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Olivines of Igneous Rocks

N. A. Krivolutskaya[a] and N. I. Bryanchaninova[b]

[a] *Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 119991 Russia
e-mail: nakriv@mail.ru*

[b] *Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia
e-mail: ni@igem.ru*

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Abstract—Olivine is one of the most widespread minerals on the Earth, being the main component of the mantle in accordance with existing views. Olivine undergoes only minor alterations in going down to the depth of 350 km, but at deeper levels it can be transformed to β-modification (wadsleite) and, at the depth of 520 km, further to γ-modification (ringwoodite). Olivine occurs either as the main or auxiliary mineral for crust rocks (ultrabasites, basites, and kimberlites) and also as accessory mineral in acidic rocks. Depending on its genesis olivine contains isomorphous impurities of Cr, Ni, Ti, Mn, Ca, Co, etc. The composition of olivine and igneous inclusions entrapped during its growth constitutes important diagnostic criteria which identify the genesis of ore deposits. Regular variations of the content of basic end-members (forsterite and fayalite) and the availability and abundance of impurity elements make them suitable as indicators of ore formation process for various deposits. This point was exemplified by chromite-bearing massifs of the Polar Urals and platinum-copper-nickel deposits of Norilsk Ore Region. Olivine is commonly used as natural fireproof raw material.

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INTRODUCTION

Olivine is a variable-composition mineral which is commonly represented by the formula $(Mg,Fe)_2[SiO_4]$; it crystallizes in the rhombic system and owes its name to the olive-green color. Along with the basic end-members, magnesial forsterite (Fo) and ferrous fayalite (Fa), it also invariably contains a minor amount of manganese tephroite end-member. Minerals characterized by significant levels of all the three components have a rare occurrence, which is also true of forsterite-tephroite intermediate-composition compounds. The fayalite-tephroite series compounds are somewhat more frequent, and the most abundant ones are intermediate-composition members of the forsterite-fayalite series, sometimes referred to as hortonolites (which is an outdated term) but most often simply called olivines. A characteristic isomorphous impurity occurring in olivine in amounts no larger than several tenth of one per cent is nickel. The discovery in South Africa of nickel olivine liebenbergite $(Ni_{1.52}Mg_{0.33}\cdot Fe_{0.10}Co_{0.05})[SiO_4]$ in 1973 has brought a new, nickel, end-member into the olivine group.

Modern mineralogical classification [1, 2] attributes to the olivine group eight minerals which are members of either the olivine subgroup (fayalite Fe_2SiO_4, forsterite Mg_2SiO_4, tephroite Mn_2SiO_4, liebenbergite Ni_2SiO_4, and calcium olivine Ca_2SiO_4) or the monticellite subgroup (glaucocroite $CaMnSiO_4$, kirchshteinite $CaFeSiO_4$, and monticellite $CaMgSiO_4$). All the above-listed minerals, except for calcium olivine, occur in nature, and liebenbergite, glaucocroite, and kirchshteinite belong to rare minerals. Liebenbergite and glaucocroite do not occur in Russia, while some minerals of the monticellite-kirchshteinite series containing >50% $CaFeSiO_4$ were found in wollastonite skarns of Tazheran alkali carbonate apatite massif (West Baikal) [3].

The olivine subgroup is comprised of minerals with the general formula M_2SiO_4, and the monticellite subgroup, of those with formula $CaMSiO_4$. It should be noted that, earlier, monticellite subgroup minerals were not classed with the olivine group [3, 4]. Russian mineralogical reference books assign fayalite, forsterite, tephroite, and liebenbergite to olivine genus,

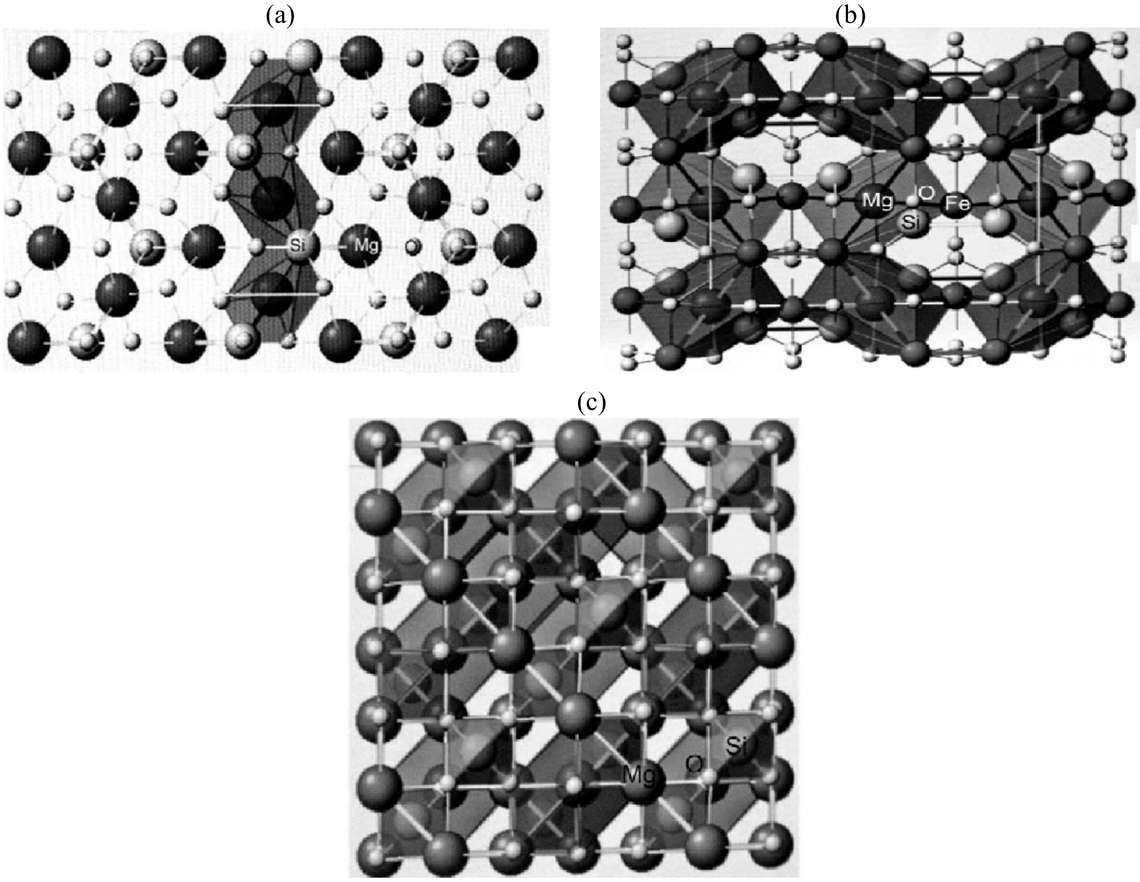

Fig. 1. Structures of (a) olivine, (b) wadsleite, and (c) ringwoodite [according to http://webmintral.com].

and monticellite, kirchshteinite, and glaucocroite, to monticellite group. The difference between genus and group consists in that minerals from the same group, by contrast to minerals of the same genus, do not form continuous solid solutions with one another. The international classification is based on subgroups, rather than on genera and groups.

