

Review

Low-Sulfide Platinum–Palladium Deposits of the Paleoproterozoic Fedorova–Pana Layered Complex, Kola Region, Russia

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Abstract: Several deposits of low-sulfide Pt–Pd ores have been discovered in recent decades in the Paleoproterozoic Fedorova–Pana Layered Complex located in the Kola Region (Murmansk Oblast) of Russia. The deposits are divided into two types: reef-style, associated with the layered central portions of intrusions, and contact-style, localized in the lower parts of intrusions near the contact with the Archean basement. The Kievev and the North Kamennik deposits represent the first ore type and are confined to the North PGE Reef located 600–800 m above the base of the West Pana Intrusion. The reef is associated with a horizon of cyclically interlayered orthopyroxenite, gabbro-norite and anorthosite. The average contents of Au, Pt and Pd in the Kievev ore are 0.15, 0.53 and 3.32 ppm, respectively. The North Kamennik deposit has similar contents of noble metals. The Fedorova Tundra deposit belongs to the second ore type and has been explored in two sites in the lower part of the Fedorova intrusion. Mineralization is mainly associated mainly with taxitic or varied-textured gabbro-norites, forming a matrix of intrusive breccia with fragments of barren orthopyroxenite. The ores contain an average of 0.08 ppm Au, 0.29 ppm Pt and 1.20 ppm Pd. In terms of PGE resources, the Fedorova Tundra is the largest deposit in Europe, hosting more than 300 tons of noble metals.

Keywords: PGE; low-sulfide Pt–Pd ore; contact-style; reef-style; Fedorova–Pana Complex; Kola Region

1. Introduction

About 30 Paleoproterozoic mafic-ultramafic layered intrusions hosting large Cr–Cu–Ni–PGE–V deposits are known within the Fennoscandian Shield (Figure 1). Approximately a third of these are located within the Kola Region, including several ore-bearing intrusions belonging to the Monchegorsk and the Fedorova–Pana Complexes and considered significant ore districts of the Kola platinum-metal province [1]. A characteristic feature of low-sulfide Pt–Pd deposits is the enrichment of the sulfide ore in PGE, whereas Ni and Cu contents of the ores are subordinate. In contrast, Cu–Ni sulfide deposits have relatively low PGE tenors [2–5]. All of the most important PGE deposits globally—supplying

the bulk of platinum metals to the world market, such as the Merensky Reef, the UG-2 chromitite and the Platreef of the Bushveld Complex (South Africa), the JM Reef of the Stillwater Complex (MT, USA), and the Main Sulfide Zone of the Great Dyke (Zimbabwe)—belong to the group of low-sulfide Pt–Pd deposits.

The layered intrusions of the Fedorova–Pana Complex have traditionally been considered as nickel targets and thus were prospected for nickel from the 1930s onwards, with little success. A new impulse to conduct research on the intrusions was provided by the discovery of high PGE contents and the mineral findings in the 1980s [6,7]. This led to a reconsideration of the ore potential of the intrusions and the concentration of efforts on searching for PGE deposits.

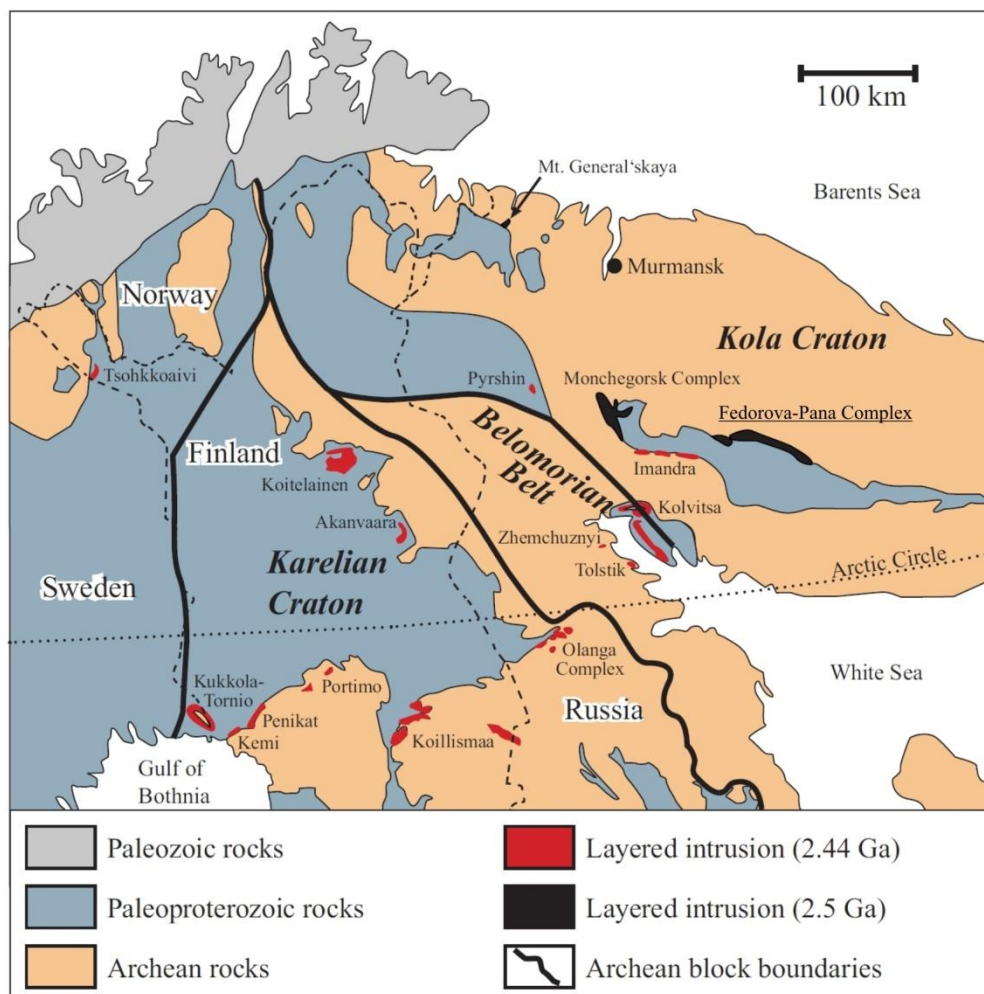


Figure 1. Simplified geologic map of the northeastern part of the Fennoscandian Shield, showing the location of Paleoproterozoic layered intrusions. Modified after [8].

The company JSC Pana, founded by the academician Felix Mitrofanov at the end of the last century, has attracted a number of large investors such as Barrick Gold Corporation, BHP Billiton, Bema Gold Corporation, Uralminerals and others. As a result of the geological exploration in the Fedorova–Pana Complex, the Fedorova Tundra, Kievev, North Kamennik and East Chuarvy deposits were discovered. Among these, the Fedorova Tundra deposit constitutes a world-class deposit that has nearly reached the production stage. Thus, the Fedorova–Pana Complex has become the most important platinum-bearing area in the Kola region [3] and the second most important in Russia after the Noril'sk ore province [9–11].

The aim of this review is to present the geology, geochemistry and genesis of the most important low-sulfide Pt–Pd deposits of the Fedorova–Pana Complex, to compare them with deposits from the Portimo Complex in Finland as the closest analogs, and to outline the main directions for future research.

2. Geologic Setting

The Paleoproterozoic is one of the most important periods of global mafic-ultramafic magmatism in the Earth's history (e.g., [12]). Expressions of the magmatic activity are recorded in a number of voluminous layered intrusions, dike swarms, and volcanic suites across the Canadian Shield and the Fennoscandian Shield in northern Europe [13]. On the basis of coeval magmatism, it was suggested that the Fennoscandian Shield was situated along the southern margin of the Superior craton at the end of the Archean [14]. The tectonic setting, as well as the mantle source of magmatism, remain under debate, but most researchers prefer a rift-related mantle plume melting model followed by large-scale contamination with older felsic crustal rocks to explain the trace element and isotopic signature of the igneous rocks [15–20].

Several studies have demonstrated considerable petrological and stratigraphic similarities between the layered intrusions on both shields [21–23]. The Fennoscandian layered intrusions, however, seem to be more significant with respect to PGE, Ni, Cu, Cr, and V mineralization. Several well-known PGE and Cr occurrences, as well as subeconomic to economic deposits, are associated with the Finnish intrusions [24]. Until recently, base metal and precious metal mineralization in the Russian part of the Fennoscandian Shield seemed to be less prominent. However, geological exploration over the past decades has shown that these intrusions host a spectacular range of mineralization styles, from stratiform chromitites and basal contact-style PGE–Ni–Cu mineralization to different types of PGE reefs in the lower and upper portions of the intrusions [8,22,25–33].

One of the most remarkable Fennoscandian intrusions in terms of PGE mineralization is the 2.5 Ga Fedorova–Pana Complex, as it hosts the largest volume of PGE resources in Europe, exceeding 400 tons in total [34]. These are hosted by internal PGE reefs associated with interlayered pyroxenite, gabbro-norite and anorthosite, and Cu–Ni–PGE mineralization at the basal contact of the intrusion [22].

2.1. Geology of the Fennoscandian Shield

The Fennoscandian Shield of northern Europe consists of three tectonic units: (1) the Kola domain, (2) the Karelian domain, and (3) the Belomorian mobile belt (Figure 1). The main episode of continental growth of the Kola domain occurred due to terrane accretion from 2.9 to 2.7 Ga [35]. High-pressure granulites from the Belomorian mobile belt suggest that the Kola domain collided with the Karelian domain at 2.72 Ga, thus producing the Fennoscandian Shield. It subsequently recorded two distinct periods of mantle plume activity associated with intraplate rifting toward the end of the Archean. The first magmatic event occurred only in the Kola domain, producing the 2.5 Ga General'skaya, Monchepluton, Main Ridge, and Fedorova–Pana layered intrusions [15,36,37]. The second magmatic event, at 2.44 Ga, affected the entire shield forming numerous layered intrusions, such as the Kemi, Penikat, Portimo, Koillismaa, Näränkäväära, Koitelainen, and Akanvaara intrusions in Finland; the Pyrrshin, Imandra Lopolith, Kandalaksha, Kolvitsa, Olanga, and Burakovsky in Russia; and the Kukkola–Tornio intrusion bordering Sweden and Finland [8,15]. According to Bleeker and Ernst [14], these two episodes can be correlated with the 2.5 Ga Mistassini and the 2.48 to 2.45 Ga Matachewan events in Canada, respectively.

