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East Scandinavian and Noril'sk Plume Mafic Large Igneous Provinces of Pd–Pt Ores: Geological and Metallogenic Comparison

F. P. Mitrofanov[a], T. B. Bayanova[a], A. U. Korchagin[a], N. Yu. Groshev[a],
K. N. Malitch[b], D. V. Zhirov[a], and A. F. Mitrofanov[c]

[a] *Geological Institute, Kola Science Center, Russian Academy of Sciences,*
ul. Fersmana 14, Apatity, Murmansk oblast, 184209 Russia

[b] *Zavaritsky Institute of Geology and Geochemistry, Ural Branch, Russian Academy of Sciences,*
Pochtovyi per. 7, Yekaterinburg, 620151 Russia

[c] *Moscow State University, Moscow, 119991 Russia*

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Abstract—This paper compares the geological, geophysical, and isotopic geochemical data on the Paleoproterozoic East Scandinavian Pd–Pt province in the Baltic Shield and the Late Paleozoic Noril'sk Pd–Pt province in the Siberian Craton. Both provinces contain large magmatic PGE deposits: low-sulfide in the Baltic Shield and high-sulfide in the Siberian Craton. Multidisciplinary evidence shows that the East Scandinavian mafic large igneous province, which has a plume nature, is intracratonic and was not subjected to the crucial effect of subduction-related and other contamination processes, whereas the Noril'sk province is pericratonic with substantial crustal contamination of the intrusive processes. Low-sulfide Pd–Pt deposits dominate in the East Scandinavian province, while high-sulfide Ni–Cu–PGE deposits play the leading role in the Noril'sk province. The U–Pb, Sm–Nd, and Rb–Sr isotopic data indicate multistage and long-term (tens of millions of years) geological history of mafic large igneous provinces. The plume magmatism with specific geochemistry and metallogeny is probably related to lower mantle sources.

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INTRODUCTION

This paper gives the results of an investigation of the large East Scandinavian and Noril'sk ore provinces in comparison with published data on similar provinces. Platinum and palladium are important metals of new postindustrial 21st-century technologies. Only in recent years have their prices in the world's market increased three to four times and reached 1700 and 700 USD per troy ounce.

The magmatic sulfide Ni–Cu–PGE and low-sulfide Pd–Pt deposits are the most important among many economic types of Pd–Pt mineralization. In Russia, the first type is well known at the Nori'sk and Monchegorsk deposits. The second type, first characterized by Sluzhenikin et al. (1994) as a special and genetic type, is exemplified in the Noril'sk deposits and deposits of the East Scanidinavian province, recently discovered by Russian and Finnish geologists. The difference between these types is the relative significance of PGE mineralization. In the sulfide type, PGE are accompanying components, while ferrous metals play the lead role, whereas in low-sulfide ore of the second type, Pd, Pt, and Rh are the major metals, while nonferrous metals are of secondary importance. This principle of PGE ore subdivision into sulfide and low-sulfide types (groups) serves as the basis for the classification proposed by Naldrett (2003) and in other recently published fundamental works (Dodin et al., 2001; Likhachev, 2006, etc.). In the 20th century, the main PGM production (up to 90%) was related to processing of Noril'sk high-grade Ni–Cu–PGE ore. PGE were by-products, although as early as 2000–2001, their contribution to the price structure in the world's market was about 50%. According to Russian and American specialists (Dodin et al., 2001), in the 21st century, the main PGE production in Russia will be related to mining of low-sulfide ore, the resources of which in the Noril'sk district are estimated at thousands of tons (PGE grade 3–9 gpt). As of 2010, the PGE resources of the Kola region were estimated at hundreds of tons (grade 2–10 gpt). The voluminous literature concerns sulfide deposits. The information contained in this paper is mainly concerned with low-sulfide PGE ores, which remain poorly described in the literature.

LINKS OF LARGE LOW-SULFIDE DEPOSITS TO LARGE IGNEOUS PROVINCES (HOT PLUME FIELDS)

Large igneous provinces (LIPs) (Campbell and Griffiths, 1990) as derivatives of deep mantle plumes were discussed at the International Conference on

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Corresponding author: F.P. Mitrofanov. E-mail: felix@geoksc.apatity.ru

Continental Volcanism held in China in May 2006 (Yi-Gang Xu, 2007). In addition to alkaline and komatiite LIPs, a special group of LIPs is made up of mafic intraplate continental provinces (Bleeker and Ernst, 2006) consisting of rift-related thick sedimentary and volcanic sequences, dike swarms, and intrusions of mafic and ultramafic rocks.

Grachev (2003), Pirajno (2007), Bogatikov et al. (2010) adduce geological, geophysical, and geochemical evidence for links of LIPs to deep mantle plumes. With allowance for experience in studying Precambrian regions, where many ancient geological and geophysical features of terrestrial structures have not been retained, F.P. Mitrofanov proposed the following various in ranks indicators of ancient intracontinental mafic LIPs:

—enormous area of rocks associated with deep gravity anomalies induced by the crustal–mantle (granulite–mafic) layer at the base of the crust;

—a rift-related (anorogenic) assembly disharmonic with respect to the older basement structure, which is expressed as multipath extensional faulting that controls the arrangement of grabens, volcanic belts, extended dike swarms, and radial intrusive bodies;

—the long-term, multistage, and pulsatory character of tectonics and magmatism; breaks in sedimentation and related erosion; early manifestations of tholeiitic basaltic (trap), high-magnesian (boninite-like), and alkaline magmatism in domains with the continental crust with the formation of leucogabbro–anorthosite complexes; possible final spreading of the Red Sea type;

—sills, lopoliths, sheetlike intrusions, large dikes, and dike swarms; multiphase and layered intrusions, which differ in geochemistry from spreading and subduction-related rocks (Bleeker and Ernst, 2006), with trends of fine fractionation (layering) and restricted development of intermediate and felsic rocks; often with final leucogabbro and anorthosite and abundant pegmatoid mafic varieties;

—a characteristic undepleted mantle geochemistry of rocks and ores with anomalously high contents of siderophile–chalcophyle elements and LILE marked by Nd^{143}/Nd^{144}, Sr^{87}/Sr^{86}, Os^{187}/Os^{188}, and He^3/He^4 isotope ratios;

—large orthomagmatic Cr, Ni, Cu, Co, PGE ±Au, Ti, and V deposits related to intracontinental mafic LIPs.

The vast Paleoproterozoic East Scandinavian mafic LIP, today covering about a million square kilometers, occupies the eastern Baltic (Fennoscandian) Shield, the basement of which is exposed in the Kola–Lapland–Karelia Craton, was formed by mature Archean granulite and gneiss–migmatite crust as early as 2550 Ma ago. The main structural features of the East Scandinavian mafic LIP and characterization of economic Pd–Pt and Ni–Cu–PGE deposits localized therein have been described in recent publications by Mitrofanov, E.V. Sharkov, V.F. Smolkin, A.U. Korchagin, T.L. Grokhovskaya, T.B. Bayanova, S.I. Turchenko, etc. Having omitted details, we emphasize certain geological and geophysical features of this Paleoproterozoic ore-bearing mafic LIP.

According to geophysical data, the lower crust of the eastern part of the shield is composed of a transitional crust–mantle layer (V_p = 7.1–7.7 km/s). Deep xenoliths of granulites and garnet anorthosite ~2460 Ma in age, which were carried up from this layer by the Kandalaksha explosion pipes, are comparable in composition with the bodies exposed at the surface (data of V.R. Vetrin cited after Verba et al., 2005). In other words, this implies that enormous masses of deep magmas not only ascended as volcanic rocks, dikes, and other intrusions, but also underplated the crust (Mitrofanov, 2005). The exposed portion of the shield extends beneath the sedimentary cover toward the northern Russian Platform as a vast Paleoproterozoic Baltic–Mid-Russia wide arc—intracontinental orogen (Mints, 2011). Thus, the long-term perspective of the province for economic deposits is increasing.

The anorogenic pattern of grabens, dike swarms, and belts (trends) of intrusive bodies independent of the Archean gneiss–migmatite framework is clearly seen in the Geological Map of the Fennoscandian Shield (2005). The studied intrusions, along with related deposits and occurrences, make up extended paths (belts) in the northern part of the province: the NW-trending Kola Belt and the NE-trending Karelian Belt with concentration of intrusions in the Monchegorsk ore cluster (Fig. 1), see also Bayanova et al. (2009).

