Mantle signature of the Arkhangelskaya kimberlite pipe, NW Russia

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Introduction

The kimberlites of the Zimnyi Bereg area in Arkhangelsk, NW Russia, belong to the Late Devonian, 360-380 Ma, Arkhangelsk Alkaline Igneous Province (Mahotkin et al., 2000, and references therein) (Fig. 1). Based on petrographical and geographical characteristics the kimberlites can be divided into two groups: a micaceous Western Group (Zolotitsa and Mela fields) and mica-poor Eastern Group (Kepino-Pachuga and Verkhotina-Soyana fields) that resemble South African Group II and I kimberlites, respectively. Both groups host an economic diamond deposit: the Lomonosov deposit in the Zolotitsa field and the Grib pipe in the Verkhotina-Soyana field. Kimberlites of both groups contain megacrysts (e.g. Kostrovitsky et al., 2004) and other lithosphere-derived materials, including peridotite xenoliths (Malkovets et al. 2003; Sablukova et al., 2003). Mantle xenoliths in Lomonosov are extremely altered compared to Grib. For this reason, most of the xenolith P-T estimates come from the latter (Fig. 2).

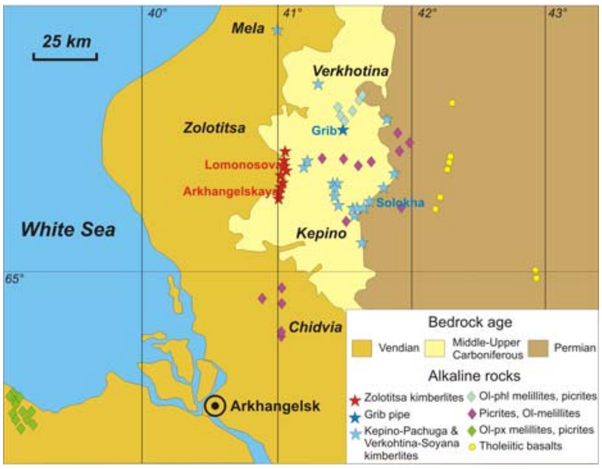

Fig.1. Simplified geological map of the Arkhangelsk alkaline igneous province. Redrawn after Krotkov et al. (2001).

The focus of this work is on the Arkhangelskaya kimberlite pipe of the Lomonosov diamond mine. The objective is to obtain additional information on the stratigraphy, compositional variability and evolutionary history of the lithospheric mantle. This study is closely linked to modelling of the 1000-km mantle transect across the Karelian and Kuola-Kuloi cratons (Peltonen et al., this volume).

Samples and analytical techniques

Xenocryst minerals (garnet, chromite and clinopyroxene) from the Arkhangelskaya pipe were extracted from a heavy mineral concentrate provided by ALROSA Co Ltd. Mineral grains were chosen randomly and should represent the entire range of compositional populations within the kimberlite. Major element compositions were determined by a Cameca Camebax SX100 EMP at GTK and trace elements were analyzed by LA-ICP-MS at the University of Frankfurt. The garnets were classified based on their major element composition according to Grütter et al. (2004). For equilibration temperatures of garnets and chromites the Ni (Griffin et al., 1989; Ryan et al., 1996) and Zn (Ryan et al., 1996) thermometers, respectively, were applied. Equilibration pressures and temperatures of the peridotitic cpx were calculated according to Nimis & Taylor (2000).

Thermobarometry

Single-cpx thermobarometry defines a cool continental geotherm (Fig. 2) that lies between the 36 mW/m^2 conductive model geotherm by Pollack & Chapman (1977) and the 36 mW/m^2 geotherm by Kukkonen et al. (2003), the latter calculated for the 600 Ma Karelian Craton. In this paper, the metamorphic pressures are transformed into depth values by assuming that the pressures are representative of lithostatic pressures. Then, the petrological pressure values can be transformed into depth values using the following relationship:

$$Z = \frac{P}{9.81\rho_M} - \frac{\rho_C}{\rho_M} H + H$$

Where Z is depth (m), H is thickness of crust (m), P is the pressure (Pa) and ρ_M and ρ_C are the mantle and crust densities, respectively. For instance, applying

2800 kg m^{-3} for the crust and 3360 kg m^{-3} for the upper mantle density, a crustal thickness of 36 km (representative for the Arkhangelsk area), and a petrological pressure value of 4 GPa, the corresponding depth value is 127.4 km.

