Accessory Cr-Spinels in the Section of the Nude-Poaz Massif in the Monchegorsk (2.5 Ga) Mafic-Ultramafic Layered Complex (Kola Peninsula, Russia): Comparison with Ore-Forming Chromites

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Abstract: The paper studies accessory Cr-spinels from deep drill holes crossing the Nude-Poaz massif, which is a part of the Monchegorsk mafic-ultramafic layered complex (2.5 Ga, Kola Peninsula, Russia). Cr-spinels occur as two morphological types that differ in their chemical composition, i.e., Cr-spinels of the first type are more aluminous, while Cr-spinels of the second type are more ferruginous and titaniferous. Cr-spinels of the Nude-Poaz massif are characterized by a Fe-Ti trend known for layered intrusions in the world. Cr-spinels of the Nude-Poaz massif quite clearly differ in composition from chromites of the Sopcheozero deposit: they are more ferruginous and less chromous. The specific composition of Cr-spinels in rocks of the Nude-Poaz massif can be correlated with the sequence of the magmatic phases intrusion.

Keywords: Cr-spinels; Monchegorsk layered complex; Nude-Poaz massif; Kola Peninsula

1. Introduction

Chromite occurs in various forms, like a number of other minerals concentrating commercially valued metals. It is mainly associated with ultramafic rock massifs, where chromite can be observed as disseminated or individual bodies (beds and lenses) with some of them producing major deposits. In petrological studies, Cr-spinels are considered a clue to understanding the evolutionary processes of magmatic melts [1,2]. These investigations revealed that compositions of Cr-spinels should be studied in detail not only in different intrusions but also within the same layered complex. Thus, comparing compositions of Cr-spinels from various horizons helps to understand whether they belong to the same or different magmatic phases.

In the rocks of the Monchegorsk layered mafic-ultramafic complex (hereinafter referred to as the Monchegorsk Complex or MC, Figure 1) in the northeastern part of the Fennoscandian Shield, Cr-spinels occur as several types, i.e., ore, vein, and accessory minerals. Ore chromites of the Sopcheozero deposit are best studied due to their industrial value [9]. Vein chromites have been found in MC quite recently and described for the Moroshkovoye Lake site [10]. Accessory Cr-spinel is present in almost all types of MC rocks.
In the early 2000s, four boreholes (1880, 1881, 1882, 1883, see Figure 1) were drilled at the depth of 502.5 to 740 m during prospecting for platinum group metals (PGM) within the east-north-east trending branch of MC. The works were carried out by JSC “Central Kola Expedition” (CKE), JSC “Pana”, MMC “Norilsk Nickel”, and LLC “Pechenganologiya” within the Nude-Poaz and Vurechuaivench massifs. The obtained data on these deep drill holes provided a far clearer view at both features of the geological structure of the Nude-Poaz and Vurechuaivench massifs, and localization of the platinum group elements (PGE) sulfide mineralization in them [11]. The Nude-Poaz massif itself was crossed by the drill hole 1882 in its central part and by the drill hole 1880 in the eastern part. During the study of cores from these drill holes, horizons with accessory Cr-spinels were discovered. The current article is dedicated to the results of studying these Cr-spinels and their comparison with Cr-spinels from other MC massifs (first of all, ore chromites of the Sopcheozero deposit).

2. Geological Structure of the Monchegorsk Complex and Former Research

Several authors [12–14] believe that MC consists of two large fragments, i.e., the Monchetundra intrusion (or massif) and Monchepluton (Figure 1). Despite their close age (2497 ± 3–2501 ± 8 Ma) [15,16], the Monchetundra intrusion and Monchepluton have complicated interrelations that reflect different sequences of intrusion of their major magmatic phases [10,14] and got shaded by intense postmagmatic tectonic processing. Thus, compiling the consolidated geological column of MC is quite challenging. Notably, considering the Monchetundra intrusion and Monchepluton as one complex is reasoned by...
their spatial proximity, in addition to geochronological data. The former is very important as we believe the Monchetundra intrusion includes, apart from itself, the South Sopchinsky and Gabbro-10 massifs [14].

From two [17] to three [18] zones are defined in the Monchetundra intrusion section based on deep drilling results (drill holes 765 and M-1). According to [18], these zones include the following rocks: lower zone—plagio-pyroxenites, plagio-peridotites, norites, olivine norites, peridotites, olivinites (ultramafic bodies); middle zone—mainly medium-grained trachyidi gabbro-norites; upper zone—massive coarse-grained gabbro-norites, leucogabbro, and gabbro-anorthosites.

Structurally, the Monchepluton comprises two branches, as follows: (1) an north-north-east-trending branch, including Mts. Nittis, Kumuzhya, and Travyanaya, i.e., the so-called NKT massif, and (2) an east-north-east-trending branch, including the Sopcha, Nude-Poaz, and Vurechuaiwench massifs. As shown in Figure 1, the so-called Dunite block with the Sopchezero chromite deposit is located between the NKT and Sopcha massifs. The position of the Dunite block in the MC section was debated. Many geologists considered it to be a giant xenolith, i.e., an early phase that preceded the formation of most rocks in the Monchepluton, based on the presence of dunite xenoliths in underlying norites and plagioclase orthopyroxenites [19–21]. However, it was quite convincingly proved in [15] that the Dunite block was a regular member of the Monchepluton section.

The repetition of horizons with olivine rocks in the Monchepluton section (Ore Layer 330 of the Sopcha massif and rocks enclosing the Critical Horizon of the Nude-Poaz massif) is associated with additional impulses of magmatic matter [15]. Different parts of the Monchepluton section contain different types of Cu-Ni-PGE sulfide mineralization (contact, vein, reef). The richest Cu-Ni vein ores had been mined out in the NKT massif by the early 1970s. The main PGE-bearing object, i.e., the Vurechuaiwench reef deposit, was put on the state balance in 2009 but has never been mined yet. In addition, non-industrial Fe-Ti-V mineralization is associated with the Gabbro-10 massif.

