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Paleoproterozoic East Pana Layered Intrusion (Kola Peninsula, Russia): Geological Structure, Petrography, Geochemistry and Cu-Ni-PGE Mineralization

Pavel Pripachkin *, Tatiana Rundkvist and Nikolay Groshev

Geological Institute—Subdivision of the Federal Research Centre, Kola Science Centre of the Russian Academy of Sciences, Fersman St. 14, Apatity 184209, Russia; t.rundkvist@ksc.ru (T.R.); nikolaygroshev@gmail.com (N.G.)
* Correspondence: pripaul@rambler.ru

Abstract: The East Pana intrusion is a part of the Paleoproterozoic Fedorova–Pana complex (FPC), which belongs to the group of Fennoscandian layered mafic–ultramafic massifs. This article discusses the magmatic stratification of the East Pana intrusion, as well as Cu-Ni and platinum-group elements (PGE) mineralization (PGE zones A, B and C) in its various parts with a total length of more than 20 km, including the East Chuarvy PGE deposit. Based on the whole-rock data on the distribution of major, trace, and ore-forming elements, it is assumed that PGE zone A belongs to the main ore–magmatic system of the FPC, while PGE zones B and C belong to the minor ore–magmatic systems. At the same time, additional magmatic injection played an important role in the formation of economic Cu-Ni-PGE mineralization (PGE zone B), characterized by high PGE concentrations and moderate palladium enrichment. On the normalized distribution spectra of trace elements, the crystallization products of this injection (Gabbronorite Zone 2) have a positive Zr-Hf anomaly, which distinguishes it from host rocks with an anomaly of the opposite sign (Gabbronorite Zone 1, Gabbro Zone). It is assumed that this portion of magma was intruded as a sill of crystal mush, the fractionation of which at depth led to its enrichment with residual liquid.

Keywords: layered intrusions; mafic rocks; Cu-Ni-PGE mineralization; East Pana intrusion; Kola Peninsula

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1. Introduction

Active exploration work carried out within the Paleoproterozoic layered intrusions of the Fennoscandian Shield in recent years made it possible to estimate the reserves of platinum group elements (PGE) in them. PGE are the main useful components of ores with subordinate values of Cu, Ni, and Au [1–5]. The largest reserves are concentrated in the Finnish intrusions of Kontiyarvi, Akhmavaara and Narkaus in the Portimo complex and in the Penikat intrusion, as well as in the Russian intrusions of Vuruchuaivench, Monchetundra and South Sopcha of the Main Ridge and Monchegorsk complexes and within the Fedorova, West Pana and East Pana intrusions of the Fedorova–Pana layered complex. The most remote of them is the East Pana intrusion. Nevertheless, in 2006 the East Chuarvy PGE deposit was discovered there for the first time in the Kola Peninsula [6–8].

Since the so-called PGE zone B, hosting the East Chuarvy deposit, [9] is ~400 m away from the lower contact of the intrusion, the deposit can be attributed to the reef type of PGE mineralization, which is characterized by ore bodies extending for tens of kilometers with a thickness of only a few meters. In contrast to the well-known continuous Merensky and UG-2 reefs in the Bushveld complex [10] and the J-M reef in the Stillwater massif [11], the PGE zone B extends for 17 km along scattered mineralization points found in eluvium and is not always confirmed in drill holes. Many mineralized levels of the Fennoscandian layered intrusions are discontinuous and have similar characteristics: e.g., the FT-1 and FT-2 reefs in the Fedorova intrusion [12,13], the South Reef, and the extremely PGE-rich discontinuous sulfide zones of the Olivine Horizon in the West Pana massif [14,15], as well as a number of PGE reefs in Finnish intrusions [2]. The size of the East Chuarvy deposit within the PGE zone B is small—only a few tons of precious metals [7]. However, the study of the ore body associated with the discontinuous zone of PGE mineralization is important for understanding the key process responsible for its formation and prospecting of new PGE deposits in discontinuous ore zones, which are widespread not only in the Fedorova–Pana complex but also in Fennoscandia as a whole.

This article presents an attempt to characterize the most important ore-forming processes of the East Pana intrusion by summarizing data on the geological structure and geochemical features of the PGE mineralization, as well as the result of a review study of petrography, the composition of rock-forming minerals and the geochemistry of representative rock types throughout the intrusion section.

2. Geological Structure and Ore Potential of the East Pana Intrusion

2.1. History of Geological Exploration

The East Pana intrusion (or massif) is a part of the Fedorova–Pana Paleoproterozoic layered ultramafic–mafic complex (FPC) located in the central part of the Kola Peninsula (Figure 1). The century-long history of the study of FPC, originating in the first decades of the last century, is described in detail in [16].

In 1979, scientists from the Geological Institute of the Kola Branch of the USSR Academy of Sciences determined there were elevated PGE contents (up to 4–5 ppm) in samples with sulfide copper-nickel mineralization from the Fedorova, Lastyavr, and West Pana massifs. They also discovered for the first time in the ores of Massiv-1 (a part of the Fedorova massif) a palladium-bearing mineral, merenskyite [17].

In the 1990s, the Geological Institute of the Russian Academy of Sciences (GI KSC RAS) began the search for industrial PGE mineralization in the FPC massifs. To carry out these works, GI KSC RAS established the Russian geological exploration company—JSC Pana. In turn, JSC Pana found interested investors for this project—BHP Billiton, Barrick Gold Corporation and Bema Gold Corporation. As a result of cooperation with a number of other Russian companies—JSC Central Kola Expedition, JSC Murmansk Exploration Expedition, LLC Ural Minerals and JSC Urangeo—it was possible to include several PGE deposits in the state balance sheet, which, as expected, belong to the main ore–magmatic system of the FPC [13]: in 2007, the Fedorova Tundra deposit; in 2008, the Kievey deposit in the West Pana massif [18,19]; and in 2015, the North Kamennik deposit also in the West Pana massif [5].

Until the 1990s, the East Pana intrusion was poorly studied, because no significant sulfide mineralization was found there. However, following the successful prospecting and exploration work for PGE in the Fedorova and West Pana massifs, the same work was launched in the mid-1990s within the East Pana massif.

Thus, in 1995–1998 JSC Pana searched for PGE mineralization in the most exposed areas of the East Pana massif: Sungyok, Chuarvy, East Chuarvy, Churozero and Predgorny (Figure 1). Geologists S.M. Karpov, V.V. Subbotin and A.N. Kulakov found ore occurrences with high PGE contents here [16]. The employees of the GI KSC RAS at the Sungyok and Chuarvy sites also studied zones of postmagmatic rock transformations that could be associated with the PGE mineralization [20].

In 2000, JSC Pana continued prospecting at the Churozero site. At the same time, the staff of the GI KSC RAS began to study in detail the PGE mineralization of East Pana intrusion, mainly in the Sungyok area. The ores were found to belong to the low-sulfide type with a sulfide content in the rock of no more than 0.1% and a very fine (less than 0.5 mm) grain size. The sulfides are mainly represented by pentlandite, chalcopyrite and pyrrhotite; platinum group minerals (PGM) and noble metal minerals are represented by moncheite, kotulskite, merenskyite, electrum and, to a lesser extent, by cooperite and isoferroplatinum [21].

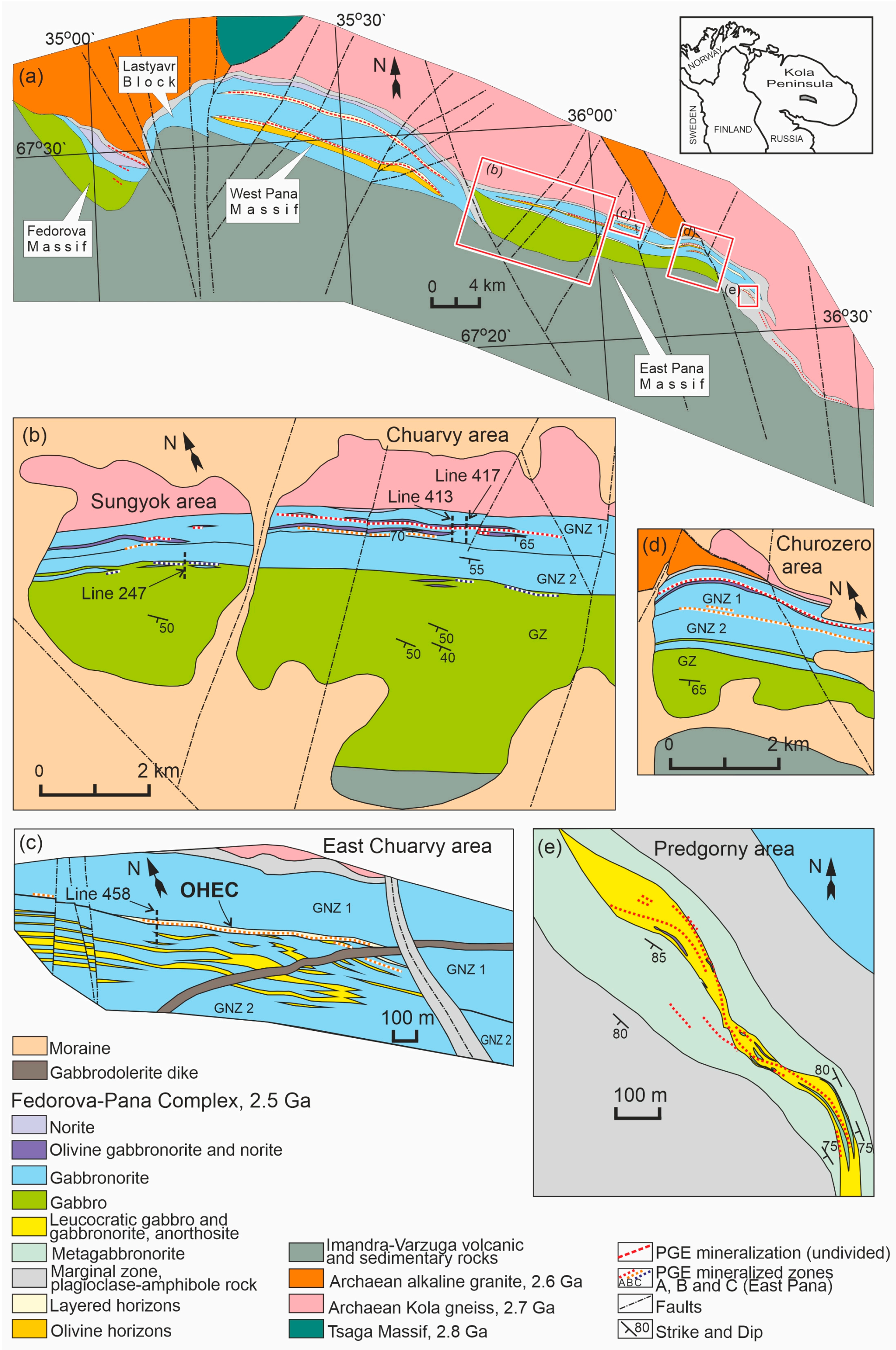

Figure 1. Geological scheme of the Fedorova–Pana layered complex (**a**) and detailed areas of the East Pana massif (**b**–**e**). OHEC—Ore Horizon of the East Chuarvy deposit. Modified after [6,22].

In 2002–2005, JSC Pana, together with the representative of Bema Gold Corporation in Russia, KMGK LLC, performed prospecting and appraisal work at the Churozero, Predgorny and East Chuarvy sites. As a result of these works, a new industrial PGE prospect was identified within the East Pana massif—the East Chuarvy deposit. The reserves of PGE (with an average total PGE + Au content of 7.9 ppm) were calculated for this site and subsequently included in the balance sheet of the State Committee on Reserves in 2006 [7].

Researchers from the GI KSC RAS studied the sulfide and PGE mineralization of the East Chuarvy deposit [23–27]. Low-sulfide ores are mainly represented by pyrrhotite, chalcopyrite and pentlandite, while the overall average sulfide content of the ore is about 0.6 wt%. The main mode of PGE occurrence in ores in the East Chuarvy deposit, similar to most large low-sulfide deposits in the world, are PGM and solid solutions of Pd in pentlandite. In medium-quality ores, approximately half of the total Pd is concentrated in pentlandite [25].