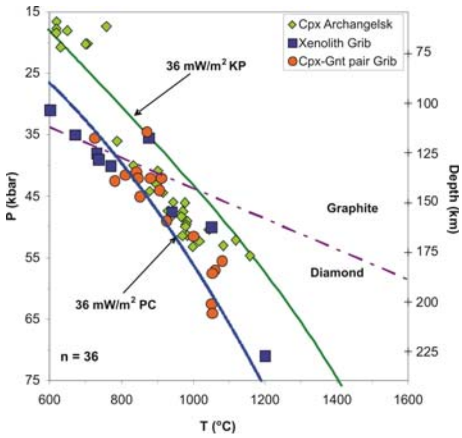

Fig. 2. P-T data from Arkhangelskaya cpx xenocrysts. Mantle xenoliths from Malkovets et al. (2003) and Sablukova et al. (2003), garnet-cpx aggregates from Kostrovitsky et al. (2004). Reference geotherms from Pollack & Chapman (1977; PC) and Kukkonen et al. (2003; KP). The diamond-graphite transition after Kennedy & Kennedy (1976).

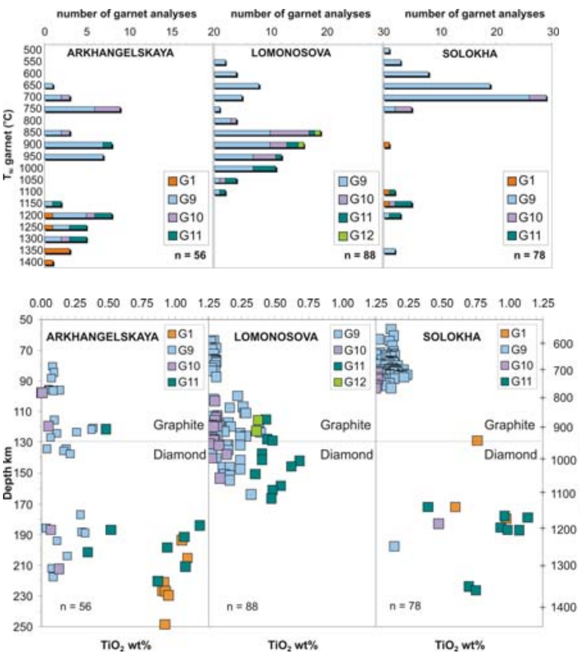

Fig. 3. Distribution of T_{Ni} and TiO_2 vs. depth for the Arkhangelskaya xenocryst pyropes. Lomonosova and Solokha data (Malkovets et al., 2007) shown for comparison.

Garnet and chromite thermometry

The T_{Ni} data of Arkhangelskaya garnet xenocrysts show a bimodal distribution of temperatures, including a lower temperature population at 650-1000°C consisting of G9 and G10 garnets, and a higher temperature group at 1150-1450°C containing G9, G10, G1 and G11 varieties (Fig. 3). The TiO_2 contents of garnets provide evidence of compositional variation within the mantle. 800°C corresponds to the break in TiO_2 contents of garnets at approximately 100 km in depth. It separates low TiO_2 (<0.2 wt%) shallow pyropes from a deeper horizon, 800-1000°C (100-140 km) exhibiting a wider range. There is also a notable gap in pyrope temperatures at 1000-1150°C corresponding to 140-175 km. The deep mantle extends down to 230 km and contains G1 and G11 grains with high contents of TiO_2 (up to 1.25 wt%), which is interpreted as a melt-metasomatic signature. The Zn thermometry of the Arkhangelskaya chromites reveals continuous sampling pattern between 600-1100°C (65-165 km), suggesting that chromites and garnets are partly derived from different mantle horizons and lithologies. Abundant chromites have diamond indicative compositions with low $Fe^{3+}/(Cr+Al+Fe^{3+})$ (Fig. 4).

