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Mantle xenocrysts from the Arkhangelskaya kimberlite (Lomonosov mine, NW Russia): Constraints on the composition and thermal state of the diamondiferous lithospheric mantle

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ABSTRACT

The Arkhangelskaya kimberlite pipe belongs to the Zolotitsa kimberlite field in the Arkhangelsk region, NW Russia. It is the first pipe of the Lomonosov diamond mine to be put into production, with 2 million tons of ore already extracted. In this study major and trace element compositions of garnet, clinopyroxene (Cpx), Mg-ilmenite and chromite xenocrysts from the Arkhangelskaya pipe have been used to infer information about the compositional variability of the mantle underlying the Zolotitsa field. Single-grain thermobarometry of peridotitic Cpx xenocrysts yields a cool cratonic geotherm that follows a ca. 36 mW/m^2 conductive model. Equilibration temperatures of garnet and chromite grains based on Ni- and Zn-thermometry, respectively, indicate a sampling interval of ca. 70–230 km of the lithospheric mantle when projected onto the Cpx-derived geotherm. The major element chemistry of Mg-ilmenite xenocrysts suggests that almost optimal redox conditions for diamond preservation prevailed in the mantle during the time of emplacement of the host kimberlite magmas. Garnet major and trace element compositions combined with the Cpx-geotherm indicate that the peridotitic diamond window extends from 130 to 210 km under Zolotitsa and that the deeper parts of the lithosphere have been affected by metasomatic events. Arkhangelskaya seems to have sampled the bulk of its diamonds from the deepest portion of the diamond stability field, between 190 and 210 km. In comparison, the neighbouring Lomonosova and Pionerskaya pipes are known to have collected their diamonds from 130–160 km. The comparable grade of the three pipes suggests that diamondiferous material is generously distributed within the diamond stability field. The remarkable difference evidenced by garnet composition and thermobarometry between Arkhangelskaya and the two other Zolotitsa pipes probably derives from differences in rheology and eruption rates of the rising kimberlite magmas.

1. Introduction

The kimberlites of the Zimnyi Bereg (Winter Coast) area in Arkhangelsk, NW Russia (Fig. 1), belong to the Late Devonian, 360–380 Ma, Arkhangelsk Alkaline Igneous Province (Mahotkin et al., 2000; Pervov et al., 2005 and references therein). In addition to kimberlites, this province comprises a wide variety of ultramafic rock-types, including alkaline picrites and olivine lamproites (Mahotkin et al., 2000; Garanin 2004; Downes et al., 2005). Based on petrographical and geographical characteristics the kimberlites can be divided into two groups (e.g. Beard et al., 2000; Mahotkin et al., 2000; Sablukova and Sablukov, 2008; Ustinov et al., 2008): mica-poor Eastern Group (Kepino-Pachuga and Verkhotina-Soyana fields) and micaceous Western Group (Zolotitsa and Mela fields) that resemble South African Group I and II kimberlites, respectively, in terms of mineralogy and chemical composition. Both groups host an economic diamond deposit: the Lomonosov deposit consisting of 6 individual pipes on a 9.5 km N–S chain belongs to the western Zolotitsa field whereas the Grib pipe (Rubanova et al., this issue) is located in the eastern Verkhotina-Soyana field. Studies of inclusions in diamonds and carbon isotope work have shown that that majority of the diamonds in the Arkhangelsk kimberlites are of harzburgitic paragenesis (Sobolev et al., 1973, 1997; Galimov et al., 1994). The crystals are mostly rhombododecahedrons and octahedrons, the latter form being more common among the smaller grain sizes, <1.0 mm (Garanin et al., 1998a).

Kimberlites of both groups contain megacrysts (Mahotkin et al., 2000; Kostrovitsky et al., 2004) and other lithosphere-derived materials, including xenoliths of peridotite (Sablukova, 1995; Bobrov et al., 2003; Malkovets et al., 2003a; Sablukova et al., 2003) and eclogite (Bobrov et al., 2003; Malkovets et al., 2003b) and abundant mantle xenocrysts (Sobolev et al., 1992; Sablukov et al., 1995; Garanin

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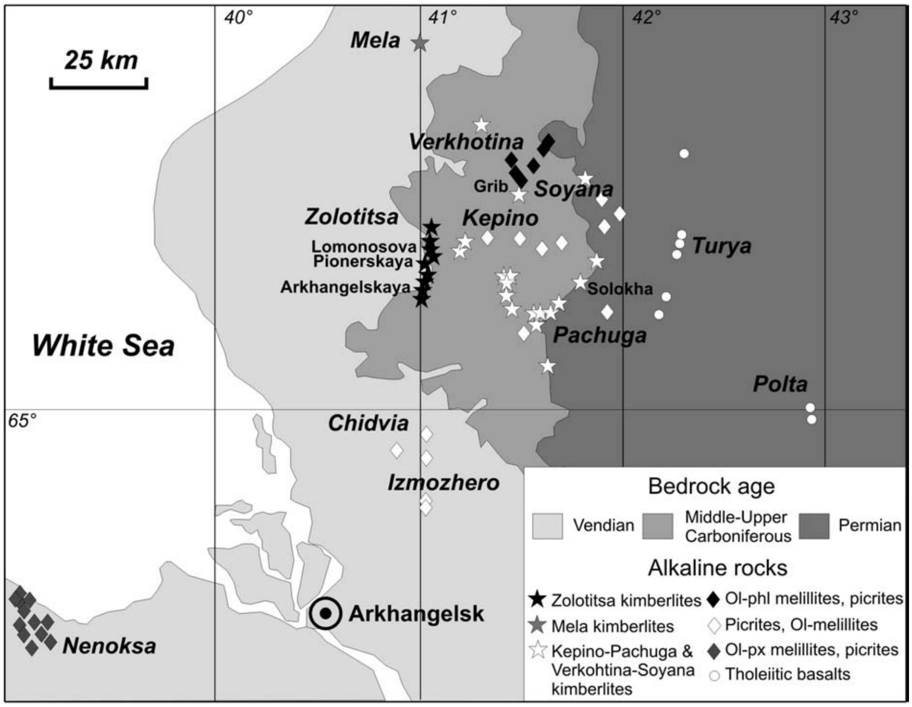

