Geologian tutkimuskeskus, Opas - Geological Survey of Finland, Guide 45

Research and exploration - where do they meet?

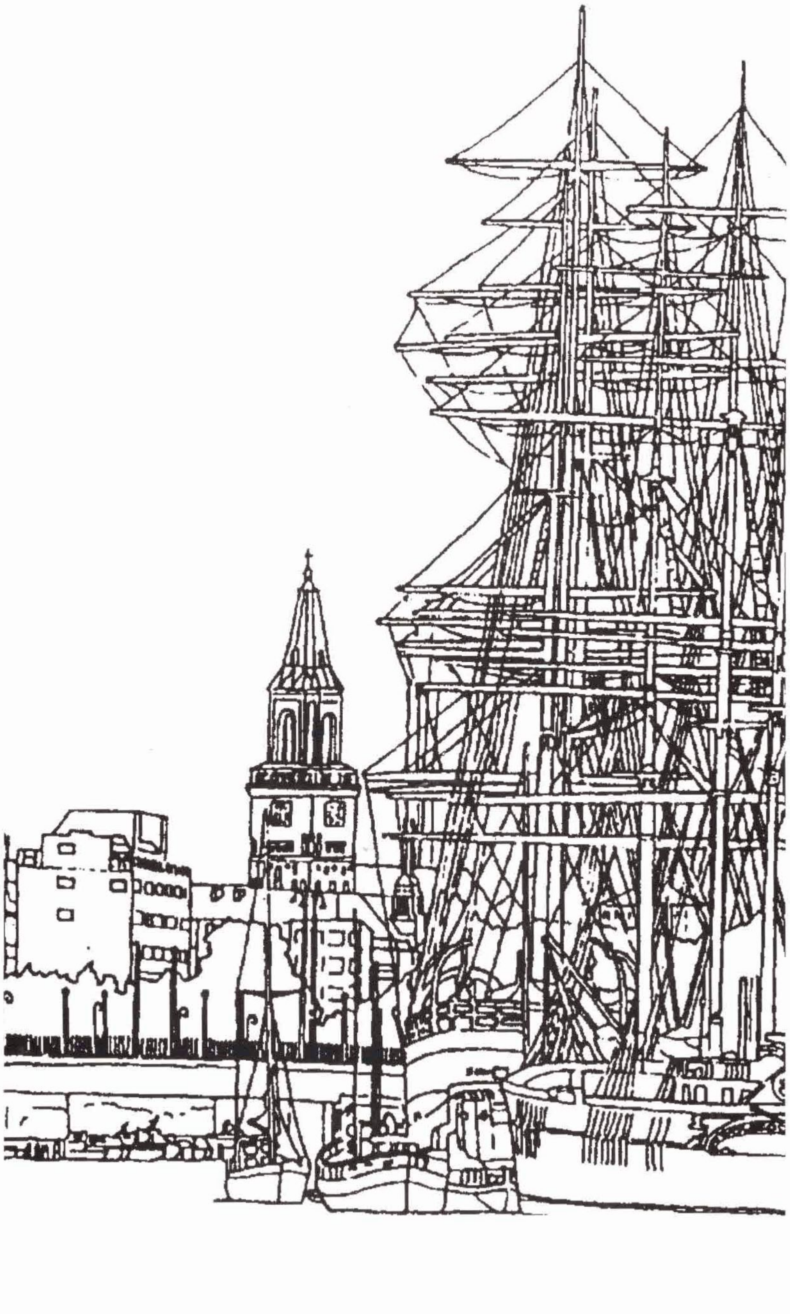
4th Biennial SGA Meeting

August 11-13, 1997, Turku, Finland

Excursion Guidebook

B4
Ore Deposits in the Kola Peninsula, Northwestern Russia

edited by Felix Mitrofanov, Mikhail Torokhov and Markku Iljina



Society for Geology Applied to Mineral Deposits

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ORE DEPOSITS OF THE KOLA PENINSULA, NORTHWESTERN RUSSIA

edited by Felix Mitrofanov, Mikhail Torokhov and Markku Iljina

Espoo 1997

Mitrofanov, F., Torokhov, M. & Iljina, M. (eds.) 1997. Ore deposits of the Kola Peninsula, Northwestern Russia. Research and exploration — where do they meet? 4th Biennial SGA Meeting, August 11–13, 1997, Turku, Finland, excursion guidebook B4. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 45 pages, 18 figures and 5 tables.

The guidebook "Ore deposits of the Kola Peninsula, NW Russia", has been prepared for the field trip to be held as part of the 4th Biennial SGA Meeting. The principal aim is to describe the best-known and the most easily accessible deposits of the Kola Peninsula, those that are currently being exploited or are subject to feasibility studies. Recent research results regarding the geology, metal concentrations and mineral reserves are given for the Pechenga Cu-Ni ore field, the banded iron formation of the Olenegorsk region, the Cu-Ni-PGE ores of the Monchegorsk region, the chromite ores of the Imandra Complex, and the apatite ores of the Khibiny alkaline massif. The guidebook also contains descriptions of the localities to be visited. A list of selected references is given after each chapter.

Excursion held on: August 13–20, 1997

Key words (GeoRef Thesaurus, AGI): metal ores, copper ores, nickel ores, iron formations, platinum ores, chromite ores, layered intrusions, phosphate deposits, Precambrian, field trips, guidebook, Pechenga, Olenogorsk, Monchegorsk, Imandra, Khibiny, Kola Peninsula, Russian Federation

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ISBN 951-690-681-8
ISSN 0781-643X

Mitrofanov, F., Torokhov, M. & Iljina, M. (toim.) 1997. Ore deposits of the Kola Peninsula, Northwestern Russia. Research and exploration — where do they meet? 4th Biennial SGA Meeting, August 11–13, 1997, Turku, Finland, excursion guidebook B4. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 45 sivua, 18 kuvaa ja 5 taulukkoa.

Kuolan niemimaa on eräs tärkeimmistä vuoriteollisuusalueista Venäjällä. Se tuottaa merkittävän osan Venäjän tarvitsemasta fosforista, nikkelistä, kuparista, raudasta, alumiinista, harvinaisista maametalleista ja kiilteestä. Tällä hetkellä aktiivinen malminetsintä kohdistuu platinametalleihin, titaaniin, molybdeeniin, zirkoniin, scandiumiin, hopeaan, vanadiiniin, kromiin, kultaan ja timantteihin. Tätä etsintätyötä tekevät sekä venäläiset että ulkomaiset yhtiöt venäläisten yhteistyökumppaneiden kanssa.

Tässä ekskursio-oppaassa kuvataan lyhyesti Petsamon kuuluisan nikkelimalmikentän, Olenegorskin alueen raitaisten rautamuodostumien, Monchegorskin ja Imandran kerrosintruusioiden sekä Hiipinän alkali-intruusion geologiset pääpiirteet, metallogenia ja mineralogia viidessä erillisessä kirjoituksessa. Mainituilla kohteilla on kaivostoimintaa ja eräissä on lisäksi käynnissä aktiivinen malminetsintä sekä hyväksikäyttötutkimuksia.

Ekskursioaika: 13–20. elokuuta 1997

Avainsanat (Fingeo-sanasto, GTK): metallimalmit, kuparimalmit, nikkelimalmit, rautamuodostumat, platinamalmit, kromimalmit, kerrosintruusiot, fosfaattiesiintymät, prekambri, ekskursiot, oppaat, Petsamo, Olenogorsk, Monchegorsk, Imandra, Khibiny, Kuolan niemimaa, Venäjä

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CONTENTS

PREFACE

The Kola Region, which administratively belongs to the Murmansk Oblast' of the Russian Federation, is a large industrial centre producing apatite, nickel, copper and cobalt, and a mining area for iron, aluminum, titanium, zirconium, rare-earth elements, other rare metals, and dimension stone. It is a high potential region for gold, PGE, chromite, titanium, vanadium, molybdenum, zirconium and kyanite (given the necessary exploration).

The principal aim of the field trip is to introduce participants to the geology and ores of the currently operating underground mines and open pits, i.e. the copper-nickel ores worked by Pechenganickel and Severonickel, the iron ores of OAO "OLKON" and the apatite and nepheline ores of AO "Apatit". Economic geologists in the Kola Region are at present concentrating their efforts on mineralization types that are not yet being exploited, especially the low-sulphide PGE and Cr deposits. The present situation therefore offers a rewarding background for a post-symposium excursion under the initial motto of the 4th Biennial SGA Meeting "Research and Exploration — where do they meet?".

An information package giving more detailed descriptions of the general geology of the Kola Peninsula and related mineralizations will be provided separately. This will include the works "Kola Belt of Layered Intrusions" (eds. F. Mitrofanov & M. Torokhov, 1994) and "Geology of the Kola Peninsula" (ed. F. P. Mitrofanov, 1995) and a map to a scale of 1 : 1 500 000.

Felix P. Mitrofanov

ITENERARY

Wednesday 13.8., DEPARTURE FROM TURKU

Bus collects participants from hotels, transports them to Turku train station. Train to Rovaniemi leaves 19:37 pm

Thursday 14.8., DRIVE TO PECHENGA, RUSSIA

Arrive Rovaniemi 7:42 am
Board bus and begin drive to Pechenga, breakfast in Rovaniemi, lunch enroute
Overnight in the Hotel Pechenga, Zapolyarny

Friday 15.8., PECHENGA NICKEL ORES

Stop 1. Kola Super-Deep Drillhole (SD-3)
Stop 2.
Stop 3.
Stop 4.
Overnight in the Hotel Russ on the shore of Lake Imandra (12 km from town Apatity)

Saturday 16.8., BANDED IRON FORMATIONS

Stop 1.
Stop 2. Pechegubsk deposit
Overnight in the Hotel Russ

Sunday 17.8., MONCHEGORSK LAYERED COMPLEX

Stop 1. Ultramafic cumulates, NKT, Mt. Kumuzhja
Stop 2.
Stop 3. Critical Horizon and Terrasa deposit, Mt. Nyud
Overnight in the Hotel Russ

Monday 18.8., IMANDRA LAYERED COMPLEX

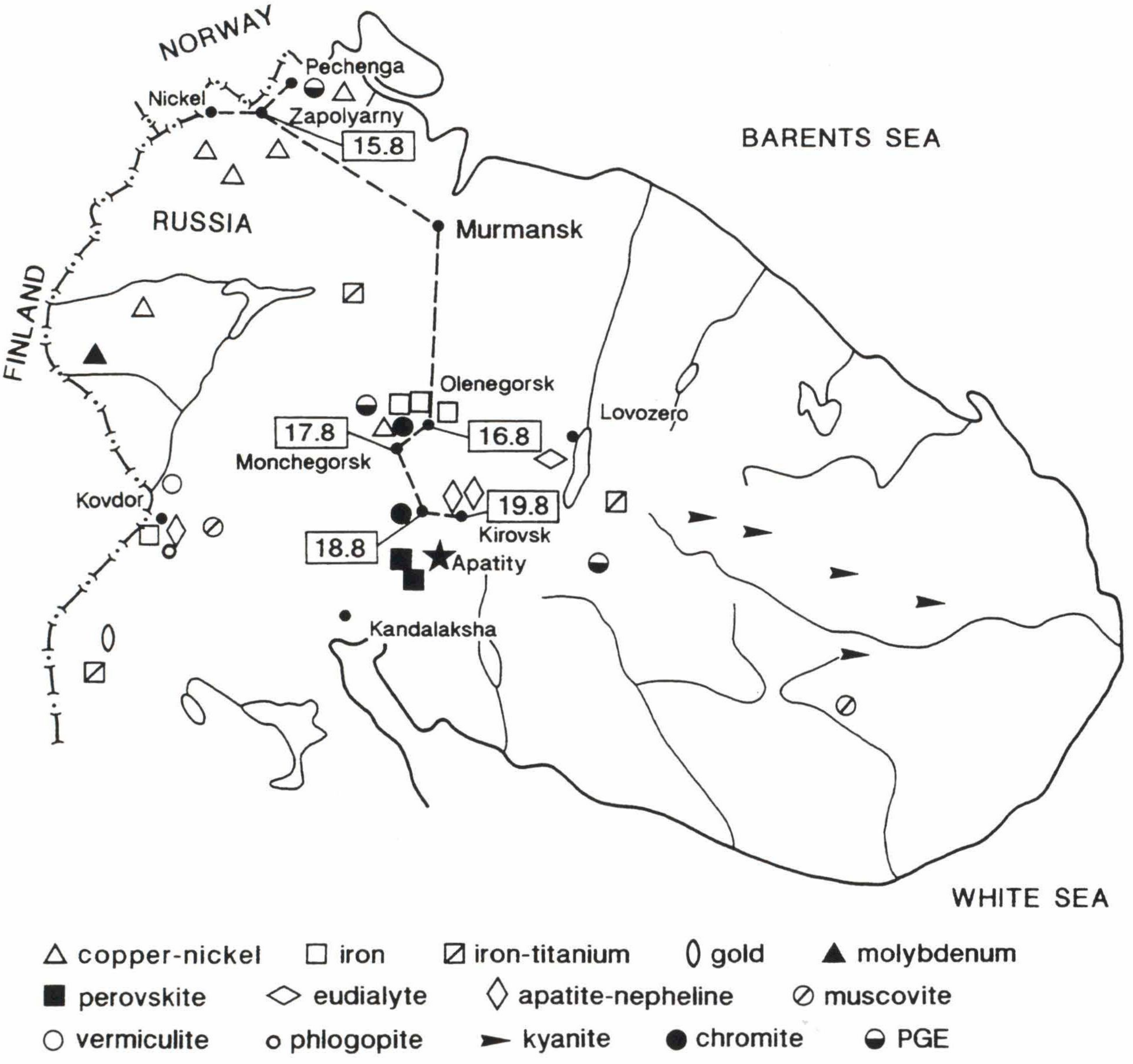
Stop 1. Marginal Zone and Lower Layered Zone
Stop 2. Bolshaya Varaka chromite deposit
Overnight in the Hotel Russ

Tuesday 19.8., KHIBINY ALKALINE INTRUSION

Stop 1.
Stop 2. 45
Overnight in the Hotel Pechenga, Zapolyarny

Wednesday 20.8., DRIVE TO ROVANIEMI

Arrive Rovaniemi approximately 9:00 pm
End of excursion



Route Map showing the main mineral deposits of the Kola Peninsula. 1 — copper-nickel; 2 — iron; 3 — iron-titanium; 4 — gold; 5 — molybdenum; 6 — perovskite; 7 — eudialyte; 8 — apatite-nepheline; 9 — muscovite; 10 — vermiculite; 11 — phlogopite; 12 — kyanite; 13 — chromite; 14 — PGE.

Ore deposits of the Kola Peninsula, NW Russia
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Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 11–17, 1997.

SULPHIDE Cu-Ni DEPOSITS OF THE PECHENGA ORE FIELD

by
V. F. Smolkin, Yu. N. Yakovlev and St. V. Sokolov

Smolkin, V. F., Yakovlev, Yu. N. & Sokolov, St. V. 1997. Sulphide Cu-Ni deposits of the Pechenga ore field. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 11–17, 4 figures and one table.

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GENERAL GEOLOGY

The Pechenga structure occupies an area of over 2000 km^2. It is divided by the Poritash fault into two major tectonic-lithological units called the Northern Pechenga and Southern Pechenga Zones (Fig. 1).

The Northern Pechenga Zone forms a monocline structure with transverse and diagonal faults, of which some are synsedimentary. The largest composite strike-slip and reverse faults dip to the south at 30–35° to 50–55°. Seismic studies have shown that the dip becomes gradually less steep with depth. The depositional evolution of the Northern Pechenga Zone took place over a long time period of about 500 Ma as a result of recurrent sedimentary-volcanic cycles totalling 8.5 km in thickness (Kozlovsky, 1987; Mitrofanov and Smolkin, 1995; Smolkin et al., 1996; Melezhik, 1996). Four major cycles have been distinguished, each of which begins with metasedimentary rocks and ends with a thicker pile of volcanic rocks. They were deposited 2.4 to 1.9 Ga ago, and hence are assigned to the Early Karelian Complex. The ore-bearing intrusions are primarily found in the sedimentary part of the uppermost cycle.

The Southern Pechenga Zone consists of highly metamorphosed rocks, some of which can be correlated with the volcanic rocks of the upper part of the Northern Zone, whereas others make up several sequences belonging to the Late Karelian Complex, as evidenced by the available age determinations, yielding ages of about 1.85 Ga (Balashov, 1996). The estimated total thickness of the Southern Zone rocks is 3.0–3.5 km.

