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Comparison of East-Scandinavian and Norilsk large plume mafic igneous provinces of PGE ores

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Abstract. The paper is devoted to issues related to the formation of large low-sulfide PGE ore provinces – East-Scandinavian and Norilsk. Basing multidisciplinary data it has been inferred that East-Scandinavian province is being attributed to an intracratonic type without subduction and crust contamination (with Pt-Pd low-sulfide mineralization to predominate). Norilsk province belongs to pericratonic one with PGE – Ci-Ni rich sulfide mineralization to prevail. It has been shown that the main ore provinces PGE metals essentially formed at later stage of existence and initial break-up of supercontinents – predominantly 2.7-2.5 Ga and 1.8-1.7 Ga as a unique case in the Late Paleozoic (Norilsk). For the first time long duration (dozens of Ma) and multistage nature of ore-magmatic system evolution for the East-Scandinavian mafic Large Igneous Province have been demonstrated and this has made it possible to propose it for Norilsk. Comparison of low-sulfide PGE and sulfide Cu-Ni (with PGE) potential of the mafic intrusions is possible using a series of geological, geophysical and geochronological (U-Pb on zircon and baddeleyite, Sm-Nd on rock-forming and sulfides minerals) and isotope geochemical (ε_{Nd}(T), T_{Dm}, I_{Sr}, $^3He/^4He$) indicators.

Аннотация. Статья посвящена проблемам датирования малосульфидных ЭПГ руд на примере двух крупных провинций – Восточно-Скандинавской и Норильской. На основе мультидисциплинарных данных делается вывод, что Восточно-Скандинавская провинция относится к интракратонному типу формирования без процессов субдукции и коровой контаминации (в основном с развитием малосульфидной Pt-Pd минерализацией). Норильская провинция относится к перикратонной с богатой ЭПГ и Cu-Ni сульфидной минерализацией. Показано, что основные провинции с ЭПГ минерализацией в мире формируются на поздних стадиях развития и распада суперконтинентов в эпохи 2.7-2.5 млрд лет и 1.8-1.7 млрд лет и только Норильская провинция является исключением, поскольку ее формирование происходит в позднем палеозое. Впервые приводится длительное время формирования (сотни млн лет) и многостадийное развитие рудно-магматических систем на примере Восточно-Скандинавской обширной изверженной провинции и делается вывод о возможности применения такой схемы изучения к Норильской провинции. На основе многочисленных изотопно-геохимических (ε_{Nd}(T), T_{Dm}, I_{Sr}, $^3He/^4He$) и геохронологических (U-Pb по циркону и бадделеиту, а также Sm-Nd по породообразующим и сульфидным минералам) индикаторов, а также геологических и геофизических данных проводится сравнение потенциалов формирования малосульфидных ЭПГ и сульфидных Cu-Ni (с ЭПГ) руд этих двух провинций.

Key words: LIP, Norilsk, East-Scandinavian, isotope data, metallogenesis, supercontinent, PGE

Ключевые слова: большие изверженные провинции, Норильская, Восточно-Скандинавская, изотопные данные, суперконтинент, элементы платиновой группы

1. Introduction

The paper shows results of the interdisciplinary research undertaken on the basis of data obtained by Russian experts for the two large ore-bearing provinces as compared to the published data related to the similar ore-bearing sites.

As per numerous estimates, Pt and Pd belong to major metals of the postindustrial XXI century of new technologies. Only during recent months of this year, the price for these metals grew three to four times to reach 1,700 and 700 US dollars per ounce.

Among many types of commercial Pd and Pt deposits, of great importance are now magmatogene sulfide PGE-Cu-Ni and low-sulfide Pt-Pd ones. In Russia, the first type is well known by the example of the Norilsk and Monchegorsk deposits. The second one was found and described by V. Distler and S. Sluzhenikin as a special type (*Sluzhenikin et al*., 1994). It is represented both in the Norilsk deposits and in the recently discovered East-Scandinavian province by Russian (Kola Peninsula) and Finnish geologists. These two types differ in prevalence of PGEs. Thus, in the first case, PGEs are extracted as a by-product along with the economic concentrations of nonferrous metals while in low-sulfide ores Pd, Pt, and Rh are main elements with nonferrous metals being accessory. The same principle for distinguishing PGE ores between sulfide and low-sulfide types backed the classification of deposits by *A. Naldrett* (2003) and in many other recent summary publications (*Dodin et al*., 2001; *Likhachyov*, 2006, etc.).

In Russia in the twentieth century, main national production (up to 90 %) of platinum-group elements (PGE) was related to the processing of rich sulfide Cu-Ni ores in Norilsk. PGEs have been metallurgical by-products, although in 2000-2001 their commercial share in the world's reserves was about 50 %. The estimates of Russian and American experts in economic geology (*Dodin et al*., 2001, etc.) assume that in the twenty-first century, PGEs will mainly be produced in Russia from low-sulfide ores with reserves in Norilsk of thousands of tons at concentrations of 3 to 9 ppm. On the Kola Peninsula, PGE reserves were estimated at hundreds of tons at concentrations of 2-10 ppm. The estimated PGE resources of the both provinces are regarded as very large, and this determines the relevance of comparing geology of the ore-bearing low-sulfide deposits in these provinces.

Numerous Russian and international publications are devoted to sulfide deposits. This research has been mainly focused on poorly highlighted issues of the low-sulfide PGE ore generation.

2. Relationship of Pt-Pd provinces with large igneous provinces, LIP (hot plume fields)

Large igneous provinces (or LIPs, by *Campbell, Griffiths*, 1990) as derivatives of deep mantle plume or asthenospheric upwelling processes were minutely discussed in May 2006 in China at the International Continental Volcanism Conference (*Yi-gang Xu*, 2007). A special LIP group along with alkaline, komatiite, felsic ones, is represented by mafic intraplate continental provinces (or mafic LIPs, by *Bleeker, Ernst*, 2006) composed of thick riftogene sedimentary and volcanic rocks cogenetic with dike swarms and mafic-ultramamfic intrusions.

Grachyov (2003), *Pirajno* (2007), *Bogatikov et al.* (2010) cite main geological, geophysical, and geochemical features of geological processes within LIPs related with deep mantle plumes. Taking into account experience of studying ancient (Precambian) areas where most geological and geophysical features of geological units, bodies, and rock compositions fail to be preserved, Felix P. Mitrofanov proposed the following indicators of various rank for intraplate mafic LIPs:

– presence of gravitational anomalies caused by a crust-mantle layer in the crust bottom;

– riftogene (anorogenic) structural ensemble with manifestations of multipath fault tension tectonics identified by the distribution of grabens and volcanic belts, elongated dike swarms, and radial belts of intrusions;

– long duration, polystage and pulsating nature of tectonics and magmatism, continental discontinuities and erosion with early stages of tholeiite-basalt (trappean), boninite-like and subalkaline magmatism in the continental crust, and possible closing stages of the Red Sea spreading magmatism;

– intrusive sills, lopoliths, sheet-like bodies, large dikes and dike swarms. The intrusions are often layered, being different from rocks typical of subduction and spreading zones in terms of nature (*Bleeker*, *Ernst*, 2006), with trends of thin differentiation (or layering), with limited development of intermediate and felsic rocks, often with leucogabbro and anorthosite ends and abundant pegmatoid mafic varieties;

– typical mantle geochemistry of rocks and ores, isotope mantle tracers: Nd^{143}/Nd^{144}, Sr^{87}/Sr^{86}, Os^{187}/Os^{188}, He^3/He^4;

– mafic intracontinental LIPs accommodate large orthomagmatic Cr, Ni, Cu, Co, PGE (±Au), Ti, V deposits.

The Palaeoproterozoic East-Scandinavian Large Igneous Province (ESCLIP) with a modern area of ca. 1,000,000 km^2 occupies the eastern part of the Baltic (or Fennoscandinavian) Shield which basement is represented by the mature Archaean granulite and gneiss-migmatite crust formed > 2550 Ma. Main features of the structure and description of commercial Pt-Pd and Cu-Ni-PGE deposits are given in modern publications of F. Mitrofanov, Ye. Sharkov, V. Smolkin, A. Korchagin, T. Bayanova, S. Turchenko, etc. It is worth noting certain preserved geological and geophysical features of this ancient (Palaeoproterozoic) ore-bearing mafic LIP.

