VII International conference

Ultramafic-mafic complexes: geology, structure, ore potential

FIELD TRIP GUIDEBOOK

Sulphide Cu-Ni deposits of the Pechenga ore field

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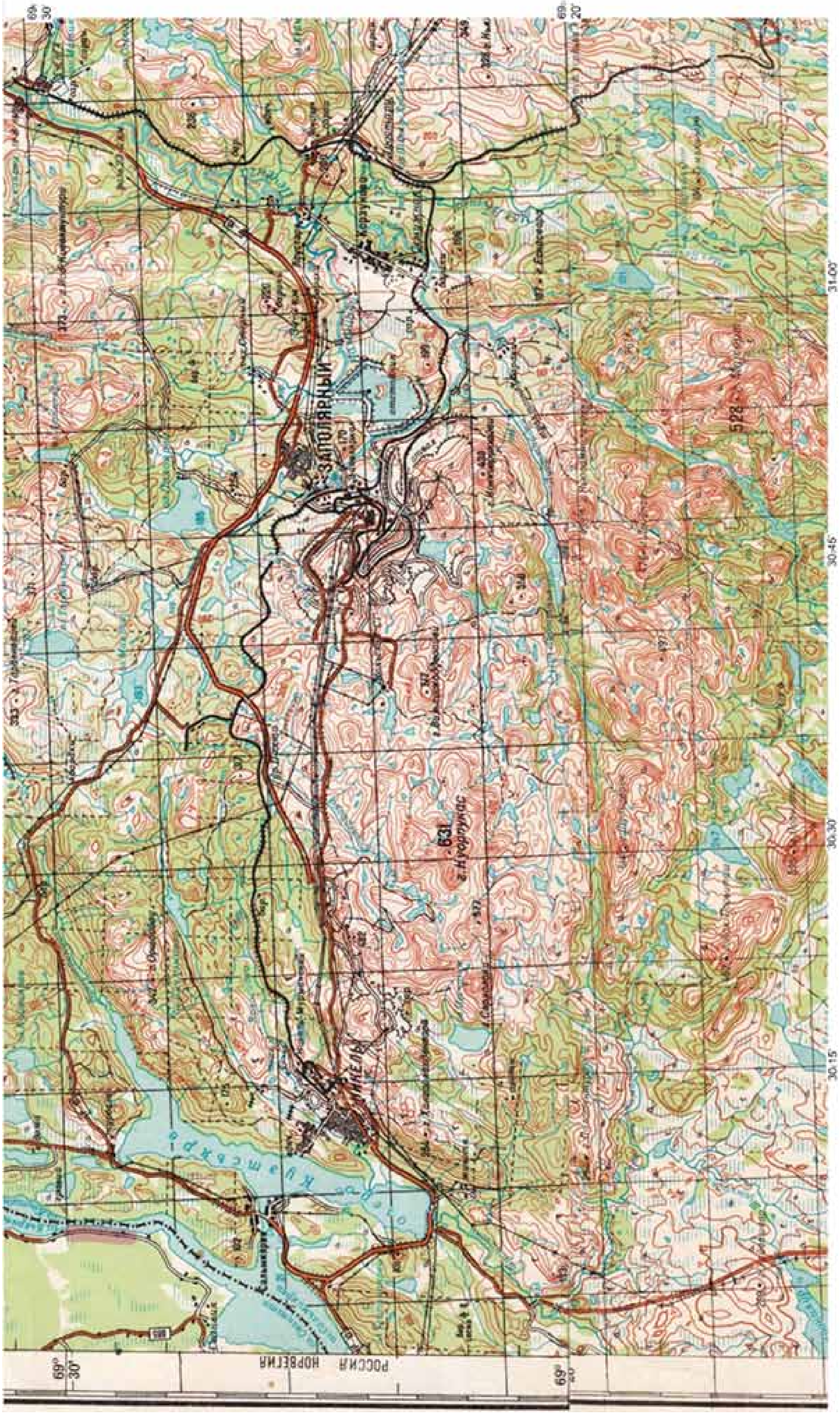
Cover photograph: Pillow lava of tholeiitic basalt of the Matert Formation. Photo: N. Groshev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НОРВЕГИЯ
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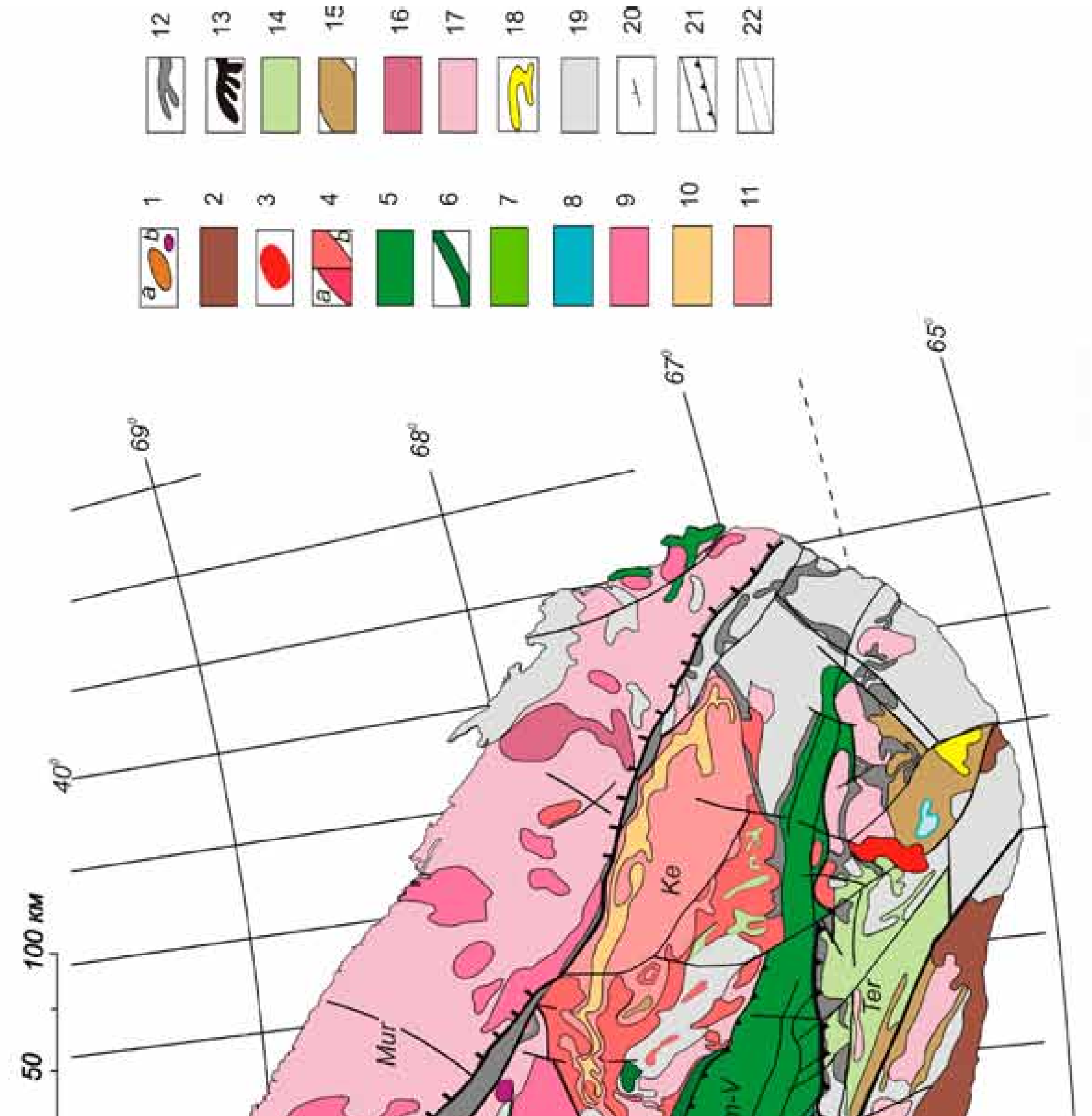

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GEOLOGICAL MAP OF THE KOLA SUBPROVINCE OF THE FENNOSCANDIAN SHIELD

(Mitrofanov et al., 1995)

1 – Paleozoic alkaline intrusive complex;

1 – Neoproterozoic sedimentary rocks.

Paleoproterozoic: 3 – granite, granodiorite, diorite; 4 – charnockite (a), alkali granite, including of the archean time (b); 5 – volcanic and sedimentary rocks; 6 – anorthosite and gabbro-anorthosite, including of the archean time; 7 – basic and intermedia granulite; 8 – asid granulite. M*ezo and Neoarchean*: 9 – granodiorite, diorite, enderbite; 10 – aluminiferous gneiss; 11 – asid gneiss; 12 – fragments of the greenstone belts; 13 – fragments of the banded iron formation; 14 – gneiss, schist; 15 – amphibolite, gneiss; 16 – granodiorite, diorite; 17 – plagiogranite, granite-gneiss; 18 – kyanite-garnet-biotites gneiss; 19 – granite-gneiss, gneiss, migmatite.

20 – element posizion; 21 – subvertical faults; low-angle thrust. 22 – other fault.

Units: *Mur* – Murmansk, *Ko1* – Central Kola, *Bel* – Belomorian, *Kar* – Karelian; *Ter* – Tersky, *Ke* – Keivy, *In* – Inari. Archean greenstone belts: *Jon* – Ena, *K-V* - Kolmozero-Voronja. Granulite belts: *LGB* -Laplandian, *KGB* – Kandalaksha-Kolvitsa. Paleoproterozoic belts: *Pe* – Pechenga, *Im-V* – Imandra-Varzuga, *S-K* – Salla-Kuolojarvi.

THE PECHENGA STRUCTURE

General geology

The Pechenga structure, which is presently the best studied structure of the Kola region, occupies an area of over 2 000 km^2. It is divided by the Poritash fault into two major tectonic-lithological units called the Northern Pechenga and Southern Pechenga Zones (Fig. 1a).

The Northern Pechenga Zone forms a monocline structure with transverse and diagonal faults of which some are syn-sedimentary. The largest, composite strike-slip and reverse faults dip steeply to the south. The rocks dip in southern directions 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 c. 500 Ma as a result of recurrence of sedimentary-volcanic cycles totaling 8.5 km in thickness [Smolkin et al., 1995 a, b, 1996; Kola Superdeep. 1998]. Four major cycles have been distinguished with each of them beginning with metasedimentary rocks and ending with a thicker pile of volcanic rocks (Table 1). They were deposited c. 2.4 to 1.9 Ga 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 strongly metamorphosed rocks; some of them can be correlated with the volcanic rocks of the upper

