diagram also demonstrates curves of the evolution of the Pb isotopic composition of the mantle and the lower and upper crust based on the model elaborated by Stacey and Kramers (1975). The Pb isotopic compositions of kimberlites are close to the mantle curve but deviate toward the values for the lower crust (the Grib pipe) or the upper crust (kimberlites of the Zolotitsa occurrence). Thus, the isotopic heterogeneity of the mantle, including Pb isotopes, is established within a relatively small territory of the Zimny Bereg field.

The age of kimberlite sources may be approximately estimated from the calculated model Nd age ($t_{\text{Nd}}(\text{DM})$). Since the sources of Devonian kimberlites vary from slightly depleted to slightly enriched mantle, the calculation of the model age becomes rather uncertain. In general, an older model age (~1 Ga) has been obtained for sources of low- and medium-Ti kimberlites from the Zolotitsa and Verkhotina occurrences, whereas a source of high-Ti and other kimberlites from the Kepina occurrence was probably formed later, about 0.8 Ga ago. The long gap (up to a billion years) between the enrichment of the source and the emplacement of kimberlite pipes created favorable conditions for enrichment of the source in fluids and/or crustal components. We emphasize once again that we deal now only with tentative estimates that retain a number of uncertainties.

The effect of volatiles (CO₂, H₂O). The substantial role of water in transportation of diamonds was noted recently. The water content increases in the intermedi-