Olivine is an orthosilicate comprised of independent isolated $[SiO_4]^{4-}$ tetrahedra integrated into a crystal lattice through M^{2+} cations surrounded by six oxygen ions in octahedral coordination. There are two nonequivalent octahedral cationic sites M_1 and M_2 characterized by chaotic arrangement of the Mg^{2+}, Fe^{2+}, Mn^{2+}, and Ni^{2+} cations. As to monticellite, it is structurally similar to olivine though has orderly arranged cations: $M_1 = Mg^{2+}$, Fe^{2+}, Mn^{2+}; $M_2 = Ca^{2+}$ [2].

Olivine belongs to the most widespread minerals on the Earth. Also, chondrites (stony meteorites) and pallasites (iron stony meteorites which appear as an iron-nickel sponge having its pores filled with olivine) are composed of olivine, which was detected in lunar soil as well. Olivine-enstatite stony meteorites comprise minerals related to the olivine group: cubic ringwoodite and monoclinic wadsleite which are described by the formula $(Mg,Fe)_2[SiO_4]$ [1]. Ringwoodite and wadsleite are forsterite polymorphs widely spread in Earth's depths.

With Earth's depths being inaccessible for humans and no direct data on their composition available, the condition of the substance down to ~150 km depths can be judged from analysis of samples of rocks (xenoliths) which are brought to the Earth's surface through volcanic eruptions or mountain formation processes. Modern concepts treat the upper mantle as composed of primarily pyrolite or piclogite, a hypothetic substance whose main components are olivine (forsterite), pyroxenes, and garnet, with olivine accounting for ~60 and ~40% of pyrolite and piclogite, respectively [5]. Direct structural examinations in X-ray high-pressure chambers showed that forsterite undergoes only minor alterations down to 350-km depths, and in excess of this level it can be transformed to β-modification (wadsleite) comprised by less distorted Si-tetrahedra and cationic polyhedra. The trend to weaker distortion of the coordination polyhedra can also be seen in the subsequent rearrangement of the β-modification at deeper levels (~520 km) to the spinel-type γ-modification (ringwoodite) comprised of regular Si-tetrahedra and virtually undistorted cationic octahedra [5]. The olivine, wadsleite, and ringwoodite structures are shown in Fig. 1.

In crustal rocks, olivine is the main or auxiliary rock-forming mineral for ultrabasites, basites, and kimberlites; it occurs as an accessory mineral in acidic rocks as well. For example, individual fayalite crystals were detected in rapakivi granites of Ukraine and Finland, and forsterite is a common accessory mineral in magnesial skarns. In Russia, olivine rocks, specifically dunites, olivinites (90–100% olivine), wehrlites, lherzolites, and harzburgites (40–90% olivine) form large ultrabasic massifs in the Urals; they occur as smaller intrusive bodies in Chukotka and Kamchatka, as well as in Near-Baikal Area and in Karelia. In ultrabasic rocks, olivine always consists of a mixture of forsterite (Fo) with a not very large (up to 23%) amount of fayalite (Fa). Intermediate-composition olivine ($Fa_{8–53}$) occurs as phenocrysts in basalts of different ages, as well as in Siberian traps and modern volcano lavas in Kamchatka. Fayalite phenocrysts ($Fa_{82–98}$) were found in diabases, dacites, and acid lavas from Vesuvius [3]. Olivine, specifically forsterite ($Fa_{4–16}$), often represented by chrysolite, its transparent olive-green variety, is common in kimberlites. The most deep-lying ones are forsterite grains ($Fa_{6–8}$) revealed for diamond crystals in kimberlites.

Significant fluctuations (within 18–60% Fa on the whole) in the content of the main components, Fe and Mg, were revealed for olivines of effusive and intrusive igneous rocks of the Siberian trap province to whose north-western edge the Norilsk Ore Region is confined. Some of its widespread ultrabasite-basite massifs are associated with platinum-copper-nickel deposits whose reserves and mineral composition are unparalleled elsewhere on the planet.

Due to hydrothermal-metamorphic processes olivine in most cases is replaced by serpentine group minerals and, under profound secondary alterations, this leads to formation of yellow-green rocks called coils. Ural coil has long been used as an ornamental stone. Transparent olivine crystals, known as chrysolite or peridot, have been used as gemstones since ancient times.

Various studies have shown that, depending on the formation conditions, olivine contains Cr, Ni, Ti, Mn, Ca, Co, etc. as isomorphous impurities in the MO_6^- octahedra [6, 7]. According to microanalysis data, olivine from chromite-bearing massifs of the Urals has minimal impurities (0.1–0.7% NiO and 0.06–0.14% MnO). Olivines from Ural Platinum Belt rocks are characterized by a generally higher content of impurity elements (up to 0.4% NiO and up to 0.33% MnO), because nickel and manganese are supplemented by calcium whose content varies from 0 to 0.66% CaO [8]. Olivine from kimberlite xenoliths contains 0.3–0.4% impurity NiO, and that included in diamonds, 0.02–0.08% Cr_2O_3 additionally, which constitutes its distinguishing feature [9].

Regular variations in the content of basic end-members (forsterite and fayalite) and in the availability and abundance of impurity elements in olivines from various genetic complexes make olivine suitable as indicator of ore formation processes for various deposits, specifically, for diamonds in kimberlites, chromite and titanium magnetite deposits in ultrabasites, and platinum deposits in layered basite-ultrabasite complexes and alkaline intrusions. Examples of application of olivine typomorphism in studies of chromite-bearing massifs in the Polar Urals and Norilsk deposits will be demonstrated below.

Olivine finds practical application as refractory raw material. Refractories comprised mainly of forsterite (Mg_2SiO_4) and containing 50–60% MgO, 25–40% SiO_2, are attributed to the magnesia-silica type. They are obtained from natural dunites, serpentinite, olivinites, and talc magnesites with addition of periclase powder. Magnesia-silica refractories are molded with a binder addition and calcined at 1450–1550°C (or are used without calcination). The basic properties of these refractories include open porosity of 22–28% and softening onset temperature under load of 1610–1620°C. Magnesia-silica refractories are used for lining nozzles of open-hearth regenerators and glass-melting furnaces, steel-pouring ladles (in particular, for printed mass), and melting units for nonferrous metals, as well as for manufacture of steel-pouring glasses, etc. Unmolded magnesia-silica refractories are suitable as additions for metallurgical powders.