More than 20 PGM and gold minerals and several unnamed mineral phases have been identified in the ores of the East Chuarvy deposit. The most common precious metal minerals are listed in order of abundance: cooperite-braggite (Pt,Pd,Ni)S, kotulskite Pd(Te,Bi), vysotskite (Pd,Pt,Ni)S, sperrylite $PtAs_2$, moncheite $(Pt,Pd)(Te,Bi)_2$, stillwaterite Pd_8As_3, palladoarsenide Pd_2As, keitconnite $Pd_{3-x}Te$, merenskyite $(Pd,Pt)(Te,Bi)_2$ and gold (Au,Ag,Pd) [24–26]. A new mineral—mitrofanovite (Pt_3Te_4) was discovered in the low-sulfide disseminated ore of the East Chuarvy deposit. The mineral was named after Academician F.P. Mitrofanov, who made a great contribution to the study of the FPC [27].

2.2. Regional Position

An important point in creating a model for the evolution of the Paleoproterozoic layered mafic–ultramafic intrusions and the genesis of their ore mineralization was the concept of mantle plumes—hot mantle flows that can produce manifestations of basic magmatism at a considerable distance from plate boundaries [28–34]. This concept was widely applied to the layered intrusions of the Kola region by Academician F.P. Mitrofanov [35–37]. At the same time, the authors drew attention to the fact that the intrusive massifs of the northeastern part of the Fennoscandian Shield, which have an established metallogenic specificity, constitute elongated extended belts in the northern part of the province—the Kola (northwestern strike) and Fenno–Karelian (northeast strike) with a concentration of massifs in the area of the Monchegorsk ore cluster [37].

According to F.P. Mitrofanov and his colleagues, during the Early Paleoproterozoic (2550–1980 Ma), the most favorable for the formation of Pt-Pd ores was the Sumian stage, which is closely associated with intrusive magmatism of high-Mg siliceous, boninite-like and anorthositic magma [38,39]. Within the Kola Belt, the main representative of these ore-bearing intrusives is the FPC (2530–2450 Ma); within the Fenno–Karelian Belt, there are also several characteristic examples with an age of 2450–2400 Ma [37].

The FPC, which includes the East Pana massif (Figure 1), is one of the largest intrusions of this type in the Fennoscandian Shield [40]. The geotectonic position of the layered intrusions of the Kola Belt (Mount Generalskaya, massifs of the Main Range and Monchegorsk layered complexes, FPC) is of the same type at the boundary of the Lower Proterozoic sedimentary–volcanogenic rocks of the Pechenga–Imandra–Varzuga paleoriftogenic structure with the Archean basement rocks.

In the modern erosional section, the length of the East Pana intrusion is more than 30 km, the width is from 0.5–0.6 km to 6–7 km and the total area is about 105 km^2. To the south, the East Pana intrusion is in contact with the rocks of the Imandra–Varzuga zone. The northern contact of the East Pana massif dips steeply to the south at an angle of 60–80°, and the dip of the rocks varies from 50° in the western part of the intrusion to 60–70° in its central and eastern parts. Alkaline granites and Archean granite gneisses are in contact with the massif in the northern part almost throughout its entire length (Figure 1) [22,41,42].

2.3. Magmatic Stratification

Until the early 2000s, many researchers considered the FPC to be initially a single intrusive body, subsequently broken up into tectonic blocks that were displaced relative to each other and, as a result, eroded to varying degrees [41,43–45]. According to this model, the two largest FPC blocks are the Fedorova and Pana massifs, separated by the thick Tsaga fault zone. Directly in the fault zone is the Lastyavr block, which includes Massif-1, which is similar in composition to the Fedorova massif, and a number of smaller bodies. The Pana massif, in turn, is divided by submeridional tectonic faults into the West and East Pana blocks.

Based on this approach, it was believed that the FPC section contains a syngenetic series of rocks from peridotites to gabbro. Proponents of this model believed that the blocks were significantly displaced relative to each other in the horizontal and vertical directions, which caused various parts of the FPC section to outcrop on the surface. Thus, the zone of ultramafic rocks (plagiopyroxenites) exists only in the Lastyavr block; norites are predominant in the Fedorova block, gabbronorites predominate in the West Pana block and gabbro in the East Pana block.

Differences in the structure of geological sections and individual stratigraphic horizons in the FPC blocks (along with the explanation of this fact using complex tectonic constructions) convinced a number of researchers of an alternative point of view. The FPC massifs, according to the latter, are previously isolated magma chambers, although they are united by a single source and a close time interval of formation [5,13,16,18,46]. Based on this theoretical approach, these researchers proposed to allocate independent massifs as part of the FPC: Fedorova, Lastyavr, and West and East Pana (Figure 1). At the same time, the isotopic age of intrusion of various phases ranges from 2526 $\pm$ 6 (orthopyroxenites) to 2485 $\pm$ 9 (gabbronorites) Ma for the Fedorova massif [47]; for the West Pana massif, from 2491 $\pm$ 1.5 (gabbronorites) to 2509 $\pm$ 6.2 (anorthosites) Ma [15,37]; and for the East Pana massif, from 2464 $\pm$ 12 (gabbro-pegmatites) to 2487 $\pm$ 10 (gabbro) Ma [41,48].

This article proposes a simplified scheme for the geological structure of the East Pana intrusion by O.V. Kazanov [6,49] used to put the East Chuarvy deposit on the state balance sheet [7]. In the section of the East Pana intrusion, the following are distinguished (Figures 1 and 2): the lower marginal zone (MZ), gabbronorite zone 1 (GNZ 1), gabbronorite zone 2 (GNZ 2) and gabbro zone (GZ).

The MZ is a band of predominantly altered fine-grained gabbronorites 30–50 m wide at the contact of the intrusion with Archean rocks. Fine-grained olivine gabbronorites were found at the Chuarvy site, which, apparently, are rocks of the East Pana intrusive endocontact [42].

The GNZ 1, composed mainly of taxitic gabbronorites, stretches out the entire length of the intrusion. The maximum thickness of the zone is reached at the Churozero site and is 550 m. Two subzones can be distinguished in the section: GNZ 1a and GNZ 1b (Figure 2A–C). Taxitic gabbronorites with fine-to-medium grain size dominate within GNZ 1a. GNZ 1b is characterized by a more complex structure. In addition to the predominant poikilitic gabbronorites, medium-grained olivine gabbronorites, as well as leucogabbro, norites, pyroxenites and pegmatoid gabbroids are widespread there (Figure 3). The upper part of GNZ 1b at the East Chuarvy site (Figure 2C) is characterized by pronounced petrographic and textural diversity and is identified as the East Chuarvy Ore Horizon (OHEC).

The GNZ 2 is distinguished in the stratigraphy of the East Pana intrusion by the simplest geological structure with a predominance of medium-grained gabbronorites. The thickness of GNZ 2 varies from 350 to 1000 m. Melanocratic gabbroids and pyroxenites occur at the base of the zone in the form of extremely thin and discontinuous layers. Leucocratic gabbroids form sparse layers in the middle and upper parts of GNZ 2 (Figures 1c and 2C).

The GZ, about 3000 m thick, is mainly composed of coarse-grained leucogabbro, among which are interlayers of leucogabbronorite, pigeonite gabbronorite and olivine gabbro are present. The latter occurs at two levels of the zone section: in the lower part, at the contact with GNZ 2, and in the middle part, 1100 m from the base of the GZ.

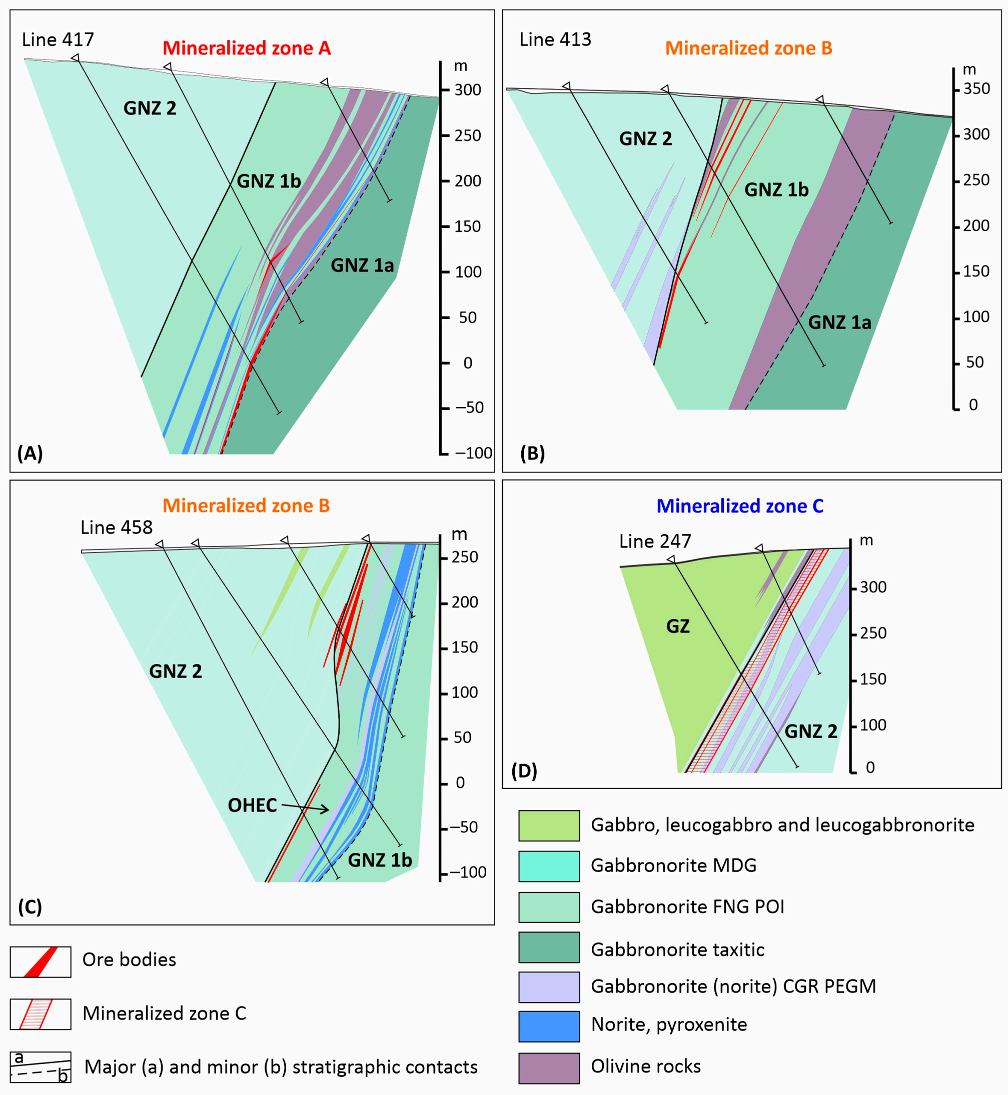

Figure 2. Schematic geological sections through the PGE zones of the East Pana intrusion: PGE zone A (**A**), PGE zone B (**B**,**C**), PGE zone C (**D**). GNZ, gabbronorite zone; GZ, gabbro zone, OHEC, Ore Horizon of the East Chuarvy deposit; FNG, fine-grained; MDG, medium-grained; CGR PEGM, coarse-grained to pegmatoid; POI, poikilitic. Lines of geological profiles and their location within the areas are shown in Figure 1. Modified after [50].

Figure 3. Rocks of the East Pana massif (outcrops in the Sungyok area): layering in gabbronorites from GNZ 1, Pavel Pripachkin for scale (**a**), anorthosite layers (**b**,**c**), olivine gabbronorites (**d**), olivine crystals are clearly visible on the weathered surface (**e**).

2.4. Levels of Sulfide Cu-Ni-PGE Mineralization

The PGE mineralization studied in the Sungyok, Chuarvy, East Chuarvy, Churozero and Predgorny areas (Figure 1) is located at three levels of the East Pana massif, called PGE zones A, B and C [6]. Each zone is confined to the boundary of a stratigraphic unit (GNZ 1b, GNZ 2 and GZ) and differs from the others in geochemical characteristics.

PGE zone A is located within GNZ 1 where it is associated with the lower part of fine-grained poikilitic gabbronorite interbedded with olivine rocks (GNZ 1b subzone; Figure 2A). PGE zone A has been traced for more than 20 km along the strike and is represented in the Sungyok, Chuarvy, East Chuarvy, Churozero and Predgorny sites. The mineralized rocks are characterized by relatively high sulfide content (up to 5 vol.%) and significant enrichment in palladium (Pd/Pt = 5–6). The richest intersection is located at the Chuarvy site, where the ore zone, consisting of three ore bodies with a total thickness of 7 m, contains 0.8 ppm Pt and 3.4 ppm Pd [9].

