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SHORT COMMUNICATIONS

Petrological Features of Olivine–Phlogopite Lamproites of the Sayan Region: Evidence from Sr–Nd Isotope and ICP-MS Trace-Element Data

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INTRODUCTION

The only occurrence of Middle Riphean diamondiferous magmatism in the Siberian Craton is the diamondiferous lamproites of the Sayan region, which are located in the Ingashi River basin, a right tributary of the Oka River, in its middle reaches. The lamproites form a series of vein bodies and together with local halos of indicator minerals compose the Ingashi lamproite field, ~30 km long and 5–8 km wide (Fig. 1).

The diamond potential of the Sayan region lamproites was first established in 1960–1964 by geologists from the Nizhnyaya Uda expedition, TGF IGU. Eight diamond crystals with a total mass of 28.9 mg were found during the small-volume sampling (15 samples 30.8 m^3 in total volume) of weathered residues of lamproite bodies. Six crystals were found in the Iskra lamproite vein and two crystals, in the Bilyunik vein. One 1.2-mg diamond was extracted from a crushed lamproite sample (1 kg in weight) from the Iskra vein. The diamonds are mainly deformed crystals or fragments of rhombododecahedra; there are also flattened rhombododecahedra, intergrown octahedra with well-shaped convex faces covered by ditrigonal growth layers. They are mainly colorless, and occasionally brownish.

The lamproite veins of the Sayan region are confined to the central part of the Urik–Iya graben, which is characterized by abundant diverse magmatism. Three recurrent magmatic cycles (1640 ± 100 Ma, 1268 ± 123 Ma, and 543–880 Ma) produced rocks evolving from diabases to ultramafics and lamproites at the orogenic stage and from diabases to picrite basalts and alkali ultramafics at the protoplatform stage [2]. Since 1.5 Ga, the Urik–Iya graben has existed as a stable intracratonic area. The lamproite veins of the graben are restricted to its main fault zone, which was initiated in the Middle Proterozoic during the postcollisional collapse of the orogen [1]. The fault system hosts most of the Neoproterozoic basic dikes of the Nersin Complex, which are petrological indicators of the break-up of the Rodinia supercontinent [3]. According to Yarmolyuk and Kovalenko [3, 4], the lamproite bodies of the Sayan region can be regarded as indicators of the earliest stages of the supercontinent break-up in the Middle Riphean along the boundary zone between Laurentia and Siberia.

The petrographic, mineralogical, and petrochemical characteristics of the diamondiferous lamproites were described in detail elsewhere [5, 6].

METHODS AND MATERIALS

The paper presents the first precise geochemical (ICP-MS) and isotopic (Sr–Nd) data on the lamproite bodies of the Sayan region. Whole-rock lamproite samples were preliminarily purified from xenoliths and xenocrysts of the country and metamorphic rocks under a binocular microscope. Trace-element contents were determined by ICP-MS using standard techniques at the Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, with a measurement accuracy of no less than 10% for contents >1 ppm and no less than 15–20% for contents of 1.0–0.1 ppm.

The Nd isotopic compositions and Sm and Nd concentrations were measured on a Finnigan MAT 261 eight-channel mass spectrometer in static mode at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. Sm and Nd were extracted following the technique described in [7]. The laboratory blanks were 0.03–0.2 ng Sm and 0.1–0.5 ng Nd. The measured $^{143}Nd/^{144}Nd$ ratio was normalized to $^{146}Nd/^{144}Nd = 0.7219$ and brought to $^{143}Nd/^{144}Nd = 0.511860$ in the La Jolla Nd standard. The measurement accuracies were ±0.5% (2σ) for Sm and Nd concentrations, ±0.5% for $^{147}Sm/^{144}Nd$, and ±0.005% for