The long Early Paleoproterozoic (2530–2200 Ma) geological history of the East Scandinavian mafic LIP (ESMLIP) consists of several stages separated by breaks in sedimentation and magmatic activity marked by conglomerates. The Sumian stage (2550–2400 Ma) crucial in the metallogeny of Pd–Pt ores was related to emplacement of high-Mg and high-Si boninite-like and anorthosite magmas (Mitrofanov, 2005; Sharkov, 2006). The ore-bearing intrusions were first emplaced in the Kola Belt (Fedorov Pana and other intrusions, 2530–2450 Ma) and later on in the Fenno-Karelian Belt (2450–2400 Ma) (Bayanova et al., 2009). The subsequent stages (Sariolian, Jatulian, Ludicovian) are also distinguished by specific cycles of sedimentation, volcanism, and intrusive magmatism.

The Paleozoic–Early Mesozoic Noril'sk mafic province is commonly regarded as a special part of the giant Siberian trap superplume (Dobretsov, 1997; Pirajno, 2007; Bogatikov et al., 2010), although genetic links of the ore-bearing Noril'sk intrusions with traps are not as evident to other specialists. The rift system in the northwestern corner of the Siberian Platform is related in its evolution to the intersection of the Arctic Belt with the Yenisei–Khatanga belts

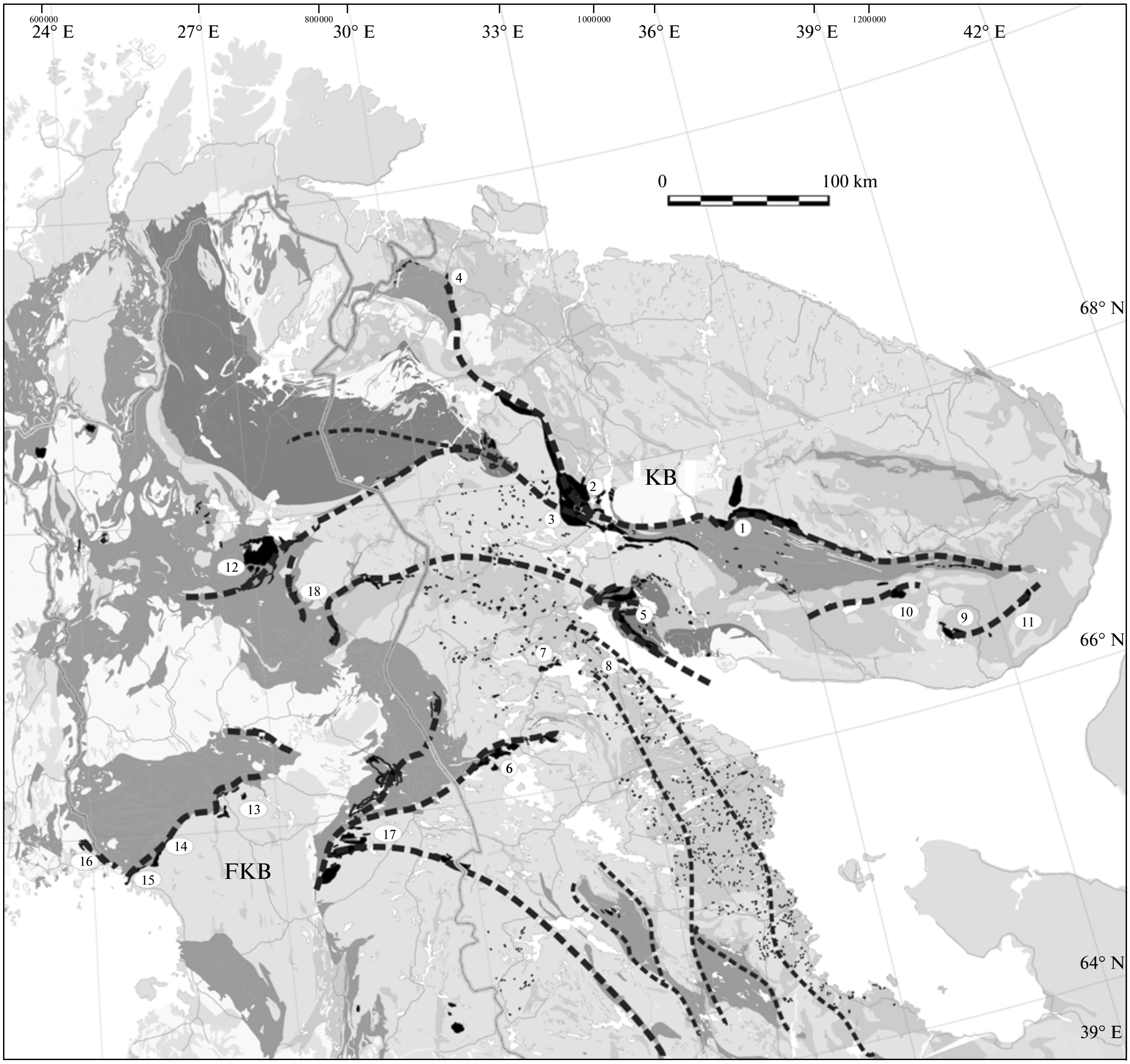

Fig. 1. Rift belts and known Paleoproterozoic mafic complexes in northern ESMLIP. KB, Kola Belt; FKB, Fenno-Karelian Belt. Main layered complexes (numerals in figure): 1, Fedorov Pana; 2, Monchepluton; 3, Monchetundra, Volchetundra, gabbro of the Main Range; 4, Mt. General’skaya; 5, Kandalaksha and Kolvitsa intrusions; 6, Lukkulaisvaara; 7, Kondozero massif; 8, Tolstik; 9, Ondomozero; 10, Pesochny; 11, Pyalochny; 12, Keivitsa; 13, Portimo Complex (Kontijarvi, Siikakama, Ahmavaara); 14, Penikat; 15, Kemi; 16, Tornio; 17, Koillismaa Complex; 18, Akanvaara. Hundreds of intrusive bodies are out of scale.

(Dodin et al., 2001) and rifts in the basement of the West Siberian Plate. The Noril’sk mining district is situated in the uplifted part of this triple junction (Fig. 2). According to Dyuzhikov et al. (1988), this district occurs at the western end of the Yenisei–Olenek ore belt 300 km in width and more than 1000 km in extent. Therefore, a size of the entire volcanic–plutonic mafic structure may be enormous.

The deep structure of the Noril’sk province (Fig. 3) allows us to relate the formation of related Ni–Cu–PGE deposits with paleorift systems of the lithosphere to geological and geophysical parameters typical of such structures. These systems are characterized by high-gradient troughs of the basement, numerous grabens and horsts in the crust, high- density ruptures in the crust, large bodies of mantle matter, the occurrence of waveguides with inversion of seismic wave velocities, and appearance of a transitional seismic layer between the crust and the mantle with $V_p = 7.3$ km/s. The specificity of such structures is an important tectonic criterion for regional forecasting. The deep structure of the Igarka–Noril’sk district corresponds to the