PGE zone B is closely associated with the contact between GNZ 1 and GNZ 2, mostly located within GNZ 1 (Figure 2B,C). The mineralization of PGE zone B was traced in the occurrences of the Sungyok, Chuarvy and East Chuarvy deposits. The amount of sulfides in mineralized rocks varies in the range of 0.5–2 vol.%, Pd/Pt ratio, 1.5–2.5. The concentrations of Pt and Pd in the ore of the East Chuarvy deposit average 2.4 and 5.2 ppm, respectively [7].

PGE zone C, confined to the boundary between GNZ and GZ (Figure 2D), was found only in the western part of the East Pana massif, within the Sungyok and Chuarvy sites. The mineralized rocks are characterized by an almost complete absence of visible sulfides and are enriched in platinum (Pd/Pt < 1). In the drill hole in the Sungyok area, PGE zone C has a thickness of 1.6 m and a total PGE content of 2.1 ppm [7].

Thus, PGE mineralization is regularly distributed along the section of the East Pana intrusion and changes from bottom to top from the relatively sulfide- and palladium-enriched to the virtually sulfide-free platinum-enriched mineralized rocks.

3. Materials and Methods

During the period from 2000 to 2015, the authors participated in the exploration of the FPC, which include geological mapping, drill core documentation and petrographic studies of the East Pana intrusion jointly with LLC KMGC and other organizations. Part of the author's materials on geology, petrography and mineralogy of the East Pana massif were included in the internal reports of JSC Pana and LLC KMGC. The results of these studies were partially published [6,7,9,51–53]. In this article, we present mostly unpublished material collected during exploration work.

The petrographic characteristic is based on the study of 700 thin sections using an Axioplan microscope and is supplemented by 57 microprobe analyses of rock-forming minerals (Supplementary Materials Tables S1–S6). The chemical composition of minerals was determined by an electron probe microanalyzer (Cameca MS-46, Paris, France) at an accelerating voltage of 22 kV and probe current of 30–40 nA. Artificial and natural compounds were used to determine Si, Ca (wollastonite), Al ($Y_3Al_5O_{12}$), Na, Ti (lorenzenite), Mg (forsterite), Fe (hematite), Mn ($MnCO_3$) and K (wadeite).

When the grains were very small, the composition of mineral phases was measured using a scanning electron microscope (SEM), LEO-1450 (Carl Zeiss, Oberkochen, Germany) and a Bruker Quantax-200 energy dispersive detector (Bruker, Bremen, 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).

The geochemical composition of the Cu-Ni-PGE mineralization is based on a core sampling of drill holes and is included in the open [42] and internal reports of JSC Pana [22,54], as well as in the final report on the East Chuarvy deposit [50]. The analyzes of Au, Pt, Pd, Cu, Ni and S were carried out in the laboratory of CJSC "Regional Analytical Center Mekhanobr Engineering Analit", St. Petersburg (Russia). Analysis for Au, Pt and Pd was performed in accordance with the author's method of this laboratory for assay (Pb) atomic absorption determination, certified in the form of enterprise standards STP 1402.151.1-96 (assay concentration itself) and STP 1402.151.0-96 (atomic absorption definition). Atomic absorption determination of the content of noble metals was performed sequentially from a single solution with atomization in an acetylene–air flame on a PERKIN-ELMER 603 atomic absorption spectrophotometer (PERKIN-ELMER, Waltham, MA, USA).

To study the geochemical features of the PGE zones A and B, 641 analyses were used (Table 1), in which the sum of Pt + Pd + Au exceeds 0.5 ppm. Zone C is characterized using 35 analyzes in which the content of Pt > 0.1 ppm.

Table 1. Content of PGE, Au, Cu and Ni in the prospective areas of East Pana massif.

	Chuarvy Area		East Chuarvy Area		Churozero Area		Predgorny Area	
Elements	**Value Range**	**Average (n = 29)**	**Value Range**	**Average (n = 446)**	**Value Range**	**Average (n = 39)**	**Value Range**	**Average (n = 121)**
Pt, ppm	0.06–2.42	0.37	0.025–17.2	1.61	0.05–2.2	0.58	0.03–2.77	0.43
Pd, ppm	0.33–9.28	1.59	0.12–67.49	3.6	0.46–18.27	3.49	0.36–9.18	1.59
Pt + Pd, ppm	0.5–12.0	2.0	0.5–80.0	5.0	0.5–20.47	4.16	0.5–12.0	2.0
Pd/Pt	2–12	4.5	0.3–43.0	2.8	1–12	5.6	1.6–102.6	4.7
Cu, %	0.05–0.13	0.052	0.04–1.91	0.066	0.06–0.41	0.087	0.02–13.25	0.22
Ni, %	0.04–0.07	0.038	0.04–0.55	0.038	0.009–0.49	0.099	0.007–0.62	0.109
Au, ppm	0.005–0.33	0.06	0.01–4.16	0.203	0.01–0.66	0.141	0.01–0.67	0.094
(Pt + Pd)/S, ppm/%	1.92–138	16.26	0.43–1756	54	2.16–578.5	52	0.24–662	47

Note: Sampling data with Pt + Pd < 0.5 ppm are excluded from consideration; n, number of analyses. Chyarvy, Churozero and Predgorny areas represent the PGE zone A, East Chuarvy area represents the PGE zone B.

The bulk chemical composition was determined in 73 samples at the Chemical Analytical Laboratory of the GI KSC RAS. The following methods were used: flame atomic absorption (Si, Al, Fe, Mg, Ca and Mn), flame emission (Na and K), photocolorimetric (Ti), gravimetric (loss on ignition (LOI) and H_2O-) and volumetric (CO_2, FeO) analyses (Supplementary Materials Table S7). There were 39 samples analyzed for trace elements at the Institute of Geology and Geochemistry, Uralian Branch of the Russian Academy of Sciences (Yekaterinburg) in solid samples by inductively coupled plasma ionization mass spectrometry (ICP-MS, ELAN 9000) with preliminary microwave and autoclave decomposition (Supplementary Materials Table S8).

4. Results

4.1. Petrography

The East Pana intrusion is composed of gabbros, gabbronorites, norites, orthopyroxenites, websterites, olivine and olivine-bearing gabbronorites, olivine gabbros, troctolites, olivine norites, anorthosites and metamorphosed varieties of these rocks (Figures 4–7).

The gabbro is a meso–leucocratic medium-coarse-grained homogeneous or mottled rock (plagioclase and augite-plagioclase cumulate). The leucocratic gabbro passes into anorthosite. The gabbro is composed of plagioclase (labradorite), augite, enstatite (up to 10%), quartz (up to 10%), olivine (up to 5%) and secondary minerals—amphiboles and clinozoisite (Figure 4a,b). The mottled structure of the rock is due to groups of plagioclase grains up to 10–50 mm in size, which have an irregular or oval shape. The plagioclase in gabbro has a gray color with a clearly visible lilac tint in the specimen; in a thin section, plagioclase is colorless or slightly colored in brownish tones and often weakly zonal. Generally, the gabbro is partially amphibolized and saussuritized. The gabbro often contains a metamorphic association of minerals represented by actinolite hornblende, biotite, ilmenite (partially replaced by titanite), apatite and garnet. The content of oxides of Fe, Ti and titanite can, in some cases, reach 10% of the rock volume. Sulfides occur as single grains.

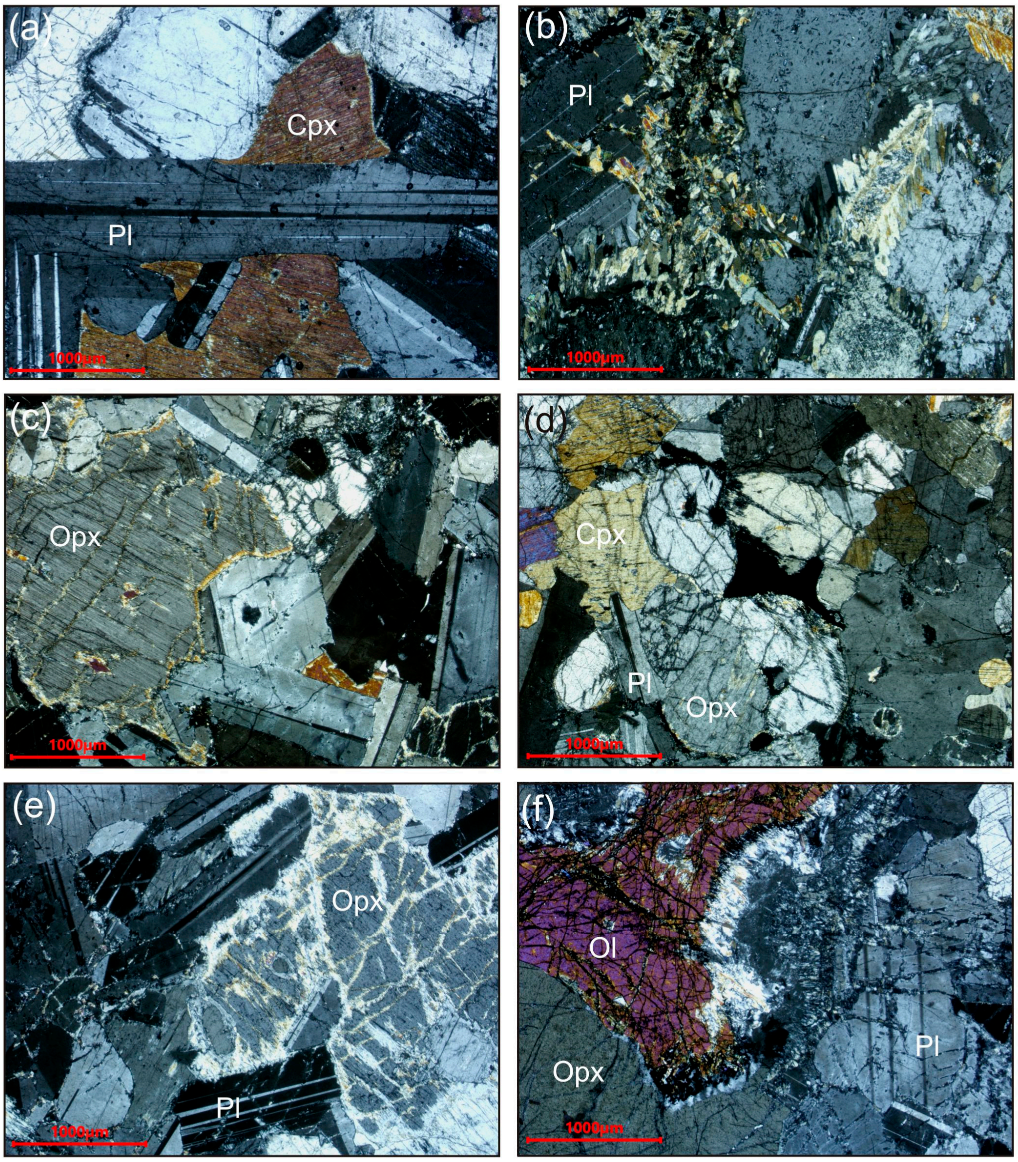

Figure 4. Rocks from the East Pana massif (Sungyok site): gabbro (**a**), amphibolized gabbro (**b**), gabbronorite (**c**), gabbronorite with sulfide mineralization (black) (**d**), norite (**e**), olivine norite (**f**). Photomicrographs in crossed polarized light. Opx—orthopyroxene, Cpx—clinopyroxene, Pl—plagioclase, Ol—olivine.

The gabbronorites are mesocratic fine-medium grained, both homogeneous and trachytoid (Figure 4c). Enstatite–augite–plagioclase cumulates predominate, plagioclase and augite–plagioclase cumulates are less common. Gabbronorites are composed of plagioclase (50%–65% of the rock volume), enstatite (5%–25%), augite (20%–45%) and alteration products of these minerals. Plagioclase (labradorite) forms euhedral crystals 1–4 mm in size. In a thin section, the color of plagioclase varies from colorless to brown and sometimes the crystal is weakly zonal. Plagioclase is slightly altered, sometimes partially replaced by clinozoisite. Enstatite forms short prismatic crystals 2–4 mm in size or oikocrystals up to 6 mm in size. Secondary changes in enstatite are partial or complete anthophyllitization and actinolithization. Augite forms oval or irregular grains up to 2 mm in size. As a rule, the mineral is not altered or weakly actinolithized. Gabbronorites with inverted pigeonite occur in the form of layers and lenses. The metamorphosed varieties contain actinolite, anthophyllite and minerals of the epidote group. Accessory minerals of gabbronorites are magnetite, ilmenite, titanite and sulfides (Figure 4d).