The presence of chromite mineralization in MC rocks is another clearly crucial factor. However, it was poorly studied until quite recently.

Only in the 1940–50s, prospecting for Cu-Ni sulfide ores revealed the chromite mineralization in cores of drill holes in the southwestern part of the Monchepluton. It was not studied in detail, except for sampling of the ore interval of the drill hole 1031 drilled in 1957. Therefore, the Monchepluton potential for chromite ores was negative up to the 1970s. However, V.S. Dokuchaeva was the first to suggest that commercial concentrations of Cr could be discovered in the Dunite Block, based on compared compositions of ore chromite in the Monchepluton and chromite from Ural deposits [20]. But only almost 20 years later, in 1994, executives of MMC “Norilsk Nickel” decided to restart geological prospecting in the Monchegorsk area, using facilities of the “Severonickel” plant. As a result, the Sopchezero stratiform chromite deposit was discovered and studied afterward [9,15,22,23].

It is defined that with the weighted average of Cr₂O₃ in the ore bed of 23–24%, the content alters irregularly in it. The north-western part of the deposit hosts a “stream” of rich ores with a Cr₂O₃ content of more than 30%. The south-eastern part of the deposit shows a weak transverse “stream” with a Cr₂O₃ content of 25–30% [9,22,23]. However, despite such values, it is much lower than in ores from some analogous sites in the world (in particular, the average Cr₂O₃ content in chromites of Zimbabwe is 41%, in chromites of South Africa—37%) and Russia [9]. That might be the reason to stop the mining of the Sopchezero deposit that started in 1999. Nevertheless, similar sites are well-mined abroad, e.g., the Kemi deposit in Finland with the average Cr₂O₃ content in the ores of just over 26% [24].

Noteworthy, recent studies of individual minor chromitite bodies in the Sopchezero deposit provided the basis for a very original hypothesis, considering these bodies as dikes—peculiar conduits of magma saturated with chromite [25].

Xenoliths of chromite-bearing rocks are recently found in olivine orthopyroxenites of the NKT massif [26]. Three varieties of xenoliths are detected here, as follows: chromite
harzburgite, chromite-rich harzburgite and massive chromitite. The authors emphasize that the scope of these rocks spreading in the NKT massif is still unclear and it is possible to discover major ore gulfs equivalent to the Sopcheozero chromite deposit [26].

A.Yu. Barkov et al. studied an ore occurrence of chromite-magnesiochromite (up to 20−25 modal %) on the slope of Mt. Kumuzhya (NKT massif), where they found microinclusions of sulfides and PGE-bearing phases in a mineralized harzburgite [27]. For the ore occurrence, a very unusual morphology of the weathered surface was described, with large spheroids (up to 3−4 cm) of rhombic pyroxene standing out markedly among the matrix of fine-grained olivine and chromite [27].

Accessory chromites in MC were given irregular study with a varied degree of detail. Within the Monchetundra intrusion, the study of accessory Cr-spinels was aimed at solving a local rather than the fundamental problem. Cr-spinels from rocks at two levels of the lower zone exposed by the drill hole M-1 were analyzed, i.e., in melanonorites (interval 781–811 m) and ultramafic bodies (olivinites) (interval 2059–2350 m). It was noted that the fields of their compositions significantly overlap; however, in melanonorites, Cr-spinels with a higher Al₂O₃ content were found, while they are absent in ultramafic rocks (olivinites). Thus, it was concluded that melanonorites and olivinites cannot be considered a single unit, but referred to as different complexes [17]. M. Lyulko came to the same conclusion that olivinites were foreign bodies and not members of the layered series in the Monchetundra intrusion [28].

Accessory chromites were also found in studying rocks and ore mineralization of the South Sopchinsky massif (Figure 1) in two polished sections from the core of the drill hole 1826 (the lower part of the section). In olivine norites, Cr-spinel grains were enclosed within crystals of magmatic minerals—olivine and orthopyroxene; compositionally, the mineral refers to ferriahulomochromite [29].

Among metanorites of the Moroshkovoye Lake area (Verhny Nude block, Figure 1), vein Cr-spinels were first discovered as two minor (up to 10−20 cm thick, up to 1 m long) schlieren-like bodies [10,29]. These works indicate that vein Cr-spinels differ compositionally from ore chromites of the Sopcheozozero deposit and accessory Cr-spinels from other massifs of the Monchepluton [10], being closer to Cr-spinels of the Imandra lopolith [30]. Both vein (Moroshkovoye Lake) and accessory (South Sopchinsky massif) Cr-spinels show high contents of iron and titanium and low contents of alumina [29].

In the Monchepluton accessory Cr-spinels were studied in almost all of its main massifs. Cr-spinels from the Ore Layer 330 of the Sopcha massif [15,31], as well as chromites from dunite bodies in the northeastern part of this massif [32], were studied in sufficient detail. Within the thin Ore Layer 330, Cr-spinels show zoning in the chemical composition of the nuclear and peripheral parts of their grains. D.A. Orsoev suggested that the Cr-spinels he described had the magmatic nature predetermined by changes in physical-chemical settings of the magma crystallization [31].

Slightly higher chromite contents compared to other rocks (up to 5 vol. %) were recorded in dunite bodies among pyroxenites in the northeastern part of the Sopcha massif [33]. Later, the genetic link between the dunite bodies of the Sopcha massif and the Dunite block was proved [32]. The content of Cr₂O₃ in the largest dunite body varies from 0.90 to 1.09 wt. %, which corresponds to the sparsely disseminated ore [32].

