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TYPOMORPHIC FEATURES OF GROUNDMASS MINERALS FROM DIAMONDFEROUS KIMBERLITES OF YAKUTIA

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Introduction

The Yakutian kimberlite province, occurring in the northeast of the Siberian platform, includes five industrial diamondiferous fields (listed below, as objects of this study except for the Nakynsky field). By present time the groundmass mineralogy of this kimberlite has been insufficiently studied. However, some publications are available on the typical features of oxide minerals of the Yakutia kimberlites, e.g. Blagulkina et al., 1975; Kornilova et al., 1983; Verzhak et al., 1989; Bovkun, 1999, 2000; Krotkov et al., 2001; Garanin, 1984, 2009). More detailed studies have been conducted on the bulk minerals in the African and Canadian kimberlites, e.g. Haggerty et al., 1976; Boyd et al., 1977; Boctor et al., 1979; Dawson, 1980; Agee et al., 1982; Mitchell, 1986; Armstrong et al., 2004; Mitchell et al., 1998; Fedortchouk & Canil, 2004; Roeder et al., 2008. They examined an issue related to the evolution of individual intrusive phases in the intricately built pipes (Shee, 1982; Hall et al., 1986; Salpas et al., 1986, etc.). Nevertheless, comprehensive studies of groundmass mineral typomorphism for the Yakutian kimberlite province have not been accomplished yet.

Petrography and petrochemistry

Kimberlites have been studied in the pipes: Internatsionalnaya, Mir, 23 KPSS - Malobotuobinsk field; Udachnaya, Zarnitsa - Daldyn field; Aikhal, Yubileinaya, Sytykanskaya - Alakit-Markha field; Zapolarnaya - Verhnemunsk field. Some texture-structural varieties of kimberlites have been recognized in this study (Fig. 1): porphyritic kimberlite (PK), kimberlite breccias (KB) and autoliths kimberlite breccia (AKB). KB characterized by different saturation xenoliths of country rocks (from 5% and more). AKB contains subrounded fragments of pre-existing solid igneous material and country rock xenoliths. PK is the rock of massive texture with country rocks less than 5%, where macrocrysts occur in the groundmass (basis, matrix). The matrix minerals contain the second generation of euhedral primary olivine and/or phlogopite, together with perovskite, spinel, diopside, monticellite, apatite, sulfides, calcite, and

primary late-stage serpentine. The grain size of groundmass minerals ranges from 0,005 mm to 1 mm, most of them are euhedral. The most common are carbonate and serpentine, their contents varying from 10-50% and 20-70%, respectively.

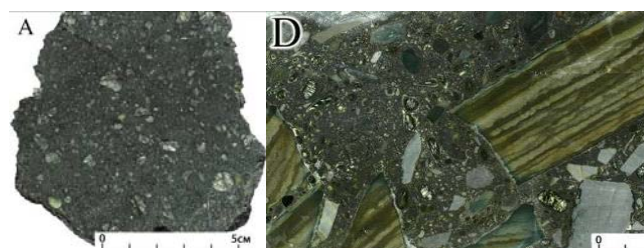


Fig. 1. Structure and texture differences of kimberlites. A- PK (Internatsionalnaya pipe), D- rich-xenolith KB (pipe Zapolarnaya).

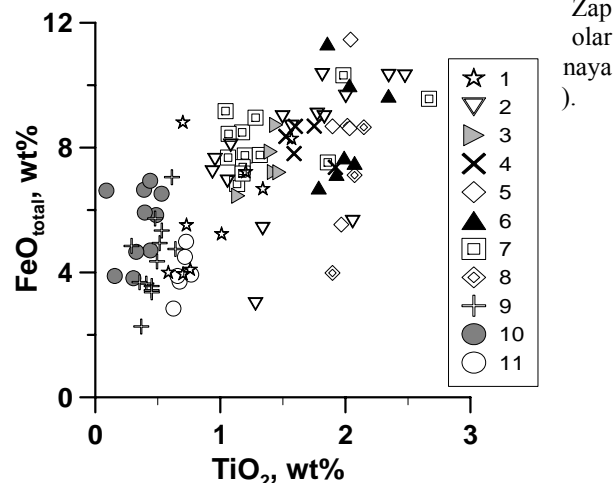


Fig. 2. Compositions of kimberlite from pipes: 1- Yubileinaya, 2- Udachnaya-east, 3- Udachnaya-west, 4- Mir, 5- Komsomolskaya, 6- Zarnitsa, 7- Zapolarnaya, 8- Sytykanskaya, 9- Aykhal, 10 - Internatsionalnaya, 11- 23 KPSS.