Geophysical survey demonstrated the lower part of the Earth crust in the eastern part of the shield to be represented by a transitional crust-mantle layer (Vp = 7.7-7.1 km/s). Deep xenoliths in the Kandalaksha explosion pipes elevated from this layer have the compositions of granulite and garnet anorthosite with an age of 2460 Ma typical of most bodies in the province (*Verba et al*., 2005). This shows that masses of deep matter arose not only in the form of volcanic, dikes, and intrusions, but also emplaced to the crust bottom in the course of vast underplating (*Mitrofanov*, 2010). The outcropped part of the province continues under the platform cover in the northern part of the Russian platform in the form of vast Palaeoproterozoic Baltic-Central Russian wide arc, or intracontinental orogen (*Mints*, 2011). This certainly expands long-term commercial opportunities of the province.

Anorogenic autonomous pattern of grabens, dike swarms and belts (rays) of intrusive bodies independent from the structure of the enclosing Archaean gneiss-migmatite frame, is prominent in the Geological Map of the Fennoscandian Shield (2005). The studied intrusions with deposits and prospects compose elongated belts (rays), e.g. northwesttrending Kola belt in the northern part of the province, and northeasttrending Fenno-Karelian belt with the concentration of intrusions in the well-known Monchegorsk ore node (Fig. 1, see also *Bayanova et al*., 2009).

In the Early Palaeoproterozoic (2550-1980 Ma) epoch of the long history of the ESCLIP evolution, a few stages separated by breaks (conglomerates) sedimentation and magmatism have been distinguished. The Sumi (2550-2400 Ma) stage was principle in the metallogeny of Pt-Pd ores related to the intrusive siliceous highly Mg boninite-like and anorthositic magmatism (*Mitrofanov*, 2005; *Sharkov*, 2006). Such ore-bearing intrusions formed earlier in the Kola belt (Fedorov-Pana and other intrusions: 2530-2450 Ma) and later in the Fenno-Karelian belt (2450-2400 Ma), according to (*Bayanova et al*., 2009; *Ekimova et al*., 2011). Following stages (Sarioli, Jatuli, and Ludi) are also notable for features typical of independent sedimentation, volcanism, intrusive magmatism, and Cu-Ni metallogeny cycles (Pechenga type). These data show ample grounds for understanding immense volumes and homogeneity of igneous rocks and ore profile of the early ESCLIP development stage as a result of very deep plume processes. Geochemistry of igneous rocks (magmas) (see below) does not contradict this conclusion.

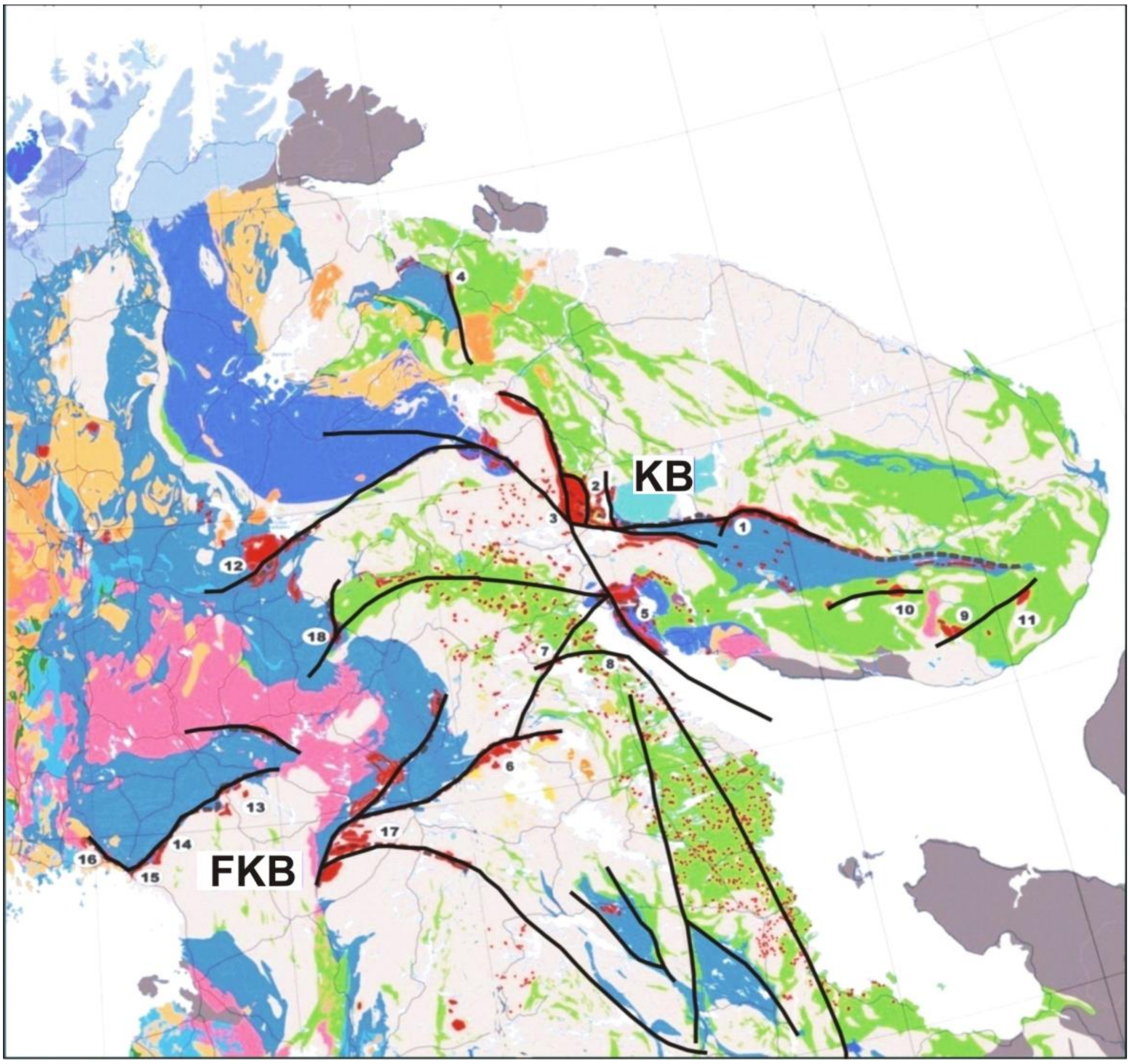


Fig. 1. Trends of riftogene belts and known Early-Proterozoic mafic complexes in the north of ESCLIP: (**KB**) – Kola belt; (**FKB**) – Fenno-Karelian belt; **N** – numbers of main layered complexes: 1 – Fedorov-Pana; 2 – Monchepluton; 3 – Monchetundra, Volchetundra, Gabbro of the Main Ridge; 4 – Mt. Generalskaya; 5 – Kandalaksha and Kolvitsa intrusions; 6 – Lukkulaisvaara; 7 – Kondozero intrusion; 8 – Tolstik; 9 – Ondomozero; 10 – Pesochny; 11 – Pyalochny; 12 – Keivitsa; 13 – Portimo Complex (Kontiyarvi, Siika-Kämä; Ahmavaara); 14 – Penikat; 15 – Kemi; 16 – Tornio; 17 – Koillismaa Complex; 18 – Akanvaara. And hundreds of small-scale bodies

The Norilsk Palaeozoic – Early Mesozoic mafic province is considered by prominent Russian and foreign researchers (*Dobretsov*, 1997; *Pirajno*, 2007; *Bogatikov et al*., 2010, *Krivolutskaya*, *Rudakova*, 2009, etc.) as a special unit of the giant Siberian trappean superplume although direct genetic affinity of ore-bearing Norilsk intrusions with traps is not obvious for many experts. Evolution of a rift system in the northwestern corner of the Siberian craton associates with the intersection of the Arctic belt with the Yenisei-Khatanga (*Dodin et al*., 2001), with rifts of the Western Siberian plate basement. It forms triple junction of rifts which most elevated part accommodates the Norilsk ore mining area (Fig. 2). According to *O. Dyuzhikov et al.* (1988), it occurs in the western end of the Yenisei-Olenyok ore belt with a width of 300 km and length of over 1,000 km. The total dimensions of the whole mafic volcanic and plutonic unit can be enormous.

