

Geochemistry of Garnet Megacrysts from the Mir Kimberlite Pipe (Yakutia) and the Nature of Protokimberlite Melts

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Abstract—The chemical compositions of garnets from a megacryst association of the Mir kimberlite pipe have been studied. By petrogenetic elements, the garnet megacrysts can be classified as high-Ti and low-Cr pyrope. The megacryst TiO_2 contents of the Mir pipe correlate inversely with the MgO and Cr_2O_3 contents. Modeling of the composition of garnets through a fractional crystallization process showed that the most suitable composition of the melts parental for the garnets of the megacryst association is picrite. The composition of garnets crystallized from the kimberlite does not correspond to the composition of the natural garnets from the Mir pipe. The kimberlites contain less Ti, Zr, Y, and HREEs, but are more enriched with strongly incompatible elements (LREEs, Th, U, Nb, Ta, and Ba) than the model composition of the melt suitable for crystallization of the garnet megacrysts.

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The association of discrete xenocrystals of mantle minerals is typical for all kimberlites and, in particular, is a substantial component of the Mir pipe kimberlites. The most common minerals of the megacryst association are garnet, picroilmenite, and olivine. The garnets of the megacryst association typically have increased TiO_2 , which depends on both the composition of the medium and the formation temperature. For ilmenite of this association, admixtures of Cr_2O_3 and Al_2O_3 are typical. In most kimberlite bodies, megacrysts of one or several minerals of the clinopyroxene \pm orthopyroxene \pm phlogopite \pm zircon association may also be present. Despite the large number of works devoted to the origin of minerals of the megacryst association as a whole, and garnet in particular, the nature of their parent melts and details of the crystallization process remain a controversial issue. There are two main points of view on the nature of the parental melt. Some researchers [1] suggest crystallization of the megacrysts directly from the kimberlite magma. Another point of view assumes that the association of low-Cr megacrysts is a product of crystallization of magma of the asthenospheric oceanic

island-type basalts at high PT parameters in the lower horizons of the lithospheric mantle [2–4]. Such conclusions were obtained on the basis of calculations of fractional crystallization [2] considering compositions of REEs of megacrysts, as well as from isotopic data [3, 5]. The isotopic compositions of the kimberlites and the megacrysts are similar, so the original magma for the megacrysts and kimberlites has a common asthenospheric source [5]. The chemical compositions of garnet megacrysts from the South African kimberlites correspond to the process of fractional crystallization in a closed system [6]. A large number of garnets (2300 grains) from the South African kimberlites was studied [7], leading to the suggestion that the process may be more complex and include a peridotite matrix assimilation and hybridization. The magma from which megacrysts crystallized is also often referred to as proto-kimberlitic, suggesting that it might evolve towards kimberlite as a result of interaction with the lithospheric mantle base and assimilation of rocks enriched with incompatible elements [4]. According to the results of the study of mantle material from the Udachnaya pipe kimberlites, the compositional similarity and the likely genetic and spatial connection of garnet megacrysts and deformed peridotites were proposed [4, 5]. Therefore, the study of the geochemical and isotopic composition of megacrysts provides a unique opportunity to assess the composition of the proto-kimberlitic magma and to obtain new information about processes at the bottom of the lithospheric mantle, including kimberlite genesis.

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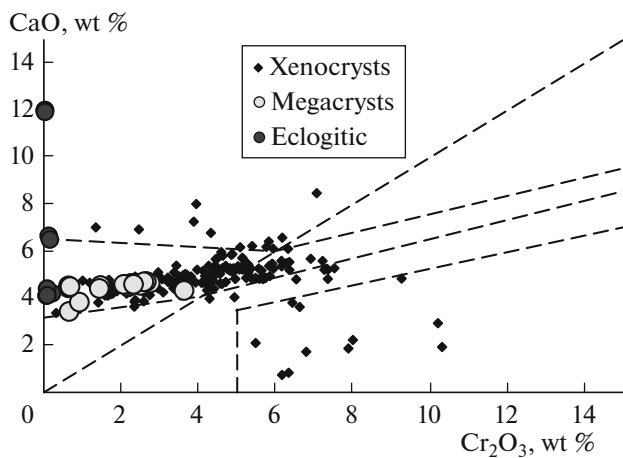


Fig. 1. Distribution of CaO–Cr₂O₃ for garnets from kimberlites of the Mir pipe.