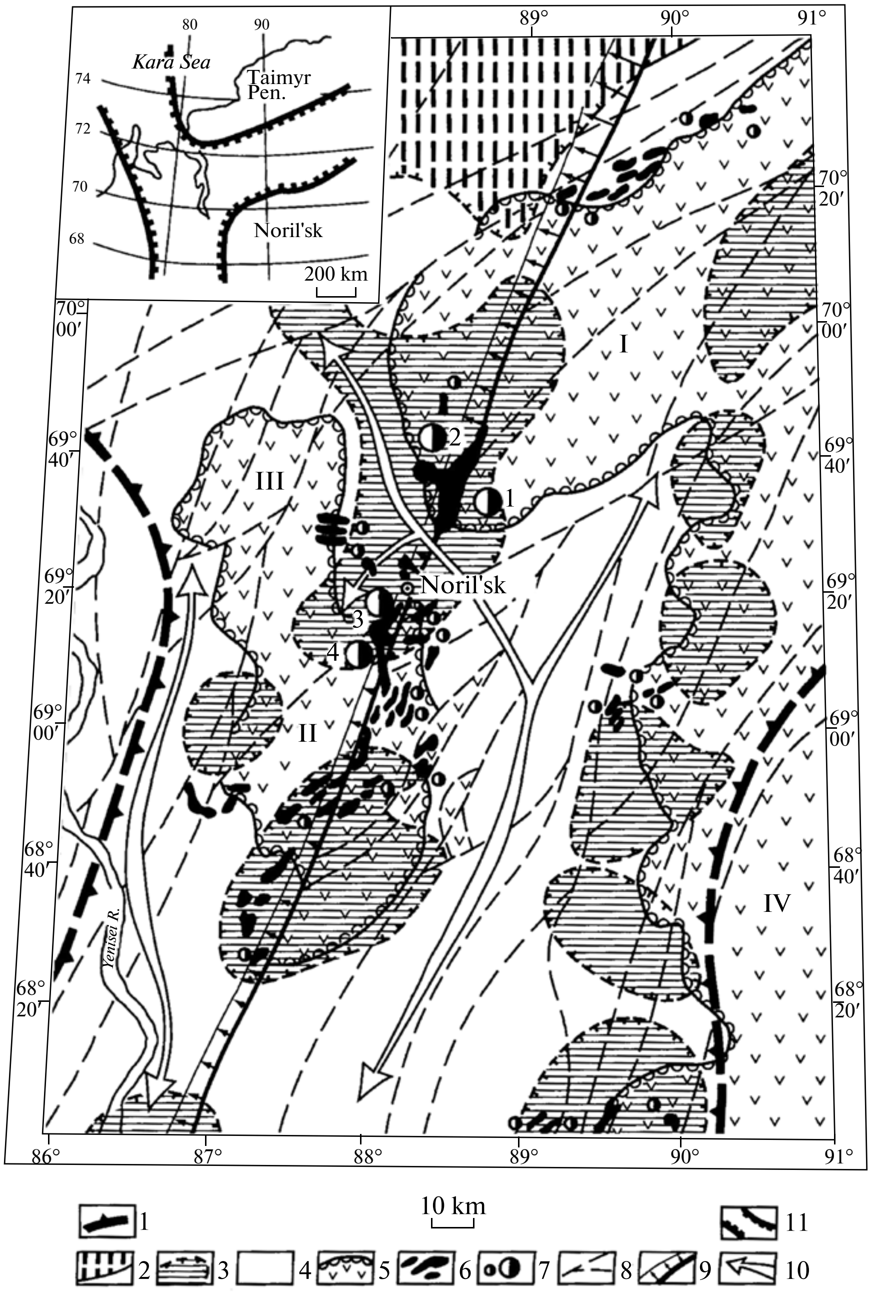

Fig. 2. Deep structure of Noril'sk district, after Dyuzikov et al. (1988). (1) Region of low-density upper mantle; (2) inferred regional aeromagnetic anomaly; (3) regional aeromagnetic anomaly; (4) Paleozoic sedimentary rocks; (5) volcanic rocks in trap basins; (6) mafic–ultramafic intrusions; (7) ore occurrences, ordinary and unique sulfide Ni–Cu–PGE deposits, low-sulfide PGE deposits; (8) faults; (9) Noril'sk–Kharaelakh deep fault; (10) axial zones of Khaitan–Rybnino and Dudinka swells; (11) triple junction of rifts (in inset). Trap basins (numerals in figure): I, Kharaelakh; II, Noril'sk; III, Vologochan; IV, Syverma; ore deposits (numerals in figure): 1, Talnakh; 2, Oktyabr'sky; 3, Noril'sk-1; 4, East Noril'sk.

nonplatform blocks of the lithosphere with the differentiated crust of the transitional (suboceanic) crust, which retained elevated mobility throughout its evolution from the Riphean and Vendian to the Late Paleozoic (Dyuzhikov et al., 1988). This block is separated by deep faults from the adjacent Taimyr and Tunguska geoblocks, which are regarded as a rigid framework with characteristic deep structure (Fig. 3). The long-term discontinuous history with repeated resumptions is recorded in the sedimentary and volcanic sequences of the Igarka–Noril'sk district (Tuganova, 2000). The first Riphean (probably Paleoproterozoic) phase of this process was expressed in accumulation of a thick sequence of coarse clastic sediments along with tholei-

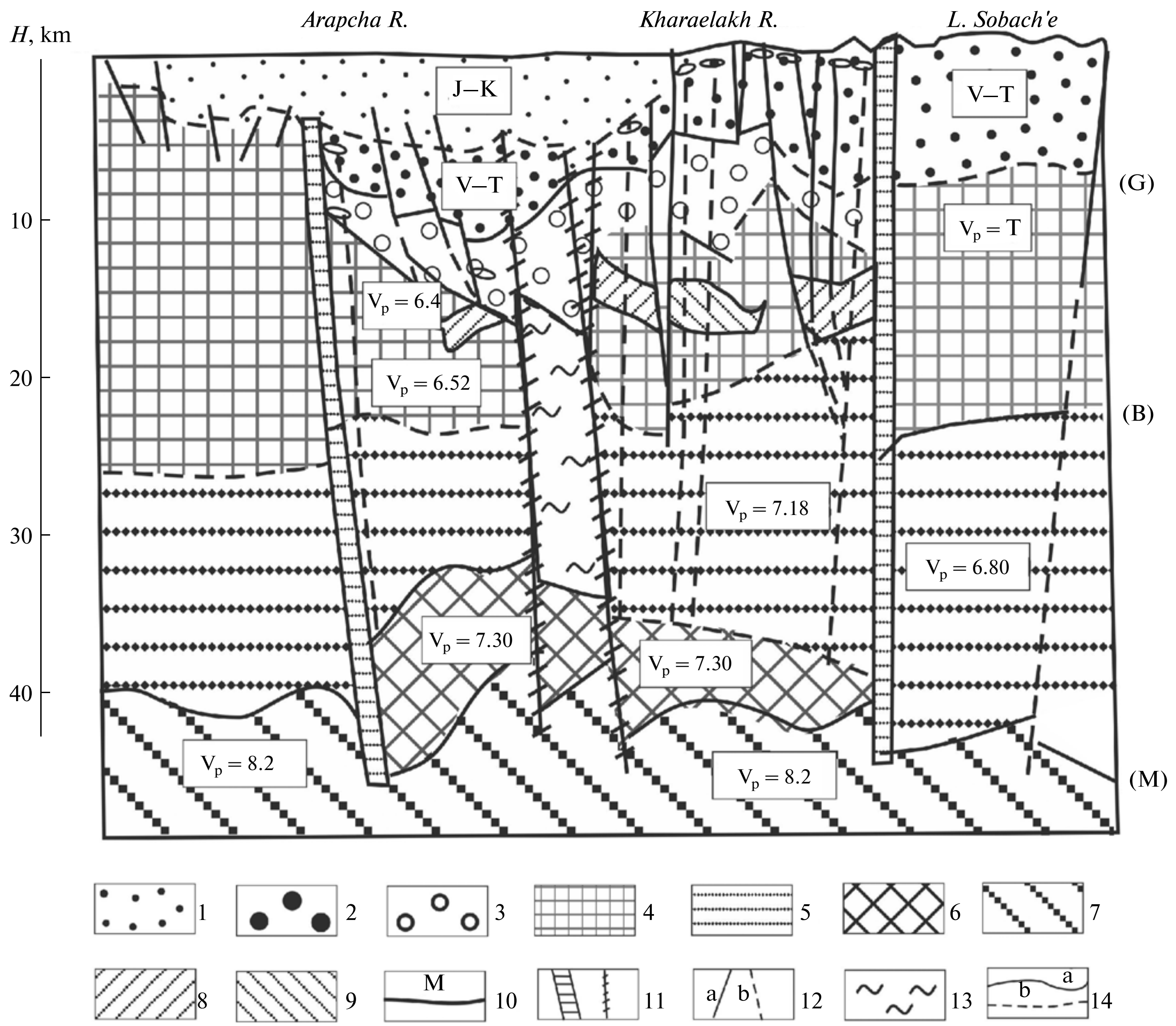

Fig. 3. Seismogeological section along Dikson–Khilok profile, after Egorkin et al. (1984). (1–7) Shells of Earth's crust: (1) Jurassic–Lower Cretaceous complex, (2) Vendian–Triassic sedimentary–volcanic complex with Ni-bearing intrusions, (3) Paleoproterozoic sedimentary–volcanic complex, (4) granitic layer (G), (5) basaltic layer (B), (6) transitional crust–mantle layer, (7) mantle; (8) low-density lenses; (9) high-density lenses in consolidated crust; (10) Moho surface (M); (11) mantle faults that bound rift system as whole and separate blocks of rift system; (12) crustal blocks: (a) proved and (b) inferred; (13) low-density conduit of magmas and fluids; (14) seismic boundaries in Earth's crust: (a) proven and (b) inferred.

itic, picritoid, and trachybasaltic volcanic rocks. The Vendian marine molassoid red beds underlie the Lower Paleozoic marine terrigenous carbonate rocks often with sulfates, which are especially characteristic together with rock salt beds of the Devonian stage of rifting. The deposition of the Carboniferous coal-bearing sequence gave way to the vigorous Late Paleozoic–Early Mesozoic reactivation of the rift system with volcanism, emplacement of intrusions, ore formation, and development of the vast trap province.