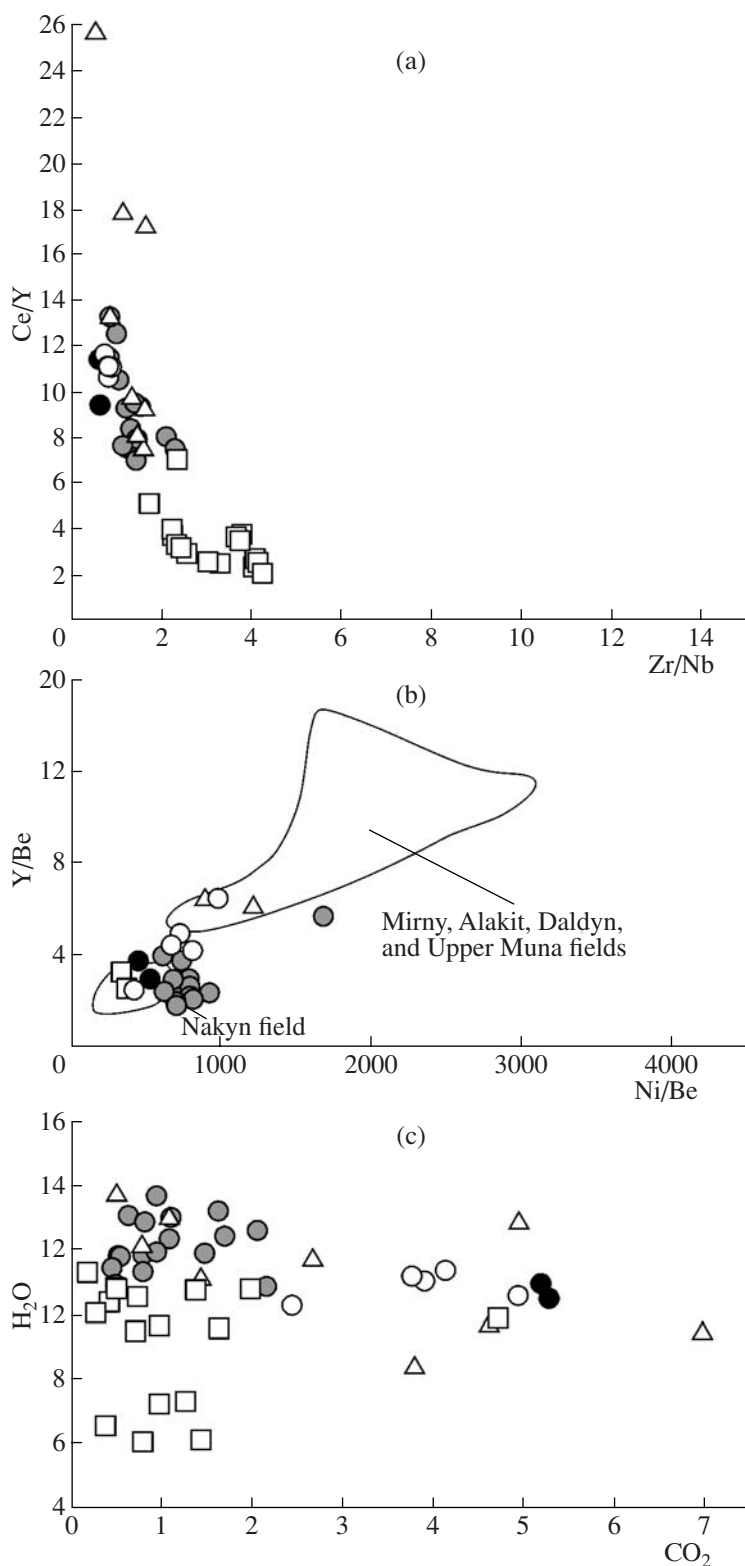


Fig. 10. (a) Ce/Y vs. Zr/Nb, (b) Y/Be vs. Ni/Be, and (c) H₂O vs. CO₂, after the data presented in Tables 2 and 3. See Fig. 3 for legend.

ate zone of the mantle, and this implies that the lower mantle can produce hydrous fluid that facilitates the delivery of diamonds from the lower mantle to the lithosphere (Litasov and Ohtani, 2003).

The H₂O and CO₂ concentrations in the Grib pipe vary in the series PK–autoliths–AKB (Fig. 10c). The CO₂ content (wt %) decreases from 5 in PK to 4 in Av and 1 in AKB. The shift in H₂O content is less apprecia-

ble, although the total water content in AKB (11–12 wt %) is somewhat higher than in PK (11 wt %). It is suggested that lapilli (autoliths) are a juvenile product intermediate in composition between the intruding silicate magma and its volatile fraction (Lloyd and Stoppa, 2003; Mitchell, 1997). Taking the properties of CO₂ and H₂O into account, the fragmentation of kimberlite magma can occur only at a depth no greater than 500 m from the surface (Kjarsgaard, 2003). In the opinion of Skinner and Marsh (2003), a source of a large explosion eruption is located approximately 1 km below the ground surface and instantaneously spreads along the magmatic column down to 2 km. At a depth of 100 km and under a pressure of 3 GPa, the melt contains about 20 wt % CO₂ (Wilson and Head, 2003).

The formation of the Grib pipe was described in detail by Verichev et al. (2003), who drew attention to the temporary plugging of the conduit, which was accompanied by accumulation of gases, their subsequent inrush, and ejection of a considerable volume of pyroclastic rocks with freeing of a new tubular cavity then filled with massive and porphyritic kimberlites.

Lapilli (autoliths) indicate a juvenile, primary character of volatile constituents of magma. In kimberlites, the cores of lapilli are commonly composed of olivine or phlogopite and very rarely of country rock fragments, indicating that most lapilli were formed at a great depth. The gas phase (fluid) could have existed as an independent phase separately from silicate melt. In most cases, it was carbon dioxide. The magmatic carbonate contained in kimberlites mostly is a derivative of the mantle CO₂ (Brey and Ryabchikov, 1994). The occurrence of hydrous mineral phases (phlogopite, serpentine) shows that some amount of juvenile H₂O occurs in fluids together with F and Cl.

It is assumed that it is precisely volatile components, their composition, and phreatomagmatic eruptions induced by them that control the style of kimberlite emplacement to a greater degree than the geological setting (Skinner and Marsh, 2003). The CO₂/H₂O ratio in the fluid phase exerts an effect on the temperature of the kimberlite solidus. H₂O-rich kimberlites crystallize largely at a depth and do not reach the surface until an explosion has occurred. Conversely, CO₂-rich kimberlite magmas depleted in water as a result of phlogopite crystallization reach the surface. Small-scale phreatomagmatic processes are possible during deposition of pyroclastic flows, as took place while the Grib kimberlite pipe was formed.

The contribution of the ancient crust to the kimberlite sources is discussed in recent publications. Distinct negative Ti, Zr, Th, U, Nb, and Ta anomalies are typical of low-Ti kimberlites from the Zolotitsa occurrence (Fig. 5). To a lesser degree, this feature is expressed in medium-Ti kimberlites of the Grib pipe. In both cases, the melts are depleted in the above elements. The low Nb/La ratio of the Zolotitsa kimberlites testifies to the participation of crustal material in their source. The

Pb isotopic composition of kimberlites deviates from the mantle curve toward the lower crustal curve (the Grib pipe) or the upper crustal values (kimberlites of the Zolotitsa occurrence). In the opinion of Helmstaedt and Gurney (1995), the proposed genetic models of kimberlites belonging to groups I and II in South Africa come into conflict with hot spot conjectures. In particular, intracratonic structural elements, including the paths of hot spots, although they localize kimberlites, disturb the mantle root and thus make kimberlites barren with respect to diamond. These authors prefer the idea of the influence of a megalith made up of remains of subducted oceanic lithosphere. Heaman et al. (2004) considered multistage modification of the lithospheric mantle beneath the Slave Craton, including several episodes of mantle metasomatism. We discussed the same for kimberlites of the Zolotitsa occurrence in the Arkhangel'sk region (Bogatikov et al., 2001; Kononova et al., 2002). It was assumed that collision and/or subduction along with mantle metasomatism occurred at the boundary between the Belomorian and Kola blocks. As a result, kimberlites of the Zolotitsa and Verkhotina occurrences were formed here, being related to sources pertaining to enriched mantle of EM1 type, whereas kimberlites of the Kepina occurrence were derived from depleted mantle.