2.2. Geology of the Fedorova–Pana Complex

Intrusions of the Fedorova–Pana Complex form an almost continuous belt of layered massifs with a northwesterly strike, located at the northern edge of the Imandra–Varzuga paleorift structure (Figure 2). The total length of the belt is about 90 km, with a width of up to 6–7 km. The northern contact zones of all massifs contain fine-grained gabbroids and have intrusive relationships with

basement rocks. The rocks in these zones are often schistose and altered to amphibolites. The southern contact, dipping south–west at an angle of 40–50°, is a fault along which volcano-sedimentary rocks were thrust onto the intrusions.

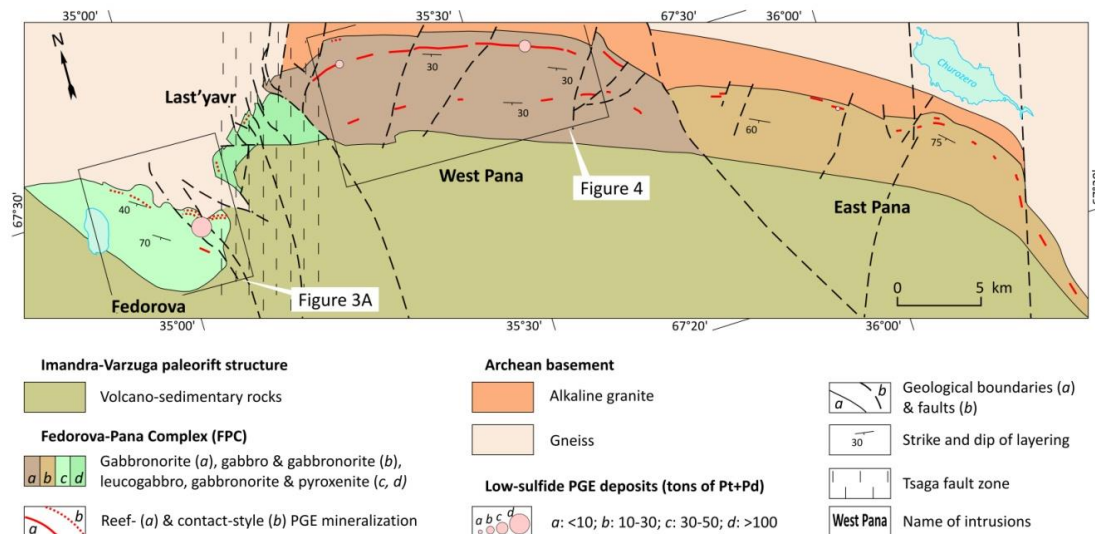


Figure 2. Simplified geologic map of the Fedorova–Pana Complex, showing the location of low-sulfide PGE deposits. Modified after [38].

The Fedorova–Pana Complex consists of four intrusions (from west to east): Fedorova, Last'yavr, West Pana and East Pana (Figure 2). Despite the single stage Fedorova–Pana intrusion model being used in several publications [3,22,39], most researchers believe that each intrusion represents a distinct magmatic chamber with a largely independent stratigraphy and its own history of formation [40–44].

The Fedorova intrusion forms a lens dipping to southwest with a thickness of 4 km and a length of about 15 km, which is cut by the Tsaga fault in the southeast (Figure 3a). Three stratigraphic zones are distinguished (from the bottom upwards): (i) the Norite–Gabbro-norite Zone (or Taxitic Gabbro-norite), (ii) Leucogabbro–Gabbro-norite Zone and (iii) Leucogabbro Zone [42].

The Norite–Gabbro-norite Zone with an average thickness of 250 m contains numerous fragments of orthopyroxenites measuring from several tens of cm to 100 m across. PGE mineralization, up to 280 m thick, is predominantly associated with taxitic (varied-textured) gabbro-norites and norites (Figure S1). The Fedorova Tundra deposit is hosted by this zone.

Next is the Leucogabbro–Gabbro-norite Zone which consists of an alternation of medium-grained gabbro-norite and coarse-grained leucogabbro. The zone appears to be older than the underlying Norite–Gabbro-norite Zone as it is intruded by veins of taxitic gabbro-norites [45]. The maximum thickness of the zone is 600 m at the Bol'shoy Ikhtegipakhk site in the eastern part of the intrusion, where it overlies a lens of orthopyroxenite about 1 km long and up to 200 m thick. The latter rock is identical to orthopyroxenite fragments from the Norite–Gabbro-norite zone. Along the contact between the leucogabbro and the orthopyroxenite occurs an 8 m thick troctolite layer showing a gradational contact to the overlying rocks (Figure S2) and containing PGE mineralization (up to 49 ppm). This PGE-bearing layer is termed the FT-1 Reef (Figure 3b) [31].

At the top of the sequence is the Leucogabbro Zone. It is characterized by a coarse alternation of leucogabbros and leucogabbro-norites and contains another 1 m thick troctolite layer with PGE mineralization (up to 2 ppm). The latter is referred to as the FT-2 Reef.

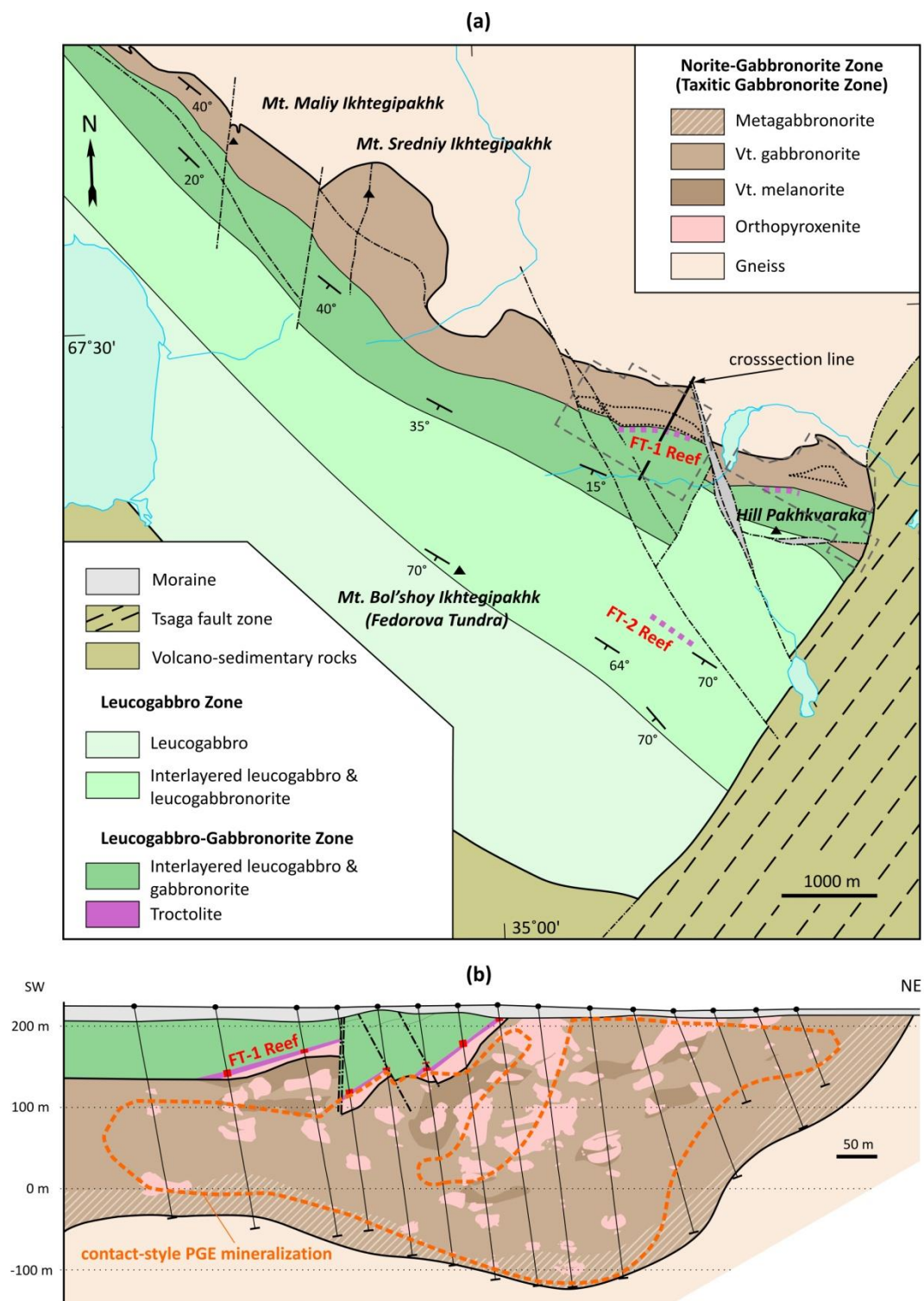


Figure 3. Simplified geologic map of the Fedorova intrusion (a) and schematic geologic cross-section through the Fedorova Tundra deposit (b). Purple dotted lines show the position of the PGE reefs on the map as well as red rectangles on the cross section pointing at mineralized borehole intervals. Black dotted lines indicate areas enriched in orthopyroxenite fragments (“orthopyroxenite lenses”); the grey dashed line shows the Bol’shoy Ikhtegipakhk and Pakhkvaraka sites of the deposit. Modified after [31].

The Last'yavr intrusion is a lens-like body measuring 5×1.8 km, with a northeast strike and displays southeasterly dipping layering. The intrusion is intensively tectonized since it is almost completely located in the area affected by the Tsaga fault zone (Figure 2). In its relatively unaltered western part, the Last'yavr intrusion strongly resembles the Fedorova intrusion and has a stratigraphy consisting of 50 m of taxitic gabbro, overlain by 200 m of orthopyroxenite (constituting a large fragment of the early phase of the intrusion) and units of gabbro and leucogabbro up to 1 km thick [41].