The Noril'sk province differs from the Paleoproterozoic ESMLIP not only in the time of origin but also in the special geodynamic setting. The ESMLIP is a true intracatonic rift structure, whereas the Noril'sk province was situated in the Paleozoic at the margin of the Early Precambrian Siberian Craton in the zone of its conjugation with the Hercynian West Siberian paleoocean. This statement coincides with the global review published by Groves et al. (2005), where the Noril'sk province (Dodin et al., 2001) is characterized as a craton margin or an intercratonic rift zone. It is important that the Pechenga Ni–Cu sulfide province that formed after the development of the ESMLIP about 2 Ga ago also was located at the active margin of the Paleoproterozoic Svecofennian paleoocean, and its narrow rift–spreading structure of the Red Sea type, as well as gabbro–wehrlite magmatism, completely fits such a disposition. The localization of mafic LIPs within cratons (1) or at their margins (2) explains their metallogenic specialization with low-sulfide Pd–Pt deposits (1) and important role of sulfide Ni–Cu–PGE deposits that owe their origin to contamination with crustal sulfur (2) (Dodin et al., 2001; Starostin and Sorokhtin, 2010).

It is evident that characterization of the Early Paleoproterozoic geological situation at the Baltic Shield recently defined as the PGE-bearing ESMLIP of plume nature (Bayanova et al., 2009), or the Baltic LIP with high-Mg and high-Si igneous rocks (Bogatikov et al., 2010) and the Kola–Lapland–Karelian plume province (Smolkin et al., 2009), fills a substantial gap in the understanding of geological events and Pd–Pt and Ni–Cu metallogeny of the most important Late Neoarchean–Early Paleoproterozoic transitional period in the Earth's evolution (2.7–2.2 Ga ago). In classic metallogenic summaries (Naldrett, 2003; Groves et al., 2005), this period is characterized by the unique Stillwater, Great Dike of Zibabwe, Bushveld, and Sudbury ore-bearing complexes. Meanwhile, the geological setting and nature of these world's unique objects are so complex and unusual that they cannot be coordinated in space and time with regional geological frameworks. That is why the mechanisms and sources directly unrelated to endogenic activity of the Earth are often involved in their interpretation, e.g., astrobleme for the Sudbury or a relict mantle cluster anomalously enriched in metals. Such an exotic explanation in combination with insufficient isotopic data does not answer the question whether there are any spatiotemporal links for these objects to the evolution of their immediate geological framework. Correspondingly, the forecast of such objects in the Earth's crust is currently hampered or even impossible.

The situation with Scandinavian and Noril'sk ore-bearing objects has been better ascertained. The available data allow us to consider these mafic and ultramafic intrusions as cogenetic constituents of vast mafic LIPs along with thick volcanic sequences, dikes, and sedimentary rocks. On the basis of certain criteria, the plume nature of these global structures has been accepted (Bayanova et al., 2009).

PERIODICITY (METALLOGENIC EPOCHS) OF THE FORMATION OF Pd–Pt DEPOSITS AND RELATIONS OF THEM TO THE HISTORY OF SUPERCONTINENTS

Groves et al. (2005), Robb (2008), Rundqvist et al. (2006) discussed nonuiform distribution of large ore deposits in time and space. As concerns large orthomagmatic sulfide Ni–Cu–(PGE) and low-sulfide Pd–Pt–(Ni, Cu) deposits, it was shown that the most favorable conditions of their formation and retention are directly related to the especially high temperature in the mantle, giving rise to melting of high-Mg magmas enriched in ore elements, and to the large thickness and buoyancy of the subcontinental lithospheric mantle. Such conditions in Earth's evolution are simulated primarily for Neoarchean komatiite provinces and for provinces of mafic and ultramafic rocks in supercontinents, i.e., for continental lithospheric plates with the mature Precambrian and less frequent Phanerozoic crust.

The main world resources of Pd–Pt ores hosted in layered intrusions (~60 kt) are contained in the Neoarchean and Paleoproterozoic deposits (2.7–2.5 and 2.0–1.9 Ga), while Ni ores are hosted in the Neoarchean komatiites, Mesoproterozoic and Late Paleozoic deposits (Groves et al., 2005). These epochs coincide in time with the existence of the thick (250–150 km) continental lithosphere all over the world, completion of collision and subsequent ascent of superplumes, which developed over more than 200 Ma (Condie, 2004). The structures that host low-sulfide Pd–Pt deposits were typically within-plate (Groves et al., 2005), whereas the high-grade sulfide Ni–Cu deposits were formed at the active margins of continental plates (Pechenga, Jinchuan, Noril'sk), where mantle melts were contaminated with crustal materials, primarily with crustal sulfur.

The authors of recent publications on global geodynamics and metallogeny emphasize important implications of the transitional period in Earth's evolution 2.7–2.2 Ga ago, when Archean plume tectonics gave way to plate tectonics. This is especially evident for the Kaapvaal and East European cratons. Some geological characteristics of this period were considered by Groves et al. (2005) and Bogatikov et al. (2010). In addition to everything else, a promising model that assumes substitution of shallow subduction of the young oceanic lithosphere for deep subduction of the cold ancient oceanic lithosphere enriched in crustal slabs is discussed in these publications; in addition, isometric, thick, light, and buoyant Archean continental plates and the deposits incorporated therein could be retained after subsequent global catastrophes more readily than the newly formed linear orogenic structure. It is also suggested that enrichment in PGE and Ni of Early Precambrian mantle-derived magmas might be related to active ancient cosmic bombardment of the Earth. The Sudbury deposit is one proven example of this.

Thus, according to the currently accepted concepts, many metals are characterized by nonuniform chronological distribution caused by variable ore-forming and ore-retentive processes. The orthomagmatic low-sulfide Pg–Pt deposits are directly related to the early history of the Earth, in particular, to the high temperature and fertile composition of mantle sources. The retention of these deposits in the Early Precambrian crystalline shields is maintained by the large thickness and buoyancy of the early continental lithosphere.

PROVINCES OF ORTHOMAGMATIC Pd–Pt AND SULFIDE Ni–Cu DEPOSITS AND ORE-BEARING MASSIFS: DURATION OF THEIR FORMATION

Time is a key parameter for understanding many geological processes. The timing of Early Precambrian geological processes can be based only on correct isotopic dating of geologically documented reference objects. The long multistage formation history of the ESMLIP has been ascertained to date on the basis of more than 100 U–Pb, Sm–Nd, and Rb–Sr age determinations (Bayanova, 2004; Bayanova et al., 2009).

The results substantially change the notions assuming short-living mantle plumes and short-term ore formation, which were suggested on the basis of sporadic age determinations of rocks and minerals belonging to complexly built rock associations (Grachev, 2003; Piranjo, 2007; Yi-Gang Xu, 2007). It has been shown, for example, that the Kola domain of the ESMLIP consists of pulsatorily formed Paleoproterozoic (Sumian, Sariolian, Jatualian, Ludicovian) volcanic groups and comagmatic plutonic rocks and dikes of the Pechenga–Imandra–Varzuga Rift Zone conjugated with the Lapland–Kolvitsa Granulite Belt. This complex system formed 2530–2200 Ma ago. Such a duration (>300 Ma) of plume activity is consistent with the evidence for a superplume that existed in the Paleoproterozoic Laurentia–Baltica (Sunderland) supercontinent (time interval of 2505–2110 Ma) with several events and radial magmatic centers dated at 2505, 2450, 2200, and 2100 Ma (Bleeker and Ernst, 2006).

