Russian Academy of Science
Geological Institute of Kola Science Centre

Two types of ore-bearing mafic complexes of the Early Proterozoic East-Scandinavian LIP and their ore potential

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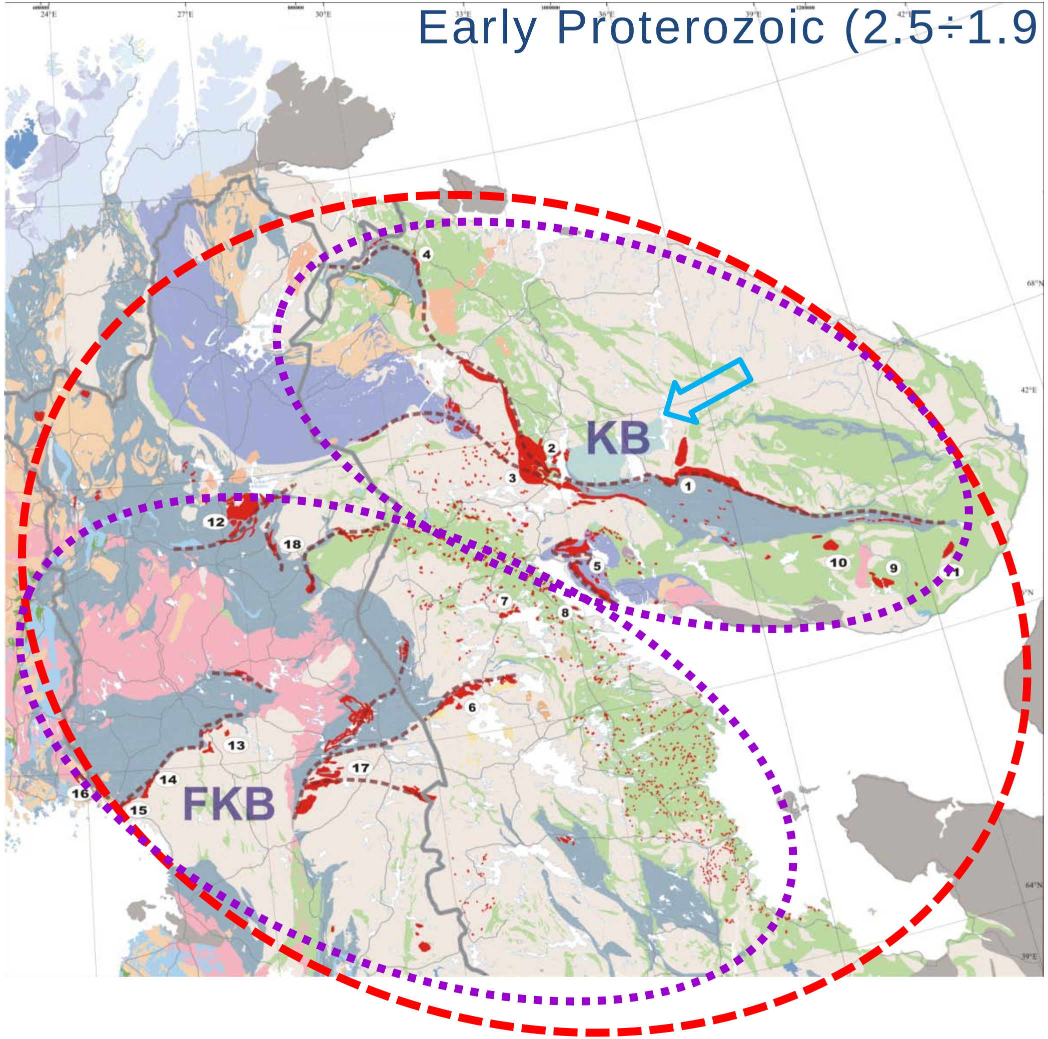
Early Proterozoic (2.5÷1.9 Ga) East-Scandinavian LIP



Region of our investigations

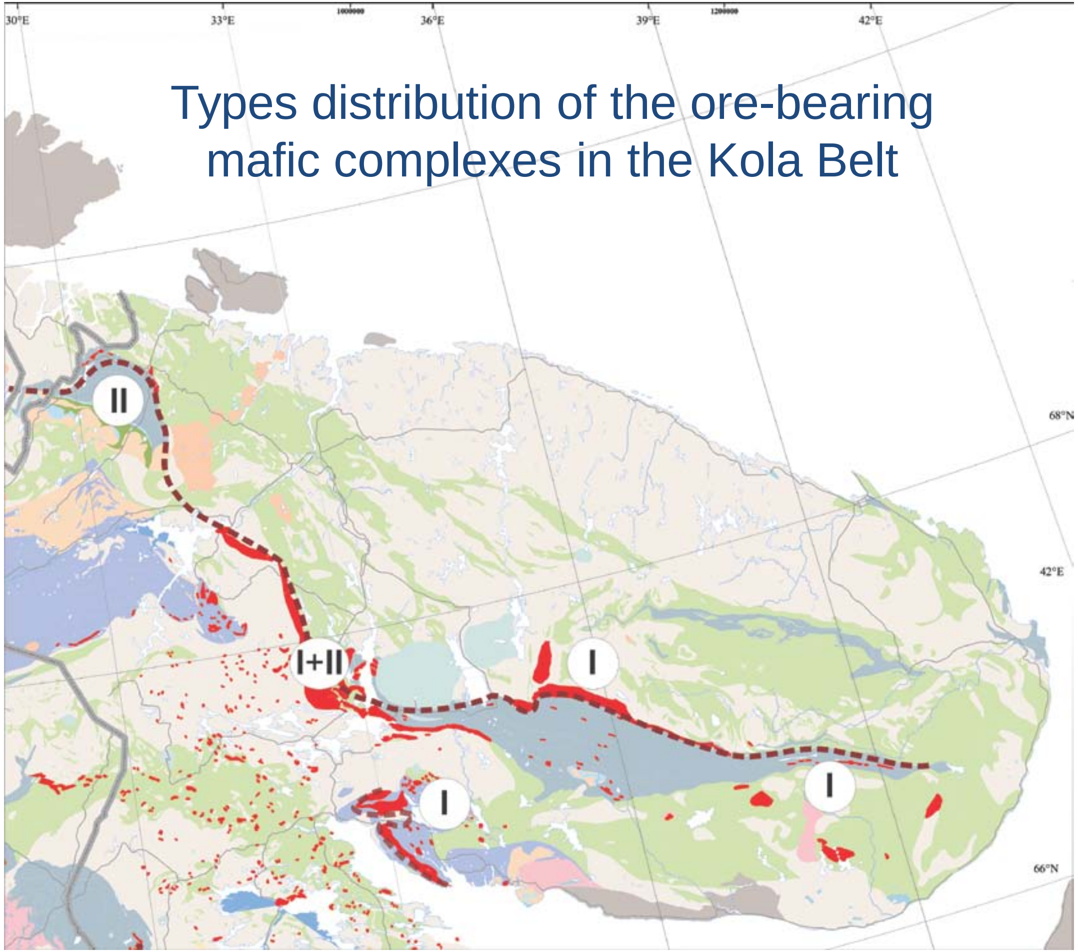
Fig. 1. **Geological sketch of the East-Scandinavian Large Igneous Province (LIP) with the ore-controlling rifts and major Early Proterozoic layered complexes with PGE mineralization highlighted**:

- Early Proterozoic layered complexes with PGE mineralization; FKB - Fenno-Karelian belt; KB - Kola belt; - number of layered complexes: 1- Fedorovo-Pansky; 2 - Monchepluton; 3 -Monchetundrovsky; 4 - m. Generalskaya; 5 - Kandalakshsky and Kolvitsky; 6 - Lukkulaysvaara; 7 - Kovdozersky; 8 - Tolstic; 9 - Ondomozersky; 10 - Pesochny; 11 - Pyalochny; 12 - Keivitsa; 13 - Portimo; 14 - Penikat; 15 - Kemi; 16 - Tornio; 17 - Koillismaa; 18 - Akanvaara

Two types of the ore-bearing mafic complexes are allotted in the East-Scandinavian large igneous province (LIP).

I

PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)



II

Intrusions with the rich sulfide Ni-Cu ore (with Co, S, PGM, Se, Te, etc.)

These types differ in geodynamic setting, structure, isotope geochemistry, petrology and mineralogy:

PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

#	Search indicator affiliation	Parameters
1.	Geophysics	Presence of the granulite-mafic (anortosite) layer with the crust-mantle characteristics (Vp = 7.7-7.1 km/s) formed as a result of plume underplating (composition of the layer is defined on the basis of deep crustal xenoliths in the volcanic pipes) detected by the deep geophysical methods in the foot of the crust.
2.	Structure	Regional: distribution of a discordant ensemble of rift-related volcano-sedimentary flexures, dikes, and polyphase layered mafic intrusions over a vast area of Archaean basement domains. Local: ore bodies occur at basal (lower) contacts, extended reef beds, in the deposits of pegmatoid mafic rocks, in veined and offset settings.
3.	Geodynamic setting	Large-scale, long-term, and pulsating style of deep plume or asthenosphere-related upwelling processes causing the formation of the vast non-subduction-type igneous mafic intraplate continental province (LIP's). Change of geodynamic Archaean orogenic regime with intracontinental rifting (with origination of variously oriented ensialic belts). Ore-controlling mafic-ultramafic intrusions form at an initial (pre-rift) stage of continental rifting.
4.	Composition	Siliceous high-Mg (boninite-like) and anorthositic magmas. Cyclic (regular poly-stage style) structure of the layered intrusions and abrupt variability of the cumulus association stratigraphy and geochemical melt profile. There are two to five and more megacycles in the majority of the Palaeoproterozoic layered intrusions. The megacycles represent regularly layered series from ultramafic varieties to gabbroids. The ore is confined to the most contrasting series of alternating thin rock layers differing in composition from leuco- and mesocratic gabbro to norite, anorthosite, plagiopyroxenite, inequigranular and inhomogeneous textures (e.g., varitextured gabbro), leucocratic varieties (leucogabbro, anorthosite, spotted gabbro), inequigranular, coarse-grained and pegmatoid rocks with eruptive magmatic relationships. All known stratiform reef-type deposits are confined to the borders of the megacycles, which mainly reflect the interchange of the high-Cr magma with the low-Cr one. Intense manifestation of deep reducing fluids enriched with the compounds of C, F, Cl, H, etc. is typical in the rock associations. Mineralogical factors: PGMs associate with the disseminated sulphide mineralization, anomalously high concentration of PGEs in sulphides, platinum metal distribution coefficient between liquating silicate and sulphide melts of >100000.
5	Isotope geochemistry	Deep mantle magma source initially is enriched with ore components (fertile source) and lithophile elements. It is reflected in such isotope indicators as εNd(T) @ -1 to -3, I_{Sr}=$^{87}Sr/^{86}Sr$ @ 0.702-0.705, $^{3}He/^{4}He=n\bullet(10^{-5}-10^{-6})$ where n denotes a natural number of 1 to 9. Magma and ore source differs from that of Mid-Ocean Ridges and subduction zones.
6.	Geochronology	Intraplate mafic extensive igneous provinces with low-sulphide platinum-palladium deposits (East Scandinavian Province on the Fennoscandian (or Baltic) shield, East Sayany Province at the prominence of the Siberian Platform basement, Huronian Province on the Canadian shield) are generated at the very beginning of the supercontinent break-up epochs, mostly at the Archaean – Palaeoproterozoic geochronological border, or 2600-2400 million years ago. For the East-Scandinavian province, it is the Sumi – Early Sariola epoch, or 2530-2400 million years ago. Ore-magmatic complexes evolve for a long time and in a pulsating manner (2490±10 Ma; 2470±10 Ma; 2450±10 Ma phases) with the interchange of the boninitic magmas with the anorthositic ones, and Cr and Cu+Ni ore profile with Pt+Pd and Ti+V one.
7.	Metamorphism	Known commercial deposits occur in the regionally non-metamorphosed rocks. Only Pt-Pd ore prospects are found in the regionally metamorphosed mafic complexes. There are data demonstrating that the exceeded PT parameters of the mid-temperature amphibolites facies result in the impoverishment of the ore.