The West Pana intrusion is a sheet-like body which is up to 4 km thick and extends for more than 25 km along the strike. The layering dips to the southwest at an angle of $30\text{--}35^\circ$ (Figure 4). The stratigraphy of the West Pana intrusion is rather simple. The bottom of the intrusion is represented by a thin Norite Zone (50 m), which is underlain by marginal fine-grained gabbro. The latter are often strongly altered due to a tectonic activation of the intrusion contact. The remaining part of the intrusion is practically unaltered and is predominantly composed by massive gabbroids forming the Gabbro-norite Zone (GNZ). However, it contains two layered horizons, termed the Lower and Upper Layered Horizons. The Lower Layered Horizon (LLH) lies 600–800 m above the base of the intrusion and is composed of several cyclic units of orthopyroxenite, gabbro, leucogabbro and anorthosite (Figure S3A–E) with an average total thickness of 40 m. Low-sulfide Pt–Pd mineralization, associated mainly with the second cycle of the LLH, forms the so-called North Reef. The Kievev and North Kamennik deposits are examples of the North Reef. The Upper Layered Horizon (ULH) lies about 3000 m above the base of the intrusion and is sub-divided into two parts with a total thickness of 300 m. The lower part consists of interlayered gabbros, gabbro-norites and anorthosites. The upper part shows a rhythmic interlayering of olivine gabbro, troctolite and anorthosite, and is normally referred to as the “Olivine Horizon”. PGE mineralization is associated with both parts of the ULH, but it does not form continuous ore bodies. The most prominent type of PGE mineralization is termed South Reef and occurs in the thickest anorthosite layer of the lower part of the ULH (Figure S3H).

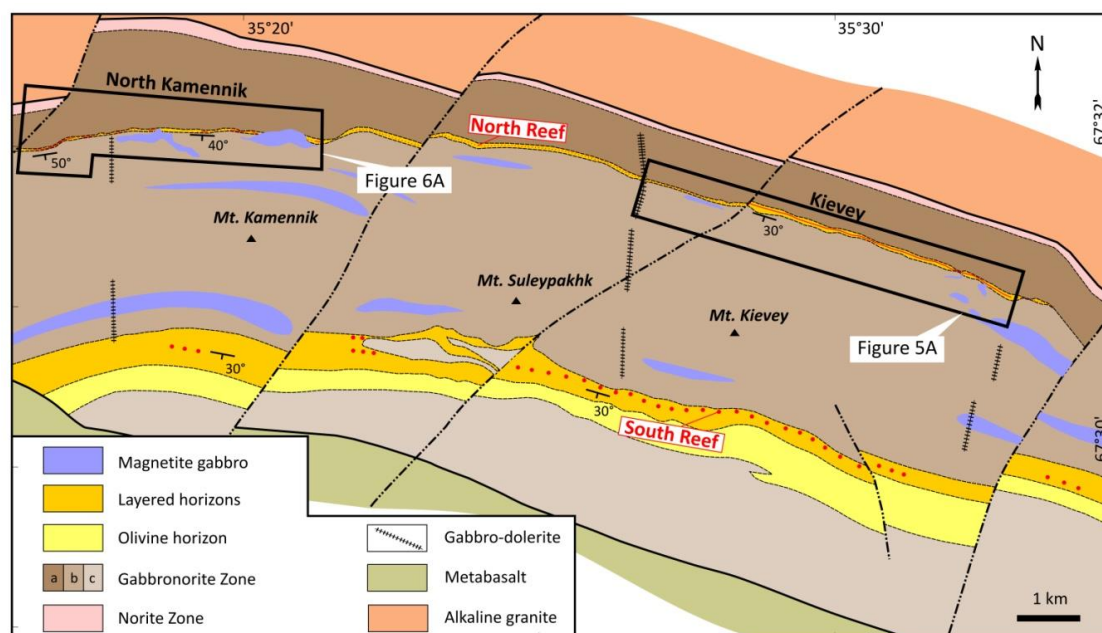


Figure 4. Simplified geologic map of the West Pana intrusion. a, b, c—GNZ1, GNZ2 and GNZ3 subzones of the Gabbro-norite Zone, respectively. Modified after [25].

The East Pana intrusion, with a strike length exceeding 20 km, is located to the southeast of the West Pana intrusion and has an exposed thickness of 4.5 km (Figure 2). It differs from the West Pana intrusion by the nature of stratification and has a distinct predominance of gabbros in the upper part of the intrusion. The East Pana intrusion comprises three zones considered to represent megacyclic units:

two Gabbronorite Zones with a total thickness of up to 1.5 km are overlain by a Gabbro Zone up to 3 km thick. Intermittent Pt–Pd mineralization is associated with the bases of each zone [46]. The East Chuarvy is a small deposit within one of them.

There is abundant evidence for the multiphase formation of the intrusions as a result of the replenishment of the magma chamber with new pulses of melt in the Fedorova–Pana Complex. The orthopyroxenite lens (2526 ± 6 Ma), Leucogabbro–Gabbronorite Zone (2518 ± 9 Ma) and the Leucogabbro Zone (2507 ± 11 Ma) of the Fedorova intrusion are considered to represent its early intrusive phases. This was succeeded by the intrusion of taxitic gabbronorites at 2485 ± 9 , hosting the contact-style Pt–Pd mineralization [22,47,48]. The cyclic layering of the LLH (2501.5 ± 1.7 Ma) in the West Pana intrusion has been explained by multiple influxes of melt, possibly using the Tsaga fault as a conduit. A reversal change in the composition of the cumulus phases at the level of the ULH of the West Pana intrusion is equally interpreted to reflect magma replenishment, in this case of a relatively primitive composition [43,49]. In addition, it is assumed that the three stratigraphic zones of the East Pana intrusion correspond to three cycles of magmatic activity [38,44].

3. Deposit Descriptions

The deposits of low-sulfide Pt–Pd ores in the Fedorova–Pana Complex are divided into two types: contact-style mineralization, localized within the marginal parts of the intrusions, and reef-style mineralization, which is concordant with the stratification of its host lithologies.

3.1. Contact-Style Deposits

Contact-style deposits include Pt–Pd mineralization at the Bol'shoy Ikhtegipakhk and Pakhkvaraka sites, which together form the Fedorova Tundra deposit, representing the largest PGE resource in Europe (Table 1). The closest analogues of the Fedorova Tundra deposit are the Ahmavaara and Konttiyarvi deposits of the Portimo Complex in Finland, which are similar in terms of the size, stratigraphic location, host lithology and geochemical characteristics of the ores (see Section 5.1 below).

Table 1. Resources and average grades for the largest low-sulfide Pt–Pd deposits of the Fennoscandian Shield.

Deposit	PGE + Au Resources (tons)	Pt (g/t)	Pd (g/t)	Au (g/t)	Ni (%)	Cu (%)	References
Portimo Complex							
Konttjärvi	83	0.41	1.44	0.11	0.06	0.13	[34]
Ahmavaara	166	0.25	1.17	0.14	0.09	0.23	[34]
SK Reef	158	0.67	2.45	0.07	0.08	0.10	[50]
Fedorova–Pana Complex							
Fedorova Tundra	348	0.29	1.20	0.08	0.08	0.12	[11,51]
Kievey North	49	0.53	3.32	0.15	0.13	0.15	[11,52]
Kamennik ¹	-	1.04	4.77	0.25	0.14	0.17	[53]

¹ Averaged data from a representative borehole ($n = 20$).

The Fedorova Tundra deposit is confined to the Norite–Gabbronorite Zone lying at the base of the Fedorova intrusion. The thickness of the zone is extremely variable, but the average is about 250 m. The most common rock types are taxitic gabbroids of variable mineral compositions, mainly mesocratic gabbronorites and to a lesser extent melanocratic gabbronorites and norites, norites, leucogabbros and olivine gabbronorites (Figure S1). The rocks are crudely layered and dip to the southwest at angles of 10° to 45° . The zone contains numerous fragments of orthopyroxenite (as well as olivine

orthopyroxenite and harzburgite) ranging in size from several tens of cm to 100 m in diameter (Figure 3b). The fragments are widely distributed along the zone, especially in its upper parts, at the Bol'shoy Ikhtegipakhk target, and define the general brecciated structure of the zone.

Large lenticular ore zones have been explored on the Bol'shoy Ikhtegipakhk and Pakhkvarka sites, which are separated from one another by a fault of northwesterly strike (Figure 3a). The ore zones consist of 2–5% of disseminated sulfides which occur interstitially to silicates in the taxitic gabbroids. The sulfide disseminations form layers that coincide with the general strike of the intrusion and follow the topography of its lower contact. The total length of the ore zones is about 3 km, with an average thickness of 60 m and a maximum thickness of up to 280 m (Figure 3b).

The ore zone occurs as a series of separate ore bodies of a complicated structure. The boundaries of the ore bodies generally coincide with the visible sulfide disseminations, forming jets and lenses of varying thickness, length and orientation. This structure is a result of the general brecciated nature of the Norite–Gabbronorite Zone. The distribution of sulfides in the ore bodies is irregular, with sulfide-enriched rocks usually separated by barren orthopyroxenites and gabbronorites.

The main ore minerals associated with the low-sulfide mineralization are chalcopyrite, pyrrhotite and pentlandite, occurring in relative proportions of 41, 35 and 24 vol. %, respectively. Pyrite, troilite, ilmenite, magnetite, mackinawite, marcasite, cubanite, millerite, bornite, sphalerite and violarite are present as secondary and accessory minerals, constituting up to 5% of the ore minerals [54].

PGE may be hosted in platinum-group minerals or be isomorphically included in base metal sulfides, mainly in pentlandite, which contains on average 420 ppm Pd [54]. Thirty minerals of PGE and gold have been found in the ore. Sulfides (braggite, vysotskite) and bismuth–tellurides (kotulskite, merenskyite, moncheite, sobolevskite) of PGE are the most common (Table 2, Figure S4). Arsenides, sulfoarsenides, stannides of PGE and native elements occur in subordinate amounts [54].