The ore-bearing gabbro-wehrlite intrusions, which are common in the central part of the Northern

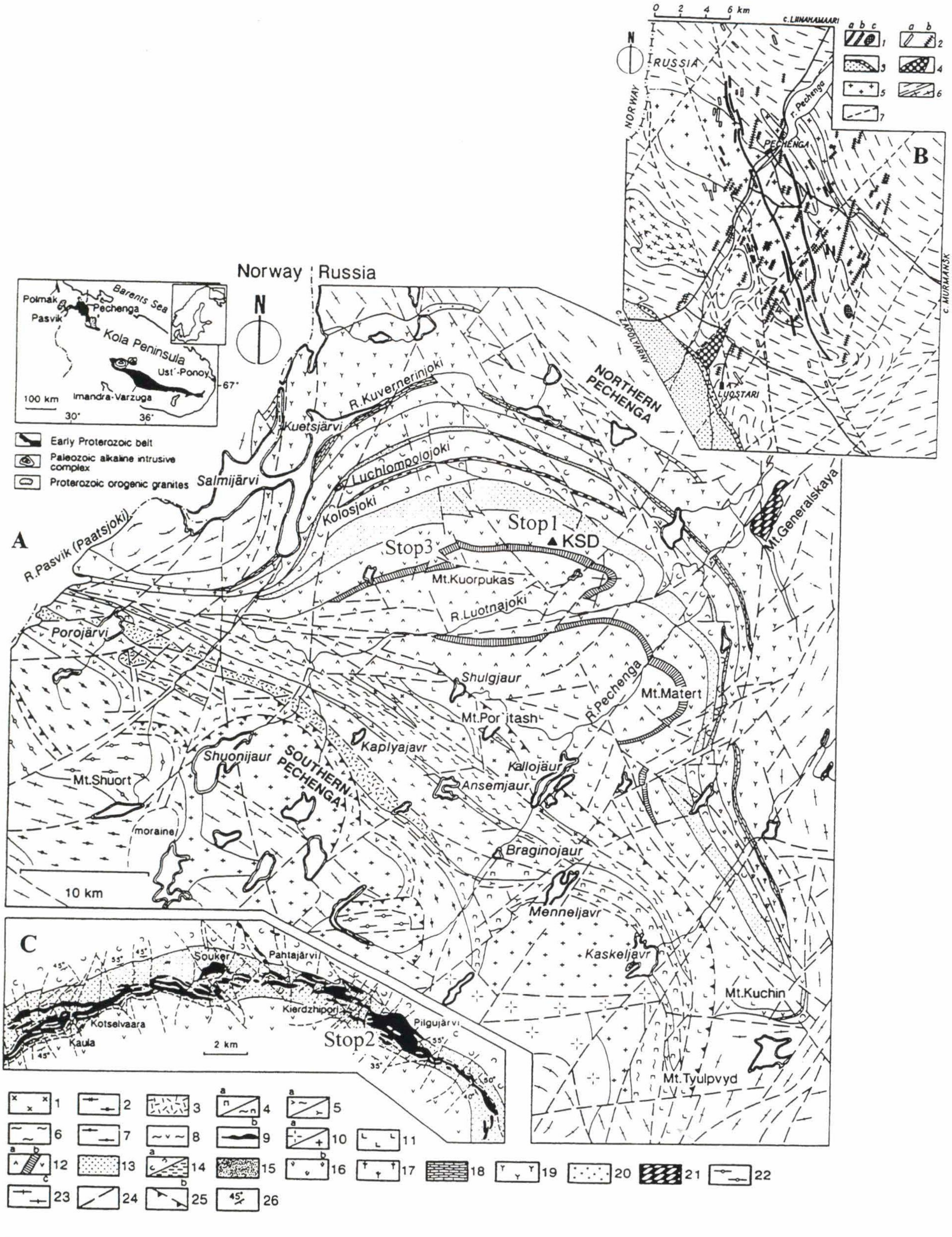

Fig. 1. Geological sketch map of the Pechenga structure (A) and northern margins (B) and the Pechenga ore field (C).
A) and C) 1 — dacite and rhyolite, the Poritash subvolcanic complex; 2 — tuff conglomerate, gravelstone and sandstone, the Kassesjoki Fm; 3 — andesite, dacite and rhyolite, the Kaplya Fm; 4 — picrite, basalt, tuff and sandstone, the Mennel Fm (a), and schistose amphibolite after picrite and basalt (b); 5 — basalt (a), andesite-basalt, andesite, tuff and sandstone (b), the Bragino Fm; 6 — sandstone, siltstone, tuff and silicite, the Kallojaur Fm;7 — biotite, two-mica and garnet-mica gneiss, the Talya Fm; 8 — schistose amphibolite of uncertain stratigraphic position; 9 — serpentinite, wehrlite, clinopyroxenite and gabbro, the Ni-bearing intrusive complex; 10 — diorite and granodiorite (a), and granite and quartz granite (b), the Kaskeljavr complex; 11 — basalt, the Suppvaara Fm; 12 — tholeiitic basalt, ferropicrite, tuff (a), siliceous schist (b), and predominantly tholeiitic basalt (c), the Matert Fm; 13 — picritic tuff of the Lammas Fm and sandstone, siltstone, sulphide-carbonaceous schist of the Zdanov Fm; 14 — tholeiitic basalt (a) and schist (b), the Zapolyarny Fm; 15 — sandstone, gravelstone and dolomite, the Luchlompolo Fm; 16 — basalt and trachybasalt, the Orshoaivi Fm; 17 — trachybasalt, trachyandesite-basalt, trachyandesite-dacite and trachyte, the Pirttijärvi Fm; 18 — quartzite and

Zone, constitute a comagmatic volcanic-plutonic association together with ferropicrite metavolcanites of the Matert Formation and the kaersutite-peridotite-olivine gabbro dike swarm of Nyasyukka. The association was formed during the maximum opening of the rift system 1980–1960 Ma ago, in the course of several tectonic impulses accompanied by the rise of a highly magnesian and Fe-rich magmatic melt. The intrusive origin of the gabbro-wehrlite bodies is confirmed by intrusive contacts with the host rocks, characteristic igneous textures and the presence of xenoliths of host rocks altered to hornfels. As indicated by the S and Pb isotope compositions, processes of assimilation and contamination of the sialic crustal material enriched in sulphur, uranium, phosphorus and other incompatible elements played a significant role when the magmatic melt was rising to the upper crustal levels.

The Pechenga structure contains over 300 intrusive bodies representing a gabbro-wehrlite association. These are concentrated mostly in the Zdanov and Lammas tuffaceous-sedimentary formations, and also occur in the underlying volcanic rocks of the Zapolyarny Formation. The intrusions are predominantly sub-concordant or phacolithic bodies with pinches and swells and with no observed feeder channels, and occur in groups concentrated at several levels. Most of the intrusions have been broken into blocks with an *en echelon* configuration. Less often there are cutting bodies confined to diagonal fault systems.

The intrusions display various degrees of differentiation and different internal structures and mineralization grades. This diversity is attributable to several factors, including varied timing of the differentiation processes of the parental melt in deep-seated magma reservoirs, transporting channels and magma chambers. The intrusions can be subdivided into poorly differentiated, chamber-differentiated and deep-differentiated types. The bodies composed of olivine-bearing and olivine-free clinopyroxenites belong to the first group. These do not exceed 10–15 m in thickness, are most commonly boudinaged and occur in separate fragments. The chamber-differentiated type makes up 22% of all the intrusions. They range in thickness from 15 to 600 m, being most commonly 25 to 100 m, and in length from 100 to 3000 m along the strike. Large chamber-differentiated intrusions contain the following range of rocks: pyroxene olivinite — wehrlite — olivine clinopyroxenite — clinopyroxenite — gabbro — orthoclase gabbro — diorite, while smaller intrusions consist of olivine clinopyroxenite, clinopyroxenite and gabbro. Macrorhythmic layering with two-member rhythms can be observed in the largest intrusions. The deep-differentiated intrusions include peridotite or gabbroic bodies of thicknesses less than 200 m.

The near-contact parts of some intrusions feature remnants of chilled zones which were originally composed of fine-grained clinopyroxenite and olivine clinopyroxenite and are now represented by chlorite-actinolite schists with occasional relicts of clinopyroxene. Compositionally, the chilled margins of the intrusions are similar to those of layered volcanic ferropicrite flows, the most notable difference being the content of ore elements. The wall rocks at the contacts have been altered to various hornfelses, adinoles and spilosites, with a total thickness of no more than 10–15 m.

The ore-bearing intrusions cut through volcanic sheets of the Zapolyarny Formation, tuffaceous-sedimentary schists of the Zdanov and Lammas Formations and sills of ophitic gabbro (or gabbro-diabase), and are in turn cut by dolerite and picrodolerite dikes compositionally similar to the mafic volcanic rocks of the overlying Matert Formation.

An age of 1970±70 Ma was obtained for the gabbro-wehrlite intrusions (whole rock, apatite) by the Pb-Pb method, and the following ages for individual bodies: Pilgujärvi — 1980±150 Ma, Kierzhipori — 1960±66 Ma, North-Kaula — Kotselvaara — 1900±55 Ma. The age of the Pilgujärvi intrusion was confirmed by the Rb-Sr method, which yielded an age of 1960±120 Ma (whole rock, clinopyroxene, apatite) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7029 (Mitrofanov and Smolkin, 1995). The Sm-Nd age of the layered ferropicrite

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dolomite, the Kuvernerinjoki Fm; 19 — andesite-basalt and dacite, the Majärvi Fm; 20 — basal conglomerate, gravelstone and sandstone, the Televi Fm; 21 — gabbronorite, the layered intrusion of Mt.Generalskaya; 22 — alumina gneiss and 23 — gneiss, amphibolite and migmatite of the Archaean basement; 24 — faults, 25 — thrusts; 26 — strike and dip. KSD-3 — Kola Superdeep Drillhole.

B) 1 — plagioclase-bearing kaersutite peridotite (a), olivine gabbro (b) and olivine pyroxenite (d), the Nyasyukka dyke complex; 2 — dolerite (a) and quartz dolerite (b); 3 — basal conglomerate and volcanic rocks, the Karelian complex; 4 — gabbronorite, Mt. Generalskaya; 5 — plagiomicrocline granite; 6 — amphibolite, gneiss and high-alumina schists (a) and anatectite-granite (b) of the Upper Archaean.

flows was 1980±40 Ma (whole rock, clinopyroxene) and the initial ^{143}Nd/^{144}Nd ratio 0.510148, corresponding to ε_{Nd} of +1.5±0.4 (Hanski et al., 1990). Similar results have been obtained by the Re-Os method: 1970±45 Ma, ^{187}Os/^{186}Os=0.935 (Walker et al., 1994).

The intrusions containing economic sulphide ores form the Western (Kaula — Ortoaivi) and Eastern (Kierdzhipori — Onki) ore clusters. The ore bodies are mostly tabular and lenticular, with veins occurring more rarely. Many bodies have complicated shapes as a result of splitting of the host intrusion and longitudinal and transverse movements along syn-ore and post-ore brittle faults. The ore bodies vary greatly in size, from 0.2 to 100 m in thickness and from 5 to 1500 m in length along the strike, depending on the thickness of the parental intrusions and the characteristics of the tectonic zones. High-grade ore deposits may occur in relatively thin bodies, however. Sulphide mineralizations can penetrate the surrounding rock by lit-par-lit injections and form veins up to a few metres thick.

The sulphide ores are subdivided into disseminated, densely disseminated, brecciated and massive types. The disseminated ores occur predominantly in the central and upper parts of the intrusions, whereas the densely disseminated ores occur near the bottom. The brecciated ores are confined to longitudinal tectonic zones along the footwall contacts, which were formed by a combination of reverse and strike-slip fault movements. The massive ores are spatially associated with the brecciated ones in most cases, but may form individual small-scale bodies. The Western ore cluster contains deposits of mostly massive and brecciated ores, while the Eastern one contains predominately disseminated ores. The ores are composed of an assemblage of pyrrhotite, pentlandite, chalcopyrite and magnetite, with some bornite, mackinawite, violarite, cubanite, sphalerite, galenite and PGM also present (Distler et al., 1990).

The Ni content of the ores is variable, being highest (10–12%) in the massive and brecciated ores, less than 6% in the densely disseminated ores and no more than 1.5% in the low-grade disseminated ones. Apart from Ni, the ores contain significant amounts of Cu and Co, but platinum-group elements are not abundant.

FIELD TRIP

The one-day excursion includes visits to 1) the Kola Superdeep Drill-hole (SD-3), which intersects the sedimentary-volcanic Karelian Complex of the Northern Pechenga Zone (0–7000m) and its Archaean basement (7000–12 256 m), 2) the Pilgujärvi intrusion, which is the largest intrusive body in the Pechenga ore field and contains the ore bodies of the Zdanov deposit, and 3) outcrops of ferropicrite lava flows, which are comagmatic with the ore-bearing intrusive rocks.

Stop 1 — The Kola Superdeep Drill-hole (depth 12 256 m)

9 km south-west of Zapolyarny at 20°10'E 69°25'N (Fig. 1).

The Kola Superdeep Drill-hole (SD-3) is located in the central part of the Northern Pechenga Zone. It intersected Paleoproterozoic (depth interval 0.00–6.84 km) and Archaean (6.84–12.25 km) rock complexes, which contain ore occurrences compositionally similar to the known deposits and ore occurrences located at or near the surface (0.0–1.0 km).

The drilling of SD-3 was implemented to solve a number of questions, one of them being the depth of the Pechenga ores. This task was successfully accomplished. In the course of drilling, the position of the productive layer deep below the surface was established, the main features of the structure of the ore field were ascertained, and several intrusions containing economic nickel-copper mineralizations were discovered. These ore bodies are located at a new, higher stratigraphic level in the productive layer, which means that the potential ore field has been expanded considerably. The geological survey conducted by the Pechenganickel Works has identified and explored several sulphide copper-nickel deposits.

Almost all types of mineralization known in the region have been found in the early Proterozoic and Archaean rock complexes intersected by SD-3 (Fig. 2.). In addition, new occurrences of rare and noble metals have been found at great depths (over 8–9 km).

The presence of ore mineralization throughout the 12-km deep section had not been expected, as it was common to think that all ore-forming processes wane below 5 km because of the lack of open fractures serving as circulation paths for ore-bearing solutions. The rocks at great depths have zones of fracturing, decompaction and tectonic deformations, however, which are locally accompanied by an influx of mineralizing waters. Thus it is possible that the ore mineralization may extend even deeper than the final depth attained by SD-3.

The first evidence for ore mineralization in the rocks of the SD-3 section was presented by Kozlovsly (1987) in his monograph. In the late 1980's gold mineralization was found in the gneiss and amphibolite of the Archaean complex, and later platinum-group metals were discovered in the amphibolites. Descriptions of the ore mineralization in rocks of the Archaean complex are provided by Mitrofanov et al. (1990) and Mitrofanov (1991).

More than 40 ore minerals including native elements and alloys (11 species), sulphides and their analogues (22), oxides (8) and silicates (2) has been identified in the SD-3 section (Table 1). Among a number of observations on the mineralogy published elsewhere one curious one deserves mention here: the composition of certain minerals appears to be depth-dependent.

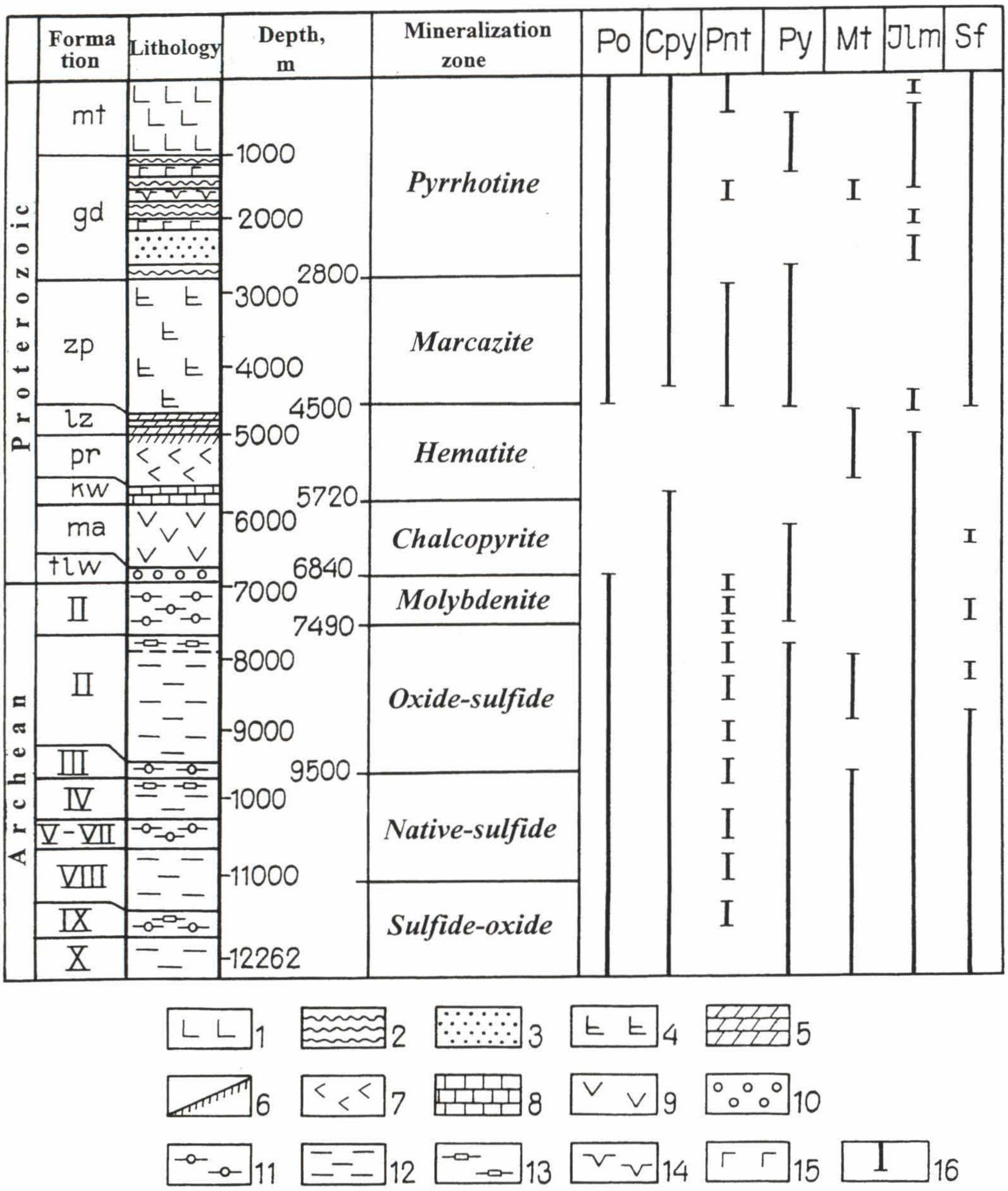

Fig. 2. Mineralization zones in the SD-3 section. 1 — ferropicrite; 2 — siltstone, sandstone, phyllite; 3 — arkosic sandstone; 4 — actinolitized tholeiite basalt; 5 — dolomite, sandstone; 6 — sericite schist; 7 — trachybasalt; 8 — dolomite, arkosic sandstone; 9 — meta-andesite-basalt with interbeds of picrite; 10 — polymict conglomerate, gravelstone, sandstone; 11 — biotite-plagioclase gneiss containing high-alumina minerals; 12 — biotite-plagioclase gneiss containing high-calcium minerals; 13 — banded iron formation; 14 — serpentinite; 15 — gabbro, gabbro-diabase; 16 — ore minerals: Po — pyrrhotite, Cpy — chalcopyrite, Pnt — pentlandite, Py — pyrite, Mt — magnetite, Ilm — ilmenite, Sf — sphene. Proterozoic Formation: mt — Matert, gd — Zdanov, zp — Zapolyarny, lz — Luchlompolo, pr — Pirttijärvi, kw — Kuvernerinijok, ma — Majärvi, tlw — Televi. I — X — Archaean tectonic-lithological units.

For example, the incidence of impurities in the major sulphides increases considerably with depth yet solid solutions remain preserved. The oxides, on the other hand, "shed" their impurities and become almost stoichiometric in composition.

Table 1. Ore mineralization in the SD-3 section.

Proterozoic complex		Archaean complex	
mineral	formula	mineral	formula
MAJOR:		MAJOR:	
pyrrhotite, hexagonal	$Fe_{11}S_{12}$	gold	Au
pyrrhotite, monoclinal	Fe_7S_8	electrum	(Au,Ag)
pentlandite	$(Fe, Ni)_9S_8$	pyrrhotite, monocl.	Fe_7S_8
chalcopyrite	$CuFeS_2$	pyrrhotine, hexagon.	$Fe_{11}S_{12}$
pyrite	FeS_2	pentlandite	$(Fe,Ni)_9S_8$
magnetite	Fe_3O_4	chalcopyrite	$CuFeS_2$
ilmenite	$FeTiO_3$	pyrite	FeS_2
leucoxene	$TiO_2+FeTiO_3+SiO_2$	molybdenite	MoS_2
		magnetite	Fe_3O_4
		ilmenite	$FeTiO_3$
		sphene (titanite)	$CaTi[SiO_4]O$
MINOR AND RARE:		MINOR AND RARE:	
graphite	C	graphite	C
mackinawite	$Fe_{1+x}S$	iron	Fe
unnamed	AgS	copper	Cu
sphalerite	ZnS	zinc copper	(Cu, Zn)
galenite	PbS	silicon	Si
altaite	PbTe	cadmium	Cd
unnamed	AgTe	tin	Sn
argentopentlandite	$Ag(Fe,Ni)_8S_8$	unnamed	(Cu,Zn,Ni,Co)
bornite	Ce_5FeS_4	unnamed	(Pb_3Bi)
violarite	$FeNi_2S_4$	troilite	FeS
marcasite	FeS_2	argentopentlandite	$Ag(Fe,Ni)_8S_8$
molybdenite	MoS_2	sphalerite	ZnS
nickel cobaltine	(Co,Ni)AsS	galenite	PbS
danaite	(Fe,Co)AsS	millerite	NiS
titanomagnetite	$(Fe,Ti)_3O_4$	siegenite	$(Co,Ni)_3S_4$
chrome-spinel	$(Fe,Mg)(Cr,Al)_2O_4$	cubanite	$CuFe_2S_3$
titanium hematite	$(Fe,Ti)_2O_3$	bornite	Cu_5FeS_4
sphene (titanite)	$CaTi[SiO_4]O$	violarite	$FeNi_2S_4$
		marcasite	FeS_2
		titanomagnetite	$(Fe,Ti)_3O_4$
		chrome-spinel	$(Fe,Mg)(Cr,Al)_2O_4$
		hematite	$(Fe,Ti)_2O_3$
		rutile	TiO_2
		leucoxene	$TiO_2+FeTiO_3+Si_2$
		zircon	$Zr[SiO_4]$

Stop 2 — Ni-bearing Pilgujärvi gabbro-pyroxenite-wehrlite layered intrusion

Central and Western Ni-Cu mines at 30°45'E 69°23'N.