The petrochemical types of kimberlites were identified considering the abundance of major oxides (FeO, TiO₂, K₂O)

Extended Abstract



(Kostrovitsky et al., 2004). There are two petrochemical types of kimberlite within the diamondiferous fields of the Yakutian province: (1) magnesian, low-Ti, low-K (Mg-kimberlite) and (2) magnesian, high-Ti, low-K (Mg-Fe-kimberlite). The Aikhal, Internatsionalnaya, 23 KPSS and Udachnaya pipes are composed of Mg-kimberlites, whereas the Zarnitsa, Yubileinaya, Zapolarnaya and Mir pipes host Mg-Fe-kimberlites (Fig. 2).

Mineralogy

Olivine. Olivine is preserved in fresh kimberlites of pipes Udachnaya-east (20-65% ol), Internatsionalnaya (ol 20-35%), Zapolarnaya and Yubileinaya. Usually olivine is zonal, contains abundant ore mineral inclusions and rarely pyroxene and pyrope in rims (Fig. 3). As seen in the Fig. 4, olivines have complex zoning patterns.

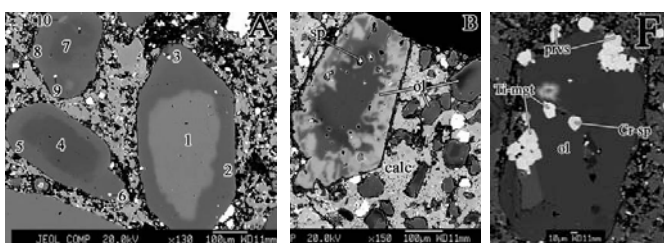


Fig. 3. Back-scattered electron (BSE) images of groundmass kimberlite from Udachnaya-east. A,B - zoned olivines (ol) from kiberlite: 1 - ol 85,3%Fo, 2 - ol 88,8%Fo, 4 - ol 90,5%Fo, 5 - ol 88,9%Fo, 7- ol 90%Fo, 8 - ol 86,7%Fo, 3 - sp, 6 - sp, 9 - sp, 10 - pyrope. F-spinel (chromite and Ti-magnetite) inclusions in olivine and sp-prvs-ol aggregates.

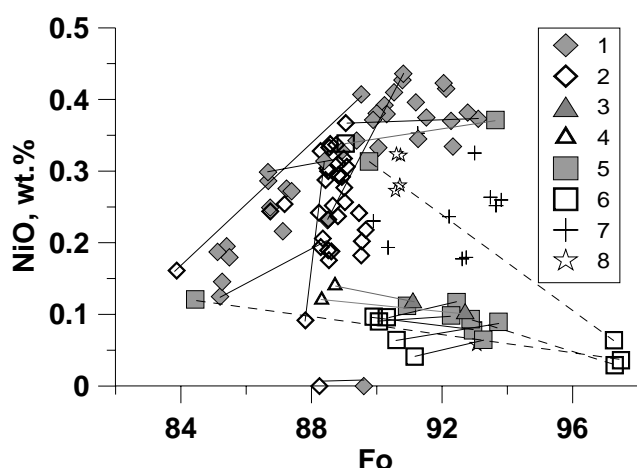


Fig. 4. Compositions of olivine: 1, 2-core and rim of phenocryst Udachnaya-east, 3,4 - core and rim of phenocryst Udachnaya-west, 5,6-core and rim of phenocryst Internatsionalnaya, 7-core of phenocryst Zapolarnaya, 8- core

of phenocryst of Yubileinaya. Core and rim of some single grains are jointed by lines.

