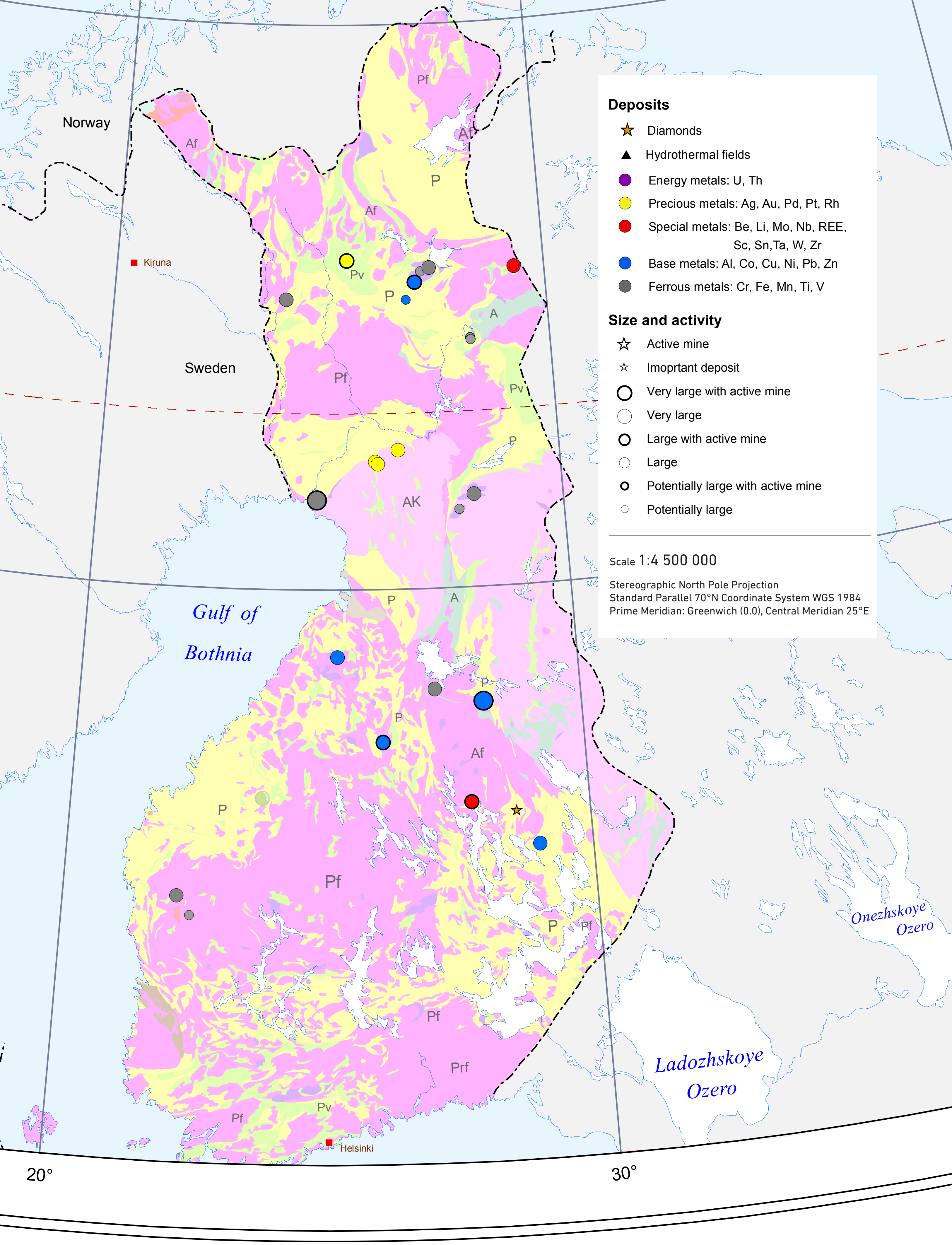


Deposits
Diamonds
Hydrothermal fields
Energy metals: U, Th
Precious metals: Ag, Au, Pd, Pt, Rh
Special metals: Be, Li, Mo, Nb, REE, Sc, Sn,Ta, W, Zr
Base metals: Al, Co, Cu, Ni, Pb, Zn
Ferrous metals: Cr, Fe, Mn, Ti, V
Size and activity
Active mine
Imoprtant deposit
Very large with active mine
Very large
Large with active mine
Large
Potentially large with active mine
Potentially large
Scale 1:4 500 000
Stereographic North Pole Projection
Standard Parallel 70°N Coordinate System WGS 1984
Prime Meridian: Greenwich (0.0), Central Meridian 25°E
Norway
Sweden
Kiruna
Helsinki
Gulf of Bothnia
Ladozhskoye Ozero
Onezhskoye Ozero
Pf
Af
P
Pv
A
AK
Prf
20°
30°

CHAPTER 8
FINLAND

Authors: Asko Kontinen, Raimo Lahtinen, Pasi Eilu, Jouni Luukas, Kaj Västi, Tero Niiranen, Tuomo Törmänen, Tuomo Karinen, Tapio Halkoaho, Hannu Makkonen, Janne Hokka, Akseli Torppa, Niilo Kärkkäinen, Esa Heilimo, Laura Lauri, Marja Lehtonen and Hugh O'Brien

Geological Survey of Finland (GTK)

MAIN GEOLOGICAL FEATURES OF FINLAND

Modified after Raimo Lahtinen (GTK)

Archaean

The Archaean crust, either exposed or concealed under Palaeoproterozoic cover rocks and granitoids, occurs in the eastern and northern parts of Finland. The Karelian Province comprises Mesoarchaean 2.8–3.0 Ga lithologies, but rocks older than 3.0 Ga have locally been found. The central part of the Karelian province is mainly Neoarchaean, having plutonic and volcanic rocks of 2.75–2.70 Ga in age. This age difference is also seen in the nature of volcanic rocks, where the older rocks formed in within-plate, probably oceanic, environments, whereas younger volcano-sedimentary belts show arc-type characteristics (Sorjonen-Ward & Luukkonen 2005, Hölttä et al. 2008). Sanukitoid-type plutonic rocks of the Archaean domain have ages grouping at 2740 and 2718 Ma (Heilimo et al. 2011). The Belomorian province is dominated by 2.9–2.7 G granitoids and includes volcanic rocks formed at 2.88–2.82 Ga, 2.8–2.78 Ga and 2.75–2.66 Ga. The Kola province is a mosaic of Mesoarchaean and Neoarchaean units, together with some Palaeoproterozoic components. The Archaean growth (accretion) of this province occurred from 2.9 Ga to 2.7 Ga and was followed by a collision with the Karelian craton at 2.72 Ga along the Belomorian province.

Palaeoproterozoic cover rocks of the Archaean continents

Rifting of the Archaean crust began in northern Fennoscandia and became widespread after the emplacement of 2.50–2.44 Ga, plume-related, layered gabbro-norite intrusions and dyke swarms (Iljina & Hanski 2005). Erosion and deep weathering after 2.44 Ga was followed by the Huronian glaciation, and later deep chemical weathering again covered large areas in the Karelian province at ca. 2.35 Ga (Laajoki 2005, Melezhik 2006). Rifting events at 2.4–2.1 Ga are associated with mostly tholeiitic mafic dykes and sills, sporadic volcanism and typically fluvial to shallow-water sedimentary rocks (Laajoki 2005, Vuollo & Huhma 2005). Local shallow-marine environments were marked by deposition of carbonates at 2.2–2.1 Ga, showing a large positive $\delta^{13}C$ isotope anomaly during the Lomagundi–Jatuli Event (Karhu 2005, Melezhik et al. 2007). 2.05 Ga bimodal felsic-mafic volcanic rocks of alkaline affinity are intercalated with deep-water turbiditic sediments along the present western edge of the Karelian province.

No clear examples of subduction-related magmatism between 2.70 and 2.05 Ga have been found in Finland. The 2.02 Ga felsic volcanic rocks in Lapland (Kittilä) occur in association with oceanic island arc-type rocks and are the oldest candidates for Palaeoproterozoic subduction-related rocks (Hanski & Huhma 2005). Associated continental within-plate volcanic rocks are possibly related to the continuing craton break-up. Bimodal alkaline-tholeiitic magmatism in central Lapland shows that rift magmatism continued further until 1.98 Ga (Hanski et al. 2005). Jormua–Outokumpu ophiolites, tectonically intercalated with deep-water turbidites, are a unique example of Archaean subcontinental lithospheric mantle with a thin veneer of oceanic crust formed at 1.95 Ga along the western edge of the present Karelian province (Peltonen 2005a).

Proterozoic orogenic rocks

The main events in the Palaeoproterozoic orogenic evolution of Fennoscandia can be divided into the Lapland–Kola orogen (1.94–1.86 Ga; Daly

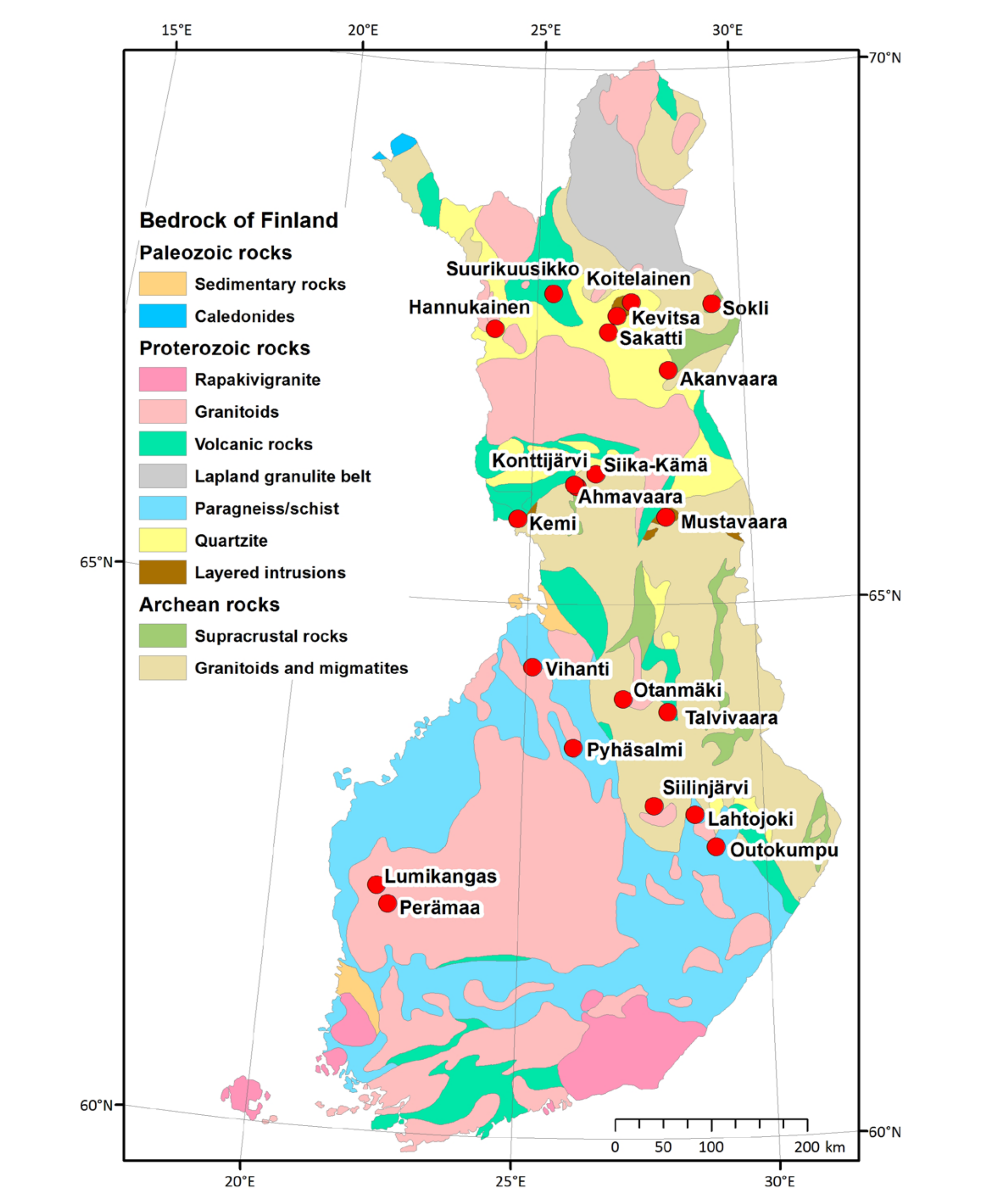


Figure 1. Simplified geological map of Finland

et al. 2006) and the Svecofennian orogen (1.92–1.79 Ga; Lahtinen et al. 2005, 2008). Whereas the Lapland–Kola orogen shows only limited formation of new crust, the composite Svecofennian orogen produced a large volume of Palaeoproterozoic crust in the Svecofennian province.