Using isochron U–Pb and Sm–Nd isotopic geochronological methods, long multiphase formation was established for the large Fedorov Pana intrusion bearing economic Pd–Pt mineralization: the main gabbronorite phases are dated at 2526 ± 6–2507 ± 11 and 2493 ± 8–2485 ± 9 Ma, and supplementary leucogabbro–anorthosite phases are dated at 2470 ± 9 and 2447 ± 12 Ma (Bayanova, 2004; Groshev, Nitkina, and Mitrofanov, 2009). Similar magmatic pulses were established in many other ore-bearing and prospective intrusions of the Kola region: Monchegorsk, Monchetundra, Mt. General'skaya, Imandra, etc. The ore-bearing layered mafic intrusions of the Fenno-Karelian Belt (Penikat, Burakovka massifs, etc.) similar in all characteristics to the Kola counterparts are younger (Iljina, Hanski, 2005). The onset of their formation is estimated at 2460 Ma (2530 Ma for the Kola intrusions).

On the basis of the above data, two main paths (belts) of mafic intrusions bearing economic Pd–Pt and, to a lesser extent, Ni–Cu mineralization differing in age were established in Kola Peninsula, Laplandia, and North Karelia (Fig. 1). Smolkin et al. (2009) assume that two vast plume fields different in age are contoured in the northeastern Baltic Shield (Fig. 4). Numerous similar mafic–ultramafic intrusions dated at 2500–2300 Ma are known in this vast territory, including their metamorphosed counterparts, which were transformed into coronite (drusite) rocks in the Belomorian Domain (Bogatikov et al., 2010) and the Lapland–Kolvitsa Granulite Belt (Mitrofanov and Nerovich, 2003).

As concerns the Noril'sk ore-bearing systems, a model of evolution of the Taimyr–Noril'sk province (six stages) was elaborated by Dodin et al. (2001) based on correlation of geological events (table). Note that the high-sulfide (Ni, Cu) and low-sulfide (PGE) stages of ore formation are separated in time; however, this has not yet been proved or refuted by isotopic methods.

Dobretsov et al. (2008) noted that trap magmatism at the Siberian Platform developed from the Proterozoic to Mesozoic with a maximum at the Permian–Triassic boundary. New Ar^{40}/Ar^{39} estimates have specified the upper chronological boundary of the trap magmatism at 265–255 ± 6 Ma (Vasil'ev et al., 2010).

Recent geological and petrological data (Krivolutskaya and Rudakova, 2009) show that intrusive rocks of the Noril'sk Complex are not comagmatic with any of the tholeiitic basalts in the region and represent an independent line of magmatic evolution that differs from traps, as was suggested by Godlevsky (1959), Tuganova (2000), Dodin et al. (2001), and Likhachev (2006). It is commonly accepted that intrusions especially enriched in sulfide ore require diverse multistage preparation in the course of magma emplacement (contamination, magma mixing, separation of immiscibile liquids, etc.) and during crystallization (immiscibility in the magma chamber, fractionation, etc.) (Naldrett, 2003).

The Noril'sk province, although Russia's richest source of Ni, Cu and Pd, Pt, remains insufficiently studied in many respects. A systematic isotopic study of the complete set of rocks still awaits implementation. Only selected rocks from a limited number of ore-bearing and barren intrusions different in composition and geological setting have been involved in research. Such important questions as a chronological relationship between high-sulfide Ni–Cu and low-sulfide Pd–Pt mineral assemblages remain ambiguous (Sluzhenikin and Distler, 2010).

About 200 U–Pb SHRIMP-II age determinations of single zircon grains were performed at the Center of Isotopic Research, VSEGEI (Malitch et al., 2009, 2010a, 2010b). In all localities of the ore-bearing Talnakh intrusion, including the upper gabbrodiorite with low-sulfide Pd–Pt mineralization, most of the 99 zircon grains belong to clusters with a crystallization age of 280 and 260 Ma; the youngest cluster is dated at 230 Ma. Among 14 zircon grains from the Vologochan intrusion with subeconomic Ni–Cu–PGE mineralization, two groups of zircons fell into the 265–220 Ma interval and one grain was dated at 331.6 ± 4.1 Ma. In the rocks of Kharaelakh intrusion with economic mineralization, four groups of zircons with different morphology, geochemistry, and U–Pb and Hf isotopic

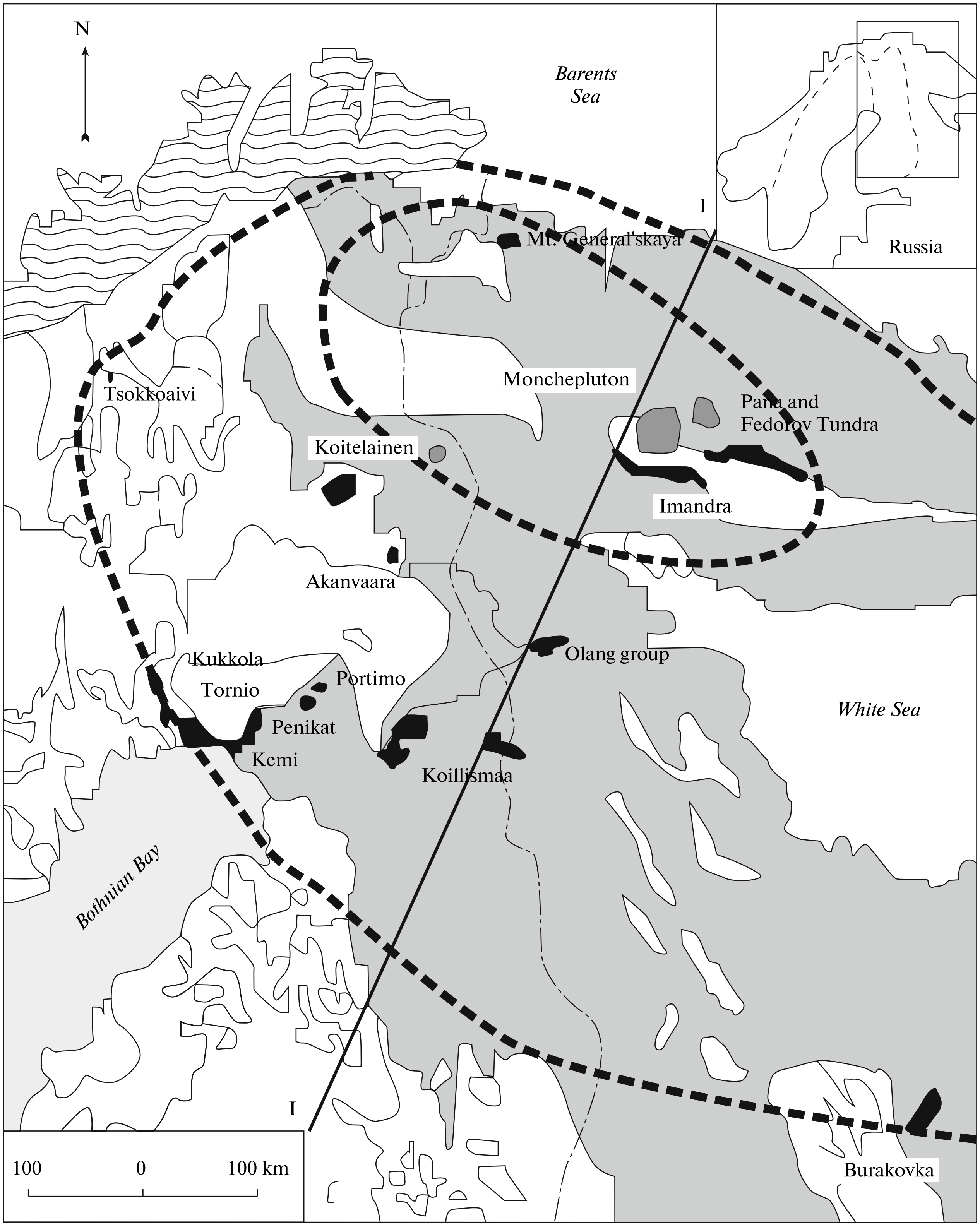

Fig. 4. Manifestation of Early Paleozoic superplume in eastern Baltic Shield with two plume fields differing in age (dashed lines), after Smolkin et al. (2009). The minor and major plumes started to evolve 2.53 and ~2.46 Ga ago, respectively.