Accessory Cr-spinels from the NKT, Sopcha, and Nude-Poaz massifs were described in [34,35]. These articles highlight forms of Cr-spinel occurrence in various rocks of these massifs, as well as their chemical compositions. Notably, the paper [34] studies a few samples taken from different massifs irregularly (NKT—4, Sopcha—11, Nude-Poaz—3). Despite strong fluctuations, the authors identified general trends for changes in chemical compositions of the studied Cr-spinels, depending on their position in the studied parts of the Monchepluton section. Such features include the enrichment of Cr-spinels with titanium in marginal parts of the massifs (first of all, NKT), and increased FeO and Fe₂O₃ contents from dunites and peridotites to overlying pyroxenites and norites in central parts [34].
The paper [35] presents data on the composition of accessory Cr-spinels from the NKT, Sopcha, and Nude-Poaz massifs based on a larger number of analyses compared to [34] (in total, 39). Unfortunately, this article provides no clear link between the samples and the sections within specific massifs, and as for the NKT and Sopcha massifs, they are separated in no way at all. Therefore, the paper draws only general conclusions; the authors do not emphasize specific formation settings of individual massifs (phases) in the Monchepluton associated with peculiar features of the chromite composition. The data in the article suggest the magmatic origin of Cr-spinels. It is also indicated that the composition of Cr-spinels is consistent with changes in the composition of the melt during the basaltic magma crystallization and controlled by changes in the temperature and oxygen regime [35].

3. Geological Structure of the Nude-Poaz Massif

The Nude-Poaz massif, the largest in the ENE-trending branch of MC (Figure 2), was studied by many researchers [15,19,36–38]. The massif is a layered body composed of norites mainly. The most generalized section of the Nude-Poaz massif includes the following units (Figure 2c) (from bottom to top): endocontact rocks; bottom melanocratic norites (80–100 m); poikilitic norites (80–100 m); olivine norites (up to 120 m); norites (200 m). The layers steeply dip towards the central part of the body, the bottom of which is cup-shaped [37]. The massif overlies Archean diorite-gneisses of the basement.

The massif section is complicated by the so-called Critical Horizon, which is located close to the boundary between the upper layer of norites and olivine norites (with orthopyroxenite lenses), though it is not a regular element of magmatic layering (Figure 2b,c). The Critical Horizon shows an alternation of meso- and melanocratic norites, plagiorthopyroxenites, gabbronorites, and harzburgites. Lenses of cordierite hornfels and interlayers of high-alumina schists, nests, and veins of gabbro-pegmatites, as well as bodies of micro-grained norites and gabbronorites crumpled into complex folds, are also found among the rocks of the Critical Horizon. Its thickness reaches 50 m. The rocks of the Critical Horizon are associated with Cu-Ni (±PGE) mineralization of no commercial value.
According to V.F. Smolkin, who partially accumulated and supplemented the point of view [19,39], the rocks in the Critical Horizon zone are the product of the mixing of ultramafic and mafic melts and rocks of the host Archean complex. At the first stage, the horizon was the roof of the primary chamber, initially filled with a high-Mg melt, the crystallization of which led to the formation of olivine-bearing rocks. Contact hybrid rocks (micronorites), hornfelses, and shales have arisen at the boundary between the melt and the roof, composed of high-alumina and quartz-feldspar Archean gneisses. At the second stage, a new inflow of norite-gabbronorite melts occurred, which penetrated already into the upper part of the Nude-Poaz chamber [15]. E.V. Sharkov considers the micronorites of the Critical Horizon to be a conduit for an additional portion of the norite melt enriched in sulfides and PGE [40,41].

The article [23] gives dates showing the time of formation of the rocks of the Critical Horizon and the upper part of the Nude-Poaz massif: gabbro-pegmatites of the Critical Horizon, from 2504.4 ± 1.5 Ma [42] to 2500 ± 5 Ma [43], norites in the upper part of the Nude-Poaz Massif, 2493 ± 7 Ma [44].

The upper part of the Nude-Poaz massif section is accreted by the Vurechuaivench massif composed of gabbro-norites with interlayers of anorthosites mainly (Figure 1) [15,45]. Some authors believe that the Vurechuaivench massif represents the same magmatic phase as the upper (above the rocks of the Critical Horizon) norites of the Nude-Poaz massif [46]. The others consider gabbro-norites and anorthosites of the Vurechuaivench to be an independent magmatic phase [47]. The well-known deposit of PGE sulfide ores is associated with the Vurechuaivench massif [48].

4. Materials and Methods

Noteworthy, finds of accessory Cr-spinels in the rocks of the Nude-Poaz massif are extremely rare. Accessory Cr-spinels were found only in six of about 200 samples from the drill holes 1880 and 1882 (drilled by JSC CKE in 2001) that crossed the Nude-Poaz massif (Table 1).

Table 1. List of samples.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample No. (Drill Hole/Depth)</th>
<th>Rock</th>
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<tbody>
<tr>
<td>1</td>
<td>1880/334.0</td>
<td>Mesocratic norite fine-to medium-grained</td>
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<tr>
<td>2</td>
<td>1880/336.3</td>
<td>Mesocratic norite fine-to medium-grained</td>
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<tr>
<td>3</td>
<td>1880/342.7</td>
<td>Mesocratic norite fine-to medium-grained</td>
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<tr>
<td>4</td>
<td>1880/395.8</td>
<td>Orthopyroxenite fine-to medium-grained</td>
</tr>
<tr>
<td>5</td>
<td>1882/326.3</td>
<td>Melanocratic olivine norite medium-grained</td>
</tr>
<tr>
<td>6</td>
<td>1882/486.5</td>
<td>Melanocratic olivine norite medium-grained</td>
</tr>
</tbody>
</table>

Microphotographs in transmitted and reflected light were taken using an Axioplan microscope (Carl Zeiss, Oberkochen, Germany) with a TopCam 16.0 MP digital camera.