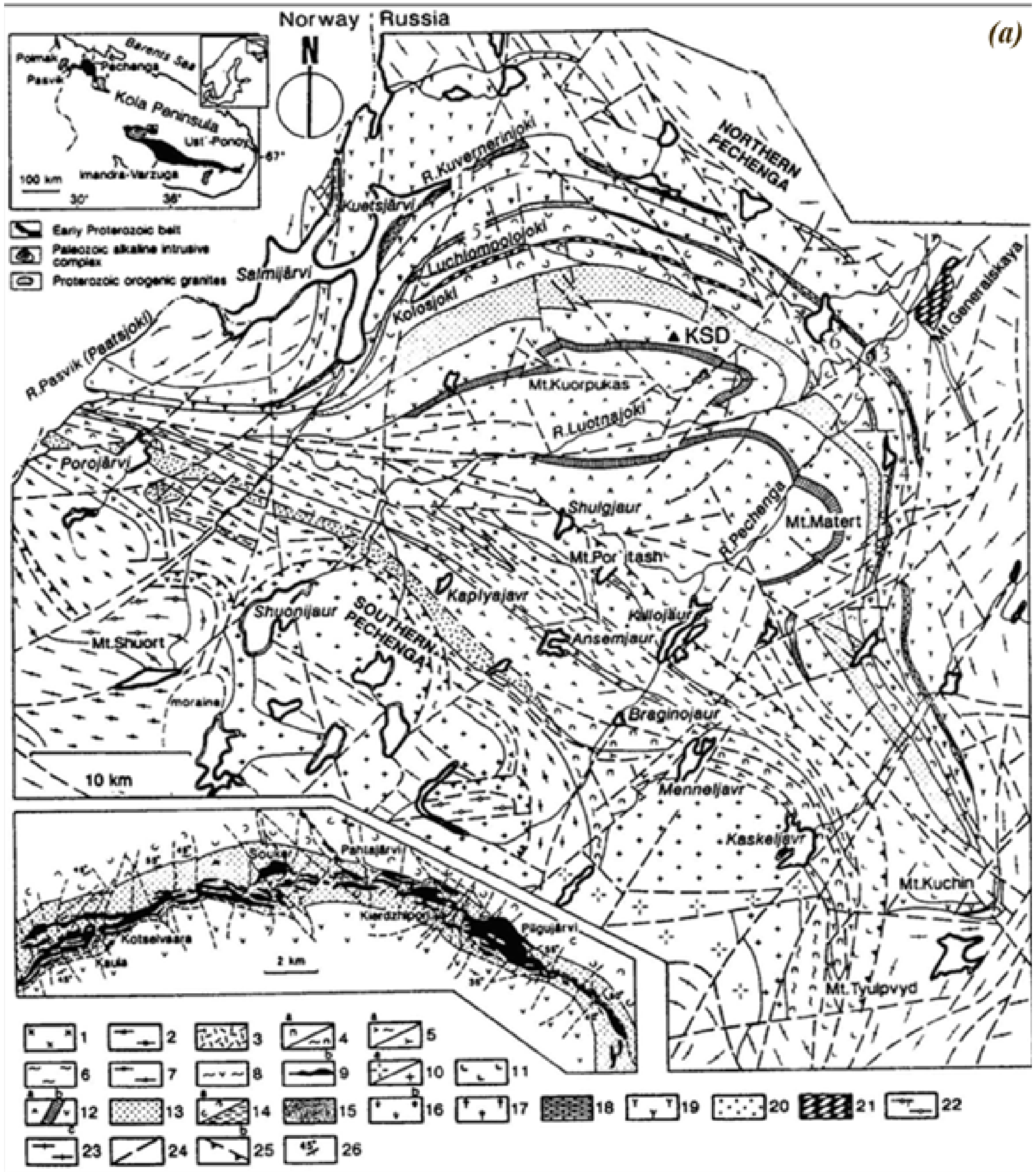
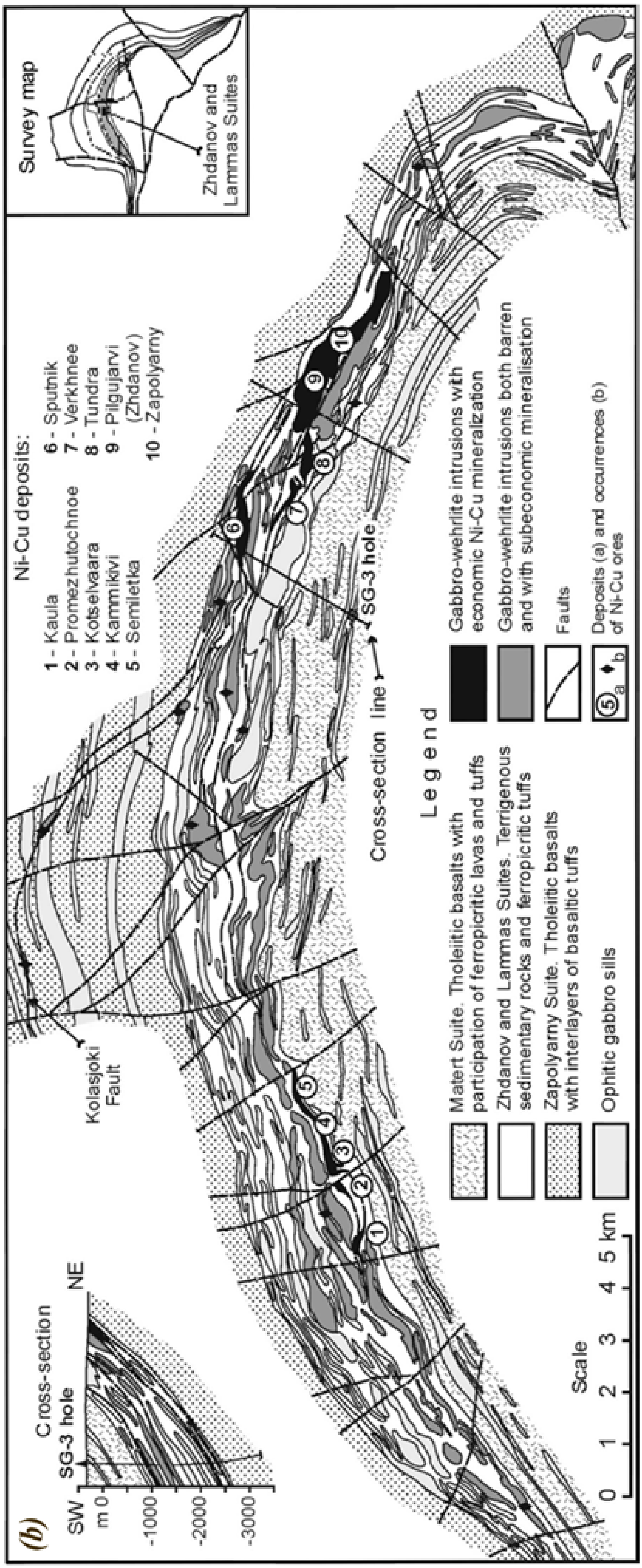


Fig. 1. Geological sketch map of the Pechenga structure (a) and ore area (b), from [Smolkin et al. 1995 a]. 1 – dacite and rhyolite, the Poritash subvolcanic complex; 2 – tuff conglomerate, gravelstone and sandstone, the Kassesjoki Fm; 3 – andesite, dacite and rhyolite, the Kaplya Fm; 4 – picrite, basalt, 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 turbidite, 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 – trachy-basalt, trachyandesite-basalt, trachyandesite-dacite and trachyte, the Pirttijärvi Fm; 18 – quartzite and 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.



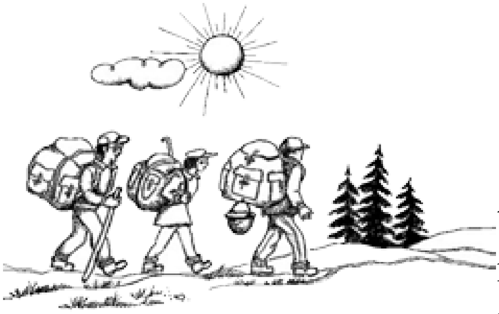
(b)
Cross-section
SW
NE
SG-3 hole
m 0
-1000
-2000
-3000
Scale
0 1 2 3 4 5 km
Kolasjoki Fault
Ni-Cu deposits:
1 - Kaula
2 - Promezhutochnoe
3 - Kotselvaara
4 - Kammikivi
5 - Semiletka
6 - Sputnik
7 - Verkhnee
8 - Tundra
9 - Pilgujarvi (Zhdanov)
10 - Zapolyarny
SG-3 hole
Cross-section line
Survey map
Zhdanov and Lammas Suites
Legend
Matert Suite. Tholeiitic basalts with participation of ferropicritic lavas and tuffs
Zhdanov and Lammas Suites. Terrigenous sedimentary rocks and ferropicritic tuffs
Zapolyarny Suite. Tholeiitic basalts with interlayers of basaltic tuffs
Ophitic gabbro sills
Gabbro-wehrlite intrusions with economic Ni-Cu mineralization
Gabbro-wehrlite intrusions both barren and with subeconomic mineralisation
Faults
Deposits (a) and occurrences (b) of Ni-Cu ores

Table 1. Stratigraphic scheme of the Pechenga structure and isotope ages.

Eon	Complex	Superhorizon	Lithostratigraphic unit	Volcanic, sedimentary formation; intrusive complex	U-Pb ages (Ma)
Palaeoproterozoic	Karelian	**SOUTHERN PECHENGA ZONE**			
		KALEVIAN	**Porojarvi Group** Kasesjoki Fm	Conglomerate-shale; molassoid Dacite-rhyolitic subvolcanic complex	
			Kaplya Fm **Ansemjoki Group** Mennel Fm Bragino Fm Kallojaur Fm	Andesite-dacite-rhyolite Picrite-basalt Picrite-basalt-andesite Tuff-shale Intrusive plagiogranite complex	1939±м7[2]
		NORTHERN PECHENGA ZONE			
		LUDICOVIAN	**Pilgujärvi Group** Suppvaara Fm Matert Fm Lammas Fm (Upper Productive) Zdanov Fm (Lower Productive)	Gabbro-wehrlitic complex Tholeiitic basalt Ferropicrite-basalt Terrigenous (shale) Flyschoid	1980±10[1] 1985±10[1]
		UPPER JATULIAN	**Kolosjoki Group** Zapolyarny Fm Luchlompolo Fm	Tholeiitic basalt Terrigenous-tuff-carbonate	2140±5[3]
		LOWER JATULIAN	**Kuetsjärvi Group** Orshoaivi Fm Pirttijärvi Fm Kuvernerinjoki Fm	Basalt Trachybasalt Quartzite-carbonate	2340±3[3]
		SARIOLIAN	**Ahmalahti Group** Majärvi Fm Televi Fm	Andesite-basalt Basal conglomerate	
Layered intrusion Mt. Generalskaya					2505–2496[4]
ARCHEAN BASEMENT					2700–3000

Literature sources of age data: [1] Smolkin et al., 2003, Smolkin et al., 2018; [2] Skuf'in et al., 2003; [3] Skuf'in et al., 2013; [4] Amelin et al., 1995; Baynova et al., 1999.

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. The estimated total thickness of the Southern Zone rocks is 3.0–3.5 km. The Southern Pechenga Zone is not considered anymore in this account, and the following description of the geology of the Pechenga structure is limited to the Northern Pechenga Zone.



NORTHERN PECHENGA ZONE

The Kola Superdeep Well (SG-3) transected the contact between the supracrustal rocks of the Karelian Complex and the tonalite-trondhjemite-granodiorite association of the Archaean basement at a depth of 6842 m [Kola Superdeep. 1998). The basement is heterogeneous and contains various gneisses with zircon ages of 2.85–2.80 Ga and amphibolites, ferruginous quartzites, migmatite-granites of late Archaean age. More ancient (2.99–2.91 Ga) rocks include tonalitic gneisses revealed by erosion in the area north of the Pechenga greenstone belt. The rocks of the basement were intensively tectonised and metamorphosed during the Palaeoproterozoic time. In the Mt. General'skaya area (Luostari railway station), erosion has exposed mafic rocks of a layered intrusion with zircon ages of 2505–2496 Ma [Bayanova et al., 1999], which are overlain by terrigenous sediments containing gabbro-norite clasts. These sedimentary rocks begin the Palaeoproterozoic sequence described below.

The Ahmalahti Group (Sariola)

The Ahmalahti Group is composed of basal polymictic conglomerates and arkosites of the Televi Formation and volcanic rocks of the Majärvi Formation, having a total thickness from 1 600 m (central zone) to 100–200 m (flanks). Three major sequences of approximately equal thickness have been recognized in the sedimentary succession. At the base of each sequence, coarse, cross-bedded units of conglomerates and gravelstones occur with the clast composition being dominated by plagiogranites, granodiorites, and granite-gneisses. The middle and upper parts of the sequences are composed of gravely and coarse-grained psammites. The formation of the terrigenous deposits proceeded under transgressive conditions, as is evident from the facies distribution. Near the Russian-Norwegian national border, the basal sedimentary horizon sharply wedges out, and volcanogenic rocks directly overlie the Archaean granite-gneiss basement.