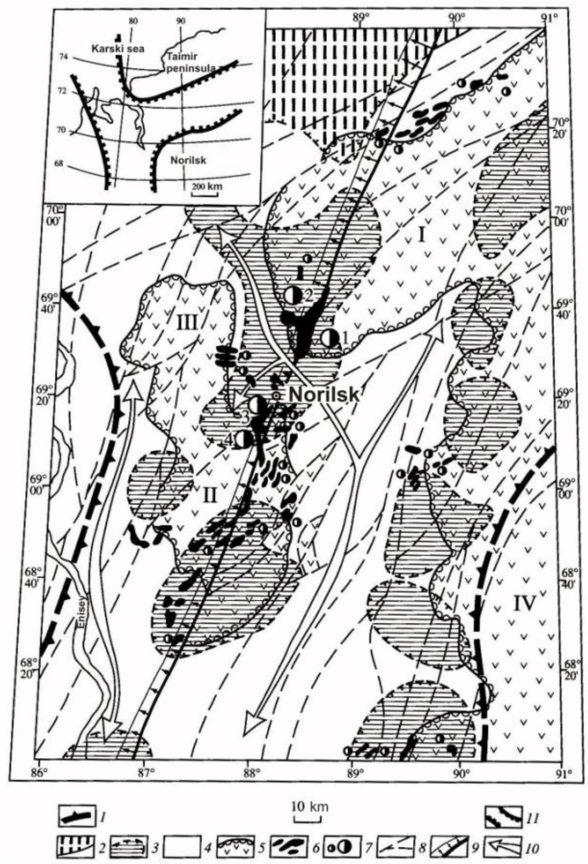
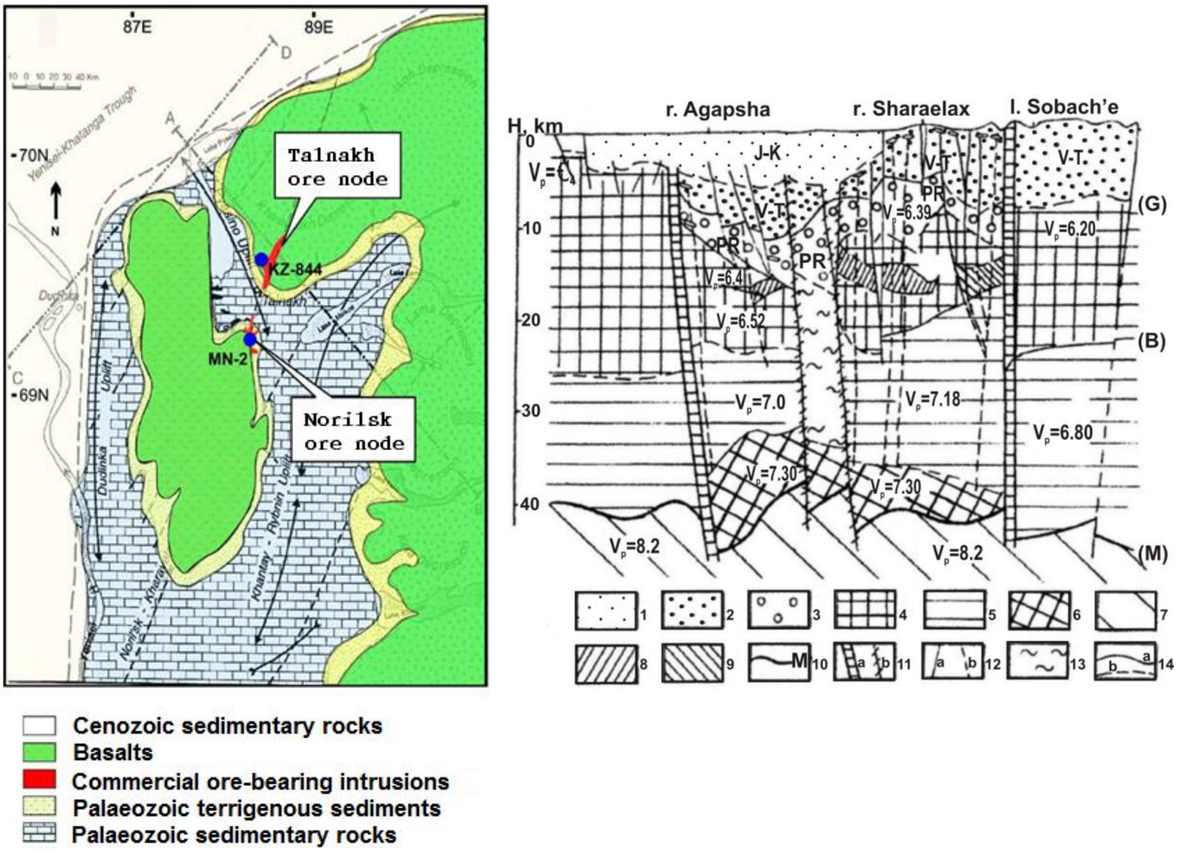


Fig. 2. Deep structures of the Norilsk area (*Dyuzhikov et al*., 1988): 1 – domain of decompressed upper mantle; 2 – contours of the estimated regional aeromagnetic anomalies; 3 – contours of regional aeromagnetic anomalies; 4 – Palaeozoic sediments; 5 – volcanogenic traps (I – Kharayelakh, II – Norilsk, III – Vologochan, IV – Syvermin); 6 – mafic-ultramafic intrusions; 7 – ore prospects, ordinary and unique sulphide Pt-Cu-Ni deposits, low-sulfide deposits (1 – Talnakh, 2 – Oktyabr, 3 – Norilsk I, 4 – Eastern-Norilsk), 8 – faults, 9 – Norilsk-Kharayelakh deep-seated fault, 10 – axial zones of the Khaytan-Rybninsk, Dudinka Embankments, 11 – triple junctions of rifts (inserted)

The analysis of the deep Norilsk province structure (Fig. 3) allows researchers to associate formation of PGE-Cu-Ni deposits with paleorift systems of the lithosphere that have typical geological and geophysical features. These are high-gradient depressions of the basement, saturation of the crust with horsts and grabens, high-density crust splits, large volume of erupted mantle substance, presence of layers (waveguides) with the inversion of seismic velocities, manifestation of an intermediate seismic layer between the crust and mantle (V_p = 7.3 km/s). The specific nature of such units can be an important tectonic criterion of the regional forecast. In terms of deep structure, the Igarsk-Norilsk area is referred to as non-platform geoblocks of the lithosphere with the differentiated crust of the intermediate (suboceanic) type that is highly movable along the whole evolutional history from the Riphean and Vendian to the late Palaeozoic (*Dyuzhikov et al*., 1988). This block is separated by mantle faults from the Taimyr and Tungus geoblocks representing its rigid frame, and has a typical deep structure (Fig. 3). The volcano-sedimentary units of the Igarsk-Norilsk area indicate that the rift forming processes here had a prolonged interrupted history, and repeatedly renewed (*Tuganova*, 2000). This process started in the Riphean (probably, in the Proterozoic) to result in accumulation of a 5-km thick layer of coarsely fragmented sediments, and tholeitic, picritoid, and trachybasaltic volcanics. Red molassoids formed in the Vendian while marine platform predominantly terrigenous and carbonate sediments with minor sulphates date back to the Early Palaeozoic. The latter together with saline beds is especially typical for the Devonian riftogene stage, and after the Carboniferous coals accumulated, the riftogene system started to extensively reactivate in the Late Palaeozoic – Early Mesozoic with vigorous volcanism, intrusion, and ore generation to form a vast trappean province.



A) Sketch of the Norilsk province

B) Seismic geologic cross-section along the Dikson-Khilok profile

Fig. 3. Sketch of the Norilsk ore province (A) and seismic geological cross-section along the Dikson-Khilok profile (B) (after *Yegorkin et al*., 1984)
1-7 – Earth crust's shells (1 – terrigenous J-K complex, 2 – volcano-sedimentary V-T complex with Ni-bearing intrusions, 3 – volcano-sedimentary PR complex, 4 – granite (G), 5 – basalt (B), 6 – intermediate layer between the crust and mantle, 7 – mantle); 8 – decompressed lenses; 9 – lenses with increased density in the consolidated crust; 10 – Mohorovičić discontinuity (M); 11 – mantle faults that confine a – rift system as a whole, and b – separate blocks of the rift system; 12 – crustal faults (a – traced, b – estimated); 13 – decompressed magma and fluid channel; 14 – seismic boundaries of the Earth crust (a – confident, b – estimated)

It is obvious that the Norilsk province differs from the Early Proterozoic ESCLIP not only in time of emplacement, but also in geodynamic setting. ESCLIP is a real intracraton riftogene unit while the Norilsk province located in the Palaeozoic at the active margin of the Siberian craton, where it joins with the Hercynian Western Siberian palaeoocean. This conclusion about the Norilsk province (*Dodin et al*., 2001) agrees with a recent global summary review by *D. Groves et al.* (2005) who define geological and tectonic position of the Norilsk province as "craton margin", "intercratonic rift zones" of mantle plume nature. It is important to emphasize that the Pechenga Cu-Ni sulfide province, a terminal part of the long-lived (2550-1980 Ma) intracontinental ESCLIP, about 2 billion years ago appeared to be at the active margin of the Proterozoic Svecofennian palaeoocean, and its narrow rift-spreading structure and gabbro-wehrlite magmatism correspond to this location. The Norilsk province was almost in the same position in the Late Palaeozoic. This may also account for certain similarity of the both units, especially, in terms of Cu-Ni metallogeny.