The chemical composition of minerals (Cr-spinel, magnetite and also orthopyroxene and plagioclase—see Supplementary Materials Table S1) was studied by the X-ray spectral method, using an electron probe microanalyzer (Cameca MS-46, Paris, France) with the accelerating tension of 22 kV and the probe current of 30–40 nA. The following standards were used: wollastonite (Si, Ca), forsterite (Mg), synthetic Y₃Al₅O₁₂ (Al), lorenzenite (Ti), metallic vanadium (V), chromite (Cr), synthetic MnCO₃ (Mn), hematite (Fe), metallic nickel (Ni), sphalerite (Zn). Detection limits of electron microprobe analyses (wt.%): Ca—0.03, Mg—0.1, Ni—0.01, Al—0.05, Si—0.05, Mn—0.01, Fe—0.01, Zn—0.01, Ti—0.02, Cr—0.02, V—0.02.

The study of the mineral morphology, imaging in back-scattered electrons BSEs, and preliminary chemical analyses were executed on polished sections with the use of a scanning electron microscope (SEM), LEO-1450 (Carl Zeiss, Oberkochen, Germany), with
an energy dispersive X-ray analytical device (EDS) at the Laboratory of Physical Methods for studying rocks, ores, and minerals of the Geological Institute of the Kola Science Centre of the Russian Academy of Sciences (GI KSC RAS).

When the grains were very small, the composition of mineral phases was measured using the Bruker Quantax-200 energy dispersive detector (Bruker, Bremen, Germany) to an LEO-1450 scanning electron microscope. Once chrome-spinelid grains were saturated in ilmenite or magnetite inclusions produced by the decomposition of the solid melt, the analysis was provided with a wide beam (beam diameter up to 40 µm) to measure the average mineral composition. BSE images were obtained using an LEO-1450 scanning electron microscope (Carl Zeiss, Oberkochen, Germany).

FeO\text{total} was recalculated for formula values of Fe\text{+2} and Fe\text{+3} according to the stoichiometric formula.

5. Results

We have studied Cr-spinels from a norite sequence in the Nude-Poaz massif. The authors used some material of the vertical drill holes 1880 and 1882 from the depth of more than 500 m deep that cross-cut the bottom of the massif (Figure 2b,c and Figure 3). The drill hole 1882 near the top of Mt. Nude intersected norites and olivine norites. A low bed of albite-quartz metasomatite that corresponds with rocks of the Critical Horizon occurs at the depth of 389.0 m. The near-bottom zone is composed of melanocratic norites. The drill hole 1880 in the central part of Mt. Poaz intersected a monotonous norite sequence, in which the bottom part hosts a thin layer of melanocratic norites. The bottom part of the Nude-Poaz massif is marked by a 30 m-thick layer of quartz gabbro. Besides, Figure 2c shows the drill hole 1393; Cr-spinels from one of its intervals had been formerly analyzed [34]. The section of the drill hole 1393 is based on data by JSC CKE.

![Figure 3. Stratigraphic columns of drill holes 1880 and 1882 (Nude-Poaz massif).](image-url)
Analyses of geological sections across the Nude-Poaz massif showed that the 150–250 m-thick zone with the accessory Cr-spinel mineralization stretched in the sub-latitudinal direction for over 3 km. Occurrences of Cr-spinel mineralization are detected at two levels, i.e., in the upper part of the lens of orthopyroxenites and olivine norites, and also below it, in melanocratic norites, closer to their contact with the underlying diorite-gneisses (Figures 2 and 3).

5.1. Petrography

The rocks of the Nude-Poaz massif correspond to the mafic ones of low alkalinity [15] and are represented by enstatite, olivine-enstatite, and plagioclase-enstatite cumulates. Magmatic amphibole was not observed in the rocks of the Nude-Poaz massif, but amphibolization is widespread in its marginal parts. Orthopyroxenes from norites of the Nude-Poaz massif, according to [34] are characterized by constant composition and high Mg content: En 80.7–84.8. According to our data, in the rocks from drill hole 1880, orthopyroxene has a composition of En 75.5–84.8, orthopyroxene in the samples from drill hole 1882 has the composition En 83.2–84.4 (Supplementary Materials Table S1). Olivines from norites of the Nude-Poaz massif, according to [34] are also characterized by a constant composition: Fo 83.4–84.8.

The petrographic study of transparent sections of the drill holes 1880 and 1882 at different depths revealed accessory Cr-spinels. Their dissemination in the rock is mainly represented by single grains up to 100–150 µm long. Microphotographs of typical Cr-spinel-bearing rocks are shown in Figure 4.

Figure 4. Cr-spinel in rocks from drill holes 1880 and 1882 (Nude-Poaz massif). (a,b) Cr-spinel in norite, sample 1880/342.7; (c,d) Cr-spinel in olivine norite, sample 1882/326.3. Photos of thin sections: (a,c) without analyzer; (b,d) crossed nicols. Pl—plagioclase, Ol—olivine, Opx—orthopyroxene, Chr—Cr-spinel.

In sample 1880/342.7, the rock is medium-grained mesocratic norite (Figure 4a,b) composed of cumulus grains of orthopyroxene and intercumulus plagioclase. Orthopyroxene is partially replaced by amphiboles, i.e., anthophyllite and actinolite. Single segregations of clinopyroxene are observed. Cr-spinel forms oval or irregular grains, less often square
sections. The Cr-spinel content in the rock is about 2%. The size of Cr-spinel grains is 0.006–0.02 mm. Cr-spinel commonly occurs at boundaries between grains of orthopyroxene and plagioclase, as well as within grains of orthopyroxene, plagioclase, and clinopyroxene. Plagioclase in sample 1880/342.7 corresponds to labrador (An 72.4; Ab 26.8; Or 0.8).

In sample 1882/326.3, the rock is medium-grained melanocratic olivine norite (Figure 4c,d). Olivine and orthopyroxene form cumulus grains, plagioclase forms intercumulus. The olivine grains are framed by chlorite and talc rims. Some orthopyroxene grains contain clinopyroxene ingrowths. Single grains of Cr-spinel are found inside orthopyroxene crystals.

