CRATONIC CONDITIONS BENEATH ARKHANGELSK, RUSSIA: GARNET PERIDOTITES FROM THE GRIB KIMBERLITE

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INTRODUCTION

Kimberlite-derived xenoliths provide constraints on the composition, structure, and thermal state of the upper mantle underlying Archean cratons. The first kimberlite pipes were found in the Arkhangelsk kimberlite province in the early 1980's. Subsequently, 50 more pipes were discovered, 15 of them diamondiferous. Although the kimberlites in the Arkhangelsk kimberlite province were discovered decades ago, the mantle xenoliths found in these kimberlites have not received much attention. The main reason is that the well-known kimberlite pipes of Lomonosovo group are extremely altered. Xenoliths of the recently discovered, richly diamondiferous Grib kimberlite pipe have become the subject of special interest due to the abundance of fresh, large garnet and garnet-spinel lherzolite xenoliths. To date, there have been only preliminary petrological studies of mantle xenoliths of the Arkhangelsk kimberlite province (Sablukova, 1995; Sablukova et al., 1995; Verichev et al., 1998). The aim of this paper is to report on the first stage of our detailed studies of these xenoliths as they reveal knowledge of the nature of the lithosphere beneath the Verkhotina kimberlite field.

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 (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); (2) on the NE side of the Onega Peninsula, separated from the Zimniy Bereg by the Gulf of Dvina.
A short intense, widespread phase of Late Devonian (~380-360 Ma) mafic, alkaline-ultramafic and carbonatitic magmatism immediately followed large-scale lithospheric doming of the East European

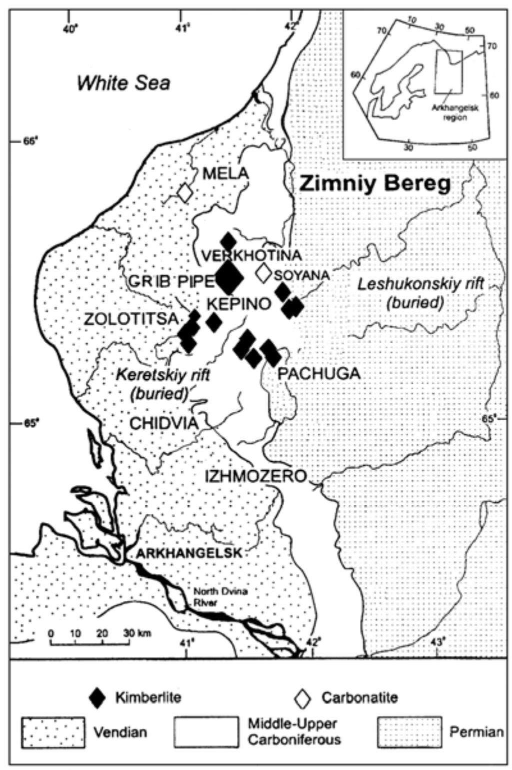

Figure 1: Simplified geological sketch map of the Arkhangelsk Alkaline Igneous Province (Mahotkin et al., 2000).

Platform (Mahotkin et al., 2000). The Late Devonian magmatism of the Kola region forms one of the world's largest intrusive and sub-volcanic alkaline provinces.

The Kola Alkaline Province outcrops over an area of ~100 000 km^2 and comprises 24 igneous complexes (Kogarko et al., 1995; Mahotkin et al., 2000).

Kimberlites are the predominant rock-type 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) has terminated the long-established notion (e.g., Sablukova et al., 1995) that only the Western Group kimberlites are potentially valuable economically (Verichev et al., 1998).

XENOLITH PETROGRAHY

A suite of approximately 90 mantle xenoliths was obtained from the Grib pipe. Most are <10 cm in diameter, with a few as large as 20 cm. This suite of mantle xenoliths encompasses garnet peridotites, pyroxenites, and eclogites. The present study addresses the detailed mineralogy and geochemistry of a selected sampling of 16 garnet peridotites. The peridotite set includes 13 garnet lherzolites and 3 garnet harzburgites. Megacrysts (commonly <5 cm in size) are also abundant in the Grib pipe. Pyrope, chrome-diopside, and picroilmenite are most abundant, and phlogopite, olivine, and orthopyroxene occur in minor accounts, along with traces of chrome spinel. Megacrysts of single crystals of chrome-diopside are rare; most diopside megacrysts are polycrystalline intergrowths and/or contain smaller grains of minerals from the megacrystal assemblage.