The Pilgujärvi intrusion is the largest in the Eastern ore cluster and occupies the central part of the cluster. The intrusion is not monolithic, but it is represented by a number of massifs that have complicated autonomous structures and are thrust one upon the other in a northeastern direction (Fig. 3).

The northern fragment, or Main Massif, is bowl-shaped in longitudinal section and sheet-like in cross-section. Having an average thickness of about 500 m, it extends for over 2200 m on the surface and down to 2 km along the dip. The contact of its footwall dips to the southwest at an angle of 45–55°. It is complicated by a thick mineralized zone of crushing and brecciation, the movement along which was a combination of transcurrent and reverse faults. The Massif is bordered in the northeast by a steeply dipping transcurrent fault with an offset extending more than 100 m and wedges out in the southeast to form a "tongue" filling a longitudinal northwest-dipping syncline fold. The Central and Eastern bodies of brecciated and disseminated ores are confined to the Main Massif. These bodies are being worked by the Central Mine.

The differentiated Upper Massif is situated further south. The South-Eastern Massif (together with the South-Eastern Ore Body) forms a smaller syncline deformed by reverse-slip and strike-slip faults. This massif is characterized by an alternation of intrusive rocks (serpentinite and gabbro) and tuffaceous-sedimentary schists that have been altered to hornfels. In addition, drill holes intersected two blind ore massifs that are thrust one upon the other, and upon the Upper Massif along a system of *en echelon* reverse faults. The blind ore massifs contain bodies of disseminated, nested-disseminated and brecciated ores (Bystrinskoye and Tayozhnoye).

The following zones (from bottom to top) can be distinguished in the composite section of the Main Massif, which contains the most complete range of rocks:

1. The lower marginal zone. Fine-grained and very fine-grained chlorite-actinolitized clinopyroxenite and olivine clinopyroxenite with a total thickness of 2 to 5 m. Below this is a footwall zone of hornfels represented by spilosite and adinole.

2. The peridotite (wehrlite-olivinite) zone. In the central part of the massif this zone is composed of serpentinized pyroxene olivinite and wehrlite together with serpentinite, while in its peripheral parts it consists of chlorite-serpentinized olivine pyroxenite. The average thickness of the zone is 135 m. Its thickest parts are confined to the hinges of syncline folds, and the thinnest parts occur in zones of transcurrent faults. The serpentinites contain hydrothermal-metasomatic veins composed of hydrogarnet-vesuvianite-diopside, diopside, serpentine (chrysotile, antigorite), chlorite-calcite and talc.

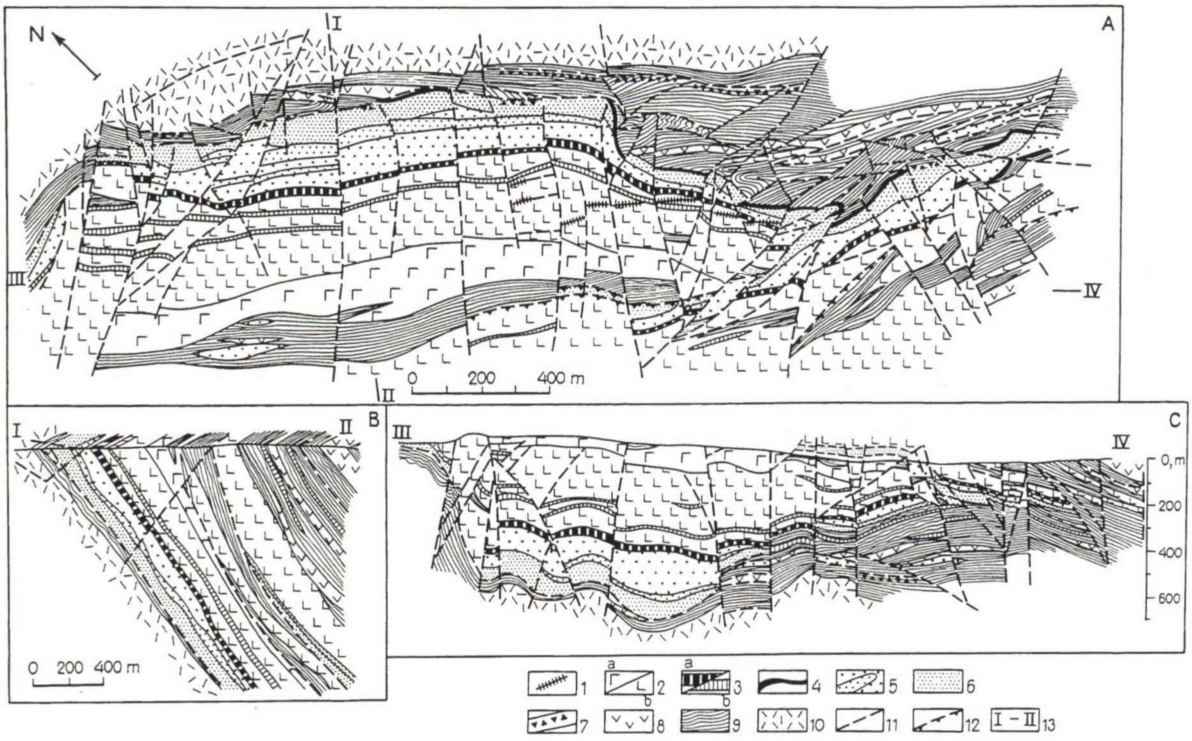

Fig. 3. Geological sketch map and cross-sections of the Pilgujärvi layered intrusion and the Cu-Ni ore deposits. 1 — dolerite dikes; 2 — pegmatoid and orthoclase gabbro (a), mesocratic and melanocratic gabbro (b); 3 — titanomagnetite olivinite, olivine-bearing pyroxenite and gabbro-pegmatite of the intermediate bed (a), plagiopyroxenite (b); 4 — schist and pyroxenite of chill zones; 5 — wehrlite and serpentinite with lenses of pyroxene olivinite; 6 — serpentinite with disseminated sulphide ore; 7 — brecciated sulphide ore; 8 — pillow and massive lavas of tholeiite basalt, the Matert Fm; 9 — schists, tuffites and hornfels, the Zdanov Fm; 10 — tholeiite-basalt lavas and tuffs, the Zapolyarny Fm; 11 — steeply dipping faults; 12 — reverse-slip faults; 13 — geological cross-sections.

3. An intermediate zone composed of (from bottom to top) actinolite-chloritized olivine pyroxenite (6.3 m), serpentinized titanomagnetite olivinite (4.7 m) and actinolitized titanomagnetite plagiopyroxenite with nests of gabbro-pegmatite and xenoliths of hornfels (3.0 m).

4. The gabbro-pyroxenite zone, average thickness 141 m.

5. The gabbro zone, average thickness 86 m.

   These two zones contain massive, banded and trachytoid saussuritized gabbro alternating with massive chlorite-amphibolized plagiopyroxenites, and nests and veins of plagioclasite.

6. The gabbro-pegmatite zone, average thickness 93 m. The lowermost part of this zone consists of massive coarse-grained gabbro, and the upper, apical zone of pegmatoid and orthoclase gabbro with hornfels microxenoliths.

7. The upper marginal zone is present locally. Reaching as much as 10 m in thickness, it consists of actinolitized fine-grained clinopyroxenite, albitized diorite and hornfels.

The boundaries between the zones can be sharp or gradual, and their orientation does not always coincide with that of the outer contacts of the massif. The observed banded and planparallel structures normally roughly follow the zone boundaries on the geological map, although their dip angles in cross-sections are more gentle. This situation may have arisen from the fact that the framing rocks wgre fairly mobile when the melt was emplaced, while the dip of the feeder channel was originally more gentle (10–15°).

Relics of magmatic minerals are represented by olivine (18.1–25.9% Fa; 0.11–0.36% CaO; 0.12–0.27% NiO), clinopyroxene — titanaugite (1.0–1.9% TiO_2, f=19–38%), kaersutite (5% TiO_2), plagioclase, orthoclase, and the accessory spinelides Ti-chromite — Cr-Ti-titanomagnetite — titanomagnetite (2.9–13.2% TiO_2), ilmenite and fluorapatite. The calculated crystallization temperatures are 1145°C for olivine (Häkli geothermometer), 960–940°C for clinopyroxenite in peridotite, and as much as 800°C for clinopyroxene in gabbro (Davis and Boyd geothermometer). The maximum pressure in the melt did not exceed 6–7 kbar.

The metamorphic paragenesis in metaperidotite is represented by serpentines (lizardite, chrysotile, antigorite), chlorite, actinolite, tremolite, talc, carbonates and magnetite, that in metapyroxenite, by actinolite, chlorite and leucoxene, and that in gabbro by albite, clinozoisite, actinolite, chlorite and leucoxene.

The rock-forming, ore and volatile components of the rocks of the Pilgujärvi intrusion are distributed unevenly. The lower part of the intrusion contains elevated amounts of MgO, Cr, Ni and in some instances FeO, while the intermediate bed is rich in TiO_2 and the upper part bears increased amounts of CaO, Al_2O_3, TiO_2, LREE and alkalis, owing to successive crystallization, the accumulation of chromite, olivine, titanomagnetite and clinopyroxene, and the flotation of early plagioclase. At the final stage, a residual feldspathic melt was pressed out and pegmatoid nests enriched in volatiles were formed simultaneously. The content of volatiles (P_2O_5, S) is noticeably increased in the lower and upper near-contact zones and in the bed of titanomagnetite olivinite. Some increase in platinum group elements (Pt, Pd) and Au is found not only in the sulphide beds but also below the intermediate zone. The sulphur in the rocks and ores of the Pilgujärvi intrusion is enriched in the heavy isotope (δ^{34}S from +2.7 to +5.4 ppm, average +4.2) relative to meteoritic sulphur.

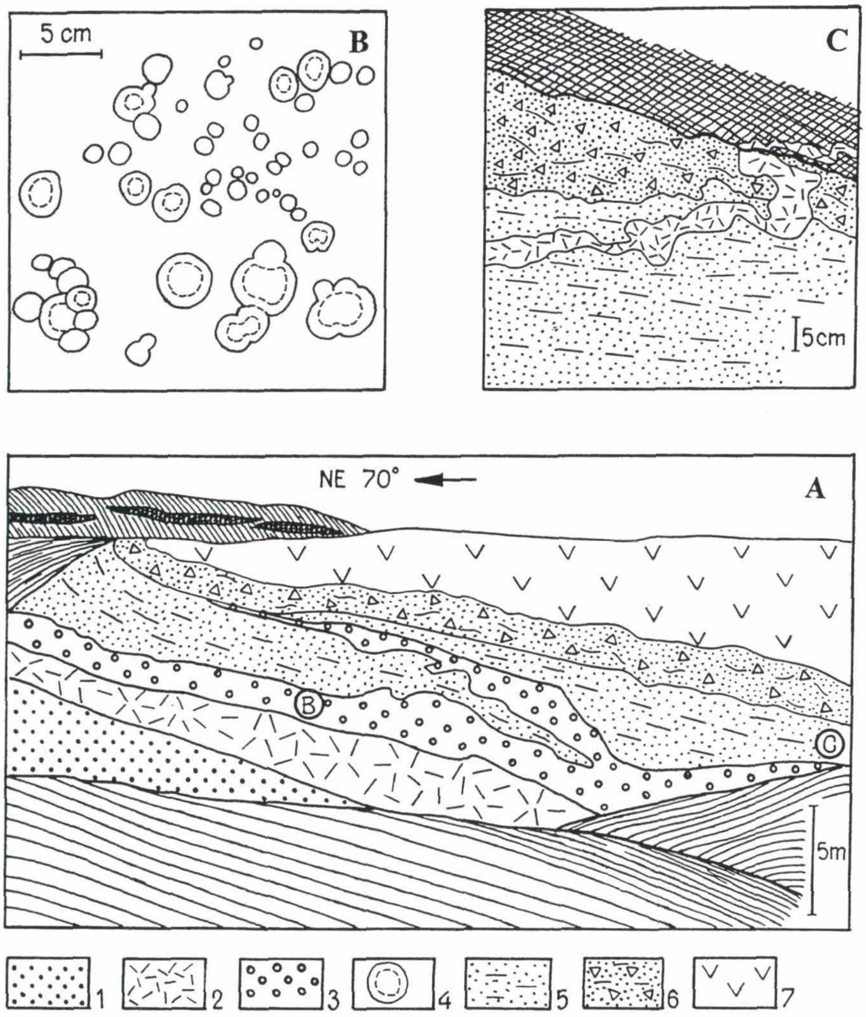

Fig. 4. Layered ferropicritic lava flow and the overlying bed of siliceous tuff-chemogenic-sedimentary rocks, Mt. Kuorpukas. A — generalized sketch map of the outcrop; B — distribution and zoning of globules; C — a thin ferropicrite-basalt vein (apophysis) in tuffosilicite. 1 — olivine ferropicrites; 2 — clinopyroxene ferropicritic basalts; 3 — globular ferrobasalts; 4 — globules; 5 — massive and thin-banded tuffosilicite; 6 — fine-clastic tuffosilicite; 7 — gabbro-diabase.

Stop 3 — The Matert Volcanic Formation, globular and layered ferropicritic lava flow

North-western slope of Mt.Kuorpukas, 5 km southeast of the Kotselvaara mine, at 20°22'E 69°24'N.

The upper part of the section through the northern zone contains volcanic ultramafic (ferropicritic) rocks, which form massive and pillowed lavas, layered lava flows, tabular sill-type bodies, lava breccia and tuff beds, and thin dikes, making up a volcanic-plutonic association. These rocks occur at five levels: at the base of the volcanic Zapolyarny Formation, in the tuffaceous-sedimentary Zdanov and Lammas Formations, and in the lowermost, middle and uppermost parts of the volcanic Matert Formation. Alternating with tholeiite basalts, the ferropicritic volcanic rocks of the Matert Formation make up as much as 4.5% of its total thickness, including massive lavas (3%), pillow lavas (1%) and tuffs (0.5%). The lava flows range in thickness from 3 to 25 m, and a few of them are as much as 50 m thick and can be traced for 2.5–3 km along the strike. Tuffs make up a significant part of the Lammas cross-section.

The most complete section of relatively thick layered flows consists of the lower and upper chilled zones, the lower zone of olivine ferropicrite (olivine cumulate), the middle zone of fine-grained clinopyroxene ferropicritobasalt (clinopyroxene cumulate), and two upper zones of ferrobasalt composition. The rocks in these upper zones have a spinifex texture (of the olivine and, less often, pyroxene types) or a globular structure. Thinner flows do not contain zones with a spinifex texture or globular structure, and their MgO content is lower because of the smaller amounts of olivine in the lower zone.

Typical features of the volcanic ferropicritic rocks are the increased fayalite component in the olivine (16% Fa), and the titanium-rich varieties of the rock-forming (titanaugite, kaersutite, biotite) and accessory (Ti-chromite, Cr-ulvospinel, ilmenite) minerals. In addition, these rocks typically contain large amounts of FeO+Fe$_2$O$_3$ (14–16%), TiO$_2$ (1.3–4.0%) and P$_2$O$_5$ (0.15–0.35, occasionally up to 0.88%) and an increased LREE content (8–10 times higher than in MORB) (Hanski & Smolkin, 1995).

The middle part of the section through the Matert Formation is exposed by erosion on the north-western slope of Mt.Kuorpukas. This part is composed of (from bottom to top) pillow lavas of tholeiite basalt with thin (0.1, 2.5 m) interbeds of tuffosilicite, a layered volcanic ferropicrite flow, which marks a seam of high-silica chemogenic-tuffaceous-sedimentary rocks (8–10 m), and a tabular body (sill) of ophitic gabbro more than 50 m thick.

The layered ferropicrite flow can be observed at the base of an extended scarp outcrop (Fig. 4). The vertical section of the flow can be subdivided into three zones (from bottom to top) of: serpentinized olivine ferropicrite greater than 4 m thick, 3.5 m of fine-grained pyroxene ferropicrite-basalt and 0.5 to 1 m of globular ferrobasalt. There are no sharp boundaries between the zones. The lower contact of the flow is covered by glaciogenic overburden whereas the upper contact is exposed at the excursion site. At the very top of the flow there is a thin, 3–5 cm layer of ferrobasalt that has experienced submarine alteration and is anomalously low in SiO_2 (38.7%). A sharp contact separates the ferrobasalt and the overlying sequence of 3–5 cm of dark-grey, fine-grained tuffite, 1 to 4 m of massive fine-grained tuffite and 3.5 to 4 m of fine-clastic tuffites. In the upper part of the layered flow there is a thick apophysis of globular ferrobasalt, which penetrates the overlying tuffosilicite and gradually wedges out towards the southeast over a distance of 25 m. In addition, there are thinner apophyses (1–2 cm) of markedly altered ferrobasalt containing 39.1% SiO_2. It has been suggested that upon eruption under subaqueous conditions, the lava flow was buried under high-siliceous turbidite sediments as a result of a catastrophic subaqueous avalanche. Later, the remainder of the melt penetrated the overlying sediments and formed apophyses reaching the roof of the sedimentary layer, which was subsequently covered by sediments.

The globular rocks provide a brilliant example of silicate immiscibility in a ferropicrite melt. The globules represent unevenly distributed, ball-shaped pale-grey aggregates 2 to 50 mm in size. As they were pushed closer together, they were pressed into each other and then adhered, the interglobular matrix commonly being preserved. The globules and cementing matrix are similar in their TiO_2, P_2O_5 and F contents but differ in their proportions of mineral phases and their zoning. Other distinctive features are the contents of SiO_2 (47.5 and 43.4%, respectively), Na_2O (2.9 and 0.4%), K_2O (0.3 and 1.5%) and Ni (135 and 85 ppm) and the Fe/(Mg+Fe) value (0.60 and 0.36).

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Editorial handling Eero Hanski and Markku Iljina

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August 11–13, 1997, Turku, Finland, excursion guidebook B4.
Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 21–24, 1997.