A collection of discrete garnet grains of 5 to 10 mm in size from the Mir pipe kimberlite has been studied by us. The garnets have rounded or fragmented shapes, in the latter case being pieces of larger crystals. The color characteristics of the garnets range from dark brown to orange–yellow. Such colors are characteristic of garnets from megacryst associations, eclogite, pyroxenite, and partly deformed peridotites. Five of the twenty grains studied by chemistry belong to an eclogite paragenesis and are not considered in the further work.

By their major elements composition, the studied garnet megacrysts correspond to high titanium low chromic pyropes. The results of microprobe analyses did not reveal any significant systematic zoning in the garnet composition from center to edge. The contents of TiO₂ vary within 0.4–1.0 wt %; Cr₂O₃, 0.6–3.6 wt %. In the Cr₂O₃ vs. CaO diagram [8], the garnet compositions are localized in the low-Cr region of a lherzolite trend, which is typical of the garnets of a megacryst association (Fig. 1). Their MgO content varies from 18.9 to 21.3 wt % with (Mg# = Mg/(Mg + Fe) × 100) ranging from 75 to 82.7.

In the megacryst garnets from the Mir pipe, the TiO₂ contents have a negative correlation with the contents of MgO and Cr₂O₃ (Fig. 2). The garnet megacryst compositions from the Monastery pipe [7] correspond to the same trend with smaller variations in the TiO₂ and Cr₂O₃ and form a trend parallel to our data on the TiO₂–MgO plot.

All the garnets studied display a normal distribution pattern of chondrite-normalized [9] REEs with an even plateau in the region of heavy and medium REEs and a sharp decrease of LREEs (Fig. 3). The REE content in the Sm–Lu segment is about 10 chondritic units for MREEs and slightly higher for HREEs. The distribution pattern of PM-normalized (Primitive Mantle) incompatible elements in the garnet

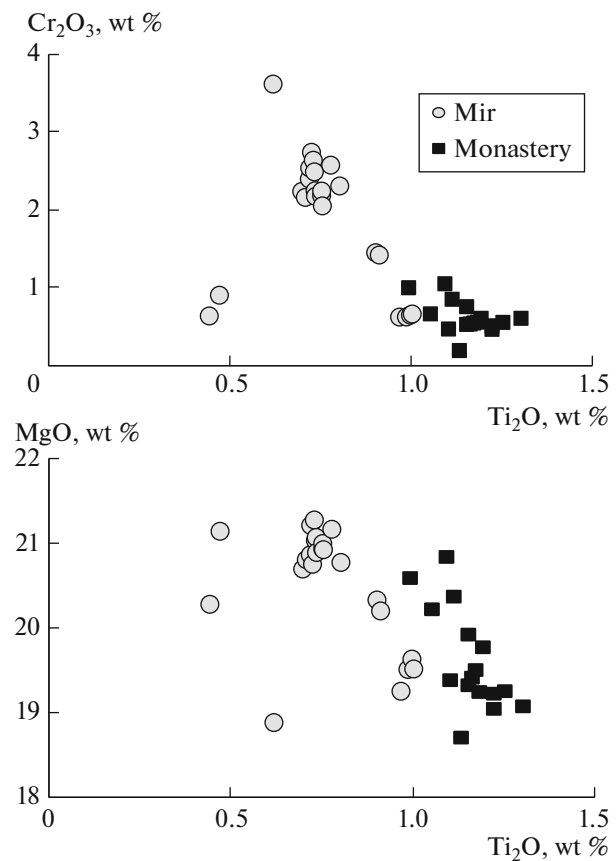


Fig. 2. Variations of the contents of TiO₂, MgO, and Cr₂O₃ in megacrysts of garnet from the Mir (Yakutia) and Monastery (South Africa) kimberlite pipes.

megacryst of the Mir pipe is almost the same in all samples in the segment of Nd–Lu, but demonstrates a large scatter of values for the most incompatible elements (Ba–Sr) (Fig. 3). Negative Ba, Sr, and La and positive Zr and Hf anomalies are clearly expressed in the distribution pattern of incompatible elements of all the garnets. Minor minima of Sm and Y are observed. The set of garnet samples from the Mir pipe shows a positive correlation of Ti, Zr, Y, and Sc vs. HREE. The nature of these correlations is discussed in detail below.