Chromite Ore Prospecting Based on the Iron Content in Olivine

Ultrabasic massifs of the Polar Urals accommodate commercially valuable clusters of chromite ores. The

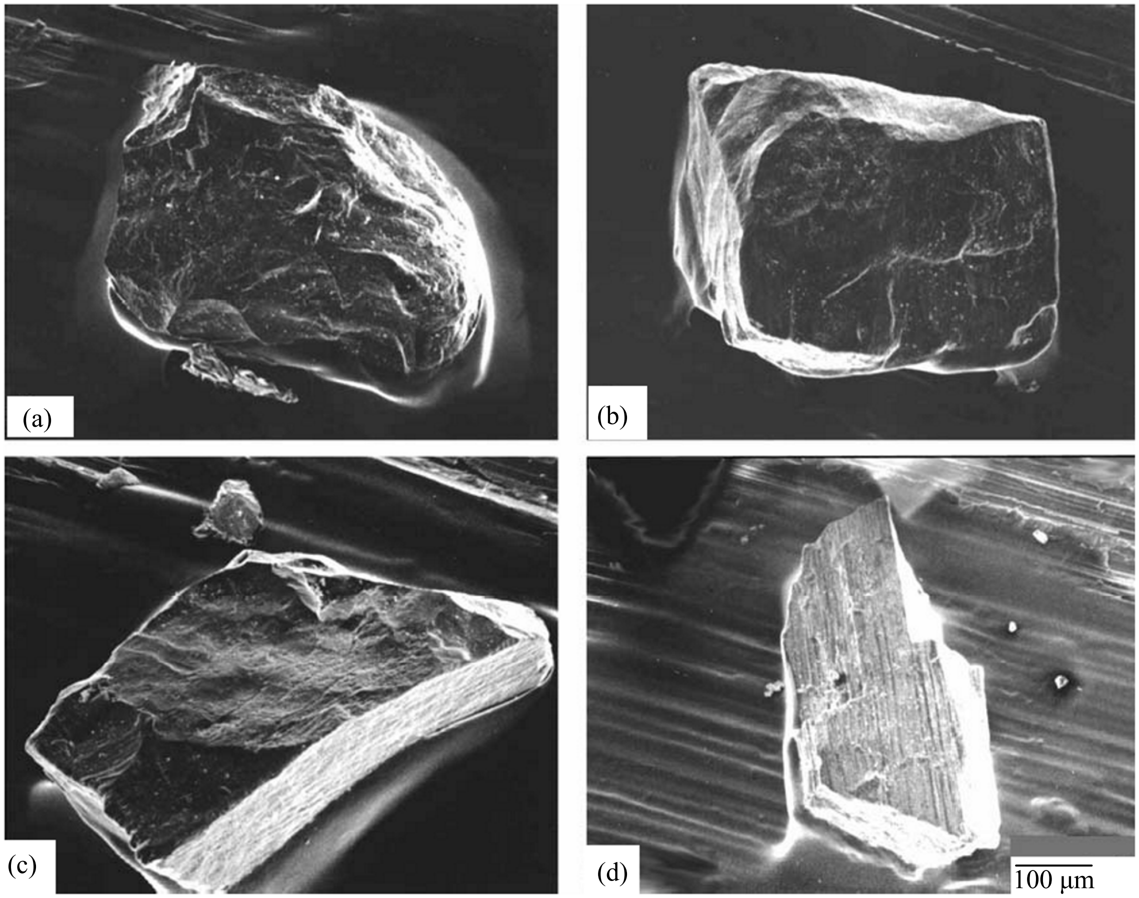

Fig. 2. Olivine grain shape for the Polar Urals ultrabasic rocks: (a) spherical, (b) tabular, (c) flat tabular, and (d) elongated prismatic.

South-Urals chromite ore base, which fully satisfied the needs of the former Soviet Union, after its collapse went to Kazakhstan, in which situation the development of Polar Urals chromite ore deposits was initiated. The Polar Urals Belt ultrabasites are classed with mantle restites. Three large Polar Urals massifs, Syumkeu, Raiiz, and Voikar-Syn'in, stretch from north to south for about 200 km and occupy an area of 3000 km^2, which accounts for nearly 20% of all the rock exposures for this formation in the Urals. In plan view, these are lenticular-shaped massifs with 20–60-km longitudinal and 2–20-km transverse sizes.

Dunites, harzburgites, and lherzolites are the main types of ultrabasite rocks, which occur in complex relationships within a megataxitic (spotty) texture they form. Because of the megataxitic texture of alpine-type ultrabasites of the massifs their mapping should be based on aggregated units, complexes, rather than on individual varieties of rocks. The ultrabasite massifs have a coarsely zoned internal structure, within which the lherzolite-harzburgite (H) complex is succeeded by the dunite (D) complex via the dunite-harzburgite complex (DH) with the dunite content varying from 10 to 70% toward a higher content in large dunite bodies.

Both chromite ores and host rocks contain micromineral phases of native minerals and of copper, nickel, iron, gold, silver, and platinum group element sulfides. Platinum group elements act as a kind of "geochemical tracers" which always occur in native phases and other metal sulfides [7]. Platinum group elements in the Polar Urals ultrabasites do not present any commercial value.

Olivine is the main rock-forming mineral for all ultrabasic rocks, whose content varies from 65–75% in lherzolites at the massif periphery to 90–99% in dunites at the massif center. The olivine grain size in rocks ranges from 0.2 to 8 mm and reaches 20 cm in pegmatoid dunites. Olivine does not have its own crystallographic forms and is dominated by rounded grains (Fig. 2a) and tabular-shaped crystals (Fig. 2b).

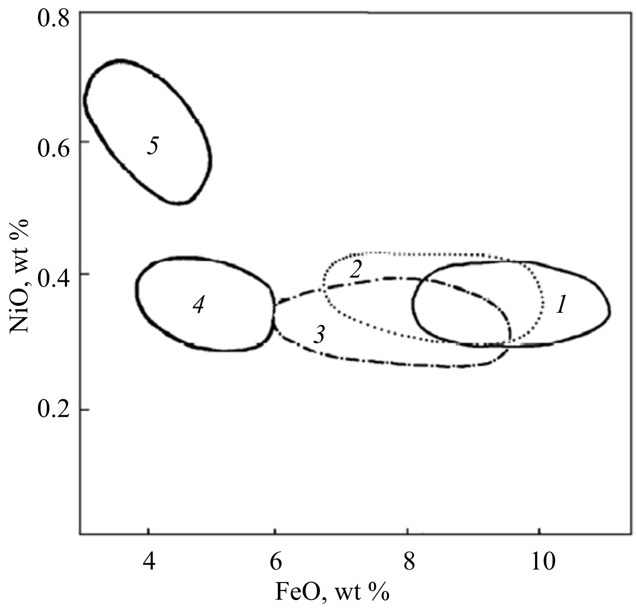

Fig. 3. Iron to nickel oxide ratio in olivine from ultrabasic rock complexes. Field nos.: (*1*) harzburgite, (*2*) dunite–harzburgite, and (*3*) dunite complexes, (*4*) progressive metamorphism zone rocks, and (*5*) chromite ores.