Table 2. Platinum group minerals from low-sulfide Pt–Pd ores of the Fedorova–Pana Complex.

Mineral	Abbreviation	Formula	Deposit/Occurrence					
			FT	NK	K	FT1	FT2	SR
Platinum	Pt	Pt	•			•		
Hongshiite	Hng	PtCu		•	•			•
Isoferroplatinum	Ifp	Pt ₃ Fe	•	•	•		•••	•
Niggliite	Nig	PtSn	•					
Rustenburgite	Rust	(Pt,Pd) ₃ Sn	•	•	•			
Palladium	Pd	Pd	•			•	•	•
Skaergaardite	Skr	PdCu				•		•
Bortnikovite	Btn	Pd ₄ Cu ₃ Zn					•	
Zvyagintsevite	Zvg	Pd ₃ Pb		•	•	•	•	•
Paolovite	Plv	Pd ₂ Sn	•	•	•			
Atokite	Atk	(Pd,Pt) ₃ Sn	•	•	•		•	•
Palarstanide	Pls	Pd ₅ (Sn,As) ₂	•	•	•		•	
Kojonenite	Kjn	Pd _{7–x} SnTe ₂		•				•
Telargpalite	Tlr	(Pd,Ag) ₃ Te	•	•	•			•
Kotulskite	Kot	Pd(Te,Bi)	•••	•••	•••	•	•	•
Michenerite	Mch	PdBiTe	•	•	•			
Merenskyite	Mer	PdTe ₂	•••	•••	•••			•
Moncheite	Mon	Pt(Te,Bi) ₂	•	•••	•••	•		•
Telluropalladinite	Tlp	Pd ₉ Te ₄		•	•			•
Keithconnite	Keit	Pd ₂₀ Te ₇	•	•	•	•	•	•
Sopcheite	Sop	Ag ₄ Pd ₃ Te ₄	•	•	•	•		•
Lukkulaisvaaraite	Luk	Pd ₁₄ Ag ₂ Te ₉		•				
Tornroosite	Tor	Pd ₁₁ As ₂ Te ₂	•	•	•			•
Temagamite	Tmg	Pd ₃ HgTe ₃	•	•	•			
Sobolevskite	Sob	PdBi	•	•	•			
Froodite	Fro	PdBi ₂	•					

Table 2. Cont.

Mineral	Abbreviation	Formula	Deposit/Occurrence					
			FT	NK	K	FT1	FT2	SR
Mertieite I	Mrt-I	Pd ₁₁ (Sb,As) ₄	•	•	•		•	•
Isomertieite	Iso	Pd ₁₁ Sb ₂ As ₂		•				
Sperrylite	Sper	PtAs ₂	•	•	•	•••	•	•
Vincentine	Vin	Pd ₃ As	•	•	•			•
Atheneite	Atn	Pd ₂ (As _{0.75} Hg _{0.25})	•					
Palladoarsenide	Pal	Pd ₂ As	•	•	•			
Arsenopalladinite	Apd	Pd ₈ (As,Sb) ₃		•				
Stillwaterite	Stl	Pd ₈ As ₃	•	•	•	•••	•	•
Stibiopalladinite	Sbp	Pd ₅ Sb ₂						•
Hollingworthite	Hol	RhAsS	•	•	•	•		•
Irarsite	Irs	IrAsS	•	•	•	•		•
Platarsite	Pars	PtAsS				•		
Menshikovite	Men	Pd ₃ Ni ₂ As ₃	•					•
Braggite	Br	PtS	•••	•	•••	•	•••	•••
Vysotskite	Vys	(Pd,Ni)S	•	•••	•••	•		•••
Laflammeite	Lfl	Pd ₃ Pb ₂ S ₂						•
Laurite	Lrt	RuS ₂		•	•			•
Malanite	Mln	CuPt ₂ S ₄		•	•			
Coldwellite	Cdw	Pd ₃ Ag ₂ S	•					•
References			[54]	[25,55]	[54]	[45]	[31]	[54,56]

Abbreviations. FT, Fedorova Tundra deposit; NK, North Kamennik deposit; K, Kievev deposit; SR, South Reef; FT1 and FT2, FT-1 and FT-2 reefs in the Fedorova intrusion respectively; •••—main minerals, •—subordinate minerals.

The Pt + Pd content in the ore averages 1.49 ppm with Pd/Pt = 4.1, the average Cu and Ni content is 0.12 and 0.08 wt. %, respectively, at a ratio of Cu/Ni = 1.5 (Table 1). According to our estimate, the relative concentration of PGE (Pt + Pd) / S is 4.8. It corresponds to the definition of low-sulfide Pt–Pd ores ((Pt + Pd)/S > 4–5 ppm/wt. %) proposed in [5]. The Pt, Pd and Au resources of the Fedorova Tundra deposit amount to 348 tons (Table 1).

3.2. Reef-Style Deposits

The most important low-sulfide Pt–Pd deposit representing reef-style mineralization in the Kola Region is the North PGE Reef of the West Pana intrusion. In terms of its thickness, length, morphology and PGE contents, the North Reef is, to some degree, comparable to the classical reefs of the Bushveld and Stillwater Complexes, but even more so the PGE reefs of the Penikat and Portimo intrusions. Other examples of reef-style PGE mineralization of the Fedorova–Pana Complex include the South Reef in the West Pana intrusion [3], two reef-style horizons in the Fedorova intrusion [31] and three horizons in the East Pana intrusion [44]. All these horizons have either PGE concentrations that are too low to be economic, have an intermittent nature of mineralization, or are very small (e.g., the East Chuarvy deposit in the East Pana intrusion, which contains about 8 tons of noble metals).

Two low-sulfide Pt–Pd deposits have been explored within the North Reef: the Kievev deposit in the eastern flank and the North Kamennik deposit in the western portion of the intrusion (Figure 4). As yet, the PGE mineralization in the central part of the reef (North Suleypakhk site) remains uneconomic.

3.2.1. Kievev

This deposit includes a 6 km long part of the North Reef from the Mar’jok to the East Kievev site (Figure 4). The LLH in the deposit area is a layered body with an average thickness of about 40 m, composed of a variety of rock types forming between two to five cycles. The LLH is sandwiched between two more than 800 m thick slightly differentiated units of gabbro-norite, namely fine-grained gabbro-norites of GNZ1 below the LLH, and medium-grained mesocratic gabbro-norites (GNZ2) above the LLH (Figure 4). A laterally extensive layer (up to 1.5 km along strike) of fine-grained feldspathic

orthopyroxenite or melanocratic norite, with a thickness of several tens of centimeters to a meter, often occurs at the base of the LLH and is used as a marker horizon [30].

The internal structure of the LLH is cyclic and is caused by several units of basal orthopyroxenite or norite overlain by gabbronorites and anorthosite (Figure S3A–E). The average unit thickness is about 10–15 m. The number of cycles in the LLH varies from one to five. Commonly, two or three cycles can be reliably identified. Low-sulfide PGE mineralization is associated with the second and subsequent cycles.

The thickness of mineralized horizons containing 1–3% of disseminated sulfides varies from tens of centimeters to 6 m. It has been empirically established that the greater the thickness of the LLH, and with it the amount and total thickness of melanocratic cumulates, the higher the content of sulfides and PGE.

The deposit contains two ore bodies (Figure 5). The main ore body extends almost without interruptions for about 6 km along strike. It has an average thickness of 1.7 m and is associated with the second cycle of the LLH. There is some lateral variation in lithology; in the west, the ore is associated with a pyroxenite layer at the base of the cycle, whereas in the east, the ore is associated with interlayered norite, gabbronorite, and leucogabbro. The thin discontinuous upper ore body can be traced for a maximum strike length of 900 m in the central portion of the deposit. It is located in the third LLH cycle at the interface between interlayered norites and gabbronorites with overlying leucogabbro.

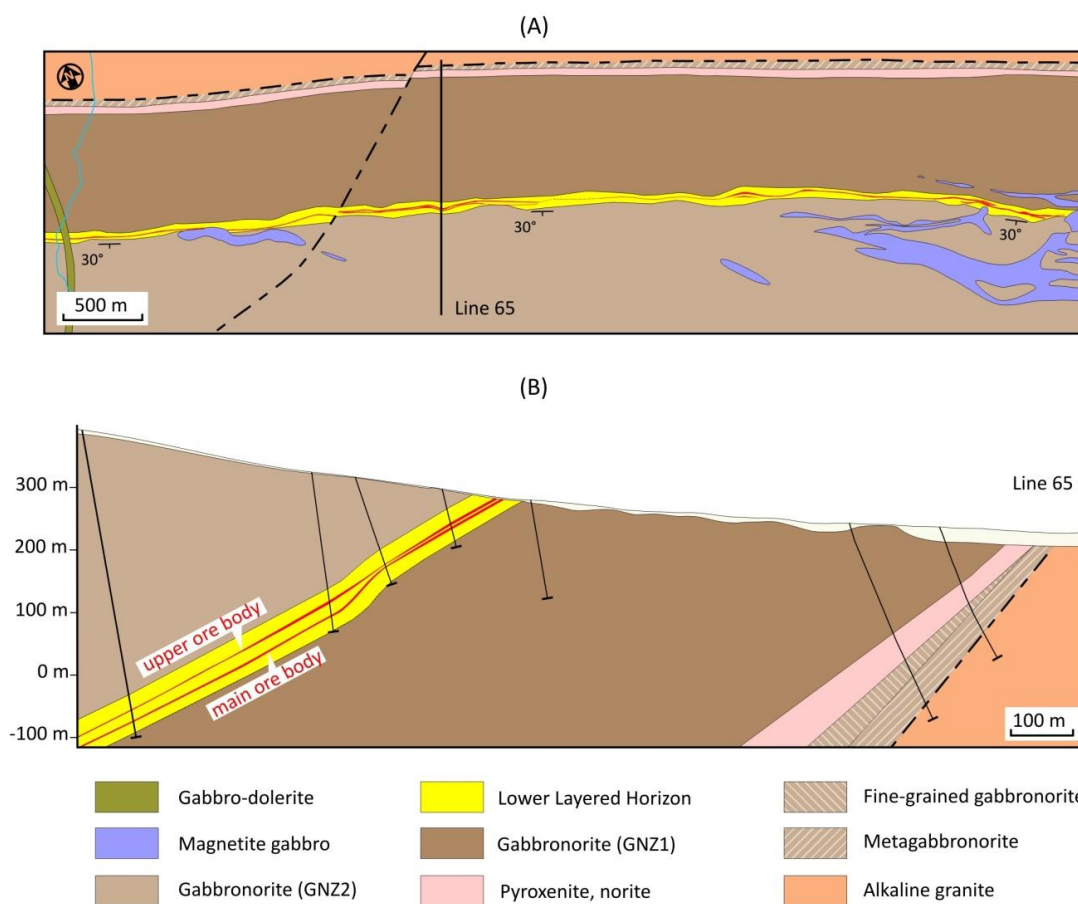


Figure 5. Simplified geologic map (A) and schematic geologic cross section (B) of the Kievev deposit. Red lines show position of ore bodies. Modified after [30].