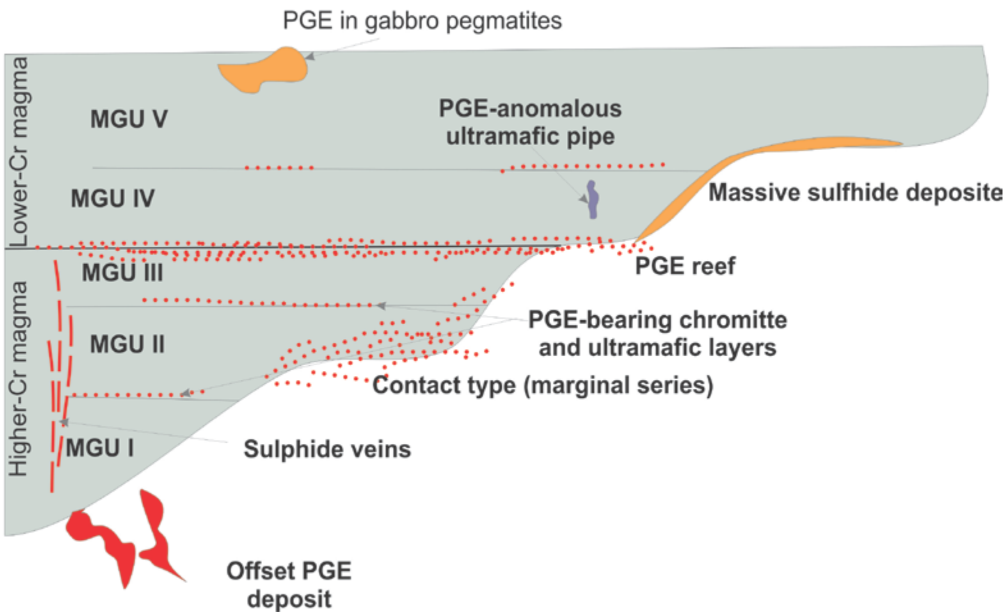
Intrusions with the rich sulfide Ni-Cu ore (with Co, S, PGM, Se, Te, etc.)

#	Search indicator type	Parameters
1.	Geophysics	Presence of local gravity anomalies concentrated in narrow linear zones in accordance with the geophysical data. The ascent of the Moho discontinuity from the level of 40-42 km in the framing up to 39-38 km in the ore-controlling series.
2.	Structure	Regional: narrow extensive belts in the whole composite ensemble of the Palaeoproterozoic orogens within the crystalline shields (e.g., Pechenga structure). Ore-bearing intrusive bodies are injected in the upper part of the Early Palaeoproterozoic volcano-sedimentary cross-section. Local: ore locates in the basal intrusive contacts in the redeposited veined bodies, including offset setting.
3.	Geodynamic setting	Ore genesis processes and magmatism tend in time and space during the period of the geodynamic regime interchange from the intracontinental rifting (ensialic) to the Red Sea-type (ensimathic) early spreading. Ore-controlling mafic-ultramafic intrusions are generated at a final stage of the continental rifting.
4.	Composition	Initial magma is depleted and similar to the Mid-Ocean Ridge Basalt (MORB) in terms of rare earths distribution. Ferropicritic Fe-Ti enriched magma derivatives generate single volcano-plutonic rock series. For intrusive ore bodies, gabbro-wehrlite composition, subvolcanic and hypabyssal crystallization setting, wide rock differentiation with the formation of syngenetic wehrlite-clinopyroxenite-gabbro- orthoclase gabbro sequence are typical.
5	Isotope geochemistry	Upper mantle source of the depleted magma with isotope indicators: εNd(T) @ +0.5 to +4, I_{Sr}= $^{87}Sr/^{86}Sr$ @ 0.703-0.704, $^{187}Os/^{188}Os$ @ 0.935±0.03 (single measurement).
6.	Geochronology	Spreading mafic magmatism in the crystalline shields occurred at a late stage of the intracontinental rifting, finishing the Transitional period and starting the typical Lithospheric Plate Tectonic epoch (2200-1980 Ma). In the Fennoscandian Shield, this is the Svecofennian paleoocean origination stage.
7.	Metamorphism	Collision metamorphism results in the formation of redeposited (remobilized) ore bodies both inside ore-bearing bodies and offset settings.

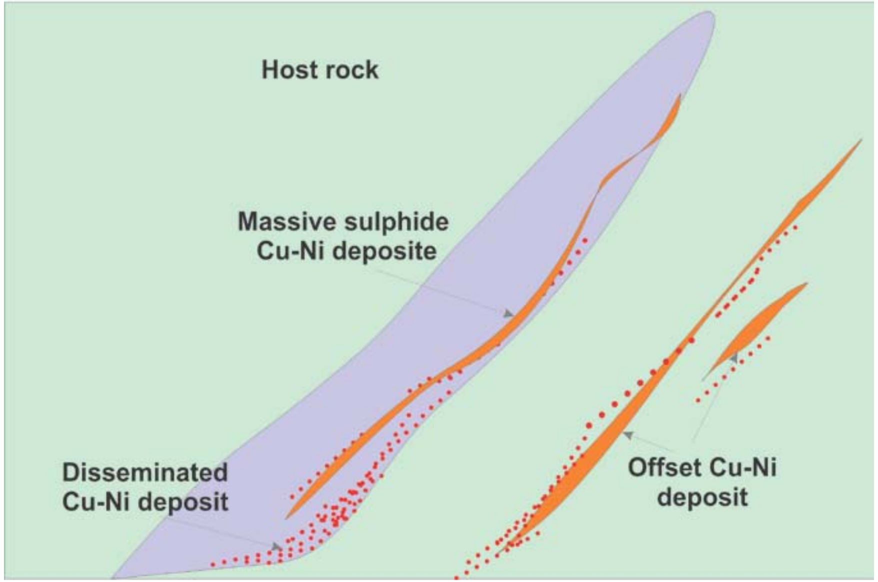
PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)0

Intrusions with the rich sulfide Ni-Cu ore (with Co, S, PGM, Se, Te, etc.)

LOCATION OF PGE MINERALIZATIONS (THEORETICALLY COMPLETE COMPLEX)



LOCATION OF Cu-Ni MINERALIZATIONS (Type II)