The Palaeoproterozoic rocks in the Lapland-Kola orogen include small amounts of juvenile, 1.96–1.91 Ga, island arc-type rocks and large volumes of felsic granulites (Daly et al. 2006, Huhma et al. 2011). The oldest rocks in the central Svecofennian province are the 1.93–1.92 Ga island-arc rocks in the Savo belt. Arc-type volcanic rocks are slightly older (ca. 5–10 Ma) than granitoids, but the igneous rocks are predominantly 1.89–1.87 Ga in age in the Central Finland granitoid complex (CFGC) and surrounding belts (Kähkönen 2005). Sedimentary rocks are typically metapsammites with local intercalations of black schists and tholeiitic lavas. Abundant, ca. 1.80 Ga, plutonic rocks occur in northern Finland.

The southern part of Svecofennia in southern Finland (Väisänen & Mänttäri 2002) comprises arc-type volcanism at 1.90–1.88 Ga with partly coeval plutonism at 1.89–1.87 Ga. Sedimentary sequences also include metacarbonate rocks, whereas graphite-bearing rocks are rare. Two metamorphic peaks, at 1.88–1.87 and 1.83–1.80 Ga, have been detected in southern Svecofennia. A major unconformity between them is indicated by the occurrence of lateritic palaeosols (Lahtinen & Nironen 2010) and ≤ 1.87 Ga quartzites and meta-arkoses (e.g., Bergman et al. 2008). Younger syn- to post-tectonic granites (1.85–1.79 Ga) are common in southern Svecofennia.

Rocks of the Mesoproterozoic rapakivi granite association (1.65–1.47 Ga) are locally voluminous and especially characteristic for southern Finland (Rämö & Haapala 2005).

MINING HISTORY - FINLAND

Pasi Eilu (GTK)

16th – 19th Centuries

The Ojamo iron ore mine, which started production in 1530, is regarded as the first metal mine in Finland. Following this, over 350 metal mines had been in operation before World War II. The scale of production in these mines was modest, although mining played an important role in the slowly developing society. Before the 1920s, the mines mainly produced iron ore for iron works in southern Finland. Sulphide ore production was mostly from one mine, Orijärvi (Cu-Zn) in SW Finland. From 1530 until the end of the 19th Century, metal ore production totalled 1.4 Mt, of which sulphide mines comprised 1.0 Mt (most of which was produced after 1850) and the iron mines 0.4 Mt (Puustinen 2003).

20th Century

In Finland, the modern mining industry started to form along with the Outokumpu mine. The deposit was discovered in 1910 (Stigzelius 1987) and in 1928 it became the largest sulphide ore mine in the country. Small-scale production started immediately in 1910, production gradually increased in the 1920s and 1930s and total ore output was almost 6 Mt between 1930 and 1945. During its lifetime, 1910–1989, about 28 Mt of ore was mined and 1 Mt copper produced (Puustinen 2003). The Petsamo (Pechenga) nickel deposit was found in 1921, in the then north-easternmost corner of Finland (Haapala & Papunen 2015). The development of a mine at Petsamo was complicated, but eventually, in the period 1936–1944, about 0.5 Mt of ore was mined, first as a Finnish-Canadian cooperation, and during World War II by Germany. The war between Finland and the Soviet Union ended in September 1944, and the Petsamo region was subsequently ceded to the Soviet Union.

Soon after the war, in the late 1940s, the Aijala (Cu) and Otanmäki (Fe-Ti-V) mines were opened. Otanmäki gradually developed into a globally significant vanadium mine, responsible for about 10 % of the world's vanadium production during the 1960s and 1970s (Illi et al. 1985). Seven metal mines were opened in the 1950s, including the Vihanti (Zn) and Kotalahti (Ni) mines. The most active mine development period in Finland was 1960–1980, when more than twenty metal mines started production. The most important were the still operating Kemi Cr and Pyhäsalmi Zn-Cu mines. As a consequence, total yearly metal ore output peaked in 1979 at slightly over 10 Mt. A few small mines were opened in the 1980s, but a number of major mines were closed in the same period, and total production gradually declined to about 3 Mt in the early 2000s (Puustinen 2003).

Before the opening of the Talvivaara and Kevitsa mines in 2008 and 2012, respectively, the largest sulphide mine in Finland was Pyhäsalmi. The deposit was discovered in 1958 when a local farmer dug a well through the overburden till into a subcrop of the massive ore (Helovuori 1979). By the end of 2014, over 53 Mt of ore had been mined and the remaining ore has secured a further 5 years of production.

The Kemi chromite deposit was found 1959 by a local layman (Alapieti et al. 2005). Open-pit chromite mining began in 1966 and ferrochrome production in 1967 at nearby Tornio, at the far northern end of the Gulf of Bothnia. Stainless steel production at Tornio commenced in 1976. In 2006, the underground mine became the sole source of ore. Its current design capacity is 2.7 Mt/y of ore. The known ore reserves will enable mining to continue for several decades, and a recent seismic reflection survey suggests that the ore extends possibly beyond 2 km depth (Huhtelin 2015).

Currently, we are living in a new era in Finnish mining history. Two major mines, Kittilä Suurikuusikko (gold) and Talvivaara (nickel), were opened in 2008, and the Kevitsa Ni-Cu-PGE mine in 2012. These three mines have multiplied Finnish metal ore output to about 14 Mt/y in 2014. In addition to these major deposits, a number of smaller projects have recently started; these include the Jokisivu mine which produced its first gold in 2008, and the Pampalo gold and the Kylylahti Outokumpu-type Cu-Co-Ni-Zn mines which opened in 2011. The Laiva (Laivakangas) gold mine in western Finland also went into production in 2011, but is presently in care and maintenance.

The Talvivaara Ni-Zn-Cu-Co deposit was discovered in 1977 (Loukola-Ruskeeniemi & Heino 1996). The resource was found to be large but of low grade, and it was concluded at the time that exploitation was not economically viable using conventional metal extraction techniques. Bio-heap leaching was later found to be a suitable method for operating this sulphide deposit. The mine successfully produced the first metals in October 2008, and has been in production since 2010. With the total resource of 2100 Mt @ 0.22 % Ni, 0.50 % Zn, 0.13 % Cu and 0.02 % Co, Talvivaara has the potential to become a globally significant producer, especially for nickel. However, the bio-heap leach process, a global first for a Ni mine, and the complete metal extraction process, have had a number of complications, and the mine has yet to reach the expected production levels.

The Geological Survey of Finland (GTK) discovered gold in the Suurikuusikko area of the Central Lapland greenstone belt in 1986 (Wyche et al. 2015). A preliminary estimate of inferred resources in 2000 amounted to 8.3 Mt @ 6.1 g/t gold. Construction of the mine began in June 2006 (Agnico Eagle Mines ltd), and the mine was named after the local municipality of Kittilä. The first gold was poured on 14 January 2009. The annual production has been 4-5 tons of gold, but is expected to increase to 7.5 tons in 2016. At the end of 2014, the total pre-mining resource (total resources + mined ore) amounted to 57.6 Mt @ 4.38 g/t Au. The deposit is known for about 4 km along strike, and is open both along strike and to a depth of 1.5 km.

The Kevitsa Ni-Cu-PGE deposit was found in 1987 (Mutanen 1997). Gold Prospecting AB (later Scandinavian Minerals Ltd.) claimed the deposit in 2000 and started planning for a mine. First Quantum Minerals Ltd. (FQM) bought Scandinavian Minerals Ltd. in 2008, built the mine, and started production in 2012. The current pre-mining resource (total resources + mined ore) is 272 Mt @ 0.40 % Cu, 0.30 % Ni, 0.015 % Co, 0.24 g/t Pd, 0.19 g/t Pt, and 0.11 g/t Au. In 2014, 7 million tonnes of ore was processed at Kevitsa.

By far the largest industrial minerals mine in Finland is the Siilinjärvi mine (Kemira Corp. 1979–2007, Yara International ASA 2007–), hosted by an Archaean carbonatite intrusion (O'Brien et al. 2015). First indications of the carbonatite were found in a railway cutting in 1950, and exploration began in full by GTK in 1958. The deposit was test-mined during 1975–1979, and full-scale production started in 1980. In 2014, the mine produced 11 Mt of apatite ore, from which about 0.95 Mt tonnes of apatite concentrate were recovered as the main product, with by-product carbonates and mica also recovered. By the end of 2014, 271 Mt of ore has been mined at Siilinjärvi: the remaining resources are reported to be 1617 Mt @ 3.8 % P_2O_5.

PYHÄSALMI AND VIHANTI DEPOSITS

Jouni Luukas & Kaj Västi (GTK)

The Vihanti–Pyhäsalmi area is located on the NE edge of the Svecofennian domain, in the NW part of the Raahe–Ladoga suture, previously commonly called the Main Sulphide Ore Belt of Finland (Kahma 1973). The Raahe–Ladoga suture has been described as a collisional boundary zone between Proterozoic and Archaean domains (Lahtinen 1994). The Vihanti–Pyhäsalmi area comprises the central part of the northwestern Savo schist belt (Vaasjoki et al. 2005) and is 10–40 km wide and about 300 km long.

Most of the massive sulphide deposits in the area are hosted by metavolcanic rocks, locally also by metasedimentary rocks, in a Palaeoproterozoic island arc environment, close to the Archaean Karelian craton. In the Pyhäsalmi region, volcanic activity started in an extensional continental margin with felsic volcanism and continued in a rifted marine environment with mafic volcanism. Large-scale hydrothermal alteration and mineralisation occurred close to the centres of mafic volcanism. This 1.93-1.92 Ga bimodal volcanic event represents the lowermost volcanic unit in the Raahe-Ladoga Zone. In the northwestern end of the area (Vihanti area), volcanogenic rocks are predominantly intermediate and felsic in composition. These compositionally different units have been named as the Pyhäsalmi and Vihanti groups. Without a longer hiatus, volcanic activity continued at 1.89-1.88 Ga with more calc-alkaline volcanism (Kousa et al. 1997). The Vihanti–Pyhäsalmi metallogenic area includes a large number of Zn-Cu deposits and prospects. It is particularly known for the two world-class VMS-type Zn deposits at Pyhäsalmi and Vihanti, but there also are a few smaller mines and a number of unexploited deposits and occurrences. Currently, only the Pyhäsalmi mine is active. In the vicinity of Pyhäsalmi there are three smaller mined VMS-type deposits: Mullikoräme, Ruostesuo and Kangasjärvi.