The basal horizons of the overlying Majärvi Formation comprise tuff layers and thin flows of low-titanium and picritic basalts, whereas the main part of the succession is composed of basaltic andesite and, less commonly, andesite and andesite-dacite flows 0.5 to 15–25 m thick. The lower flows are mainly represented by massive varieties, and amygdaloid zones are widespread in the upper flows. The sporadic occurrence of pillow lavas suggests that sometimes eruptions occurred below sea level. Basaltic andesites are characterised by distinct enrichment in LREE and show a negative Eu anomaly. A U-Pb zircon age of 2340 ± 3 Ma was recently obtained for the Majarvi Formation by Skufin et al. [2013].

Kuetsjarvi Group (Jatulian)

The first one of the three formations of this group, the Kuvernerinjoki Formation (thickness up to 400 m), rests upon the weathering surface of the basaltic andesitic rocks of the Majärvi Formation. The lower part of the formation is composed of mature, grayish or reddish feldspar-quartz and arkoses, hematite-bearing psammites of variable grain size and gravelstones and quartzous conglomerates. The upper part consists of dolomites and their breccias. In the Luottnjoki Creek area, two horizons of stromatolitic dolomites separated by oncolitic dolomites have been recognized. The lower part of the terrigenous sequence exhibits thin horizontal layering, whereas its upper part shows the alternation of cross, wavy, and cross-wavy bedding, as well as characteristic structural elements, such as erosion surfaces, soft sediment deformations, and neptunian dykes. Accumulation of the sediments took place in a shallow basin. Metasedimentary rocks of the Kuvernerinjoki Formation are conformably overlain by subalkaline volcanic rocks of the Pirttijärvi Formation with a thickness varying from 150–250 m to 1 000 m. The lower part of the formation is characterized by metatuffs and thin lava flows of picritic basalts and the middle and upper parts contain trachybasalts and basaltic trachyandesites. The latter form flows 0.5 to 25 m in thickness and horizons of lava breccia, tuffolava and tuff. Lava flows often show an upper amygdaloidal zone composed of more acid or alkaline (dacite and trachyte) rocks. Separate dacite sills of the subvolcanic type also occur.

Subalkaline volcanic rocks are overlain by a well traceable marker horizon from 10 to 40 m in thickness, consisting of tufoconglomerates and tuffaceous shales, which are often underlain and overlain by pillow lavas.

The composition of the pebbles and volcanic bombs correspond to that of the underlying volcanic rocks, while in the case of the shales, a greater role is played by products of decomposition of mainly volcanogenic material in a subaqueous environment.

Higher in the section occur volcanic rocks of various composition, belonging to the Orshoaivi Formation. They constitute massive and rarely pillowed basaltic lavas, intervening layers of tuffs, and also subvolcanic bodies of basaltic trachyandesite and dacite composition. Judging from interlayering of volcanic rocks of different composition, there was a gradual change of magmatic sources. Volcanic rocks of both formations are enriched in light REE, and sometimes exhibit a Eu anomaly, with the most enriched ones being trachytes and the least enriched picritic basalts.

For volcanic rocks of the Kuestjärvi Group, a subaerial environment of eruption is established. Basaltic eruptions were mainly of the fissure type, episodically interrupted by subaqueous eruptions. Acid and alkaline melts were typically erupted from central-type volcanoes. One of them is exposed by in the city of Zapolyarny. Such volcanoes are characterized by the presence of abundant eruption breccias containing fragments of late-Archaean granite, granite-gneiss, and amphibolite, and grayish quartzite similar to that occurring in the underlying formations.

Kolosjoki Group (Ludicovian)

The basal part of the Kolosjoki Group is composed of red arkose sandstone, gravelstone, conglomerate, dolomite, jasper, and tuffite of the Luchlompolojoki Formation, with a total thickness from 80 to 150 m and, sometimes, to 400 m. By going from the formation base upward, a gradual transition from coarse- to finegrained terrigenous and carbonate, and then to carbonaceous-siliceous deposits can be observed, accompanied by parallel changes from massive to coarsely and wavy cross-bedded, and then to fine-wavy cross-bedded textures. Based on the isotopic study of detrital zircon grains, the sources of the detrital material, apart from the underlying volcanic rocks, were rocks of late-Archaean age (2.7–2.8 Ga). The upper part of the red dolomites incorporates bio-herms of stromatolite. The section terminates with the carbonate-chlorite and carbonate-sericite-chlorite schists 5–60 m in thickness, which were formed after the tuffites and vitroclastic tuffs of basaltic or picritic composition.

The contact between the metasedimentary rocks of the Luchlomplojoki Formation and volcanic rocks of the overlying Zapolyarny Formation is often disturbed by tectonic dislocations of different age. The base of the Zapolyarny Formation includes intensely foliated ferropicrite lava flows with an MgO content of 15–19 wt.%. They recorded the first occurrence of ultramafic volcanism in the Pechenga area.

In the central part of the Pechenga structure, the Zapolyarny Formation consists of two members separated by a discrete, relatively thin (up to 70 m) horizon of agglomerate and tuffaceous shale. The total thickness of both members is 1600 m in natural outcrops, and 2000 m in the SG-3 section. These members are composed of massive (72 %) and less common pillow (23 %) lavas, with separate layers of lava breccia, tuff breccia, tuffagglomerate, hyaloclastite, and tuff. Compared to the lower member, the flow thickness in the upper unit decreases, varying here from 0.5 to 20 m, and the degree of sequence contrast increases. The thickness of tuff beds is from 3 to 5 m. Besides eruptive rocks, there are also wide occurrences of sills of ophitic gabbro. The chondrite-normalised REE spectra of volcanic rocks of both members are similar to those of MORB, though they are somewhat enriched in light REE. The U-Pb zircon age of the volcanic rocks is equal to 2140±5 Ma [Skufin et al., 2013].

Pilgujarvi Group (Ludicovian)

The supracrustal rocks of the Pilgujärvi Group are subdivided into two tuffaceous-sedimentary (Zhdanov and Lammas) and two volcanogenic (Matert and Suppvaara) formations. The Zhdanov Formation, which is mainly composed of terrigenous rocks, rests upon the basalts of the Zapolyamyi Formation without visible signs of hiatus and angular unconformity. It hosts numerous gabbro-wehrlite intrusions containing industrial deposits of copper-nickel sulphide, and was earlier known as the «Productive member». The Zhdanov Formation has been divided into three major sequences. The first one is composed of basal aleurolites, and psammitic and psammitic-pelitic beds, the second one of phosphate-bearing gravelly-psammitic-pelitic and carbonate-pelite beds, and the third one of tuffogenous-sedimentary and tuffogenous-volcanogenic beds. Within the formation, there are widely developed beds of sulphide- and carbon-rich black shales with a high content of organic material, lenses of phosphate-bearing conglomerates, siliceous slates, and carbonate-, phosphate-, quartz- and sulphide-rich concretions.

The overlying Lammas Formation is characterised by a variable thickness (from 5–10 to 400–600 m) and the dominance of tuffs of basaltic and ferropicritic composition. Its lower boundary is marked by the appearance of psephitic tuffs, intensively altered by hypergene processes. The greatest thickness of the unitis established in the areas of Lammas and Valas rivers, and also in the Kotselvaara open pit, indicating centres of volcanic eruptions. In the Lammas Formation, lense-like layers containing pebbles and separate boulders are also found which are composed of plagiogranite, granite-gneiss and quartzite, and might represent glacial dropstones.

The central or core part of the Northern Pechenga Zone is occupied by basaltic and ferropicrtic volcanic rocks of the Matert Formation. In the Pechenga ore camp area, they lie conformably on metasediments of the Lammas or Zhdanov Formation, but on the western flank of the Pechenga structure, they lie non-conformably on rocks of the Pirttijarvi Formation. The area of development ofthe mentioned volcanism is divided by syn-sedimentary faults into three blocks: Kuorpukas, Matert and Suppvaara. The two first constitute volcanic rocks of the Matert Formation and the last those of the Suppvaara Formation.

Three subunits have been distinguished in the section of the Matert Formation. The lowermost has an average thickness of 1600 m and consists of interlayered massive and pillowed lava flows of tholeiitic basalts, beds of lava breccias, tuffs, tuffites, and hyaloclastites of mafic composition and thin lenses of sulphide-bearing and carbonaceous shales. In the lower and middle parts of the section, there are also layered ferropicritic lava flows, which belong to the third and fourth cycle of ultrabasic volcanism at Pechenga.

The second unit also contains highly siliceous beds of turbiditic type, representing a marker horizon. They can be followed along strike for more than 20 km from Lake Ostrovnoe (in the east) to Kuorpukas Mt. and further to the Russian-Norwegian national border (in the west). The thickness ofthe horizon varies from 5–10 m to 200–300 m. Characteristic features include graded bedding, combination of massive and small clast size rocks, the presence of carbonate concretions and volcanic bombs of ferropicrites, and also small fragments of granophyric granite, grains of plagioclase, microcline, high-Fe clinopyroxene-hedenbergite, quartz and ilmenite. The felsic rocks show high contents of SiO_2 (74–84 wt. %) and Zr (up to 740 ppm), a strong enrichment in LREE, distinct negative Eu anomaly and narrow range of $\delta_{18}O$ from +9.4 to +10.7. On the northern slope of the Kuorpukas Mt., these deposits lie on a ferropicritic lava flow having a montmorillonitic crust of submarine weathering. Yet, the source of the detritus, as demonstrated by isotopic analyses of detrital zircon grains, was granitoids of late-Archaean age (2.65 Ga).

The third subunit of the Matert Formation is composed in the area of Lake Shulgjaur of massive and pillowed tholeiitic basalts, hyaloclastites, rare lenses of tuffs and sulphidic and carbonaceous shales, attaining a total thickness of 1500 m. In the middle part of the unit (Dvoinaya Mt., Lake Shulgjaur), alternation of massive and pillowed lavas and layered ferropicritic lava flows of the fifth cycle of the ultrabasic volcanism is observed.

The succession of the Northern Pechenga Zone is terminated by the volcanic rocks of the Suppvaara Formation, which in most cases show tectonic contacts and are clearly distinguished on magnetic maps. The geological mapping has shown that the volcanic rocks of the Matert Formation wedge out towards the flanks of the Northern Zone, whereas the Suppvaara volcanic rocks are traced to the south-eastern flank of the Southern Pechenga Zone, i.e. to the Tyulpvyd tundra and Peschanoe Lake areas. The Suppvaara Formation consists of monotonously alternating thick flows of massive and pillow basalts; its sequences lack ferropicrites and high silica rocks. The thickness of the formation is up to 1700 m.

Volcanic rocks of the Matert and Suppvaara Formations are generally represented by massive (47 % on average) and pillowed (40 %) mafic lavas, breccias (1 %) and tuffs (8 %). In addition, they are associated with ferropicrites and their tuffs (4 %), with the percentage of pillow lavas increasing in the Suppvaara Formation up to 70 %. The volcanism took place mainly in a deep-water environment in a slope area with highly differentiated relief, which resulted in sharp variations in flow thicknesses, facies transition from massive to pillow lavas, and the formation of turbidite beds with graded bedding. The greater thicknesses of basalt tuffs in the Ostrovnoe Lake area and their gradual reduction towards the Kuorpukas block may indicate a southward migration of eruption centres. The volcanism was accompanied by the emplacement of dolerite and picrite-dolerite dykes of two generations, which cross-cut sedimentary rocks and nickel-bearing gabbro-wehrlite intrusions of the Zhdanov Formation.