It is possible to suggest that the Scandinavian and Norilsk complexes of mafic-ultramafic ore-bearing intrusions are cogenetic components of large mafic igneous provinces (LIPs) together with thick volcanics, dikes, and sedimentary rocks. The East-Scandinavian mafic large igneous province (ESCLIP) is ascribed to the intracratonic type as opposed to the Norilsk province assigned to the pericratonic type. This nomenclature allows studying features of the geological evolution and ore content of these geodynamically different provinces.

3. Cyclic nature (metallogenic epochs) of Pt-Pd deposit formation and relationship with the history of the supercontinents

Some recent investigations (*Groves et al*., 2005; *Robb*, 2008) are focused on the irregular distribution of various large metallic deposits in time and space. For two types of large orthomagmatic sulfide PGE-Cu-Ni and low-sulfide Pt-Pd (+Ni, Cu) deposits, it is believed that the most favourable conditions of formation and preservation are directly related to extra high temperatures in the mantle resulting in melting of high-Mg magmas enriched with mantle-related ore elements, and to the thickness and buoyancy of subcontinental lithospheric mantle (SCLM). Such conditions in the evolving Earth are simulated for komatiite provinces mainly of the Late Archaean age and for mafic-ultramafic provinces of the supercontinents – continental lithospheric plates with mature Precambrian, or rarely Phanerozoic crust. This is demonstrated by diagrams plotted by *D.J. Groves et al.* (2005) where it is obvious that the world Pt-Pd ore resources in layered intrusions tend to the Late Archaean and Early Proterozoic deposits with ages from 2.7-2.5 to 2.0-1.9 Ga, and Ni ores to the Late Archaean komatiites, Mesoproterozoic and Late Palaeozoic deposits. These epochs coincide with the time when the thickest (250-150 km) continental lithospheres, or supercontinents, existed in different regions as a result of collision and subsequent intensive plume processes with the evolutional duration of over 200 Ma (*Condie*, 2004). Structures enclosing low-sulfide Pt-Pd deposits are typically intraplate (e.g., ESCLIP), and those accommodating rich sulfide Ni-Cu deposits evolved at the active margins of continental plates (by the example of Pechenga, Jinchuan, Norilsk) where the mantle substance was apparently enriched with crustal component (mainly, with crustal sulfur) under the subduction conditions. A 2.7-2.5 Ga supercontinent is referred to as Kenorland in modern publications, a 1.9-1.7 Ga one as Columbia (or Nana), and a ~0.25 Ga one as Pangea (*Lubnina*, 2009). Moreover, it is evident that for the both type Russian Siberian deposits, of a great importance is the Late Proterozoic epoch at 0.8-0.6 Ma, i.e. the time of the Rodinia supercontinent stabilization.

Recent publications are devoted to global geodynamics and metallogeny emphasize, especially for the Kaapval and East European cratons, an important role of the transitional period in the Earth's evolution (2.7-2.2 Ga) when the plume tectonics was replaced by modern tectonics of large lithospheric plates. Some geological features of this period are described by *Groves et al.* (2005), *Bogatikov et al.* (2010), etc. who also discuss a promising model of replacing shallow subduction of hot juvenile oceanic lithosphere with deep subduction of cold ancient oceanic lithosphere enriched with crustal slabs. In addition, isometric thick light and buoyant Archaean continental plates and enclosed deposits are considered to have more potential of preservation under subsequent global disasters than the younger linear orogenic lithosphere. It is supposed that the enrichment of the Early Precambrian mantle magmas with platinum-group elements and nickel is related to the Early Precambrian active meteorite bombardment of the Earth with Sudbury being one of the best examples.

Thus, according to modern ideas, many metallic deposits are irregularly distributed in time due to ore-forming and preserving processes in the course of the Earth's evolution. The origin of the orthomagmatic low-sulfide Pt-Pd deposits is directly related to the earlier Earth's history with high temperatures and fertile (enriched) composition of mantle sources and their preservation on the Early Precambrian crystalline shields is promoted by thickness and buoyancy of earlier continental lithospheres.

4. Duration of the formation of the provinces containing orthomagmatic Pt-Pd and sulfide Cu-Ni deposits and ore-bearing intrusions

The "time" issue is one of the key geological processes. For the palaeonthologically almost silent Early Precambrian epoch, the issue may be solved only on the basis of geologically well-tied correct isotope dating of the reference geological sites. A long-term history of the East-Scandinavian mafic igneous ore-bearing province is now identified on the basis of hundreds of such coordinated U-Pb, Sm-Nd, Rb-Sr and rare Re-Os data (*Bayanova*, 2004; *Bayanova et al*., 2009, etc.).

Results have been obtained that significantly change the ideas of many researchers (*Grachyov*, 2003; *Yi-gang Xu*, 2007, etc.) on the short-living history of plume igneous and ore-bearing processes, which are supposed on the basis of individual age measurements for rocks and minerals of the composite geological complexes. It is shown (*Bayanova et al*., 2009) that the Kola system of ESCLIP, for example, is composed of various volcanic series of the Sumi, Sarioli, Yatuli, and Ludi (Palaeoproterozoic) formed in a pulsating manner while the comagmatic intrusive and dike rocks of the Pechenga-Imandra-Varzuga rift structure are associated with the obduction-like Lapland-Kolvitsa granulite belt. The time of the system generation is very prolonged within the age interval of 2540-1980 Ma, i.e. ca. 550 million years. Such a new estimate of a very long-term (> 500 Ma) existence of a plume can also be recognized in the figure by *W. Bleeker* and *R. Ernst* (2006) on the 2505-2110 Ma single superplume in the Early Proterozoic Laurentia-Baltica supercontinent with different-in-age events and radial loci of magmatism in the epochs of 2505, 2450, 2200 and 2100 Ma (Fig. 4).

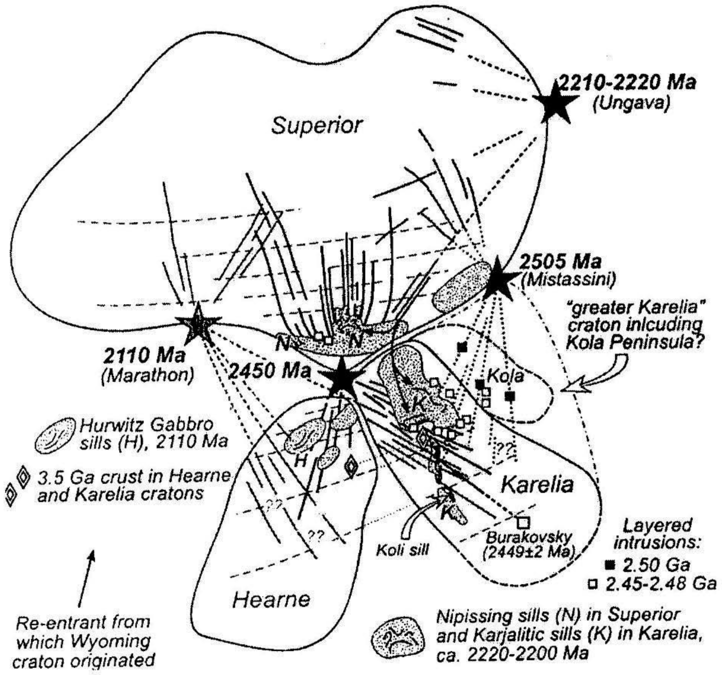


Fig. 4. Sketch of main superplume events in the interval of 2505-2110 Ma within Laurentia-Baltica supercontinent (*Bleeker, Ernst*, 2006)

For the large-scale commercial Pt-Pd ore-bearing Fedorov-Pana intrusion of the Kola belt, isochrones-derived U-Pb and Sm-Nd isotope geochronological methods (*Bayanova*, 2004; *Bayanova et al.*, 2009; *Groshev et al.*, 2009, etc.) established polyphase nature and long-term formation of the intrusions (two main gabbronorite phases of 2526±6 – 2507±11 to 2493±8 – 2485±9 Ma; two additional anorthositic phases of 2470±9 and 2447±12 Ma). The same igneous pulses were identified in many other ore-bearing intrusions and prospects of the Kola region, i.e. Monchegorsk and Monchetundra, Generalskoye, Imanda, etc.