The main ore minerals are chalcopyrite, pentlandite, and pyrrhotite, accounting for up 47, 32 and 21 vol. % of the sulfides, respectively. Minor, accessory and secondary minerals are ilmenite, magnetite, pyrite, mackinawite, marcasite, millerite, godlevskite, polydymite, cubanite,

bornite, covellite, digenite, chalcocite, sphalerite and violarite. Rare accessory minerals are galena, argentopentlandite, molybdenite, linnaeite, cobaltite, acanthite, hessite, hawleyite and clausthalite [54].

The grain size of the sulfides reaches one millimeter in the fine- and medium-grained gabbro, norite and orthopyroxenite, whereas the coarse-grained and strongly altered gabbroids contain polymineralic clots of sulfides up to 2–3 cm in size. The sulfide impregnations are almost always surrounded by reaction rims of secondary minerals (amphiboles, chlorite, clinozoisite etc.).

More than 40 minerals of PGE and gold are found in the ores of the deposit. Bismuth–tellurides (moncheite, kotulskite and merenskyite) and sulfides (braggite and vysotskite) of PGE predominate (Figure S4), whereas arsenides and tellurides of PGE as well as Au alloys are found in minor amounts (Table 2). It is assumed that a significant proportions of the PGE (up to 50%) in the ore of the deposit is concentrated in pentlandite containing an average of 1800 ppm Pd [54].

The average content of metals in the ores is given in Table 1 and the relative concentration of PGE ((Pt + Pd)/S) is estimated at 7.2. The total reserves of noble metals of the Kievev deposit amount to 49 tons.

3.2.2. North Kamennik

The North Kamennik deposit was discovered in 2015. It is located on the western flank of the LLH in the West Pana intrusion (Figure 4). The mineralization is also concentrated in the North PGE Reef and can be traced for several kilometers to the east. The length of the North Kamennik deposit is 5.2 km, and it is confirmed to a depth of 200–250 m below surface. The LLH is present along almost the entire area of the deposit. An 800 m long gap in the eastern part of the deposit is a consequence of a late magmatic body of magnetite gabbro replacing the LLH (Figure 6).

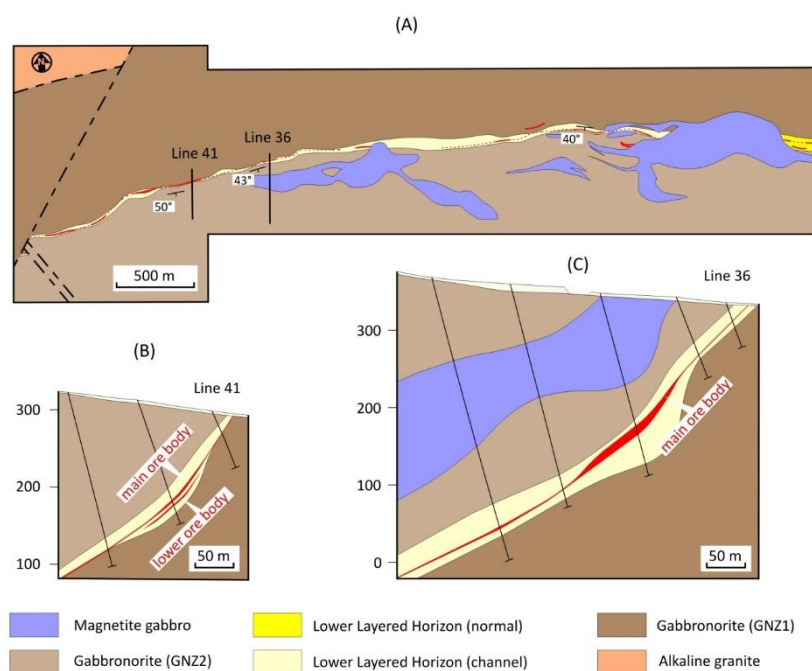


Figure 6. Simplified geologic map (A) and schematic geologic cross sections (B,C) of the North Kamennik deposit. Red lines show position of ore bodies. Modified after [30].

As in the Kievev deposit discussed above, the LLH in the North Kamennik deposit is also characterized by interlayered anorthosite, leucocratic gabbro, gabbro, norite and pyroxenite, dipping south at 35–50°. However, unlike in the Kievev deposit, it is difficult to single out and trace individual cycles in the North Kamennik deposit because melanocratic rocks are much less common. Instead, troctolites and olivine gabbro occur in the central portion of the LLH, and these

rocks generally host PGE mineralization (Figure S3F,G). The thickness of these relatively magnesian differentiates increases in pothole-like structures, which consist of thickened portions of the LLH transgressing into the floor rocks [25]. Since the formation of the LLH is traditionally explained by the injection of new magma into the chamber, it is assumed that such depressions are the result of magmatic erosion of cumulates by the replenishing magma. The thickness of the LLH in the western part of the deposit varies from 5 m up to 70 m in potholes, whereas the average thickness is 30–40 m. In the eastern part of the deposit, the LLH is less variable and its thickness ranges from 50 m to 80 m.

Ivanov and colleagues [53] suggested to divide the LLH into two facies, namely a channel facies and a normal facies, with the former being predominant in the North Kammenik area (Figure 6), whereas the latter occurs mainly in the Kievev area (Figure 5).

The PGE ore bodies are located mainly in the central or lower part of the LLH and form interlayers and lenses, occurring generally concordant with the stratification of the LLH (Figure 6). The thickness of the ore-bearing zone is usually 3–10 m and reaches up to 35 m in potholes. It appears that mineralization is generally absent where the thickness of the LLH is less than 10 m. The most consistent, rich and thick mineralized intervals form the main ore body, whereas other intervals are referred to as the lower ore body and a series of ore lenses lying mainly below the main ore body. Mineralization can be associated with all types of rocks. The analysis of geological cross-sections shows that the greater the thickness of the LLH, the greater the amount and total thickness of the olivine-bearing layers (and melanocratic cumulates), and the greater the potential for ore bodies. The main ore body occurs along the western and eastern parts of the deposit, with a length of 1700 and 900 m, respectively, and separated by a barren portion of the LLH measuring about 1400 m. The thickness of the main ore body varies from 0.3 to 4.8 m, averaging 1.6 m.

The mineral composition of the ore of the North Kamennik deposit is similar to that of the Kievev deposit (Table 2). The main sulfides are chalcopyrite, pyrrhotite and pentlandite in ratios similar to those in the Kievev ore body (48%, 26% and 26%, respectively). Pentlandite contains about half of all Pd, with the maximum concentration in this mineral reaching 3.15 wt. %. More than 30 minerals of PGE and Au are found in the deposit. The main minerals of PGE are sulfides (vysotskite) and bismuth–tellurides (kotulskite, moncheite and merenskyite) of Pt and Pd (Table 2, Figure S4). Less frequent are native gold, sperrylite, sopcheite, palladium arsenides, etc. [54].

The average content of metals in a representative drill hole is given in Table 1. The North Kamennik deposit resembles the Kievev deposit in almost all parameters. As the North Reef is interrupted in two places, the resources of PGE at the North Kamennik deposit are several times smaller compared to those of the Kievev deposit. The discovery of the North Kamennik deposit proves the presence of economic ore bodies at both ends of the West Pana intrusion. This suggests that similar deposits may be found in the central portion of the North Reef.

4. Whole-Rock Geochemistry of the Ores

A total of 26 samples, covering the low-sulfide deposits in the Fedorova and the West Pana intrusions, were analyzed to characterize the lithophile and chalcophile element distribution. The full dataset of whole-rock geochemical analyses, including partially published data by the authors [53,57–59], can be found in Supplementary Table S1.

4.1. Lithophile Elements

In terms of primitive mantle-normalized incompatible element patterns, most mineralized rocks of the deposits have fractionated spectra with a negative Nb–Ta anomaly and strong positive Sr and Eu anomalies (Figure 7A–F), including pegmatoids and taxitic gabbro-norites from the Fedorova Tundra and the North Kamennik deposits (Figure 7A,C). Considering the average spectra of the deposits, it appears that the negative Zr–Hf anomaly becomes more pronounced in an eastward direction from the Fedorova Tundra to the Kievev deposit (Figure 7E). Only the rocks of the Fedorova reefs, represented by troctolite and leucogabbro, showing a relatively poorly fractionated trace element

pattern with a negative Ta anomaly, do not have negative Nb anomalies (Figure 7B). The La/Nb ratio in these rocks ranges between 0.9–1.6, indicating that the Fedorova reefs are represented by the primitive mineralized rocks of the complex. The remaining ore samples of the Fedorova–Pana Complex have similar patterns to those of gabbro from the marginal zone at Mt. Travyanaya and to the metagabbro of the Vuruchuyvench massif of the Monchegorsk Complex (Figure 7E,F) [60,61].