In the area of the tuffaceous-sedimentary and volcanogenic rocks of the Pilgujarvi Group, lenticular sills of ophitic gabbro are widespread. In terms of their geochemical features, they are similar to tholeiitic basalts of the Matert Formation, and are therefore their comagmatic varieties. Under tectonic deformations, they behave as monoliths and often occur in the frontal parts of thrust structures.

The above-mentioned tholeiitic basalts and ophitic gabbros show flat REE patterns that suggests their similarity to the MORB-type volcanic rocks. However, they differ from the latter in having higher K, Rb and Ba contents, which is probably a result of contamination of the parent magma with sialic material. Tholeiitic basalts of the Zhdanov and Matert Formations are almost identical with respect to their REE spectra. The volcanic rocks of the Matert Formation from the central Pechenga structure and its eastern margin (Kuchin Mt.) are also close to each other in this parameter, despite the different degree of metamorphism (prehnite-pumpellyite and amphibolite facies, respectively). Metabasalts of the Suppvaara Formation in the northern and southern zones exhibit a noticeable enrichment in LREE.

Ferropicritic volcanic rocks and comagmatic intrusive gabbro-wehrlites show strong enrichment in light REE and a somewhat lower content of heavy REE. They are also enriched in total FeO (>14 wt. %), Cr, Ni, Ti, Zr, P, and S [Smolkin 1992; Hanski, Smolkin 1995]. Ferropicrites of the same facies types (massive and pillow lavas, layered flows and tuffs) from different levels show significant geochemical similarity, which suggests a stable composition of their parent magma for a long period of time. Thus, geochemical and isotope data suggest the coeval existence of two independent mantle sources: the depleted, shallow magma source for tholeiitic basalts, and a metasomatically transformed, deeper source for ferropicrites.

Ore-bearing intrusions

The ore-bearing gabbro-wehrlite intrusions, being common in the central part of the Northern Zone, constitute a comagmatic volcanic-plutonic association together with ferropicrite metavolcanites of the Matert Formation and the kaersutite peridotite-olivine gabbro dyke swarm of the Nyasyukka complex. The association formed during the maximum opening of the rift system c. 1980–1960 Ma ago in the course of several tectonic impulses, which were accompanied by the rise of highly magnesian and Fe-rich magmatic melts. The intrusive origin ofthe gabbro-wehrlite bodies is confirmed by intrusive contacts with the host rocks, magmatic textures (porphyritic, poikilophitic, poikilitic, panidiomorphic, fluidal, etc.) and the presence of xenoliths of host rocks altered to hornfels. As indicated by 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.

In the Pechenga structure, there exist over 300 intrusive bodies of the gabbro-wehrlite association. They are concentrated mostly in the Zdanov and Lammas tuffaceous-sedimentary formations, and also occur in the underlying volcanic rocks of the Zapolyarny Formation. These bodies occupy an area of 19.1 km^2 or 25 % of the total area that includes the host tuffaceous-sedimentary rocks. The intrusions are predominantly sub-concordant or phacolith-shaped bodies with pinches and swells and without feeder channels. The bodies occur as groups concentrated at several levels. Most of the intrusions have been broken into blocks with an en echelon configuration. More rarely, there are cutting bodies confined to diagonal fault systems.

The intrusions display various degrees of differentiation, different internal structures and mineralisation grades. This diversity is accounted for by several factors including various timing of the differentiation processes of the parental melt which took place in deep-seated magma reservoirs, in transporting channels and in magma chambers. The intrusions can be subdivided into poorly differentiated, chamber-differentiated and deep-differentiated. Bodies composed of olivine-bearing and olivine-free clinopyroxenites belong to the first group. Such bodies do not exceed 10–15 m in thickness; most commonly they are boudinaged and occur in separate fragments. Chamber-differentiated intrusions make up 22 % of all the intrusions. Their thickness ranges from 15 to 600 m, being most commonly between 25 and 100 m, and the length is from 100 to 3 000 m along 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 sequences can be observed in the larger intrusions. Deep-differentiated intrusions include peridotite or gabbroid bodies with thicknesses less than 200 m.

In the near-contact parts of some intrusions, there are remnants of chilled zones, which were originally composed of fine-grained clinopyroxenite and olivine clinopyroxenite and are now represented by chlorite-actinolite schists with rare relics 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). The intrusions are, in turn, cut by dolerite and picrodolerite dykes compositionally similar to mafic volcanic rocks of the overlying Matert Formation.

The gabbro-wehrlite intrusions were formed in several stages:

1. Emplacement of magmatic melts into the system of pre-existing diagonal faults and formation of thin, steeply dipping and poorly differentiated lenticular and dyke-like bodies of the Pahtajärvi group.
2. Emplacement of melts as intercalated injections into the tuffaceous-sedimentary Zdanov Formation, predominantly in the Western ore cluster and the central part of the Pechenga ore field, and the formation of intrusions with low-grade ore, such as North Kaula. Apparently, most intrusions of the western (from Kaula to the state boundary) and eastern (Lammas-Kuchitundra) flanks were formed at this stage. The stage was terminated with the intrusion of the earliest dolerite and picrodolerite dykes.
3. Intrusion of magmatic melts into relatively large chambers and the formation of commercial ore bodies of the Eastern ore cluster, containing predominantly disseminated ores. These chambers were formed due to simultaneous movements of host rock blocks along the system of transverse and longitudinal faults.
4. Emplacement of melts into the tuffaceous-sedimentary Zdanov and Lammas Formations to produce commercial ore-bearing intrusions of the Western ore cluster, rich in massive and brecciated ores. The third and fourth stages were terminated with the intrusion of later dolerite and picrodolerite dykes.

The age of the Pilgujärvi intrusion has been determined at 1980 ± 10 Ma and 1987 ± 5 Ma by the U-Pb method for baddeleyite and zircon, respectively [Smolkin et al. 2003]. The previous dates obtained by the Pb-Pb, Sm-Nd, and Re-Os methods for ferropicritic intrusive and extrusive rocks are compatible with these dates [Hanski et al. 1990, Smolkin 1992, Walker et al. 1997).

The intrusions containing commercial sulphide ores are concentrated in the Western (Kaula-Ortoaivi) and Eastern (Kierdzhipori- Onki) ore clusters (Fig. lb). The ore bodies are mostly tabular and lenticular; veins occur more rarely. Many bodies have complicated shapes formed as a result of splitting of the parental intrusion and longitudinal and transverse movements along syn- and post-ore brittle faults. The size of the ore bodies varies greatly (from 0.2 to 100 m in thickness and 5 to 1 500 m in length along strike), depending on the thickness of parental intrusions and the characteristics of tectonic zones. High-grade ore deposits, however, may occur in relatively thin bodies. Sulphide mineralization can penetrate the surrounding rock by «lit-par-lit» injections and form veins up to a few meters thick.

The sulphide ores are subdivided into disseminated, densely disseminated, brecciated, and massive. Disseminated ores occur predominantly in central and upper parts of the intrusions, whereas densely disseminated ores occur in near-bottom parts. 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. In most cases, massive ores are spatially associated with the brecciated ores. However, the former may form individual small-scale bodies. The Western ore cluster contains deposits of mostly massive and brecciated ores. The Eastern ore cluster contains predominately disseminated ores. The ores are composed of an assemblage of pyrrhotite, pentlandite, chalcopyrite and magnetite. In addition, bornite, mackinawite, violarite, cubanite, sphalerite, galenite and platinum - bearing minerals are present.

Ni content in the ores is variable: it is highest (10–12 %) in massive and brecciated ores, being less than 6 % in densely disseminated ores and no more than 1.5 % in low-grade disseminated ores. Apart from Ni, the ores contain commercial amounts of Cu and Co.

Nyasyukka dyke complex

In the Archaean basement north of the Pechenga structure, there occur coeval and comagmatic mafic to ultramafic dykes assigned to the Nyasyukka dyke complex (Fig. 2), which is known to contain a non-economic sulphide mineralisation. The north-west-trending dyke swarm is located within the area of a single tectonic zone, extending from the eastern shore of Lake Nyasyukka to Lake Heinäjärvi and being oriented diagonally with respect to the orientation of the Palaeorift system. The dykes constitute three separate subparallel series located within a distance 1–2 km from each other and extending up to 25 km along strike. This demonstrates various degrees of differentiation of the parental magma in deep-seated magma chambers and subsequent opening of a system of fractures. The western and eastern series are composed of olivine-gabbro dykes with their length varying from 1 to

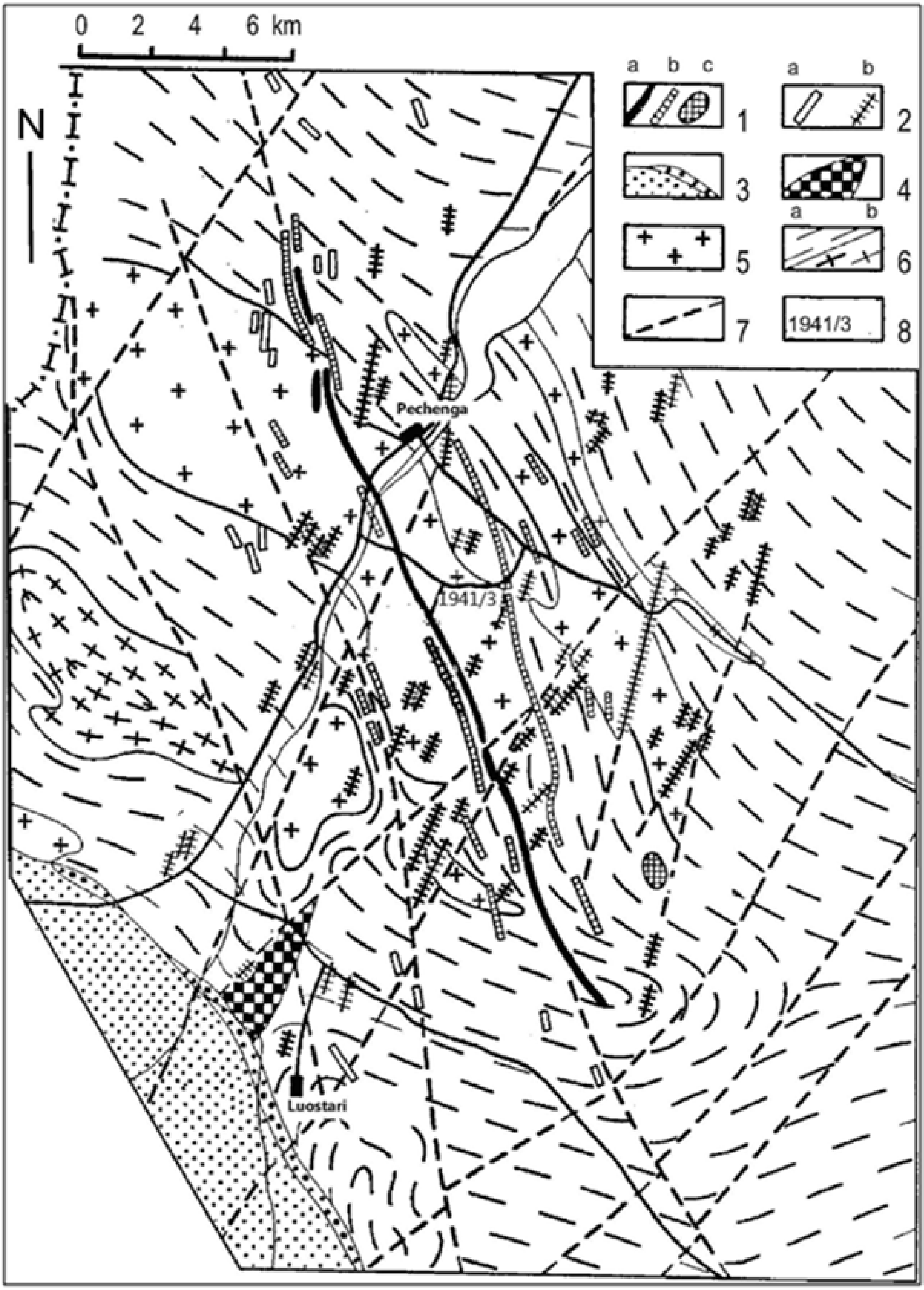


Fig. 2. Geological sketch map of the Nyasyukka dyke complex. 1 – the Nyasyukka dyke complex: a – peridotite, b – olivine gabbro, c – olivine pyroxenite; 2 – Palaeoproterozoic dykes: a – dolerite, b – quartz dolerite; 3 – basal conglomerate and volcanic rocks of the Pechenga Complex; 4 – Mt. Generalskaya mafic layered intrusion; 5 – Archaean plagio-microcline granite; 6 – Archaean amphibolite, gneiss, high-Al schist; 7 – fault; 8 – U-Pb age.