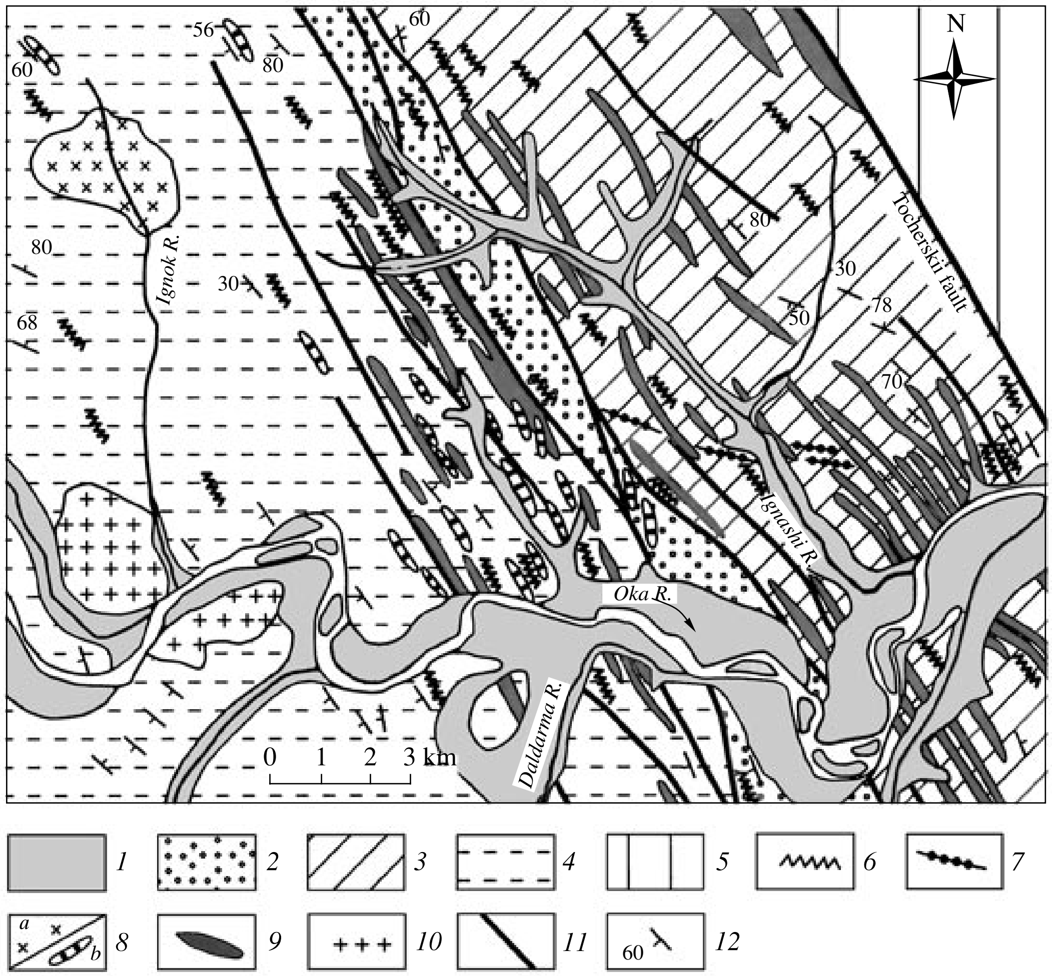

Fig. 1. Geological sketch map of the central part of the Urik–Iya graben (Ingashi–Ignok divide) according to [1]. (*1*) Quaternary alluvial deposits; (*2*) deposits of the Ermasokhin Formation (Early Riphean); (*3*) undifferentiated deposits of the Urik and Ingashi formations (Early Proterozoic); (*4*) undifferentiated deposits of the Bol'shaya Rechka and Daldarma formations (Early Proterozoic); (*5*) Early Precambrian complexes of the Sharyzhalgai inlier of the basement of the Siberian craton; (*6–10*) intrusive complexes: (*6*) gabbrodolerites of the Nersin Complex (Late Riphean), (*7*) lamproites (Middle Riphean), (*8*) (*a*) massifs and (*b*) large dike bodies of granitoids of the Chernaya Zima Complex (Early Riphean), (*9*) gabbrodiabases of the Angaul Complex (Early Riphean); (*10*) granitoids of the Sayan Complex (Early Proterozoic); (*11*) fault; and (*12*) dip and strike of bedding.