Magnesium-rich cores of phenocrysts with a high content of NiO (0.32-0.46 wt%) occur more frequently. Udachnaya-east zonal groundmass olivines differ from other: uniform Fo (86-90%) in the rims, positive correlation between Fo and NiO in the core and weak negative correlation between Fo and CaO in the core. The lowest NiO in olivine of Internatsionalnaya and Udachnaya-west (<0.1-0.2%) evidently indicates a significant metasomatic mineral processing, which occurred not just in the edge, but also in the central parts of grains.

Monticellite. Groundmass monticellite (mont) forms a small (up to 60 μ m) idiomorphic and irregularly-shaped grains, and in places it forms clusters around olivine phenocrysts. A resorption of the rims is observed in the monticellite grains due to the late stage replacement by calcite and serpentinization (Dawson, 1983, Mitchell, 1986). Monticellite was not found in KB. Zoning of monticellite looks as alternated concentric areas of varying ferrum coefficient (Fig. 5A). Monticellite "pseudomorphs" after olivine and diopside occurs rarely (Fig. 5B - 5, 6).

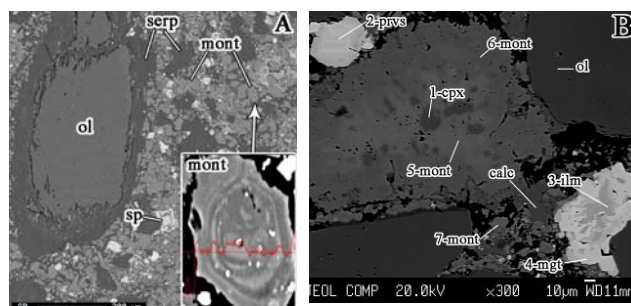


Fig. 5. BSE images of groundmass minerals in PK from pipe Zapolarnaya (A), aphanite kimberlite from pipe Ydachnaya-east (B). There is big zoned monticellite zoomed in the right bottom corner of image A.

Spinel. We have studied spinel of different paragenetic associations: the groundmass spinel; aggregates with ilmenite and perovskite; spinel inclusions in olivine, ilmenite, perovskite and phlogopite. Groundmass spinel usually occurs as euhedral zoned grains from 5 to 150 μ m (Fig. 6). Many pipes contain zoned and homogeneous spinel grains having an atoll rim with more abundant Fe and Ti. The gaps between the core and atolls are filled with carbonate and (or) serpentine. In the zoned spinel grains the central part is usually occupied by chromite; the intermediate zone is composed of ulvospinel or titanomagnetite; the rim is formed by titanomagnetite (Fig. 7). Al-spinel was detected in the titanomagnetite rims in the aphyric kimberlite of Udachnaya-east pipe at high density of monticellite and the complete absence of phlogopite in

Extended Abstract



groundmass (Fig. 6D-pln). Virtually all zoned groundmass spinel belongs to the magnesium-ulvospinel-magnetite trend (MUM by Mitchell, 1986). Spinel of Mg-kimberlite is distinguished by higher chromium. Spinel from KB of many pipes hosts no ulvospinel and titanomagnetite. The spinel inclusions in olivine are factually high-chromium and magnesium chromites, rarely ulvospinel and Ti-magnetite. Spinel inclusions in perovskites of Zarnitsa pipe bear more magnesium and chromium than of spinel in ilmenite and phlogopite.

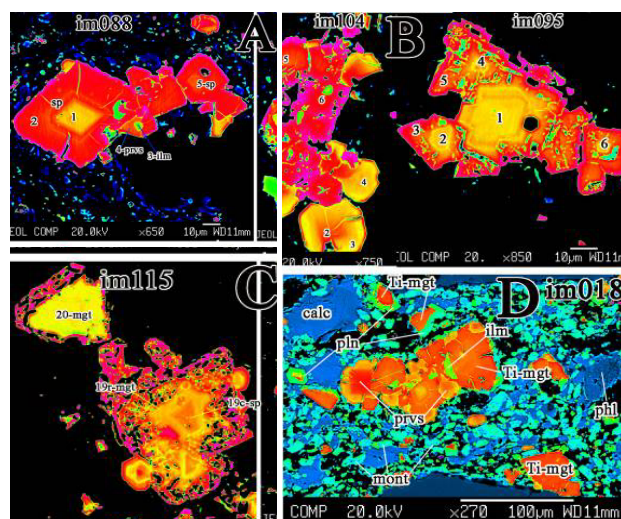


Fig. 6. Groundmass sp from pipe Ydachnaya-east (BSE images). A- PK, B- rich- xenolith KB, C- poor-xenolith KB, D- aphyric kimberlite.