8 km and thickness from 30 to 130 m. The central dyke series contains larger dykes of amphibole- and plagioclase-bearing peridotite up to 22 m in length and from 40 to 150 m in thickness, and a number of smaller dykes with similar composition. At the southern end of the eastern series, there is a stocklike plagioclase- and olivine-bearing pyroxenite body with a size of 0.4 × 0.9 km. Some dykes are disturbed by north-east trending faults. In terms of their REE spectra and other incompatible element characteristics and also isotopic data (Sm-Nd), the dyke rocks are very close to gabbro-wehrlites and ferropicrites but differ due to their lower degree of differentiation. Based on Sm-Nd isochron data, the age of the dyke complex is 1956 ± 20 Ma, while the conventional U-Pb analysis of baddeleyite from olivine gabbro has yielded an age of 1941 ± 3 Ma [Smolkin et al., 2015]. These dates have been confirmed by in situ SHRIMP analysis of zircon from olivine gabbro using.

On the basis of the above mentioned isotopic data, one can conclude that the emplacement of the dyke complex post-dated the eruption of ferropicritic volcanic rocks of the Matert Formation and the emplacement of the ore-bearing Pilgujarvi intrusion by c. 40–45 Ma, concluding the ferropicritic magmatism in the Pechenga area.

Ferropicritic rocks

The upper part of the magmatic section through the Northern zone contains mostly basaltic rocks but also ferropiciric rocks, which form massive and pillowed lavas, layered lava flows, tabular sill-type bodies, lava breccias and tuff beds, and thin dykes. 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. 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 %). Lava flows range in thickness from 3 to 25 m. A few of them are as much as 50 m thick and can be traced for 2.5–3 km along 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 ferropicrit-basalt (clinopyroxene cumulate), and two upper zones of ferrobasalt composition. The rocks in these upper zones have a spinifex texture (of olivine, and more rarely, pyroxene types) or globular structure. Thinner flows do not contain zones with a spinifex texture and (or) globular structure, and the MgO content in them is lower because of less amounts of olivine in the lower zone.

Typical features of volcanic ferropicritic rocks are the increased fayalite component in olivine (16 % Fa), and the titanium specialisation of rock-forming (titanaugite, kaersutite, biotite) and accessory (Ti-chromite, Cr-ulvospinel, ilmenite) minerals. In addition, these rocks typically have high contents of $FeO+Fe_2O_3$ (14–16 %), TiO_2 (1.3–4.0 %), P_2O_5 (0.15–0.35, rarely up to 0.88 %) and an increased content of LREE (2–4 times higher than in MORB).

The middle part of the section of the Matert Formation is exposed by erosion on the northwestern slope of Mt. Kuorpukas (Fig. 3). This part is composed of (from bottom to top) pillow lavas of tholeiite basalt with thin (0.1, 2.5 m) inter beds of tuffosilicite, a layered volcanic ferropicrite flow, which marks a seam of high-silica chemogenic-tuffaceous-sedimentary rocks (8–10 m), and a more than 50 m thick tabular body (sill) of ophitic gabbro.

The layered ferropicrite flow can be observed at the base of an extended scarp outcrop (Fig. 3). The vertical section of the flow can be subdivided into

Fig. 3. Layered ferropicritic lava flow, Mt. Kuorpukas. 1 – olivine ferropicrite; 2 –clinopyroxene ferropicritic basalt; 3 – globular ferrobasalt; 4 – massive, thin-banded and fine-clastic turbidites; 5 – ophitic gabbro.

the zones (from bottom to top) that are composed of serpentinised olivine ferropicrite (more than 4 m thick), finegrained pyroxene ferropicrite-basalt (3.5 m), and globular ferrobasalt (0.5–1.0 m). There are no sharp boundaries between the zones. The lower contact is covered with drift. The upper contact has a pronounced, sharp boundary between a thin (3–5 cm) bed of ferrobasalt, that has experienced subaqueous diagenesis (halmyrolysis) and is anomalously low in SiO_2 (38.7 wt. %), and a bed of dark-grey, fine-grained tuffosilicilith (3–5 cm), overlain first by massive fine-grained (1.0–4.0 m) and then by fine-clastic (3.5–4.0 m) tuffosiliciliths. In the upper part of the layered flow, there is a thick apophysis of globular ferrobasalt, which penetrates the overlying tuffo-silicilith and gradually wedges out towards the south-east over the distance of 25 m. In addition, there are thinner apophyses (1–2 cm) of strongly altered ferrobasalt containing 39.1 wt. % SiO_2. It is suggested that upon eruption in 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 with sediments.

Globular rocks provide a brilliant example of silicate immiscibility in a ferropicritic melt. 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 was commonly preserved. In terms of the TiO_2, P_2O_5 and F contents, which are elevated, the globules and the cementing matrix are similar. The proportions of mineral phases and the zoning are different in the globules and the matrix. Other distinctive features are the contents of SiO_2 (47.5 and 43.4 wt. %, respectively), Na_2O (2.9 and 0.4 wt. %), K_2O (0.3 and 1.5 wt. %), Ni (135 and 85 ppm), and the $(FeO+Fe_2O_3)/(FeO+Fe_2O_3+MgO)$ ratio (0.60 and 0.36).

Peridotitic dyke of the Nyasyukka dyke complex

Dykes of the Nyasyukka complex constitute three separate, subparallel dyke suites with a north-westerly orientation. They cut rocks of the late Archaean basement complex without having caused strong contact effects. The central suite contains the thickest, slightly differentiated dyke of peridotitic composition. Its width varies from 40 to 150 m. Along strike, it can be followed for 22 km. The dyke is excavated in the Kirikovan quarry for dimension stone (Fig. 4), and it is crossed by the highway.

Peridotites are kaersutite-bearing and show a porphyritic structure. Originally they were composed of 25–45 vol. % of olivine (Fo 70 mole %), 10–25 vol. % of augite and 10–35 vol. % of kaersutite. Minor phases include orthopyroxene, plagioclase, biotite, chrome-bearing magnetite, ilmenite, apatite and weak sulphide dissemination. Kaersutite forms oikocrysts up to 2–3 cm in size, enclosing euhedral grains of olivine and augite. Olivine is partly replaced by bowlingite (saponite) and, more rarely, by talc and serpentine and clinopyroxene and kaersutite by actinolite and chlorite. In peridotites, there are rare irregular pods of melanocratic olivine gabbro. The presence of kaersutite points to an elevated water content of the parental magma. The composition of the kaersutite in peridotite dykes and ferropicritic volcanic rocks is similar.

Characteristic features of the perdidotitic and other dykes of the Nyasyukka complex are contents of TiO_2 and total FeO, and also the enrichment in LREE, which is similar to that in the rocks of the Pechenga ore-bearing intrusion and ferropicritic volcanic rocks. At the same time, they are separate in space due to differentiation of ferropicritic magma at depth in an intermediate magma chamber.

Fig. 4. Peridotite of the Nyasyukka dyke complex in the Kirikovan quarry.

Display of samples from the Pilgujarvi layered intrusion, Zapolyarny city

The Pilgujärvi intrusion is the largest and most intensively studies of the ore-bearing intrusions in the Pechenga ore camp [Smolkin, 1977; Copper-nikel… 1999]. It hosts the large, commercial Zdanov Ni-Cu sulphide deposit and related open pit (Fig. 5). Currently, underground mining is practiced. The bulk of the ore is composed of disseminated ore, and less common are massive, breccia-like, vein-disseminated and densely disseminated types.

The structure of the intrusion is cut by subvertical and thrust faults, and it consists of a number of large blocks. The most complete section occurs in the so called Main massif, which represents an intrastratal concordant intrusive body which is elongated in the north-west by 2200 m and dipping to the south-west at an angle of 45–55 ° (Fig. 6). The massif is traced to a depth of 2000 m without significant thinning and the thickness of the massif ranges from 300 to 500 m. In cross section, it has plate-like and longitudinally a bowllike shape.

On the flanks, the intrusion is bordered by transverse, steeply dipping faults. In general, the intrusion occurs concordantly in relation to the surrounding tuffaceous sedimentary rocks of the Zhdanov Formation, but in some cases, there is a discordant relationship with earlier ophitic gabbro sills. On the other hand, rocks of the intrusion are cut by steeply dipping dykes of fine-grained dolerite; in a few cases ferropicritic micro dykes with porphyritic olivine grains have been met.

A characteristic feature of the massif is the presence of well-preserved chilled margins and zones hornfelsification in country rocks, and the presence of hornfelsed xenoliths in contact with clinopyroxenites and gabbro.

Fig. 5. Panorama over the Central open pit, where ore of the Zhdanov deposit has been mined.

According to V. Smolkin [Copper-nikel…, 1999], the general section of the Main massif consists of the lower and upper marginal zones (chilled), wehrlite-olivinite zone, intermediate (critical) horizon, gabbro-pyroxenite, gabbro and gabbro-pegmatoid zone. The lower marginal zone is composed of fine-grained, amphibolitised and chloritised, olivine-bearing and olivine-free clinopyroxenite with a total thickness of 2–5 m, and the upper marginal zone comprises clinopyroxenite, diorite and hornfels. The wehrlite-olivinite