The Fenno-Karelian ore-bearing mafic intrusions (Penikat, Burakovo intrusions, etc.) are very similar to the Kola layered ore-bearing mafic intrusions and show the isotope age determinations (*Iljina, Hanski*, 2005) to indicate their younger age (emplacement age of 2460 Ma as contrast to 2530 Ma for the Kola region). On the basis of these data, *V. Smolkin et al.* (2009) suppose it is possible to contour two different in age vast plume fields in the northeastern Baltic Shield (Fig. 5).

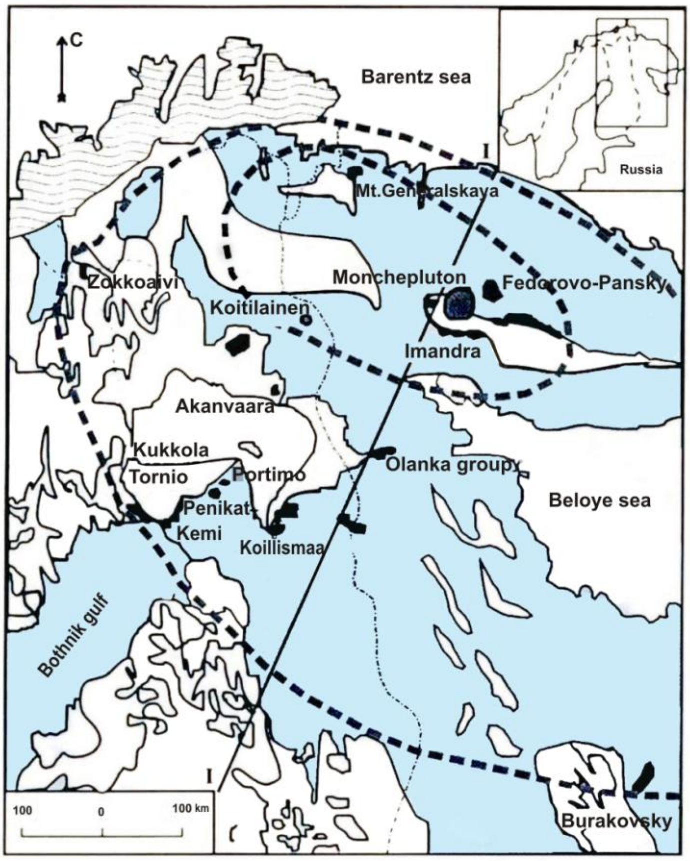


Fig. 5. Sketch of the Early Proterozoic superplume manifestations in the eastern part of the Baltic Shield with two plume fields different in age (*Smolkin et al.*, 2009); minor plume initiated ~2.53 Ga and large one – 2.46 Ga (added by F. Mitrofanov)

The large plume encompasses not only well-known economic ore intrusions, but also their metamorphosed analogs, including coronitic (drusitic) bodies of the Belomorian domain and Lapland-Kolvitsa granulite belt (*Mitrofanov, Nerovich*, 2003; *Bogatikov et al*., 2010).

Reference geological sites of the Norilsk province have not yet been sufficiently studied by isotope methods regardless of the fact that new isotope ages have recently been determined by ultra modern methods in Russia (VSEGEI, IGEM RAS) and abroad. Unfortunately, no systematic research has been carried out, and age was determined only for certain rocks from a small range of intrusions different in terms of geological setting, composition, and ore profile. However, it is still to find out whether these intrusions have the same age, and whether the ore-bearing intrusions are cogenetic with any trappean basalts of various stratigraphic positions.

On the basis of single measurements, some researchers of the Norilsk complex assume and even insist that the formation period for various Norilsk ore-magmatic systems (rich in sulfides and low-sulfide) was quite short (<1 Ma), and it took place ca. 250 Ma. It is believed that this was a main episode of plume magmatic activity at the Palaeozoic – Mesozoic boundary resulted in the emplacement of the Norilsk rich ore province and world largest Siberian tholeiite plate-basalt province.

Meanwhile, most recently the Isotope analytical center at VSEGEI implemented about 200 single U-Pb age measurements of the zircon crystallization at Shrimp-2. The zircon in the Norilsk igneous rocks is represented in the form of mono- and polyphase grains divided into four varieties. *Malitch et al.* (2012; 2010a) demonstrated that in all the parts of the Talnakh commercial ore-bearing intrusion, including upper gabbro-diorite with low-sulfide Pt-Pd mineralization, 99 grains are dominated by zircons with crystallization age clusters of ca. 280 and 260 Ma with the least cluster corresponding to 230 Ma. For 14 grains of the Vologochan intrusion with non-commercial PGE-Cu-Ni ores, two age groups of zircons in the interval of 265-220 Ma, and a zircon with crystallization age of 331.6±4.1 Ma are revealed. In the rocks of the Kharayelakh commercial ore-bearing intrusion, four zircon groups are established (*Malitch et al*., 2010b) with various morphological, geochemical, U-Pb and Hf isotope parameters, and four age clusters, and namely, 347±16; 265.7±11; 253.8±1.7; 235.9±6.1 Ma. In the Norilsk-1 intrusion, zircons also have a significant crystallization interval (261.3±1.6; 245.7±1.1; 236.5±1.2; 226.7±0.9 Ma), and baddeleyite from the olivine gabbro gave an age of 290±2 Ma (*Malitch et al*., 2012). Similar results are obtained for other five intrusions of the Norilsk province.

Majority of zircons, including those in the cores of polyphase grains, belongs to igneous group because of melt inclusions, and to high-temperature (~900 °C) variety. This is corroborated by REE concentration, Th/U ratios, and REE distribution style. There are no xenogenic zircons captured from the frame. Only a single grain of ancient xenogenic zircon with the concordant age of 1914±92 Ma was found in the hybrid gabbro-diorite in the upper part of the Norilsk-1 intrusion.

Table. Stages of the Taymyr-Norilsk province formation (after *Dodin et al*., 2001)

Stages	Processes and events
I. Pre-ore stage	1. Collision of the Taymyr-Severnaya Zemlya area and Siberian platform 2. Subduction of the oceanic crust: enrichment of fluid flows with H_2O, S (including heavy), and halogenides 3. Eliquation of contrasting magmas 4. Segregation into ultramafic, mafic, high-sulfur and low-sulfur anorthositic melts
II. Six-phase volcanic stage	5. Rifting: arrival of Cu, PGM, fluid-enriched magmas through decompression in the open system – zones of deep-seated faults 6. Formation of magma chambers, including those in the black-schist seams
III. Main intrusive and ore-bearing stages	7. Emplacement of layered PGM, Cu, and fluid-enriched mafic-ultramafic magma into the discrete structures of rift troughs on the shoulders of the main rift
IV. Main ore-bearing and intraintrusive stages	8. Intrusion of sulfide-bearing melt – "ore intrusion" 9. Chamber liquation
V. Ultimate intrusive and intraore stages	10. Formation of rhythmic layering 11. Intraore alkaline metasomatism: generation of zoned Cu, Ni, PGE ore beds of Norilsk-Talnakh type
VI. Post-intrusive and ultimate ore-bearing stages	12. Arrival of low-sulfur melt: generation of low-sulfide PGE ore

Since geological methods have not yet (?) yielded difference in age and polyphase nature of the Norilsk intrusions, and xenogenic zircons have not been found, it is should be thought that all the found baddeleyite and zircons are magmatic. Their age clusters varying from 350 to 220 Ma show long-term pulsating crystallization of the initial melt in various intermediate igneous chambers and/or mixing of various melts. In any case, this time interval from 350 to 220 Ma apparently indicates long-term evolution of the Norilsk ore-magmatic system. On the basis of coordination of numerous geological and geodynamic reconstructions (Table), *Dodin et al.* (2001) demonstrated a long-term six-stage evolutional model of the Taimyr-Norilsk province. It should be emphasized that rich in sulfide (Ni, Cu, PGE) and low-sulfide (PGE) ore formation stages are separated in time, but this has not yet been confirmed or rejected by isotope geochronology.