It is commonly accepted that Th, U, Nb, and Ta minimums on spidergrams as indications of depletion are characteristic of melts that are related to sources formed as a result of a staged process including mantle metasomatism with participation of fluids released by dehydration of the ancient continental crust. As has been shown recently by seismic tomography, buried relics of the oceanic lithosphere (megaliths) underlie whole continents. Such relics likely are a mixture of restites and subducted material that continued to release volatile components while plunging into the transitional zone (Helmstaedt and Gurney, 1995). Variable $\delta^{13}\text{C}$ values of diamonds from kimberlites of the Slave Craton (ultradeep with $\delta^{13}\text{C} = -2$ to -8‰ , peridotitic with $\delta^{13}\text{C} = +1$ to -12‰ , and eclogitic with $\delta^{13}\text{C} = -5$ to -19 and even -35.8‰) (Davies et al., 2003) corroborate the possibility of their formation at different depths.

CONCLUSIONS

Prospecting for diamond-bearing kimberlites remains a task of current importance. The relevant forecasting criteria have substantially changed over recent years. The mineralogical criteria often do not work because of different reasons. In some cases, indicative minerals are lacking, e.g., in pipes of the Zolotitsa occurrence. In other cases, such minerals are identified in barren kimberlites, where diamonds have been completely oxidized. New data testify to the heterogeneity of the upper mantle even within small areas (Pokhilenko et al., 2003). In this paper, attention is drawn to the additional geochemical and petrological

features of kimberlites that differ in diamond resource potential. The Devonian diamond-bearing kimberlites located in the north of the East European Platform show geochemical features that admit a contribution of subducted crustal material to their composition.

The relationship Y/Be versus Ni/Be previously proposed as a criterion in the Yakutian diamond province may be applied to the Zimny Bereg field. The compositions of kimberlites from the Grib pipe and the pipes of the Zolotitsa occurrence plotted on the Y/Be–Ni/Be diagram fall in the field of the high-grade Nakyn kimberlite field and partly the Mirny field of the Siberian Craton.

The depletion of kimberlites in Th, U, Nb, and some other trace elements; the appreciable shift of Pb isotopic compositions of kimberlites toward less radiogenic values; and the deviation of model curves of the evolution of Pb isotopic compositions of kimberlites from the Zolotitsa and Verkhovina occurrences toward the upper and lower crustal curves testify to the participation of crustal material in sources of kimberlites.

Kimberlites of the Grib pipe are distinguished from all other analyzed samples of the Zimny Bereg field by the lowest HREE contents.

The Grib pipe is composed of kimberlites that are classed with moderate-Ti varieties. However, the Ti contents are variable and the diamond-bearing varieties (mainly AKB) contain Ti in the same amounts as diamond-bearing Zolotitsa kimberlites.

Thus, the compositional variation of kimberlites and their diamond resource potential are controlled by heterogeneity of the mantle and kimberlite sources even over a relatively small area (60 × 85 km) of the Zimny Bereg field. This heterogeneity is recorded in various attributes. Petrological and geochemical criteria are rather informative and may be used in addition to previously applied tectonic and mineralogical indicators.

ACKNOWLEDGMENTS

We thank the Department of Diamond Geology of the Central Institute of Geological Exploration for Base and Precious Metals for the samples from the Grib pipe kindly placed at our disposal. We are also grateful to specialists of analytical laboratories of the Institute of Precambrian Geology and Geochronology, RAS; the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements; and the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, RAS, for performing analytical procedures. This study was supported by the Russian Foundation for Basic Research (project no. 06-05-64017) and the Council for Grants of the President of the Russian Federation for Support of Leading Scientific Schools (grant no. 2006-RI-112.0/001/009).