The norites (Figure 4e) are homogeneous meso–melanocratic, fine-to-medium-grained rocks (plagioclase–enstatite cumulates) graded into orthopyroxenites (enstatite cumulates). Intensively metamorphosed norites retain the structural and textural features of primary rocks; the orthopyroxene is replaced by a fine needle-like aggregate of amphiboles, among which anthophyllite predominates.

Olivine and olivine-bearing gabbronorites, olivine gabbro, troctolites and olivine norites (Figure 4f) form layers and lenses at different levels of the massif section. The most common rocks are olivine gabbronorites (olivine–plagioclase cumulates with intercumulus augite and enstatite) meso–melanocratic and medium grained. They contain plagioclase (40%–60%), olivine (5%–40%, more often 10%–15%), enstatite (up to 45%), augite (5%–20%), single grains of ore minerals, titanite, biotite and secondary minerals.

In layers sufficiently sustained along the strike, there is a gradual transition from host olivine-free poikilophytic gabbronorites or gabbro to olivine-bearing varieties. In these rocks, small (1–1.5 mm) oval olivine grains are usually embedded in enstatite or augite. The content of olivine is 1%–2% of the rock volume. Closer to the inner parts of the layers, the olivine content increases and reaches 30%–40%; the grain size of olivine reaches 2 mm. The distribution of olivine grains in the rock is uniform.

Olivine is usually partially or completely replaced by secondary minerals: amphibole, chlorite, talc, serpentines (bowlingite and antigorite) and magnetite. Secondary silicates form intricately built rims around olivine grains, and magnetite fills cracks in the olivine. Strongly metamorphosed olivine rocks are diagnosed by the nature of pseudomorphs; areas of oval or complex shape are observed in thin section, where the finest magnetite grains, talc and chlorite plates are visible.

The Ore Horizon of East Chuarvy (OHEC) gabbronorites were identified as a separate group. OHEC is dominated by fine-grained mesocratic gabbronorites (augite–plagioclase cumulates with intercumulus enstatite). Less common are augite–enstatite–plagioclase cumulates and plagioclase cumulates with pyroxenes in the intercumulus (Figure 5a,b). OHEC also contains websterite lenses (enstatite–augite cumulates), gabbro and quartz gabbro (Figure 5c,d) (augite–plagioclase cumulates), anorthosites (plagioclase cumulates with intercumulus augite), and gabbro–pegmatite lenses. Among the gabbronorites of OHEC, varieties with inverted pigeonite are often found. These varieties are found here much more often than in other parts of the East Pana massif. Orthopyroxenes and clinopyroxenes form complex intergrowths with each other. Ingrowths of clinopyroxene in orthopyroxene also contain regular ingrowths of orthopyroxene (Figure 6). The composition of orthopyroxene, clinopyroxene, plagioclase and olivine from the OHEC is given in Supplementary Materials Tables S1–S4 and S7. The composition of these minerals from other parts of the East Pana massif is also given there. There are no sharp differences in the composition of minerals.

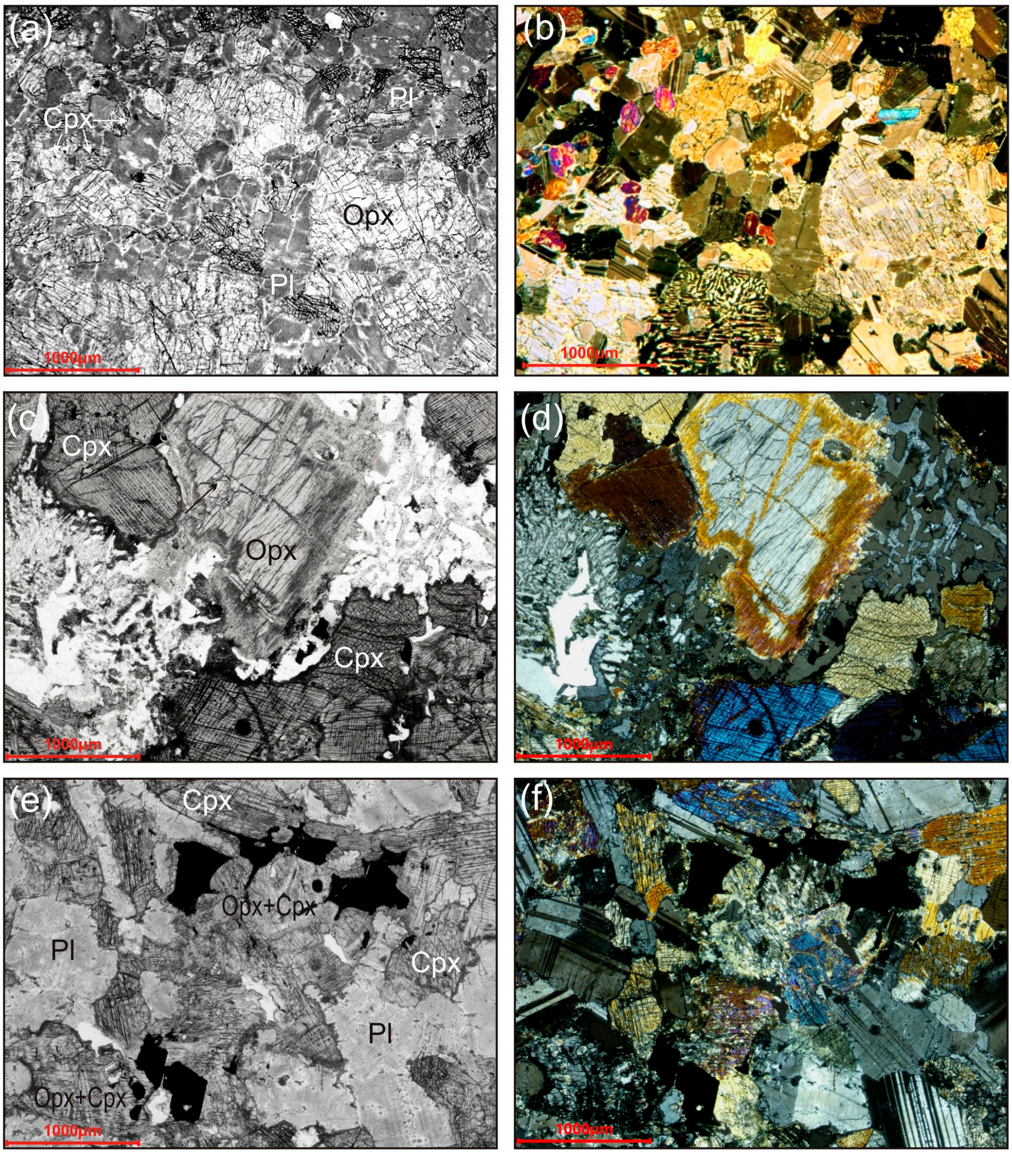

Figure 5. Photomicrographs of the rocks from the OHEC of the East Chuarvy site: fine-grained gabbronorite, augite–plagioclase cumulate—typical OHEC rock (**a**,**b**), medium-grained quartz gabbro (**c**,**d**), fine-grained quartz gabbronorite with sulfide mineralization (black) (**e**,**f**). (**a**,**c**,**e**)—in plane-polarized light; (**b**,**d**,**f**)—in cross-polarized light. Opx—orthopyroxene, Cpx—clinopyroxene, Pl—plagioclase.

Most of the rocks from the East Pana massif are metamorphosed in amphibolite facies (Figure 7). Amphibolized rocks are the most common (Supplementary Materials Tables S5 and S6). The pyroxenes are replaced by a fine needle-like aggregate of amphiboles, while the plagioclase is slightly altered. With more intense amphibolization, plagioclase is also replaced by actinolite and clinozoisite.

In the upper part of the section of the massif for several hundred meters, the rocks of the Gabbro Zone are strongly amphibolized. The most intense metamorphic processes occurred in the zone of the eastern wedge, out of the massif in the Predgorny site. In tectonic zones, mafic rocks have been transformed into schists. Schists after gabbroids contain actinolite, actinolitic hornblende, clinochlore, minerals of the epidote group, quartz, oligoclase–andesine and individual relics of strongly altered primary igneous plagioclase.

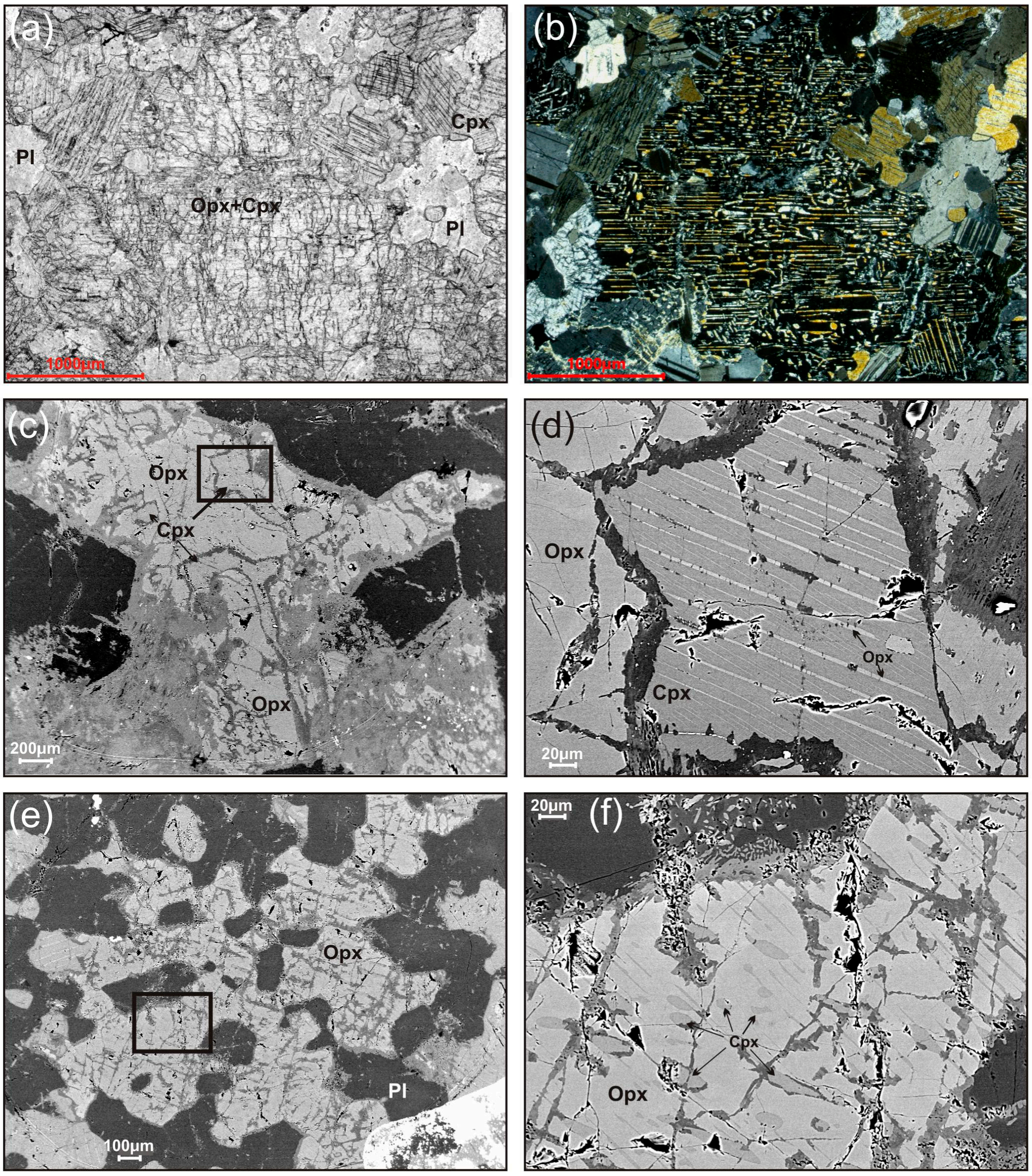

Figure 6. Rocks of the East Chuarvy site: poikilitic gabbronorite, in the center of the image there is a large oikocrystal of inverted pigeonite (**a**,**b**), large ingrowths of clinopyroxene in orthopyroxene (**c**), an enlarged part of figure (**c**), one can see thin ingrowths of orthopyroxene in clinopyroxene (**d**), oikocrystal of orthopyroxene with plagioclase chadacrysts and small clinopyroxene ingrowths (**e**); enlarged section of figure (**e**,**f**). (**a**,**b**)—Photomicrographs ((**a**)—in plane-polarized light, (**b**)—in cross-polarized light), (**c**–**f**)—BSE images. Opx—orthopyroxene, Cpx—clinopyroxene, Pl—plagioclase.