BANDED IRON FORMATIONS

by
P. M. Goryainov, G. I. Ivanyuk and N. N. Golikov

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INTRODUCTION

Including the deposits at Finnmarken in Northern Norway, there are over 400 occurrences of banded iron formation known on the Kola Peninsula. Rocks of the iron formations represent assemblages at amphibolite and granulite facies and consist of basic crystalline schists and amphibolites, biotite and alumina gneisses, leptites (metamorphosed felsic volcanics/volcaniclastic sediments), carbonate schists, diopside-magnetite rocks and iron quartzites. The iron formation rocks occur among oval-lenticular blocks of grey gneiss (migmatite-tonalite-granodiorite) that range from 500 to 1000 km^2 in size. Foliation in the grey gneiss varies from nearly isotropic to highly foliated, and where apparent the foliation is nowhere seen to be intersected by the rocks of the banded iron formation: the contacts are strictly conformable.

Two groups of deposits can be distinguished by rock type association: (1) the amphibolite type, where the iron quartzite is closely confined to the amphibolite layer and (2) the leptite type, where the iron quartzite occurs within various alumina gneisses and amphibolite tends to be concentrated near the contact with the tonalite (Goryainov, 1990; Goryainov & Balabonin, 1988). The Pecheguba and Uraguba deposits are examples of the amphibolite rock paragenesis but all the major BIF ore deposits (Olenegorsk, Kirovogorsk, Bauman, Komsomol and Ivar) belong to the second, leptitic type.

A notable feature of the productive ore sequence is its symmetrically zoned structure: the rock succession *tonalite — amphibolite — leptites — iron quartzite — leptites — amphibolite — tonalite* remains invariable regardless of the thickness of the ore-bearing

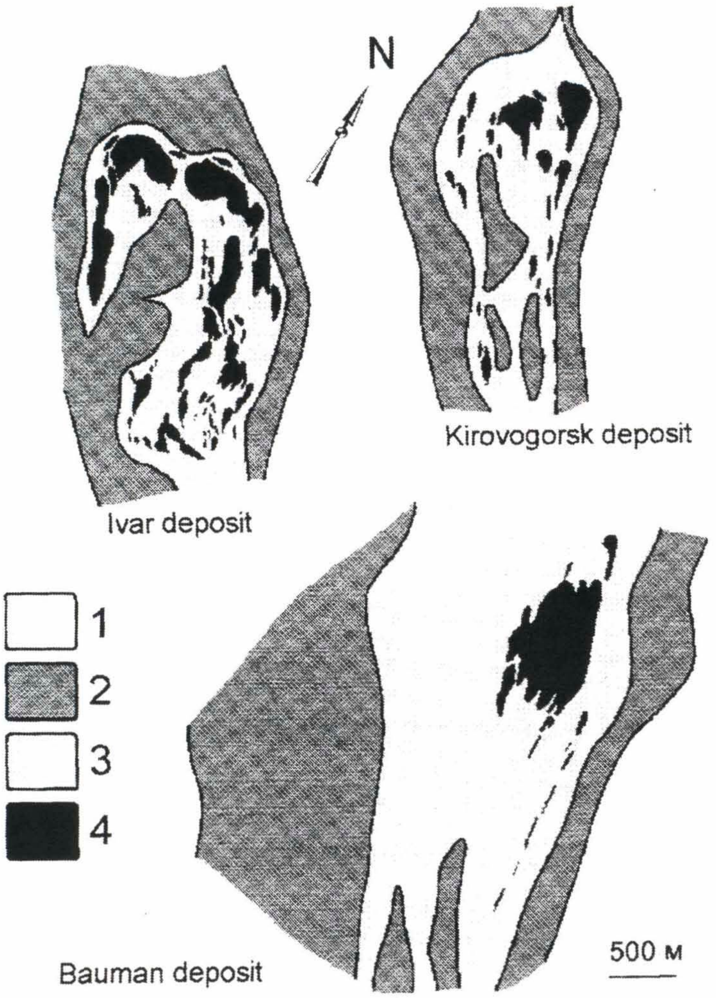

Fig. 1. Zoning of BIF deposits of the Kola Peninsula. 1 — tonalite; 2 — amphibolite; 3 — leptites; 4 — BIF.

unit, and does not change when the ore body is disrupted into a number of smaller bodies (Fig. 1). Moreover, the same succession is observed not only in single-lens but also in complex, multi-lens types of deposits.

More than 70 years of intensive exploration led to the discovery of a huge number of BIF ore occurrences, but only the Near-Imandra area has been the target of commercial mining. This area includes 4 functioning mining operations (Olenegorsk, Kirovogorsk, Bauman and October deposits).

THE MAIN NEAR-IMANDRA STRUCTURE

All the deposits in this region were discovered in 1931–1932 owing to the studies of O. A. Vorob'ev, N. S. Zontov, A. Yu. Serk and D. V. Shifrin. Already by that time the structural plan of the region was clearly defined from magnetic surveys as an oval-shaped ("Main") structure with BIF deposits located in peripheral areas. Subsequent investigations made it possible to compile a detailed map of the Main structure. The 20 km tonalite oval is surrounded by a band of BIF rocks; the thickness of the band ranges from 200 m at the Kakhozero deposit to 3 km at the Ivar deposit (Fig. 2).

In the 1930s, D.V.Shifrin considered the lens of the Main Near-Imandra Structure to be the core of a large anticline, and the deposits to be the cores of tightly compressed synclines. In the 1960s, A. I. Balakai, V. A. Tyuremnov and G. I. Bobryshev suggested that the BIF deposits are fragments of a single unit on the limbs of tens of kilometers scale folds. At the same time, however, P. M. Goryainov proved that the idea of a syncline fold is not reconcilable with

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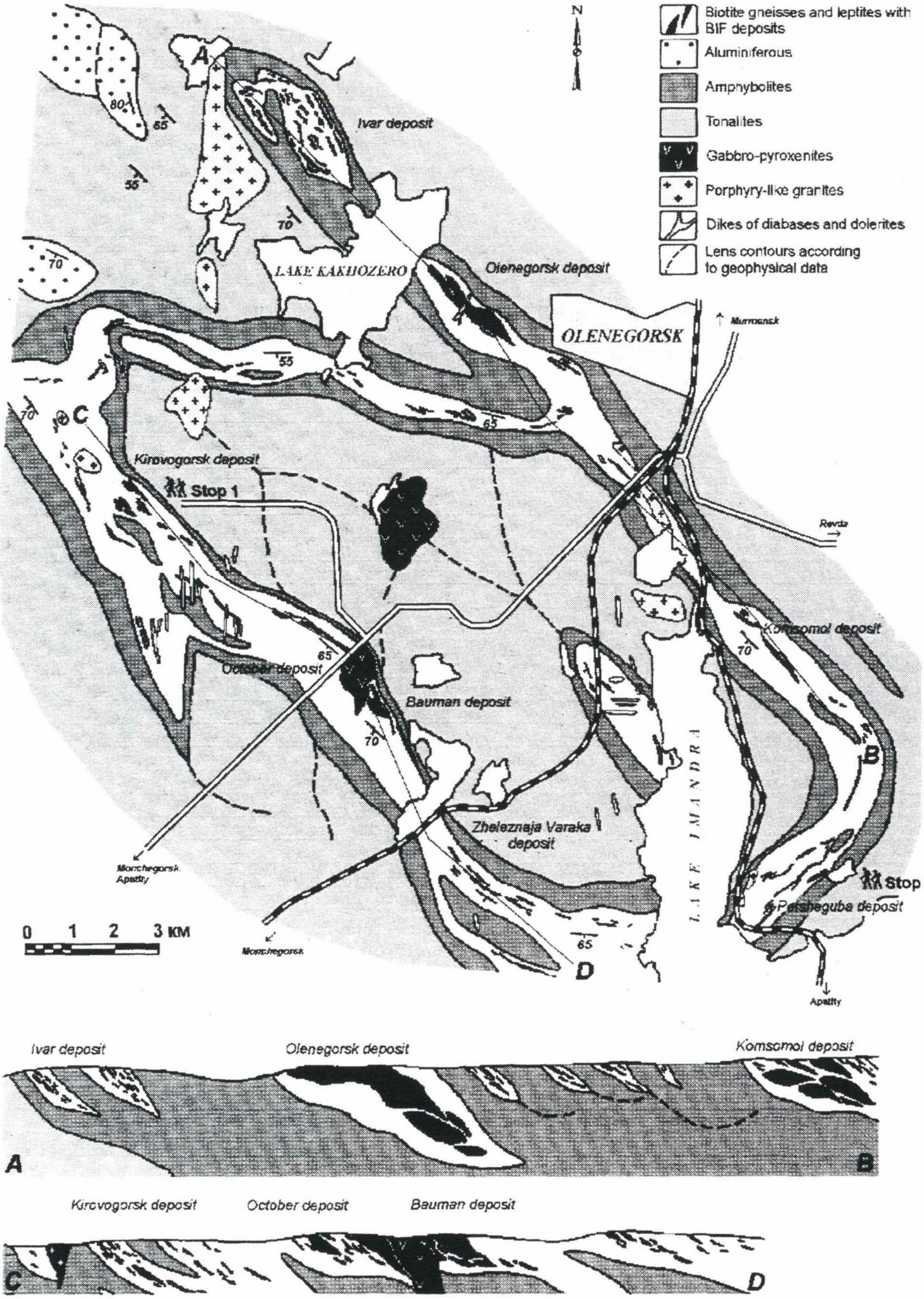

Fig.2. Geological map of the Main Near-Imandra structure.

the settings of the ore deposits. This conclusion has been confirmed by further investigations and by information acquired during mining. At present, most investigators, regardless of their opinions on the genesis, accept that: (1) the ore complexes of the Main Structure are monoclines that fill the sutures between tonalite domes (2) the iron quartzite is confined exclusively to near-surface parts of axial zones of these sutures, and (3) the ore complexes have an imbricate-lens structure (Goryainov, 1990; Ivanyuk et al., 1996).

In its northernmost part, the Main Structure is traversed by the Kolozero-Kirovogorsk fault zone, which controls the Kirovogorsk and Ivar deposits. These two deposits differ from the rest in the fact that although being combined into a single cluster, the iron quartzite bodies are highly disrupted. The Kolozero-Kirovogorsk fault zone serves also as a boundary between the northwestern and the southeastern parts of the Near-Imandra region (the northwestern part is notable for the presence of monotonous alumina gneiss), and controls small massifs of porphyritic granites. However, this zone has no effect on the contours of the BIF oval: they have been neither displaced nor deformed.

This excursion will include the most representative, in our opinion, BIF deposits of the Near-Imandra region: Kirovogorsk and Pecheguba. These represent the leptitic and amphibolitic types, respectively.

FIELD TRIP

Stop 1 — Kirovogorsk deposit

The deposit is situated at the intersection of the Main Structure oval and the Kolozero-Kirovogosk fault zone that borders the BIF distribution area on the northwest. A prominent zoning is observed in the structure of the productive unit: its marginal parts are composed of hornblende gneiss and amphibolite 300–600 m in thickness, followed by melanocratic biotite gneiss. In the axial part of the productive unit the most abundant rocks, along with the iron quartzites, are leptites and leucocratic alumina gneisses; the latter represented by nodular, two-mica and epidote-biotite varieties.

The iron quartzite in the Kirovogorsk deposit does not occur in a single ore body (as is the case with the Olenegorsk and Komsomol deposits), nor in several bodies stretched out in a line (the Pecheguba deposit). It is found in three clusters of tightly packed lenses of different size, and in accompanying smaller lenses (Fig. 3). All the clusters are isolated from each other; in the zone of expected continuation of a cluster there are small ore lenses, which are also isolated from each other and from the other clusters. The iron quartzite, as elsewhere, has sharp contacts with the host alumina gneiss, and its smooth contours are not deformed by the numerous faults marked by diabase and granite pegmatite dykes, blastomylonites and micaceous rocks.

In cross-section, the ore bodies have a typical drop-like shape (Fig. 4). Thicker parts of the clusters face upwards, and the "tails" are directed downwards along dip. The near-surface parts of the ore bodies were deformed by extensive thrusting, especially intense in zones where the rocks are overturned. The thrusts took place within the limits of the iron quartzite and did not extend outside the clusters (Goryainov, 1990). Pegmatite and diabase dykes combine to form a stockwork net. The two dyke sets are offset by 30° relative rotation and the dykes are "hanging", i.e. have no roots and do not affect the surrounding quartzite. As in other deposits, the number of dykes, especially of basic dykes, abruptly decreases beyond the limits of the productive unit.

By the percentage of the main rock-forming minerals, the iron ore of the Kirovogorsk deposit can be subdivided into hematite-magnetite, magnetite and sulphide-magnetite quartzites, magnetite-diopside rocks and magnetite-bearing carbonate schists. As in most other deposits, the hematite-magnetite quartzite is confined to the inner parts of the ore bodies, whereas sulphide-bearing quartzite, diopsidite and carbonate schists occur in the outer parts. The iron quartzite is a banded rock composed of rhythmically alternating bands. The bands differ in mineral and granulometric composition, and have different percentages and properties of minerals. Depending on the mineral composition, the colour of the rocks can be black-and-white, grey, greenish-grey, pink-grey, or completely black. The ore shows a whole range of structures, from massive, disseminated and gneissoid, to prominently banded (planparallel, lenticular-banded, fine-plicative and brecciated). The most abundant mineral assemblages in the Kirovogorsk deposit are magnetite(±hematite)-actinolite-quartz (50%), magnetite-diopside-actinolite-quartz (16%), and magnetite-diopside-hornblende-quartz.

Carbonate schists form thin (from tens of centimeters to a few meters) conformable lenticular bodies that occur at the contact with iron quartzite. These are light-grey massive or slightly banded medium-grained rocks composed of granoblastic aggregates of dolomite, calcite and magnetite with subordinate amounts of diopside, biotite, andradite and forsterite. Near the contact with the iron quartzite, andradite-hornblende-diopside, scapolite-epidote-calcite and magnetite-diopside metasomatic zones are common, ranging in thickness from a few centimeters to a few tens of meters.

The quarry is 168 m deep. The design capacity of the mine is 5000 thousand tons of ore per year. In 1996, the extraction was 3537 thousand tons (against 3905 thousand tons planned). Since 1978, the mine has produced 53 739 thousand tons of ore. The extracted ore contained 1028.2 thousand tons of metal.

As of January 1, 1997, the remaining economic reserves of the deposit were 66 665 thousand tons (category B+C1). Accounting for planned losses and working out, the amount of economic reserves is enough for 14 years of mining.

The total iron content at cut-off is 14%. The minimum industrial content of total iron in a calculated block is 25%; the ore reserves containing 14–25% iron and occurring in the blocks of the quarry, are regarded as economic.

Prospects for further development of the deposit will involve underground mining.

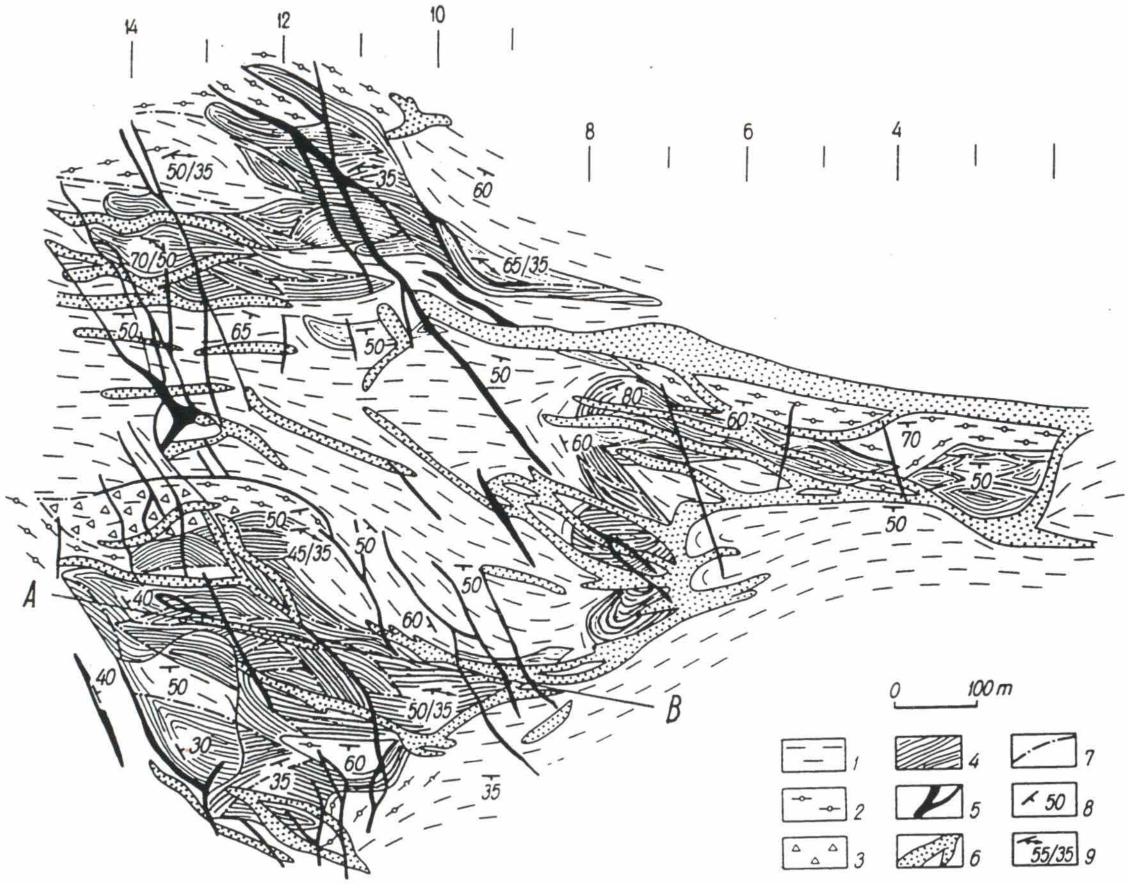

Fig. 3. Geological map of the Kirovogosk deposit (Goryainov, 1990). 1 — acid gneiss; 2 — alumina gneiss; 3 — brecciated biotite gneiss; 4 — iron quartzite; 5 — diabase, dolerite; 6 — pegmatite; 7 — blocking in the ore; 8 — gneissosity; 9 — strike and dip.

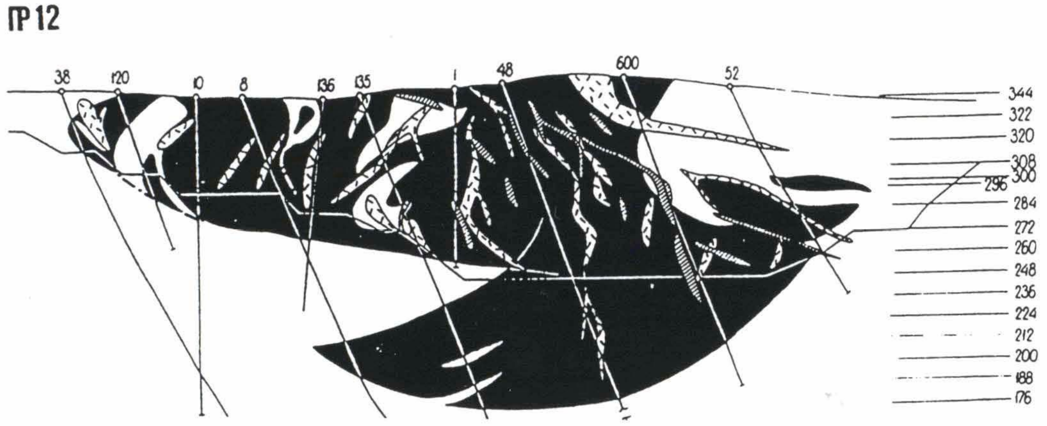

Fig. 4. Cross-section of the Kirovogorsk deposit. Black — iron quartzite; hatched — diabase; stipple — pegmatite.