REFERENCES

1. O. L. Anderson, "The Role of Fracture Dynamics in Kimberlite Pipe Formation," in *Proceedings of 2nd International Kimberlite Conference* (Washington, DC, 1979), pp. 344–353.
2. O. A. Bogatkov, V. K. Garanin, V. A. Kononova, et al., *The Arkhangel'sk Diamond-Bearing Province: Geology, Petrography, Geochemistry, and Mineralogy* (Moscow State Univ., Moscow, 1999) [in Russian].
3. O. A. Bogatkov, V. A. Kononova, V. A. Pervov, and D. Z. Zhuravlev, "Sources, Geodynamic Setting, and Outlook for Diamond Resource Potential of the Northern Margin of the Russian Plate: Sr–Nd Isotopic and ICP-MS Geochemical Data," *Petrologiya* **9** (3), 227–243 (2001) [*Petrology* **9** (3), 191–203 (2001)].
4. G. P. Brey and I. D. Ryabchikov, "Carbon Dioxide in Strongly Silica Undersaturated Melts and Origin of Kimberlite Magmas," *Neues Jb. Mineral. Monatsh.*, No. 10, 449–463 (1994).
5. A. A. Burmistrov, K. V. Garanin, V. I. Starostin, and L. S. Yuzhakov, "A Comparative Study of Petrophysical Parameters of Porphyritic Kimberlite in the Grib Pipe (Arkhangel'sk Region) and Aikhal (Yakutia)," in *Geology of Diamonds—the Present and the Future (Geologists to Fiftieth Anniversary of the Town of Mirny and Diamond Mining Industry of Russia)* (Voronezh State Univ., Voronezh, 2005), pp. 762–772 [in Russian].
6. R. M. Davies, W. L. Griffin, S. Y. O'Reilly, et al., "Geochemical Characteristics of Microdiamonds from Kimberlites at Las De Gras, Central Slave Craton," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0048, 2003).
7. K. J. Fraser, C. J. Hawkesworth, A. J. Erlank, et al., "Sr, Nd, and Pb Isotope and Minor Element Geochemistry of Lamproites and Kimberlites," *Earth Planet. Sci. Lett.* **76**, 57–70 (1985).
8. Yu. Yu. Golubeva, V. A. Pervov, and V. A. Kononova, "Petrogenesis of Autoliths from Kimberlitic Breccias in the Grib Pipe (Arkhangel'sk Region)," *Dokl. Akad. Nauk* **410** (6), 789–794 (2006) [*Dokl. Earth Sci.* **411** (8), 1257–1262 (2006)].
9. L. M. Heaman, D. F. Kjarsgaard, and R. A. Creaser, "The Temporal Evolution of North American Kimberlites," *Lithos* **76**, 377–397 (2004).
10. H. H. Helmstaedt and J. J. Gurney, "Geotectonic Controls of Primary Diamond Deposits: Implications for Area Selection," *J. Geochem. Explor.* **53**, 125–144 (1995).
11. B. Kjarsgaard, "Behaviour of Kimberlite Magma in the Upper Crust and at Surface," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0294, 2003).
12. V. A. Kononova, L. K. Levsky, V. A. Pervov, et al., "Rb–Sr–Nd Isotopic Systematics of the Mantle Sources of Potassic Ultramafic and Mafic Rocks in the North of the East European Platform," *Petrologiya* **10** (5), 493–509 (2002) [*Petrology* **10** (5), 433–447 (2002)].
13. V. A. Larchenko, V. P. Stepanov, G. V. Minchenko, et al., "Age of Igneous Rocks, Ore-Bearing Sequence and Middle Paleozoic Reservoir Rocks in the Zimny Bereg Diamond-Bearing Region (Arkhangel'sk Diamond-Bearing Province)," in *Geology of Diamonds—the Present and the*