At the contact of the East Pana intrusion with alkaline granites, amphibole rocks with plagioclase relics, plagioclase–clinozoisite–amphibole rocks, and chlorite–amphibole schists are developed. Fine-grained, schistous near-contact amphibole rocks alternate with interlayers of weakly altered mafic rocks.

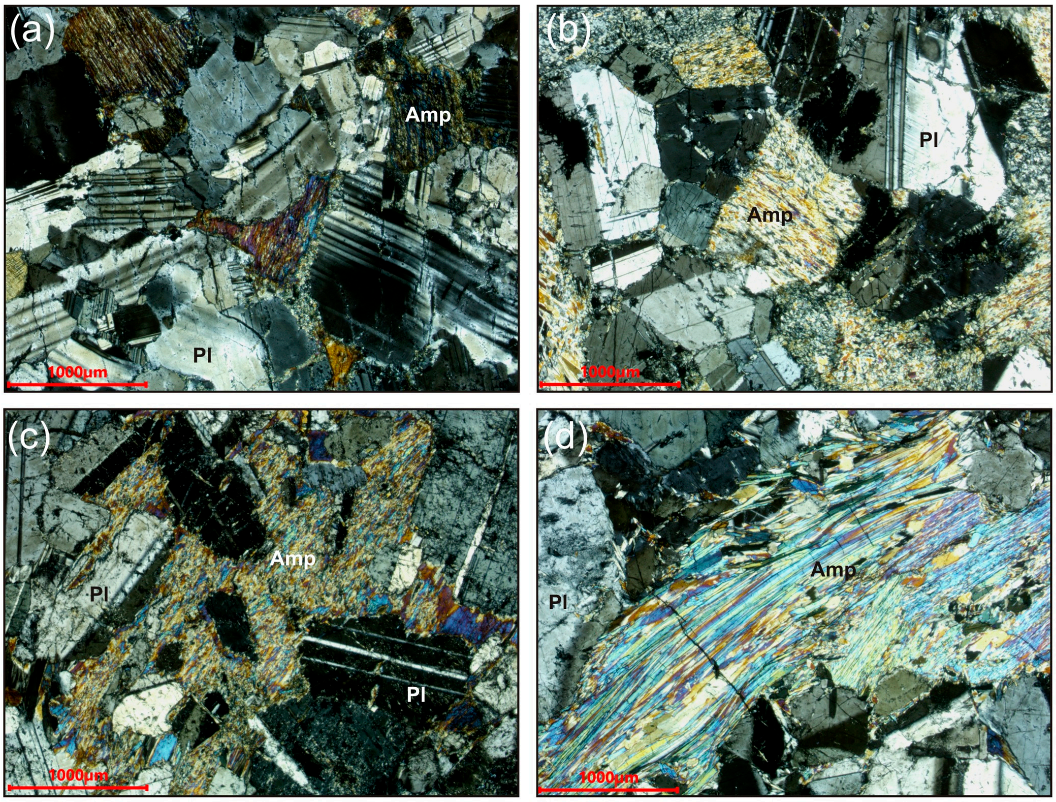

Figure 7. Metamorphosed rocks of the East Pana massif (Predgorny area): tectonically altered gabbronorite, fine grains of plagioclase can be seen (**a**), amphibolized gabbronorite (**b**), amphibole pseudomorph after a poikilitic crystal of orthopyroxene (**c**), amphibole aggregate develops after gabbronorite (**d**). Photomicrographs in cross-polarized light. Amp—amphibole, Pl—plagioclase.

4.2. Geochemistry of the Rocks of the East Pana Massif

4.2.1. Lithophile Elements

The bulk chemical composition of 73 rock samples from the East Pana massif is given in Supplementary Materials Table S7. On the AFM diagram (Figure 8a), the compositions of most of the rocks are grouped along the FM line, tending to the calc-alkaline mafic rock field, except for the leucogabbro and anorthosites, which are defined by a slightly increased content of alkali metals, mainly Na, relative to other rocks. Some gabbro samples of the East Pana massif are characterized by increased iron content. In the TAS diagram (Figure 8b) most rocks are located in the gabbro field.

The gabbronorites of the East Chuarvy deposit were singled out as a separate petrographic group. However, in terms of chemical composition, the varieties of gabbronorites do not show differences. On the AFM and TAS diagrams, gabbronorites form a single field (Figure 8).

Variation diagrams (Figure 9) demonstrate the chemical composition features of the East Pana massif rocks. The most magnesian rocks are norites, plagiopyroxenites and olivine gabbronorites. The least magnesian are anorthosites and leucogabbro. The content of TiO_2 in most rocks does not exceed 1.5 wt%. The most aluminous rocks are leucogabbro and anorthosites and the least aluminous are norites, plagiopyroxenites and olivine gabbronorites. The chromium content in the rocks is low. It should be added that chrome spinels were not found in the rocks of the East Pana massif. The highest content of Na_2O is observed in leucogabbro and anorthosites. The Na content in the rocks significantly exceeds the K content.

The variation diagrams do not show any differences in composition between the gabbronorites of the layered series and the gabbronorites of the East Chuarvy deposit. All rocks of the East Pana massif are classified by their chemical composition as mafic rocks of low alkalinity.

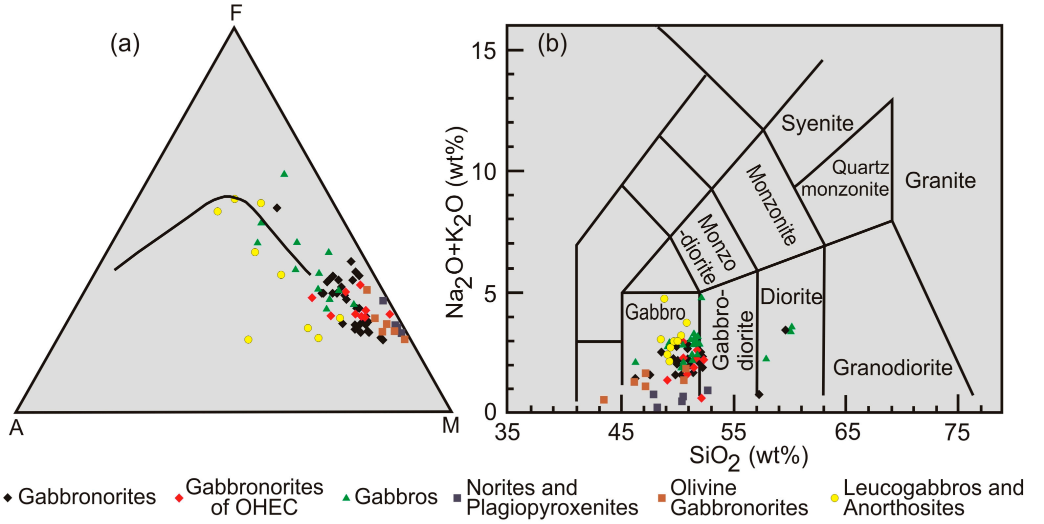

Figure 8. Rocks from the East Pana massif on the AFM diagram (**a**) and TAS (total alkali-silica) diagram (**b**) for plutonic rocks proposed by [55].

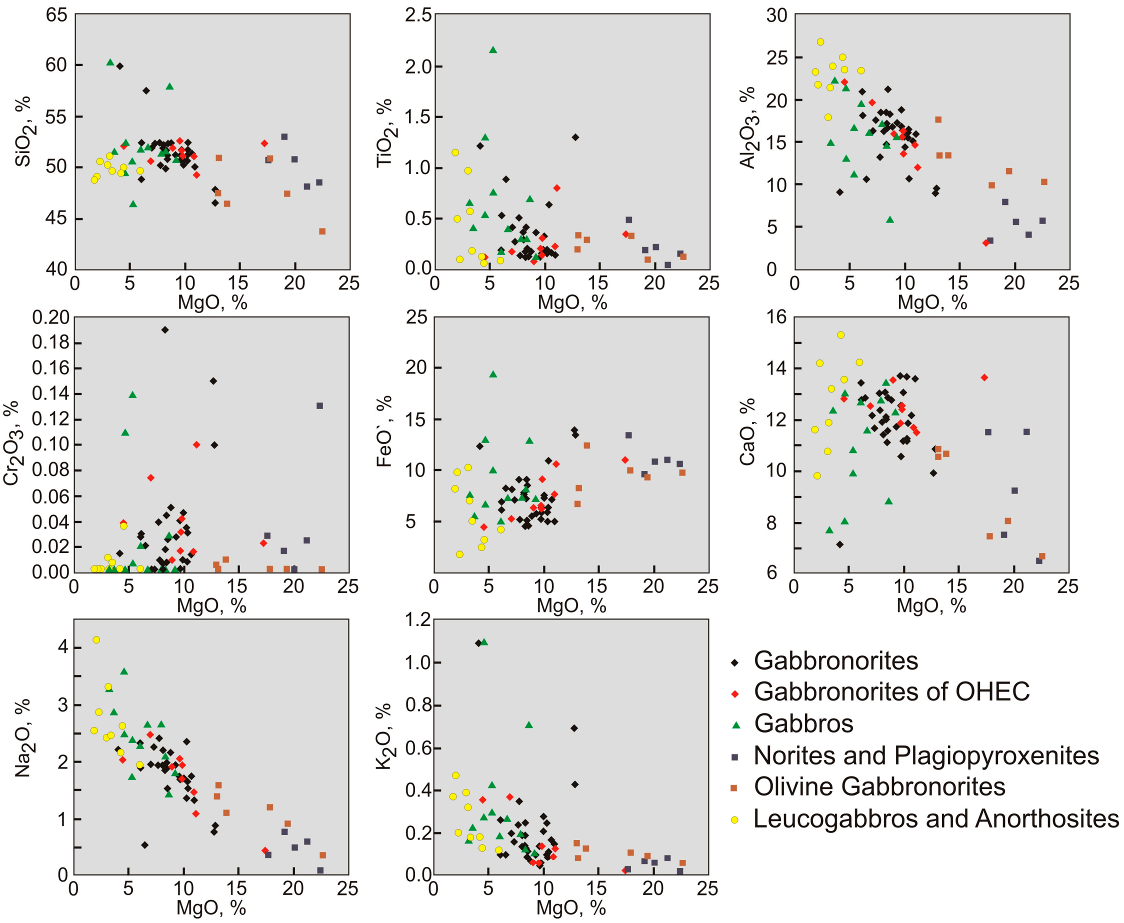

Figure 9. Rocks of the East Pana massif on variation diagrams MgO vs. SiO_2, MgO vs. TiO_2, MgO vs. Al_2O_3, MgO vs. Cr_2O_3, MgO vs. FeO′, MgO vs. CaO, MgO vs. Na_2O, MgO vs. K_2O. FeO′ = FeO + $0.9Fe_2O_3$.

The contents of rare and rare-earth elements (RE and REE) in the rocks of the East Pana massif in 39 analyzes are included in Supplementary Table S8. The total REE content in the rocks of the East Pana massif is low, except for gabbro pegmatites and dikes. The total content of REE in the rocks of different sites differs insignificantly. In gabbronorites from the GNZ, the total REE content is 7.6–23.5 ppm; in the rocks of the GZ, from 6.95 to 27.6 ppm. In gabbronorites and metagabbronorites on the eastern flank of the massif (Predgorny site), the total REE content is from 6.4 to 15.4 ppm. At the East Chuarvy site, the total REE content in the OHEC gabbronorites is from 10.7 to 28.7 ppm, while in GNZ 2 gabbronorites, this value is slightly higher, from 13.0 to 36.2 ppm. Elevated total REE contents are observed in gabbro-pegmatites, from 88.3 to 405.3 ppm, and in the metagabbrodolerite dike, 136.9 ppm.

Chondrite normalized REE patterns are shown in Figure 10a,c,e,g. All rocks of the East Pana massif are characterized by a negative slope of the REE curves and a slight enrichment in light rare-earth elements (LREE). The most horizontal REE patterns are characteristic of the OHEC gabbronorites from the East Chuarvy area ([La/Yb]n = 1.3–4.8). According to this parameter, they differ from the GNZ 2 gabbronorites ([La/Yb]n = 2.2–4.0) and gabbronorites from other sites ([La/Yb]n = 1.5–7.6). A stable enrichment in LREE can be seen from the rocks of the GZ ([La/Yb]n = 2.9–4.9).

