ECLOGITES FROM THE GRIB KIMBERLITE PIPE, ARKHANGELSK, RUSSIA

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INTRODUCTION

Eclogite xenoliths in kimberlites and alkali basalts are of great scientific interest because they can provide information on the chemistry, mineralogy, and petrology of the mantle, as well as on the evolutionary history and interaction between the mantle and the crust. The origins of such eclogitic nodules have been actively discussed for more than 30 years. However, it is now generally agreed that the majority of the mantle eclogites had their ultimate origin from precursors in the ancient crust. That is, they are the products of subduction of oceanic crust beneath a craton, associated with devolitalization and possible partial melting. Nevertheless, much remains to be unraveled concerning such a complicated scenario. In this paper, we apply the results of our study of eclogitic xenoliths from the newly discovered Middle Paleozoic diamondiferous kimberlite pipe, Grib, in the Arkhangelsk Province of Russia.

GEOLOGY OF THE ARKHANGELSK REGION

The East European Platform, a collage of Archaean cratons and Early Proterozoic mobile belts, underlies most of western Russia and the Baltic states. Riphean to Paleozoic sediments cover most of the platform to the south and east of Scandinavia. In its eastern part, there are two Archean cratons, Kola and Karelis, separated by the Early Proterozoic Belomorian mobile belt.

The small-volume Arkhangelsk igneous activity is mostly in the form of sub-volcanic pipes (diatremes), together with some sills and dikes (Sinitsin & Grib, 1995). Clusters of diatremes form several igneous fields (Fig. 1), each with distinctive petrological characteristics. The fields occur in two groups on the SE side of the White Sea: 1) along and up to 100 km inland from the Zimniy Bereg (i.e. Winter Coast); and 2) on the NE side of the Onega Peninsula, separated from the Zimniy Bereg by the Gulf of Dvina. A short, intense, and spread phase of Late Devonian (~380-360 Ma) mafic, alkaline-ultramafic, and carbonatitic magmatism, immediately followed by large-scale lithospheric doming of the East European Platform (Mahotkin et al., 2000).

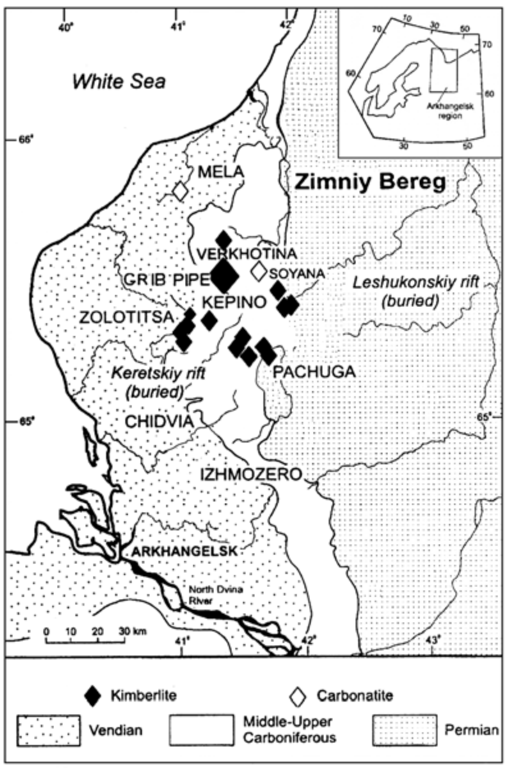

Figure 1: Simplified geological sketch map of the Arkhangelsk Alkaline Igneous Province (Mahotkin et al., 2000).

The Late Devonian magmatism of the Kola region forms one of the largest intrusive and sub-volcanicalkaline provinces in the world. The Kola Alkaline Province outcrops over an area of ~100,000 km^2 and is comprised of 24 igneous complexes (Kogarko et al., 1995; Mahotkin et al., 2000).
Kimberlites are the predominant feature in the Zolotitsa and Mela fields, and a component of the Kepino-Pachuga and Verkhotina-Soyana fields. They can be divided geographically (Fig. 1) into a predominantly mica-poor, Eastern Group and a predominantly micaceous, Western Group, superficially similar to Group I and Group II South African kimberlites, respectively (Parsadanyan et al., 1996). The discovery in 1996 of the richly diamondiferous Grib kimberlite pipe (also known as Anomaly 441) terminated the long-established notion (e.g., Sablukova et al., 1995) that only the Western Group kimberlites are potentially economic (Verichev et al., 1998).