To model the composition of garnets, an approach based on the covariance of the content of elements in the process of fractional crystallization [10] was used. A positive correlation between Ti, Zr, Y, and HREEs [6, 7, 10] is always observed in samples of the megacryst association [6, 7, 10], which suggests that the latter behave as incompatible elements during the crystallization of asthenospheric melts in the lithospheric mantle. In order to reproduce the positive correlation between these elements, the total distribution coefficient (K_d) of Y between a solid and a melt for the crystallizing mineral association should not exceed 1, preferably being about 0.5 [10]. Otherwise, a negative

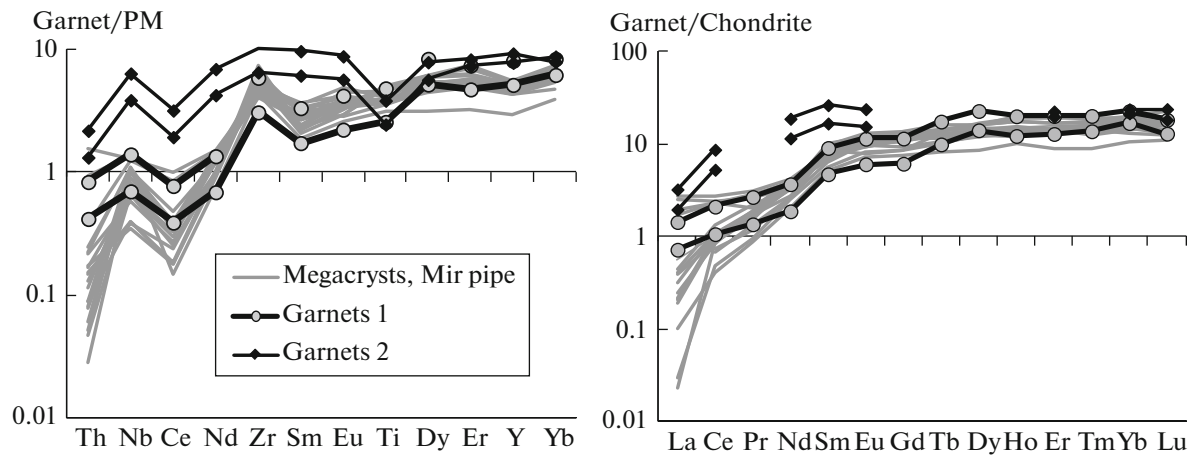


Fig. 3. Chondrite and primitive mantle [9] normalized trace and rare earth elements in megacryst garnet from Mir pipe in comparison with garnet compositions obtained in the modeling of fractional crystallization. Garnets 1 come from a melt of picrite composition, and garnets 2 come from a melt of the Mir pipe kimberlite composition.

correlation will be observed between Y, HREEs, and Zr. Most of the Kd (Y) mineral/melt values given in the literature for garnet [10] are too high (2–8) and inapplicable for modeling the fractional crystallization of garnet in the lithospheric mantle. Therefore, to simulate the fractional crystallization of garnet in the lithospheric mantle, a set of Kd, obtained as a result of experiments at high pressures of 7 GPa, was chosen [11]. The modal composition of the crystallizing mineral association is taken as 30% garnet, 30% clinopyroxene, and 40% olivine + orthopyroxene together, since both of these minerals practically do not contain incompatible elements. Despite the fact that ilmenite is one of the most common minerals of the megacryst association, it is not used in the calculations, because its crystallization would lead to a rapid drop in the TiO_2 content in the melt. This would result in a negative correlation of Ti vs. Y and Zr, which is not observed in natural garnets. Most likely, ilmenite is formed at later stages of the process, when garnet ceases to crystallize. Various types of basic and ultrabasic rocks with an asthenospheric source were tested as primary melts: intraplate continental and oceanic basalts and kimberlites.

The modeling results demonstrated that the most suitable melt composition for crystallization of the garnets megacryst association is a picrite magma. Particularly good reproducibility of the natural compositions is observed when modeling crystallization of HIMU-type picrite from the St. Helena oceanic basalt complex [12], as well as picrite of Kerguelen Island [13]. Of the continental magmas, mejmechites of the Kotui province have a suitable composition, but with the exception of the richest Zr and Y varieties (Fig. 4). The results of calculations of picrite fractional crystallization are in good agreement with natural data both in the correlation of contents of Y, Zr, and Ti in

the garnets, and in the distribution patterns of incompatible elements (Fig. 4).