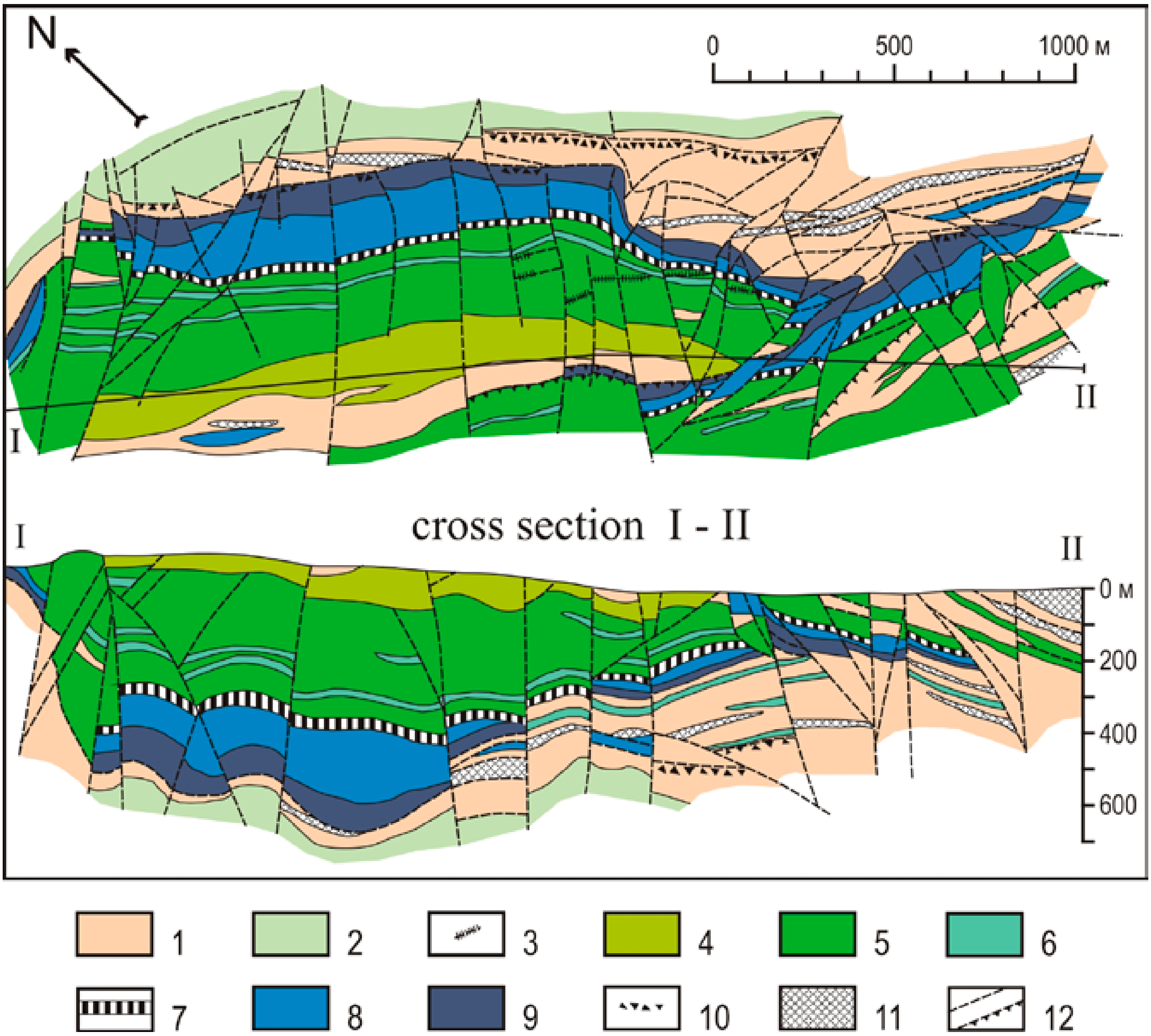


Fig. 6. Geological sketch map and cross-section of the Pilgujarvi layered intrusion and its Ni-Cu ore deposits, from [Smolkin, 1977]. 1 – Aleuro-psammitic shales and metatuffites, Zdanov Fm; 2 – Metavolcanic rocks of basaltic composition, Zapolyarny Fm; 3 – Metadolerite dykes; 4 – Coarse-grained and vari-textured gabbro; 5 – Fine- to medium-grained gabbro; 6 – Clinopyroxenites and olivine clinopyroxenites; 7 – Layer enriched in titanomagnetite; 8 – Serpentinised wehrlites; 9 – Serpentinised wehrlites with disseminated sulphides; 10 – breccia and massive ore; 11 – ophitic gabbro; 12 – steeply dipping faults and reverse-slip faults.

zone (average thickness 135 m) is dominated by serpentinised wehrlites (< 75 vol. % Ol), ore-bearing and barren serpentinite, in which there are lense-like interlayers of serpentinised rocks rich in olivine (>75 vol. % Ol). Cumulus minerals in the rocks of this zone are olivine (Fa 18–25 mole %) and chrome spinel and intercumulus minerals clinopyroxene (titanoaugit), amphibole (kaersutite) and Ti-biotite. In rare cases, there are relics of intercumulus plagioclase replaced by chlorite. Clinopyroxene forms porphyritic crystals enclosing poikilitically serpentinised olivine grains. Chrome spinel forms several generations, one of which (titano-chromit) occurs as inclusions in olivine and a later one (titano-chrome-magnetite and titano-magnetite) in clinopyroxene.

The intermediate (critical) horizon has a thickness of 8–16 m and is composed (from bottom to top) of fine-grained olivine pyroxenite, peridotite, and mineralised plagiopyroxenite. A titanomagnetite mineralisation is represented by dense oxide dissemination. The horizon is characterised by the first appearance of cumulus clinopyroxene and titanomagnetite. The content of cumulus olivine in the rocks is reduced to 10–20 vol. %. Intercumulus phases are kaersutite, biotite and plagioclase. Within the intermediate horizon are hornfelsed host rock xenoliths, as well as veins of coarse-grained gabbro-pegmatite enriched in apatite.

The gabbro-pyroxenite, gabbro and gabbro-pegmatite zone, with a total thickness of about 300 m, occupies more than two-thirds of the total volume of the Main massif, which distinguishes it from other intrusions of the Pechenga ore field. From bottom to top, the section shows a change of melano- and mesocratic gabbro with layers plagiopyroxenite to mesocratic gabbro with well-defined trachytoid textures, and then to pegmatoid and orthoclase gabbro with a massive or taxitic texture. The lower boundary of the gabbro zone is marked by the first appearance of cumulus plagioclase and dissappearance of olivine. Cumulus minerals in the rocks of this zone are plagioclase, clinopyroxene (titanaugite), titanomagnetite and ilmenite and interculululus minerals are kaersutite and biotite. Potassic feldspar occurs as a antiperthitic lamellae in plagioclase grains rims of plagioclase crystals in the gabbros in the uppermost part of the massif.

The general sequence of rocks the Pilgujarvi intrusion corresponds to the following order of the appearance of mineral associations: CrSp + Ol Ol + Cpx Cpx + Pl + Amph. The sequence of crystallisation Ol Cpx Pl is in good agreement with the variation of the normative composition of the rocks across the intrusion and with the ratios of normative amounts of olivine, clinopyroxene and plagioclase, and with the experimentally determined cotectic relations of the corresponding phases.

The rocks of the intrusion have been metamorphosed under conditions of the greenschist facies. Peridotites were affected successively by serpentinisation (lizardite, antigorite), chloritisation and talc formation, and clinopyroxenites by actinolitisation and chloritisation, and gabbros by saussuritisation with complete replacement of plagioclase by aggregates of albite and zoisite. In the central part of the tectonic blocks, there are preserved relics of primary minerals olivine, clinopyroxene and Cr-spinel. Hydro-thermal-metamorphic veins are widely developed in serpentinites composed of serpentine (serpophite, chrysotile asbestos, antigorite-chlorite) rodingite (hydrogarnet-vesuvianite), talc-carbonate and diopside-antigorite. In serpophitic veins, there are rounded segregations of sulphides containing high-cobalt pentlandite. Diopside in the veins has a light or light pink colour and form fan-like aggregates.

Pillow lavas and hyaloclastites of tholeiitic basalts of the Zapolyarny Formation, Nikel-Zapolyarny road

During the construction of the highway, volcanic rocks of the Zapolyarny Formation were exposed. The volcanic rocks are represented by massive and pillowed lavas and hyaloclastites, exhibiting foliation and brecciation along fault zones. In one of the fault zones are confined thin, steeply dipping ultramafic intrusions of the first phase (Pahtajarvi etc.) that contain non-industrial sulphide mineralization.

On the southern slopes of the Kotselvaara Ortoaivi Mts. and by the Yla-Souker brook, erosion has exposed tholeiitic basalts of the Matert Formation (Fig. 7 a, b). They occur as pillowed lavas and massive and variolitic lavas, tuffites and hyaloclastites. At the edge of the pillows, there is a fine-grained zone, whereas the centre is made of more crystallised albite-chlorite-

Fig. 7 a, b. Pillow lava of tholeiitic basalt of the Matert Formation.

amphibole aggregates. Occasionally, amygdaloidal textures are found. The inter-pillow space is filled with hyaloclastic material or a quartz-rich mass. Basaltic lavas are constantly associated with sills of ophitic gabbro. The latter have a relatively homogeneous structure and reach 100 m in thickness.

Northern Kotselvaara differentiated intrusion, southern slope of the Kotselvaara Mt.

North of the Kotselvaara quarry, erosion has revealed thin, differentiated, barren intrusion. At its lower contact, a well-preserved chilled margin is preserved. At the contact with hornfelsed phyllitic schists, the zone is composed of finegrained, quenched clinopyroxenite (Fig. 8). As the distance from the contact increases, the grain size of the rock also increases and olivine grains appear. The amount of olivine gradually increases and the rock changes to olivine clinopyroxenite.

Higher in the section overlies a zone of serpentinised peridotite (wehrlites) with a porphyritic structure. In the central part of this zone, the northern part of the intrusion is thrusted over its southern part. A complex net of serpentinised rocks is located near the thrust plane, having a central

Fig. 8. Chilled lower contact of the Northern Kotselvaara differentiated intrusion against footwall phyllitic schists.

Fig. 9. A network of serpentine veins cutting metaperidotite of the Northern Kotselvaara intrusion. Central parts of the veins are composed of magnetite and marginal parts serpentine in contact with host serpentinite.

zone made of magnetite, and fragments of boudinaged, less-altered rocks and also subhorizontal veins made of chrysotile asbestos (Fig. 9). The upper part of the intrusion, partly covered by dumps, is composed of medium-grained gabbro. It contains relics of clinopyroxene and feldspar completely replaced by chlorite-albite-zoisite aggregates. Between the peridotite and gabbro units, there is a thin horizon of small-medium-grained amphibolitised clinopyroxenite with small pockets of coarser varieties.

Ferropicritic tuffs of the Lammas Formation, western flank of the Kotselvaara open pit

The Lammas Formation consists of pyroclastic deposits of mostly ferropicritic composition – psephitic-psammitic tuffs, agglomeratic tuffs, lava breccia and tuffites. It varies in thickness, ranging from tens to hundreds of meters. The maximum thickness is achieved on the east bank of the creek Lammas (c. 500 m) and in the Kotselvaara area (up to 350 m), which represent remnants of volcanic centers. Here the rocks are dominated by the most coarse-fragmental varieties.

In the sections there is a certain rhythmic variation. At the base of each sequences, there are the most coarsest deposits, which change to tuffites when going upwards the section. The clasts are represented by amoeboid, flame-like, or irregularly rounded fragments of folded serpentine-talc-chlorite-amphibole aggregates. The matrix material is composed of carbonate, chlorite, actinolite and leucoxene. The MgO content of the tuffs ranges from 10 to 16 wt. %. Among the tuffs, there are carbonate-bearing and carbonate-free types. Table 2 shows a chemical analysis of a tuff sample from Stop 5. The most complete section is located on the upper horizons of the western part of Kotselvaara quarry which is inaccessible for visiting. On the western border of the quarry, remnants of bedrock outcrops are preserved.

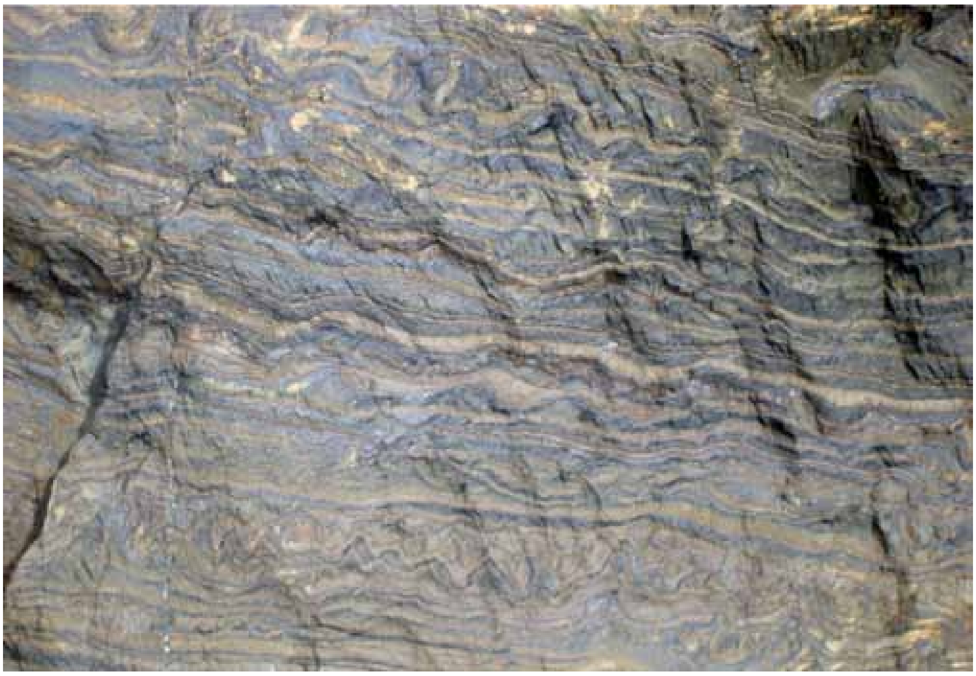


Fig. 10. Ore-bearing country rock close to the contact of a serpentinite body. Rhythmically bedded metasediment with subhorizontal layering and tight crenulation folds. Kotselvaara open pit.