The vast majority of rocks in the East Pana massif are characterized by small positive Eu anomalies. Of the 39 rocks analyzed, positive Eu anomalies are observed in 33 cases. Pronounced negative Eu anomalies are characteristic of gabbro–pegmatites ([Eu/Eu*]n = 0.2).

Distribution diagrams of RE in the rocks of the East Pana massif are shown in Figure 10b,d,f,h. Most rocks are characterized by pronounced positive Sr anomalies. Positive Sr anomalies, as well as positive Eu anomalies in the REE plots, indicate the accumulation of plagioclase in these rocks during the differentiation of the magma. Most of the rocks show negative Nb anomalies. Negative Zr and Hf anomalies are observed for all the analyzed rocks, except for the OHEC and GNZ 2 gabbronorites of the East Chuarvy site. Each of the OHEC samples differs in the nature of the spectrum of RE. The GNZ 2 rocks of the East Chuarvy area show a more consistent character of the RE spectra. They also differ from the rocks from all other areas in positive Zr and Hf anomalies and pronounced Th anomalies.

The gabbro–pegmatites of the East Chuarvy site contain an increased amount of most RE compared to gabbronorites. Trace element distribution diagrams for gabbro–pegmatites demonstrate negative Sr anomalies.

The metagabbrodolerite dike from the Predgorny area contains an increased amount of RE and corresponds in composition to numerous dikes of the Imandra–Varzuga zone, the composition of which is discussed in detail in [56].

4.2.2. Ore-Forming Elements

To characterize the geochemistry of ore-forming elements in the mineralized zones of the East Pana intrusion, we use the results of core sampling from drill holes mostly reported in [42,50]. After applying various sampling conditions (Figures 11–13), 676 samples with known concentrations of Au, Pt, Pd, Cu, Ni and S were studied. The samples characterize PGE zone A at the Chuarvy and Churozero sites (68 samples), as well as at the Predgorny site (127 samples) (Table 1, Figure 11). The most numerous are samples (446) from the East Chuarvy deposit, which characterizes PGE zone B (Table 1, Figure 12). The results of core sampling of two drill holes, which intersected the PGE zone C in the Sungyok site (Figure 13) (35 samples), were provided to the authors by A.A. Kalinin. Representative drill hole columns for each mineralized zone are shown in Figure 14.

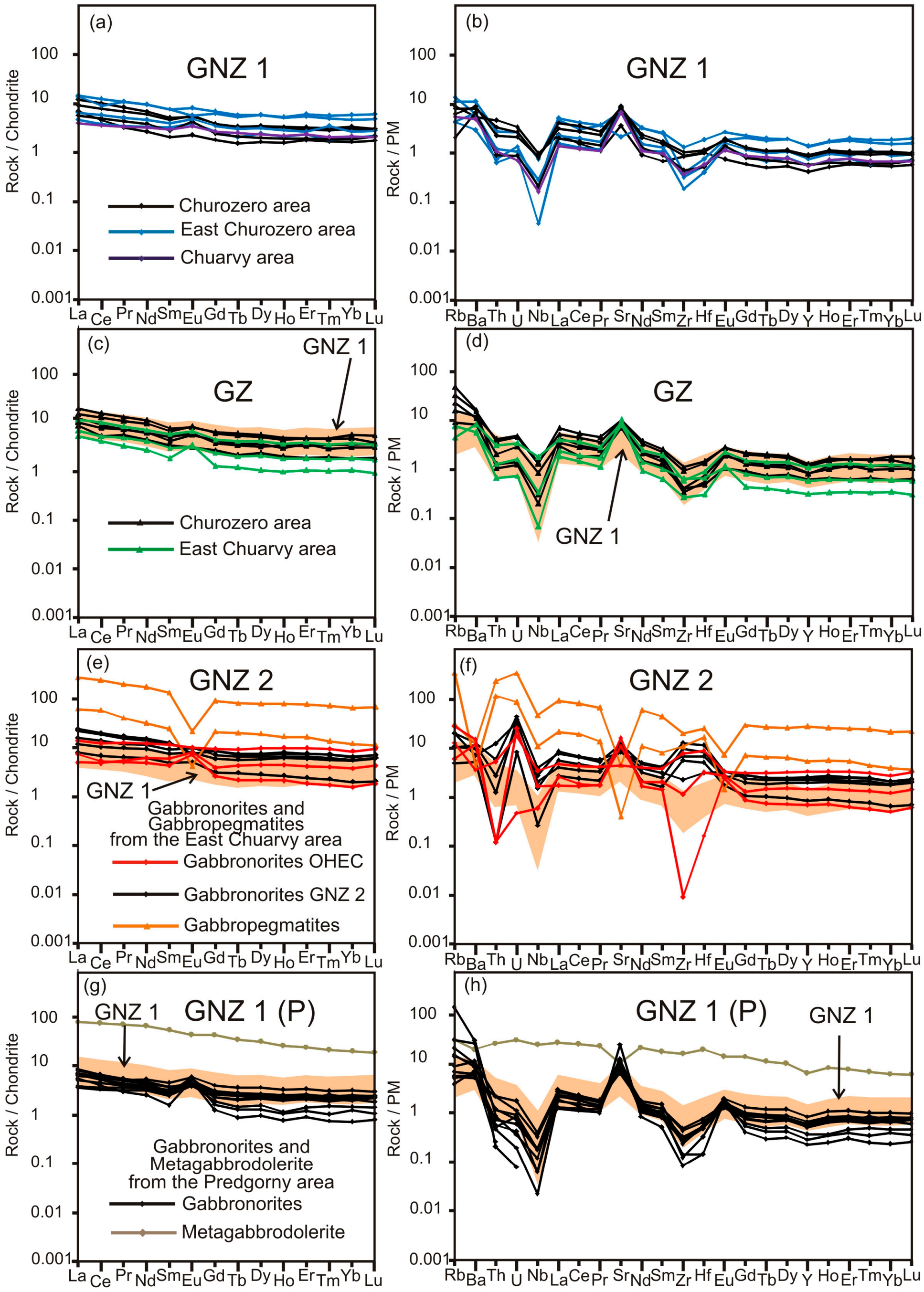

Figure 10. Chondrite-normalized rare earth element patterns (**a**,**c**,**e**,**g**) and the primitive mantle-normalized trace element diagrams (**b**,**d**,**f**,**h**) for the rocks of East Pana massif. Normalization factors from [57,58]. GNZ, GZ (see Figure 2). P—Predgorny area.

The concentrations of Au, Pt and Pd in PGE zone A, in some cases exceeding 20 ppm, correlate well with S, Cu and Ni (Table 1, Figure 11a–c), indicating sulfide control of PGE mineralization. The Cu/Ni ratio shows the presence of two trends (Figure 11c): in one this ratio is ~1 and in the other, it is ~2. Apparently, a significant contribution to the emergence of the first trend is made by nickel, which is included in the silicate minerals of olivine rocks. However, on average, the PGE zone A, in terms of sulfide enrichment in copper (Cu/Ni average = 1.3), is close to the sulfides of the North PGE reef in the West Pana massif (Cu/Ni average Kievey deposit = 1.1) [13].

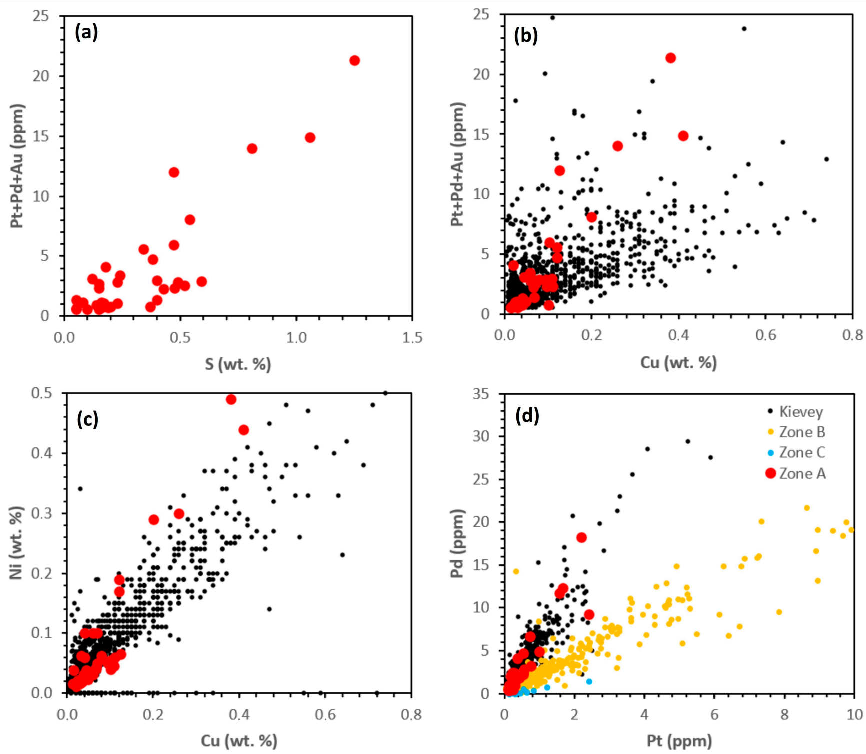

Figure 11. Binary diagrams S vs. Pt + Pd + Au (**a**), S vs. Pt + Pd + Au (**b**), Cu vs. Ni (**c**) and Pt vs. Pd (**d**) for the mineralized rocks of the PGE zone A (35 samples, representative drill holes P-253 and P-350 of the Churozero and Chuarvy sites, respectively) compared with other PGE zones of the East Pana intrusion and the Kievey deposit in the North PGE reef of the West Pana intrusion. Analytical data for core samples from [42,50], Pt + Pd + Au > 0.5 ppm.

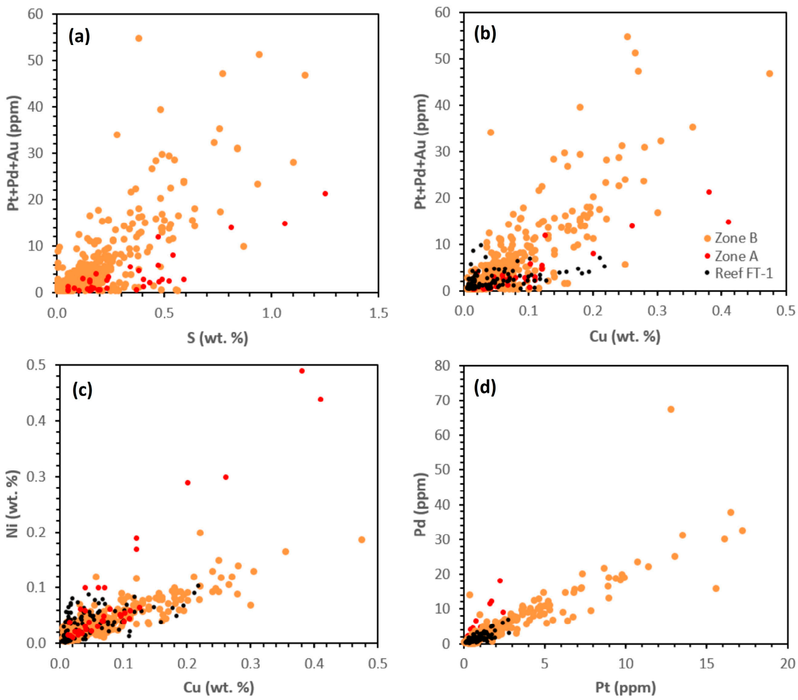

Figure 12. Binary diagrams S vs. Pt + Pd + Au (**a**), S vs. Pt + Pd + Au (**b**), Cu vs. Ni (**c**) and Pt vs. Pd (**d**) for the mineralized rocks of the PGE zone B (402 samples, East Chuarvy deposit) compared with other PGE zones of the East Pana intrusion and the FT-1 reef in the Fedorova intrusion. Analytical data for core samples from [50,59], two grab samples of the FT-1 reef from [13]. Pt + Pd + Au > 0.5 ppm.