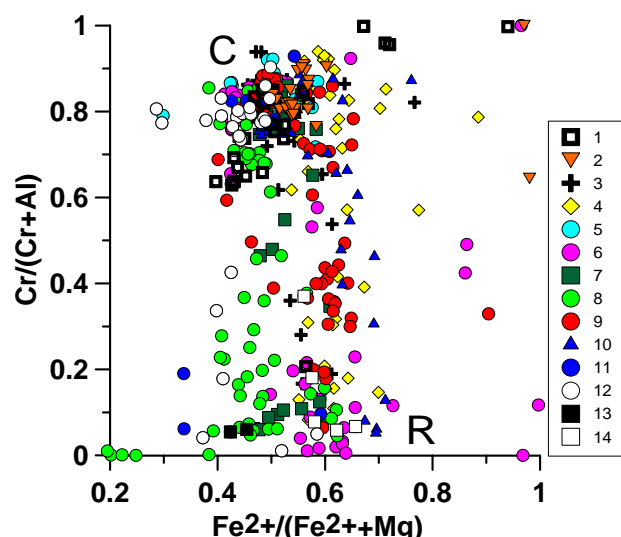


Fig. 7. Composition of groundmass spinel from kimberlite. 1- Sitykanskaya, 2- 23 KPSS, 3- Komsomolskaya, 4- Mir, 5- Internatsionalnaya, 6- Zarnitsa, 7- Udachnaya-west, 8- Udachnaya-east, 9- Aykhal, 10- Yubileynaya, 11-

Zapolarnaya, 12- spinel inclusions in olivine (Internatsionalnaya, Udachnaya), 13- spinel inclusions in ilmenite and phlogopite (Zarnitsa), 14- spinel inclusions in perovskite (Zarnitsa). C-cores, R-rims.

Perovskite. Perovskite often occurs as aggregates with spinel, marking the co-crystallization (Fig. 8). Groundmass perovskite occurs mostly in PK. Perovskite from KB Sytykanskaya and Zarnitsa pipes differs from the rest by the skeletal forms of growth (Fig. 8B) and the presence of Ti-magnetite rims around perovskite. In Mg-kimberlites perovskite has not been detected. All studied perovskites are zoned. Content of LREE in perovskites are reduced mostly, and CaO increases from core to rim grains. Zoning can be cyclical in nature with rhythmic alternation of layers in respect of major oxides (Fig. 8B).

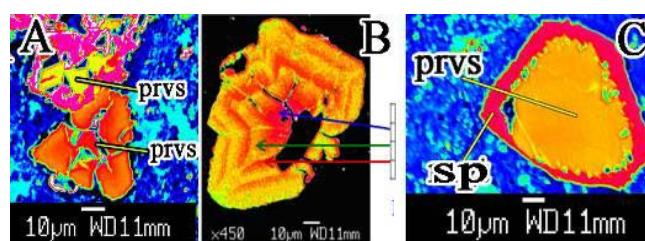


Fig. 8. Groundmass prvs in kimberlite Zarnitsa (BSE images). A- PK (in autholite), B- rich- xenolith KB, C- poor-xenolith KB.

Phlogopite. Phl is characterized by high Mg, relatively high Ti, but low chromium. Phl rims with high content of BaO in the rims (3-12 wt.%) occurs only in porphyry kimberlite in many explored pipes (Fig. 10A). Considering the TiO₂ abundance the groundmass phlogopite can be divided into two groups (Fig. 9B): (I) low-Ti (<2 wt.% TiO₂) and (II) high-Ti (from 2 to 4 wt.% TiO₂), basically corresponding to Mg and Mg-Fe types of kimberlite

The zoned groundmass phlogopite is distinguished by increasing BaO and Al₂O₃ in the marginal parts, with slightly decreasing TiO₂, K₂O and FeO. The central parts of phlogopite are generally more titaniferous and potassic than the rims.