At the entrance to the Kotselvaara quarry, in its western side, occur tuffaceous-sedimentary rocks of the Zhdanov Formation, which are country rocks for ore-bearing intrusions. They show a rhythmically-bedded structure and tight crenulation folds and represent interbedded pelites, aleurolites, phyllites and tuffites, containing an unevenly distributed dissemination of pyrrhotite (Fig. 10).

Fragments of spinifex-textured ferropicrite of the Matert Formation, southern entrance of the Kotselvaara open pit

In the upper parts of differentiated ferropicritic lava flows and rarely in pillow lavas, thin zones of spinifex-textured rocks are observed, which are commonly formed by large crystals of clinopyroxene and less commonly olivine. One of these lava flows occurs on the southern slope of the Kotselvaara Mt. It has been penetrated by several exploration holes, and today fragments of it still remain on the surface. In one of the biggest fragments, well-developed pyroxene spinifex texture is seen. Its whole-rock composition corresponds to that of ferrobasalt (Table 2).

Table 2. Chemical analyses of ferropicritic tuff (P1), spinifex-textured ferrobasalts of (S-3r) and samples from layered lava flows (wt. %).

	Stop5 PI	Stop6 S-3r	Stop 7 0	1	2	3	4	5	6G	7M	10
SiO_2	39.22	48.28	44.00	43.15	43.80	43.56	47.35	47.59	47.10	43.80	49.43
TiO_2	2.44	2.94	1.48	1.44	1.49	1.28	2.34	2.33	3.03	3.72	2.29
Al_2O_3	7.39	9.02	5.34	5.04	4.90	4.39	6.50	7.63	9.28	10.48	7.63
Fe_2O_3	2.69	2.33	1.14	3.04	3.31	4.36	0.70	1.55	2.34	3.66	2.24
FeO	13.52	11.40	13.60	11.45	11.14	10.23	12.04	12.98	11.73	15.24	12.21
MnO	0.16	0.14	0.12	0.17	0.17	0.15	0.22	0.18	0.18	0.20	0.16
MgO	15.71	8.82	20.10	22.57	23.12	21.35	11.65	12.44	8.50	7.22	10.57
CaO	6.57	10.62	6.39	4.05	3.47	5.45	14.53	10.61	11.80	9.54	8.15
Na_2O	0.13	2.44	0.12	0.06	0.11	0.11	1.06	0.16	2.57	0.41	0.22
K_2O	0.42	0.10	0.01	0.01	0.01	0.02	0.02	0.01	0.13	1.48	0.02
H_2O	6.45	2.86	6.13	7.54	6.65	7.37	2.83	3.33	2.80	3.30	4.33
F	–	0.040	0.041	0.045	0.044	0.044	0.049	0.060	0.069	0.095	0.063
P_2O_5	0.23	0.28	0.17	0.13	0.12	0.14	0.15	0.17	0.25	0.33	0.19
CO_2	3.61	–	0.09	0.11	0.84	–	0.43	0.29	–	0.09	1.06
S	0.54	0.45	0.82	0.51	0.43	0.44	0.03	0.04	0.55	0.02	1.71
Cr_2O_3	0.220	0.072	0.310	0.390	0.340	0.350	0.090	0.220	0.090	0.040	0.270
V_2O_5	0.050	0.078	0.010	0.007	0.008	0.040	0.014	0.013	0.014	0.010	0.010
Ni	0.085	0.019	0.150	0.169	0.165	0.180	0.027	0.090	0.019	0.012	0.110
Co	0.012	0.006	0.014	0.017	0.015	0.012	0.010	0.013	0.007	0.007	0.013
Cu	0.024	0.017	0.015	0.018	0.017	0.018	0.022	0.020	0.007	0.012	0.027

G = globule, M = matrix.

Globular ferropicrites of the Matert Formation, Kotselvaara Mt, Souker brook

One of the characteristic features of ferropicritic volcanic rocks is the presence of globular structures. They are confined to the upper part of layered lava flows and form a zone up to several meters in thickness. Globules represent spherical segregations with a light gray color and a diameter from 2–5 to 25–50 mm. The boundary to the dark-colored greenish-gray matrix is sharp, sometimes accentuated by thin light, a more glass-like rim. The globules are unevenly distributed. Sometimes they form pseudolayers of agglomerated globules ranging from 0.5 to 1.5 m in thickness (Fig. 11 a, b). The lower boundary of the pseudolayers is sharp and wavy, and the top is more complex due to a decrease in the number and size of the globules.

In outcrops, one can see how globules tend to approach one another, are pressed into each other and stick together (Fig. 11 c, d). Small globules have a vitreous appearance. The larger ones are crystallised and contain elongate, prismatic, skeletal and often zoned grains of clinopyroxene (titanoaugite, 40–50 %), needle-like grains of Ti-amphibole (kaersutite, 1 %), skeletal grains of ilmenite and titanite (5–6 %), and also orthoclase-albite mass in the groundmass. The matrix is more melanocratic due to a larger amount of clinopyroxene (60–65 %). Its ground-mass is composed of leucoxene-epidote-albite-orthoclase aggregates. The globules differ clearly from the matrix in their chemistry. They contain more SiO_2 and Na_2O, while K_2O is higher in the matrix (Table 2). Apart from volcanic flows, globular rocks have also been encountered in ferropicritic sills, including ore-bearing ones.

Globular ferropicrites are products of liquid immiscibility due to enrichment in volatile components (P, F, S) upon submarine eruption and subsequent crystallisation of two immiscible melts [Smolkin, 1992]. The separation of the two liquid took place after the onset of crystallisation of the first phase of clinopyroxene. This phase differs from the later crystallised ones in being lower in Cr, Ti, and Fe.

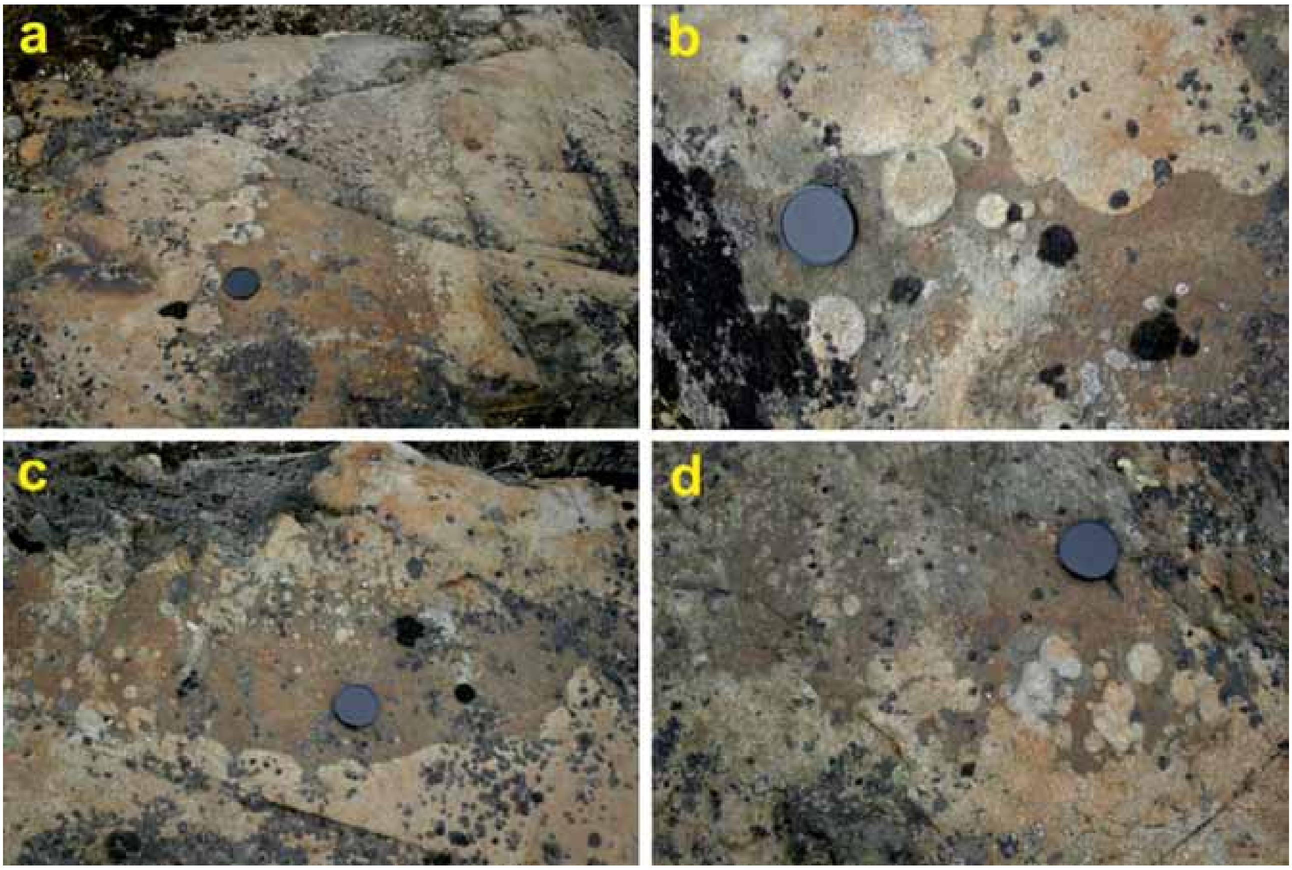
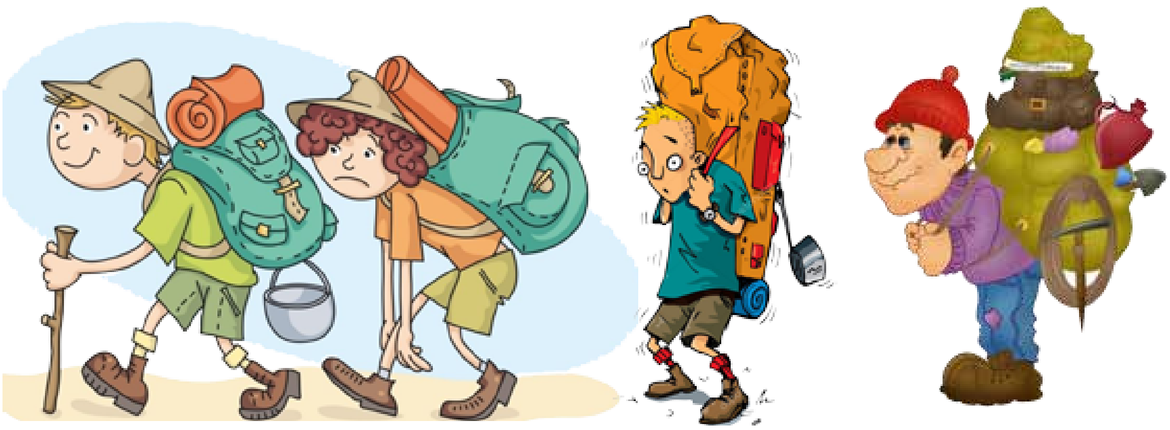


Fig. 11. Globular ferropicritic lava. from [Smolkin, 1992]. A – general view showing «leucocratic» and «melano-cratic» pseudolayers; B – lower wavy boundary of a leucocratic pseudolayer; C – upper boundary of the same pseudolayer (in the upper part of the photograph); D – process of adjoining, adhesion and coalescence of globules. Kotselvaara Mt., Souker brook.