Pyhäsalmi

The metavolcanic rocks of the Pyhäsalmi group in the Pyhäsalmi mine area belong to the Ruotanen Formation (Puustjärvi 1999). Voluminous piles of sodium-rich quartz plagioclase-phyric rhyolitic metavolcanic rocks with abundant mafic dikes form the lowermost part of the formation. This Kettuperä gneiss unit (sample A0751 in Helovuori 1979) in the Pyhäsalmi group is interpreted here as the oldest felsic volcanic member of the Ruotanen Formation. New zircon U-Pb dating results give an age of 1924±3 Ma, which is a reliable age for volcanism in the Pyhäsalmi group (Kousa et al. 2013). This unit is overlain by voluminous felsic pyroclastic breccias which are usually totally altered into cordierite-sericite schists. The pyroclastic unit shows abundant sulphide dissemination and the major sulphide ore is located here. The felsic volcanic rocks are overlain by massive mafic lavas which form the uppermost part of the Ruotanen Formation. The intermediate volcanic rocks with minor calc-silicate interlayers belong to the overlying Vihanti group.

The Pyhäsalmi deposit is hosted by a volcanic sequence composed of lapilli tuffs, coherent lava flows and sill-shaped intrusions of varied composition (Figure 2). Rhyolitic volcaniclastic rocks are the most common host rock near the sulphide deposit. Total production since the beginning of mining has been 50 Mt (end of 2012) grading 0.92 % Cu, 2.47 % Zn and 37.2 % S. The ore contains, on average, 0.4 g/t Au and 14 g/t Ag (Mäki et al. 2015).

Vihanti

Volcanic activity in the Vihanti area took place in two stages (Rauhamäki et al. 1980). The earlier cycle started under marine conditions and com-

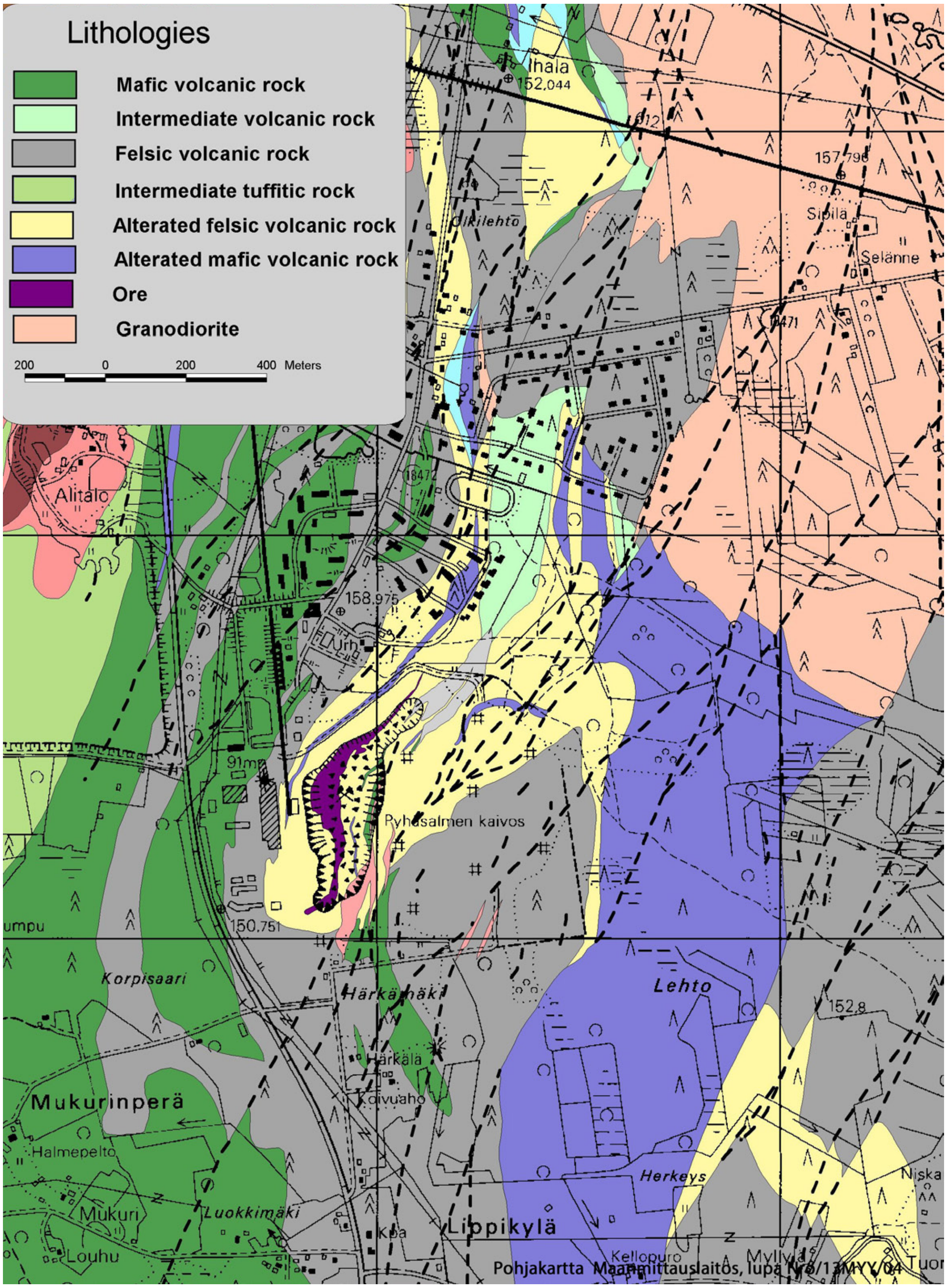


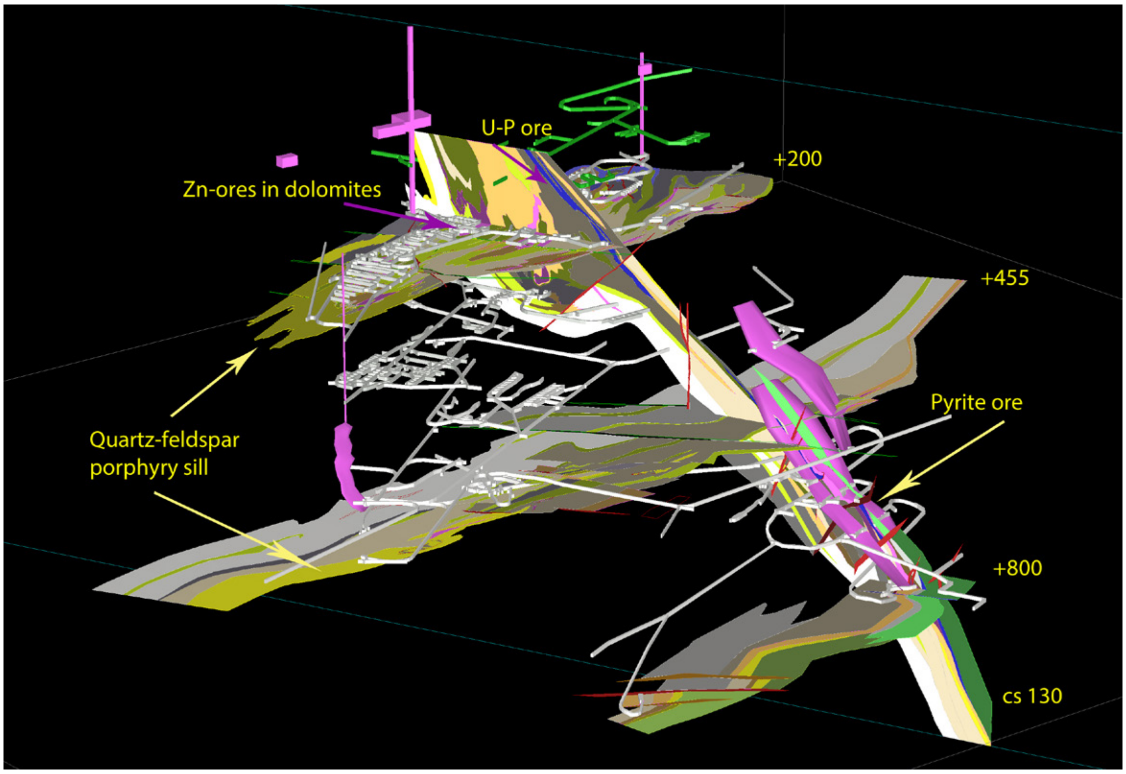
Figure 2. Geological map of the Pyhäsalmi mine area.

prised felsic volcanic rocks and chemically precipitated carbonate rocks, and is characterised by the formation of Lampinsaari-type ore bodies. The deposition of volcanic and carbonate rocks continued concurrently with ore formation, culminating in the stages of zinc ore deposition.

After mineralisation, more felsic volcanic rocks were erupted during the later cycle. Graphite tuff between the zinc ore and the later volcanic cycle refers to reducing conditions (op. cit.).

The Vihanti Zn-Pb-Ag deposit is situated in the northwestern part of Raahe-Ladoga zone. An essential part of this rock assemblage is composed of what is called the Lampinsaari-type rock association comprising felsic metavolcanic rocks, calcsilicate rocks and graphite tuffs (Luukas et

Figure 3. Geological cross sections of the Vihanti mine, viewed from the southwest. Intermediate volcanic rock (possibly tuffite) is indicated in green, skarn-banded felsic volcanic rock in grey, skarn and dolomite in orange, cordierite-sillimanite gneiss in yellow, younger dikes in red, pyrite ore in dark purple and zinc ore in pale purple.



al. 2004). The deposit consists of five types of mineralisation: zinc, copper, pyrite, lead-silver-gold and uranium-phosphorous ore (Figure 3). According to Autere et al. (1991), the U-P type is the oldest, whereas the Pb-Ag and Zn ores are the youngest. There are about 20 separate ore bodies that have been mined out. The metal content and size varies greatly between the different bodies. The Zn ores, hosted by dolomite and calcsilicate rocks, were by far the most important ore types for the economy of the mine, containing over 75 % of the total ore resource. Minor Zn ore bodies were mined out along the southern fold limb down to +800 level. Zn-ores are typically situated in tectonically thickened skarn-dolomite-serpentinite beds in the upper levels of the deposit. Although the Zn-ores contain some Ag and Au, a separate disseminated Pb-Ag ore type is located in close connection to the Zn-ores. The best Pb-Ag ores were in the western part of the mine. Pyrite- or pyrrhotite-rich ores which are situated in the upper parts of the mineralised horizon are called pyrite ores. The Hautaräme and Hautakangas ore bodies on the downward dipping limb area are compact pyrite ores hosted by felsic volcanic rocks and calcsilicate rocks. Cu-ores in the felsic volcanic rocks are disseminated ore types, which are closely related to the pyrite ores. The fifth separate ore type is uranium-phosphorous ore which forms a non-continuous layer in the upper part of U-P-horizon, the downward dipping limb area. This unexploited ore type is hosted by felsic volcanic rocks interbanded with calcsilicate rocks (Rehtijärvi et al. 1979). The underground production from the Vihanti mine was 28 Mt ore which contained 4 % Zn, 0.4 % Cu, 0.36 % Pb, 25 ppm Ag and 0.44 ppm Au.