$^{143}Nd/^{144}Nd$. Nine replicate measurements of $^{143}Nd/^{144}Nd$ in the La Jolla Nd standard averaged 0.511842 ± 8 (2σ). The $\varepsilon_{Nd}(T)$ values were calculated using present-day values for the chondrite reservoir (CHUR) $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$ [8]. Model ages, $T_{Nd}(DM)$, were calculated in accordance with model [9], assuming a linear evolution of Nd isotopic composition of the depleted mantle since 4.5 Ga up to the present-day value $\varepsilon_{Nd}(0) = +10$ ($^{143}Nd/^{144}Nd = 0.513151$ and $^{147}Sm/^{144}Nd = 0.2136$).

The Sr isotopic composition and Rb and Sr contents were analyzed on a Finnigan MAT 262 mass spectrometer at the Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences following the technique of [10].

We studied lamproites from the Pravoberezhnaya (sample P1/02) and Iskra (sample I2/02) veinlike bodies. Sample P1/02 is a carbonatized olivine–phlogopite lamproite. The groundmass is made up of serpentine–calcite pseudomorphs after olivine, phlogopite laths, high-Mn ilmenite, Cr-spinel, Ti-magnetite, perovskite, and a microcrystalline chlorite–serpentine–calcite matrix. Sample I2/02 is a mica-rich lamproite with an altered groundmass consisting of phlogopite laths, pargasite, K-magnesioarfvedsonite, Nb rutile, Cr-spinel, baotite, armalcolite, and priderite. The geochemical characteristics of more altered lamproites from the Bilyunik vein were also studied.

RESULTS AND DISCUSSION

Figure 2 shows primitive mantle-normalized incompatible element patterns for the lamproites of the Sayan

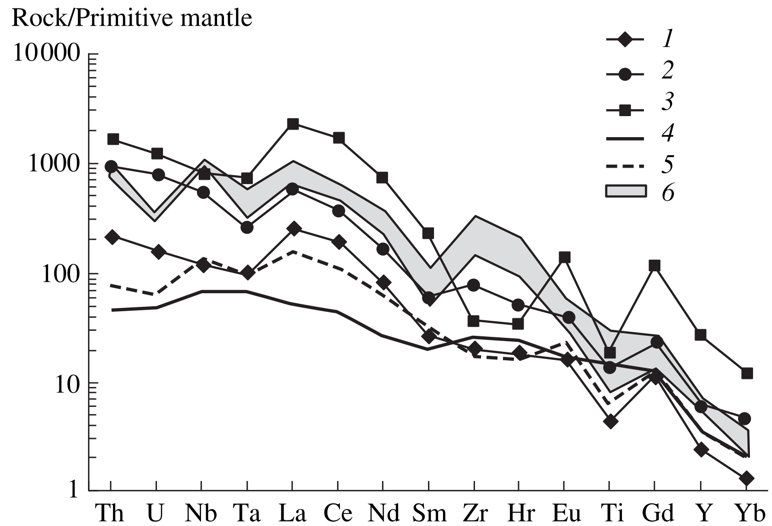

Fig. 2. Incompatible element distribution patterns for the lamproites of the Sayan region: (*1*) Pravoberezhnaya vein, (*2*) Iskra vein, (*3*) Bilyunik vein, (*4*) ocean island basalts [11], (*5*) olivine lamproites of the Kola craton [13], and (*6*) lamproites of Australia [12].

region compared with lamproites from Australia [12], the Kola Peninsula [13], and ocean island basalts [11]. The lamproite veins of the Sayan region show uniform distribution patterns of the indicator incompatible elements. This suggests that the veins were related to a common parental melt. The distribution of trace elements in various lamproite veins can reflect mantle and crustal contamination, complicated in some cases by magmatic differentiation. The rocks show negative anomalies of Nb, Ta, and Ti, as well as depletion in Zr and Hf relative to rare earth elements, which is typical of the Late Devonian olivine lamproites from the eastern margin of the Archean Kola craton [13]. The latter are considered as derivatives of melts generated by the influence of an ascending plume on the enriched lithospheric mantle. The negative anomalies of HFSE relative to the rare earth elements are usually explained by the enrichment of deep-seated melt sources in aqueous or carbonate fluids [14]. In contrast to the lamproites of the Sayan region and Kola craton, the Late Proterozoic and Miocene olivine and leucite lamproites of Australia display significant positive anomalies in Zr and Hf (Fig. 2), which are usually considered as geochemical peculiarities of the source region [12].