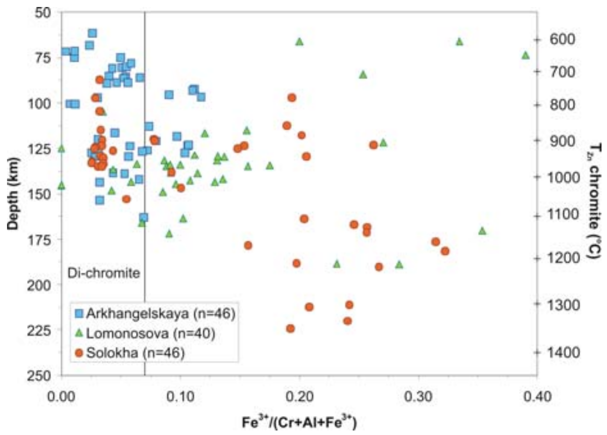

Fig. 4. Fe3+/(Cr+Al+Fe3+) for xenocryst chromites from Arkhangelskaya. Lomonosova and Solokha data (Malkovets et al., 2007) shown for comparison.

Discussion

The mantle sampling pattern of Arkhangelskaya clearly differs from that of Lomonosova (another high-grade pipe of the Lomonosov deposit) and also from Solokha (a low-grade pipe from the Kepino field) (Figs. 1, 3 and 4). Lomonosova shows continuous mantle sampling (garnet and chromite) until ca. 180 km with most of the grains originating from 110-160 km, which is also the G10 garnet bearing horizon. Solokha, on the other hand, has mostly sampled its garnets from a low-temperature (550-800°C) graphite-bearing part of the mantle at 60-100 km, with another less prominent sampling peak at 160-210 km. Solokha chromites display a wide range of temperatures, 700-1350°C (80-225 km), mostly filling the wide discontinuity seen in the garnet thermometry. The sampling pattern of Arkhangelskaya is intermediate to Lomonosova and Solokha, with surprisingly few samples originating from the diamond stability field (140-210 km) considering the high-grade of the pipe. The chromite pattern resembles that of Lomonosova but the bimodal distribution of garnet is more similar to Solokha, although not as skewed towards low temperatures. Interestingly, the cpx sampling (Fig. 2) runs uninterrupted from 100 km to 175 km and accross the discontinuity at 140-175 km seen in the garnet data. The cpx-grains should, however, originate from garnet-peridotites following the compositional criteria of Nimis & Taylor (2000). This is strongly supported by the realistic shape of the cpx geotherm. The absence of garnet xenocrysts between 140-175 km remains, therefore, somewhat enigmatic.

The evidence from the three individual kimberlites demonstrates that there is a strong compositional variability in the mantle underlying Zolotitsa field. Chromite thermometry from Lomonosova and Arkhangelskaya pipes bears evidence of a relatively uniform chromite-bearing layer underlying the Zolotitsa field. Major differences being reflected in the presence/absence and the composition of garnet. Malkovets et al. (2007) suggested that garnet and diamond are secondary phases, created by the same metasomatic event, that included invasion of the highly refractory lithosphere by fluids from asthenosphere-derived melts to produce subcalcic garnet and diamond. The distribution of garnet (and diamond) in the mantle would then be controlled by the presence of ancient structural conduits and, thus, strong lateral mineralogical variation on small scales would be expected.

Conclusions

Mantle xenocrysts in the Arkhangelskaya pipe demonstrate that the lithosphere underlying the Kola-Kuloi Craton is comparable in depth to the adjacent Karelian Craton (Peltonen et al., this volume), and has been affected by metasomatic events, especially near the asthenosphere-lithoshpere boundary. The distribution of G10 garnets in Arkhangelskaya shows that the peridotitic diamond window extends down to 210 km under Zolotitsa, even though it seems that the pipe itself has sampled its diamonds only between 190-210 km – whereas the neighboring Lomonosova pipe has sampled its diamonds from 130-160 km. The comparable grade of these two pipes suggests that the diamondiferous material is generously distributed within the diamond stability field. The differences between the sampling patterns of Zolotitsa (Arkhangelskaya, Lomonosova) and Kepino (Solokha) kimberlites can probably be explained by the model suggested by Malkovets et al. (2007). However, the remarkable difference evidenced by garnet composition and thermometry between the Arkahgelskaya and Lomonosova pipes, located just within a few kilometer distance from each other (Fig. 1), most likely derives from some other factors, such as differences in rheology and eruption rates of the rising kimberlite magmas – or even from inhomogeneities in the kimberlite itself.

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