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

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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

Region of our investigations

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

Types distribution of the ore-bearing mafic complexes in the Kola Belt
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)**

<table>
<thead>
<tr>
<th>#</th>
<th>Search indicator type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>1.</td>
<td>Geophysics</td>
<td>Presence of the granite-mafic (anorthosite) 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.</td>
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<td>2.</td>
<td>Structure</td>
<td>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.</td>
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<td>3.</td>
<td>Geodynamic setting</td>
<td>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 enstic belts). Ore-controlling mafic-ultramafic intrusions form at an initial (pre-rift) stage of continental rifting.</td>
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<td>4.</td>
<td>Composition</td>
<td>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 sequences from ultramafic varieties to gabbroids. The ore is confined to the most contrasting series of alternating thin rock layers differing in composition from leucoxene and mesocratic gabbro to norite, anorthosite, plagiopyroxenite, inequigranular and inhomogeneous textures (e.g., ventxsted 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 liqating silicate and sulphide melts of ≥100000.</td>
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<td>5.</td>
<td>Isotope geochemistry</td>
<td>Deep mantle magma source initially is enriched with ore components (fertile source) and lithophile elements. It is reflected in such isotope indicators as δNd(T) @ -1 to -3, εNd@t=2470±10 - 705, εHf = εHf+n(10^-10) where n denotes a natural number of 1 to 9. Upper mantle source of the depleted magma with isotope indicators: δNd(T) @ +0.5 to +4, εNd = εNd at 87Sr/86Sr @ 0.703-0.704, δ18O/δ18O @ 0.935±0.03 (single measurement).</td>
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<td>6.</td>
<td>Geochronology</td>
<td>Intrusions with the rich sulfide Ni-Cu ore (with Co, S, PGM, Se, Te, etc.)</td>
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<td>7.</td>
<td>Metamorphism</td>
<td>Collision metamorphism results in the formation of redeposited (remobilized) ore bodies both inside ore-bearing bodies and offset settings.</td>
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</table>
PGE-bearing mafic-ultramafic layered intrusions
Pt-Pd (with Ni, Cu, Au, Co and Rh)

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

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

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

After Markku Iljina, 1994
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)

The biggest European PGE deposit FEDOROVA
Typical Fedorova Section

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

Contact Type

gneisses
gabbro-norite
gabbro
pyroxenite
Amphibolite

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

Reef Type

Northeast-to-Southwest crossection of the Lower Layered Horizon in the West Pana Massif, through drill hole P-13, looking West
Interim / Transitional Type ($I \div II \rightarrow$ both PGE ores and Cu-Ni ores)

Sopcha intrusion (Monchepluton), Monchegorsk region
Intrusions with the rich sulfide Ni-Cu ore
(with Co, S, PGM, Se, Te, etc.)

Sketch of the Pechenga structure
Intrusions with the rich sulfide Ni-Cu ore
(with Co, S, PGM, Se, Te, etc.)
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 $\varepsilon_{\text{Nd}}(T)$ from -1 to -3, ISr($87\text{Sr}/86\text{Sr}$) from 0.702 to 0.704, $3/4 = (10^{-5} \text{ to } 10^{-6})$. 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 ($2490 \pm 10 \text{ Ma}; 2470 \pm 10 \text{ Ma}; 2450 \pm 10 \text{ Ma}; 2400 \pm 10 \text{ Ma}$), 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 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: $\varepsilon_{\text{Nd}}(T)$ +0.5 to +4, ISr=$87\text{Sr}/86\text{Sr}$ 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.
THANK YOU FOR ATTENTION!