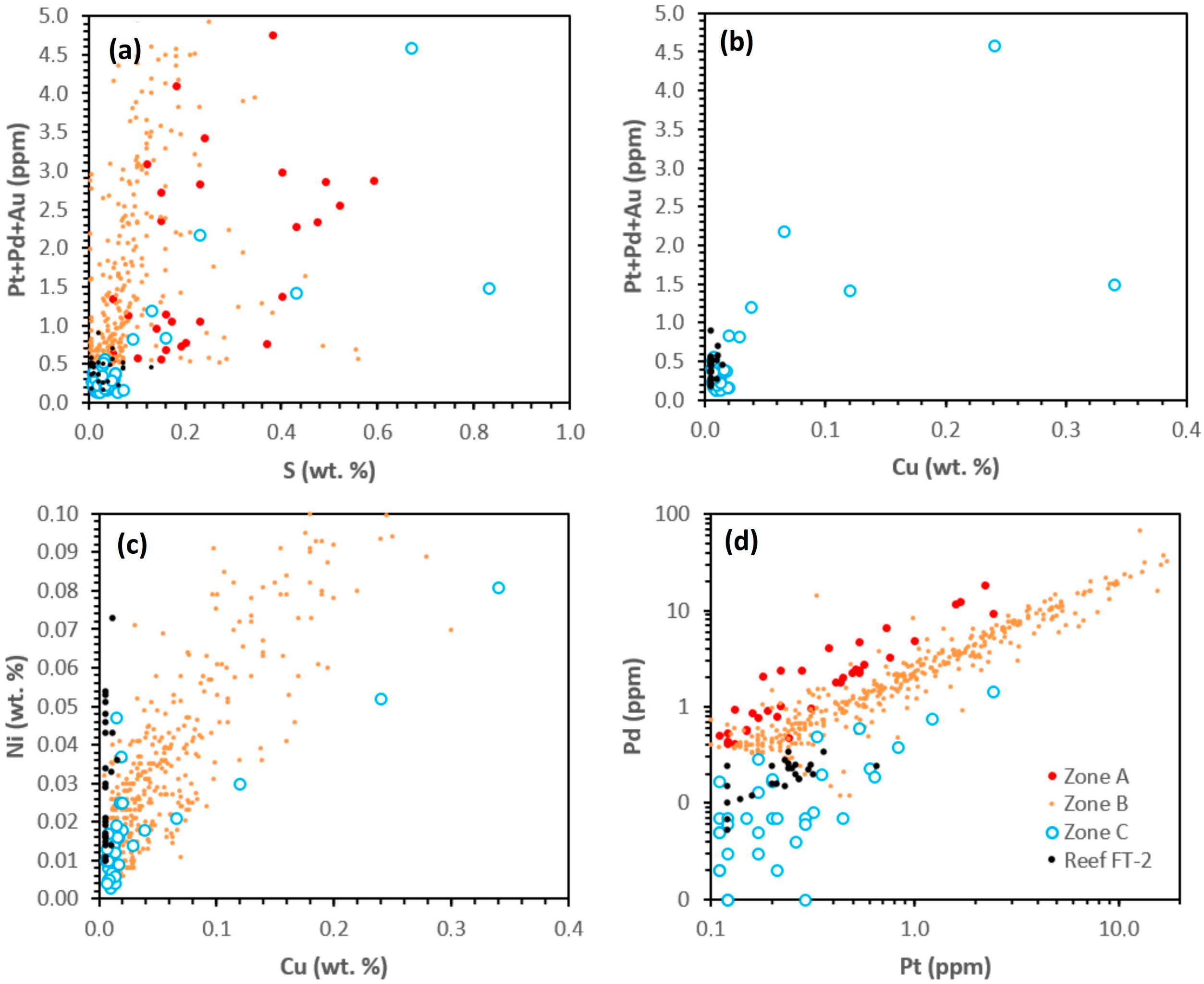

Figure 13. Binary diagrams of S vs. Pt + Pd + Au (**a**), S vs. Pt + Pd + Au (**b**), Cu vs. Ni (**c**), and Pt vs. Pd (**d**) for the mineralized rocks of the PGE zone C (35 core samples from drill holes P-494 and P-501 of the Sungyok site) compared with other PGE zones of the East Pana intrusion and the FT-2 reef in the Fedorova intrusion. Analytical data for core samples from [50]; one grab sample of the FT-2 reef from [13] and the rest are channel samples from [12]. Sampling condition for the zone C and FT-2 reef: Pt > 0.1 ppm.

A similar observation can be made for palladium (Figure 11c), which is strongly dominant over platinum in the PGE zone A rocks (Pd/Pt av. = 5.6, Table 1). The most eastward section of the PGE zone A (Predgorny area) is very similar with regards to its geochemical characteristics (Pd/Pt av. = 4.7, Cu/Ni av. = 1.4, Table 1) to both the western parts of this zone and the north PGE reef of the West Pana massif. It should also be noted that this area is similar to the mineralized rocks of the Fedorova Tundra deposit with Pd/Pt = 4.1 and Cu/Ni = 1.5 [13]. In addition, according to the drilling intersections in all areas, PGE zone A is the longest mineralized zone of the East Pana intrusion traced with numerous breaks over a distance of more than 20 km (Figure 1).

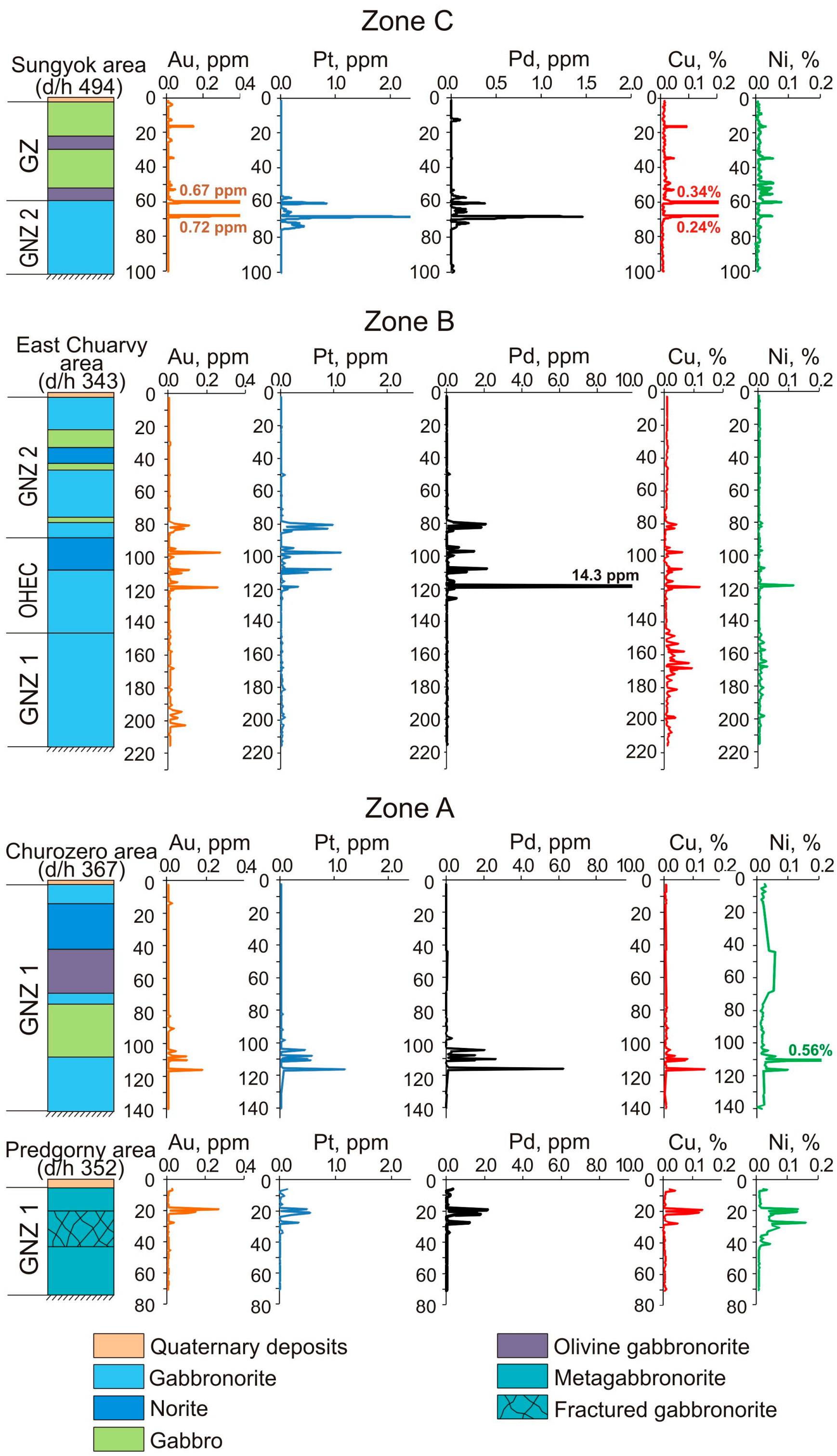

Figure 14. Stratigraphic columns for representative drill holes in the PGE zones of the East Pana intrusion with variations of Au, Pt, Pd, Cu and Ni.

Sulfides from the PGE zone B, as shown in Figure 12a, on average, are about three times richer in noble metals than the sulfides of PGE zone A. A more pronounced enrichment of sulfides of PGE zone B with copper (Figure 12c) can be noted. The average Cu/Ni ratio in the mineralized rocks of PGE zone B is higher than in PGE zone A and reaches 1.7. In contrast to the PGE zone A, PGE zone B is characterized by a less-noticeable enrichment of palladium: Pd/Pt av. = 2.6 (Table 1). In terms of copper enrichment in sulfides and the

PGE ratio, the mineralized rocks of the PGE zone B are very close to the FT-1 reef in the Fedorova intrusion (Cu/Ni av. = 1.7; Pd/Pt av. = 2.1) [13]. Compared to PGE zone A, the drilled extent of PGE zone B is smaller at about 15 km. However, the zones are very similar in terms of the number of breaks in the mineralization distribution.

The PGE zone C differs sharply from the other ore zones of the East Pana intrusion not only in extent and geological position but also in all geochemical characteristics (Figure 13). Near the boundary between GNZ 2 and GZ, PGE zone C can be traced in the eluvium for a distance of about 8 km. In single drill holes, the zone is represented by 15–20 m thick intervals with elevated PGE concentrations at the level of 0.1–0.5 ppm Pt and Pd. Individual samples from PGE zone C show high concentrations of PGE (up to 2.4 ppm Pt and up to 1.5 ppm Pd) and Au (up to 0.7 ppm in core samples and up to 2.2 ppm in surface samples), which have a broad correlation with sulfur (Figure 13 a). The absence of correlation between PGE and S at low concentrations seems to be a result of the low accuracy of S determination at its content below 0.05 wt%. On the other hand, this can be explained by the development of two types of PGE mineralization in zone C, one of which has been formed in the postmagmatic stage and is represented by PGE minerals associated with the intervals of rock metasomatism and cracks in rock-forming minerals [60]. The PGE zone C is enriched in Pt relative to Pd: the Pd/Pt ratio rarely exceeds 1, averaging 0.5, which is close to the geochemical characteristics of the FT-2 reef in the leucogabbro zone of the Fedorova intrusion (Figure 13c), as well as the reef horizon in the Volchetundra massif of the Main Ridge complex [61].

Plots showing primitive mantle–normalized chalcophile element patterns in the mineralized sections of the East Pana massif areas compared to the Bushveld Complex and Stillwater Complex show that the PGE zone C differs markedly from these deposits as well (Figure 15). At the same time, the PGE zones A and B show sufficient similarity with the mineralized units of the Bushveld and Stillwater massifs.