The isotopic geochemical data for samples P1/02 and I2/02 are given in the table. In the diagram of $\varepsilon_{Nd}T$ versus initial $^{87}Sr/^{86}Sr$, these samples plot within the field of enriched mantle EM-1 (P1/02) and between the fields of the EM-1 and EM-2 mantle sources (I2/02), near the isotopic compositions of batholiths corresponding to the ancient continental crust [15]. The elevated $\varepsilon_{Nd}T$ and I_0Sr values in lamproite I2/02 suggest a possible contamination of the melts by the Precambrian continental crust. In terms of Nd and Sr isotopic composition, the lamproites of the Sayan region are similar to lamproites from west Greenland, the western USA, and Central Aldan, and the potassic ultramafic rocks from the northern Eastern European Platform.

Based on geochemical and isotope-geochemical data, the lamproites of the Sayan region can be ascribed to the Laurasian group of lamproites and kimberlites [16]. They differ from the Group II kimberlites of southern Africa and lamproites of west Australia (Gondwana group) in the nature of the mantle source (EM2-type enriched mantle).

Figure 3 shows the Nd isotopic evolution of lamproites from the Sayan region and Kostomuksha and

Nd and Sr isotopic composition of the lamproites of the Sayan region

Sample	Age, Ma	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2S	$(^{143}Nd/^{144}Nd)_0$	ε_{Nd} (0)
P1/02	1200	12.22	117.1	0.0631	0.511077	5	0.510580	–30.5
I2/02	1200	7.48	36.1	0.1251	0.511881	4	0.510895	–14.8
Sample	ε_{Nd} (T)	T_{Nd} (DM), Ma	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2S	$(^{87}Sr/^{86}Sr)_0$
P1/02	–10.1	2091	48.92	658.34	0.21277	0.70813	5	0.70451
I2/02	–3.9	2177	113.70	924.69	0.35320	0.70824	4	0.70614

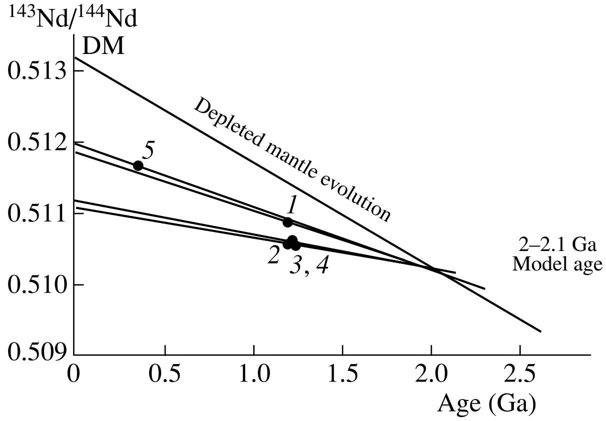

Fig. 3. Nd isotope composition versus rock age. (*1, 2*) lamproites of the Sayan region, samples I2/02 and P1/02, respectively; (*3, 4*) lamproites of Kostomuksha [17]; and (*5*) melilitite of the Arkhangel'sk diamondiferous province [17].

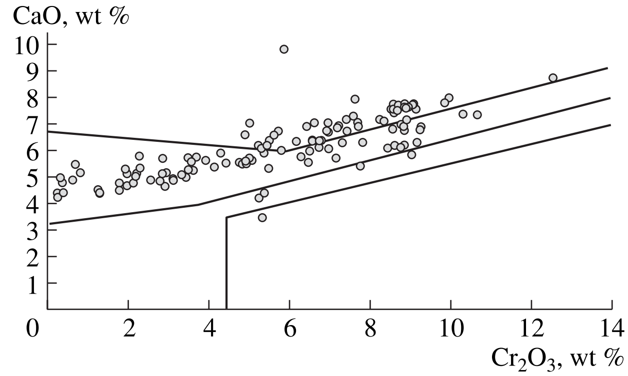

Fig. 4. Compositions of pyropes from the Iskra lamproite vein in the Cr_2O_3–CaO diagram (n = 131).