Formation stages of unique PGE deposits in Taimyr–Noril'sk province, after Dodin et al. (2001)

Stage	Process and event
I. Premagmatic and preore	1. Collision of Taimyr–Severnaya Zemlya Domain and Siberian Platform 2. Underthrusting of oceanic crust and enrichment of fluid flows in H_2O, S (including heavy), and halogenides 3. Melting of contrasting magmas 4. Separation of immiscible ultramafic, mafic, high-S, and low-S anorthositic melts
II. Six-phase volcanic	5. Rifting and supply of magmas enriched in Cu, PGE, and fluids by means of decompression in open system of deep fault zones as satellite rifts 6. Formation of magma chambers, in regions with black shale sequences too
III. Main intrusive and ore	7. Emplacement of layered ultramafic–mafic magma enriched in PGM, Cu, and fluids into discrete rift troughs on shoulders of main rift
IV. Main ore and intra-intrusive	8. Emplacement of sulfide-bearing melt (ore intrusion) 9. Separation of immiscible melts in magma chamber
V. Final intrusive and intra-ore	10. Formation of rhythmic layering 11. Intra-ore alkaline metasomatism, formation of zonal ore lodes unique in reserves and PGM content (Noril'sk–Talnakh type)
VI. Postintrusive and final ore	12. Supply of low-S melt and formation of low-sulfide PGM ore unique in resources and occasionally in PGM grade

parameters make up four age clusters: 347 ± 16, 265.7 ± 11, 253.8 ± 1.7, and 235.9 ± 6.1 Ma (Malitch et al., 2010b). In the Noril'sk-1 intrusion, zircons are also characterized by a significant interval of crystallization: 261.3 ± 1.6, 245.7 ± 1.1, 236.5 ± 1.2, and 226.7 ± 0.9 Ma, whereas the age of baddeleyite from olivine gabbro was estimated at 290 ± 2 Ma (Malitch et al., 2009). Similar results have been obtained for five other massifs of the Noril'sk province.

In contrast to the interpretation given by Petrov et al. (2010), most zircons, including cores of polyphase grains, are magmatic and contain melt inclusions with a homogenization temperature above 900°C. This is also supported by Th and U contents, Th/U ratios, and REE patterns. The zircons entrapped from the framework are either absent or they are minimal in number. A single zircon grain with a concordant age of 1914 ± 92 Ma has been found in hybrid gabbrodiorite from the upper part of the Noril'sk-1 intrusion. In addition, some groups of zircon contain carbon dioxide and water–salt fluid inclusions. It is assumed that these zircons crystallized after infilling of the intrusive chamber with melt.

The data published by K.N. Malitch give good reason to suppose that clusters of magmatic baddeleyites and zircons 350 to 220 Ma in age correspond to long-term pulsatory crystallization of the initial melt in various transitional magma chambers and/or to magma mixing. In any case, this time interval confirms the long evolution of the Noril'sk ore-magmatic system.

SPATIOTEMPORAL RELATIONSHIPS OF ROCK ASSOCIATIONS SPECIALIZED FOR LOW-SULFIDE Pd–Pt AND SULFIDE Ni–Cu–PGE MINERALIZATION

According to Sluzhenikin and Distler (2010), low-sulfide Pd–Pt ores contain no more than (i) 0.20–0.25% Cu + Ni, (ii) 0.3–2.0, 3–12, and (iii) up to 20–60 gpt PGE in subeconomic, ordinary, and bonanza ores, respectively. The PGE (gpt) to S (wt %) ratio is always >5, occasionally reaching 40–70 and even 300. In contrast, in sulfide Ni–Cu–PGE ore, PGE/S ratio is <5, commonly 1.5–3.5. The mining companies in their exploration and technological practice strive to separate ore provinces, districts, and ore-bearing intrusions into Ni–Cu with additional PGE and Pd–Pt with additional Ni–Cu types. This principle also forms the basis of deposit classification elaborated by Naldrett (2003) and of other basic concepts (Dodin et al., 2001; Likhachev et al., 2006, etc.).

The largest low-sulfide PGE deposits are related to the Neoarchean–Paleoproterozoic layered mafic intrusions. Their unique examples are well known: the Windimurra Mine, Australia (2.8 Ga); Stillwater, United States (2.7 Ga); Great Dike, Zimbabwe (2.58 Ga); Bushveld, South Africa (2.06 Ga). These are very large solitary deposits, which do not reveal obvious links to LIPs. The geodynamics of their formation and temporal relationships between various types of mineralization remain ambiguous. The ore-bearing intrusions of the East Scandinavian and Noril'sk mafic LIPs, where both types of PGE mineralization occur, occupy a special place in this series of large deposits. These Russian examples of superlarge PGE and base-metal provinces should be supplemented by the Voronezh and Eastern Sayan provinces, as well as by the ore-bearing Dovyren, Chinei, and other layered intrusions in southern Siberia (Tolstykh et al., 2008).

About 20 economic PGE base-metal deposits are known to date in the ESMLIP. The low-sulfide Pd–Pt deposits are predominant in the Early Paleoproterozoic (2530–2400 Ma) Kola and Fenno-Karelian intrusive belts. In Russia, these are explored deposits hosted in the Western and Eastern Pana, Vuruchuaivench, and Lukkulaisvaara layered intrusions and incompletely explored Burakovka, Mt. General'skaya, and other deposits. The sulfide Ni–Cu–PGE deposits are also known (Monchegorsk, Fedorov Tundra in Russia).

Deposits of both types have been explored in the best studied Fedorov Pana intrusion (Mitrofanov, 2005; Korchagin et al., 2009; Bayanova et al., 2009). The low-sulfide PGE mineralization hosted in this intrusion is controlled by stratiform lodes (reefs) within the roughly layered gabbronorite series with pyroxenite and anorthosite as end members. Two different types of mineralized reefs are distinguished: (1) finely and rhythmically differentiated (layered) units with low-grade (<1 gpt) PGE mineralization, which are syngenetic to the general rough layering, and (2) thick (up to 100 m) economic composite PGE reefs (5–7 gpt PGE), where anorthosites are mostly late magmatic injections enriched in volatile components. The subeconomic C- and H-reefs (Groshev, Nitkina, and Mitrofanov, 2009) composed of leucocratic gabbronorite and troctolite (2526 ± 6 to 2507 ± 11 Ma) are coeval with gabbronorite and serve as illustration of the first type. The second type is illustrated by the economic northern (lower) and southern (upper) reefs of the Kievei Pd–Pt deposit hosted in the Western Pana layered intrusion (Mitrofanov, 2005; Korchagin et al., 2009) composed of pyroxenite, norite, gabbro, anorthosite (northern reef) and gabbronorite, troctolite, anorthosite (southern reef). The age of host rocks is estimated at 2500–2490 Ma, whereas supplementary ore-forming anorthosite injections are dated at 2470 ± 9 and 2447 ± 12 Ma (Bayanova, 2004).

The Fedorov Tundra sulfide Ni–Cu–PGE deposit is localized at the lower contact of the sheetlike roughly layered mafic body (Fig. 5). Nevertheless, it was established that this is a later (2493 ± 8 to 2485 ± 9 Ma) ore-bearing gabbronorite intrusion emplaced into the older layered pluton formed 2526 ± 6–2507 ± 11 Ma ago (Groshev, Nitkina, and Mitrofanov, 2009) rather than a basal bottom layer. This phenomenon may be called local underplating (Mitrofanov, 2010).

Thus, the Fedorov Pana ore-bearing intrusion shows that economic low-sulfide and sulfide deposits may occur in the same mafic intrusions but are related to different intrusive phases being combined in the frames of common deep-seated ore-bearing system.

In the Noril'sk province, all intrusions are currently regarded as single-phase, although this is not evident to some researchers. Occurrences of low-sulfide PGE mineralization of the Upper Talnakh type (Sluzhenikin et al., 1994; Dodin et al., 2001) were established not only in the known intrusions bearing economic mineralization (Noril'sk-1, Talnakh, Kharaelakh) but also in the intrusions with sulfide deposits, which were regarded as subeconomic (Noril'sk-2, Chernogorsky), as well as in intrusions pertaining to the Zubov leucocratic type (Zub-Marksheidersky, Pyasino–Vologochan). Despite some differences, all occurrences of low-sulfide PGE mineralization have much in common. The low-sulfide PGE-bearing lodes occupy a special position with respect to the main orebodies. They are localized near the upper contacts of intrusions (the so-called upper gabbroic zone) and separated from sulfide ore lodes by barren rocks more than 50 m in thickness. The upper contact zone is composed of various rocks: eruptive breccia, olivine-free and olivine-bearing gabbrodolerite, gabbrodiorite, leucogabbro, and taxitic Cr-bearing gabbro. Leucogabbro and especially taxitic Cr-bearing gabbro are the main host rocks for low-sulfide PGE. Leucogabbro does not form a continuous layer at the roof of the intrusion but occurs as lenses a few meters to hundreds of meters long. Their thickness is also variable and attains 25 m. As seen in the section, they contact with country rocks or are separated from them by marginal gabbrodolerite, gabbrodiorite, or eruptive breccia. Taxitic gabbro frequently occurs at several levels close to the bottom of leucogabbro layers. These rocks are separated by a transitional zone a few centimeters in thickness rather than by a sharp boundary.