5. Spatio-temporal relationships of rock associations and ore profile with low-sulfide Pt-Pd and sulfide PGE-Cu-Ni deposits

After *S. Sluzhenikin* and *V. Distler* (2010), low-sulfide Pt-Pd ores (LS type) contain ≤0.20-0.25 % Cu-Ni, >0.3-2.0 ppm PGE (non-commercial), 3-12 ppm PGE (conventional, rich ore), and up to 20-60 ppm PGE (top cut grade) with PGE (total, ppm) to sulfur (wt %) ratio of over 5 in all cases, through 40-70 up to 300. In contrast, sulfide PGE-Cu-Ni ores (S type) demonstrate PGE to sulfur ratio below 5, being usually 1.5-3.5. When exploring and prospecting, mining companies tend to divide provinces, regions, and individual ore-bearing intrusions into Cu-Ni (with additional PGEs) and Pt-Pd (with additional Cu, Ni) ones. The same principle of division underlies a deposit classification by *A. Naldrett* (2003) and is discussed in other publications (*Dodin et al*., 2001; *Likhachyov*, 2006, etc.). In the East-Scandinavian large igneous province and Norilsk mafic igneous province the both types of deposits are present.

In ESCLIP about two dozens of commercial low-sulfide (LS type) and sulfide (S type) ore deposits are known today. The Kola and Fenno-Karelian belts of Early Proterozoic (2530-2400 Ma) layered mafic intrusions are dominated by low-sulfide Pt-Pd deposits. In the Russian territory, these are explored (West and East Pana, Vurechuaivench, Lukkulaisvaara) and some underexplored (Burakovo, Generalskoye, etc.) deposits. Some intrusions of these belts contain sulfide PGE-Cu-Ni deposits (Fedorova Tundra and Monchegorsk in Russia), but main sulfide deposits locate in the Pechenga structure and surroundings and have an age of 2200-1980 Ma.

In the best studied large Fedorov-Pana intrusion (Fig. 6), deposits of the both types are explored (*Mitrofanov*, 2005). Low-sulfide PGE mineralization in the intrusion is controlled by sheet-like horizons, or reefs, in the coarsely layered gabbronorite series composed of pyroxenite to anorthosite. There are two types of mineralized reefs, and namely a thinly and rhythmically differentiated (or layered) horizons slightly enriched with PGEs (<1 ppm), syngenetic with the overall coarse layering of the intrusion, and more complicated and thicker (up to 100 m) commercial PGE reefs (up to 5-7 ppm PGE), anorthositic components of which mainly represent new injections of volatile-rich magma.

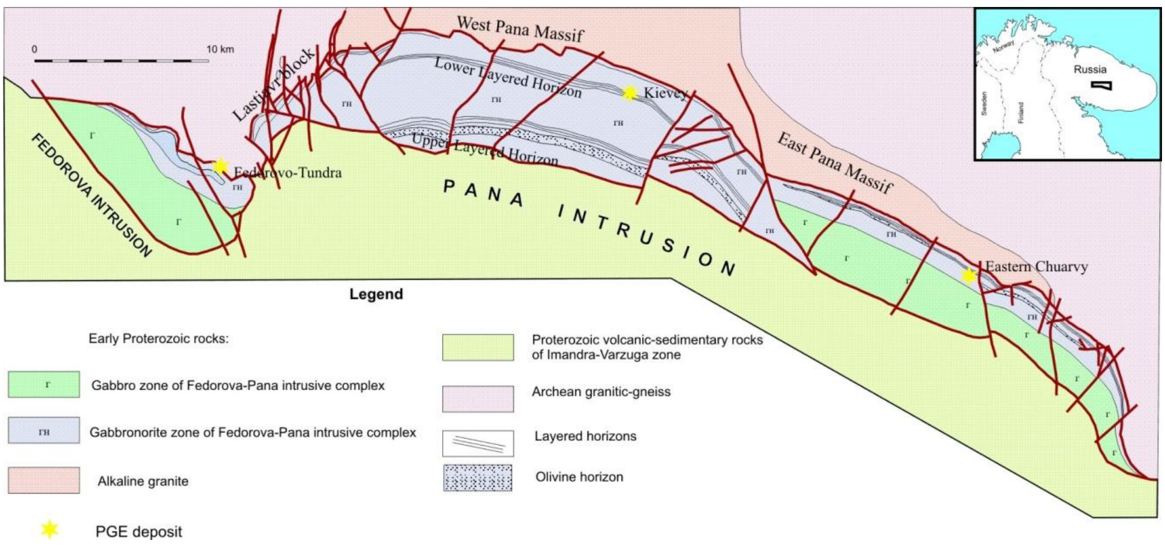


Fig. 6. Sketch geological map of the Fedorov-Pana intrusion

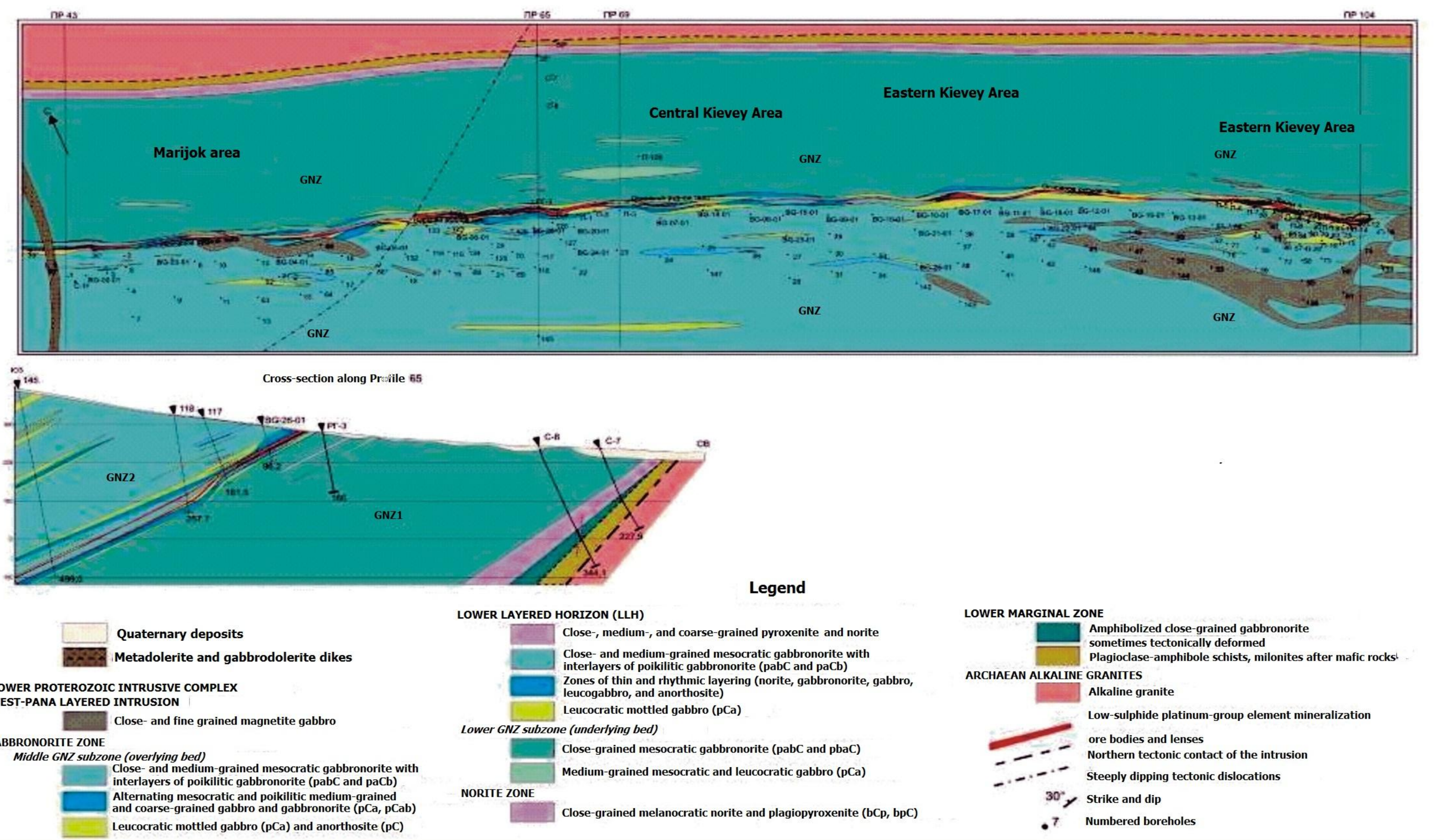


Fig. 7. Geological map and cross-section of the Kievey deposit (*Korchagin et al*., 2009)