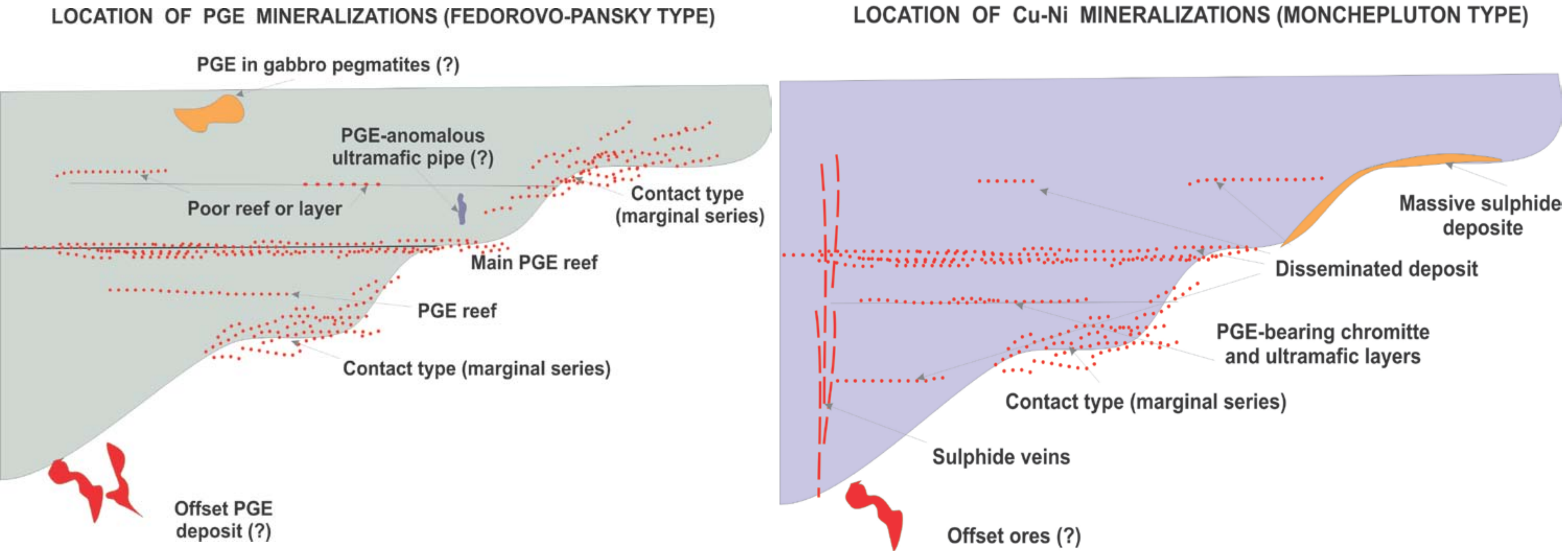


Characteristics:	reef	contact type
Thickness	0.5-2 m	10-200 m
grade	4-100 g/t	0.3-5 g/t
mining method	underground	open pitable
other	difficult to mine	easy to mine

After Markku Iljina, 1994

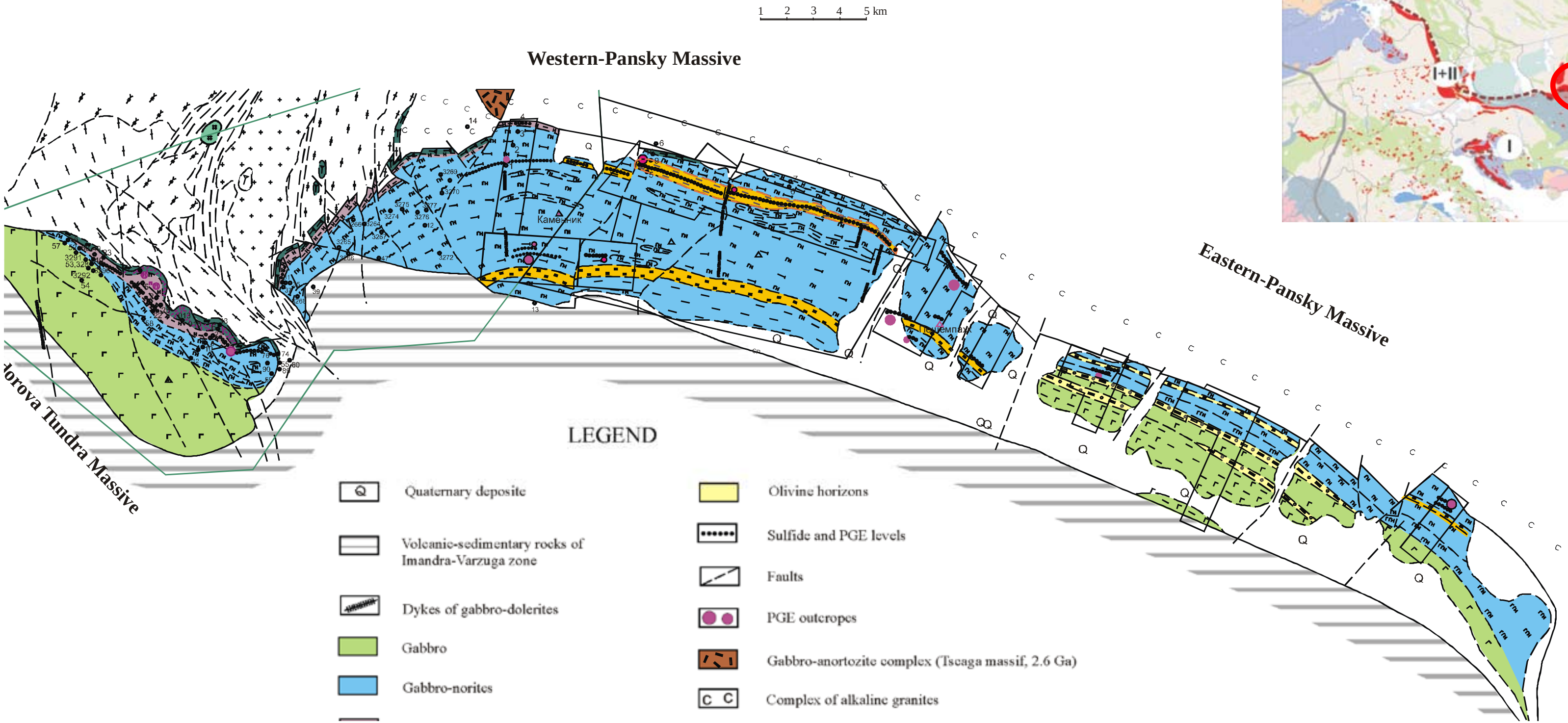
Characteristics:	Massive sulphide	Disseminated sulphide
Thickness	0.1-20 m	10-150 m
grade	1-10 %	0.1-0.5 %
mining method	underground	open pitable

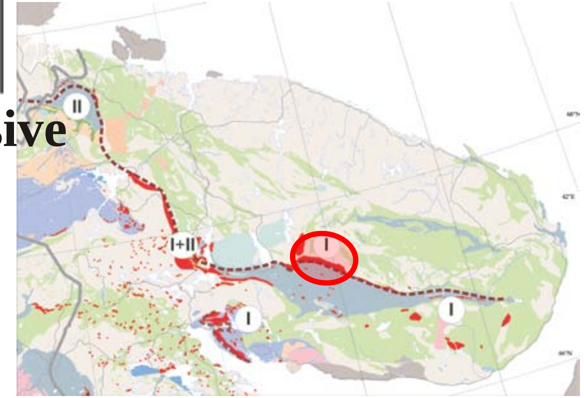
PGE-bearing mafic-ultramafic layered intrusions



PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

Geological Map of the Federovo-Pansky Intrusive

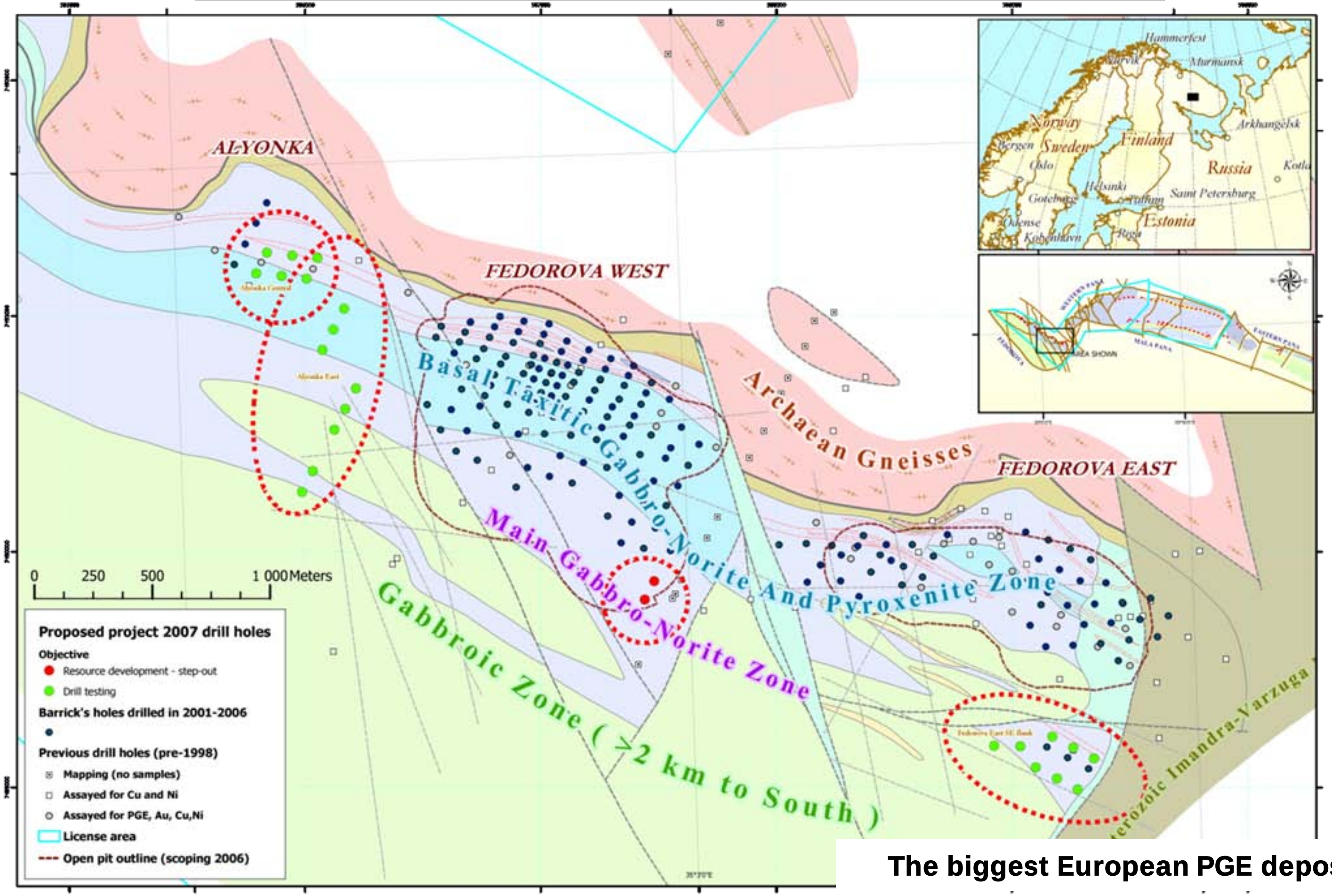




The intrusion is 90 kilometers long and down to 4 kilometers thick.
Since 1990, the intrusion has been drilled for the total of over 150,000 running meters, and three low-sulphide (with only 0.5 to 5 % of base metal sulphides) PGE deposits and a series of PGE prospects have been established here

PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

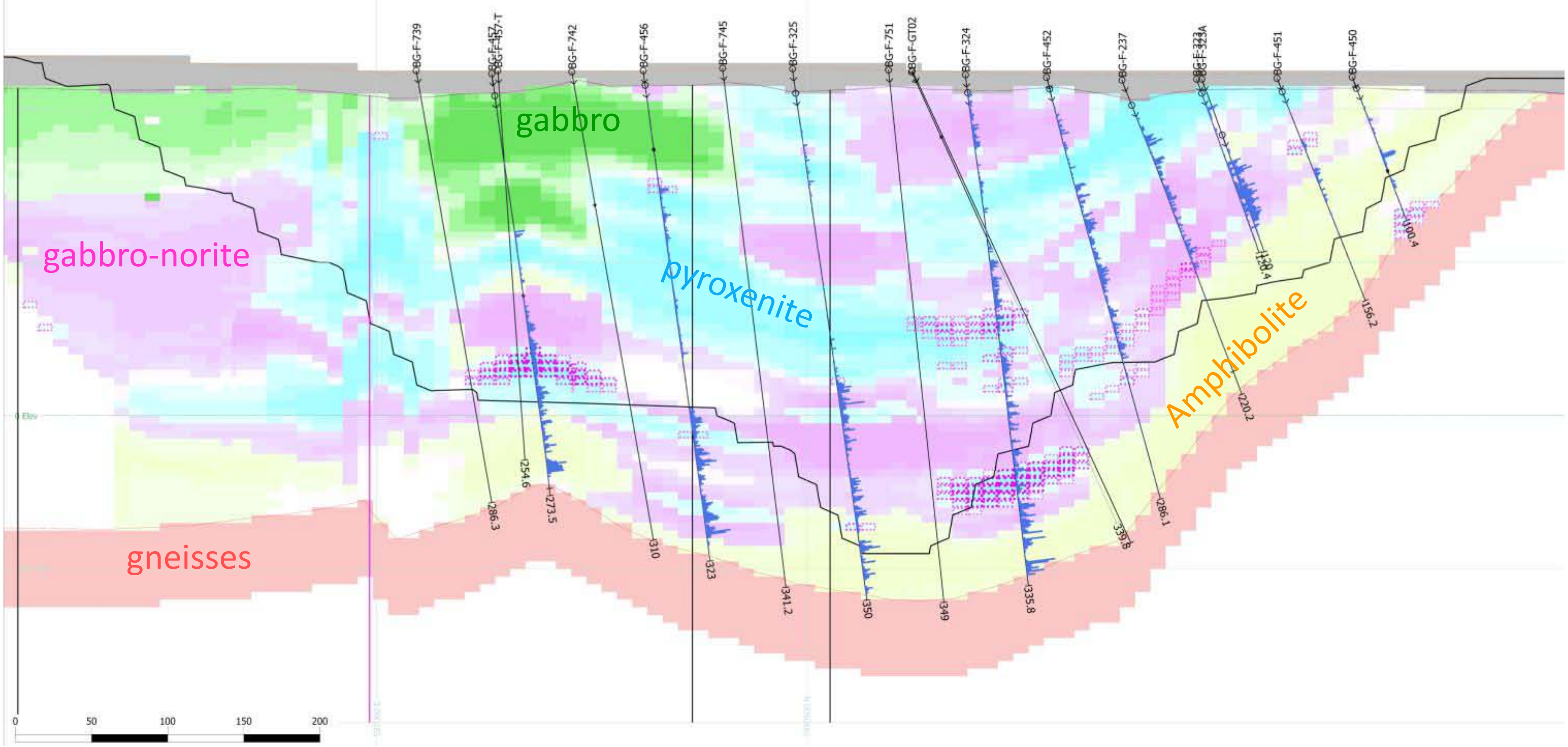
Contact Type



The biggest European PGE deposit FEDOROVA

PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

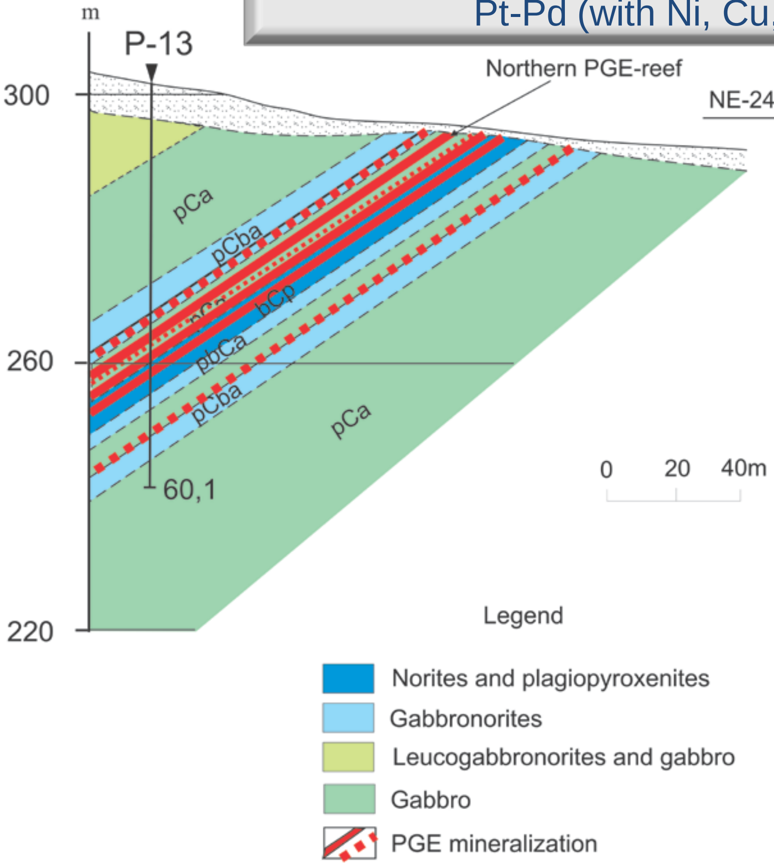
Contact Type



Typical Fedorova Section

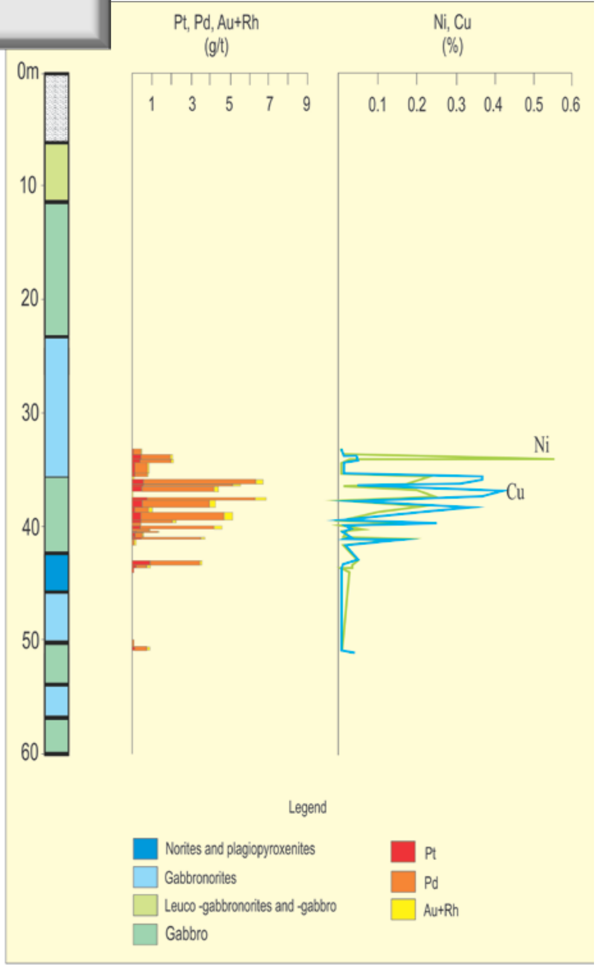
PGE-bearing mafic-ultramafic layered intrusions

Pt-Pd (with Ni, Cu, Au, Co and Rh)



Northeast-to-Southwest crossection of the Lower Layered Horizon in the West Pana Massif, through drill hole P-13, looking West