- Future (Geologists to Fiftieth Anniversary of the Town of Mirny and Diamond Mining Industry of Russia)* (Voronezh State Univ., Voronezh, 2005), pp. 322–347 [in Russian].
14. A. Le Roex, D. Bell, and P. Davis, "Petrogenesis of Kimberley Group I Hypabyssal Kimberlites: Evidence from Bulk Rock Geochemistry," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0097, 2003).
 15. E. Lepekhina, S. Presnyakov, D. Mutukov, et al., "Single Grain U–Pb Zircon Dating (Shrimp II) from Grib Kimberlite Pipe (Zimny Bereg, Archangelsk Region, Russia)," in *Proceedings of the 32nd International Geological Conference* (Florence, 2004).
 16. K. Litasov and E. Ohtani, "Hydrous Lower Mantle: the Water Source for Wet Plumes?," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0031, 2003).
 17. F. E. Lloyd and F. Stoppa, "Pelletal Lappilli in Diatremes: Some Inspiration from the Old Masters," *Geolines* **15**, 65–71 (2003).
 18. V. Malkovets, L. Taylor, W. Griffin, et al., "Cratonic Condition beneath Arkhangelsk, Russia: Garnet Peridotites from the Grib Kimberlite," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0220, 2003).
 19. W. F. McDonough and S. S. Sun, "The Composition of the Earth," *Chem. Geol.* **120**, 223–253 (1995).
 20. R. H. Mitchell, *Kimberlites: Mineralogy, Geochemistry and Petrology* (Plenum Press, New York, 1986).
 21. R. H. Mitchell, *Kimberlites, Orangeites, and Related Rocks* (Plenum Press, New York, 1995).
 22. R. H. Mitchell, *Kimberlites, Orangeites, Lamproites, Melilitites and Minettes: A Petrographic Atlas* (Almaz Press, Thunder Bay, 1997).
 23. D. R. Nelson, "Isotopic Characteristics of Potassic Rocks: Evidence for the Involvement of Subducted Sediments in Magma Genesis," *Lithos* **28**, 403–420 (1992).
 24. V. A. Pervov, E. S. Bogomolov, V. A. Larchenko, et al., "Rb–Sr Age of Kimberlites of the Pionerskaya Pipe (Arkhangel'sk Diamond-Bearing Province)," *Dokl. Akad. Nauk* **400** (1), 88–92 (2005b) [*Dokl. Earth Sci.* **400** (1), 67–71 (2005b)].
 25. V. A. Pervov, V. A. Larchenko, V. P. Stepanov, et al., "Kimberlite Sills along the Mella River (Arkhangel'sk Diamond-Bearing Province): New Data on Age, Lithology, and Mineral Composition," in *Geology of Diamond—the Present and the Future (Geologists to Fiftieth Anniversary of the Town of Mirny and Diamond Mining Industry of Russia)* (Voronezh State Univ., Voronezh, 2005b), pp. 558–571 [in Russian].
 26. L. N. Pokhilenko, A. A. Tomilenko, S. S. Kuligin, and V. V. Khletov, "The Upper Mantle Heterogeneity: Thermodynamic Calculations and Methods of Mathematical Statistics," in *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0007, 2003).
 27. N. A. Prusakova, "Deep Structure of the Zimny Bereg Kimberlite Field, Arkhangel'sk Oblast," *Rudy Met.*, No. 2, 53–63 (2006).
 28. S. S. Shevchenko, K. I. Lokhov, S. A. Sergeev, et al., "Isotopic Studies in VSEGEI. Outlook of Applying Results to the Forecasting and Prospecting of Diamond Deposits," in *Proceedings of Scientific and Practical Conference on Efficiency of Forecasting and Prospecting of Diamond Deposits: The Present and the Future (Diamonds-50)* (VSEGEI, St. Petersburg, 2004), pp. 383–387 [in Russian].
 29. E. M. W. Skinner and J. S. Marsh, "Kimberlite Eruption Processes," *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0040, 2003).
 30. P. L. Smedley, "Trace Element and Isotopic Variation in Scottish and Irish Dinantian Volcanism: Evidence for an OIB-Like Mantle Source," *J. Petrology* **29** (2), 413–443 (1988).
 31. C. B. Smith, "Pb, Sr, and Nd Isotopic Evidence for Sources of Southern African Cretaceous Kimberlites," *Nature* **304**, 51–54 (1983).
 32. J. S. Stacey and J. D. Kramers, "Approximation of Terrestrial Lead Isotope Evolution by a Two-Stage Model," *Earth Planet. Sci. Lett.* **26** (2), 207–221 (1975).
 33. W. R. Taylor, L. A. Tompkins, and S. E. Haggerty, "Comparative Geochemistry of West African Kimberlites: Evidence for a Micaceous Kimberlite and Member of Sublithospheric Origin," *Geochim. Cosmochim. Acta* **58**, 4017–4037 (1994).
 34. V. I. Vaganov, *Diamond Deposits of Russia and the World* (Geoformmark, Moscow, 2000) [in Russian].
 35. E. M. Verichev, V. K. Garanin, K. V. Garanin, et al., "Geology, Composition, Formation Mechanism, and Exploration Methods of the Grib Kimberlite Pipe," in *Mineral Forecasting, Prospecting, and Exploration of Mineral Deposits on the Turn of the 20th Century* (Voronezh State Univ., Voronezh, 2003), pp. 43–48 [in Russian].
 36. L. Wilson and J. W. Head, "Diatremes and Kimberlites. 2. An Integrated Model of the Ascent and Eruption of Kimberlite Magmas and the Production of Crater, Diatreme, and Hypabyssal Facies," *Proceedings of the 8th International Kimberlite Conference* (Long Abstract FLA 0244, 2003).