Stop 2 — Pecheguba deposit

The Pecheguba deposit is located in the southeastern part of the Main Structure, where the BIF rocks encircling the tonalite oval strike towards the northeast and dip steeply to the southeast. The structural-lithologic complex of the Pecheguba deposit is an assemblage of lens-shaped bodies composed of hornblende amphibolite, leptites, iron quartzite, alumina and biotite gneiss (Goryainov, 1976). The BIF formation constitutes two bands of strongly flattened lens-shaped bodies of different scale (from a few meters to 2.6 km in length and half a meter to 100 m in thickness). The ore bodies strike to the northeast and dip to the southwest (Fig. 5). In the central parts of the thickest lenses, the ores are plicative in texture, whereas in marginal parts and in thinner lenses the texture is planparallel (Yegorov & Ivanyuk, 1996).

Most quartzites are represented by the magnetite-cummingtonite-quartz paragenesis. However, in the near-contact zones between the ore bodies and the gneiss, the dominant assemblage is magnetite-cummingtonite-quartz, with diopside

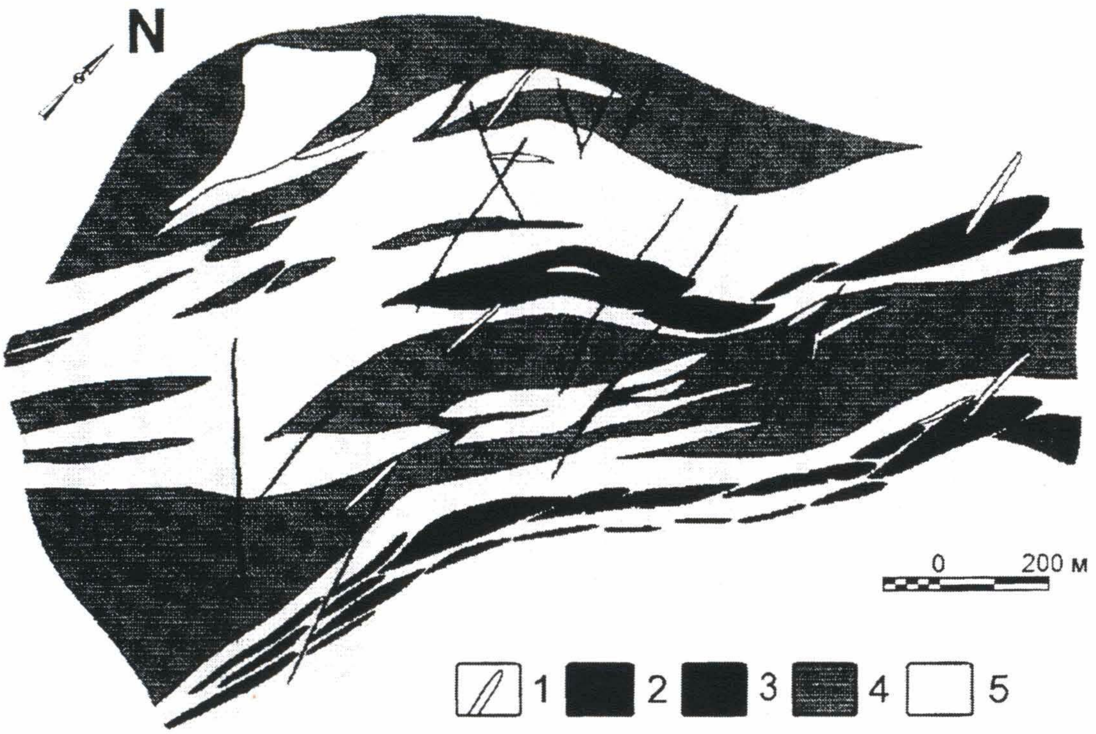

Fig. 5. Geological sketch map of the Pecheguba iron ore deposit. 1 — granite pegmatite; 2 — diabase; 3 — iron quartzite; 4 — amphibolite; 5 — gneiss.

and the replacing cummingtonite having reaction relationships. In addition, there are zones where both diopside and cummingtonite are reabsorbed by hornblende in association with garnet, and the process locally results in the formation of magnetite-quartz-hornblende rocks. One of the ore bodies, in its peripheral parts, contains thin (5–10) interbeds of diopside- and andradite-rich carbonate schists, which are separated from the BIF rocks with a rim of strongly boudinaged coarse-grained magnetite-diopside rocks.

Intrusive rocks, which are represented by granite pegmatite, diabase and gabbro-diabase, are emplaced in the gneiss-iron ore unit, but do not deform the structure of the deposit.

The ore is of poor quality; the ore reserves are about 60 million ton. The deposit is not mined.

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Editorial handling Hugh O'Brien

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Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 27–29, 1997.

THE MONCHEGORSK LAYERED COMPLEX AND RELATED MINERALIZATION

by
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Neradovsky, Yu. N., Borisova, V. V. & Sholokhnev, V. V. 1997. The Monchegorsk Layered Complex and related mineralization. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 27–29, 2 figures.

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GENERAL GEOLOGY

The Monchegorsk Layered Complex (2493±7 Ma, U Pb), referred to below as the Monche Pluton, and its related ore fields are part of the Pechenga-Imandra-Varzuga belt. The area was under extensive research, exploration and exploitation in 1930–1970 (Kozlov, 1973, Gorbunov et al., 1985). Mining operations as such have now ceased, but a new exploration boom has been targeted on platinum-group elements (Mitrofanov et al., 1994), and a chromite mineralization has recently been discovered (A.S.Galkin, chief geologist of the "Severonikel" Plant, personal comm.).

The Monche Pluton, which crops out over an area of more than 60 km^2 (Fig. 1), consists of two branches: a meridional one 7 km long marked topographically by Mt. Nittis, Mt. Kumuzhja and Mt. Travyanaya (the N-K-T branch), and a latitudinal one of 9 km comprising of Mt. Sopchuaivench, Nyuduaivench and Poazuaivench (the Sopcha-Nyud-Poaz branch). The latter is topographically 300 m lower that the N-K-T branch. The surrounding rocks are late Archaean biotite and amphibole-biotite gneisses, which also host banded iron formation and sillimanite-garnet-biotite gneisses (2932–2630 Ma) and the Palaeoproterozoic subracrustal rocks and diabase of the Imandra-Varzuga belt (2453–1765 Ma).

The cumulate sequence (Fig. 2) comprises the following main units (from bottom to top): (i) the quartz biotite norite and gabbronorite immediately above the basal contact (8 to 50 m thick), (ii) mafic and feldspathic ultramafic rocks (5 to 100 m thick), (iii) peridotite (harzburgite) (100 to 200 m thick), (iv) a composite unit of pyroxenite, olivine pyroxenite and peridotite (harzburgite) (250 to 400 m thick), (v)

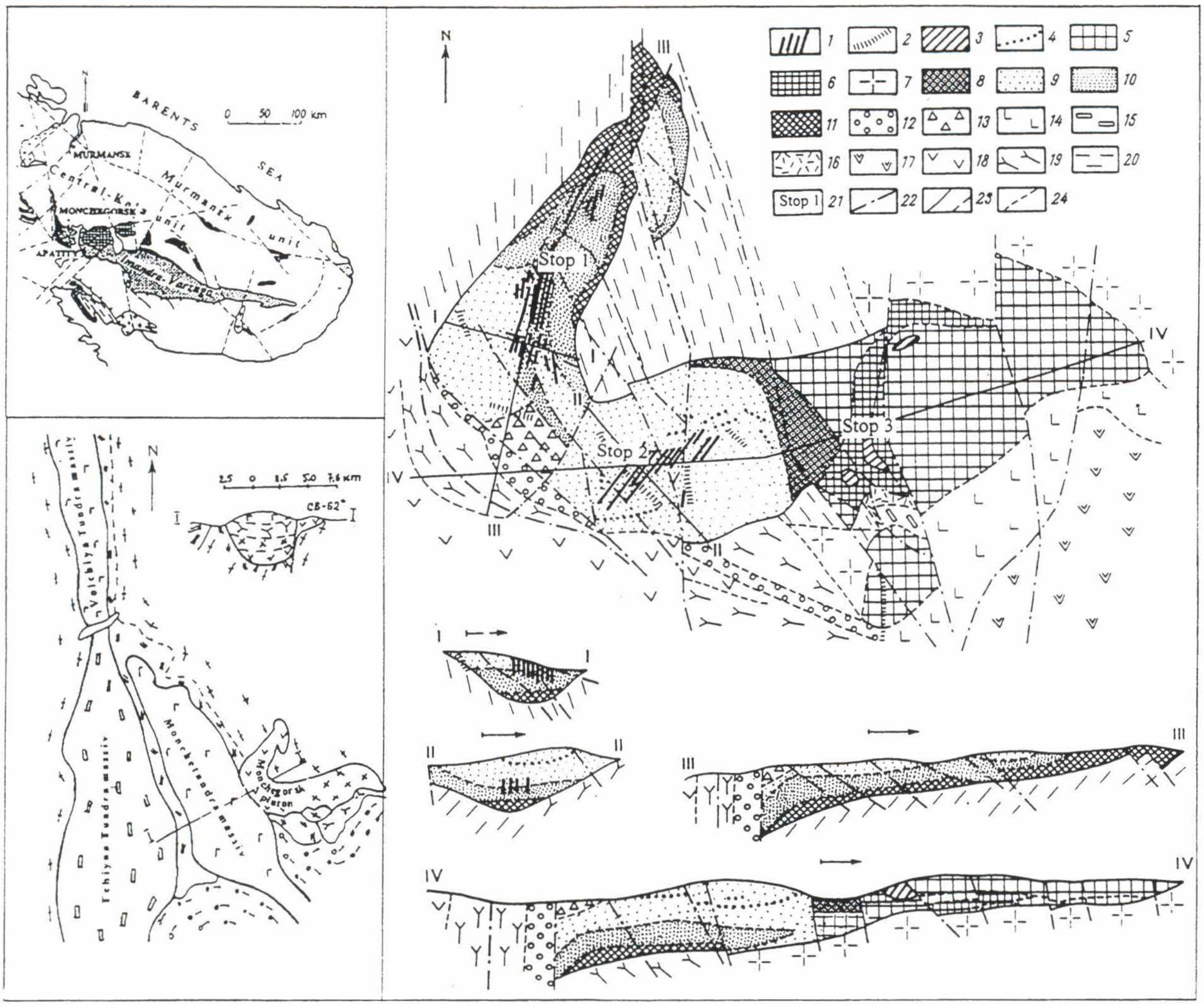

Fig. 1. Geological map of the Monchegorsk Pluton. 1 — nickel copper sulphide veins; 2 — diabase and dolerite dykes; 3 — rocks of the "critical horizon" of Mt. Nyud; 4 — ore beds of Mt. Sopcha; 5 — leucocratic and mesocratic norite; 6 — olivine norite; 7 — diorite and granodiorite; 8 — plagioclase orthopyroxenite; 9 — orthopyroxenite; 10 — alternating orthopyroxenite, olivine orthopyroxenite and harzburgite; 11 — harzburgite; 12 — alternating pyroxenite, harzburgite and norite; 13 — dunite; 14 — metamorphosed gabbronorite; 15 — quartz metagabbro and the sedimentary-volcanic complex of the Imandra-Varzuga zone; 16 — andesite, dacite and tuff; 17 — metamorphosed diabase and vesicular rocks; 18 — massive leucogabbro; 19 — metamorphosed and schistose gabbro; 20 — amphibole-biotite gneiss and amphibolite; 21 — stop number; 22 — faults; 23 — borders of the Monchegorsk Pluton (mapped / inferred); 24 — lithological boundaries.

melanorite (300 m thick) and pyroxenite (bronzitite) (300 to 700 m thick) and (vi) leuco-mesocratic norite (up to 300 m thick). The meridional branch (N-K-T) is composed predominantly of ultramafic rocks, pyroxenites and peridotites, while the latitudinal branch (Sopcha-Nyud-Poaz) is composed of both mafic and ultramafic cumulates. The cumulates are then cut by numerous veins of gabbro pegmatite, diorite, diabase, porphyrite and lamprophyre.

The igneous layering varies from vertical to horizontal, but is generally directed towards the convergence of the two branches, where the individual layers are also at their thickest. These features and the flow structures suggest that the feeder of the intrusion was underneath this junction area.

MINERALIZATION

The sulphidic nickel-copper-PGE mineralization has been economically the most important. In addition, there are chromite occurrences related to the peridotite and dunite of the Mt. Sopcha area and titanomagnetite layers associated with the metagabbro of the Nyud and Poaz areas (Fig. 2).

The main types of sulphide mineralization

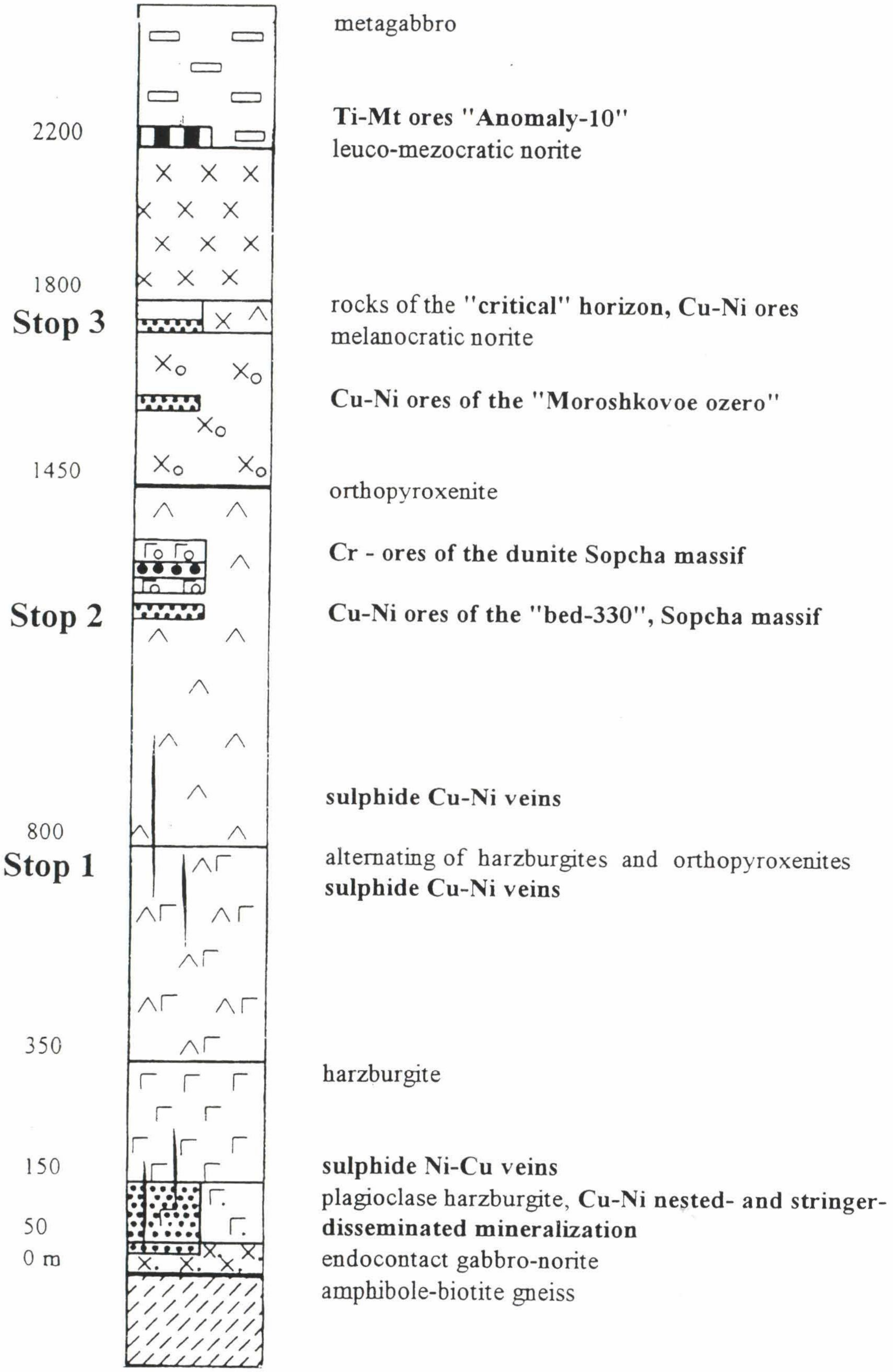

Fig. 2. Schematic geological cross-section of the Monchegorsk Pluton and the location of Cu-Ni, Cr and Ti-Mt mineralizations.

are (i) syngenetic bleby or disseminated ores and (ii) epigenetic sulphide veins. Several deposits have been explored, including (1) those at the base of the N-K-T branch, (2) a layer in Mt. Sopcha known as "Bed 330", (3) layers in the olivine norite in Mt. Nyud, (4) a "critical horizon" in Mt. Nyud, (5) sulphide veins in the N-K-T branch and (6) sulphide veins in the Sopcha area.

Over 40 ore minerals have been identified in the sulphide-bearing rocks. The main minerals are pyrrhotite, pentlandite, chalcopyrite, magnetite, chromite and pyrite, while titanomagnetite, ilmenite, bornite, cubanite, millerite and mackinawite are present in lower amounts. The most common platinum-group minerals (15 species identified) are native platinum, niggliite, kotulskite, sopcheite, michenerite, braggite and cooperite. PGM are commonly found as inclusions in major sulphides. Other minor minerals are native gold, and gold and silver tellurides (hessite, sylvanite, calaverite). The zone of oxidation contains violarite, marcasite, chalcocite, covellite, ochre and oxides as scarce secondary minerals.

FIELD TRIP

We will visit three localities: 1, a section of ultramafic cumulates and sulphide dykes, Mt. Kumuzhja; 2, "Ore Bed-330", western slope of Mt. Sopcha, and 3, the "critical horizon" of the Monche Pluton, Mt. Nyud (Fig. 1).

Stop 1 — Ultramafic cumulate and related sulphide mineralization, Mt. Kumuzhja

A section through ultramafic cumulates of the N-K-T and sulphide mineralization, Mt. Kumuzhja, 67°55'N, 32°46'E.

This part of the N-K-T cumulate sequence consists of alternating orthopyroxenite and harzburgite in the lower part and exclusively orthopyroxenites in the upper part. The harzburgite and orthopyroxenite have a pronounced trachytic texture due to the orientation of the prismatic orthopyroxene crystals. Otherwise the cumulates are medium-grained and dark grey to nearly black. The cumulus olivine has a Fa content of 11–13% and the orthopyroxene 11–12% Fs, whereas the rare clinopyroxene has 6% Fs and the plagioclase 57% An. Actinolite, talc, chlorite, serpentine and carbonate are found as secondary minerals.