The U-P mineralisation, with over 1 Mt of low grade ore, has never been exploited. In addition to the Vihanti deposit, there are a couple of smaller unexploited deposits. Although intense exploration has been carried out, only minor showings have so far been detected in the Vihanti district.

OUTOKUMPU Cu-Co-Zn

Asko Kontinen (GTK)

The Outokumpu deposit, which was mined until 1984, contained c. 30 million ton @ 3.8 wt.% Cu, 0.24 wt.% Co, 1.07 wt.% Zn, 0.12 wt.% Ni, 0.8 g/t Au and 8.9 g/t Ag. Since the discovery of the Outokumpu ore in 1910 a dozen more similar, but smaller and metal-poorer, semimassive to massive Cu-Co-Zn sulphide deposits have been discovered in the Outokumpu mining district. Three of these have been exploited, including Vuonos, Luikonlahti and the currently mined Kylylahti deposit (Peltonen et al. 2008; Kontinen 2012a). The host assemblage of the Outokumpu deposits also contains low-grade Ni occurrences that were mined at Vuonos for 5.5 million ton @ 0.2 wt.% Ni.

The Outokumpu mining district is part of the Palaeoproterozoic North Karelia Schist Belt and is confined within the boundaries of the Outokumpu Allochthon (also known as the 'Outokumpu Nappe Complex' or 'Outokumpu Nappe'). It contains serpentinite bodies fringed with the dolomite-skarn-quartz rock and black schist host rock assemblage of the polymetallic and polygenetic Outokumpu-type copper-cobalt-zinc and Kokka-type nickel mineralisation.

More than 85 % of the Outokumpu Allochthon is composed of schistose, metaturbiditic wackes and pelites, which occur in sequences dominated by medium to thinly bedded psammites. Metavolcanic rock intercalations and synsedimentary magmatic intrusions are not found in the apparently kilometres-thick, now complexly folded and faulted, turbidite package. Models involving relatively deep water deposition of the turbidites, probably at continental slope-rise fans in a passive margin type environment, have been proposed (Kontinen & Sorjonen-Ward 1991, Peltonen et al. 2008, Lahtinen et al. 2010). The wacke schist sequence contains layers of black schists (partly black turbidite muds), which appear to be thicker and more common in the presumably lowermost parts of the allochthon (Loukola-Ruskeeniemi 1999, Kontinen et al. 2006). These schists contain abundant organogenic graphite (5–10 %) and commonly also iron sulphides (5–20 wt.%). They are strongly enriched in Ni, Cu and Zn relative to the upper crust or average shale compositions (Loukola-Ruskeeniemi 2011). The cobalt content is systematically relatively low, 33 ppm on average. The low Co distinguishes the black shales from the semimassive to massive Co-Cu-Zn mineralisation, which has much higher Co contents and Co/Ni ratios. The black-schist sulphides also have isotope compositions indicating a crustal source of their Pb, versus the obvious mantle source of Pb in the most pristine parts of the sulphide bodies (Peltonen et al. 2008). Redox-sensitive metals such as Sb, Se, Mo, V and U occur in the black schists in elevated concentrations (Kontinen et al. 2006; Loukola-Ruskeeniemi 2011), attesting to at least periodically anoxic-sulphidic depositional conditions, but also to a generally oxygenated atmosphere at the time of the Outokumpu sedimentation (Kontinen & Hanski 2015).

The turbiditic wacke-shale sediments in the Outokumpu Allochthon were deposited subsequent to 1920±20 Ma, which is the age of their youngest dated detrital zircon grains (Lahtinen et al. 2010). The black-schist interleaved lower units of the allochthon host numerous fault-bound (exotic) bodies of mantle peridotite-derived serpentinite with variable components of 1.96 Ga gabbroic, basaltic and plagiogranitic rocks (Peltonen et al. 2008). Because of their older age than the sedimentation of the enclosing turbidites, these peridotite-gabbro-basalt bodies are interpreted as fragments of 1.95 Ga old mafic-ultramafic oceanic floor/crust, tectonically incorporated into the turbidite sediments during the early obduction of the Outokumpu Allochthon at ca. 1.90

Ga (Peltonen et al. 2008). Serpentinites in the ophiolite fragments show at their margins, especially where located against graphitic-sulphidic schists, an omnipresent listwaenite (carbonate, carbonate-silica) to birbirite (silica) alteration. Where ideally developed, the alteration zonation is, from serpentinite to black schist: 1–5 m of carbonate, 5–15 m of carbonate-silica (listwaenite), and 15–40 m of silica rock (birbirite). These zones are metamorphosed and recrystallised to dominantly carbonate, tremolite±diopside and quartz rocks, respectively. Attesting to their peridotitic origin all these rocks consistently contain 1000-4000 ppm Cr and Ni, and nearly always chromite. Particularly thick alteration zones are typically flanked by especially thick zones of sulphide-rich black schist.

Some of the Outokumpu area serpentinite bodies host, in their deformed-metamorphosed carbonate-silica alteration envelopes, massive to semi-massive Cu-Co-Zn and disseminated Ni sulphides of the Outokumpu and Kokka type, respectively. Of these two mineralisation types, the economically far more significant Outokumpu Co-Cu-Zn is, in all cases, found with a parallel zone of Ni-dominated mineralisation in the hosting skarn-quartz rocks. In contrast, the Kokka Ni mineralisation occurs widely also in environments without any Co-Cu-Zn mineralisation. Weak Ni mineralisation is, in fact, a ubiquitous feature of the Outokumpu alteration assemblage, which systematically contains 1000–4000 ppm whole rock Ni predominantly located in disseminated pyrrhotite and pentlandite. The concept of Kokka-type Ni mineralisation refers to irregular zones of more elevated Ni contents and Ni sulphides within the alteration zones, commonly in locations of intense shearing and in proximity to highly sulphidic black schists (Huhma 1975).

Within the Outokumpu district there are only minor differences between the individual deposits apart from size and features caused by variations in metamorphic grade, which increases in the area from east to west, from lower amphibolite to upper amphibolite facies (Säntti et al. 2006; Kontinen et al. 2006, Peltonen et al. 2008). All the ore bodies contain, as their main sulphide minerals, variable contents of pyrite, pyrrhotite, chalcopyrite, sphalerite, pentlandite and locally cobaltite. The dominant gangue mineral is usually quartz with some tremolite±diopside although locally the latter may predominate. The sulphide bodies at Kylylahti (Figures 4 and 5), where the metamorphic grade is lowest, are predominantly pyritic and show elevated contents of more 'volatile' elements such as As, Sb and Hg, whereas the ore bodies in upper amphibolite/migmatite grade environments are generally pyrrhotitic with much lower contents of Sb, As and Hg. The impact of the metamorphic control (cf., Vaasjoki et al. 1974) also results in the presence of a large part of the Co content being in pyrite at Kylylahti, whereas at Luikonlahti nearly all the cobalt is in pentlandite. The large Outokumpu deposit is partly pyritic and relatively rich in As and Au, whereas the thinner, smaller Vuonos and Perttilahti deposits are dominantly pyrrhotitic and low in As and Au. The Luikonlahti and Hietajärvi subareas are in mid- to upper amphibolite facies environments, and their deposits are thus totally recrystallised to metamorphic granoblastic textures. They are generally pyrrhotitic and very low in As and Au. The effects of metamorphism on the Kokka type Ni occurrences are restricted mainly to an increase in the grain size of sulphides and gangue and increased remobilisation of the sulphides into blotches and veinlets.

The Outokumpu Co-Cu-Zn sulphides are interpreted to be polygenetic with a primary inhalative-exhalative Cu-Co-Zn proto-mineralisation event(s) at ca. 1.95 Ga, in a hot spring environment in spreading zones or leaky transforms in a predominantly ultramafic ocean floor (Peltonen et al. 2008). The Ni mineralisation of the carbonate-silica alteration assemblage occurred during the ca. 1.90 Ga obduction of the ophiolite fragments, inside the host turbidite sediments, when low T (<200°C) carbonaceous and sulphidic fluids altered the outer margins of the ultramafic bodies to sulphide-bearing carbonate - quartz rocks. Nickel originally bound in ferromagnesian mantle minerals, such as olivine, was relocated into sulphides during this process. The exceptionally high Ni content in the Co-Cu type ores is interpreted to reflect early syntectonic interaction of the Cu-Co-Zn protosulphides with the Ni sulphides, by simple 'mechanical' mixing of the two sulphide end-members or by fluid-assisted diffusion of Ni from the Ni occurrences into the Cu-Co bodies. Later syntectonic solid-state remobilisation and concentration of the Cu-Co-Zn-Ni sulphides into late fault-controlled positions completed the geometric style