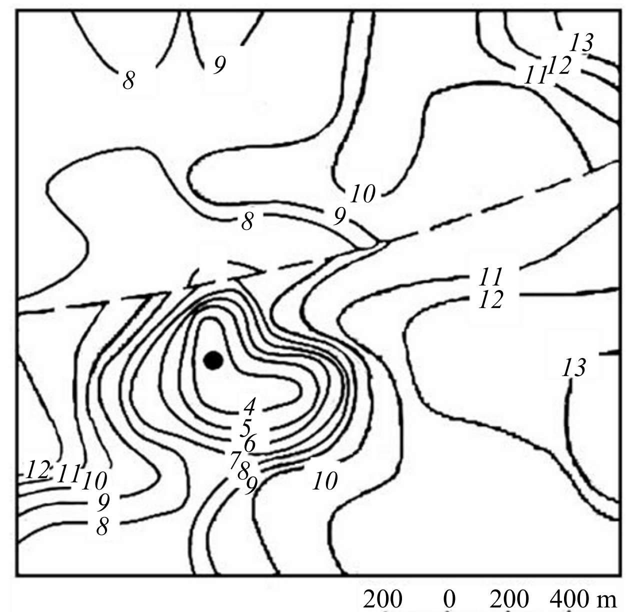

Fig. 4. Iron content map for Kershor plot olivine. Iron content isolines for olivine in the rocks are based on the content of the fayalite end-member, % Fa.

Also, there exist less common flattened tabular (Fig. 2c) or elongated grains, which look like pyroxene crystals (Fig. 2d).

Olivine is represented by forsterite; the most valuable information inherent in its composition concerns the iron concentration which tends to decrease in going from harzburgite to dunite-harzburgite and further to dunite complex (Fig. 3). The lowest iron content (3.1–5.0%) is characteristic for olivine in chromite ores and rocks from zone of progressive metamorphism. Also, olivine from ore zones contains maximal nickel impurities.

Chemical analysis of olivine shows that, along with its constitutional components MgO, FeO, NiO, MnO, SiO_2, it contains impurity Ti, Ca, Al, Na, K, and Cr. Conventional local microprobe analysis does not reveal impurity elements in significant quantities, but a dedicated microanalysis technique allows their detection down to 10 ppm. These elements can be analyzed even more efficiently by SIMS and LA-ICP-MS techniques. This group of components, which is not typical for olivine from chromite-bearing massifs, probably occurs as unstructured impurities. According to silicate analysis data, olivine contains 1–2% ferric iron. A control check of this fact with the use of Mössbauer spectroscopy (NQR) gave a negative result: No significant amounts of Fe^{3+} were found in olivine. It should be noted that iron is partially oxidized to trivalent state in the course of the chemical analysis proper. A room-temperature ESR examination of olivine revealed insignificant amount of Fe^{3+} and a characteristic spectrum of Mn^{2+}, indicating its isomorphous incorporation into olivine. The most informative characteristic of olivine from chromite-bearing ultrabasites is the ratio of the main components, Mg and Fe. Trends in variation of the chemical composition of olivine and the related variability of its crystal optical properties (refractive indices) was the focus of our studies seeking to identify prospecting indicators for chromites.

For methodical reasons we selected two plots accommodating different types of chromitite-bearing ores: a 1.3-km^2 plot in Tsentral’noe chromite deposit within the Raiiz massif (high-chromium ores suitable for metallurgical applications) and a 4-km^2 plot within the Kershor ore occurrence on the eastern slope of Voikar-Syn’in massif (high-aluminum chromite ores used in chemical industry) (Fig. 4). We chose the scales of 1:10000 and 1:25000, respectively, for the mineralogical survey on these two plots, which are associated with different vertical section levels of the ultrabasite massifs: The Tsentral’noe deposit plot occupies the most eroded part of the Raiiz massif in the apical part of a large dunite block, and the Kershor

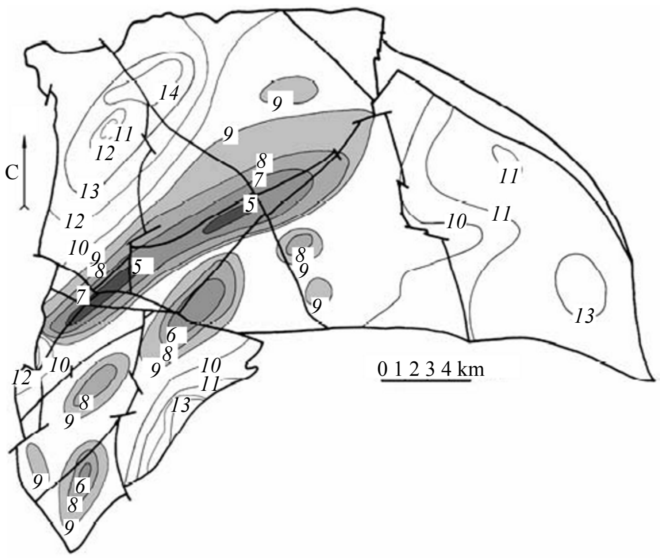

Fig. 5. Iron content map for Raiiz massif olivine, % Fa.

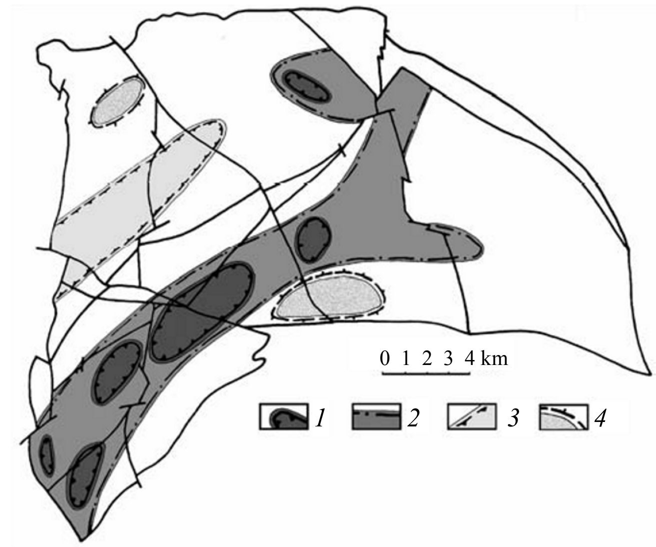

Fig. 6. Forecast-prospecting map for the Raiiz massif. Areas perspective for the discovery of (*1*–*3*) high-chromium metallurgical ore in (*1*) large, (*2*) medium, and (*3*) small deposits and (*4*) chemical-grade high-alumina ores in small deposits.

plot in the upper part of the Voikar-Syn'in massif is composed predominantly by harzburgites and lherzolites.

In both plots the iron content and refractive index of olivine tended to decrease on drawing near the chromite ore bodies (Fig. 4). Consequently, the iron content of olivine and refractive index n_g which is directly proportional thereto can be regarded as universal searching indicators for localization of a hidden chromium mineralization [10]. The range covered by these indicators is estimated at no less than 300–400 m.