Eruption Center. Zapolyarny, Cannon monument

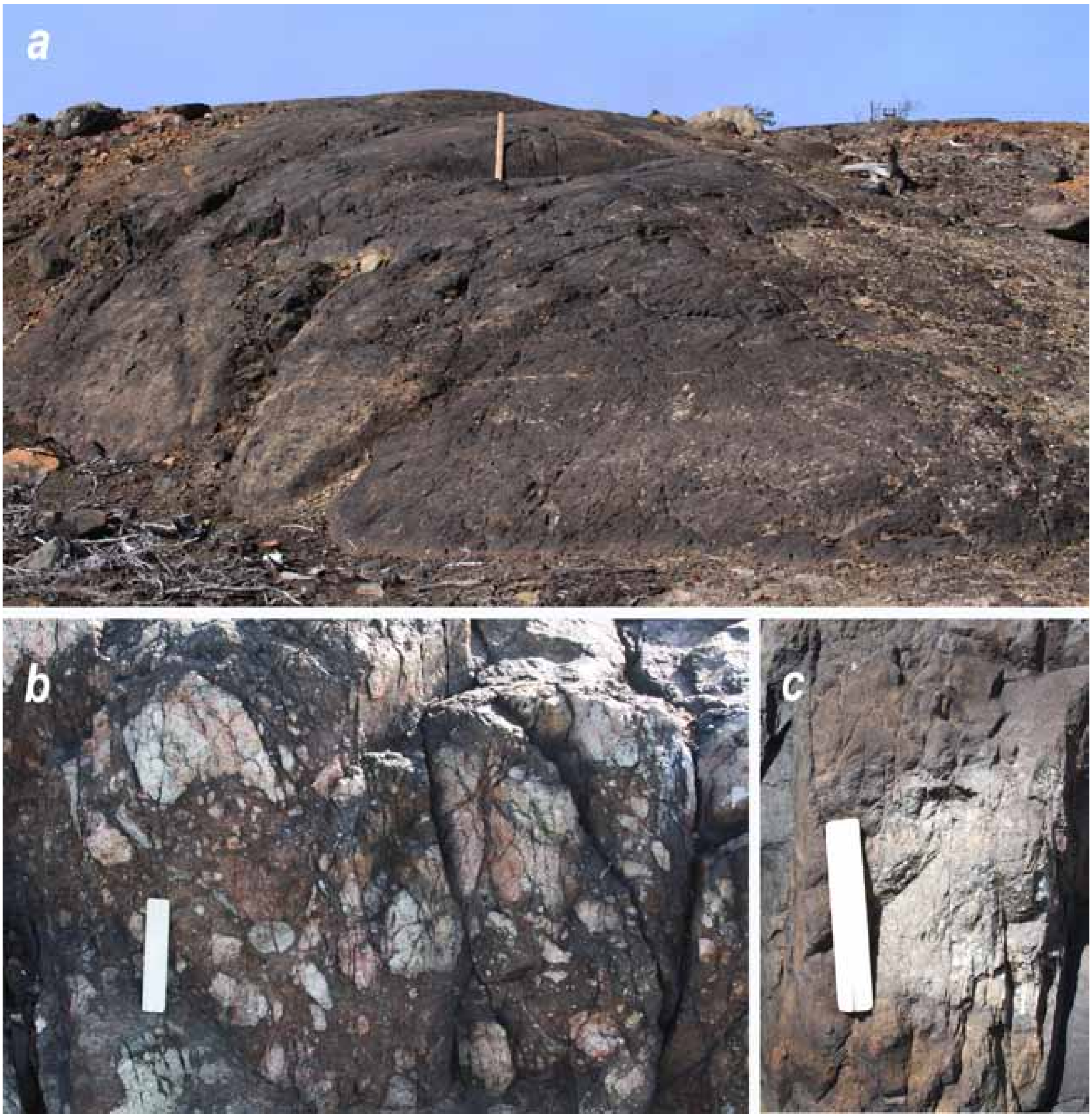


Fig. 12. Eruption center near the Cannon monument, city of Zapolyarny: general view (a), breccia with fragments of granitoids (b) and basaltic andesites (c).

The eruptive center is an example of a central-type apparatus, finds of this type are rare in the Precambrian. It is located on the edge of the city of Zapolyarny, within the area of development of volcanic rocks of the Pirttiyarvinskaya suite (Fig. 12). The eruptive center has an oval shape on the day surface and is composed of subalkaline basalts, which cement a large number of small and large clasts of granitoids and volcanic rocks. Granitoids are the basement rocks of the North Pechenga zone with an age of 2.7 Ga, and volcanic fragments have a basaltic andesite composition. On this basis, they are compared with the volcanic rocks of the Mayarvinskaya North Pechenga zone. The presence of an eruptive center with fragments of granitoids confirms the initiation of the North Pechenga zone on a continental-type crust.

Stratified intrusion Mt. Generalskaya

Within the North Pechenga region, located northeast of the Pechenga zone, several layered intrusions have been exposed by erosion: Mt. Generalskaya, Kaerikjavr-1, -2, -3, Saken et al. All these intrusions have a clearly pronounced internal rhythmic layering, discordant with the structure of the host Archean granite-gneiss complex. One of the most promising ore objects among them is the Mt. Generalskaya (Fig. 13). It is located near Luostari railway station (Fig. 14).

The geological position of the Mt. Generalskaya is well defined: 1) at the western contact, there is a well-pronounced melting of gneisses of the Upper Archean Kola Group; 2) in the basal conglomerates of the Pechenga zone in the area of Luostari pebbles of gabbronorites were found; 3) the intrusion is intersected by dikes of quartz metadolerites, similar in composition to the lower volcanogenic Majarvi Fm of the Sariolian age of the Pechenga zone.

The position of the intrusion of Mt. Generalskaya is controlled by an ancient northwest-trending fault. Its dimensions on the modern erosional

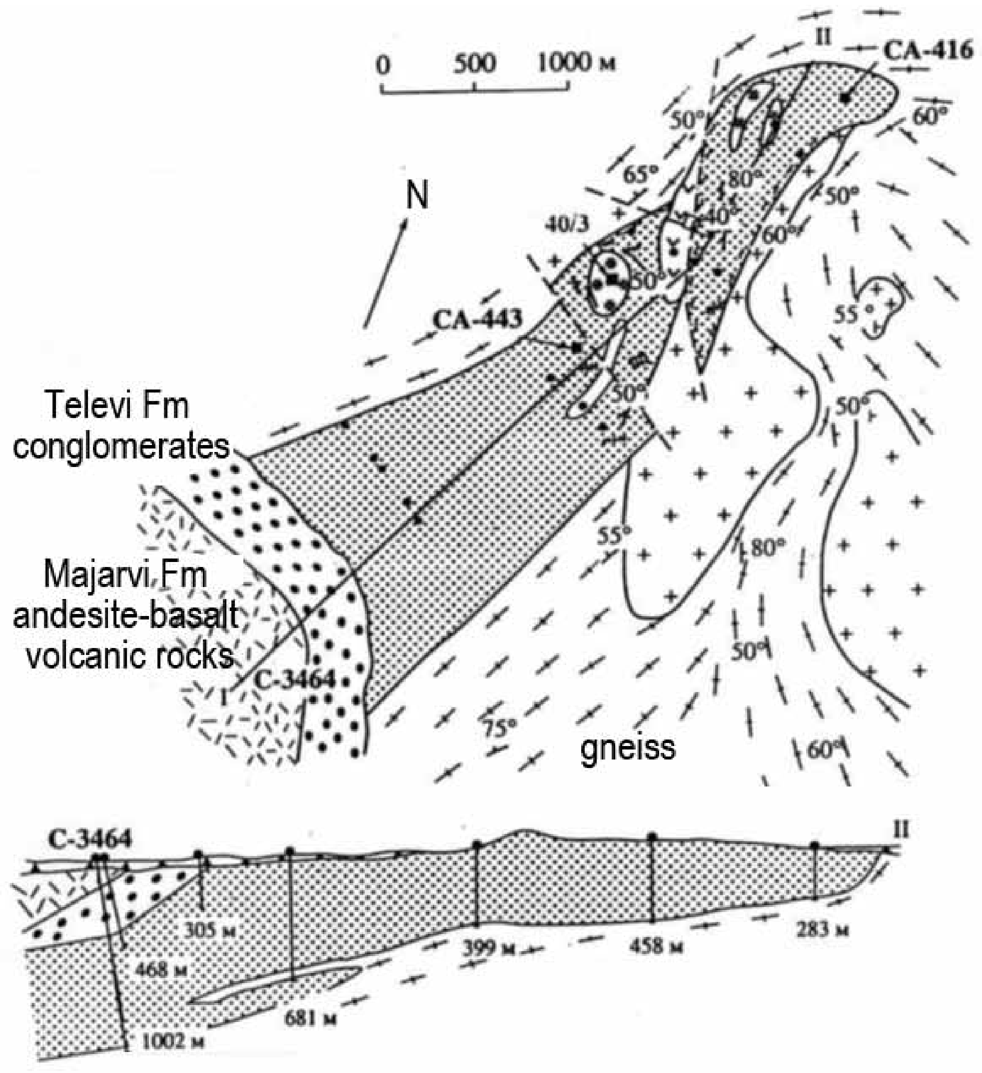


Fig. 13. Scheme of the geological structure of the layered intrusion Mt. Generalskaya.

section are about 3.5 × 1.5 km, but the true dimensions were much larger. The intrusion gently plunges to the southwest (30–35 °) under the basal Televi Fm conglomerates and Majarvi Fm andesite-basalt volcanic rocks, which form the lower part of the general section of the Pechenga zone. The Rb-Sr age of volcanic rocks determined from bulk samples is 2324 ± 28 Ma (Smolkin et al., 1995). The intrusion is elongated in the submeridional direction (NE 10–20 °), has a keel-like shape with an autonomous internal structure and a dip of the eastern and western contacts towards each other at angles of 60–65 ° and 30–50 °, respectively. The intrusion is crossed by younger faults of northeast and northwest strike, one of which divides it into two large blocks. The total thickness of the sections of intrusive rocks increases when moving to the southwest from 200–300 to 1700 m.

The vertical sections of the intrusion are dominated by gabbro-norites. According to T.L. Grochovskaya et al. (1996) in a vertical section, several series are present. The lower marginal series, up to 100 m thick,

Fig. 14. Mt. Generalskaya.

is composed mainly of quartz-bearing gabbro-norites with gabbro-ophitic and dolerite textures, and, to a lesser extent, orthopyroxenites, trachytoid microgabbronorites, and granophyre-bearing gabbronorites. In the marginal series, there are signs of contamination - microxenoliths of host rocks and an increased content of quartz.

The main part of the intrusion is composed of rocks of a layered series. It consists of several zones: lower gabbro-noritic zone (200–250 m), middle rhythmically layered zone (350–400 m), composed by olivine-bearing and olivine-free gabbro-norites and norites, gabbro, anorthosites, pyroxenites, peridotites, and upper gabbro- norite zone (up to 400 m). The layered series is dominated by mafic rocks with well-defined cumulative textures (pyroxene-plagioclase cumulates). Olivine-bearing varieties (olivine-plagioclase cumulates) occur only in the central, most differentiated part of the intrusion in the form of rare layers.

A characteristic feature of the intrusion rocks are coronitic textures - rims at the border of olivine and plagioclase. The olivine-bearing varieties of gabbronorites and anorthosites contain a high content of intercumulus material. Along with orthopyroxene and augite, pigeonite and pigeonite-augite are widespread.

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