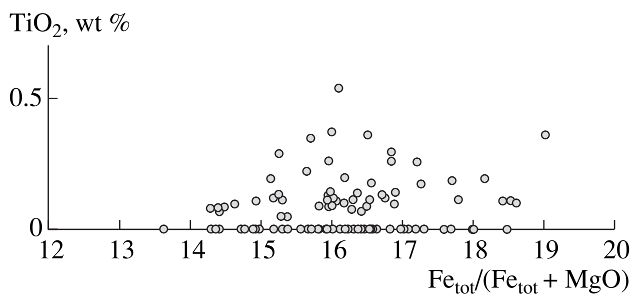

Fig. 5. Compositions of pyropes from the Iskra lamproite vein in the TiO_2–f diagram (n = 131).

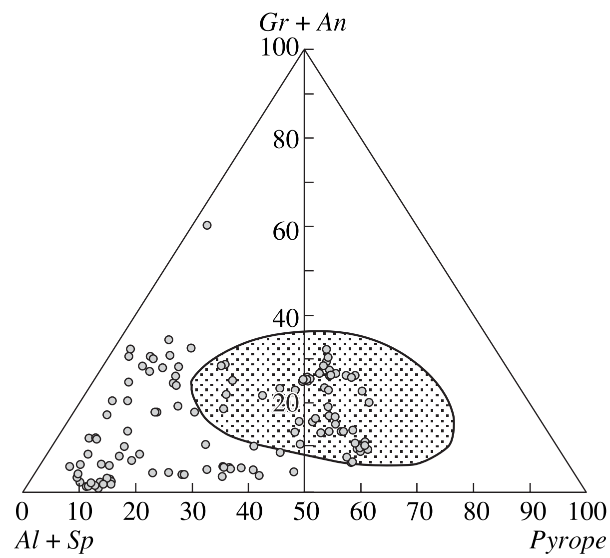

Fig. 6. Component compositions of pyrope–almandine garnets from the Iskra lamproite vein (n = 132). The shaded field includes garnets from eclogite nodules in kimberlite pipes.

melilitites from the Arkhangelsk diamondiferous province. These rocks have similar $\varepsilon_{Nd}T$ and I_0Sr values testifying to a melt generation from the EM-1 mantle source affected by an ancient enrichment event (~2.0 Ga). Lamproite sample I2/02 falls on the evolution curve of the protolith of melilitites from the Arkhangelsk diamondiferous province, and lamproite sample P1/02 plots near the trend of the Kostomuksha lamproites [17]. The model age of lamproites from the Sayan region (2.0–2.1 Ga) coincides with the age of accretion, granulite metamorphism, and granite formation in the Archean and Early Proterozoic terranes of the southern margin of the Siberian craton [18]. The negative $\varepsilon_{Nd}T$ values, low positive I_0Sr values, and negative Ti–Nb–Ta anomalies in the incompatible element distribution patterns of the Sayan region lamproites imply metasomatic alteration of the EM-1 source under the action of fluid released during the dehydration of blocks of the ancient subducted crust [16].

It should be noted that in terms of the association of high-pressure minerals, the lamproites of the Sayan region resemble the anomalous ultradeep kimberlites of the Nakyn field, Yakutia [19], which show trace-element and REE characteristics suggesting a weakly enriched source of the EM-1 type [20]. The lamproites of the Sayan region are poor in diamond indicator minerals (100–150 g/t), rich in Cr-spinel, and free of picroilmenite.