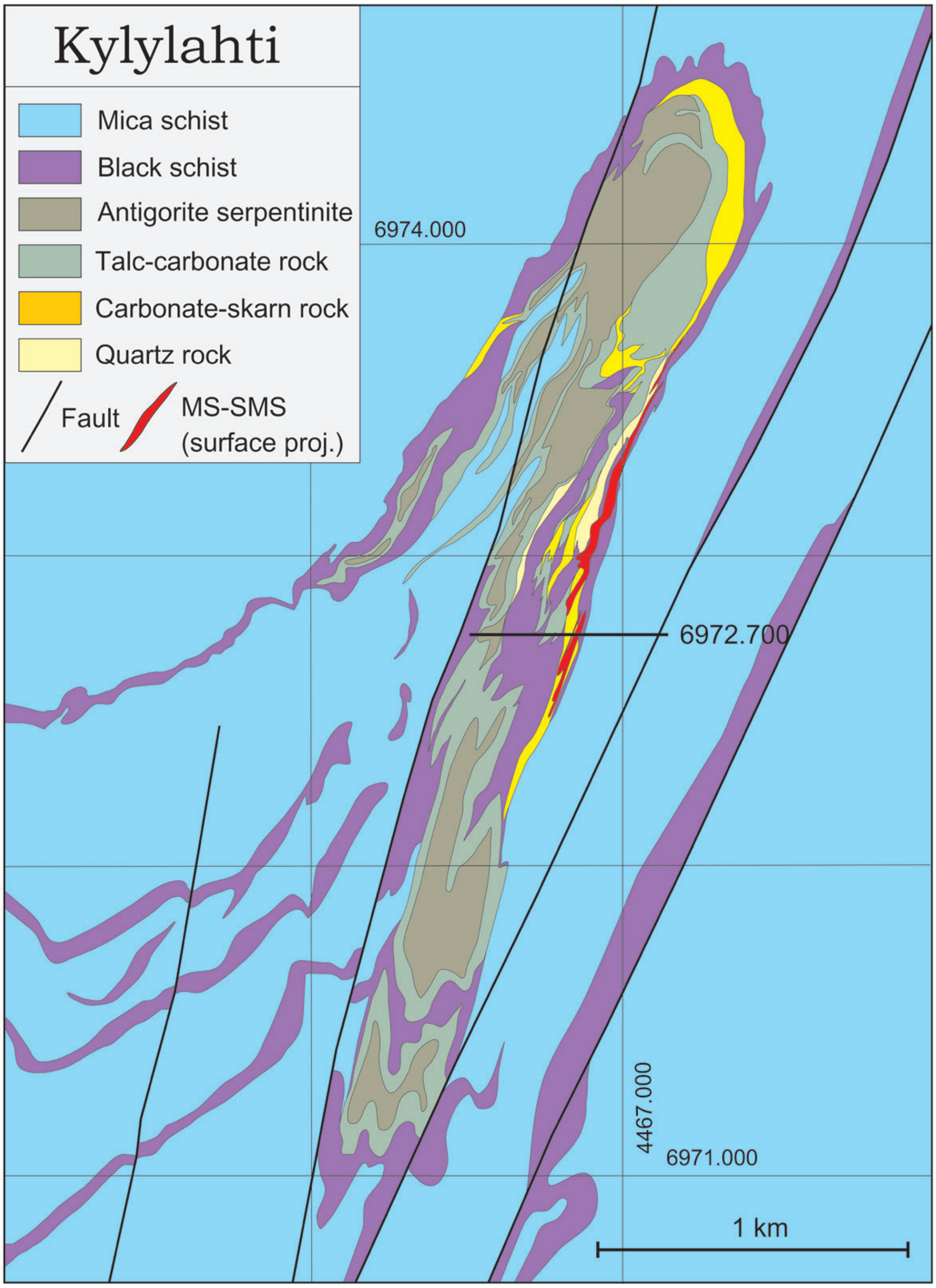
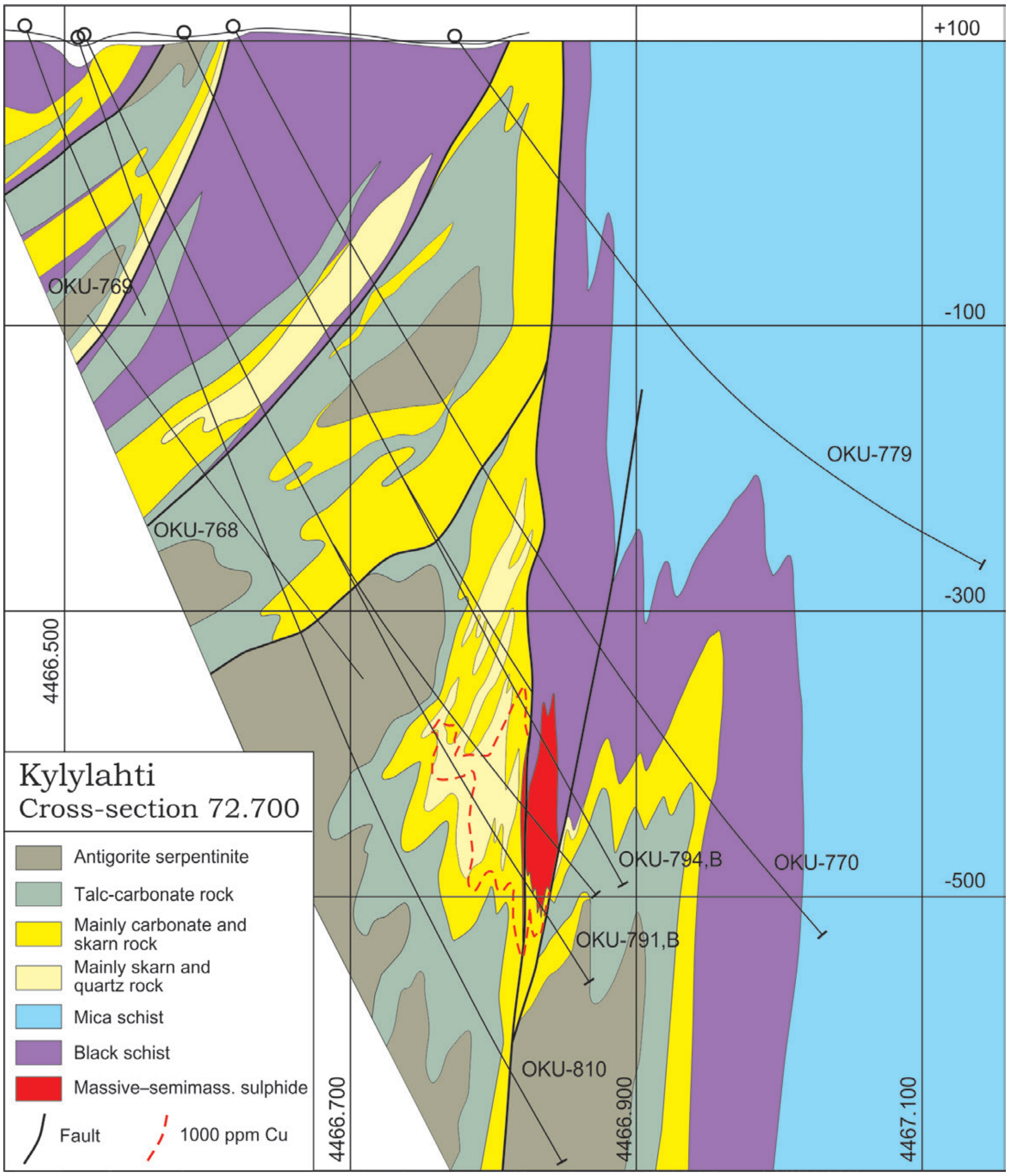


Figure 4. Geological map of the Kylylahti massif. The alteration zoning is typical for Outokumpu ultramafic massifs in lower amphibolite facies environments. Location of the massive-semimassive part (4.2 Mt @ 2.3 wt.% Cu) of the presently mined Kylylahti Co-Cu-Zn-Au deposit is outlined by a surface projection.

of the Outokumpu type deposits as thin (1–15 m) and narrow (50–450 m) but long (1– >5 km) sheets. In such serpentinite bodies or ophiolite fragments that obducted without any Cu-Co protosulphides, only irregular local Ni enrichments of the Kokka type were generated in structurally favourable positions.

In exploration for Outokumpu-type ores, it is important to recognize that valuable sulphides occur only in close proximity to serpentinite bodies of which only a fraction are found to be mineralised, obviously those that were obducted with Cu-Co protosulphides. Although some authors emphasise the role of black schists (e.g. Loukola-Ruskeeniemi 1999), it should be noted

Figure 5. A cross-section view of the eastern margin of the Kylylahti massif. See location of the profile in Figure 4.



that on the basis of Pb isotope compositions, the commonly accompanying black shales did not contribute significantly to the genesis and metal budgets of the ore bodies (Peltonen et al. 2008). Experience from past exploration largely confirms this inference as such characteristics as metal contents and ratios of the black schists have nowhere been observed as useful vectors to the Cu-Co ores. The genesis of the Outokumpu alteration assemblage and of the Kokka-type Ni occurrences did, however, involve the influx of S and of certain metals, such as As, Sb and Pb, from the black shales.

TALVIVAARA Ni-Zn-Cu

Asko Kontinen (GTK)

The Talvivaara deposit, discovered by the Geological Survey of Finland in 1977, is a very large (2 billion metric tons) low-grade, black-shale hosted, polymetallic sulphidic resource containing 0.23 wt.% Ni, 0.54 wt.% Zn, 0.13 wt.% Cu, 0.02 wt.% Co and also 16 ppm recoverable U (Loukola-Ruskeeniemi & Lahtinen 2013; Kontinen & Hanski 2015). The deposit, which has been intermittently mined since 2007, is currently the largest sulphidic Ni resource under exploitation in Western Europe. Talvivaara is located in central Finland within the Palaeoproterozoic, dominantly metasedimentary, Kainuu Schist Belt (Laajoki 1991, 2005). Several similar but much smaller mineralisations have been observed elsewhere in the central and southern part of the Kainuu belt and a couple also further south in the northernmost part of the North Karelia Schist Belt (Kontinen 2012b). Talvivaara and the smaller deposits have been found on the basis of ground and low-altitude airborne geophysical and moraine- and lithogeochemical surveys, with follow-up including mapping, boulder tracking and drilling operations.

The main components of the Proterozoic strata in the Kainuu Schist Belt (Figure 6) are: (1) Sumi-Sariola and Jatuli stage, 2.5–2.1 Ga, cratonic and epicratonic, dominantly feldspathic to quartz arenite sequences, (2) Lower Kaleva stage, 2.1–1.95 Ga, rift-related wacke-pelite sequences, and (3) Upper Kaleva stage, 1.95–1.90 Ga, deep-water turbidite wackes and pelites (Kontinen 1986, 1987, Laajoki 2005). Of these sequences, the two older ones are autochthonous strata on a deeply eroded, mainly late Archaean, mostly gneissic-granitoid basement, whereas the third is at least partly in allochthonous units carrying fault-bound, exotic ophiolitic fragments of 1.95 Ga oceanic crust (Peltonen et al. 2008 and references therein). The Lower and Upper Kaleva differ for their sediment sources, which were dominantly Archaean and/or recycled Archaean for the former and Proterozoic (mostly 1.92-2.0 Ga) for the latter (Kontinen & Hanski 2015).

The Talvivaara-type deposits occur in association with sulphide- and metal-rich carbonaceous (now graphitic) sediments. Carbonaceous sediments first appear as thin layers in the topmost 2.1 Ga dolomitic and tuffaceous strata of the Jatuli sequence. They become abundant in the upper parts of the Lower Kaleva sequence, after ca. 2000 Ma (Kontinen & Hanski 2015). Layers of carbon- and sulphide-rich sediments are also common in the deeper-water feldspathic wacke turbidites of the Upper Kaleva stage.

The giant Talvivaara deposit has an exposed strike length of about 12 km (Figure 6). It comprises one or two, originally probably <50 m thick layers of strongly metal-enriched, thick bedded to laminated graphite- and sulphide-rich muds. Muds are intercalated with cm to meter thick layers of thinly bedded to laminar pyritic muds and carbonate rocks. The primary muds have been pervasively metamorphosed and recrystallised into more coarse-grained, often quartz-plagioclase-microcline veined, quartz-anorthite-biotite-muscovite gneisses/schists interbedded with carbonate-diopside-tremolite calc-silicate rocks (Ervamaa & Heino 1980, Loukola-Ruskeeniemi & Heino 1996, Kontinen & Hanski 2015).