The experience with the above-mentioned plots was transferred to all the Polar Urals ultrabasites. The areal mineralogical mapping of the iron content for olivine from the Raiiz massif (Fig. 5) revealed the highest iron content of olivine in the rocks from north-west (11–13% Fa) and south-east of the massif (10.5–12.5% Fa), which are the sites of exposure of lherzolite–harzburgite complex rocks. Even higher iron content in olivine is known for DVC wehrlites only. The most common levels, 9–10% Fa, correspond to the background levels characteristic for dunite-harzburgite complex rocks for which there exist intermittently occurring distinct areas with abnormally low iron content. In the case of Raiiz massif, not every single anomaly is associated with ore, but classification of such anomalies is not difficult

The sublatitudinal linear band of the iron content of olivine within 2–5% Fa is a false anomaly which is not associated with chromite-bearing ore. It marks olivinites and enstatites, "zones of progressive metamorphism" characterized by a generally decreased iron content of rock-forming silicates due to redistribution of iron from silicates to oxides (magnetites) during contact metamorphism. Such false anomalies can be very easily classified on the basis of high magnetic susceptibilities of rocks. Specifically this massif lacks ore objects in this zone. However, ores occurring in a zone of progressive metamorphism are of no commercial value. It should be noted that, in chromite-bearing massifs in the Urals, such metamorphic zones occur extremely rarely.

Southward from the false anomaly there are four contrast anomalies (iron content 3–8% Fa) associated with exposures of dunite-harzburgite complex rocks having a significant dunite component or with large dunite bodies. Three of these anomalies are associated with the known South-West, West, and Tsentral'noe large/medium-sized chromite deposits. The fourth anomaly was revealed on the Upper Engai plot, which makes it highly perspective for the discovery of chromite mineralization. All the four anomalies make up a linearly elongated chain forming a single ore-bearing zone within the area of development of dunite-harzburgite complex rocks, the most perspective for the discovery of commercially valuable chromites.

Based on the mineralogical mapping results for Raiiz massif, we compiled a forecast map (Fig. 6). As

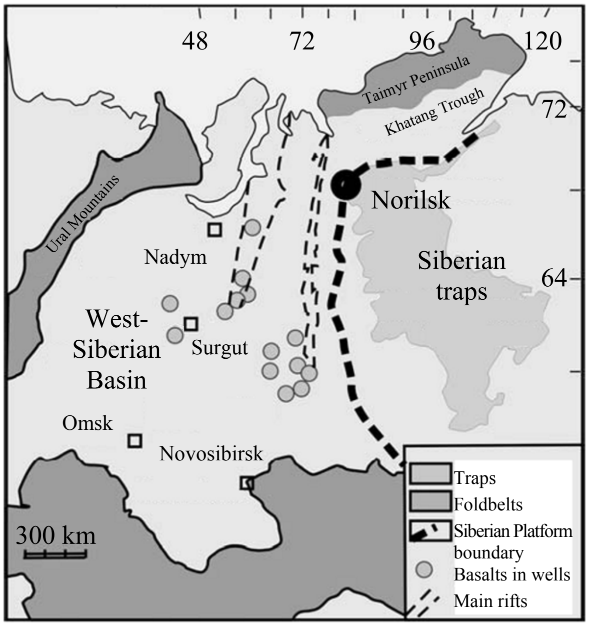

Fig. 7. Schematic map showing the distribution of traps over bedrock exposures and wells (according to [5]).

Fig. 8. Pyroxene dendrites overgrown by olivine dendrites. The end of a prospecting hammer at the photo right is shown for assessing the scale (photo made by K.A. Bychkov).

regards the discovery of new chromite deposits, the most perspective site is an arc-shaped band in the south of the massif, associated with exposures of dunite-harzburgite complex ores characterized by a significant dunite component.

In terms of the textural and structural features and the Cr_2O_3/FeO ratio (a high modulus of 3–4.2), the chromite-bearing ores from Raiiz massif deposits are close to the high-quality South-Urals ores. A fairly successful and economically efficient mining of metallurgical high-chromium ores is currently under way in the Tsentral'noe deposit. Two plots in the north-west and south of the massif are regarded as the most perspective for the discovery of chemical-grade aluminous ores. The forecast for chromite ore resources in the entire Raiiz massif is 180 million tons [11].

Olivine in Igneous Rocks of Norilsk Region

Situated in the north-west of the East Siberian platform, Norilsk Region is geologically a very special area on the Earth. First, it is part of the world's largest Siberian trap province (Fig. 7), and second, it accommodates abundant ultrabasite-basite massifs. Some of them are associated with platinum-copper-nickel deposits whose ore reserves and mineral composition are unparalleled elsewhere on the planet.

Knowledge of the olivine rock formation conditions is essential for development of an ore-formation theory for copper-nickel deposits with a view to facilitate the search for new perspective objects. The most important and complex aspect of the overall problem concerns the factors responsible for the presence of ores in only selected igneous bodies which are part of a giant community of ultrabasite-basite massifs. One of the methodological approaches taken in studies on Siberian trap olivines consisted in comprehensively analyzing high-magnesial rock olivines using advanced research methods. Three mining levels of high-magnesial rocks (picrite basalts) containing 40–50 vol % olivine were revealed within the tuff-lava rock mass. The Norilsk complex intrusions with which different-scale mineralization is associated contain olivine in amounts varying from 0 to 60 vol %.

The major features essential for deducing genetic inferences are the specific morphology and size of the olivine grains and their orientation in igneous bodies, zonal structure of mineral individuals, and variations in the content of the main components, as well as the occurrence of impurity elements in high concentrations and of numerous igneous inclusions. These characteristic features of olivine allow typization of intrusive igneous rocks and analysis of the igneous body formation processes, as well as the retrieval of information about the melts from which olivine has crystallized.

Crystal morphology of olivine. The very first knowledge of the crystallization conditions for olivine-bearing rocks is provided by olivine morphology and grain size examinations. In effusive rocks olivine occurs as large (up to 6–8 mm) idiomorphic phenocrysts in picrite basalts, being a result of deep crystallization of melt, and as small (0.1–0.2 mm) equant grains in the groundmass of plagioporphyric basalts, which resulted from rapid crystallization of olivine on the surface. However, the most unusual olivine species are dendrite-like crystals that reach 4–5 cm in length and occur in stratified flows of picrite basalts in the east of Norilsk Region (Fig. 8). Formation of such igneous stratified rocks still remains a mystery.

In intrusive rocks, the olivine grain size and morphology vary even more broadly: In the vertical section of differentiated massifs of the Norilsk complex, from top to bottom, there exist equant grains in contact gabbro-dolerites, xenomorphic large crystals in taxitic gabbro-dolerites, inequigranular idiomorphic grains (up to 0.7; 0.2–0.3; and $\leq$ 0.1 mm), and large (up to 0.8–0.9 mm) interstitial grains of leukogabbro in the upper part. Subidiomorphic crystals typically represent an early liquidus phase in the rock, and interstitial grains finalize its formation process.