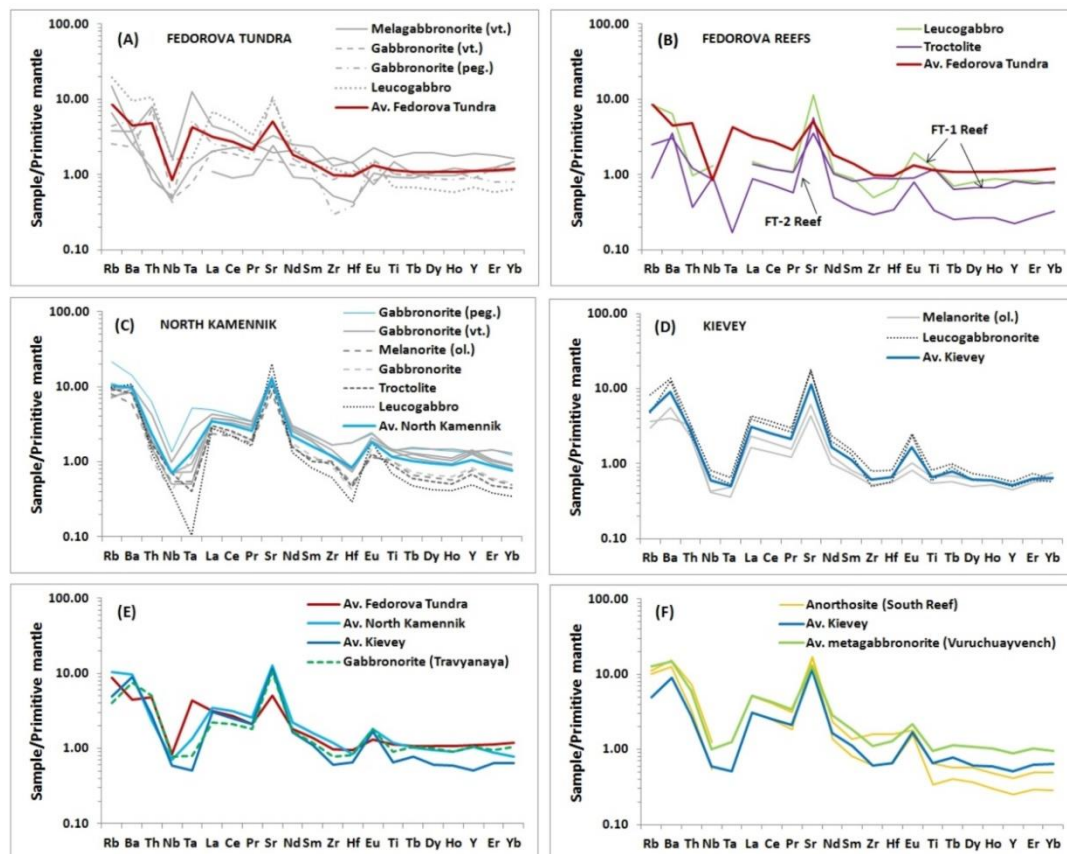


Figure 7. (A–F) Primitive mantle-normalized multielement variation diagrams of Fedorova–Pana ore types summarized for this review. Normalization values were taken from [62]. Data for the Travyanaya and the Vuruchuyvench gabbro from [60] and [61], respectively. Abbreviations: av. = average; ol. = olivine; peg. = pegmatoid; vt. = varied-textured.

Notably, most samples from Fedorova–Pana are characterized by relatively strong negative Nb–Ta anomalies similar to the Monchegorsk Complex [60]; however, the exceptionally primitive reefs of the Fedorova intrusion (Figure 7B) as well as the most primitive ophitic orthopyroxenite from Monchegorsk (Figure 10B in [60]) lack this feature, which may indicate that the parental magma to the most primitive rocks at both intrusions may not have necessarily featured a negative Nb–Ta anomaly. This is particularly important with respect to magma derivation, as negative Nb–Ta anomalies are consistent with either the melting of the asthenospheric mantle followed by crustal contamination or with the melting of the subcontinental lithospheric mantle (SCLM) [16,18,20,63,64]. Since both alternatives have been considered as a possible source for the 2.5 to 2.44 Ga magmatism across the Fennoscandian Shield, the lack of negative Nb–Ta anomalies in some of the most primitive rock types from the Monchegorsk Complex and the Penikat intrusion suggests that the widespread Nb–Ta depletion may not be a primary feature inherited from the source region but may have resulted from crustal contamination of asthenospheric mantle melt. This model would be consistent with recent Os, Nd, and Sr isotope data from Yang et al. [20], which also argue for a mantle plume rather than an SCLM source.

4.2. Chalcophile Elements

The existing sample set from the PGE deposits of the Fedorova–Pana Complex shows a broadly positive correlation between chalcophile elements and sulfur (Figure 8A–G), suggesting that the chalcophile metal abundances are mainly controlled by sulfide. The strongest correlations exist between S and Pd as well as Cu. The correlation between metals and sulfur, however, becomes notably poorer in samples with less than 0.1 wt. % S. Variations in correlation between Ni and S can be partly attributed to Ni hosted in olivine.

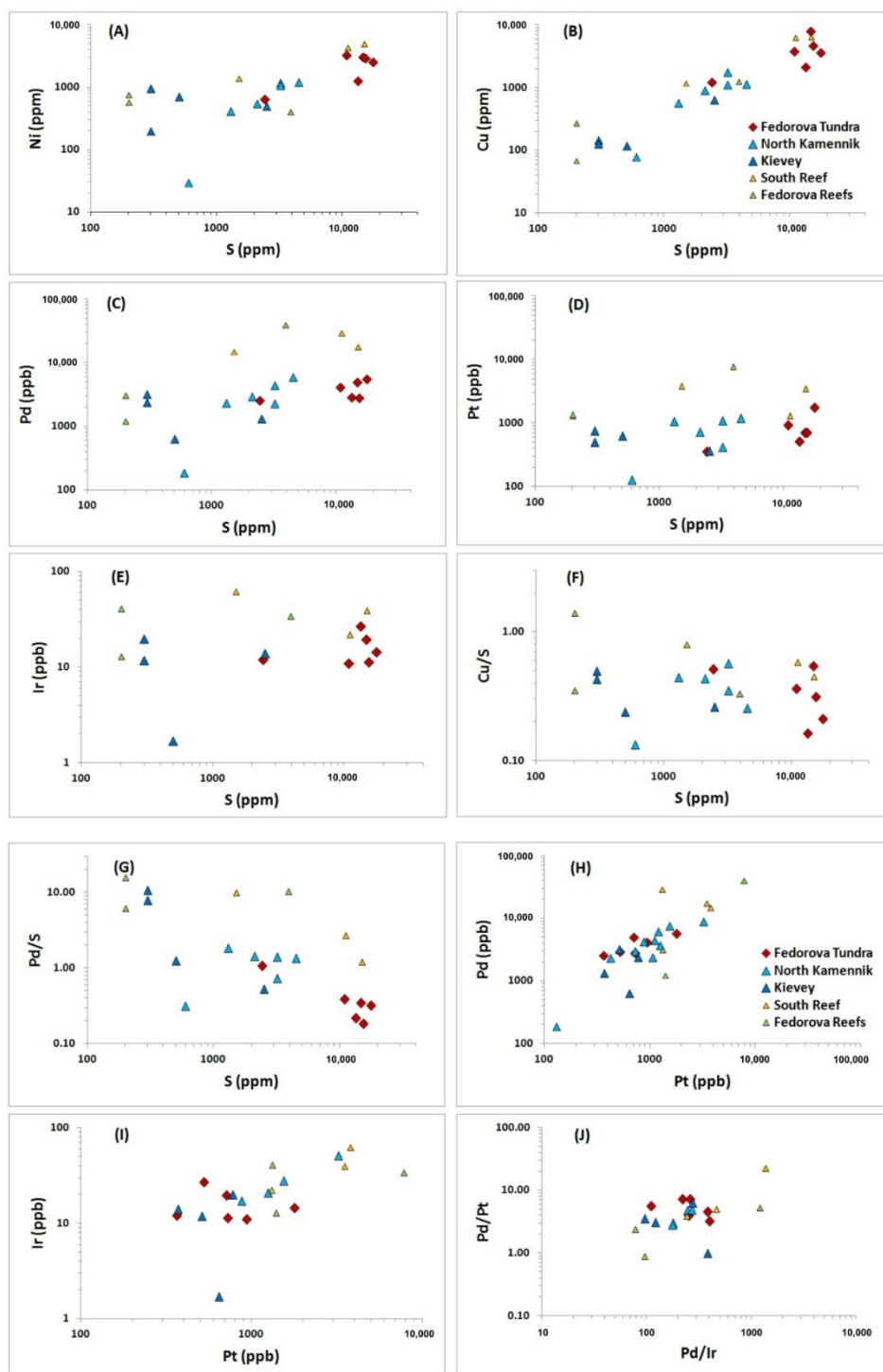


Figure 8. (A–F) Binary variation diagrams of chalcophile elements. (A) Ni vs. S. (B) Cu vs. S. (C) Pd vs. S. (D) Pt vs. S. (E) Ir vs. S. (F) Cu/S vs. S. (G) Pd/S vs. S. (H) Pd vs. Pt. (I) Ir vs. Pt. (J) Pd/Pt vs. Pd/Ir.

It should be noted that the samples from the Fedorova Tundra, the North Kamennik and the Kievev deposits form a series in which sulfur concentrations progressively decrease eastwards, while the PGE contents in the ores remain approximately constant. In addition, the South Reef in the West Pana intrusion and the reef horizons in the Fedorova intrusion have significantly higher PGE/S ratios than the economic Pt–Pd deposits in the Fedorova–Pana Complex (Figure 8C,D). We assume that the deposits and the occurrences belong to different ore-magmatic sub-systems of the Fedorova–Pana Complex. Differences between these sub-systems are most evident in a plot of Pd/S vs. S, shown in Figure 8G.

This is also evident in primitive mantle-normalized chalcophile element patterns of the analyzed samples (Figure 9). The average Pt–Pd ores from the Fedorova–Pana deposits have very similar chalcophile element patterns with positive Pd, Rh and Ir and slightly negative Pt and Ru anomalies (Figure 9D), supporting their close origin, whereas samples from the primitive rocks of the Fedorova reefs do not show a negative Pt anomaly and are depleted in Cu compared to Fedorova–Pana average (Figure 9B,C). Notably, the SK Reef and the Kontijarvi contact-style deposit (Figure 9D) in the Portimo Complex [65] share the same PGE patterns as the main reef-style and contact-style mineralization at Fedorova–Pana.