Based on drill core observations, footwall contacts the ore-bearing unit (Talvivaara Formation) grade, with the appearance of quartz wacke interbeds, into a quartz wacke unit at least hundreds of metres thick containing variably abundant interlayers of graphitic-sulphidic phyllite, metacarbonate rocks and mass-flow conglomerate (Hakonen Formation) (Figure 6, 7). The hanging-wall contact of the ore involves a rapid shift to black shale-intercalated, graphite-rich felds-

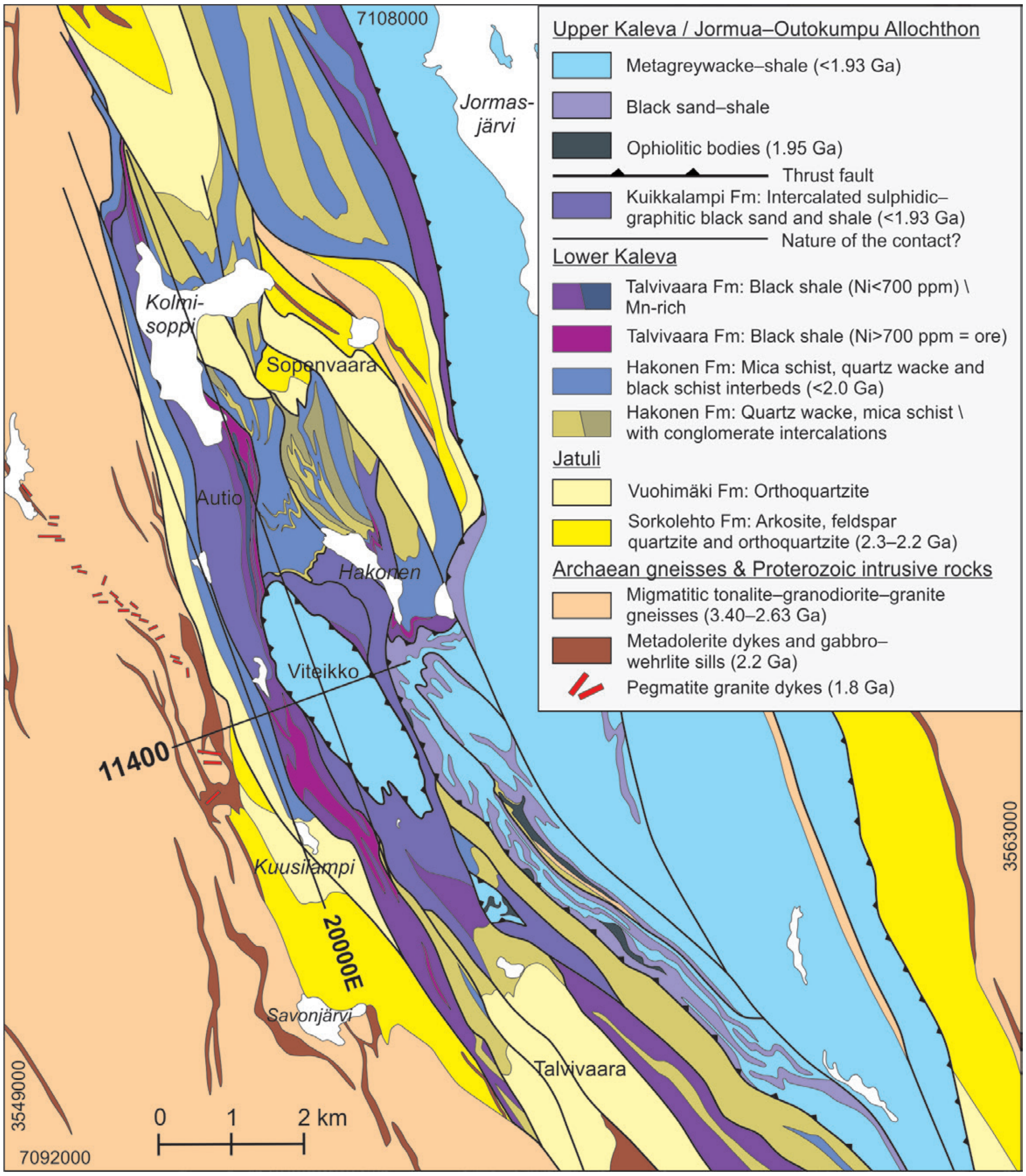


Figure 6. Geological map of the Talvivaara area showing the main lithostratigraphical units and location of the ore.

pathic wackes (Kuikkalampi Formation), representing a change, in terms of sediment source, to Upper Kaleva deposition. In its middle part, the Talvivaara deposit is overlain by a small klippe of the allochthonous Upper Kaleva turbidites with thin fault-bound lenses of talc-carbonate altered ophiolitic mantle peridotites spread all along its basal contact.

Upright compressional folding and related reverse faulting in a late stage of the tectonic deformation have contributed significantly to the volumes of minable ores by tectonic thickening of the mineralised unit. The present sulphide mineral assemblage is pyrrhotite-pyrite-sphalerite-chalcopyrite-pentlandite±alabandite, with a high variation in the pyrrhotite-pyrite ratio. All the sulphides have undergone metamorphic equilibration involving Fe derived from the epiclastic detritus; only part of the pyrite in the samples, which were originally rich in syngenetic-dia-genetic pyrite, seems to have avoided complete re-equilibration, which involved generation, mobilisation and concentration of monosulphide solid solution (mss) and intermediate solid solution (iss) in syntectonic veinlets and blebs (Kontinen et al. 2013b; Kontinen & Hanski 2015). As a consequence all the main sulphides, except pyrite, have near constant compositions throughout the minerali-

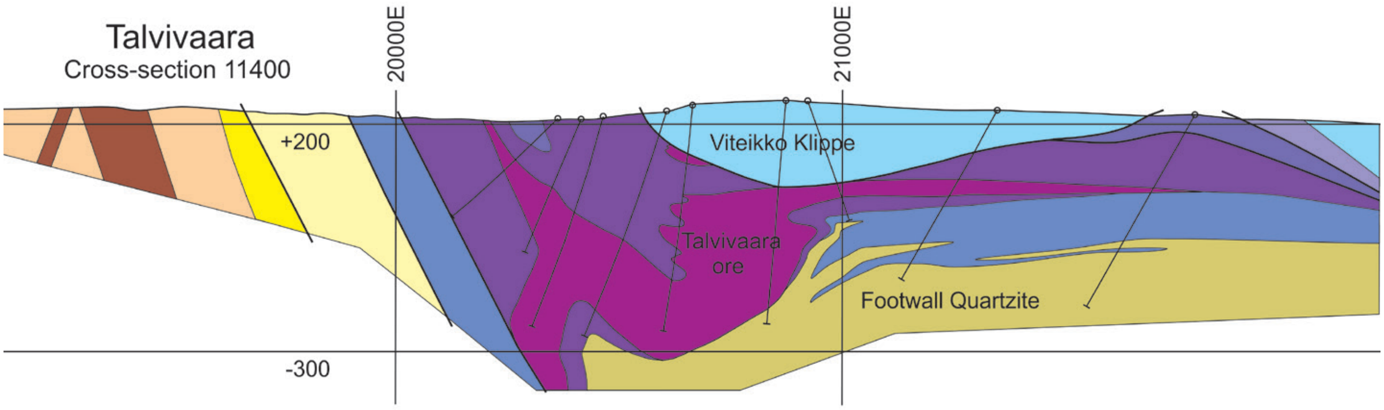


Figure 7. Vertical cross section of the Talvivaara deposit. See location of the profile and legend in Figure 6.

sation; e.g. pyrrhotite has 4930±690 ppm Ni, sphalerite 8.1±1.0 wt.% Fe and pentlandite <100 ppm Co. Besides sulphides there is significant iron only in the phlogopitic biotite. Metamorphic processes were important for the utilisation of the deposit as they relocated Ni in the easily soluble pyrrhotite and pentlandite from precursor Ni-rich phases which may have comprised high-Ni pyrite, millerite, polydymite or perhaps organometals. Pyrite contains the main part of the Co in the deposit, predominantly in coarse metamorphic pyrite (Kontinen & Hanski 2015).

In all the known Talvivaara-type occurrences the mineralised unit is characterised, for its best parts, by distinctly graphite-rich (5-15 % C as graphite) and sulphide-rich (5-30 % S in iron sulphides) mud-dominated beds with calc-silicate rock and quartz wacke intercalations. Mineralised units are located, in several cases immediately above phosphorite-chert-black shale sequences intercalated with silicate- and oxide-facies iron formations. In the largest of the known deposits, Talvivaara, the whole mineralised unit is, over its whole known extent, surprisingly uniform in its metal content and ratios. All the known Talvivaara mineralisations show a similar black-shale type enrichment in C, Fe, S and redox-sensitive metals compared to the background 'barren' black shales. Mineralised muds also show Co/Ni, Cu/Ni or Zn/Ni ratios broadly similar to the accompanying 'barren' black schists, or Kalevian black shales in general.

Following the discovery of the Talvivaara deposit, a submarine hydrothermal source of the excess base metals was proposed (Ervamaa & Heino 1980), and has remained the explanation, with some variations, in several subsequent studies (Loukola-Ruskeeniemi 1991, Loukola-Ruskeeniemi & Heino 1996, Loukola-Ruskeeniemi 1999). Recently, Kontinen (2012b) has presented, and Kontinen et al. (2013c) and Kontinen & Hanski (2015) further refined, an interpretation of the Talvivaara mineralisation as a synsedimentary metal enrichment under a water column that was apparently distinctly enriched in Ni, Co, Cu and Zn. The same mechanisms are most likely responsible for producing the metal enrichment in the associated 'barren' graphitic metasedimentary units. The elevated Mn and Fe contents provide support for effective cycling of Mn and Fe hydroxides-oxyhydroxides in basinal redoxclines also contributing to the high base metal levels. The very high Fe (±Mn), S and base metal contents (for black shales), as at Talvivaara, probably require far-field (as no near-field are present) hydrothermal sources. The uniformly high Ni/Cu (1.9 ± 0.6) and Ni/Zn (0.5 ± 0.1) ratios provide, however, evidence for the derivation of the base metals from a well-mixed and very large, probably oceanic seawater-type reservoir. The common presence of up to metre-thick, compositionally highly monotonous massive muds in the mineralised units as in Talvivaara implies an important role for intrabasinal resedimentation-recycling. Local cm to meter scale post-depositional metal redistribution has probably taken place to some extent already during diagenesis and early metamorphism but certainly during peak-metamorphism in the form of structurally controlled solid-state mss and iss migration with concentration into veinlets and blebs that characterize the more structurally reworked parts of the Talvivaara deposits.

SUURIKUUSIKKO GOLD DEPOSIT

Pasi Eilu (GTK)

Suurikuusikko is by far the largest of the many epigenetic gold (±copper) deposits of the Central Lapland greenstone belt. The Central Lapland greenstone belt (CLGB) is the largest mafic volcanic-dominated province preserved in Fennoscandia. It extends from the Norwegian border in the northwest to the Russian border in the southeast (and has continuations in each of the neighbouring countries). The belt was initially formed in an intracratonic rift setting related to the breakup of the Archaean Karelian craton (Hanski & Huhma 2005), and filled by clastic and chemical sedimentary and rift-related volcanic rocks, and in the central parts, by juvenile oceanic basaltic and komatiitic volcanic rocks. Extensive, apparently early, albitisation and locally abundant scapolite in amphibolite-facies parts of the region suggest that evaporites may also have been deposited in this rift environment. The area is characterised by several phases of mafic to ultramafic intrusive activity, and on the top of the sequence, by molassic sedimentary units. The deformational evolution of the CLGB in the period 1.92–1.77 Ga took place in four to five major stages: D_1 and D_2 during 1.92–1.88 Ga, $D_3 \pm D_4$ either during 1.92–1.88 Ga or 1.84–1.79, and the latest stage (D_4 or D_5) at ca. 1.77 Ga or slightly post-1.77 Ga (Hanski & Huhma 2005, Lahtinen et al. 2005, Patison 2007, Saalmann & Niiranen 2010, Lahtinen et al. 2015).