Ni-Cu sulphide dykes

The sulphide dykes are confined to the fracture system in orthopyroxenite and harzburgite. The fracturing itself is oriented parallel to the axis of the N-K-T branch. The upper parts of the dykes are located mostly in the unit of monomineral pyroxenite (bronzitite) and wedge out with depth in the unit of alternating olivine pyroxenite and peridotite (Fig. 2). The cumulates in contact with the sulphide dykes have minor alteration features, so that only some amphibole (anthophyllite) and stringers of talc-breinerite are present.

More than 50 dykes have been detected due to underground workings. These are 100 to 1400 m in length and from 5 to 50 cm in thickness. The vertical height (as measured down-dip) can reach 150 m and the bottoms of the dykes are 500–600 m above the base of the intrusion. Swelled parts of the veins can be as much as 3 m thick. Most of the dykes are tabular, and they are commonly characterized by bends, swells and step-like displacements. These sulphide dykes are spatially closely related to dioritic pegmatite dykes.

The dykes are almost exclusively composed of base metal sulphides, the rest being silicates and oxides. The mineral composition varies from pyrrhotite alone through a pentlandite-chalcopyrite-pyrrhotite assemblage (with pyrrhotite predominant) to chalcopyrite alone. Some parts of the veins consist of magnetite. The sulphides in the veins commonly change to gabbro pegmatite, and the gabbro pegmatite grades to gabbronorite. This change occurs repeatedly along the strike of the veins.

The metal and sulphur values vary as follows: Ni 2–6%, Cu 1–12%, Co 0.15–0.30%, S 9–26% (Kozlov, 1973) and PGE (in 100% sulphides) 7 g/t, with Pt/Pd=0.11.

The origin of these sulphide dykes is still under debate. They are apparently epigenetic formations, since they crosscut the cumulates, but the slight contact alteration and their internal structure support the notion of crystallization in situ.

Cu sulphide stringers

A zone of copper stringers is to be found 100–150 m below the level of the Ni-Cu sulphide dykes. These veins up to 150 m in length occur in the plagioclase peridotite and wedge out above the norite of the extreme base of the intrusion, which hosts the bleby to disseminated sulphides described below. These copper stringers have high PGE and other noble metal contents, as Pd reaches 53.7 g/t (recalculated to 100% sulphides) and the maximum Pt, Rh, Ru and Ir values are 22.4, 0.07, 0.02 and 0,02 g/t, respectively.

The basal sulphide deposit of N-K-T

The basal sulphide deposit common to so many layered complexes is unfortunately not exposed in the Monche Pluton, but it has been studied in underground mines and bore holes. The mineralization is extensive, although the metals are unevenly distributed and their contents low. It is found throughout the entire length of the N-K-T, and is as much as 40–50 m in thickness in the centre of the trough. The sulphides are hosted by a feldspathic rock unit lying in between the peridotite and gabbronorite. Ore textures vary from semi-massive through bleb textured to dissemination. The average chemical composition of the ore is: 0.29% Ni, 0.14% Cu, 0.02% Co, 1.0% S and 18 g/t PGE (in 100% sulphides), with Pt/Pd=0.11–1.0.

Stop 2 — Ore Bed-330

Peridotite and pyroxenite on the western slope of Mt. Sopcha and "Ore Bed-330" (Figs. 1 and 2), at 67°53'N, 32°47'E.

"Ore Bed-330" is a large deposit of disseminated sulphide ore in the middle of the Monche Pluton stratigraphy. Its discovery in the 1930s led to the construction of the "Severonickel" mining and smelting plant, although the deposit itself was eventually never exploited. The mineralization gains its name from the fact that it goes around Mt. Sopcha at an altitude of 330 metres a.s.l.

The deposit is mainly hosted by a discontinuous mass of olivine-bearing rocks which include dunite, peridotite (harzburgite), olivine pyroxenite and feldspathic olivine pyroxenite. This rock mass is a horizontally discontinuous "layer" which has been interpreted to represent some kind of mass flow into the much thicker bronzitite (Fig. 2) unit. The stratigraphic height of this structure is 800 metres (in Mt. Sopcha). The sulphide mineralization consists of lens-shaped bodies at several levels and it slightly cross-cuts internal "layering of the flow". The combined thickness of the sulphide lenses is 1–5 m per a section.

The sulphide dissemination is concentrated in the upper part of the olivine-bearing "flow". Typical metal and sulphur values are as follows: Ni 0.35–0.55%, Cu 0.17–0.25%, Co 0.015–0.04%, S 0.9–2.39%, total PGE (in 100% sulphides) 35 g/t, Pt/Pd=0.13.

Stop 3 — Terrasa deposit

The "critical horizon" of the Monche Pluton, the Nyud-II and Terrasa disseminated and bleby sulphide mineralization, Mt. Nyud, at 67°53'N, 32°56'E.

The critical horizon, located in the middle of the latitudinal branch of the pluton, on the western slope of Mt. Nyud (Figs. 1 and 2), consists of leuconorite, pyroxenite and peridotite. Its boundaries with the underlying and overlying cumulates are gradual.

The sulphide mineralization is found in this "critical horizon" and in the olivine norite just beneath it. These sulphides form the Nyud-II and Terrasa ore field. The "critical horizon" reaches a maximum thickness of 50 m, while the thickness of the sulphide bearing zone can be as much as 20 m. The disseminated, stringer and bleby sulphides occur in irregular, lens-shaped bodies elongated along the strike of the "critical horizon". The amounts of sulphides present vary greatly. The most common opaque minerals are pyrrhotite and composite pentlantite, chalcopyrite and magnetite grains. The nickel content is markedly increased in the sulphide schlierens, where it is more than 50 times that of copper. Typical element concentrations are: Ni 0.32%, Cu 0.32%, Co 0.013%, S 2.44%, total PGE 5.69 g/t (in 100% sulphides), Pt/Pd=0.62.

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THE IMANDRA LAYERED COMPLEX AND RELATED MINERALIZATION

by
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Torokhov, M. P., Fedotov, G. A., Karzhavin, V. K. & Sholokhnev, V. V. 1997. The Imandra Layered Complex and related mineralization. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 33–38, 4 figures and 3 tables.

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INTRODUCTION

The Imandra Layered Complex, 1500 km^2 in area, is composed of at least eight layered bodies up to 3 km thick and from a few to many tens of kilometres long (Fig. 1). The layering in the northern group of these layered bodies (Mt.Devichja, Mt.Yagelnaya, the Monche Peninsula and Prikhibinie) dips at 45–50^o (locally 90^o) to the south and southwest, whereas the dip in the southern group (Umbarechensky and Mt.Bolshaya Varaka) is more gentle (0–35^o) and towards the north. It has been deduced that the complex was emplaced originally as a lopolith and subsequently broken into the smaller bodies by faulting (Zhangurov et al. 1994). The age of the complex is Late Sumian, according to the radiometric U-Pb age of baddeleyite from a norite of the Bolshaya Varaka body, which gave 2446±39 Ma (Bayanova et al., 1995).

The Imandra Layered Complex was intruded into Archaean amphibolites or a Sumian supracrustal sequence around 2.50–2.45 Ga. The primary intrusion environment of certain bodies of the complex are unknown, however, due to poor exposure or erosion of the uppermost cumulates soon after emplacement. Recrystallization and hornfels formation are widespread in the rocks adjacent to the intrusion bodies, while noritic apophyses and xenoliths of supracrustal rocks are found in the layered bodies.

The cumulus stratigraphy of the Imandra Layered Complex has been divided into the following zones (from bottom to top):

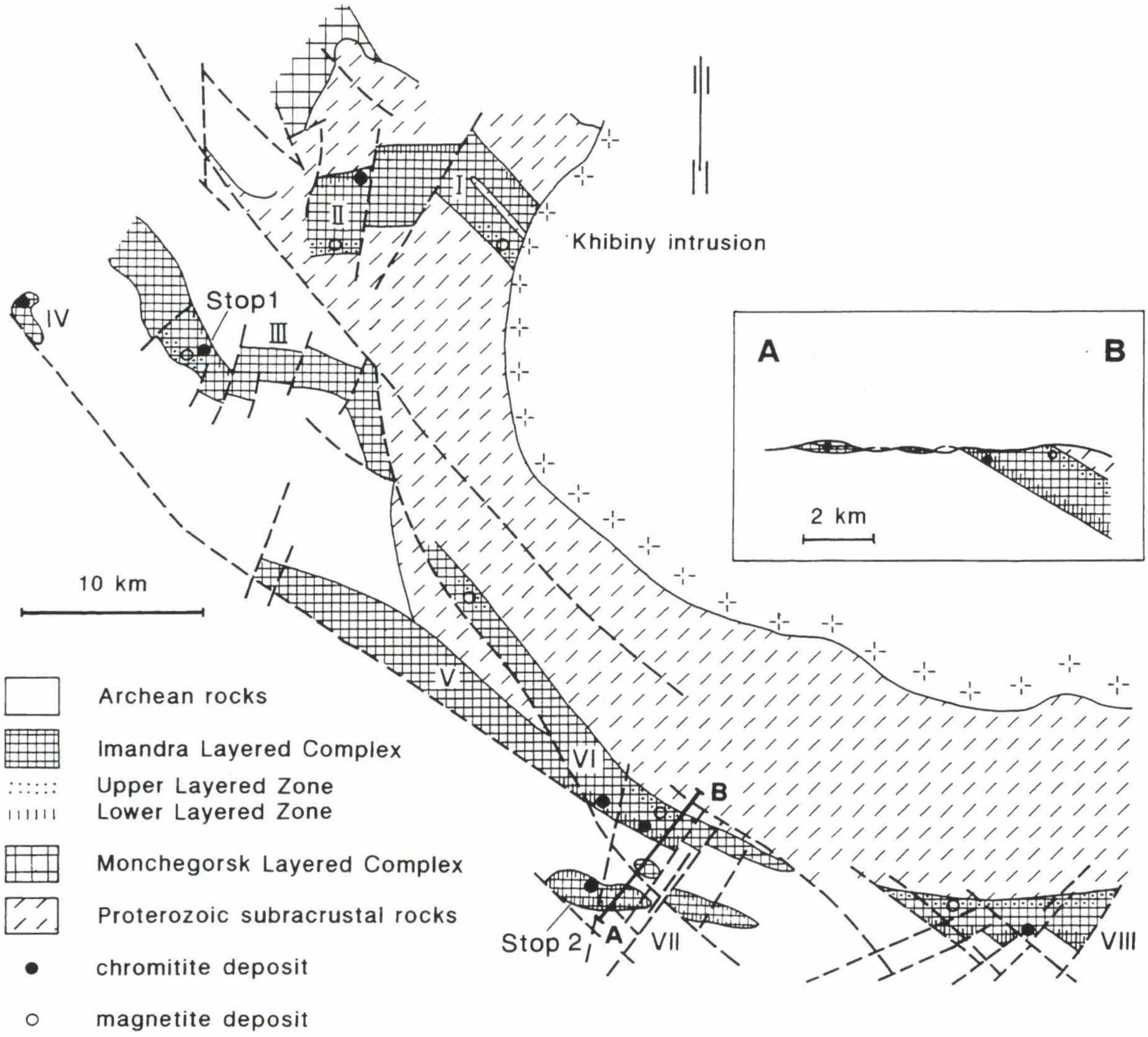

Fig.1. Geological map of the Imandra Layered Complex and its environment. Tectonic blocks of the Imandra Layered Complex: I — Prikhibinie, II — Monche Peninsula, Mt. Seyavarench, III — Mt. Devichya — Mt. Mayavr, IV — Mt. Yagelnaya, V — Jokostrovsky area, Lake Imandra, VI — Umbarechensky, VII — Mt. Bolshaya Varaka, VIII — River Chornaya area.

1. *The Marginal Zone* of taxitic mesocratic gabbro. The thickness of this zone ranges from 5–7 m in the area of Farm II (Fig. 1-6) to 90 m at Mt. B. Varaka (Fig. 1-7). Pronounced grain-size variation from place to place is characteristic of this zone.

2. *The Lower Layered Zone (LLZ).* The border with the Marginal Zone is defined by the chromitite I. The thickness of the LLZ is from 100 to 150 m, and possibly more in the centre of the intrusion. Its lowermost part (45–60 m) is composed of alternating plagioclase orthopyroxenite, poikilitic melanorite and gabbronorite. Mineralogically, these rocks are composed of cumulus orthopyroxene (40–60 %) and intercumulus plagioclase (5–30%), clinopyroxene (5–20%) and quartz (1–3%), which is commonly found in granophyric aggregates with felsic plagioclase and K-feldspar. In addition to the orthopyroxene, chrome spinel is also as a cumulus mineral. These rocks also contain thinner layers (up to 2 m) of mesocratic metagabbro, which host chromite mineralizations. On the other hand, the upper part of the LLZ consists predominantly of mesogabbronorites. Plagioclase (50–55%) is the most euhedral mineral (cumulus) in this sequence, while the intercumulus clinopyroxene content can reach 25%. The orthopyroxene (20–25%) forms large euhedral grains, which give the rock a porphyric appearance, and it also has numerous inclusions of small euhedral plagioclase laths. In addition, the whole LLZ contains biotite, sulphides, chrome spinels and ilmenite as

minor and accessory minerals.

3. *The Main Zone*. The Main Zone reaches a thickness of 2 000 m. The transition from the Lower Layered Zone is marked by a progressively increasing clinopyroxene content and a change in rock texture. The Main Zone is characterized by mesogabbronorites. In addition, there are thin (10–40 cm) interlayers of olivine-bearing gabbronorite in the lower part (ca. 100–150 m above the base) and layers of leucogabbronorites of variable thickness in the upper part. The major cumulus minerals are plagioclase (50–55%, up to 70%), orthopyroxene (15–20%) and olivine (0–10%, Fa=21–22%). The intercumulus clinopyroxene (20–30%) often forms large poikilitic grains having cumulus plagioclase inclusions. Smaller amounts of anhedral quartz (2–3%), biotite, sulphides, apatite and oxides are present in the Main Zone.

4. *The Upper Layered Zone*. The Upper Layered Zone (ULZ, ca. 300 m thick) consists of mesocratic and leucocratic gabbro and anorthosite (or gabbronorite in the lower part) giving rise to rhythmic layering in many places, and has a thick layer of anorthosite (from 7–20 to 70 m) at the very top. The only cumulus mineral is plagioclase (50–80%) while clinopyroxene (15–20%) and occasionally orthopyroxene form intercumulus phases. In addition, the ULZ contains accessory quartz (2–4%), apatite, garnet, sulphides, magnetite and ilmenite. The lower half of the uppermost thick anorthosite is slightly mineralized in PGE.

5. *The Roof Zone*. The rocks closing the roof (150–500 m) are composed predominantly of various mesocratic quartz gabbros and gabbrodiorites, and consist mostly of plagioclase (50–60%, An = 35–52) and amphibole. Quartz (up to 10%) is present throughout both as anhedral grains and as micropegmatite ingergrowths with more felsic plagioclase (An=20–25%). The accessory minerals are apatite, sphene, garnet and sulphides. The most conspicuous mineral, however, is titanomagnetite, which is found disseminated throughout the zone. The most highly enriched layer actually forms the base of the Roof Zone, and another occurs about 100 m higher up in the sequence.

Cryptic layering is depicted in the Fig. 2. The cumulus plagioclase turns out to show the widest compositional range, with an An content that increases from 64 in the Lower Layered Zone to 70 in the middle Main Zone and decreases to 48 higher up in the sequence. The En of the orthopyroxene is 73–76 up to the base of the Main Zone, decreasing to 70–72 in the middle Main Zone and finally to 60 in the Upper Layered Zone. The composition of the clinopyroxene is almost constant (En=47–50, Fs=11–16 mol.%) up to the Main Zone, becoming less magnesian in the Upper Layered Zone and Roof Zone (En=43 and 39, Fs=20 and 25 mol.%, respectively). The Wo content is constant throughout the intrusion (Wo=36–39 mol.%).

The intrusion was metamorphosed in the greenschist facies, resulting in the formation of actinolite, talc, chlorite and biotite after pyroxene, and epidote, zoisite, chlorite and carbonate after plagioclase. The strongest metamorphic recrystallization is found in the faults and close to the margins of the intrusion. The rocks of the intrusion are often tectonized and metamorphosed to chlorite-actinolite schists at the basal contact.

MINERALIZATION

Cr-Fe oxides

The following types of chrome spinellide mineralization are found in the Marginal Zone and Lower Layered Zone of the Imandra Layered Complex:

1. Accessory *chrome spinellides*. There are two distinct populations of grains: small, homogeneous, euhedral grains and larger, commonly zoned, anhedral grains occurring either in the interstices of cumulus minerals

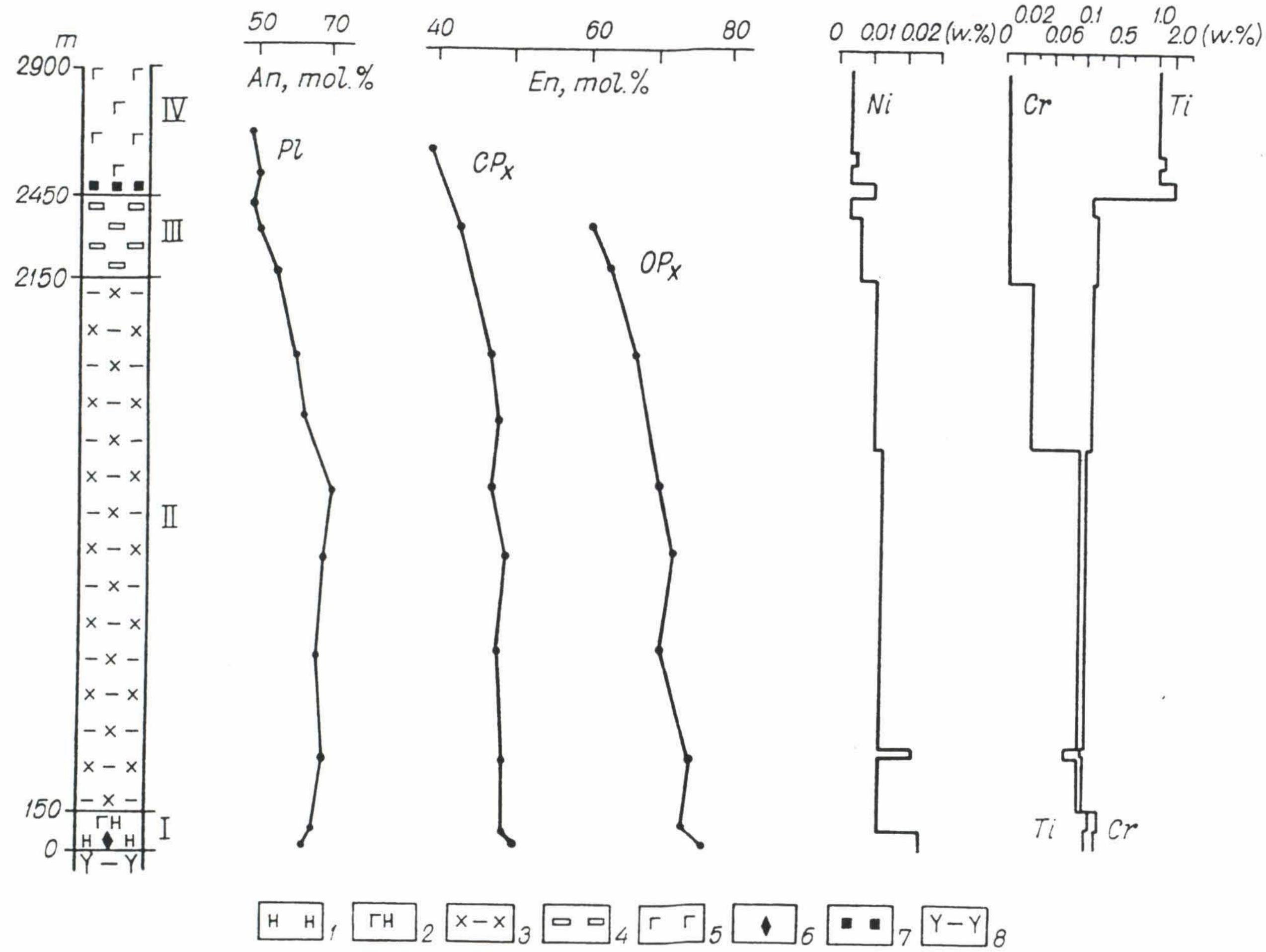

Fig. 2. Cumulus stratigraphy, cryptic layering and whole-rock variation in nickel, chromium and titanium in the Imandra Layered Complex. Lower Layered Zone (I): 1 — melanocratic norite and gabbronorite with thinner layers of leuco-mesocratic gabbroic rock, 2 — predominantly mesocratic and porphyric gabbronorite. Main Zone (II): 3 — mesogabbronorite. Upper Layered Zone (III): 4 — leucocratic and mesocratic gabbro and gabbronorite, and anorthosite. Roof Zone (IV): 5 — gabbro, diorite. 6 — chromitite layers. 7 — magnetite layers. 8 — underlying rocks (Lopian).

or as inclusions in plagioclase and biotite. The latter population is present throughout the Lower Layered Zone.