5.2. Mineralogy

The study of polished sections under an optic microscope and particularly under the electronic microscope showed that the rock encompassed two morphological types of Cr-spinels that differ in shape and inner structure of grains. Cr-spinels of the first type (Chr-1) produce better-rounded grains with a more homogenous inner structure (Figure 5a,c). Cr-spinels of the second type (Chr-2) occurs as irregular-shaped grains with a more heterogenous inner structure. They contain numerous fine inclusions of ilmenite, as well as ilmenite intergrowths as a latticed exsolution structure (Figure 5b,d). The grain size of each type ranges from 50 to 150 µm, the grains occur as intergrowths in pyroxenes and plagioclase or at the boundaries between silicate grains. No zonal structure was detected.

![Figure 5. Two morphological types of Cr-spinels from the Nude-Poaz massif in sample 1880/342.7. The first type (Chr-1) (a,c) the second type (Chr-2) (b,d). Back-scattered electron (BSE) images.](image)

Electron microscope studies and microprobe analysis showed that Cr-spinels of both varieties differ in their chemical composition. Once morphological and chemical differences between Cr-spinels were identified, it was suggested that grains encapsulated in various minerals, i.e., orthopyroxene, plagioclase, or clinopyroxene, had different compositions. Alternatively, Cr-spinel grains were detected within silicate grains and at borders between them (as noted, in particular, for chromites of the Sopcheozero deposit [22]). However, further research did not confirm these hypotheses. Cr-spinels of the first and second types neighbor in the same crystal of a silicate mineral (Figure 6).
5.3. Features of the Chemical Composition of Cr-Spinels

The two varieties of Cr-spinels in the studied samples are not uniformly distributed, i.e., some contain both varieties, while others contain only one of them. Thus, two varieties of Cr-spinel were found in sample 1880/334.0 (Figure 7), and in sample 1880/336.3 Cr-spinel is represented only by Chr-2 (Table 2). These samples, as well as the most saturated Cr-spinel sample 1880/342.7, were taken from mesocratic norites of the contact zone between norites and orthopyroxenites (Figure 3). Both types of Cr-spinels of the Nude-Poaz massif differ in their chemical composition.

![Figure 6](image1.png)

**Figure 6.** Cr-spinels in plagioorthopyroxenite of the Nude-Poaz massif, sample 1880/342.7. (a) dissemination of Cr-spinels in the sample; (b) grains of Cr-spinels in the edge part of the grain of orthopyroxene; (c) grains of Cr-spinels in plagioclase; (d) grains of Cr-spinels in orthopyroxene; (e) Cr-spinel grain in clinopyroxene; (f) Cr-spinel grains in orthopyroxene. Chr-1—high-alumina Cr-spinel, Chr-2—low-alumina Cr-spinel, Opx—orthopyroxene, Cpx—clinopyroxene, Pl—plagioclase. Back-scattered electron (BSE) images.

![Figure 7](image2.png)

**Figure 7.** Dissemination of Cr-spinels in norite from the Nude-Poaz massif (sample 1880/334.0). Chr-1—high-alumina Cr-spinel, Chr-2—low-alumina Cr-spinel, Opx—orthopyroxene, Pl—plagioclase. Back-scattered electron (BSE) images. (a) Chr-1 grains on the border between plagioclase and orthopyroxene, (b) Enlarged fragment of the upper left part of the photo (a), (c) Chr-2 grains in orthopyroxene, (d) Enlarged fragment of the photo (c).
Table 2. Chemical composition of Cr-spinel and magnetite from rocks of the Nude-Poaz massif.

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<td>1.956</td>
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Formula Coefficients

| Mi²⁺ | 0.073 | 0.056 | 0.033 | 0.032 | 0.041 | 0.025 | 0.043 | 0.049 | 0.055 | 0.046 |
| Fe³⁺ | 0.912 | 0.927 | 0.953 | 0.957 | 0.963 | 1.009 | 1.016 | 0.937 | 0.928 | 0.948 |
| Mn²⁺ | 0.022 | 0.019 | 0.021 | 0.021 | 0.022 | 0.019 | 0.022 | 0.018 | 0.017 | 0.019 |
| Zn²⁺ | 0.004 | 0.006 | 0.013 | 0.013 | 0.005 | 0.007 | 0.005 | 0.008 | 0.012 | 0.010 |
| Ni²⁺ | 0.005 | 0.003 | -     | -     | 0.002 | 0.003 | 0.005 | -     | -     | 0.003 |
| Mg³⁺ | 0.975 | 1.066 | 1.180 | 1.168 | 1.184 | 0.951 | 1.058 | 1.143 | 1.116 | 1.116 |
| Al³⁺ | 0.644 | 0.631 | 0.328 | 0.319 | 0.351 | 0.323 | 0.299 | 0.629 | 0.627 | 0.551 |
| Fe³⁺ | 0.331 | 0.261 | 0.421 | 0.435 | 0.369 | 0.547 | 0.414 | 0.189 | 0.208 | 0.220 |
| Ti⁴⁺ | 0.019 | 0.015 | 0.025 | 0.028 | 0.038 | 0.072 | 0.099 | 0.014 | 0.016 | 0.028 |
| V⁵⁺ | 0.005 | 0.007 | 0.012 | 0.012 | 0.011 | 0.020 | 0.017 | 0.007 | 0.008 | 0.007 |
| Sr⁴⁺ | 0.003 | 0.003 | 0.003 | 0.004 | 0.003 | 0.003 | 0.003 | -     | 0.004 | -     |
| Total B | 1.977 | 1.983 | 1.969 | 1.966 | 1.956 | 1.916 | 1.894 | 1.982 | 1.979 | 1.967 |

Formula Coefficients

| Mi²⁺ | 0.054 | 0.040 | 0.038 | 0.025 | 0.024 | 0.038 | 0.026 | 0.031 | 0.028 | 0.033 |
| Fe³⁺ | 0.922 | 0.958 | 0.973 | 1.005 | 1.018 | 0.947 | 0.987 | 0.993 | 0.983 | 0.960 |
| Mn²⁺ | 0.019 | 0.020 | 0.020 | 0.023 | 0.023 | 0.020 | 0.022 | 0.019 | 0.022 | 0.022 |
| Zn²⁺ | 0.013 | 0.012 | 0.012 | 0.008 | 0.008 | 0.007 | 0.007 | 0.009 | 0.007 | 0.007 |
| Total A | 1.008 | 1.030 | 1.043 | 1.061 | 1.073 | 1.012 | 1.042 | 1.052 | 1.040 | 1.022 |
Table 2. Cont.