In the CaO–Cr_2O_3 diagram (Fig. 4), randomly selected pyrope analyses (131 from 714 grains) from the Iskra lamproite vein fall within the field of lherzolitic garnets. A few pyrope analyses correspond to subcalcic garnets of the dunite–harzburgite paragenesis (including diamondiferous assemblages). The garnets

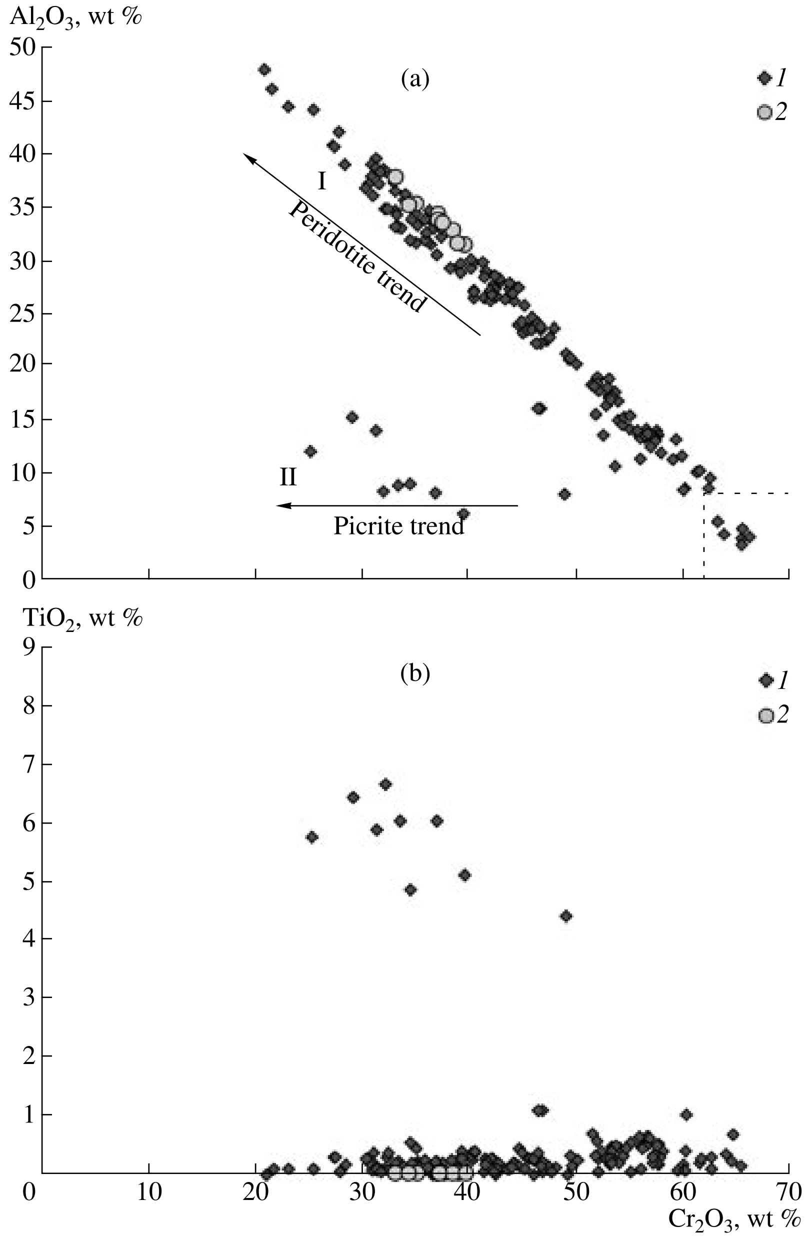

Fig. 7. Compositions of Cr-spinels from the Iskra lamproite pipe in the (a) Cr_2O_3–Al_2O_3 and (b) Cr_2O_3–TiO_2 diagrams (n = 168). (*1*) Phenocrysts and (*2*) graphic lamellae in high-Cr diopside.

of the ultarmafic paragenesis from the lamproites have relatively low TiO_2 contents (up to 0.5 wt %) and moderate $Fe_{tot}/(Fe_{tot} + Mg)$ ratios of ~16.5%, indicating the absence of pyropes of ilmenite-bearing assemblages. The lamproites are characterized by a sharp predominance of eclogitic garnets (Fig. 6) (about 80%) over peridotitic garnets (<20%).