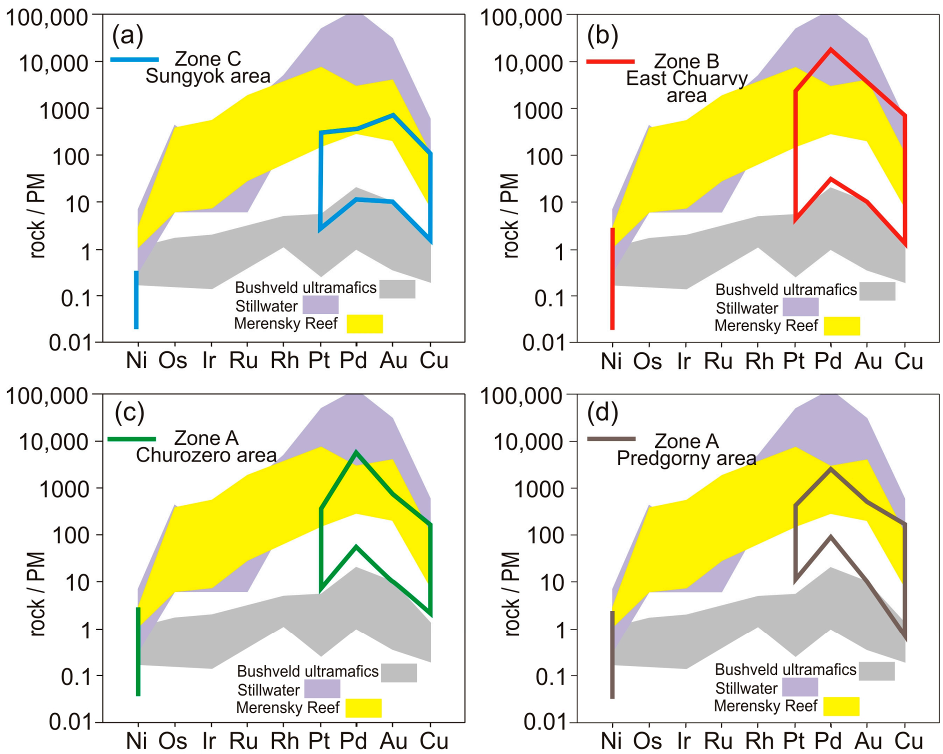

Figure 15. Primitive mantle–normalized chalcophile element patterns in the PGE zones of the East Pana massif (PGE zone B,C—(**a**,**b**), PGE zone A—(**c**,**d**)) compared to the Bushveld Complex [62] and Stillwater Complex [11]. Normalization factors from Barnes and Maier [62].

5. Discussion

In the Fennoscandian Shield Paleoproterozoic layered PGE-bearing intrusions are divided into two groups, differing in age and correlation with volcanic rocks. Earlier layered intrusions (about 2.50 Ga) are overlain by volcanic rocks with basal conglomerates at the base and are located only within the Kola province (Kola belt). This group includes the intrusions of Mount Generalskaya and Ulitaozerskaya; Monchegorsk and Fedorova–Pana complexes [63–65].

Later layered intrusions (about 2.45 Ga), which intrude volcanic rocks of rift structures, are widely represented in the Karelian province (intrusions of Tornio, Kemi, Penikat, Naryankavaara, Koitelainen, Akanvaaara, and Kovdozerskaya, Portimo (Narkaus and Sukhanko-Kontijarvi), Koillismaa, Olanga and the Burakovo–Aganozero complexes) [66–69] and are much less developed in the Kola province (Imandra complex) [3].

All of the above-layered intrusions have common structural features (wide development of macro and rhythmic layering) and composition of rocks built mainly of olivine–orthopyroxene–plagioclase paragenesis, with a subordinate role of clinopyroxene. At the same time, each of them has individual sections, different degrees of rock differentiation, and a different set of ore concentrations of nickel, chromium, and PGE [67,70–73].

For example, for Monchepluton, a generalized model of localization conditions for different types of PGE ores demonstrates the regular nature of their distribution as a result of the ore–magmatic evolution of ultramafic and mafic subchambers. It is characteristic that in each of them, there are deposits and manifestations of the basal type in the bases of the subchambers and of the reef type in the upper part. In this respect, the Monchepluton PGE deposits are similar to the PGE deposits in the layered Portimo complex, Finland [2] but differ from those of the Fedorova–Pana ore region, whose basal and reef-type deposits are confined to different massifs: the Fedorova (lower part of the cross section) and West and East Pana, respectively [3,13].

The Pd/Pt ratio can serve as one of the important parameters by which one can evaluate the similarity or differences of PGE deposits, as well as the specifics of their formation conditions. As for the PGE deposits of the Kola Belt, two groups of deposits are distinguished by the Pd/Pt ratio [74].

The first group includes objects with Pd/Pt greater than two (from 2–3 to 6–8 and more). These are the massif of Mount Generalskaya, almost all massifs and sections of the Monchepluton and the zone of its junction with the Monchetundra intrusion of the Main Range complex (the Loipishnyun deposit of the Monchetundra massif, the South Sopcha massif and the Vurechuayvench massif), as well as all PGE levels of the West Pana massif of the FPC.

The second group includes objects where, along with high Pd/Pt ratios (5–8, up to 10), ratios close to or equal to one are noted (i.e., with more "platinum" mineralization). From this group, it is necessary to single out the "Ore layer-330" (Sopcha massif, Monchepluton). In this case, we have an ambiguous situation when different types of rocks within a thin (about 5 m) layered horizon are characterized by ores with different Pd/Pt ratios (1 in peridotites and 10 in pyroxenites, [75]). Four other objects with different Pd/Pt ratios are the Monchetundra intrusion and the Volchetundra massif of the Main Ridge complex, and the Fedorova and East Pana massifs of the FPC. Within these massifs, horizons with a Pd/Pt ratio close to one are located higher in the section relative to the horizons characterized by high Pd/Pt values. Almost always, these are horizons among (or at the boundary) sequences of leucogabbro (leucogabbronorites) and anorthosites, often with the presence of olivine rocks (troctolites, olivine gabbronorites and harzburgites). Levels with high Pd/Pt ratios, as a rule, are located in the lower parts of the section, often in the so-called "marginal series" (Volchetundra and Fedorova massifs) [74].

According to this trend, the massifs of the second group are close to the Finnish Portimo complex. In this complex, the Pd/Pt ratio decreases on average from offset ores and marginal series up the section to the layered series from 3.0–6.7 and 3.6–8.0 to 0.9–4.4. [2,76]. It is noteworthy that the fluctuations in the Pd/Pt ratio in the Portimo complex are very contrasting (0.9–10.9, on average 0.9–8.0, in the layered series 0.9–4.4), which looks somewhat unusual for objects belonging to one ore–magmatic system.

In the FPC massifs for the Fedorova and West Pana intrusions, mineralization of three types (marginal—Fedorova massif, basal zone; reef—West Pana massif, North reef, Kievey deposit; reef, redeposited—West Pana massif, South reef) is characterized by a clearly pronounced palladium specialization (Pd/Pt, 2.5–9.5) and the predominance of copper over nickel (Cu/Ni—1.1–1.9) [25]. The closest analogs of marginal-type mineralization (Fedorova Tundra deposit) are PGE deposits in the marginal zones of the Portimo intrusive complex in northern Finland [68,77,78]. The features of the structure and distribution of the PGE mineralization of the North PGE reef (Kievey deposit) are largely similar to the J-M reef of the Stillwater complex and the SK reef of the Portimo complex [19,25,68,78].

As for the East Pana intrusion, the Pd/Pt values of its sections (except for the Churozero), which are reef type, show a significant similarity with the Fedorova intrusion, both with reefs and the marginal type. Thus, the East Chuarvy site (PGE zone B, average Pd/Pt value is 2.8) is close to the FT-1 of the Fedorova massif (average Pd/Pt value is 2.0, [79] and the Chuarvy and Predgorny sites (PGE zone A, average Pd/Pt values 4.5–4.7, respectively) to the rocks of the lower part of the Fedorova section (average Pd/Pt value 4.0–4.5, [13,79,80]). The Churozero area (PGE zone A, average Pd/Pt value is 5.6) is close to the North reef (average Pd/Pt value is 6.4, [19]) of the West Pana massif. In terms of the distribution of chalcophile elements normalized to the primitive mantle, these PGE zones (A and B) are close to the mineralized sections of the Bushveld and Stillwater massifs.

At the same time, PGE zone C, traced by drill holes in the Sungyok area, is enriched with Pt relative to Pd (Pd/Pt ratio rarely exceeds 1, on average—0.5), which is also close to the geochemical characteristics of the FT-2 reef in the leucogabbro zone of the Fedorova intrusion [13,79].

Thus, despite the differences in the geological structure, according to mineral compositions and lithophile element whole-rock geochemistry, it can be concluded that different FPC massifs had a common magmatic source. However, the complex of presented data on chalcophile elements geochemistry shows that the formation of various zones of PGE mineralization in the East Pana intrusion (as well as the FPC as a whole) is apparently associated with the development of various ore–magmatic systems (Table 2). The PGE zone A, with a high probability, can belong to a main ore–magmatic system of the FPC, which combines the Kievey, North Kamennik and Fedorova Tundra deposits, while the PGE zones B and C belong to the minor ore–magmatic systems of the FPC, which also include the FT-1 and FT-2 reefs of the Fedorova intrusion (Table 2).

In general, the new geochemical data show a significant similarity in the composition of lithophile elements in the rocks of all units of the section of the East Pana massif. But the positive Zr-Hf anomaly in the GNZ 2 rocks, as well as within the OHEC, makes these units stand out from the rest. This, along with the erosional relationship with the GNZ 1 unit established from geological data, indicates, in our opinion, a late intrusion of GNZ 2 magma. It is possible that this portion was intruded as a sill of crystal mush, the fractionation of which, at depth, led to its enrichment with residual liquid.

Table 2. Supposed ore–magmatic systems of the Fedorova–Pana Complex arranged in order of decrease of Pd/Pt ratio in mineralized rocks.

Ore–Magmatic Systems	Pd/Pt Ratio	Fedorova Intrusion	West Pana Intrusion	East Pana Intrusion
Minor system: several PGE occurrences at West Pana	10–12	Not found	South PGE Reef, PGE mineralization in the Olivine Horizon	Not found
Main system: one large PGE deposit at Fedorova plus smaller deposits at West Pana; several occurrences at East Pana	5–6	Basal Cu-Ni-PGE mineralization	North PGE Reef	PGE mineralized zone A
Minor system: tens of drill hole intersections at Fedorova, small PGE deposit at East Pana (East Chuarvy)	2–3	FT-1 PGE Reef	Not found	PGE mineralized zone B
Minor system: points of PGE mineralization at Fedorova; several drill intersections at East Pana	~1	FT-2 PGE Reef	Not found	PGE mineralized zone C

6. Conclusions

The East Pana massif belongs to the FPC, which is part of an older (2.5 Ga) group of mafic–ultramafic layered intrusions of the Kola Belt. It is one of the layered intrusions, where, along with high Pd/Pt ratios (5–8, up to 10), ratios close to or equal to one are noted (i.e., with prevailing platinum mineralization).

According to the geological data, East Pana is an independent-layered intrusion, consisting of three large differentiated stratigraphic units (GNZ 1, GNZ 2 and GZ), which do not occur in such a sequence in the adjacent West Pana intrusion and do not contain any marker horizons that allow merging cross sections. The PGE mineralization of each stratigraphic unit belongs to the reef type and, apparently, belongs to different ore–magmatic systems of the FPC (Table 2), which is emphasized by many geochemical characteristics (most clearly, the Pd/Pt ratio).

PGE zone A localized in GNZ 1 is the most extensive and, apparently, can be attributed to the main ore–magmatic system of the FPC, which combines the Kievey, North Kamennik and Fedorova Tundra deposits. PGE zones B and C, associated with the lower contacts GNZ 2 and GZ, respectively, obviously belong to the minor ore–magmatic systems of the FPC, despite the identification of the East Chuarvy deposit within the first. In addition to these zones, the FT-1 and FT-2 reefs of the Fedorova intrusion can be assigned to this group.

The main feature of the reef PGE mineralization in the East Pana intrusion is its discontinuous nature, despite the total length of up to tens of kilometers along the strike. The FPC is saturated with such discontinuous ore zones (e.g., the South reef of the West Pana massif), and the discovery of the small but rich East Chuarvy PGE deposit provides grounds for searching for similar new ore bodies not only in the FPC massifs but also in other layered intrusions of Fennoscandia.

The obtained geochemical data show a significant similarity in the composition of lithophile elements in general in the rocks of stratigraphic units of the East Pana intrusion. However, a noticeable difference is the positive Zr-Hf anomaly in the GNZ 2 rocks, as well as within the OHEC, which has a rather local development. This difference, along with the erosion relationships with stratification of the GNZ 1 established in the sections along the drilling profiles, in our opinion, indicates a late intrusion of the GNZ 2 magma in the form of a sill of crystal mush, the fractionation of which at depth led to its enrichment with residual liquid.

The question of the East Pana stratigraphic unit's formation requires further detailed studies, including isotope–geochronological studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13050681/s1, Table S1: Chemical composition of olivines from the East Pana massif (wt%), Table S2: Chemical composition of orthopyroxenes from the East Pana massif (wt%), Table S3: Chemical composition of clinopyroxenes from the East Pana massif (wt%), Table S4: Chemical composition of plagioclases from the East Pana massif (wt%), Table S5: Chemical composition of Mg-Fe amphiboles from the East Pana massif (wt%), Table S6: Chemical composition of Ca-amphiboles from the East Pana massif (wt%), Table S7: Chemical analysis of East Pana rocks, Table S8: Rare elements in the East Pana massif.

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