The first, non-commercial S- and N-reefs of the Fedorova Tundra chamber in the Fedorov-Pana Complex (*Groshev et al*., 2009) consist of leucogabbronorite and troctolite with the same age as the enclosing gabbronorite (2526±6 to 2507±11 Ma). The second, commercial Northern and Southern reefs of the West Pana Pt-Pd deposit, Kievey (*Korchagin et al*., 2009), are represented by pyroxenite, norite, gabbro, and anorthosite (Fig. 7, Northern, or Lower Reef) and by gabbronorite, troctolite, and anorthosite (Fig. 7, Southern, or Upper Reef). The age of the rocks enclosing the anorthosite is 2500-2490 Ma while the age of additional anorthositic injections is measured at 2470±9 and 2447±12 Ma (*Bayanova*, 2004).

The Fedorov-Pana Cu-Ni-PGE sulfide deposit occurs in the lower contact of the plate-like layered mafic body (Fig. 8). It is presently believed that this is not a bottom, or basal, unit, but a later (2493±8 to 2485±9 Ma) mineralized gabbronorite intrusion underlying an older layered intrusion formed 2526±6 to 2507±11 Ma (*Groshev et al*., 2009). This event may be referred to as local underplating.

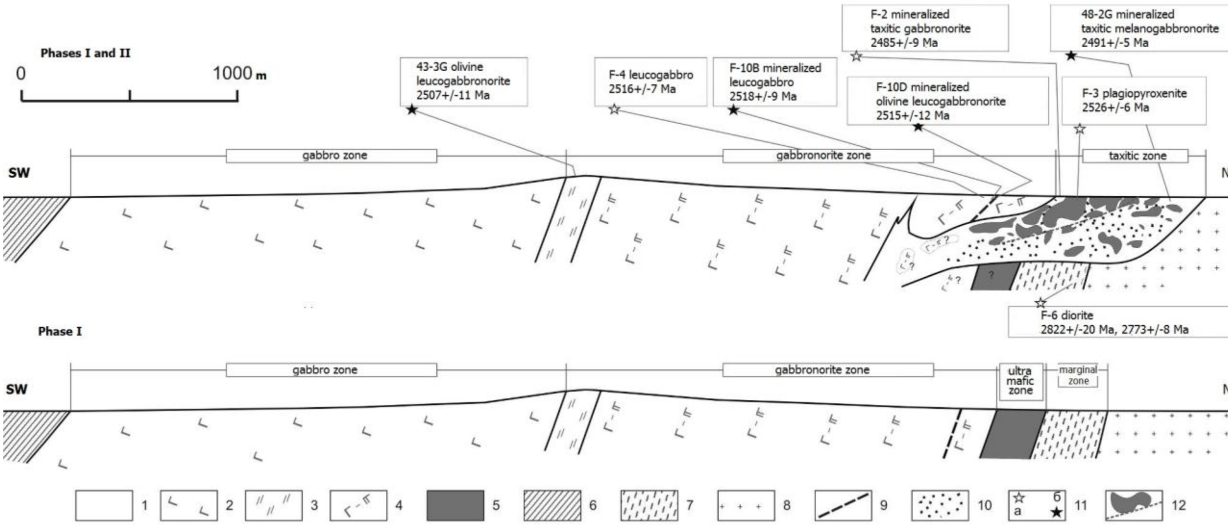


Fig. 8. Generalized geological cross-section through the Fedorova Tundra intrusion in the Bolshoy Ikhtegipakhk (upper part) and reconstruction of the intrusion structure in this area after Phase I, but before Phase II (lower part) (*Groshev et al*., 2009).

Phase II: 1 – taxitic mineralized gabbronorite; Phase I: 2 – leucogabbro, 3 – horizon of lens-like rhythmically alternating (HRA) melanocratic troctolite, olivine leucogabbronorite with inverted pigeonite and leucogabbro, 4 – alternating leucogabbronorite and leucogabbro (with interlayers of mesocratic gabbronorite, troctolite, olivine leucogabbronorite, and leucogabbronorite with inverted pigeonite), 5 – plagiopyroxenite, harzburgite, and olivine pyroxenite; 6 – Early Proterozoic Imandra-Varzuga metavolcanics; 7 – diorite (exo-/endocontact rocks of Phase I); 8 – Archaean gneiss; 9 – reef-type PGE-bearing mineralization; 10 – basal PGE-bearing Cu-Ni mineralization; 11 – geochronological sampling points; 12 – boundary between so-called Norite Zone and Taxitic Gabbronorite Zone

Thus, by the example of the Fedorov-Pana complex it is shown that commercial low-sulfide and sulfide deposits may occur in the same mafic intrusions, but have various ages, being genetically related to the evolution of a single deep-seated ore-magmatic system. The genetic affinity of various igneous phases is demonstrated by their geochemical indicators (*Groshev et al*., 2009).

In the Norilsk mafic igneous province, all the intrusions are now considered to be monophase although some researchers do not support this opinion. The manifestations of low-sulfide PGE mineralization (Upper Talnakh type, after *Dodin et al*., 2001) are found not only in the well-known commercial ore-bearing intrusions (Norilsk I, Talnakh, Kharayelakh), but also in the intrusions with sulfide mineralization which were earlier regarded as non-commercial (Norilsk II, Chyornaya Gora), as well as in the intrusions ascribed to a leucocratic type (Zub-Marksheydersky, Pyasino-Vologochansky intrusions). Despite some differences, manifestations of low-sulfide PGE-bearing mineralization have certain common features. In the cross-section of mafic-ultramafic intrusions, low-sulfide PGE-bearing horizons take quite special position towards main ore bodies, and locate in the upper endocontact of these intrusions. The horizons are isolated from sulfide ores of the main horizons with >50 meter thick barren rocks. The upper endocontact is composed of mottled structurally and texturally heterogeneous eruptive breccia, olivine-free, olivine-bearing and olivine gabbrodolerite, gabbro-diorite, leucocratic gabbroids represented by leucogabbro, and taxitic chromite-bearing gabbro. Olivine-rich rocks are minor being compositionally affiliated to picritic and troctolitic gabbrodolerite of the lower intrusive differentiates. The low-sulfide PGE ores are mainly enclosed by leucogabbro and especially taxitic chromite-bearing gabbro. Leucogabbro varieties do not compose a single horizon in the roof of the intrusions. These are common in the form of lenses with a size varying from a few meters to a few hundreds of meters. The thickness of the lenses ranges and reaches 25 meters. In the stratigraphy, these may contact with the country rocks or be separated by marginal gabbrodolerite, gabbro-diorite, and eruptive breccia. Taxitic gabbro may form a few zones in the same horizon of leucogabbroids. The main zone always tends to the bottom. There are no clear boundaries between leucocratic and taxitic gabbro although the transition is traced along the first few centimeters.

Such geological relationships in the Norilsk intrusions between the lower mafic-ultramafic intrusive differentiates with very rich sulfide mineralization, and upper leucocratic rocks with low-sulfide PGE mineralization, as well as presence of eruptive breccia between them gives hope to find evidences indicating polyphase nature of their evolution. However at present the generation of the Upper Gabbro Zone rock associations is regarded as a result of intrachamber differentiation of fluid-saturated magma melt (*Sluzhenikin*, *Distler*, 2010).

In this respect, it should be noted that the ideas on the origin of commercial PGE mineralization are presently dominated by polyphase mixing of magma injections penetrating crystallization chambers (*Robb*, 2008). Thus, in the Bushveld Complex composed of five chambers (or limbs, laccolith-like basins), the composite Platreef of the Northern Limb demonstrates mixing various magmas (rich in Mg and Cr, or U-type, and rich in Al and Cr, or T-type). Moreover, an additional cross-cutting primitive magma injection of the Merensky Reef is established in earlier layered differentiates (*Yudovskaya, Distler*, 2010).