These geological relationships between the lower picritic and troctolitic gabbrodolerites with high-grade sulfide mineralization, on the one hand, and the upper leucocratic rocks with low-sulfide PGE mineralization, on the other, along with the occurrence of eruptive breccia leave, in our opinion, hope that these intrusive bodies are multiphase. So far, the rock associations of the upper gabbroic zone are considered products of intrachamber fractionation of fluid-saturated magmatic melt (Sluzhenikin and Distler, 2010).

It should be noted in this regard that the idea of repeated mixing of various magmatic injections into the crystallization chamber currently dominates in the world literature (Robb, 2008). For example, in the Bushveld massif consisting of five chambers (limbs, or laccolith-like basins), the composite Platreef reveals indications of magma mixing (high-Mg and high-Cr U-type and high-Al and Cr-depleted T-type). An additional crosscutting injection of primitive magma of the Merensky reef was established in the earlier layered rocks (Yudovskaya and Distler, 2010). It is evident that correct genetic interpretation of a complex ore-magmatic system of the Noril'sk type needs isotopic dating of reference processes and their geochemical characterization.

In conclusion, note that in the superplume process protractedly evolving in the eastern Baltic Shield, the early (2530–2400 Ma) extensive within-plate mafic

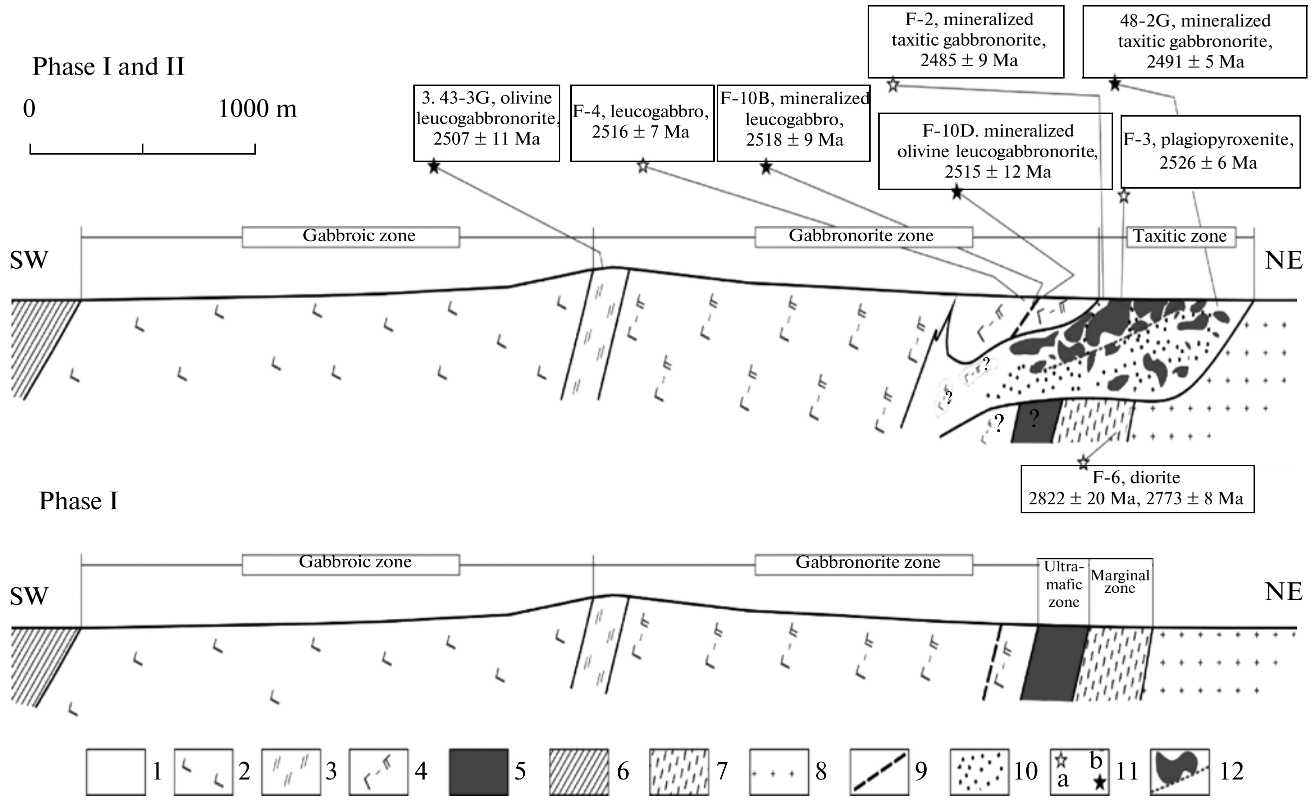

Fig. 5. Integrated geological section across Fedorov Tundra deposit at Greater Ikhtegipahk site (upper part) and reconstruction of intrusion structure at this site after first and before second intrusion phase (lower part), after Groshev, Nitkina, and Mitrofanov (2009). Phase II: (1) taxitic ore gabbronorite; phase I: (2) leucogabbro, (3) unit of lenticular rhythmic intercalation of melanocratic troctolite, olivine gabbronotite with inverted pigeonite, and leucogabbro, (4) alternation of leucogabbronorite and leucogabbro (with interlayers of mesocratic gabbronorite, troctolite, olivine gabbronorite and leucogabbronorite with inverted pigeonite), (5) plagiopyroxenite, harzburgite and olivine pyroxenite; (6) Paleoproterozoic metavolcanic rocks of the Imandra–Varzuga Zone; (7) diorite in contact zone of phase I; (8) Archean gneiss, (9) reef-type PGE mineralization; (10) basal Ni–Cu–PGE mineralization; (11) location of geochronological samples; (12) boundary of so-called norite zone and zone of taxitic gabbronorite.

magmatism with polymetallic (Cr, Ni, Cu, PGE, Fe, Ti, V) metallogeny gave way 2000–1980 Ma ago to local linear rift- and spreading-related magmatism of the Red Sea type, which formed sulfide Ni–Cu deposits of the Pechenga ore field, as well as separate alkaline plutons with carbonatites, and Ti–V and apatite mineralization (Gremykha-Vyrmes massif. etc.) (Mitrofanov, 2010). The evolution of the Noril'sk province was closely related in time (~250 Ma ago) and space to ore-bearing alkaline magmatism in the north of the Siberian Platform, including carbonatites and kimberlites typical of superplumes (Bogatikov et al., 2010).

NATURE OF MAGMA AND METAL SOURCES, EFFECT OF MANTLE AND CRUSTAL PROCESSES, MAGMATISM, AND FLUID-HYDROTHERMAL PHENOMENA

The isotopic geochemical data are largely concerned with mantle sources of initial melts and ore matter, subsequent processes in transitional chambers, which predate magma crystallization, and postmagmatic processes in the Earth's crust.

The crystallization of mafic magmas in crustal chambers and subsequent alteration of rocks were described in petrological terms by Wager and Brown (1968), Irvine (1977), Campbell and Barnes (1984), Dubrovsky (1998), Naldrett (2003), Likhachev (2006), Sharkov (2006), Robb (2008), etc. It should be noted that in genetic models of even classic world-class objects (Bushveld, etc.), the duration of processes was not taken into account due to the lack of the necessary measurements. Meanwhile, multiple supply of new batches of melt in the magma chamber is assumed a necessary condition in many genetic models. For example, the Merensky reef as the major world reservoir of PGE ore is related to one of the supplementary portions of magma enriched in Sr^{87}/Sr^{86} up to 0.709 against the background of $Sr^{87}/Sr^{86} = 0.703$ inherent to the early mafic layered section. Anorthosite potholes with higher PGE contents locally crosscut the Merensky reef. As mentioned above, the Platreef in the Bushveld massif was formed as a product of magma mixing as well (Yudovskaya and Distler, 2010). A similar situation with repeated supply of ore-forming matter was noted in the lower PGE reef at the Kievei deposit in the Fedorov Pana intrusion, where crosscutting anorthosite (Latypov et al., 1999) crystallized later than the layered mafic series, by at least ten million years: 2470 ± 9 and 2491 ± 6 Ma, respectively (Bayanova, 2004). It seems that late ore-forming anorthosites enriched in Ca and Al and depleted in Cr, and the early gabbroic rocks enriched in Mg and Cr, correspond to the T- and U-type magmas of the Platreef.