For calculations of the crystallization of kimberlite melts, Kd from [14] and the compositions of the Mir pipe kimberlites were used. The kimberlites have a wide range of incompatible element concentrations, but, in general, they contain less Ti, Zr, Y, and HREEs, but more strongly incompatible elements such as LREEs, Th, U, Nb, Ta, and Ba than picrites and modeled composition for the crystallization of megacryst garnets. The results of calculations showed that the garnet composition, which crystallized from the kimberlite, does not correspond to the composition of the natural garnets from the Mir pipe (Figs. 3, 4). It should be noted that the kimberlites have low contents of Al_2O_3 , which is insufficient to crystallize a significant amount of garnet, taking into account the fact that the degree of fractional crystallization reaches 60%. It should also be considered that the initial kimberlite melt has rather a carbonatite composition [15], which also testifies against crystallization of garnets in kimberlite.

The data obtained allow us to draw conclusions about the composition and nature of parental melts for the megacryst association of the Mir pipe garnets in the framework of the two-stage model of kimberlite petrogenesis proposed earlier by the author [4, 5, 15]. The most likely primary melts for the megacryst association are asthenospheric melts of picritic composition with Y and Zr contents of the 15–20 ppm and 180–220 ppm range, respectively. The emplacement of the asthenospheric melts resulted in the formation of a reservoir enriched with incompatible elements at the base of the lithospheric mantle, heterogeneous in composition on a scale of a first kilometers. This was accompanied by a silicate metasomatism of a peridotite substrate, fractional crystallization of the megacrysts with their removal from the system, and

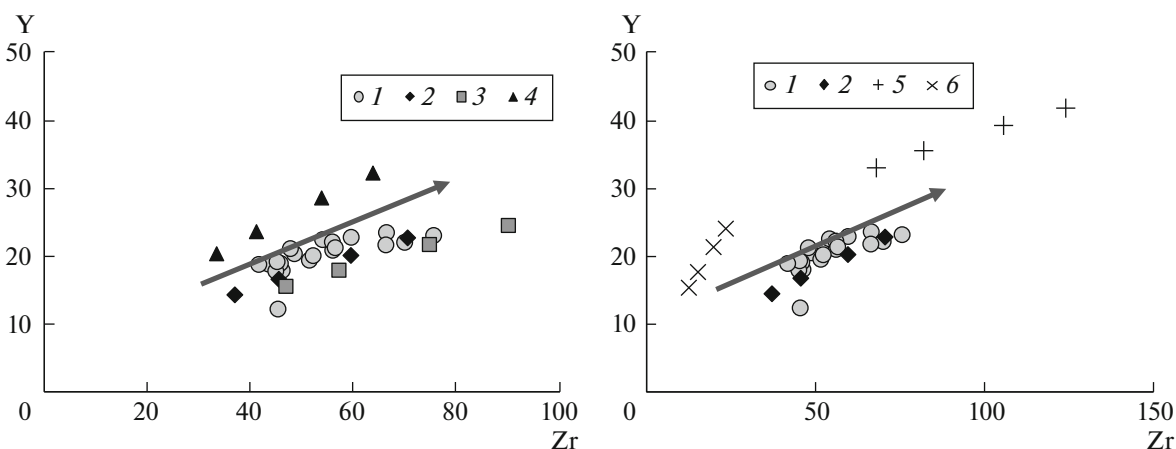


Fig. 4. Y vs. Zr diagram in megacrysts of garnet from kimberlite of Mir pipe, compared with the compositions of garnets obtained in modeled fractional crystallization. 1, Mir pipe megacrysts; (2–6) Model compositions of garnets from the following types of melts: 2, picrites of Kerguelen Is.; 3, Kotui meimechites; 4, picrites of the HIMU type, Saint Helena Island; 5, kimberlite Mir pipe., Kd from [14]; 6, kimberlite Mir pipe, Kd from [11]. The calculated compositions correspond to the degrees of fractional crystallization of 1, 20, 40, and 50% with increasing concentrations of Y and Zr.

formation of residual magmas enriched in volatile and incompatible elements. These mobile residual melts penetrated into the peridotite matrix and formed a mainly carbonatite metasomatic halo around the foci of intrusion of the asthenospheric melts. Subsequently, the enriched reservoir heating up to a temperature slightly higher than the solidus of carbonatized peridotite initiated the melting out of the actual kimberlites.

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