The topic that generates the most heated debate is the origin of the accumulations of small (<0.1 mm) granulated olivine in rocks. These accumulations are variously treated as the protosubstance for ore-bearing massifs [13], large primary olivine crystals that were recrystallized under a gas jet exposure [14], and parts of skarns [15]. The second-named concept seems to be the most plausible, since, according to our data, granular olivine is only slightly different in the composition from rock-forming olivine and contains numerous gas inclusions.

Thus, examination of the morphology and size of grains is helpful in understanding the rock formation history. Importantly, olivines from ore-bearing and barren massifs do not differ morphologically.

For gaining insight into formation of ore-bearing intrusions, of utmost importance are the size and arrangement of the olivine grains. For example, in the longitudinal section of the pipelike Talnakh intrusive body stretching for 12 km, the orientation of the olivine grains suggests a change from laminar to turbulent flow of magmas in the cross-section narrowing segments, which results in settling of the sulfide droplets onto the chamber bottom [16]. This hypothesis was indirectly confirmed by the occurrence of massive ores at the intrusion bottom, tending to the sites of the magma body expansion.

Olivine Composition

Studies of olivine composition, undertaken in the last few decades, have greatly enriched the knowledge of the Norilsk Region intrusives. Initially, the composition was determined from the optical properties, until the microprobe analysis has become routine practice for geological explorations, which allowed accumulation of fundamentally new data on the composition of all rock-forming minerals, including olivine. Those data were obtained in their substantial part by V.V. Ryabov at the Institute of Geology and Geophysics, Siberian Division, Russian Academy of Sciences.

Main components. Ryabov [17] showed that olivines from effusive and intrusive igneous rocks are close in the content of their major constituents, FeO and MgO. The composition of olivine can be generally represented as Fo_{40}–Fo_{82}. The highest magnesia content (Fo_{77}–Fo_{83}) is observed in olivines from barren intrusions (weighted average MgO content 15–18 wt %). Olivines from ore-bearing intrusions is characterized by a slightly higher iron content (from Fo_{47} to Fo_{82}, the average MgO content in the rocks being 10–12 wt %). The highest magnesia content is exhibited by olivines in picritic gabbro-dolerites from the massif bottom, and those at the massif center and top are richer in iron.

Unique crystals of contrast-zoned olivine were detected by N.A. Krivolutskaya in eastern Norilsk Region at the bottom of sill-like bodies. In the latter, the composition changes by more than 20 points, from Fo_{82} to Fo_{61}, in going from the crystal center to periphery. The zones are separated by diffuse boundaries, with zoning in olivine grains being a rare phenomenon. For example, M. Kamenetskaya [18] described a clearly zoned olivine for Udachnaya pipe kimberlites in which the core and rim are separated by very distinct boundaries and the compositions of the central part and the periphery differ by 8–9 points.

Olivines from different rocks exhibit significant overlap areas in terms of the content of the main components, forsterite and fayalite. Hence, knowledge of the total MgO content of rocks and composition of olivine is clearly insufficient for unambiguous identification of ore-bearing complexes because poorly mineralized and barren massifs may have similar features.

Impurity elements. The present stage has brought along a range of local highly sensitive methods for

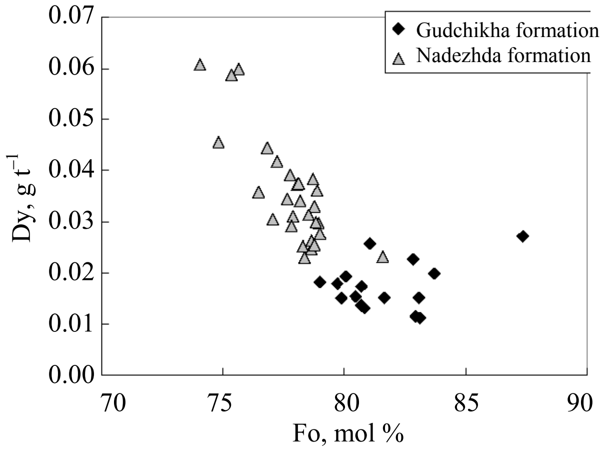

Fig. 9. The Fo–Dy plot for olivines from Gudchikha and Nadezhda formations.

mineral studies, e.g., secondary ion mass spectrometry (SIMS/ion microprobe), laser ablation inductively-coupled plasma mass spectrometry (LA ICP-MS), Raman spectroscopy, etc. When applied to studies of Norilsk Region minerals, the above-mentioned techniques and electron microprobe analysis revealed for all the available olivines an abnormal enrichment, to variable extent, in impurity elements, suitable for differentiation of probable comagmatic formations, individual rock complexes, ore bodies, etc.

It was found that ore-bearing intrusions are always significantly superior to barren ones in terms of the nickel content in olivine, which allows classification of intrusions into ore-bearing, barren, or weakly mineralized ones (Fig. 9).

Other highly informative elements include titanium and vanadium (determined by SIMS and LA ICP-MS analyses), whose content is in direct (titanium) or inverse (vanadium) correlation with the iron content of olivine and broadly varies with the rock type. For example, olivines from picritic gabbro-dolerites of ore-bearing intrusions are superior to barren ones in the content of vanadium, being behind them in the content of titanium.

Interestingly, high concentrations of rare-earth elements are observed in olivines from different intrusive massifs of Norilsk Region, as demonstrated by the example of the Talnakh, Low-Talnakh, and Zelenaya-Griva intrusions [19]. As seen from Fig. 10, olivines from Gudchikha and Nadezhda formations exhibit different enrichments in dysprosium. The analysis of the relevant data for a number of elements does not reveal any correlation between the olivine compositions for ore-bearing massifs and high-magnesial basalts occurring in the region. This allows a presumption that, most probably, the formation of Norilsk complex intrusions is associated with a special magmatic phase in the trap development period.

The ratios of the main components and the available impurities and trace impurities, as well as inclusions in olivine, specific for the high-magnesial rock olivine of the Norilsk Ore Region, are highly informative about the formation conditions for massifs and the ore potential. As regards impurity elements in olivines, the high-magnesial rocks of the tuff-lava and picritic gabbro-dolerites from ore-bearing intrusions exhibit no similarity, i.e., do not belong to comagmatic rocks.

At the same time, barren and ore-bearing massifs are similar in terms of the content of the main components of the melt inclusions in olivine. However, these massifs were characterized by different levels of accumulation of rare elements in melts from which they were formed: The ore-bearing massifs typically displayed sharply enriched spectra.

Igneous Inclusions in Olivine

The amazing ability of a growing crystal to partially entrap its feeding medium was first noticed as early as in works by Sorby and scrutinized in the classical work by E. Roedder [20]. We carried out an analysis of inclusions with the use of the up-to-date Sobolev's technique in order to determine the composition of the parental magmas for intrusions differing in the ore content. The inclusions were heated on a microthermochamber designed by A.V Sobolev and A.B. Slutskii under pure helium to temperatures close to the homogenization temperatures and subsequently quenched. The time of exposure of the samples at T > 1000°C did not exceed 5 min. The experiments were also run in a high-temperature muffle furnace by the same technique though under prolonged (10 min) high-temperature exposures of the inclusion. In most of the experiments, heating of the samples to the melting point of the last of the mineral "captive," i.e., above 1250°C, has led to partial homogenization of the inclusions (melt + fluid) [21].