All xenoliths possess a protogranular texture, with no sheared peridotites in the suite. Xenoliths of coarse peridotite are composed of olivine (55-90%), with lesser amounts of clinopyroxene (0-12%), orthopyroxene (3-15%), garnet (2-7%), and spinel (0-1%). Three of the garnet lherzolites and two of the garnet harzburgites contain phlogopite, in apparent textural equilibrium with the other primary minerals. The predominant rock types are lherzolite and harzburgite. The garnet lherzolites all contain high modal abundances of clinopyroxene and garnet. Secondary alteration has produced the development of serpentine replacing olivine and orthopyroxene.

MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS

MAJOR ELEMENTS

Olivine compositions range in Mg# from 90.8 to 93 (Table 1). The most magnesian olivine (Fo_{92-93}) occurs in spinel-garnet and garnet lherzolites and in harzburgites. Olivines from phlogopite-bearing peridotites have lower Mg# and range from 90.8 to 92.1. Concentrations of Ni in olivine range from 0.33 to 0.42 wt%.

Table 1: Composition of olivines

Sample	110/417	89/305	90/395	216
Rock	Lher	Phl Lher	Harz	Phl Harz
SiO_2	41.2	40.6	40.8	41.8
TiO_2	0.01	0.01	0.01	0.01
Al_2O_3	0.02	0.01	0.01	0.01
Cr_2O_3	0.01	0.01	0.03	0.04
FeO	8.11	8.97	7.71	7.68
MnO	0.08	0.11	0.11	0.11
MgO	50.9	49.9	51.4	50.6
CaO	0.01	0.01	0.01	0.04
Na_2O	0.04	0.01	0.02	0.01
NiO	0.36	0.33	0.41	0.41
Mg#	91.8	90.8	92.2	92.1
Total	100.7	99.92	100.5	100.7

Table 2: Composition of orthopyroxenes

Sample	110/417	89/305	90/395	216
Rock	Lher	Phl Lher	Harz	Phl Harz
SiO_2	58.3	57.5	57.6	58.6
TiO_2	0.01	0.19	0.01	0.05
Al_2O_3	0.57	0.35	0.69	0.75
Cr_2O_3	0.29	0.81	0.18	0.19
FeO	4.87	6.49	4.96	4.81
MnO	0.19	0.18	0.13	0.14
MgO	36.3	33.4	36.2	35.8
CaO	0.28	1.01	0.18	0.16
Na_2O	0.05	0.13	0.02	0.06
NiO	0.17	0.16	0.11	0.08
Mg#	93.0	90.1	92.8	93.0
Total	101	100.1	100.1	100.7

With the exception of one unusual sample (89/305), orthopyroxene compositions vary little within and between xenoliths types (MG# = 92.3-94.2; Table 2). In all cases, orthopyroxene is slightly more Mg-rich than the coexisting olivine, an indication of equilibrium (Gurney et al., 1979). Orthopyroxene compositions from different rock types are quite uniform in terms of their Cr_2O_3 and CaO contents. Only orthopyroxene from a unique, probably deep-seated phlogopite spinel/garnet lherzolite (89/305) has low Mg# (90.15), Al_2O_3, and high TiO_2, Cr_2O_3, CaO, and Na_2O (Table 2). Orthopyroxene grains are homogeneous, especially for Al_2O_3 and CaO.

Clinopyroxene in peridotite has high-Cr content (1.2-2.6 wt % Cr_2O_3) and is classified as Cr-diopside. Clinopyroxene compositions range in Mg# from 90.3 to 95.5 (Table 3). Clinopyroxene compositions are constant. Clinopyroxene from the unusual phlogopite spinel/garnet lherzolite (89/305) has intermediate Mg# (92.8), Cr_2O_3, and the highest TiO_2, Al_2O_3, and Na_2O (Table 3).