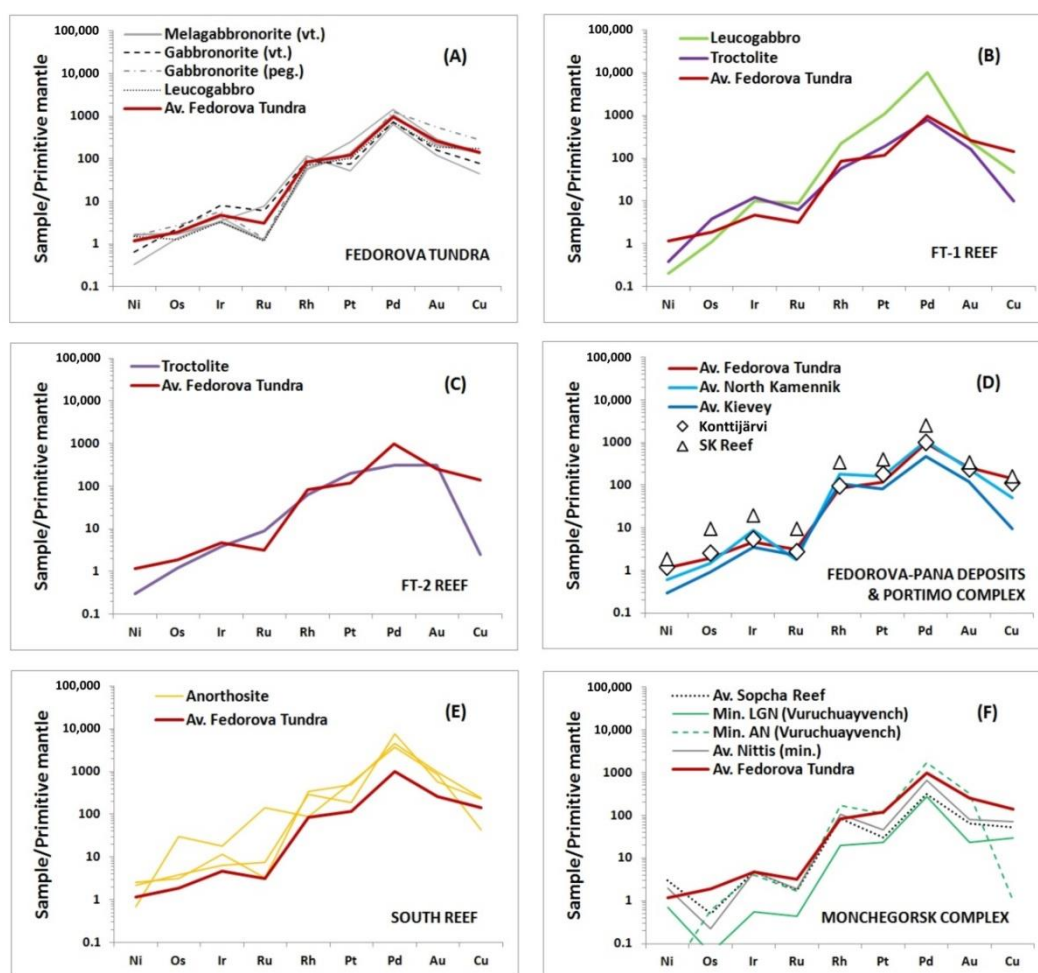


Figure 9. (A–F) Primitive mantle-normalized chalcophile element patterns of Fedorova–Pana mineralized rock types. Data for the Portimo Complex and for the Monchegorsk Complex (Nittis, Sopcha and Vuruchayvench) are from [65] and [60,61], respectively. Normalization factors are from [66]. Abbreviations: AN = anorthosite; LGN = leucogabbronorite; av. = average; min. = mineralized; peg. = pegmatoid; vt. = varied-textured.

5. Petrogenesis of the Deposits of the Fedorova–Pana Complex

5.1. Comparison with the Portimo Complex

The Paleoproterozoic Portimo Complex in northern Finland also contains significant reef and contact-style low-sulfide Pt–Pd deposits. The SK Reef forms the main ore-bearing layer and is confined to the base of the third megacyclic unit of the Narkaus intrusion in the northern part of the complex. The Suhanko and Konttijärvi intrusions in the southern part of the Portimo Complex are composed of rocks that correspond to the third megacycle of the Narkaus intrusion and contain zones of PGE-enriched sulfide dissemination with a thickness up to 170 m in their marginal series. Iljina suggested [65] that the marginal series of the Suhanko–Konttijärvi intrusion and the SK reef of the Narkaus intrusion were formed as a result of the same magmatic pulse, with a comparatively low-magnesian and low-chromium composition, and can be considered together as the Portimo Reef. In addition to the Portimo Reef, the complex contains several other, less prominent types of Pt–Pd mineralization (RK Reef, offset mineralization of Narkaus, etc.).

The SK reef is predominantly hosted by olivine cumulates at the base of the third megacyclic unit of the Narkaus intrusion, but the reef can sit below these rocks for tens of meters or in the middle of the ultramafic layer. The strike length of the reef is about 15 km, and the thickness varies from several tens of centimeters to several meters. In many intersections, the mineralization occurs in several horizons separated by PGE-poor interlayers with a thickness of several meters. The concentration of PGE can reach several tens of ppm. Numerous gabbro-pegmatites occur below the third megacyclic unit. Some of these pegmatites may contain Pd and Pt concentrations similar to pegmatites below the main ore body in the Northern Kamennik deposit. The total resources of noble metals of the SK reef exceed 150 tons (Table 1) and resemble the estimation of total resources of the North Reef [3].

The PGE-enriched disseminated sulfide layers of the Konttijärvi and Suhanko intrusions, usually 10–30 m thick, occur within their marginal series in peridotites and gabbroids, including pegmatoidal and taxitic (varied-textured) varieties. The distribution of sulfides in the marginal series is uneven. At the Ahmavaara site of the Suhanko intrusion, the mineralized zone is often divided into upper and lower marginal gabbro, between which lies an almost barren interlayer of microgabbro brecciated by the enclosing mineralized rocks. The brecciated structure of the marginal series of the Konttijärvi intrusion is due to numerous fragments of peridotites in the gabbro. The PGE content varies from anomalous values to 2 ppm, in individual samples exceeding 10 ppm. Pd/Pt and Cu/Ni ratios are close to those for the Fedorova Tundra deposit and vary between 3.5–4.7 and 2.2–2.6, respectively. The average metal content in the deposits of these intrusions is given in Table 1. The total resource of PGE and Au is 324 tons.

Iljina and Hanski proposed that the Portimo Reef formed from magmas that entrained sulfides from a staging chamber [67]. The similarity of the stratigraphy and geochemistry between the Portimo Reef and the Pt–Pd mineralization of the Fedorova–Pana Complex suggests that a similar model could be applied to the latter intrusion.

5.2. Timing of Sulfide Melt Saturation and Parental Magma Composition

The timing of sulfide melt saturation is key to understanding the genesis of magmatic sulfide deposits. It is believed that the saturation of magma with sulfur leads to the formation of an immiscible sulfide liquid, which becomes enriched in non-ferrous and noble metals during the interaction with a silicate melt due to the high partition coefficients (D) of metals with regard to sulfide melt. D is about 30,000 for metals of the platinum group, and 1000 and 500 for copper and nickel, respectively [66]. For most low-sulfide Pt–Pd deposits in layered intrusions, the source of sulfur is its parental magma [2]. The sulfur isotope composition of the Fedorova–Pana ores, with a $\delta^{34}\text{S}$ value not exceeding 1.4 per mille, is consistent with a magmatic source of sulfur [22].

Some authors [60,61,67] have proposed that PGE reefs as well as contact-style PGE mineralization form through the entrainment of sulfides from a staging chamber, but in the Fedorova–Pana Complex, the evidence is not clear at the moment.

Constraining the composition of the parental magma is rather difficult as chilled margins have not been observed in the Fedorova–Pana Complex. Siliceous high-Mg basalts are considered to represent the parental magma for other Paleoproterozoic intrusions, such as the Portimo Complex [69]. The presence of high-Mg dunitic rocks in some intrusions [60] and komatiitic chilled margins in others [70] indicates that komatiite can also be considered as a possible parental magma. Figure 10 shows the results of modeling the composition of sulfides in the Fedorova–Pana Complex based on a parental magma with composition of a basalt with approximately 7.6% MgO from the komatiitic basalt lava lake of the Vetreny Greenstone Belt containing 70 ppm Ni, 96 ppm Cu, 10.52 ppb Pt, 13.20 ppb Pd, 0.07 ppb Ir and 0.75 ppb Ru [71].

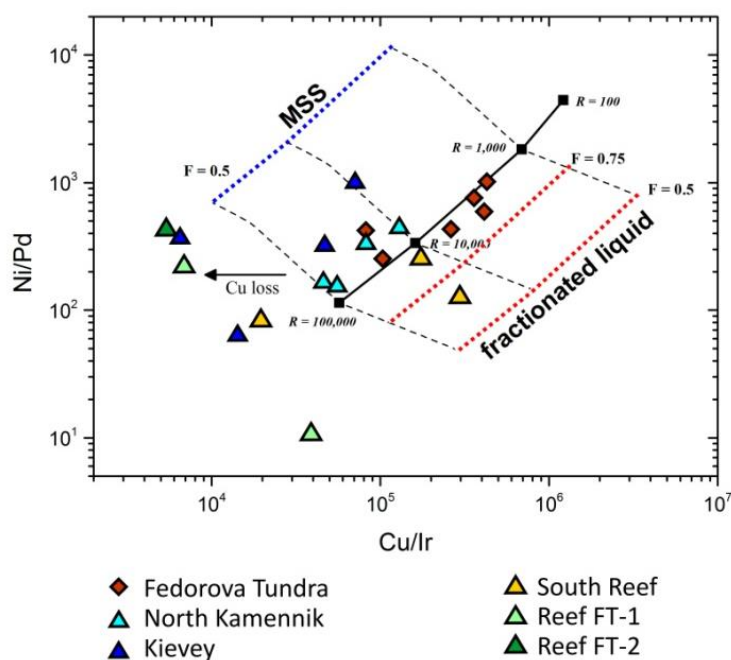


Figure 10. Binary ratio plot of Ni/Pd vs. Cu/Ir for the Fedorova–Pana low-sulfide Pt–Pd deposits. The black solid line shows model sulfide compositions at different R factors. The black dashed lines represent model compositions of monosulfide solid solution (mss), crystallizing from sulfide liquids undergoing fractionation and residual liquid. The dotted lines show different end-member mss (blue) and residual sulfide liquid (red) compositions, assuming different degrees of fractionation (F = fraction of residual liquid). Sulfide melt/silicate melt D values: 30,000 for the platinum group elements, 1000 for Cu, and 500 for Ni. Mss/sulfide melt D values as summarized in [68].