PETROGRAHY

Eclogites from Grib pipe are composed of dark-to-bright green clinopyroxene up to 3 cm and pale orangish-pink garnet up to 1.3 cm. Two of three eclogites of Group A contain phlogopite in apparent textural equilibrium with the clinopyroxene and garnet. Trace amounts of sulfide occur in some of the samples. The xenoliths are highly fractured, with moderate secondary alteration, including serpentine, chlorite, and carbonate. Kimberlite penetrates fractures in the most of the samples to various degrees. These is evidence for a late-stage partial-melting event in each sample (Spetsius and Taylor, 2002).

MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS

MAJOR ELEMENTS

The chemistries of the primary phases of the Grib eclogites are presented in Tables 1 and 2. Compositional data on coexisting garnet and clinopyroxene show that the xenoliths are classified as Group A and B eclogites, based upon the classification scheme of Taylor and Neal (1989) (Fig. 2.).
Garnets in these eclogite samples are homogeneous, within individual samples. Garnets from three eclogite samples are MgO-rich, with a pyrope component of 75 to 78%. These garnets contain higher Cr_2O_3 (0.18 to 0.73%; Table 1) and lower CaO (4.02 to 5.68%) than the other garnets and plot in the Group A eclogite range (as per Shervais et al., 1988) on a pyrope-grossular almandine+spessartine plot. Garnets from four other eclogite samples have lower MgO (43.2 to 60.2% pyrope) and average Cr_2O_3 (0.06 to 0.35%), has higher CaO (5.73 to 11.74%), and plot in the Group B eclogite range.

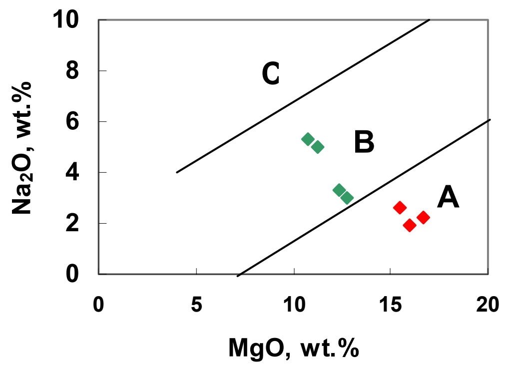

Figure 2: MgO vs. Na_2O in clinopyroxene.

Table 1: Composition of garnets

Sample	441/3	93/265	79/197	94/210
SiO_2	40.3	39.3	41.7	41.9
TiO_2	0.68	0.33	0.41	0.22
Al_2O_3	21.5	21.1	22.7	23.3
Cr_2O_3	0.53	0.06	0.41	0.18
FeO	17.4	17.8	11.4	10.2
MnO	0.28	0.42	0.38	0.33
MgO	12.8	8.44	18.51	20.6
CaO	7.03	11.7	5.01	4.02
Na_2O	0.24	0.06	0.08	0.05
Total	100.8	99.3	100.56	100.9

Table 2: Composition of clinopyroxenes

Sample	441/3	93/265	79/197	94/210
SiO_2	54.9	53.8	54.9	54.9
TiO_2	0.61	0.22	0.35	0.13
Al_2O_3	6.95	4.53	3.12	2.92
Cr_2O_3	0.31	0	0.39	0.06
FeO	6.38	5.89	3.83	3.42
MnO	0.02	0.03	0.12	0.03
MgO	10.8	12.7	15.4	16.5
CaO	14.6	19.6	19.3	19.6
Na_2O	5.31	3.05	2.6	2.28
NiO	0	0	0.1	0.1
Total	99.99	99.88	100.1	99.89

Clinopyroxenes in these eclogites are heterogeneous, especially for Al_2O_3 and Cr_2O_3. Clinopyroxenes in 79/197, 94/210 and 102/236 samples contain higher MgO (15.4 to 16.5%) and average Cr_2O_3 (0.16 to 0.39%) and lower Al_2O_3 (2.43 to 3.12%) and Na_2O (1.73 to 2.61%) compared to other samples and plot in the Group-A range on an MgO-Na_2O plot (Fig. 2; Table 2).