The crystallization of orthomagmatic ore-bearing mafic rocks in magma chambers comprises various combinations of such processes as magma separation by density, including the effect of immiscibility of silicate and ore liquids; crystal fractionation; supplementary injections of melts and fluids mixed with minerals and/or the preceding residual melt; a shift of the cotectics under variable conditions; interaction with fluid; contamination; etc. The physicochemical principles of these processes were discussed in the summaries published by Marakushev (1992), Dubrovsky (1998), Naldrett (2003), Chernyshov (2004), Likhachev (2006), and Robb (2008). The genesis of PGE deposits in the Baltic Shield was discussed by Sharkov (2006), Bogatikov et al. (2010), Grokhovskaya et al. (2000, 2003), and Dubrovsky and Rundqvist (2009).

What remains unclear in the source(s) of magma and ore matter that transformed into low-sulfide PGE lodes in the vast East Scandinavian mafic province and its counterparts. Over the extensive territory of this province, the average composition of layered intrusions differing in age and geological setting corresponds to leucocratic gabbronorite with constant isotopic parameters: $\varepsilon_{Nd} = -1$ to -3 and $I_{Sr} = 0.702$–0.704 (Bayanova et al., 2009). The constancy of these parameters, the low sulfide content in rocks and ores, and within-plate setting of the province do not allow us to assume subduction-related contamination and secondary enrichment of primary magma in ore elements and sulfur as proposed by Dodin et al. (2001) and Starostin and Sorokhtin (2010) for the Noril'sk intrusions and related high-grade sulfide lodes.

Meanwhile, the low-sulfide deposits are characterized by an anomalously high PGE concentration in the sulfide phase, which is much higher than in sulfides at Ni–Cu–PGE deposits (Naldrett, 2003). This difference causes an apparent deficiency in the mass of parental magma calculated from the commonly accepted global mean concentration in the crust with regards to the real amount of PGE in ore and rocks of layered complexes. To explain this discrepancy as applied to the main epoch of ore formation in the Late Neoarchean–Early Paleoproterozoic, a number of hypotheses have been proposed.

The first group of hypotheses assumes a special composition of the mantle geospheres at the early stage of Earth's evolution. These geospheres produced magma initially enriched in PGE. A hypothesis of heterogeneous composition of large mantle clusters retained from the early stage of Earth accretion prior to complete homogenization explains the disproportionate enrichment of particular terrestrial regions in PGE and Au, e.g., in South Africa (Robb, 2008). The hypothesis of abundant bombardment by meteorites and asteroids enriched in siderophile and noble metals suggested for the Sudbury deposit supplements this group.

In our opinion, the hypothesis of undepleted primary magmas derived from lower mantle sources is the most suitable for interpreting within-plate plume-related LIPs of the ESMLIP type. These magmas are distinguished from the upper mantle asthenospheric melts by enrichment (fertility) in both siderophile–chalcophile (PGE, Au, Ni, Cr) elements and LILE. Models of such magma formation by partial melting of protolherzolite with the active role of through-mantle metasomatism have been proposed. For high P and T, inert noble metals migrate in the form of atomic gas of intermetallides, tellurides, selenides, and hydrides. It cannot be ruled out that PGE-nanoclusters were formed with ligands in the form of complex compounds with OH^-, Cl^-, Br^-, S^-, HS^-, NO^{2-}, NO^{3-}, and CN^-. These clusters could have been incorporated into olivine and chromite in a low-S medium and into sulfides in a high-S medium (Boudreau, 2009; Sluzhenikin, 2010).

Accumulation and retention of significant PGE concentrations require long-term and stable conditions before the formation of a mantle magma source. During subsequent melting, which, on the contrary, must be short-term in order to avoid dilution of the unstable system, the metals concentrate in melts at the chemical and thermodynamic barriers, including the silica-enriched chambers in the crust–mantle layer. Such a layer >10 km thick is supposed beneath many areas in the ESMLIP (Verba et al., 2005). Note also that plume streams must be characterized by a high He^3/He^4 ratio, as is suggested in several intrusions of the Kola region (Tolstikhin et al., 1992; Bayanova et al., 2009). It should be added that the Early Paleoproterozoic belts of mafic rocks enriched in PGE inherit Archean komatiite belts, and this may explain the secondary crustal enrichment of magmas in PGE and Au (Mitrofanov, 2010).

Magmatic crystallization in intrusive chambers under closed system conditions, e.g., the Skaergaard pluton in Greenland, can be described in terms of the known models (Dubrovsky, 1998). The simulation of PGE distribution developed by Naldrett (2003) takes into account liquid immiscibility and additional concentration at liquid/solid interfaces. This model is helpful for interpreting complex multiphase and contaminated magmas. Sluzhenikin et al. (1994) called attention to the role of fluid components (OH^-, Cl^-, F^-) in the PGE concentration of leucocratic gabbroic rocks localized in the upper parts of Noril'sk intrusions. These rocks as a product of crystallization of residual melt accumulate volatile components facilitating fractionation and enrichment of low-sulfide lodes in PGE.

CONCLUSIONS

This paper presents the results of a multidisciplinary study performed by a group of specialists in various fields of geology. These results allowed us to assert that the East Scandinavian and Noril'sk ore provinces belong to the mafic large igneous provinces.

The East Scandinavian mafic large igneous province (ESMLIP) was formed in the Early Paleoproterozoic (2530–2200 Ma ago) on the continental crust of the Archean Kola–Lapland–Karelian Craton in an intracratonic geodynamic setting and under conditions of passive rifting before initial ophiolitic plutonism of the Svecofennian paleoocean (2200–2000 Ma ago). In contrast, the Noril'sk mafic large igneous province (NMLIP) was formed primarily in the Late Paleozoic–Early Mesozoic 350(?)–220 Ma ago at the active margin of the Siberian Craton during the closure of the Central Asian paleoocean.

In the ESMLIP, plume-related magmatic ore formation developed without substantial crustal contamination and with predominance of low-sulfide Pd–Pt mineralization. In the NMLIP, mantle magmas were enriched in the crustal matter (mainly sulfur) with formation of sulfide Ni–Cu ore.

From a comparison of the age and localization of the world's largest Pd–Pt and Ni–Cu–PGE ore reserves with the epochs of the major collisional and plume-related geodynamic processes, which involved enormous areas and volumes in the continental lithosphere, and consideration of the terrestrial geodynamics at different stages of its evolution, a conclusion was drawn that the main Pd–Pt and Ni–Cu–PGE ore provinces were formed mainly at the late stages of the existence of supercontinents and at the onset of their breakdown 2.2–2.5 and 1.8–1.7 Ga ago, less frequently in the Late Precambrian, and as a unique phenomenon in the Late Paleozoic (Noril'sk).

The long-term (tens of millions of years) functioning and pulsatory evolution of plume-related ore-magmatic systems has been proved for the ESMLIP and is suggested for the NMLIP. The PGE concentration in economic low-sulfide lodes (reefs) hosted in mafic intrusions is related not only to intrachamber fractionation, but also to diverse deep processes in the lower mantle. We are inclined to use the hypothesis of the lower mantle fertile (undepleted) magmas to explain the geochemistry and metallogeny of intrusive rocks in mafic LIPs.

The complex of geological, geophysical, geochronological and geochemical isotopic indicators (U–Pb, Sm–Nd, Rb–Sr, He/He isotopic systems; $\varepsilon_{Nd}(T)$, T(DM), I_{Sr}, He^3/He^4 parameters) can be helpful to forecast prospectivity of mafic intrusions for low-sulfide PGE and sulfide Ni–Cu–PGE mineralization. These indicators are used by prospecting companies working in Kola Peninsula and Lapland Finland. The same technology can be applied to Karelia, Voronezh, Eastern Sayan, and other mafic large igneous provinces.

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