Fig. 1. Simplified geological map of the Arkhangelsk alkaline igneous province. Redrawn after Krotkov et al. (2001).

et al., 1998b). Crustal xenoliths of granulite (Markwick and Downes, 2000) and eclogite (Malkovets et al., 2003b; Bobrov et al., 2005) facies rocks have been also recovered from the kimberlites.

Significantly, mantle xenoliths in the Lomonosov pipes are extremely altered in contrast to those at Grib which are more abundant, fresher and useful for extracting petrological information. For this reason, most of the xenolith P–T estimates of the Zimnyi Bereg area come from Grib, with peridotite xenoliths yielding 31–72 kbar and 600–1200 °C, corresponding to a 37–38 mW/m^2 conductive model geotherm of Pollack and Chapman (1977; Fig. 4) (Malkovets et al., 2003a; Sablukova et al.; 2003). Clinopyroxene-garnet pairs have yielded a very similar geotherm, filling many discontinuities seen in the xenolith data (Kostrovitsky et al., 2004; Fig. 4). The P–T conditions for mantle eclogites from Grib have been determined to be 35–39 kbar and 950–1050 °C (Bobrov et al., 2003). The P–T parameters for the rare pristine mantle xenoliths from Zolotitsa range between 17–53 kbar and 800–1200 °C (Sablukova, 1995). Based on single-grain Cr-pyrope thermobarometry (Ryan et al., 1996) the geotherm follows a 37 mW/m^2 conductive model (Sablukov et al., 1995).

The focus of this work is on the Arkhangelskaya kimberlite pipe that belongs to the Lomonosov diamond mine, being the first pipe put into production. The aim is to obtain additional information on the stratigraphy, compositional variability and evolutionary history of the lithospheric mantle underlying Zolotitsa by studying mantle xenocryst minerals and using the methodology described by Griffin et al. (1999, 2002). This study is closely linked to the modelling of a 1000-km mantle transect across the Karelian and Kuola-Kuloi cratons based on kimberlites in Finland and in NW Russia (Peltonen et al., 2008).

2. Samples

Xenocryst samples from Arkhangelskaya were hand picked from a heavy mineral concentrate made available for this study by ALROSA Co Ltd. Hundreds of garnet, clinopyroxene (Cpx), chromite and ilmenite xenocrysts were recovered and mounted for electron microprobe and LA-ICP-MS analyses. Garnet, chromite and ilmenite grains in this study are unsorted and represent the entire range of populations within the kimberlites. For the Cpx grains, an attempt was made to choose only peridotitic varieties, based on their bright green colour.

3. Analytical techniques

Pyrope garnet, chromite and ilmenite major element compositions were determined by a Cameca Camebax SX100 ele ctron microprobe at GTK E-beam Laboratory, applying an acceleration voltage of 25 kV, probe current of 48 nA and beam diameter of 1 µm. The parameters for eclogitic garnet were 15 kV, 20 nA and 15 µm, and for clinopyroxene 15 kV, 30 nA and 5 µm, respectively. Selected garnet xenocrysts were analyzed for trace elements by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Frankfurt, using a New Wave Research LUV213™ petrographic ultraviolet Nd-YAG laser coupled with a Finnigan MAT ELEMENT2™. The laser was run at a pulse frequency of 10 Hz and a pulse energy of 0.5 mJ with a 150 µm spot size for the measurement of garnet. Two in-house natural garnet samples (PN1 and PN2) were used as external standards, and calcium was used as an internal standard for the measurements.

The garnets were classified based on their major element compositions into harzburgitic (G10), lherzolitic (G9), wehrlitic (G12), high-Ti peridotitic (G11), low-Cr megacrystal (G1), eclogitic (G3, G4) and pyroxenitic (G4, G5) varieties according to the Grütter et al. (2004) revision of the scheme by Dawson and Stephens (1975). For equilibration temperatures of garnets the Ni thermometer (Griffin et al., 1989) was applied using the calibration of Ryan et al. (1996). The chromites were classified into Di (inclusion in diamond-type) and Cr–Ti (phenocrystic) varieties according to Fipke et al. (1995) and Sobolev (1977) and their equilibration temperatures were calculated using the Zn thermometer described also in Ryan et al. (1996). Equilibration pressures and temperatures of the peridotitic clinopyroxene were calculated using the single-grain Cpx thermobarometer of Nimis and Taylor (2000).

4. Results

The analytical database containing all major and trace element analyses obtained for this study is available as an Open file report at the Geological Survey of Finland website (Lehtonen et al., 2008a,b).