P-T ESTIMATION

The chemical compositions of coexisting minerals are useful in determining equilibrium temperatures. Coexisting garnet and pyroxene geothermometry (Ellis and Green, 1979) was applied to estimate the equilibrium temperatures at various assumed pressures, i.e., 40, 50, and 60 kbar. Group B eclogites provide higher estimated temperatures (775-1025 ^{0}C), compared with Group A eclogites (715-870 ^{0}C), for a pressure of 50 kbar. The results of the temperature estimates are shown in Table 3.

Table 3: Results of T estimations

Sample	40 kb	50 kb	60 kb	Group
79/197	710	735	765	A
94/210	695	715	735	A
102/236	840	870	900	A
73/230	985	1025	1055	B
93/265	750	770	795	B
102/254.5	770	795	820	B
441/3	955	990	1020	B

TRACE ELEMENTS

Trace-element analyses of garnet, clinopyroxene, and phlogopite were made in-situ in polished thick sections, with LA-ICP-MS at the GEMOC National Key Centre, Macquarie University, Australia. Methods and operating conditions have been described by Norman et al., 1996. All clinopyroxenes are characterized by convex-upward REE patterns (chondrite-normalized), with significant variations in the trace-element concentrations. Chondrite-normalized La values (La_n) and La/Yb ratios are 3.5-24.3 and 5.4-139 for the Group A clinopyroxenes and 0.9-13.7 and 0.7-18.7, resp., for the Group B clinopyroxenes. The garnets of the Grib eclogites display a wide range of HREE abundances (e.g., Lu_n = 6.22 – 29.64). La_n and La/Yb ratios for the garnets are 6.2-29.6 and 0.003-0.019 for Group A and 9.5-16.3 and 0.003-0.012 for Group B, resp. Gd/Yb ratios in garnets are in a range of 0.24-0.87, with an average of 0.53. None of the clinopyroxenes or garnets showed any Eu anomaly. Distributions of trace elements in garnets and clinopyroxenes are relatively uniform, with the exception of one Group A eclogite, which contains two types of clinopyroxene having different LREE and MREE abundances. These two Cpx types have La_n and La/Dy ratios 2.95 vs. 1.99 and 15.6 vs. 11.48, respectively.

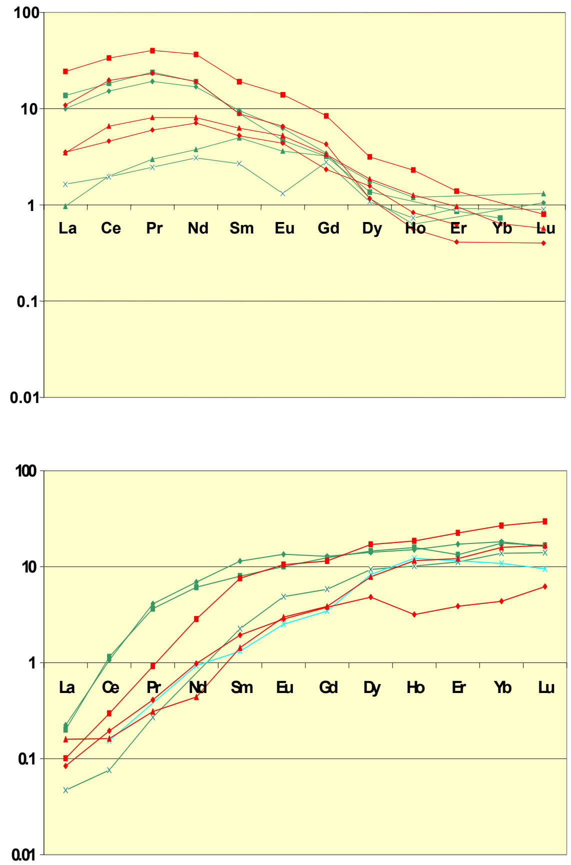

Figure 3: REE patterns of clinopyroxenes (top) and garnets (bottom) in the Grib pipe eclogites. Group A – red data points, Group B – green data points.