Olivines from picritic gabbro-dolerites (ore-bearing, to a certain extent) contain solid igneous inclusions (plagioclase, albite, pyroxenes, chrome-spinellides, apatite); vitreous and partially or entirely

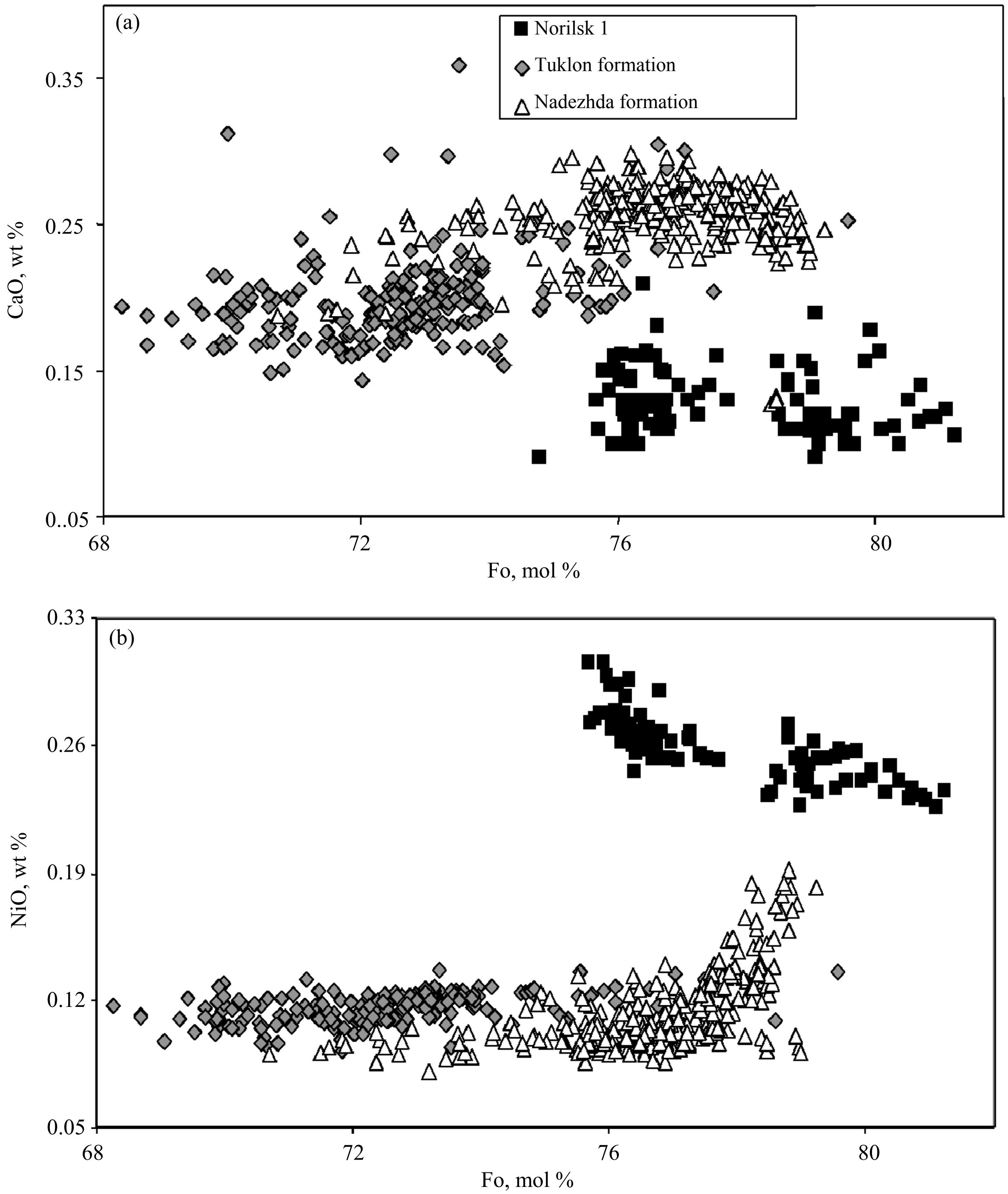

Fig. 10. (a) Fo–CaO and (b) Fo–NiO plot for picritic gabbro-dolerites from Norilsk 1 massif, Tuklon and Nadezhda formations.

devitrified melt inclusions; and fluid and combined inclusions (Fig. 11) [21]. The inclusions range from <25 to 110 μm is size.

Heating and subsequent cooling of devitrified inclusions yielded tempered glasses. Microprobe analysis showed that the latter strongly differ from the rocks in a high content of SiO_2 (55–56%) and alkalis (up to 5% in total), especially of sodium (4%). In terms of Mg, Ti, Al, Fe, and Mn content, the composition of the homogenized inclusions is comparable with that of the rocks for the corresponding intrusion (Fig. 9). The