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<td>1882/326.3 (2)</td>
<td>1882/326.3 (3)</td>
<td>1882/326.3 (4)</td>
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<td>97.013</td>
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Formula Coefficients

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The main differences between the two varieties in sample 1880/342.7 are as follows (Table 2). Chr-1 shows higher contents of Al₂O₃ (11.4–15.6 wt.%) and MgO (0.73–1.09 wt.%), but lower contents of TiO₂ (0.4–1.8 wt.%), % and FeO_total (38.8–42.7 wt.%). Chr-2 has lower contents of Al₂O₃ (5.2–9.5 wt.%) and MgO (0.43–0.72 wt.%), but higher contents of TiO₂ (0.5–2.8 wt.%), % and FeO_total (39.1–45.2 wt.%).

Orthopyroxenite (sample 1880/395.8) contains rarely disseminated magnetite and Cr-magnetite with the Cr₂O₃ content up to 14.7 wt.% (Table 2). This sample was taken from the lower part of the section, at the level of near-contact rocks. Cr-spinel in sample 1882/326.3 (melanocratic olivine norite, medium-grained) is represented by the high-aluminous variety Chr-1 (Figure 8a,b, Table 2). Cr-spinels in sample 1882/486.5 (melanocratic olivine norite, medium-grained) widely vary compositionally from the utmost high-aluminous and high-magnesian to Cr-magnetite varieties (Figure 8c–f).

![Figure 8](image-url)

**Figure 8.** Cr-spinels in the rocks of the Nude-Poaz massif. (a,b) sample 1882/326.3, Chr-1—high-aluminum Cr-spinel, (c–f) sample 1882/486.5. Opx—orthopyroxene, Pl—plagioclase, Ol—olivine, Cr-Mag—Cr-magnetite. Back-scattered electron (BSE) images.

Figure 9 provides all data available on the composition of Cr-spinels and magnetite from the Nude-Poaz massif, including those from [34,35]. The Mg vs. Al variation diagram clearly shows the division of the two varieties. This separation is also outlined in the Mg...
vs. Ti variation diagram. The Mg vs. Fe$^{2+}$ plot shows a clear inverse relationship. At the same time, in terms of the Cr, V, Mn, Zn, and Ni content, the plots show no differences between the two varieties of Cr-spinels from the Nude-Poaz massif.

![Variational diagrams of the composition of Cr-spinels of the Nude-Poaz massif.](image)

Test results on Cr-spinels from the drill holes 1880 and 1882 and data from [34,35] were also provided on diagrams in [1]. They were plotted based on statistical processing of a large number of analyses of the spinel group minerals (Figure 10) to reflect major compositional signatures of Cr-spinels. The diagrams clearly show that analyses of the samples from the Nude-Poaz massif fall into the Cr-spinel fields from the known layered intrusions. The diagrams also indicate the Fe-Ti trend for Cr-spinels of the Nude-Poaz massif, which is characteristic of most layered intrusions [1]. Notably, two morphological varieties of Cr-spinels recorded in samples from the Nude-Poaz massif produce no separate fields in diagrams in Figure 10 but fit into a single trend.
The diagrams (Figures 11 and 12) compare Cr-spinels from the Nude-Poaz massif with those from other massifs of the Monchepluton, including ore chromites of the Sopcheozero deposit. As the figures show, single data on the NKT massif suggest that Cr-spinels from this massif are close to chromites from poor ores of the Sopcheozero deposit. A more complex picture is observed for Cr-spinels from the Ore Layer 330 in the Sopcha massif, i.e., they are clearly divided into two areas: more chromous and more ferruginous. At the same time, the ferruginous Cr-spinel varieties from the Nude-Poaz massif are quite similar to those from the Ore Layer 330.

Figure 10. Trivalent ion plots (a), $\text{Fe}^{3+}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$ vs. $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$, $\text{Cr}/(\text{Cr} + \text{Al})$ vs. $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$ and $\text{TiO}_2$ vs. $\text{Fe}^{3+}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$ (b–d) for continental mafic intrusions (red lines) and Nude-Poaz Cr-spinels. Modified after [1].

Figure 11. Trivalent ion plot for Nude-Poaz Cr-spinels and chromites from Sopcheozero deposit. Modified after [22].

Figure 12. Irvine diagram [2] for Cr-spinels of the Nude-Poaz massif and chromites of the Sopcheozero deposit. Modified after [22].
6. Discussion

Comparison of Cr-spinels from the Nude-Poaz massif with those from other MC massifs (ore chromites of the Sopcheozero deposit, first of all) yielded the following regular features. We should first refer to the comparison with Cr-spinels from the Monchetundra intrusion, which genetic link to MC is the most debated.

According to [34], the Monchetundra intrusion and Monchepluton are regular parts of a single MC section. Gabbronorites and metagabbros of the Monchetundra intrusion are depleted in chromium compared to gabbroids from the Monchegorsk pluton, especially the Nude-Poaz massif. At the same time, ultramafic differentiates from the Monchetundra intrusion similar to those from the Monchepluton have an increased content of Cr$_2$O$_3$ of up to 1 wt.% in dunites [34]. In general, Cr-spinels show a decreasing trend for the Mg content from dunites and peridotites to the upper parts of the Monchetundra section [34]. These data comply with the patterns revealed for most of the layered intrusions over the world [1].