The compositional fields of Cr-spinel from the Iskra lamproite vein are shown in the Cr_2O_3–Al_2O_3 and Cr_2O_3–TiO_2 diagrams (Figs. 7a, 7b). A small fraction of Cr-spinel compositions fall within the field of chromites of the diamond association. In addition, peculiar intergrowths of Cr-diopside and Cr-spinel with a graphic texture and sizes of 3–4, occasionally up to 5–6 mm were found in the Iskra lamproite vein. The content of regularly oriented graphic chromite grains in pyroxene is 10–20%. Chromite from the graphic intergrowths shows a rather uniform composition (Fig. 7). The host pyroxene matrix shows minor compositional variations and has a lower Cr_2O_3 content and lower Fe/(Fe + Mg) ratio relative to clinopyroxene phenocrysts (Fig. 8). Graphic intergrowths of Cr-spinel in Cr-diopside could be exsolved from anomalous Cr- and Ca-rich pyropes or clinopyroxenes enriched in Ca, Al,

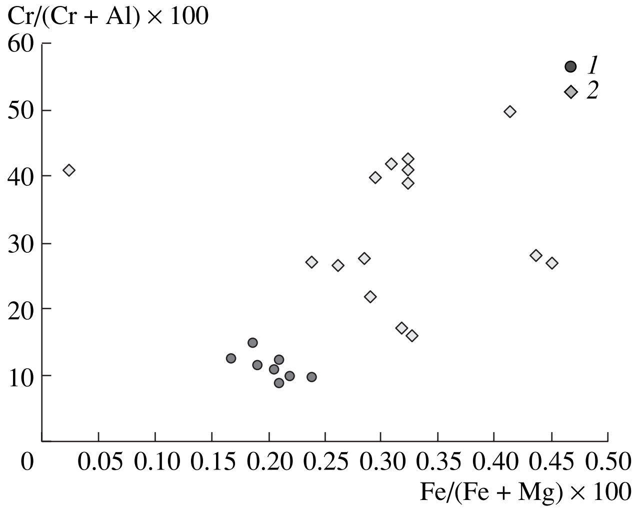

Fig. 8. Cr-diopsides and high-Cr diopsides with chromite lamellae from the Iskra lamproite vein in the Cr/(Cr + Al)–Fe/(Fe + Mg) diagram. (*1*) Diopsides with chromite lamellae and (*2*) phenocrysts of Cr-diopside.

and Cr or produced by the interaction between garnet and olivine [21].

The association and chemical systematics of high-pressure minerals indicate that the mantle protolith of the lamproites of the Sayan region contained abundant eclogites and was free of ilmenite-bearing peridotites. The lamproites of the Sayan region sampled a very minor amount of diamondiferous dunites and harzburgites from the mantle section. The proportion of ultramafic and eclogitic materials in the protolith significantly affects the SiO_2 content of mantle-derived magmatic melts [22]. According to [19], the almost complete absence of magnesian ilmenite in the kimberlites of the Nakyn field is explained by the weak metasomatic reworking of the mantle lithosphere or a deeper position of the transitional zone between the lithosphere and asthenosphere in the Middle Markha diamondiferous area.

CONCLUSIONS

(1) In terms of incompatible element distribution patterns (negative Ti–Nb–Ta anomalies and depletion in Zr and Hf relative to REE), the lamproites of the Sayan region are most similar to the Late Devonian olivine lamproites of the northern Eastern European platform.

(2) The Sr–Nd isotopic compositions of lamproites from the Sayan region suggest that they were derived from slightly enriched EM-1 mantle. An increase in $\varepsilon_{Nd}T$ and I_0Sr in the lamproite of the Iskra vein is related to the contribution of crustal materials. Based on Nd and Sr isotopic compositions, the lamproites of the Sayan region belong to the Laurasian groups of kimberlites, lamproites, and related rocks. The enrichment of the mantle source of the Sayan lamproites was presumably caused by fluids released during the dehydration of the ancient subducted crust.

(3) The model age of the enrichment of the mantle source of the Sayan region lamproites, T(Nd)DM, is 2–2.1 Ga, which coincides with that of collision between Archean and Early Proterozoic terranes in the southern margin of the Siberian craton.

(4) The association and chemical systematics of high-pressure minerals in the lamproites of the Sayan region indicate that their mantle sources contained abundant eclogites and were free of ilmenite-bearing peridotites.

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