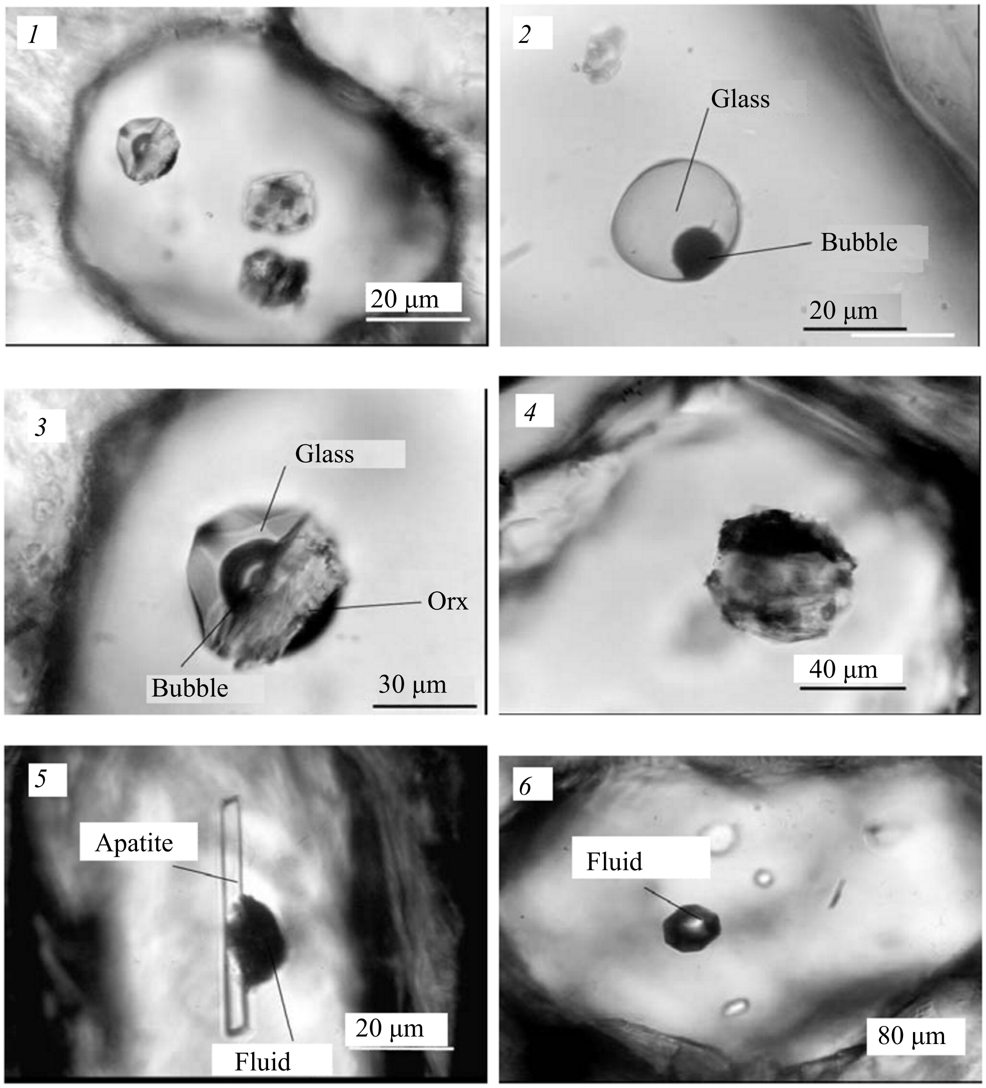

Fig. 11. Igneous inclusions in olivine. Top left to right: (*1*) olivine grain with melt inclusions and (*2–6*) vitreous, (*3*) partially devitrified, (*4*) entirely devitrified, (*5*) crystalline (apatite), and (*6*) fluid inclusion.

inclusions are also characterized by unusually low CaO concentrations (2.72% on average). As follows from the spectra of impurity elements in the inclusions, high concentrations of less common elements are characteristic for melts forming the ore-bearing massifs, as well as for rock-forming olivines. High alkali levels, also characteristic for the ore-bearing massifs, are indicative of olivine crystallization from a highly fractionated melt.

Analysis of vitreous inclusions makes the picture complete: We revealed high alkali concentrations of up to 7.65 wt % for K and 4.11 wt % for Na for the incoherent components and a highly nonuniform distribution for the volatile components; virtually sterile or abnormally enriched inclusions are observed. Using the data for vitreous inclusions, the water content in the melts was estimated at up to 1.41%. Overall, the chlorine and potassium concentrations proved to be in direct correlation, and a weak correlation exists between water and potassium. At the same time, no correlation was revealed between the content of sulfur and main components. It should be emphasized that ore-bearing and barren massifs do not differ in the concentrations of volatiles (H_2O, Cl, F) in melt inclusions. Fluid inclusions contained only low concentrations of CO_2, while other gases (hydrogen, nitrogen, methane) were lacking.

Among solid crystalline inclusions, chrome-spinellides in olivines attract the greatest interest: Data on the olivine-spinellide equilibrium allow estimating the fugacity of oxygen in melts. The spinellides are dominated by chromomagnetite which exhibits broad variations in chromium Cr# (Cr/Al + Cr) and titanium content across different intrusions. For example, the chromomagnetite inclusions in rich Talnakh ores exhibit much higher chromium content (Cr# 0.77–0.81) and a very high TiO_2 content (up to 6.77 wt %), against Cr# 0.46–0.57 in the Lower-Talnakh ores. The latter are also characterized by high vanadium concentrations for spinellide inclusions in olivine, which suggests the magma crystallization under more reducing conditions.

Formation Conditions for Ore-Bearing Intrusions

Identification of the parental melt for the Norilsk Complex intrusions is part of a more general problem of identification of the parental magmas for trap formation. It has long been believed that ore-bearing intrusions were formed from specific magmas. Since recently, the rocks of the formation of interest have been interpreted as the result of a complex process of rise from the mantle of different (picritic or tholeiitic) magmas that were subjected to differentiation in the intermediate chambers and experienced contamination with crustal material [22, 23]. However, until recently there have been no direct published data on the initial melts.

Our data on melt inclusions in olivines of different intrusions [24] suggest that, in virtually all the components (main, trace, and volatile), the composition of the glasses is maximally close to that of the Zelenaya-Griva intrusion rocks. These data are in a dramatic contrast with those for the Talnakh ore cluster massifs as regards the majority of the components, especially less common and alkaline elements, and the same is true of the olivine composition. This suggests that the olivine from Zelenaya-Griva intrusion is an intrachamber formation, because the composition of the entrapped inclusions in it is identical to that of the rocks.

As to olivine from the Talnakh ore cluster massif, this is apparently an intratelluric phase that has crystallized from a melt that strongly differed from the melt that formed the bulk of intrusion. Olivine was enriched in SiO_2, less common elements, and Ba. This route seems to be very probable in view of the fact that, since lately, there has been accumulating evidence of rising from deep inside the Earth of magmas containing a certain proportion of devitrified olivine grains, rather than of pure melts.

Our data on the composition of the fluids suggest a sharp dominance of CO_2 in the final stages of development of the massifs and a not very high water content in the melt. For melts the concentrations of volatiles, H_2O and chlorine, are close for the ore-bearing and barren intrusions. The igneous fluid in both cases was characterized by a normal level of H_2O (~1 wt %) and a minor CO_2 level; the water content was at a maximum (up to 1.7 wt %) specifically for the Zelenaya-Griva intrusion. No difference in the concentrations of volatile components (water, chlorine, and fluorine) was revealed for melts of ore-bearing and barren intrusions. These data invalidate the presumption concerning a special fluid regime for ore-bearing intrusions, at least in the olivine crystallization stage.

CONCLUSIONS

Studies of olivines from various types of geological formations show that they differ in the information value and suitability for genetic link inferring and mineralogical mapping. The most informative typomorphic property of olivine in all crustal rocks is its composition.

Within a narrow variability range for composition and properties, characteristic for olivine from Polar Urals ultrabasites, the main trend of its evolution consists in the growth of magnesia content and liberation of impurities. The highest magnesia level, the maximal nickel impurity level, and the ensuing low iron levels exhibited by olivine from ores may be helpful in chromite ore prospecting.

Olivine from igneous rocks of Norilsk Region is characterized by a more broadly varying composition. Methodologically, the composition of olivine and igneous inclusions entrapped during its growth constitutes important diagnostic criteria which identify the genesis of Norilsk platinum-copper-nickel deposits. Ore-bearing massifs are distinguished by sharply enriched rare-earth element spectra, while ore-bearing and barren massifs are close in the content of the main components of the melt inclusions in olivine. Compared to barren intrusions, olivine in ore-bearing intrusions always contains much higher concentrations of nickel and vanadium and reduced titanium concentrations. This allows classification of intrusions as ore-bearing, barren, or weakly mineralized ones even in the exploration stage.

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