Next, let us consider some similar and peculiar features of Cr-spinels from the Nude-Poaz and other massifs in the Monchepluton. The paper [22] studied varied compositions of Cr-spinels for the entire set of ore and accessory Cr-spinels of the Dunite block and the whole Monchepluton. It shows that the set of ore Cr-spinels clearly differs from the set of accessory Cr-spinels. Ore chromites are highest in Cr, while accessory varieties are more ferruginous. Cr-spinels from various parts of the section produce a clear evolutionary Fe-Ti trend (except for the special case of the Ore Layer 330), which is typical of layered intrusions [1]. In general, this trend shows a successive replacement of magnesian-chromium Cr-spinels for ferruginous-titanium varieties from early to late crystallization stages of intrusions. At the same time, if the crystallization process was not strongly affected by new portions of magma, this trend is reflected in the section of intrusions—from their lower (ultramafic) to upper (more mafic) parts. This general trend in the compositional evolution of the Monchepluton Cr-spinels is clearly seen in Figure 10.
The Al content is low in all Cr-spinels (Figure 10). Ore chromites of the Sopcheozero deposit are highest in Cr and lowest in Fe$^{3+}$ and Fe$^{2+}$. Cr-spinels from host rocks of the Sopcheozero deposit are more aluminous and ferruginous compared to ore chromites. The trend for changing the composition of Cr-spinels in the NKT massif shows a widely ranged Fe$^{3+}$ content. Cr-spinels from an ore occurrence at Mt. Kumuzhya of the NKT massif [27] occupy an intermediate position between ore chromites and accessory Cr-spinels of the Sopcheozero deposit. Points for compositions of Cr-spinels from each object produce fairly clear compact fields. The general evolutionary trend for MC Cr-spinels corresponds with trends for layered intrusions in the world [1]. At the same time, Cr-spinels from some MC massifs, the Monchepluton, first of all, have a number of peculiar features. They are particularly clear in two levels of repeated occurrence of olivine rocks in the Monchepluton section, i.e., the Ore Layer 330 in the Sopcha massif and the Critical Horizon in the Nude-Poaz massif.

Thus, zoning of Cr-spinels is observed in rocks from the Ore Layer 330 of the Sopcha massif. Some authors [15,49] noted that the chemical composition of orthopyroxene and olivine in rocks from the Ore Layer 330 was heterogeneous; the same sample contained grains of these minerals with varied iron content. These authors investigated the composition of accessory Cr-spinel as inclusions in olivine and orthopyroxene, as well as grain clusters in interstices of silicate grains. The researchers noted significantly varied concentrations of chromium, iron, magnesium, and aluminum even in one polished section and in optically homogeneous grains. Compositional variations are further enhanced in zoned Cr-spinel grains [15,49]. D.A. Orsoev studied zoned Cr-spinels of the Ore Layer 330 and showed that the core parts of the grains were higher in Al, Mg, and Cr, but lower in Ti and Fe compared to the rims [31].

Such zoning in the rocks of the Ore Layer 330 was explained by an inflow of fresh melt portions and subsequent mixing of magmas. For example, former researchers of the Ore Layer 330 suggested the magmatic origin of zoning in Cr-spinels due to changes in physical-chemical conditions during the magma crystallization [15,31,34,50]. In their opinion, the study results for rocks and minerals from the Ore Layer 330 indicate the violated equilibrium of the melt crystallization processes. It is suggested that at a certain stage of orthopyroxenite crystallization at Mt. Sopcha, even before their complete consolidation, a new portion of high-temperature magmatic melt compositionally close to peridotite intruded with several pulses [15].

Noteworthy, Cr-spinels in the Ore Layer 330 area of the Sopcha massif compositionally differ from similar formations, e.g., the Penikat intrusion (Finland), where Cr-spinels from new portions of magma are not zoned. It is known that this intrusion dated at 2440–2410 ± 64 Ma [51] contains a marginal series and five megacyclic units with an ultramafic cumulate at the basement of each unit [52]. In each cycle, Cr-spinels are associated with lower parts, i.e., orthopyroxenites, olivine ootopyroxenites, and peridotites [52]. It implies that intrusion of new melt portions during the formation of the Ore Layer 330 had specific features that affected the composition of Cr-spinels.

The Nude-Poaz massif composed of norites mainly is much lower in Cr-spinels compared to the Dunite block, NKT, and Sopcha massifs (Ore Layer 330). Cr-spinels of the Nude-Poaz massif occurs in the lower part of the section, within a lens represented by orthopyroxenites and olivine norites (including rocks of the Critical Horizon as well). The Cr-spinel mineralization is traced at different levels within the lens in orthopyroxenites, as well as in the zone of its lower contact with plagioharzburgites and melanocratic olivine norites, where Cr-spinels are confined to the latter. No Cr-spinels were actually found in norites above these rocks. It may suggest that the Nude-Poaz massif itself is a product of intrusion of several melt portions that differ geochemically, which is also emphasized by different distribution patterns of the Cr-spinel content.

Cr-spinels of the Nude-Poaz massif mostly occurs as intergrowths in orthopyroxene grains. They are represented by two morphological varieties that also differ in composition. It can be observed both under a microscope (Cr-spinels of the first type (Chr-1) are more
homogeneous in composition, while Cr-spinels of the second type (Chr-2) contain many small inclusions of ilmenite) and according to geochemical data. Importantly, these two varieties are found within the same thin section and even a separate pyroxene grain, which was not previously noted for the Monchepluton chromites. As for zoned Cr-spinels of the Ore Layer 330, these two varieties in the Nude-Poaz massif reflect specific evolution of the magmatic melt and features of the crystallization process. In particular, this indicates that the composition of Cr-spinel at the early stages of the melt crystallization was unstable. Notably, more aluminous and more titaniferous Cr-spinel separated from the melt simultaneously. The titaniferous Cr-spinel was rather unstable and decomposed with the formation of ilmenite lamellas.