The Kittilä metallogenic area covers most of the CLGB. Its extent is essentially defined by various indications of orogenic gold mineralisation with about 40 drilling-indicated deposits and occurrences currently known. These include Suurikuusikko, the largest presently active gold mine in Europe (the Kittilä Mine), one closed mine (Saattopora), and several test-mined deposits. Orogenic gold mineralisation within the CLGB can be further divided into gold-only and anomalous metal-association subtypes, as these categories were originally defined by Groves (1993) and Goldfarb et al. (2001), respectively. Within the CLGB, both subtypes are characterised by siting in lower-order structures, Au/Ag >1, quartz veining is abundant, the sulphide contents are 1–10 vol%, the dominant ore minerals are pyrite, arsenopyrite and pyrite, carbonatisation and sericitisation haloes surrounding the mineralisation (Eilu et al. 2007, Eilu 2015). Another significant factor in locally controlling gold mineralisation within the CLGB, in addition to structure, is the pre-mineral albitisation which prepared the ground by creating locally most competent units, which thus provided the best sites for local dilation, veining and mineralisation (Saalmann & Niiranen 2010). Many of the occurrences of the Kittilä metallogenic area are of the gold-only style, including Suurikuusikko, but more than a half of the occurrences also contain Co, Cu and/or Ni as potential commodities, and can be included into the subcategory of 'anomalous metal association' as defined by Goldfarb et al. (2001)

The Suurikuusikko deposit had a pre-mining gold endowment of more than 8 million ounces. The deposit is hosted by tholeiitic mafic volcanic rocks of the ca. 2.02 Ga Kittilä Group of the CLGB (Figure 8). The gold is refractory, occurring in arsenopyrite and pyrite, and the mineralisation is associated with intense pre-gold albite and syn-gold carbonate(-sericite) alteration. The deposit is within the sub-vertical to steeply east-dipping Kiistala shear zone. Numerous ore lenses are distributed along, and within this N- to NNE-trending structure (Figure 8). Individual, subparallel ore lenses appear to be controlled by multiple phases of deformation and generally have a moderate northerly plunge. Mineralised intervals have been found for over 5 km strike length in the host structure, and from the surface to a depth of >1.6 km. Four stages of sulphide formation have been detected at Suurikuusikko.

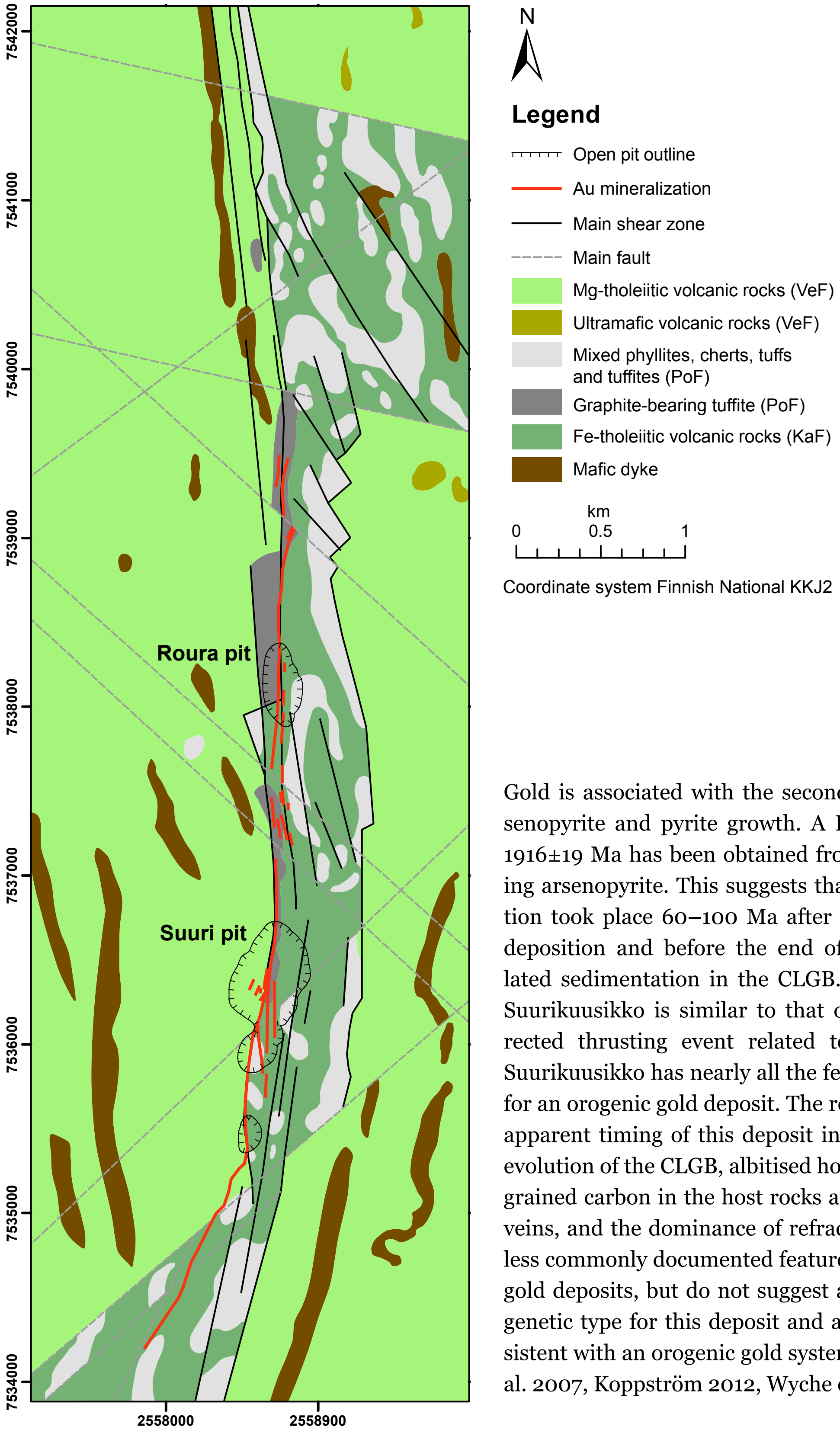


Figure 8. Geological map of the Suurikuusikko area.

Gold is associated with the second stage of arsenopyrite and pyrite growth. A Re–Os age of 1916±19 Ma has been obtained from gold-bearing arsenopyrite. This suggests that mineralisation took place 60–100 Ma after Kittilä Group deposition and before the end of collision-related sedimentation in the CLGB. This age for Suurikuusikko is similar to that of the SW-directed thrusting event related to the CLGB. Suurikuusikko has nearly all the features typical for an orogenic gold deposit. The relatively early apparent timing of this deposit in the orogenic evolution of the CLGB, albitised host rocks, fine-grained carbon in the host rocks and auriferous veins, and the dominance of refractory gold are less commonly documented features in orogenic gold deposits, but do not suggest an alternative genetic type for this deposit and are not inconsistent with an orogenic gold system. (Patison et al. 2007, Koppström 2012, Wyche et al. 2015).

THE HANNUKAINEN DEPOSIT

Tero Niiranen (GTK)

The Hannukainen Fe(-Cu-Au) deposit located in the Kolari district, western Finnish Lapland, is the largest known magnetite deposit in Finland. About 10 similar iron deposits are known from the Kolari district which forms the westernmost part of the Central Lapland greenstone belt (CLGB). The CLGB was formed during multiple stages of rifting with deposition of volcanic and sedimentary rocks in intracratonic and cratonic margin settings between 2.5 and 2.0 Ga and was subjected to metamorphism and deformation during Svecofennian orogenic events between 1.91 and 1.77 Ga (Lehtonen et al. 1998, Hanski & Huhma 2005). The supracrustal rocks of the Kolari region consist of ≥2.2 Ga Sodankylä Group quartzites and overlying 2.05 Ga Savukoski Group mafic volcanic rocks, mica schists and gneiss, dolomitic marbles and graphite bearing schists. These are overlain by <1.89 Ga Kumpu Group quartzites, conglomerates and mica schists (Hiltunen 1982, Väänänen & Lehtonen 2001). Intrusives in the area consist of 1.86 Ga Haparanda Suite monzonites and diorites and ca. 1.80 and 1.76 Ga granites (Hiltunen 1982, Niiranen et al. 2007). Structurally the Kolari district is located at the Baltic-Bothnian megashear (BBMS) which has been interpreted to represent a cratonic boundary between the Norrbotten and Karelian cratons to the west and east, respectively (Berthelsen & Marker 1986, Lahtinen et al. 2015). The dominant host rocks for the known deposits are the altered Savukoski Group mafic volcanic rock or 1.86 Ga diorite or a combination of these (Hiltunen 1982, Niiranen et al. 2007). The deposits display strong structural control by the shear and thrust structures comprising the BBMS in the area (Niiranen et al. 2007, Moilanen & Peltonen 2015).

The Hannukainen deposit was discovered in the mid 1970s and was mined by Rautaruukki Oyj from 1978 - 1990, the total production being 4.5 Mt from two open pits. Outokumpu Oyj mined an additional 0.45 Mt of ore from the Laurinoja open pit during 1991. Northland Resources S.A. carried out extensive exploration in Hannukainen from 2005-2014 culminating in a feasibility study in 2014. Based on this, the proven open pit mineral reserves of Hannukainen are 91.9 Mt @ 32.2 % Fe, 0.19 % Cu, and 0.09 ppm Au and probable reserves of 0.8 Mt @ 32.6 % Fe, 0.15 % Cu, and 0.06 ppm Au (Moilanen & Peltonen 2015).

The Hannukainen deposit consists of five elongated, lenticular, disseminated to semi-massive to massive magnetite bodies plunging gently to the SW (Figure 9). The maximum thickness of the ore bodies is 50 m and their average thickness varies from 10 to 20 m. The magnetite bodies are hosted by diopside-dominated skarns near to the contact of a 1.86 Ga old diorite on the hanging wall and mafic volcanic rock in the footwall, the skarns overprinting both of these rocks. Both the diorite and the mafic volcanic rock surrounding the ore bodies are albitised to variable degrees. Cu(-Au) mineralisation occurs chiefly within the magnetite-rich zones but weak mineralisations have been detected in the skarn and in altered wall rocks. All five magnetite bodies contain at least low Cu grades, however, the grades are highest in the Laurinoja ore body. Elevated gold grades are associated with higher Cu-grades and occur practically only in the Laurinoja ore body (Moilanen & Peltonen 2015). The sole oxide mineral in the ore is magnetite which occurs as disseminations, veins, and semi-massive to massive lenses. Pyrrhotite, pyrite and chalcopyrite comprise the dominant sulfides in sulfide-bearing parts and occur as dissemination, veins and fracture fillings.