Apatite. Groundmass apatite is more common in groundmass KB of Zarnitsa, Mir, Komsomolskaya pipes and in Mg-kimberlites. In some kimberlites apatite gather round the older minerals (spinel, phlogopite, calcite), forms atolls and radial sprays of acicular crystals. Apatites from Mg-kimberlites have the highest content of REE (up to 0.9 wt.% Ce₂O₃, up to 0.6 La₂O₃, as well as lower fluorine content.

Calcite. Groundmass calcite forms small xenomorphic grains, in places together with serpentine it is involved in the pseudomorphs after olivine and rarely forms "microliths"

Extended Abstract



(primary prismatic flow-aligned crystals (Mitchell, 1986). The distribution of calcite in groundmass is extremely irregular within any kimberlite pipe (Fig. 10). Calcite “microliths” are widespread in Mg-kimberlites, and in some kimberlites they produce the flow structure (23 KPSS and Zarnitsa pipes). The groundmass calcite displays wide content variations of trace elements, e.g. Sr and Ba. The highest concentrations of these elements are measured in calcite “microliths” (BaO up to 0.16 wt% and SrO up to 0.98 wt%) indicating their magmatic origin. Groundmass dolomite occurs in addition to the dominant calcite. In poorly-serpentinized PK of Internatsionalnaya and Mir pipes carbonate was found with MgO reaching 21 wt.%. In KB the MgO content in the calcite is about 2 wt.%.

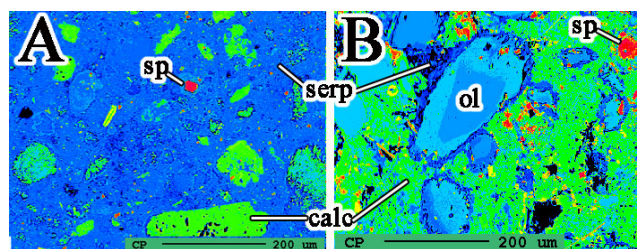


Fig. 10. Back-scattered electron images of Internatsionalnaya. A - PK; B - rich-xenolith KB.

Conclusions

Composition of groundmass minerals and their chemistry is related to petrochemical type kimberlites and depends on the structural and textural features of rocks, as well as the intensity of secondary processes. In the magnesian kimberlite groundmass there are high contents of primary calcite, high-Cr spinel, low-Ti phlogopite and LREE-enriched apatite, as well as extremely low picroilmenite and totally lacking perovskite. The Mg-Fe kimberlites are marked by widespread picroilmenite, Ti-magnetite, perovskite (including magnetite and perovskite aggregates) and high-Ti phlogopite. There are significant differences in the compositions of groundmass minerals from different structural and textural types of kimberlite. The groundmass of kimberlite breccia is featured by: high-Cr low-Ti spinel domination, mostly common for atoll structures, and possible skeletal perovskite growth. The porphyritic kimberlites typically incorporate zonal spinel, more Fo spinel cores (in comparison with spinel of kimberlite breccia) and high-BaO phlogopite in the rims.

The formation of groundmass get started with crystallization of euhedral olivine, phlogopite and spinel at $P=1.0$ GPa and $T=1030-1170^{\circ}\text{C}$ (Fedortchouk et al., 2004) and was completed by low-temperature serpentine and magnetite recrystallization. It is noteworthy, that most of groundmass minerals are characterized by wide composition variations, zoning, local heterogeneity, grain resorption and deuteric replacement. Different composition of groundmass olivine cores is possibly due to the heterogeneous composition of the primary kimberlite melt.