The comparison of chrome spinels from the Nude-Poaz massif with ore chromites from the Sopcheozero deposit suggests the following. They are more ferruginous and magnesian, somewhat more aluminous, but less chromous than chromites from the Sopcheozero deposit. Importantly, ore chromites from the Sopcheozero deposit have varieties that differ in their chemical composition [22]. However, chromite varieties of the Sopcheozero deposit occupy different positions in the rock (one is inside silicate grains, the other is at the boundaries between them [22], which is typical, by the way, for some other layered massifs—for example, for Yoko-Dovyrensky [53]). There is no such clear confinement of Cr-spinel varieties to a certain structural position in the Nude-Poaz massif. As for chromites from the Sopcheozero deposit, these varieties are associated with the stages of their formation. Chromites are attributed to the early generation or pre-olivine crystallization phase (its volume in the rock does not exceed 1%) as small (0.005–0.05 mm) inclusions in olivine (less often in orthopyroxene). Bulk ore chromites of the Sopcheozero deposit crystallized just behind this generation. Chromites of the late generation occur in interstices between orthopyroxene or olivine [22]. The late generation is chemically close to the early one. According to the authors, this may be due to the low potential of oxygen fugacity during crystallization of the ore melt, which is also emphasized by the absence of late magmatic replacement of chromite by magnetite [22]. As mentioned above, the formation of Cr-spinel in the Nude-Poaz massif was associated with the crystallization of more aluminous and titaniferous Cr-spinels.

Since the Monchepluton is a polyphase massif [10, 14, 15, 47], the composition of Cr-spinels reflects the evolution of intrusion of these phases. Ore chromites occur in early ultramafic phases composing the lower parts of the section (Dunite block with the Sopcheozero chromite deposit). They show increased contents of magnesium and chromium, as well as an unstable composition of chromites, producing different types in silicate grains and at their boundaries (Sopcheozero deposit). According to [9], the temperature of chromitites formation of the Sopheozoero deposit averages 758 °C, and the host dunites −594 °C. It is noted that the formation of high-Cr and low-Fe chromites occurs at minimal values of oxygen fugacity, and ferrous varieties are formed under more oxidizing conditions [9]. According to [35], crystallization of Cr-spinels in the MC occurred at a slowly decreasing temperature and gradually increasing oxygen fugacity.

Accessory Cr-spinels occur both at the bottom of the Monchepluton section (Dunite block, NKT massif) and higher, tending to additional phases with olivine rocks (Ore Layer 330 of the Sopcha massif, Critical Horizon of the Nude-Poaz massif). They are more ferruginous and titaniferous than ore chromites of the Sopcheozoero deposit. In the case of the Ore Layer 330, we apparently witness a fairly rapid and short-term intrusion of several subphases, which mixing is marked by the changed composition of minerals and their zoning (including Cr-spinel). The intrusion of a more protracted (and voluminous, compared to the phase that formed the Ore Layer 330) phase into the lower part of the section of the Nude-Poaz massif resulted in its normal crystallization occurred in line with the general evolutionary trend. At the same time, the Cr-spinel composition was also unstable. Morphological differences in the studied Cr-spinels from the Nude-Poaz massif indicate that minor variations in the Al, Mg, Fe, and Ti contents caused some structural
rearrangements in the Cr-spinel crystal lattice. In particular, Cr-spinels of the second variety (Chr-2) contain a significant proportion of ulvospinel mineral.

The upper parts of the MC section (upper leucocratic parts of the Monchetundra intrusion, leucogabbro-anorthosites of the Vurechaivanch massif) contain no Cr-spinels, while ilmenite and magnetite are present as accessory minerals.

7. Conclusions

1. As a result of the deep drilling of the Nude-Poaz massif, features of its internal structure were studied. The study of about 200 samples from the core of drill holes 1880 and 1882 revealed quite rare samples with the accessory Cr-spinel mineralization. This mineralization proved to be directly related to the rocks of the so-called Critical Horizon (olivine norites).

2. The study of Cr-spinels revealed that they form 2 (Chr-1 and Chr-2) morphological types (some more homogeneous, others with inclusions of ilmenite), also differing in chemical composition (some are higher in aluminous, others in titanium). At the same time, such varieties were first found in MC not only in one thin section but even in one orthopyroxene grain.

3. In the Monchepluton, ferruginous Cr-spinel varieties of the Nude-Poaz massif are chemically close to ferruginous Cr-spinel varieties of the Ore Layer 330 in the Sopcha massif. At the same time, Cr-spinels of the Nude-Poaz massif are compositionally different both from accessory Cr-spinels of the NKT massif and from ore chromites of the Sopcheozero deposit. Compared to the latter, Cr-spinels from the Nude-Poaz massif are more ferruginous and less chromium-rich.

4. In comparison with layered intrusions known in the world, accessory Cr-spinels from the Nude-Poaz massif fit into the characteristic Fe-Ti trend for their chemical composition, which is observed from early to later intrusive phases. During the magmatic phase that produced rocks of the Critical Horizon and Cr-spinels of the Nude-Poaz massif, its normal crystallization occurred in the framework of the general evolutionary trend.

5. The formation of Cr-spinels in the Nude-Poaz massif was specifically marked by their unstable composition, which manifested in simultaneous crystallization of varieties higher in alumina and titanium.

Supplementary Materials: The following materials are available online at https://www.mdpi.com/article/10.3390/min11060602/s1, Table S1: Chemical composition of orthopyroxene and plagioclase from rocks of the Nude-Poaz massif.

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