6. Nature of magma and metal sources, influence of mantle and crustal processes, magmatism, and fluid hydrothermal events

At present, while studying these issues a researcher pays attention to the analysis of data related to the nature and mantle sources for parental magma and ore substance, and their subsequent variations at deep intermediate levels prior to crystallization and post-magmatic processes in the ultimate chamber.

Chamber crystallization and subsequent variation processes are described in detail, but controversially, in terms of petrology in numerous publications, e.g. *A. Naldrett* (2003), *Ye. Sharkov* (2006), *A. Robb* (2008), etc. It should be noted that in the genetic models even for well-known intrusions like Bushveld, timing was not taken into consideration because of shortage in regular absolute isotope measurements. In the meanwhile, most model genetic reconstructions are based on repeated inflow of new magma batches into the chamber. The main world's PGE ore reservoir, the Merensky Reef, which is related to one of the additional magma injections enriched with Sr^{87}/Sr^{86} of up to 0.709 into an earlier layered stratigraphy (Sr^{87}/Sr^{86} = 0.703) of the Bushveld Complex, may serve as an example. There are also PGE-rich anorthositic potholes locally cutting the Merensky Reef established here. Similar repeated inflows of ore-forming substance are found in the Lower PGE Reef of the Fedorov-Pana intrusion where it is shown that cutting anorthosites (*Latypov et al*., 1999) crystallized a dozen of million years later than the layered mafic country rocks (2470±9 and 2491±6 Ma respectively, after *Bayanova*, 2004).

As compiled by *L. Robb* (2008), formational features of the orthomagmatic ore-bearing layered bodies in crystallization chambers may involve in various combinations such processes as density magma separation, including liquation of silicate and ore components, crystallization differentiation, additional magma and fluid injections with mixing with minerals and/or residues of previous magma batches, cotectic shifts, interaction with fluid phase, contamination, etc.

The issue of source(s) for magma and ore substance in low-sulfide PGE deposits in such extensive mafic provinces as the East-Scandinavian one still remains poorly highlighted in publications. In the vast territory, average igneous composition of the layered intrusions with different age and geological settings corresponds to leucogabbronorite with constant isotope characteristics (εNd = -1-3 and Isr = 0.702-0.704). The stability of these features, low-sulfide nature of rocks and ores, and intraplate position of the province, discard subduction contamination and secondary enrichment of the initial magma with ore elements and sulfur as it is believed for the rich sulfide deposits of the Norilsk intrusions by many researchers (*Dodin et al*., 2001; *Starostin, Sorokhtin*, 2010, etc.).

In the meanwhile, anomalously high PGE concentration in the sulfide phase is typical of low-sulfide deposits to be two to three times higher than that in the Cu-Ni (with PGE) Norilsk, Pechenga, Sudbury deposits, etc. The platinum-group metal distribution coefficients between liquating silicate and sulfide melts are 100,000 and higher, being one to three orders higher than the theoretically and tentatively proven. This associates with an apparent deficiency of parental magma volumes expressed in discrepancy of actual PGE amount (in ore and rocks of layered complexes) and amount calculated on the basis of existing Clarkes. And, to explain this discrepancy with regard to the main epoch in formation of these deposits in the Late Archaean – Early Proterozoic, there are a few groups of hypotheses.

The first group assumes special composition of mantle geospheres different from modern ones and producing initially PGE-enriched magmas for the early stages of the Earth evolution. This is a hypothesis of heterogeneous composition of large mantle clusters preserved from its complete homogenization in the first half of the planetary Earth differentiation and accounts for incommensurable enrichment of certain areas on the Earth with platinum-group elements and gold, for example, in South Africa (*Robb*, 2008). The same group includes a hypothesis of a secondary (later) abundant meteorite or asteroid bombardment of material enriched with siderophile elements and noble metals and applied to the Sudbury scenario.

Initial PGE and Au enrichment of mantle mafic magmas due to cross-mantle metasomatism from the depth of the core-mantle boundary seems to a most applicable mechanism for intraplate plume hot fields (or LIPs) and hot spots (Bushveld and like rock associations). Under high P-T conditions, noble metals migrate from these depths as atomic gas, intermetallic compounds, tellurides, selenides, and hydrides. Generation of PGE nanoclusters with ligands is possible in the form of complex compounds with such anions as OH-, Cl-, Br-, S-, HS-, NO_2-, NO_3-, CN-, etc. These clusters could be included into olivine, chromite (in case of sulfur-depleted environment) and sulfides (in case of sulfur-rich environment). Accumulation and preservation of significant PGE content require long duration and sustainability of these processes preceding the formation of a mantle magmatic hearth. Under subsequent melting which, in contrast, should be short to avoid disturbance of the instable system, metals enriched magma by again concentrating in geochemical and thermodynamic barrier traps, as well as in chambers of silica-enriched crust-mantle layers. Such a thick layer (>10 km) is traced under all parts of ESCLIP (as well as the Vindibelt layer under and around the Burakovo Intrusion). It should be noted that plume streams should have been enriched with He^3/He^4, and this is found in certain intrusions of the Kola region (*Tolstikhin et al*., 1992; *Bayanova et al*., 2009). Moreover, Early Proterozoic PGE-bearing mafic belts of the Kola region inherit location of Archaean komatiite belts. This may account for secondary crustal enrichment of magmas with PGEs and gold.

Processes of igneous crystallization in the chamber of intrusion emplacement, in case of a single closed igneous system (Skaergaard Complex, Greenland), are possible to study using the crystallization model by *T. Irvine* (1982). Model reconstructions by *T. Naldrett* (2003) may be applied for complicated polyphase and contaminated magmas as a basis since these account for liquation and concentration processes when distributing PGEs at different interfaces of magmas/crystallization cycles or fractional phases. An important role of fluid components (OH-, Cl-, F-) in PGE concentration in the leucogabbroids at the top of the Norilsk intrusions is demonstrated by many researchers (V. Ryabov, V. Distler and others). The leucogabbroids as residual melts accumulate volatiles to ensure fractionation and enrichment with PGEs in low-sulfide deposits.

7. Conclusion

The research focuses on issues related to the formation of large low-sulfide PGE ore provinces poorly covered in publications. It was based on a wide range of methods. Tectonic and palaeodynamic reconstructions were facilitated by global palaeoreconstructions, results of computational tectonophysical modeling, and diagrams for the distribution of deposits in the Earth's history in addition to conventional geological and geophysical methods. Isotope geochemical research of silicate and ore substance was performed using modern analytical equipment of GI KSC RAS, VSEGEI, and IGEM RAS (Russia).

It was inferred that the East-Scandinavian and Norilsk provinces belong to large mafic igneous provinces with the first being attributed to an intracratonic type, and the second to a pericratonic one. Correspondingly, plume igneous ore-forming processes were manifested in ESCLIP without subduction, or crust contamination (with Pt-Pd low-sulphide mineralization to predominate), and in Norilsk with subduction (with rich sulfide ore to prevail). It is shown that the main ore provinces of these metals essentially formed at later stages of existence and initial break-up of supercontinents. It happened predominantly 2.7-2.5 and 1.8-1.7 Ga, less often in the Late Precambrian, and as a unique case in the Late Palaeozoic (Norilsk).

Geological and various isotope methods applied for the first time have demonstrated long-term (dozens of million years) performance and pulsating nature of ore-magmatic system evolution for the East-Scandinavian Mafic Large Igneous Province, and make it possible to propose it for the Norilsk province. Concentration of commercial PGEs in low-sulfide reefs of layered mafic intrusions is related not only to the intrachamber magma-fluid differentiation, but also to various deep mantle, crust-mantle, and crustal processes.

To roughly estimate low-sulfide PGE and sulfide Cu-Ni (with PGE) potential of the mafic intrusions, it is possible to use a series of geological, geophysical, and geochemical, mainly isotope age (U-Pb, Sm-Nd, Rb-Sr, He-He systems) and isotope geochemical (ε_{Nd} (T), T_{DM}, Isr, He^3/He^4) indicators. These indicators are employed by exploration companies on the Kola Peninsula and in Finnish Lapland, and are suitable for Karelia, Voronezh, and other intraplate mafic provinces.

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