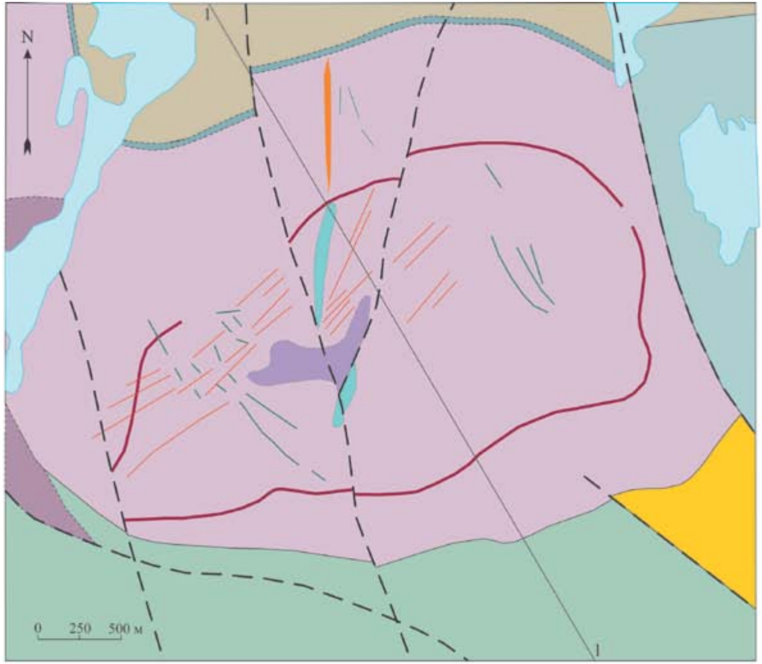
Reef Type



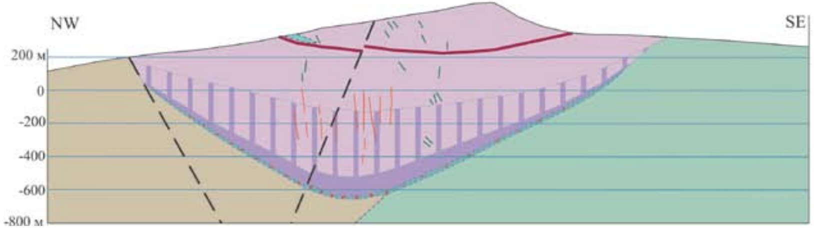
Distribution geology and Pt, Pd, Au+Rh, Ni and Cu grades across the Lower Layered Horizon in the West Pana Massif, core hole P-13.

Interim / Transitional Type (I ÷ II → both PGE ores and Cu-Ni ores)

Sopcha intrusion (Monchepluton), Monchegorsk region



Section 1-1



LEGEND

Sopcha

a, b, c, d — Quartz-porphyry; (a), "330 level" - sulphide ore (b), disseminated sulphides in "bottom" level (c), gabbro-norite (d)

Ortho-pyroxenite

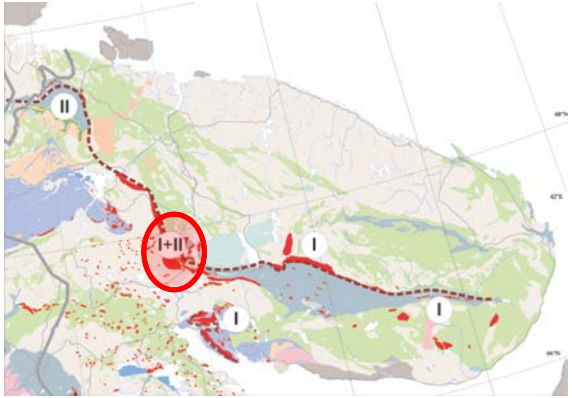
Nud

Norite and plagio-pyroxenite

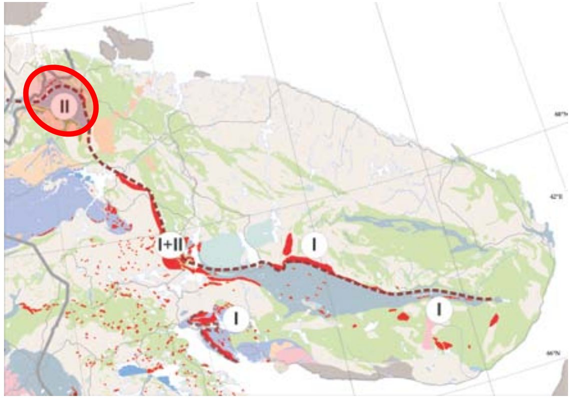
South Sopcha

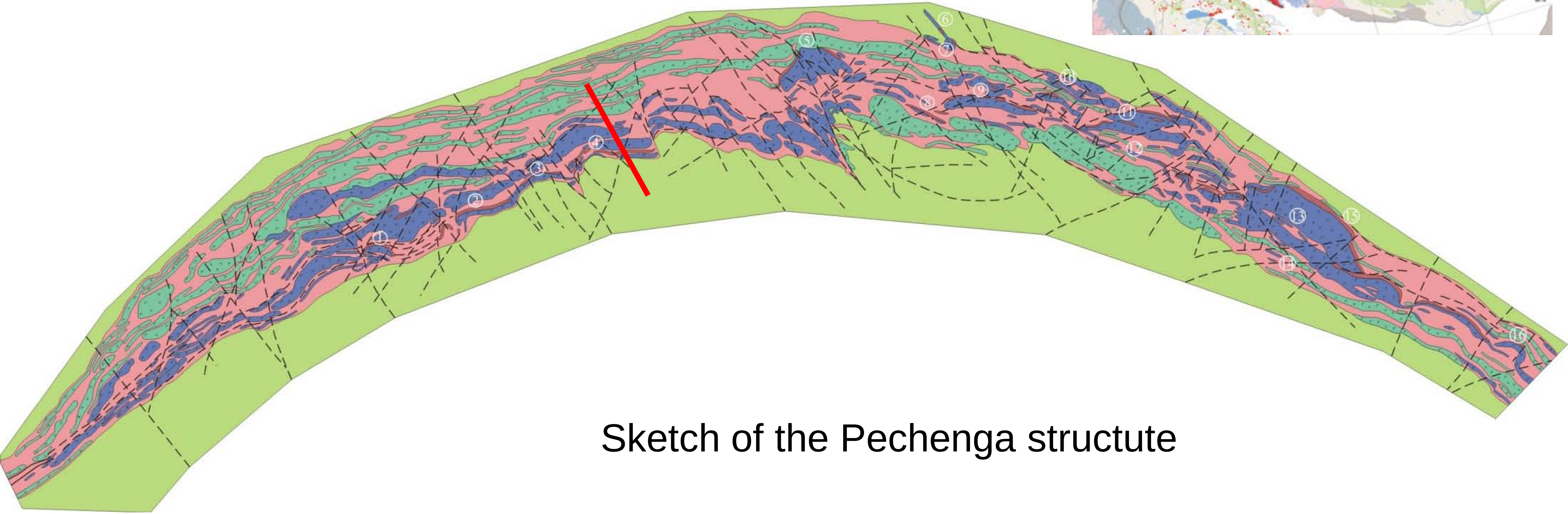
Metanorite, metaplagio-pyroxenite, metagabbro, metagabbro-norite