Representative chemical analyses of the spinels are depicted in Table 1. The spinells of the first population correspond chemically to the cores of the second group. Within the Lower Layered Zone the Cr_2O_3 and Al_2O_3 contents of the second group spinell decrease from 43.32 to 16.91% and from 10.80 to 2.23%, respectively, with stratigraphic height, while the total iron content increases from 39.21 to 75.74% (Fe_2O_3, 8.00 to 47.90%). The composition of chrome spinellide within one sample changes in a similar way from early phases (Table 1, analysis 4) to later phases (analysis 3). In general, the accessory chrome spinellides form a ferrialumochromite-subalumoferrichromite-chrome magnetite series.

2. Seams, schlierens and semimassive layers, located in the melanorite, gabbronorite and plagiopyroxenite of the Lower Layered Zone of all the tectonic blocks of the Imandra Layered Complex. The semimassive layers, referred to here as chromitites, are composed of pegmatoidal leucocratic to mesocratic gabbro with disseminated (up to 50–70 vol.%) small chromespinellide grains (0.05–0.5 mm). The Cr_2O_3 content of these layers range from 17 to 30 wt.%, and the layers themselves range in thickness from 10 cm to 2.1 m, their lower boundaries with the underlying norite being sharp, which is not the case with their upper boundaries. Quite often there is a swarm of two to four layers within few metres, these swarms then being located 25–30 m apart. Most of the layers are discontinuous along the strike or have not been traced because of poor exposure.

Table 1. Chemical composition of chrome spinellides in the Imandra Layered Complex

Oxide	1	2	3	4	5	6	7	8	9
Cr_2O_3	43.32	43.20	38.98	41.70	16.91	48.20	42.36	44.77	44.35
Al_2O_3	10.80	5.91	3.48	11.76	2.23	10.44	11.32	13.81	9.90
V_2O_5	3.51	0.75	-	-	1.33	0.37	0.61	0.41	-
TiO_2	0.48	0.54	0.16	0.14	0.65	0.00	5.32	0.71	0.81
Fe_2O_3	8.00	17.50	26.35	14.62	47.90	3.10	2.30	1.10	10.94
FeO	32.00	32.05	31.24	28.08	32.70	29.00	31.20	32.20	33.47
MnO	0.80	1.06	0.11	0.09	0.26	0.92	0.56	0.50	0.08
ZnO	0.70	0.39	0.15	0.13	0.04	-	-	-	0.42
MgO	0.47	0.44	0.74	3.58	0.20	0.93	1.24	0.47	0.10
NiO	0.03	0.03	0.11	0.10	0.02	-	-	-	0.00
Total	99.32	100.18	98.70	98.74	97.38	92.95	94.64	93.80	100.07

Type 1 chromites: 1 — Mt.Bolshaya Varaka, melagabbronorite underlying a chromitite layer; 2 — Umbarechensky massif, melanorite just above a chromitite IV; 3 — Umbarechensky massif, melanorite of the middle Lower Layered Zone; 4 — small euhedral inclusion in orthopyroxene in the previous sample; 5 — Umbarechensky massif, interstitial chromite in the porphyric mesogabbronorite of the upper Lower Layered Zone.
Type 2 chromites: 6 — Mt.Devichja, pegmatoidal schlieren; 7 — Mt.Devichja, chromitite II; 8 — Mt.Devichja, chromitite III.
Type 3 chromites: 9 — Umbarechensky massif, River Chornaya, chromite vein.

The chromite grains in the chromitite layers are similar in texture (size, exsolution textures, zonation) to the accessory chrome spinellides (type 1), but differ in chemical composition, as they belonging into the subferrialumochromite-ferrialumochromite series and are characterized by a higher Cr_2O_3 content (42–48%) and a lower total iron content (31–33%).

The chromitite layers show elevated Pt, Pd, Rh, Ru and Au (Table 2), but the base metal sulphides are virtually absent.

3. Cross-cutting chromite vein in a mesogabbronorite of the Main Zone. This unique type of chromite mineralization is found close to the River Chornaya (Umbarechensky block) and is bounded by a S-N trending fault in the gabbronorite. It forms a vein ca. 0.5 m thick that has been traced over 100 m. Chromite makes up 50–60 vol.% of the vein (Cr_2O_3 26–30%), the remainder being mainly chlorite. The hosting gabbronorite is markedly altered close to the chromitite. Chalcopyrite, pyrite and pyrrhotite are found in the interstices between the chromite grains.

The chrome spinellides of the Imandra complex resemble those of the Burakovsky Intrusion in Karelia and those of the Critical Zone of the Bushveld lopolith but are characterized by a higher chrome content relative to other trivalent cations, a low Mg content and a high ferrous-oxide content (Fig. 3).

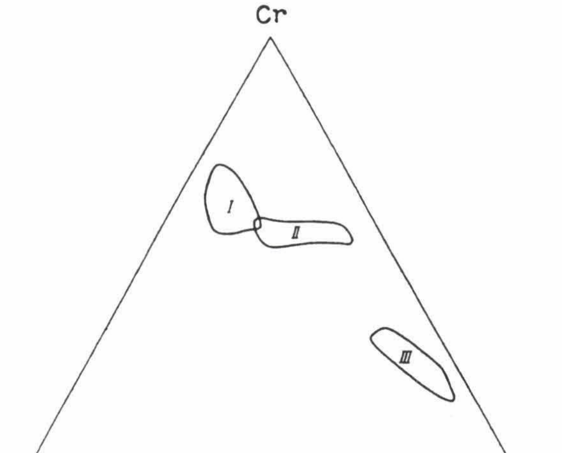

Fig. 3. Composition of chrome spinellides in the Lower Layered Zone of the Imandra Complex. I — chromite layers, Lower Layered Zone; II — accessory chromite, lower Lower Layered Zone; III — accessory chromian magnetite, upper Lower Layered Zone.

Table 2. PGE, Au and S contents in the chromitites and associated rocks of Mt. Devichja.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pt	70	130	59	150	130	16	280	350	590	75	370	210	160	180	21
Pd	23	8	1320	67	410	22	250	81	1190	75	130	17	9	61	13
Rh	-	190	-	29	38	-	51	51	-	-	37	91	35	48	-
Ru	-	120	-	81	91	-	81	60	-	-	91	140	120	47	-
Au	20	43	11	980	53	20	430	28	54	32	110	6	4	5	18
S	11	-	17	3	7	23	13	11	26	26	7	-	-	10	26

Notes: 1,2 — zoned schlieren; 3 — lower part of chromitite I; 4 ,5 — central part of chromitite I; 6 — melanorite just above chromitite I; 7,8,9 — chromitite II; 10,11,12,13 — chromitite III; 14,15 — chromitite IV.
Pt, Pd, Rh, Ru, Au in ppb, S in wt.%.

Placer chromite of the Devichja area

A placer chromite accumulation of size about 300 m x 50 m and with a chromite content of 200–400 g/t was discovered in the vicinity of Mt. Mayavr (Mt. Devichja massif). The detrital chromite is very similar in its chemical composition to the chromites in the chromitites of the Imandra Layered Complex. This and some other mineralogical features indicate that the source was the Layered Complex.

Platinum-group minerals in the chromitites of Mt.Bolshaya Varaka

Detailed mineralogical studies were performed on the PGM of Mt. Bolshaya Varaka. Minerals of the laurite-erlichmanite series dominate, whereas sperrylite is less abundant and platarsite, hollingworthite, malanite, cooperite and isoferroplatinum are rare. The bulk of the platinum-group minerals are concentrated in the interstices between silicates and chromite. Some grains of the laurite-erlichmanite series, and occasionally isoferroplatinun, are enclosed by chromite. The average grain size is 5–10 microns.

V-Ti-Fe oxides

A high-V iron-titanium oxide mineralization is hosted by the gabbroic rocks of the Roof Zone. The first and thickest magnetite layer (12 m) is located in the base of the Roof Zone (Fig. 2), having a sharp boundary with the underlying anorthosite but a gradual upper contact. The lower part of this major layer can reach 55–70 vol.% magnetite and the zones of highest grade (Table 3) have 5 wt.% TiO_2 and 0.6% V_2O_5. A magnetic survey suggests that the layer is quite extensive and traceable over the entire length of the intrusion.

The major mineral is titanomagnetite, with ilmenite and magnetite as minor minerals formed after titanomagnetite by metamorphism. The titanomagnetite to ilmenite ratio ranges from 3:1 to 5:1. Pyrite, chalcopyrite, pyrrhotite and locally sphene are also present in small amounts.

Table 3. Chemical composition of the V-Ti-Fe mineralization of the Umbarechensky massif.

no.	Interval, m	TiO_2	V_2O_5	Fe	S	Sc
Underlying anorthosite						
1	0–1.0	0.96	0.05	5.61	0.00	13
Main magnetite layer						
2	1.0–4.8	4.56	0.56	18.58	0.17	12
3	4.8–9.8	3.34	0.43	17.29	0.09	27
4	9.8–14.8	3.36	0.39	16.66	0.13	28
5	14.8–19.8	3.42	0.42	17.34	0.17	27
6	19.8–24.8	3.02	0.33	15.25	0.22	35
7	24.8–27.8	2.82	0.30	14.67	0.13	39
Overlying cumulates						
8	27.8–29.8	1.98	0.21	13.34	0.17	47
9	29.8–31.8	1.87	0.20	12.68	0.13	48
10	31.8–33.8	2.07	0.23	13.31	0.13	45
Magnetite layer no. 2						
11	0–2.0	6.27	0.57	22.35	0.05	-

Sc in ppm, other elements in weight%.

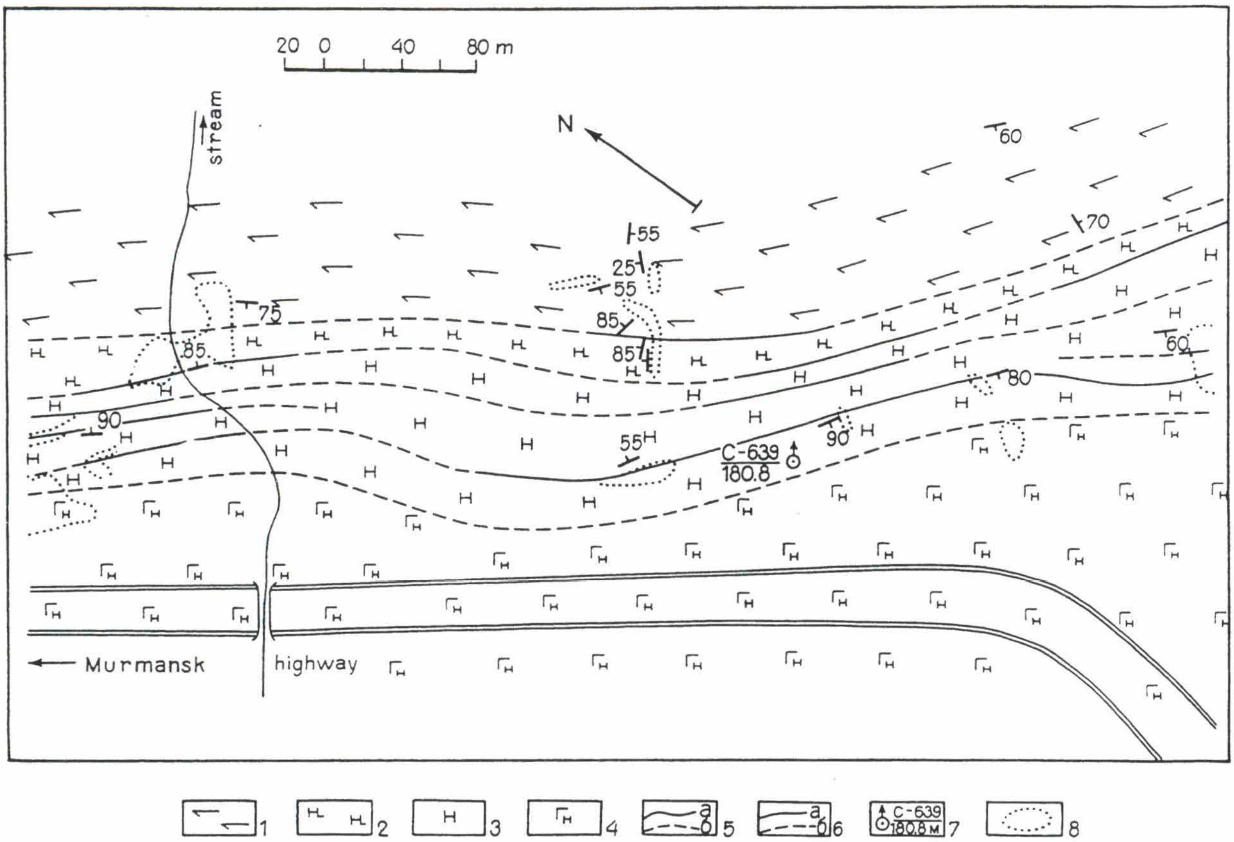

Fig. 4. Geological map of the Mt. Devichya area. 1 — late Archaean basalts and andesites, 2–4 — Imandra Layered Complex: 2 — Marginal Zone, 3 — Lower Layered Zone, 4 — Main Zone. 5 — chromitite layer, 6 — geological boundary, 7 — bore hole, 8 — outcrop.

FIELD TRIP

Stop 1 — Mt. Devichja

Marginal Zone, Lower Layered Zone and lower part of the Main Zone

The basal part of the Imandra Layered Complex, which cuts the metamorphosed late Archaean and early Paleoproterozoic andesites and basalts (Fig. 4), is exposed here in the steep slopes of a canyon and in small outcrops over an area of 100 x 800 m^2. The exposed zone is ca 100 m thick and can be traced over a distance of 800 m along the strike. The SE-NW trending (320–330°) rocks of the pluton dip 75°–90° to the southwest, and "overturned" dip angles are also found. The contact between the intrusion and the underlying rocks is exposed. At a distance of 15 m from the contact there is a zone of mesogabbronorite containing chromite schlieren and pegmatitic leuco-mesocratic amphibole-plagioclase veins (Fig. 5). The schlieren increases in thickness and frequency upwards.

Chromitite I can also be seen at this stop. The layer ranges in thickness from 0.6 to 1.7 m, and its base is uneven, but the contact with underlying taxitic rocks is sharp. There is a 10 cm transition zone at the upper contact. The same feature applies to chromitites II-IV, which we will also see. The lower half of the Lower Layered Zone (about 65 m) is composed of melanocratic poikilitic norites in the base and alternating melanocratic norite and gabbronorite with minor mesogabbronorite at the top. The upper half is composed of porphyric mesogabbronorite.

Stop 2 — Mt. Bolshaya Varaka

Chromitite ore

The chromitite deposits of Mt. Bolshaya Varaka (Fig. 1 — VII) are the most promising target for exploration and exploitation at the present time. The lowermost layer, Chromitite I, is 0.8 m thick, Chromitite II, the most important one, 0.6–2.5 m and Chromitite III, about 10 m above it, together with Chromitite IV are relatively thin, 0.25–0.5 m, being separated by a gabbronorite layer of thickness 25–30 m. Technical tests carried out by the Central Kola Prospecting Expedition gave good results, showing that the ores can be exploited well.

The potential reserves contained in the deposit, according to preliminary data from the Central Kola Prospecting Expedition, amount to 22 million tons. More precise data are not available, as a Norwegian company, "Elkem", has acquired the mining license for this site.

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Editorial handling Markku Iljina

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Edited by Felix P. Mitrofanov, Mikhail P. Torokhov & Markku Iljina
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APATITE-NEPHELINE DEPOSIT OF MT. RASVUMCHORR, KHIBINY MASSIF

by
O. B. Dudkin and V. N. Tyapina

Dudkin, O. B. & Tyapina, V. N. 1997. Apatite-nepheline deposit of Mt. Rasvumchorr, Khibiny Massif. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 45, 41–43, 3 figures and one table.

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INTRODUCTION

The world's largest endogenous deposits of phosphorus raw material are contained in the huge agpaitic nepheline syenite and foidolite massif of Khibiny (Fig. 1). The deposits were discovered in 1924 by A.E.Fersman's expedition and have been mined since 1931 (Sorensen, 1970).

Geographical position. The Khibiny massif is situated in the centre of the Kola Peninsula, 66°33'–67°55'N, 33°13'–37°16'E. Topographically, it is a dome-shaped mountain massif with the highest point 1200 m above sea level, relative elevation +900 m. The Massif is intersected by deep canyons and wide river valleys. Some of the mountains are cupped with extensive plateaus (as much as 6 x 1.5 km in area), and encircled with cirques and steep slopes. Topographic features bear evidence of glacial activity; moraine ridges are present in the river valleys. Temperatures in August range from +5 to +20°C. The town of Kirovsk, two mining settlements and 5 operating mines are situated in the area of the massif (6, 7, 8, 9, 11–13 in Fig. 1). All the mines are interconnected and linked with the processing plant by a common transport system. The distance from the Rasvumchorr mine to the Apatity station of the Murmansk-St.Petersburg railway is 24 km.