The modelling suggests that the Pt–Pd deposits of the Fedorova–Pana Complex formed at an R factor between 3000 to 100,000 (Figure 10). Besides, the average value of the ratio of the reacted masses of silicate and sulfide liquids or R factor [72] increases from the Fedorova Tundra deposit (3000–12,000) to the reef-style deposits located to the east (10,000–100,000). During further research, it would be possible (e.g., Section 5.3) to fully substantiate the applicability for the Fedorova–Pana intrusions of the Portimo model, in which contact-style PGE deposits (Suhanko, Konttijärvi) would be combined with a reef-style deposit (SK Reef) into one main mineral system (Portimo Reef). In this case, the increase of the R factor for the Fedorova–Pana deposits towards the east can be explained as follows. The formation of the main Fedorova–Pana mineral system begins with the additional intrusion of magma containing PGE-enriched sulfides. Along the basal contact of the Fedorova intrusion, representing a possible ore-bearing feeder at the base of the complex, this magma crystallized relatively quickly with a small interaction between silicate and sulfide liquid, generally reflecting the R factor of the staging chamber

at depth. However, the emplacement of the same magma in the West Pana chamber, divided into a series of pulses, led to a sequential and relatively slow crystallization of the LLH cycles (e.g., Kievey), which allowed for an additional increase in the R factor through higher degrees of interaction between silicate and sulfide liquid.

5.3. The Problem of the Duration of Crystallization of Intrusions

It is generally believed that the formation of PGE mineralization in most Russian Paleoproterozoic layered intrusions is related to prolonged igneous activity in response to a long-lived mantle plume [73] affecting the Kola Craton for more than 50 Ma, which is mainly based on ID-TIMS U–Pb age dating [15,49]. This interpretation is generally at odds with the current paradigm of relatively short-lived mantle plume magmatism and the duration of cooling of basaltic magma chambers, such as the Bushveld Complex, which crystallized in less than 1 Ma [74].

Groshev and Karykowski [75] have recently summarized published U–Pb ages for rocks from the Fedorova–Pana Complex (Table 3). The ID-TIMS ages indicate a duration of crystallization of about 80 Ma. The oldest zircon age of 2526 ± 6 Ma was obtained for the orthopyroxenite xenoliths from the Fedorova intrusion. An anorthosite from the South Reef was found to be the youngest rock of the complex with an age of 2447 ± 12 Ma. However, U–Pb SHRIMP-II dating has shown that this anorthosite contains two zircon generations: (i) magmatic high Th/U (0.9–3.7) zircon with an age of 2509.4 ± 6.2 Ma and (ii) secondary low Th/U (0.1–0.9) zircon and baddeleyite with an upper intercept age of 2476 ± 13 [75]. Thus, it seems that most of the discordant ID-TIMS ages need to be revisited.

The main challenge in establishing a sound geochronological emplacement history for the Fedorova–Pana Complex is the precise dating of different mineralized and unmineralized lithologies from the Fedorova Tundra, the Northern Kamennik, and the Kievey deposits using the same methodology. This could show that all these PGE deposits belong to the same mineral system and were formed at the same time. These types of studies are necessary and feasible as was demonstrated for the PGE deposits of the Bushveld [74,76] and Stillwater Complexes [77].

Table 3. Published isotope U–Pb rock ages of the Fedorova–Pana Complex.

Intrusions	Rock Type	Age (Ma)	Mineral	References
Fedorova	Gabbro-norite min.	2485 ± 9	4 Zrn, SD	[47]
	Gabbro-norite min.	2493 ± 8	4 Zrn, SD	[48]
	Orthopyroxenite	2526 ± 6	4 Zrn, SD	[47]
	Leucogabbro min.	2518 ± 9	3 Zrn, SD	[48]
	Leucogabbro	2515 ± 12	4 Zrn, SD	[48]
	Leucogabbro	2516 ± 7	3 Zrn, SD	[47]
	Leucogabbro-norite	2507 ± 11	6 Zrn, D	[48]
West Pana	Norite	2497 ± 3	4 Zrn, SD	[47]
	Gabbro-norite	2496 ± 7	3 Zrn, D	[47]
	Gabbro-norite	2491 ± 1.5	3 Zrn, D	[49]
	Gabbro-norite	2501.5 ± 1.7	3 Zrn, C	[15]
	Gabbro-pegmatite	2470 ± 9	3 Zrn, DC	[36]
	Magnetite gabbro	2498 ± 5	3 Zrn, DC	[78]
	Anorthosite	2447 ± 12	3 Zrn + 2Bdy, DC	[49]
	Anorthosite *	2509.4 ± 6.2	9 Zrn, DC	[75]
East Pana	Gabbro	2487 ± 10	4 Zrn, SD	[38]
	Gabbro-pegmatite	2464 ± 12	2 Zrn + 2Bdy, SD	[79]

C, concordant zircons; DC, discordant zircons with concordant ones; D, discordant zircons; SD, strongly-discordant zircons; min., mineralized; *, SHRIMP-II data from the same rock type as listed above. All errors are reported as 2σ .

6. Concluding Remarks on the Fedorova–Pana Mineralization

The intrusions of the Fedorova–Pana Complex host one of the largest PGE resources on the Fennoscandian Shield, hosted in both reef and contact-style low-sulfide Pt–Pd deposits. The largest

proportion of these resources is concentrated in the contact-style Fedorova Tundra deposit as well as in the Konttijärvi and the Ahmavaara deposits of the Portimo Complex in Finland. PGE mineralization of the Fedorova Tundra deposit is associated with irregularly disseminated sulfides in varied-textured rocks (melanorites, gabbonorites, leucogabbro, etc.) forming the matrix of intrusive breccia with a thickness of up to 280 m. The main sulfide minerals are chalcopyrite, pyrrhotite and pentlandite. PGE are hosted in platinum group minerals or isomorphically included in base metal sulfides—mainly in pentlandite. Braggite PtS, kotulskite Pd(Te,Bi) and merenskyite PdTe₂ are the most common platinum group minerals. The ores contain an average of 0.08 ppm Au, 0.29 ppm Pt and 1.20 ppm Pd.

A number of stratigraphically extensive PGE reefs occur in the Fedorova–Pana Complex: the FT-1 and FT-2 Reefs in the Fedorova intrusion, the North and South Reefs in the West Pana intrusion, and three reef-style horizons at the bases of megacyclic units in the East Pana intrusion. The PGE content in the Fedorova–Pana reefs may exceed 45 ppm (e.g., FT-1), but the majority of them have no economic value yet. At the same time, a significant proportion of the Fedorova–Pana PGE resources belongs to the North Reef, represented by two low-sulfide Pt–Pd deposits which are considered to be economically mineable underground. The typical content of Au, Pt and Pd in the North Reef ore is 0.15, 0.53 and 3.32 ppm, respectively (Kievev deposit). In contrast, the North Reef is approximately three times as rich in PGE as contact-style mineralization, but features similar mineralized host rock types and similar geochemical and mineralogical characteristics relative to the Fedorova Tundra deposit. Thus, in accordance with the suggestion by Iljina [68] that the Portimo Reef includes the SK Reef and the Konttijärvi–Ahmavaara contact-style mineralization, it can also be assumed that the North Reef and the Fedorova Tundra mineralization belong to the same mineral system.

Recent exploration in the Bushveld Complex has dramatically increased the significance of its contact-style mineralization, revealing the deep levels of the Platreef [80]. Considering recent exploration results from the Portimo, Fedorova–Pana and Monchegorsk complexes [60], contact-style low-sulfide Pt–Pd mineralization is obviously the most important PGE resource on the Fennoscandian Shield.

Despite an age of 2.5 Ga, the ore-bearing rocks of the Fedorova–Pana Complex have experienced only mild or local alteration and no metamorphism. The primary magmatic characteristics of the PGE mineralization are preserved. This makes the Fedorova–Pana Complex an important natural laboratory for mineral deposit types associated with layered intrusions. It has been suggested that the formation of the deposits requires the influx of sulfide-saturated magma [60,61,65,67]. Whether this model can be applied to the Fedorova Tundra, North Kamennik and Kievev deposits remains currently unclear. Conclusive evidence would, for example, consist of mineralized feeder conduits as well as detailed chalcophile element geochemistry through the mineralized zones. Detailed lithophile element geochemistry as well as mineral chemistry through the deposits and precise isotope ages of rocks from the Fedorova–Pana Complex could be a solid basis for a significant discussion of the PGE deposits petrogenesis in the future.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2075-163X/9/12/764/s1>. Figure S1: Different rock types from the Fedorova Tundra deposit of the Fedorova–Pana Complex. Figure S2: Different rock types from the FT-1 Reef in the Fedorova intrusion of the Fedorova–Pana Complex (borehole BG-F-501). Figure S3. Different rock types from the main ore-bearing horizons in the West Pana intrusion of the Fedorova–Pana Complex. Figure S4. BSE images of main platinum group minerals from Pt–Pd ores of the Fedorova–Pana Complex. Table S1: Whole-rock geochemistry of Fedorova–Pana ore types.

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