Quartz-diorite



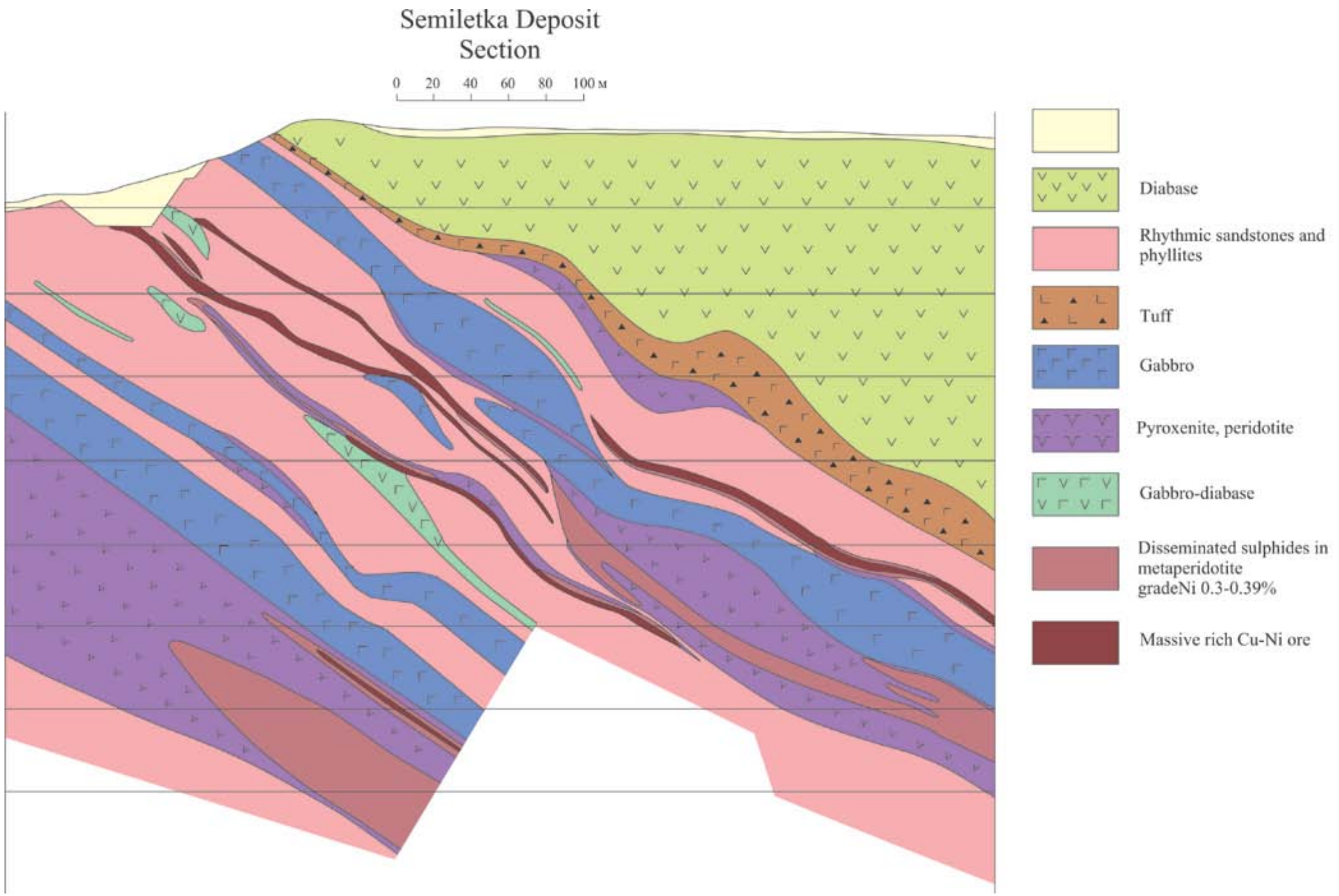
Intrusions with the rich sulfide Ni-Cu ore
(with Co, S, PGM, Se, Te, etc.)





Sketch of the Pechenga structute

Intrusions with the rich sulfide Ni-Cu ore
(with Co, S, PGM, Se, Te, etc.)



CONCLUSION

PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

The PGE-bearing mafic-ultramafic layered intrusions are associated with the first complex. They have been formed at an initial (pre-rift) stage of LIP. Features of origin of this complex are: 1) large-scale, protracted, and multiple episodes of deep mantle plume or asthenosphere upwelling; 2) the vast non-subduction-type basaltic magma in an intraplate continental setting; 3) low-sulfide Pt-Pd (with Ni, Cu, Au, Co and Rh) mineralization in different geological setting (reef- and contact type etc.); 4) anomalously high concentrations of PGEs in the bulk sulfides, inferred platinum distribution coefficient between silicate and sulfide melts of >100000. Deep mantle magma source is enriched in ore components (fertile source) and lithophile elements. It is reflected in the isotope indicators such as εNd(T) from -1 to -3, ISr(87Sr/86Sr) from 0.702 to 0.704, 3/4 = (10^-5 10^-6). Magma and ore sources differ from those of Mid-Ocean Ridge basalts (MORB), subduction-related magma but are similar to EM-I. Ore-bearing mafic complexes formed during a long period of time and by different episodes (2490±10 Ma; 2470±10 Ma; 2450±10 Ma; 2400±10 Ma), and by mixing between the boninitic an anorthositic magmas. It is known about 10 deposits and occurrences in Kola region with total reserves and resources about 2000 tons in palladium equivalent (with an average content 2-3 ppm).

Intrusions with the rich sulfide
Ni-Cu ore (with Co, S, PGM, Se, Te, etc.)

Intrusions with the rich sulfide Ni-Cu ore (with Co and poor PGE) are associated with the second mafic complex. Ore-controlling mafic-ultramafic intrusions are formed at a final stage of the intracontinental rifting of the Transitional period (2200-1980 Ma). Initial magma is depleted and similar to the MORB in terms of rare earths distribution. Enriched ferropicritic Fe-Ti derivatives of magma generate single volcano-plutonic rock series. For intrusive ore bodies rock differentiation with the formation of syngenetic wehrlite-clinopyroxenite-gabbroorthoclase gabbro sequence is typical. Upper mantle source of the depleted magma is characterized by the following isotope indicators: εNd(T) +0.5 to +4, ISr= 87Sr/86Sr 0.703-0.704. Ore-bearing intrusive bodies are injected in the upper part of the Early Palaeoproterozoic volcano-sedimentary cross-section. Ores are located in the basement of intrusions and in the redeposited veined bodies, including offset setting. Numerous Ni-Cu deposits with total reserves and resources of several million tons of Nickel equivalent (with an average grade 0,3%) have been explored, and some of them now is mining.

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THANK YOU FOR ATTENTION !