Geological investigations. The massif was mapped at a scale of 1 : 50 000 (Zak et al., 1972). The productive ijolite-urtite arc was mapped at a scale of 1 : 10 000 and a great amount of drilling was conducted in the area of the arc, including 200 drill-holes down to a depth of 1.5–2.0 km. The massif and its deposits were examined by aeromagnetic, ground magnetic, gravimetric and radiometric surveys, and deep gravimetric and seismic sounding (Kamenev, 1987).

Geological structure of the Khibiny Massif

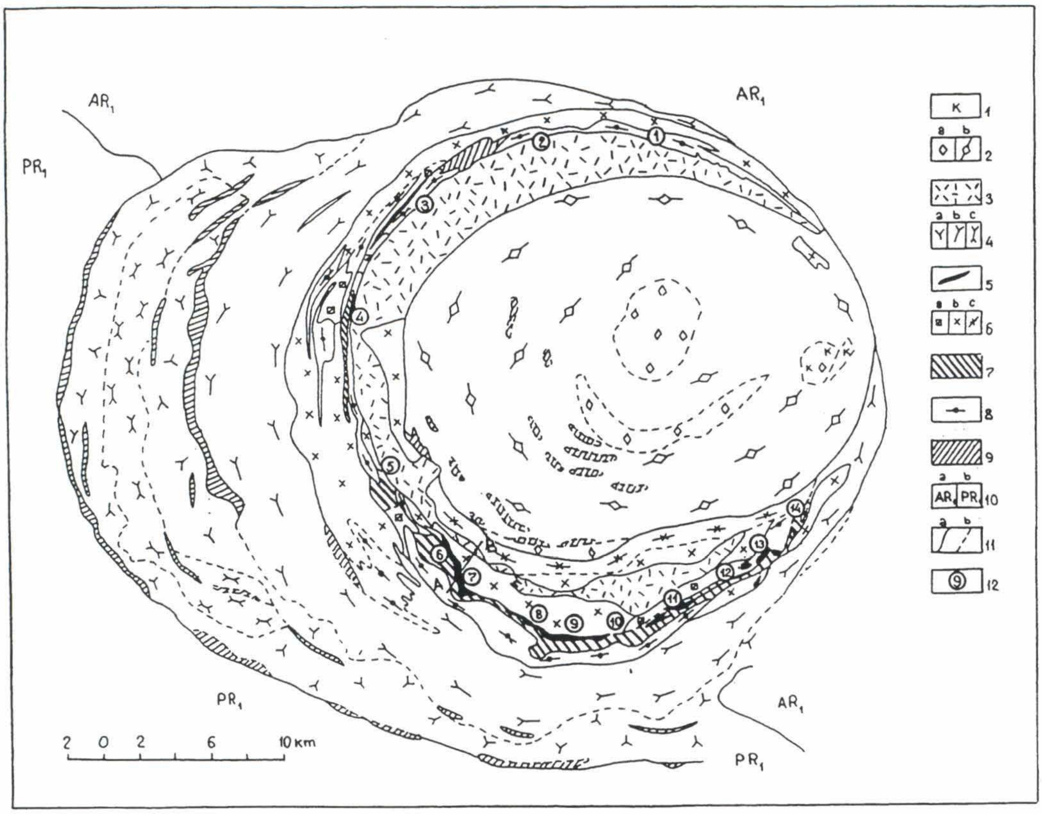

Fig. 1. A sketch map of the Khibiny massif (after V. P. Pavlov) and the location of apatite deposits. 1 — carbonatite complex; 2 — foyaite of the core: a — massive, b — trachytoid; 3 — medium-grained aegirine nepheline syenite (lyavchorrite); 4 — foyaite of the outer zone (khibinite): a — massive, b — trachytoid, c — weakly trachytoid; 5 — apatite deposits (not to scale); 6 — juvite (a), poikilitic nepheline syenite rischorrite (b), cataclastic rischorrite (c); 7 — massive ijolite and urtite; 8 — gneissoid and trachytoid ijolite; 9 — relics of hornfels, fenite, near-contact syenite; 10 — surrounding Archean and Proterozoic rocks; 11 — rock boundaries: a — established, b — inferred; 12 — apatite deposits: 1 and 2 — low-grade apatite-sphene ore occurrences in North Khibiny (3–4% P_2O_5); 3 — Partomchorr-Lyavojok (7% P_2O_5); 4 — Kuelporr and 5 — Snezhny Cirque (5–14% P_2O_5); 6 — Kukisvumchorr, 7 — Yukspor, 8 — Rasvumchorr and 9 — Plateau Rasvumchorr (up to 36% P_2O_5); Nyurpahk (13–20% P_2O_5); 14 — Oleny Stream (7–14% P_2O_5).

is shown in Figure 1. The Massif occupies an area of 1327 km^2 and is composed of several intrusive phases (Fig. 1). The intrusions were emplaced in the following succession: (1) alkaline-ultrabasic rocks, represented by relics of ultrabasic rocks and early ijolite, (2) large intrusions of agpaitic nepheline syenite in the outer arc and the core, (3) late ijolite and urtite, (4) carbonate stock. Apatite deposits (1–14 in Fig. 1) are associated with the ijolite-urtite that forms an arc in the agpaitic nepheline syenite. Proven resources of the apatite-nepheline ore are 3.8. billion tons giving 550 million tons of P_2O_5 (Kudrin & Chistov, 1996). The deposits include low-grade apatite-sphene ore occurrences (1,2, 12 in Fig. 1), relatively low-grade and diluted deposits of apatite-nepheline-feldspar and apatite-nepheline rocks (3, 5, 10, 14 in Fig. 1) and high-grade apatite-nepheline deposits (6, 7, 8, 9, 11, 13 in Fig. 1).

The geological structure of major deposits is presented in Figure 2 (Dudkin et al., 1991; Dudkin, 1993). Compact thick bodies (Fig. 2) are typical of the southern group of deposits (6–9, Fig. 1); the southeastern sector of the massif contains scattered ore blocks (Fig. 2, below; 11, 13, 14 in Fig. 1).

Mining is conducted in underground operations and open-pit quarries; the deposits of the southeastern group (13–14 in Fig.1; Fig. 2, below) are developed only by open-pit mining. The average composition of the ore is calculated to be 16% P_2O_5. Maximum annual ore extraction by the AO Apatit was 54 million tons in 1985 (Kamenev, 1987).

The extracted ore is processed by flotation. Maximum production of the apatite concentrate (1985–1990) reached 20 million tons per year, of nepheline concentrate — 2 million tons. An example of chemical composition of the ore, apatite and nepheline concentrates and pure minerals is given in Table 1. The

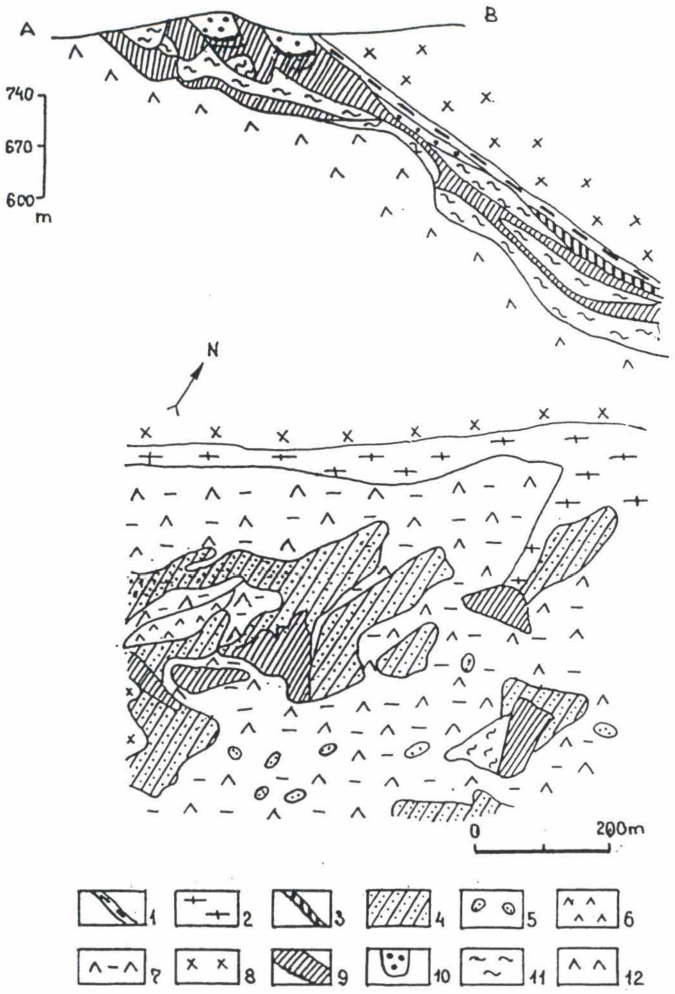

Fig. 2. Schematic structure of the largest apatite deposits of the Khibiny Massif. Top: cross-section through the Yukspor deposit (Dudkin, unpublished data); bottom: geological plan of part of the quarry in the Koashva deposit (after E. G. Balaganskaya). 1 — lujavrite; 2 — trachytoid ijolite; 3 — apatite-sphene ore; 4 — apatite breccia cemented with juvite; 5 — small xenoliths of apatite ore; 6 — fine-grained urtite; 7 — feldspathic urtite-juvite; 8 — rischorrite; 9 — apatite breccia cemented with apatite ijolite; 10 — high-grade mottled ore; 11 — lenticular-banded ore; 12 — massive urtite.

mineral composition of the produced ore (in wt.%) is: apatite 38.4, nepheline 37.1, pyroxene 12.2, amphibole biotite 1.8, natrolite+hydromica 2.4, microcline 2.3, sphene 2.7, titanomagnetite 2.1; accessory minerals (~1%) are eudialyte, astrophyllite, mosandrite, perovskite, aenigmatite and pectolite. The apatite concentrate is used to produce superphosphate and hydrofluoric acid; nepheline concentrate is used in the preparation of aluminum, soda and potash. Pilot tests of a technique to produce titanium-silicon pigment from sphene concentrate have been successfully carried out.

FIELD TRIP

The participants will visit the Rasvumchorr Mine (8 in Fig. 1), which is located inside the mountain massif, in the southern part of the ijolite-urtite arc. The road to the Mine goes via Kirovsk and the road junction "23rd kilometer" of the AO Apatit. On the way it is possible to see the location of the Kukisvumchorr and Yuksporr mines. The Rasvumchorr deposit is a massive body reaching thicknesses up to 120 m. The ore body was strongly tectonized. Mining is conducted by open-pit and underground methods.

Table 1. Chemical composition of apatite ore, concentrates and pure minerals of apatite deposits of Khibiny.

Components	1	2	3	4	5	6
SiO_2	25.54	0.57	0.16	43.77	41.99	29.52
TiO_2	0.91	0.08	n.d.	0.04	0.02	38.69
ZrO_2	0.00	n.d.	n.d.	n.d.	n.d.	0.38
P_2O_5	16.65	39.40	40.97	0.24	0.00	0.00
Nb_2O_5	0.00	n.d.	n.d.	n.d.	n.d.	0.51
Al_2O_3	15.36	0.51	0.16	29.83	33.04	0.47
TR_2O_3	0.24	0.80	1.04	n.d.	n.d.	0.54
Fe_2O_3	2.16	0.79	0.03	2.49	1.84	1.56
FeO	1.66	0.10	n.d.	0.95	0.00	0.12
MnO	0.09	0.01	0.01	0.00	n.d.	0.03
MgO	0.68	0.05	0.04	0.71	n.d.	0.07
CaO	23.08	52.32	52.47	1.22	0.04	27.38
SrO	0.74	2.53	2.84	0.00	0.00	0.22
Na_2O	7.72	0.36	0.09	12.49	16.06	0.37
K_2O	3.01	0.11	0.03	7.68	6.90	0.05
H_2O+	0.86	0.39	0.39	0.35	0.00	0.00
H_2O-	0.12	0.08	0.00	0.14	0.00	0.06
CO_2	0.18	0.09	n.d.	n.d.	n.d.	n.d.
F	1.42	3.28	3.15	n.d.	n.d.	0.17
-O~F	0.60	1.38	1.32	0	0	0.08
Total	99.82	100.00	100.06	99.88	99.89	100.34

Notes: 1 — a sample of apatite ore; 2 — apatite concentrate, after Kamenev (1987); 3 — apatite; 4 — nepheline concentrate; 5 — nepheline; 6 — sphene.

Stop 1 — Rasvumchorr Mine in the central part of the ijolite-urtite arc of the Khibiny Massif, at 67°37'N, 33°47'E

Ore breccia in the open pit

The benches of the quarry exhibit an apatite breccia composed of apatite ijolite with xenoliths of banded and mottled apatite ore. Xenoliths in the breccia comprise lenticular-banded ore (urtite and ijolite lenses and bands in coarse-grained apatite) and mottled ore (massive apatite mottled with silicates).

Visit to the Geological Survey of the Rasvumchorr Mine

Here will be provided information about mine surveying, geological documentation, stock-taking, operation prospecting, and ore production. The reserves are calculated for 8, 4 and 2% P_2O_5 cut-off; methods of calculation by blocks, sections and thickness isolines are used. Sampling is done by chemical methods and controlled by neutron activation monitoring of fluorine in apatite.

Stop 2 — Rasvumchorr Mine, at 67°37' N, 33°47'E

Here we will examine the rock underlying the ore body and representing a huge source of nepheline raw material. The boundary between the apatite body and the footwall varies depending on the accepted P_2O_5 content at cut-off (Fig. 3), demonstrating that the apatite mineralization is closely linked genetically with the urtite. Tectonic deformation is conspicuous in the bottom part of the ore body, where urtite and apatite (lenticular-banded ores) are predominant. In the upper part of the ore body, there is an apatite breccia containing large xenoliths of lenticular-banded ore and rare relics of high-grade mottled apatite ore. From the ore grade contours it can be seen that the upper contact between the ore body and the poikilitic nepheline syenite is sharp. In the ore body, alkaline pegmatite and crosscutting veins of trachytoid nepheline syenite (lujavrite) are present. Because of the presence of methane-bearing natural gases, the gas regime is controlled in the underground operations. Fractured zones of weathering penetrate deep into the mountain massif, and require support structures.

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Editorial handling Hugh O'Brien

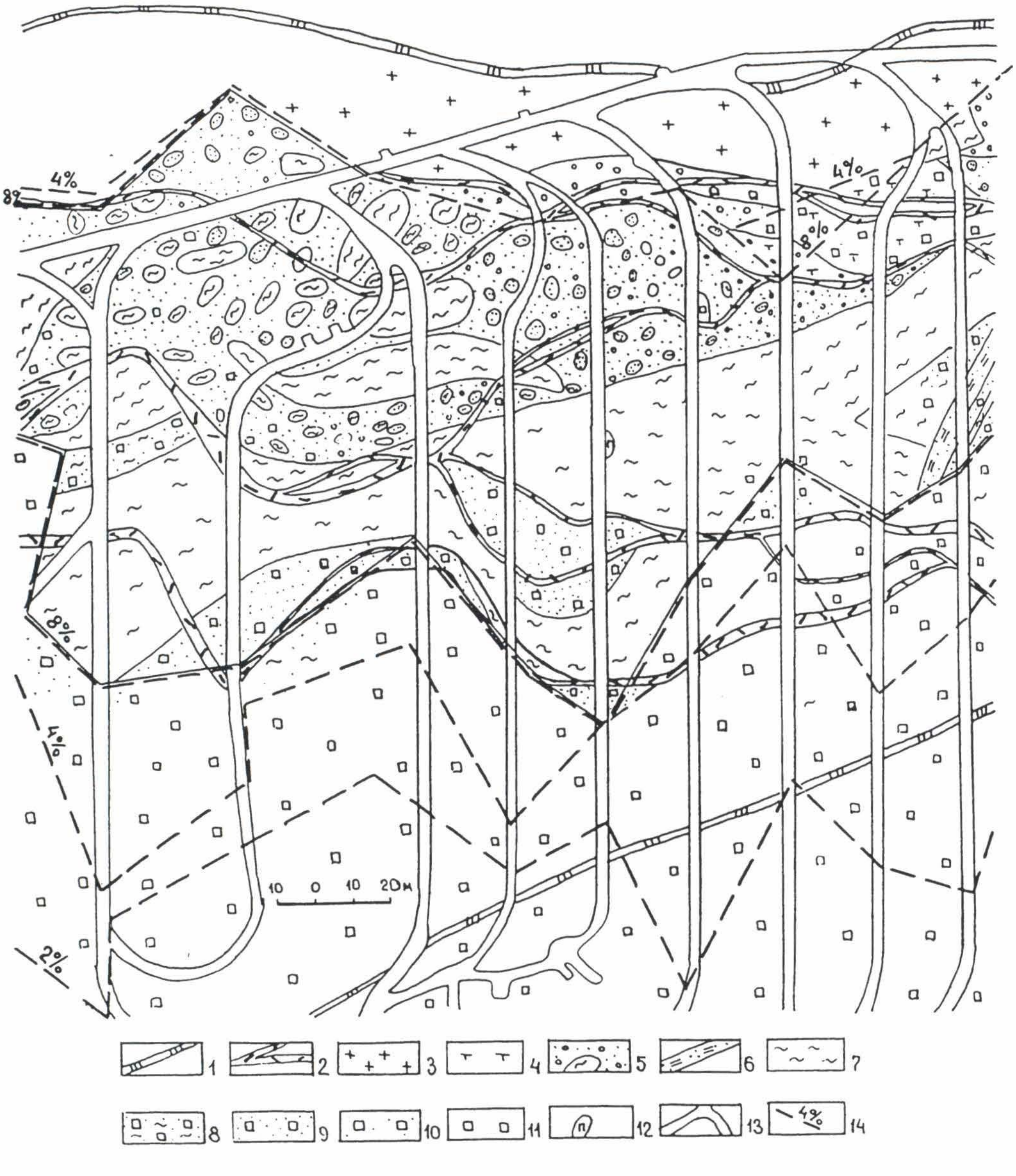

Fig. 3. Plan of the underground level of the Rasvumchorr mine (Geological Survey of the Rasvumchorr Mine, unpublished data). 1. fractured zones of weathering; 2. nepheline syenite (lujavrite) veins; 3. poikilitic nepheline syenite (rischorrite); 4. sphene mineralization; 5. apatite breccia; 6. thin-banded apatite ore; 7. lenticular-banded ore; 8. interlayered urtite and lenticular-banded ore; 9. apatite-rich urtite (banded, massive and block ore); 10. urtite enriched in apatite; 11. massive urtite, ijolite; 12. alkaline pegmatite; 13. excavations; 14. boundary outlining the area of calculated reserves with the assumed P_2O_5 content at cut-off.

ACKNOWLEDGEMENTS

We would like to thank the Geological Survey of Finland for providing the opportunity to publish this excursion guidebook. The help of Professor H. Papunen and Dr. P. Nurmi is acknowledged on this matter. The data for the separate papers were provided by the people of the Kola Science Centre and some other organisations to whom we are most grateful. Acknowledgements are also extended to S. Yu. Delenitsina and M. Hicks who helped in the compilation and improved the English of the original manuscript.

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ISBN 951-690-681-8
ISSN 0781-643X

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OY EDITA AB
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