Table 3: Composition of clinopyroxenes

Sample	110/417	89/305	53/501	93/236
Rock	Lher	Phl Lher	Lher	Lher
SiO_2	54.6	54.9	54.78	55.3
TiO_2	0.25	0.27	0.21	0.16
Al_2O_3	1.82	3.98	2.92	3.03
Cr_2O_3	2.23	1.59	1.51	2.63
FeO	3.06	1.98	1.57	1.51
MnO	0.11	0.05	0.08	0.05
MgO	16.1	14.4	15.4	14.9
CaO	19.1	19.7	20.9	19.7
Na_2O	2.51	3.09	2.26	2.85
NiO	0.01	0.01	0.01	0.02
Mg#	90.33	92.8	94.6	94.6
Total	99.71	100.1	99.7	100.1

Garnet in Grib peridotites contains high MgO, low CaO, and moderate Cr_2O_3, typical of pyrope. On the plot of Cr_2O_3 versus CaO, the pyrope compositions define a common 'lherzolitic' trend (Sobolev et al., 1973; Fig. 2). However, some of the garnet-bearing samples are, in fact, harzburgites. Concentrations of Ti in garnet ranges from 0.01 to 0.19 wt%, with the highest value 0.22 wt% in sample 89/305. Spinel in Grib peridotites can be divided into two groups. The first one is typical of chromite of peridotites with low TiO_2. Spinel from the second group has high TiO_2, FeO, and low Al_2O_3 and occurs in phlogopite-bearing lherzolites (Table 4).

Table 4: Composition of garnets and chromites

Sample	110/417	89/305	216	89/305
Rock	Lher	Phl Lher	Phl Harz	Phl Lher
Mineral	Gar	Gar	Chr	Chr
SiO_2	41.72	41.8	0.04	0.07
TiO_2	0.01	0.22	0.87	3.29
Al_2O_3	19.7	22.2	14.8	6.59
Cr_2O_3	5.37	1.91	50.4	51.3
FeO	8.64	9.67	19.1	25.1
MnO	0.36	0.52	0.01	0.01
MgO	19.4	19.4	11.7	11.4
CaO	5.69	4.31	0	0
Na_2O	0.01	0.06	0	0
Total	100.8	100.1	97.1	97.9

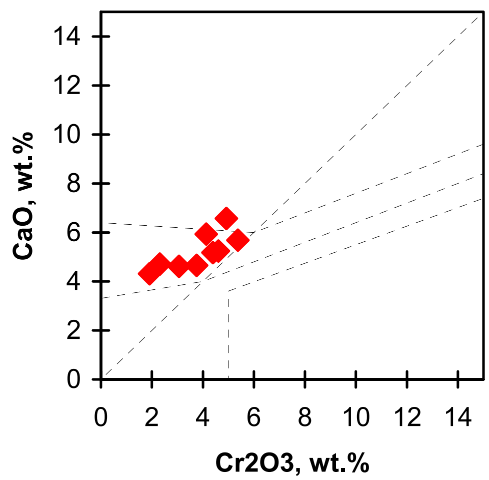

Figure 2: Cr_2O_3 vs CaO plot for garnet in Grib peridotites. Fields shown for garnets are from Sobolev et al., (1973).

P-T ESTIMATION

Garnet and orthopyroxene are relatively homogeneous, thereby implying equilibrium between these two phases. Hence, the compositions of these coexisting phases have been used for geothermobarometry estimates of the P-T conditions that existed beneath this Middle Paleozoic craton. Estimates of the pressures and temperatures are based on a combination of the Opx-thermometer of Brey and Kohler (1990) and the barometer of McGregor (1974), as well as the thermometer of Finnerty and Boyd (1984) and the barometer of McGregor (1974). Temperatures and pressures range from 31 to 62 kbar at 780-1300 ^oC and 20 to 62 kbar at 600-1100 ^oC, for these two schemes for P-T estimation. These P-T estimates define a geotherm with a relatively low heat flow of about 37-38 mv/m2.

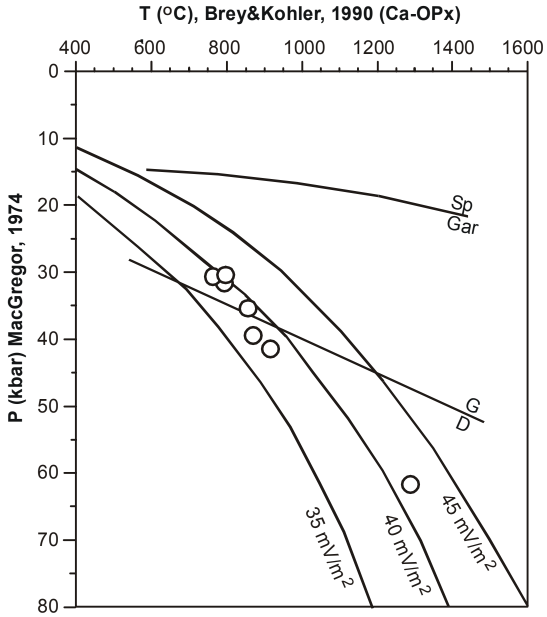

Figure 3: Equilibrium P-T estimates for the Grib peridotites according to MacGregor (1974) and Brey&Kohler (1990).