OXYGEN ISOTOPES

Clean mineral separates were prepared of garnets from 7 of the eclogite samples and oxygen isotopes were determined by the laser-fluorination technique at the University of Wisconsin, using the methodology presented in Spicuzza et al. (1998). Garnets were analyzed because they are the freshest phase in the Grib eclogites. Values of δ^{18}O values of the garnets range between 4.05 and 5.64 ‰ (Figure 3, Table 4). The high MgO garnets of Group A have a restricted range of δ^{18}O values (5.4 to 5.64‰) and lie within the mantle range of 5.4 ±0.4‰ (Mattey et al., 1994). The low-MgO garnets have a broader range of isotopic and major-element compositions. Except for sample 73/230, all garnets of the Group B eclogite have a restricted range of $\delta^{18}O$ values of 4.05 to 4.29 ‰, well below the mantle range. Garnet 73/230 has $\delta^{18}O$ value of 5.4 ‰) comparable with values of garnets of the Group A eclogites. The values of $\delta^{18}O$ show a good correlation with other elements (e.g., MgO, CaO) of garnet as reported for Siberian eclogite xenoliths (Jacob et al., 1994; Snyder et al., 1997).

Table 4: Garnet compositions and O isotopes data

Sample	Pyr	Alm	Gross	$\delta^{18}O$
79/197	65.2	20.9	10.1	5.64
94/210	70.6	18.6	7.6	5.64
102/236	63	21.1	12	5.4
73/230	50.1	33.9	15.2	5.4
93/265	31.8	35.2	27.3	4.27
102/254.5	29.9	38	27.9	4.29
441/3	46.4	33.6	13.5	4.05

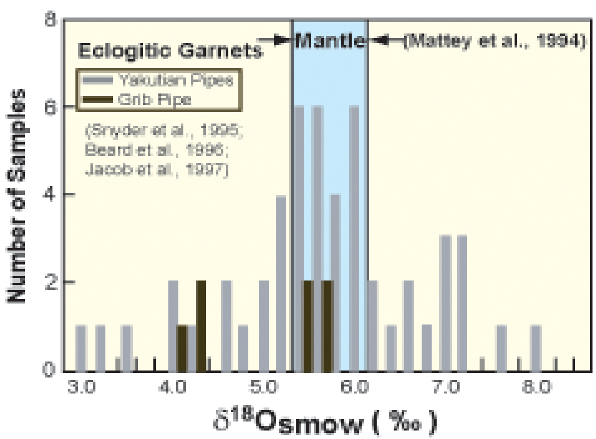

Figure 4: Oxygen isotope values for eclogitic garnets from Yakutian kimberlite pipes versus those from the Grib pipe. Note the two sets of values for the Grib garnets, which distinguish the Group A (mantle values) versus the Group B lower values.

DISCUSSION

Based upon modal and mineral compositions, the seven Grib pipe eclogites in this study were assigned to two eclogite groups: Group A (three samples) and Group B (four samples). Group A eclogites are phlogopite-bearing; their constituent minerals have high Mg# and Cr_2O_3 content, and clinopyroxenes in this group have low-jadeite component. The geochemical features of Group A eclogites resemble those of garnet pyroxenites. They are believed to be the product of high-pressure fractionates from alkaline basaltic melt in the upper mantle. Values of $\delta^{18}O$ of garnet separates from these eclogites are all within the mantle range. There is no evidence to indicate that these Group A eclogites were derived from crustal materials.

Group B eclogites have higher contents of Al_2O_3 and FeO and lower MgO and Cr_2O_3. The Group B eclogites are thought to be the metamorphic relicts of subducted oceanic crust (Taylor and Neal, 1989; Qi et al., 1994). The most compelling evidence for a crustal origin of eclogite xenoliths are stable isotope compositions that deviate from established peridotitic values, i.e., $\delta^{18}O$ values that lie beyond 5.5 ±0.4‰ (e.g., MacGregor and Manton, 1986; Jacob et al., 1994). Eclogites with high and low $\delta^{18}O$ values are believed to have obtained their isotopic compositions through low- and high-temperature seawater alteration prior to subduction (Gregory and Taylor, 1981).

Group A eclogites, worldwide, have oxygen values mostly within the mantle range. However, several Group A eclogites have been reported with values distinctly outside mantle, raising the question of crustal protoliths even for these eclogites (Viljoen, 1994; Taylor et al., 2003). However, among eclogite suites from the same pipe, Group A eclogites usually do not define the lowest values (Snyder et al., 1998). The observed oxygen isotopes of the Grib high MgO eclogites show mantle-like $\delta^{18}O$, indicating either a mantle origin or possibly oceanic crust with mantle (=MORB) oxygen values. The restricted range of compositions and high MgO, NiO, and Cr_2O_3 contents support an intra-mantle origin for these samples. In contrast, the broader range of $\delta^{18}O$ of the low-MgO, Group B eclogites is a signature of an oceanic crystal protolith.

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