Different composition of groundmass olivine core is possibly due to the heterogeneous composition of the primary kimberlite melt (Reid et al., 1975; Boyd & Clement, 1977; Skinner, 1989; Kamenetsky et al., 2007; Mitchell, 2008; Brett et al., 2009). The marginal parts of olivine rims with constant Fo have crystallized in a relatively narrow temperature range at the constant ratio of Mg/Fe in the melt-fluid saturated with olivine and carbonate (Mitchell, 1986; Kamenetsky et al., 2007) or have formed under the metasomatic effect of residual kimberlite melt on the olivine phenocrysts at the final stage of kimberlite emplacement (Kostrovitsky, 1986). Very low

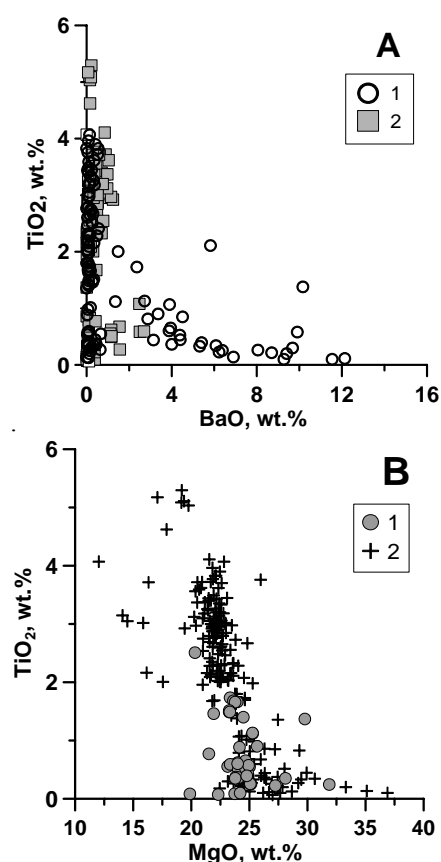


Рис. 9. Composition of groundmass phl. A: 1- PK, 2- KB. B: 1- Mg-kimberlite, 2- Mg-Fe-kimberlite.

Extended Abstract



10th International Kimberlite Conference-2012

content of NiO in olivine (<0.1-0.2%) is possibly an evidence of significant metasomatic processes, which proceeded deeper than in the grain rims. The uncommon inclusions of low-Cr high-Ti spinel in groundmass olivine rims (Udachnaya-east, Internatsionalnaya), as well as ol-prvs-sp aggregates indicate the olivine crystallization under near-surface conditions.

The inclusions of diopside in monticellite are interesting in terms of mutual exclusion of monticellite and diopside in kimberlites (Mitchell, 1998). Importantly, that the groundmass spinel composition ranges widely from chromite to pleonaste.

Importantly, that the groundmass spinel composition ranges widely from chromite to pleonaste. The atoll-spinel formation is still debatable (Reid et al., 1975, Mitchell & Clark, 1976, Agee et al., 1982, Pasteris, 1983, Armstrong et al., 1997, O'Brien et al., 1999). The atoll spinel is mostly typical for KB (Fig. 6 B, C) and uncommon for massive porphyry varieties (Fig. 6A, D). Quite the contrary, zoned spinel is much more common in PK, whereas ulvoshpnel and Ti-magnetite prevail in the rims. Thus, the xenolith-rich country rock in kimberlite melt was capable to promote spinel rapid growth, which is confirmed by the lack of Ti-rich, Cr-poor varieties of spinel in KB. In any case, the complex atoll rim formation is due to a combination of factors that mainly result from the rapidly changing conditions being far from equilibrium.

The oxygen fugacity (fO_2) during the emplacement of kimberlites was estimated from the Fe and Nb contents in perovskite (Bellis & Canil, 2006). Some kimberlites show that higher fO_2 values correlate with lower diamondiferous.

The high-BaO (3-12 wt.%) in phlogopite rims is common only for PK, where the country rock xenoliths are absent. This fact indicates that the BaO source is not associated with assimilation of carbonate host rocks. So, it can be assumed that growth of barium rims is associated with groundmass calcite recrystallization, with hot fluids effect involved. There is a positive correlation between groundmass apatite and calcite content in kimberlite. It is believed that apatite precipitates from the melt simultaneously with calcite (Mitchell, 1986).

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Extended Abstract



10th International Kimberlite Conference-2012

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Extended Abstract