TRACE ELEMENTS

Trace-element analyses of garnet, clinopyroxene, and phlogopite were made in-situ in polished thick sections, with LA-ICP-MS at Macquarie University, Australia. Methods and operating conditions have been described by Norman et al., 1996. REE patterns for lherzolitic clinopyroxene vary from primitive to weakly depleted. Chondrite-normalized ratios of La/Sm measure the slopes of the LREEs and range from 0.37 to 0.82; La/Yb represents the general slope of the entire REE pattern and ranges from 8.57 to 28.8; the Gd/Yb ratios relate to the slopes of the HREEs and vary from 0.45 to 0.48. Harzburgitic garnets are depleted in both the LREEs and MREEs and the Gd/Yb ratios vary from 0.1 to 0.25.

RE/OS SULFIDE DATING

The mineralogy and geochemistry of interstitial sulfide minerals and sulfide inclusions in minerals were carefully studied in the garnet lherzolites and harzburgites. In garnet harzburgite #53/292, a highly unusual homogeneous grain of interstitial Fe-Ni sulfide was found having anomalously high contents of Co, Os, and Pt. This sulfide grain was dated in-situ by Re/Os isotope analysis, by LA-MC-ICP-MS. The Re/Os model age is 2.9-3.1 Ga. Such an ancient age for the continental lithospheric mantle of the Arkhangelsk diamondiferous province is in good agreement with ages detected for the continental lithospheric mantle beneath Yakutia and southern Africa (Pearson et al., 1995a, b).

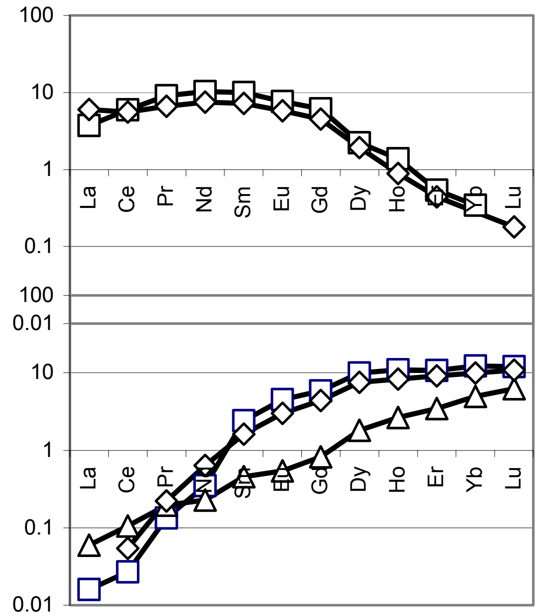

Figure 4: REE patterns of clinopyroxenes (top) and garnets (bottom) in the Grib peridotites.

CONCLUSIONS

(i) The mantle beneath the Verkhotina kimberlite field shows many features common to cratonic mantle elsewhere. The Grib pipe kimberlite contains a xenolith suite comprising mantle-derived peridotite and eclogite xenoliths (see Malkovets et al., this volume)

(ii) The peridotite xenoliths encompass a range of rock types, including garnet lherzolites, garnet garzburgites, garnet websterites, and dunites. Variations in modes and mineral compositions indicate gradations between these different rock types.

(iii) P-T estimates for the peridotite xenoliths produce a well-defined paleogeotherm below 1000 ^oC, with a defined low heat-flow of about 37-38 mw/m^2, whereas at higher T the geotherm is closer to a value of 42 mw/m^2.

(iv) The Re/Os model age of a single sulfide grain yielded 2.9-3.1 Ga. Such an ancient age for the continental lithospheric mantle of the Arkhangelsk diamondiferous province is in good agreement with ages detected for the continental lithospheric mantle beneath Yakutia and southern Africa.

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