Mineralisation at Hannukainen took place in two stages; the initial magnetite-stage was preceded by a Cu-Au stage. Fluid inclusion data suggest

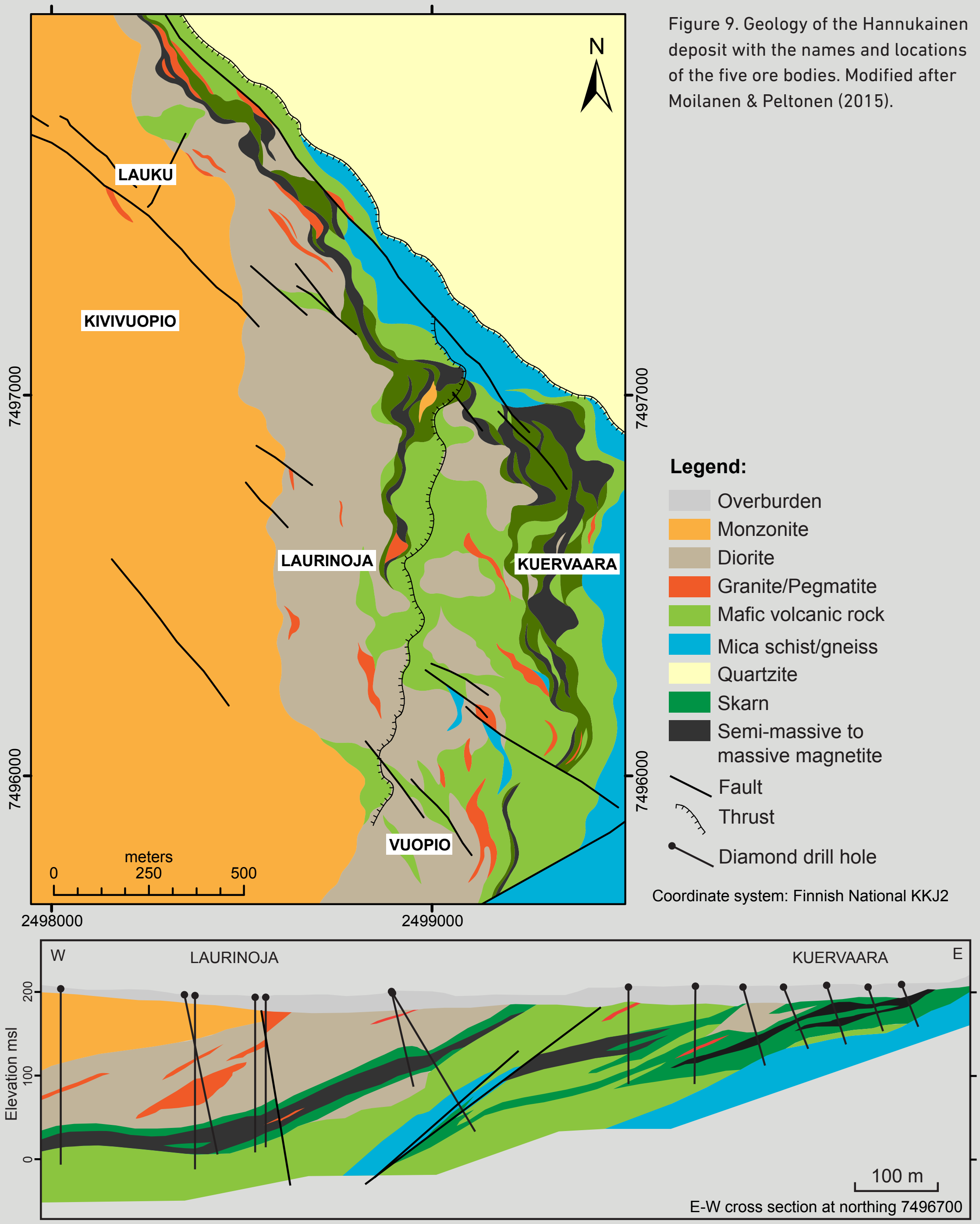


Figure 9. Geology of the Hannukainen deposit with the names and locations of the five ore bodies. Modified after Moilanen & Peltonen (2015).

that the mineralizing fluids were moderately saline (32-56 wt.% $NaCl_{eq}$) and highly saline (12-22 wt.% $NaCl_{eq}$) H_2O-CO_2 fluids during the magnetite and sulfide stages, respectively (Niiranen et al. 2007). Estimated temperatures for these stages were 450-500°C and 290-370°C respectively and pressure 1.5-3.5 kbars. U-Pb zircon age data on the hanging wall diorite (1864±6 Ma) and the coeval monzonite (1862±3 Ma) give an upper age limit for the mineralisation whereas the U-Pb zircon age of the granite (1760±3 Ma) cross-cutting the ore gives the lower age limit (Hiltunen 1982, Niiranen et al. 2007). Niiranen et al. (2007) proposed, on the basis of the 1797±5 Ma zircon age of the clinopyroxene skarn and a number of ca. 1800 Ma U-Pb ages on titanites in altered host rocks, that the mineralisation took place around 1800 Ma.

KEMI Cr DEPOSIT

Tuomo Törmänen & Tuomo Karinen (GTK)

The 2.45-2.44 Ga mafic layered intrusions of northern Finland and NW Russia record a global magmatic event with coeval intrusions and dyke swarms occurring in Australia, Canada, India, Antarctica and Scotland. The emplacement of intrusions of this age group is part of a large plume-related rifting event (Alapieti 2005). This event belongs to a global episode of igneous activity in the beginning of the Proterozoic that produced several layered intrusions and mafic dyke swarms on other cratons as well and was, at least in Fennoscandia, related to the initial breakup of an Archaean craton (Alapieti & Lahtinen 2002, Iljina & Hanski 2005).

There are about 20 of these intrusions in Finland; most of them occur along the E-W trending, 300 km long Tornio-Näränkävaara belt in northern Finland (Alapieti et al. 1990; Alapieti & Lahtinen 2002). The intrusions occur either within late Archean tonalitic gneisses or at the contact of the basement gneisses and overlying Early Proterozoic supracrustal sequences. In most cases, the original roof rocks and upper parts of the cumulate units of the intrusions have been obliterated by uplift and subsequent erosion, which took place soon after the intrusion phase. The current roof rocks (< 2.3 Ga volcano-sedimentary rocks, subvolcanic sills and polymictic conglomerates) were deposited on top of the exposed intrusions. Most of the intrusions consist of more ultramafic basal parts followed by more mafic, gabbroic upper parts. Repetition of ultramafic and mafic layers, i.e. the occurrence of megacyclic units, is a typical feature for the intrusions. Three different types of parental magmas have been recognised based on the composition of chilled margins, cumulates and cogenetic dykes. Two of these have boninitic or siliceous high-magnesian basaltic affinities, with either high- or low-Cr contents. The third magma type was a more evolved tholeiitic basalt (Alapieti et al. 1990, Iljina 1994, Iljina 2005).

The Kemi Cr deposit was found in 1959, during excavation of a fresh-water channel. Full-scale open pit mining started in 1968 and underground operations started in 2003. By the end

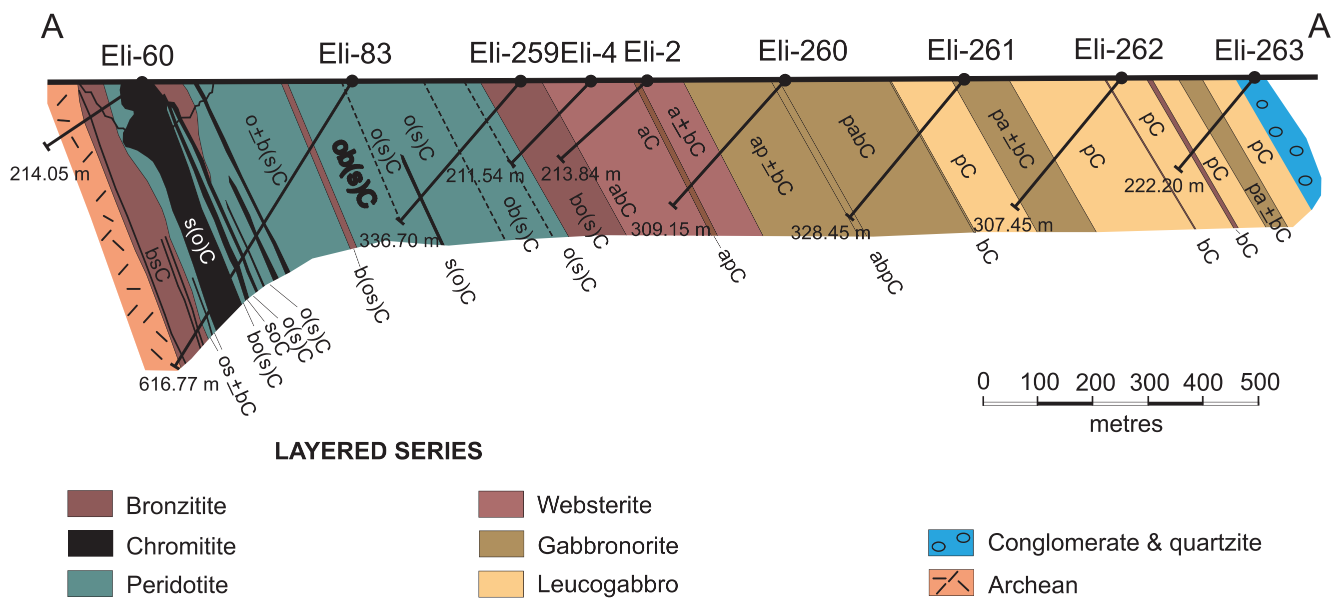


Figure 10. Cross section of the Kemi intrusion, after Alapieti & Huhtelin 2005.

of 2014 approximately 44 Mt of ore had been mined. The current mineral reserves are 50 Mt @ 26.0 % Cr_2O_3 with an additional 97.8 Mt of mineral resources @ 29.4 % Cr_2O_3 (Outokumpu press release, 2014).

The 2.44 Ga Kemi layered intrusion is 15 km long and 2 km wide. The intrusion is composed of a peridotitic, olivine-chromite cumulate lower part, pyroxenitic (bronzite-augite cumulate) mid-part, and a gabbroic (plagioclase-augite cumulate) upper part (Figure 10). A gabbro-pyroxenite sequence has been encountered in parts of the lower contact with footwall Archean granitoids, probably representing a locally preserved contact series (marginal zone) (Huhtelin 2011). Neoarchean granitoids form the intrusion footwall, and it is capped by younger, 2.15 Ga old mafic volcanics or sub-volcanic sills and by polymictic conglomerate, indicating an erosional upper contact, whereby the original roof rocks and uppermost cumulates were removed. During the Svecokarelian orogeny (1.9-1.8 Ga) the intrusion underwent amphibolite-facies metamorphism, which caused alteration of the original silicate minerals in the lower and upper parts of the intrusion, and tilted the intrusion to its present orientation.

Numerous chromitite horizons occur in the peridotitic lower part of the intrusion, of which the main chromitite layer is the most significant. It occurs approximately 50 – 150 m above the basal contact, but its location has been affected by several strike-slip faults (Alapieti & Huhtelin 2005). It has an average thickness of 40 m, varying from a few meters up to 160 m. The top of the main chromitite is layered, with sharp contacts, whereas the lower contact is more irregular, characterised by chromite disseminations and lumps of chromitite (Huhtelin 2011). The mined part of the main chromite (1.5 km in length) contains several different ore types, based on their gangue mineralogy (e.g., serpentine, chlorite, amphibole), chromite texture and grain size, Cr_2O_3-content, etc. The main products are upgraded lumpy ore and fine concentrate, which are shipped to the Outokumpu Tornio works for ferrochrome and stainless steel production.

KOITELAINEN CHROMITITE LAYERS (LC AND UC)

Tuomo Karinen & Tuomo Törmänen (GTK)

The Koitelainen intrusion belongs to the same age group of 2.45-2.44 Ga old intrusions that include, e.g. the Kemi Cr-deposit, the Mustavaara V-Fe-Ti deposit and the Ahmavaara PGE-Ni-Cu deposit. The intrusion (Figure 11) is subhorizontal, 26 x 29 km in horizontal extent and ca. 3.2 km in thickness. The footwall rocks of the intrusion are exposed in the anticlinal area in the middle of the intrusion whereas the upper parts of the intrusion are exposed at the margins. The mineralisation at Koitelainen is stratiform. There are two major, sulphide-free, PGE-enriched, chromite reefs possibly extending across the entire intrusion, and a V-rich magnetite gabbro in the intrusion (Mutanen 1997).

The Koitelainen intrusion can be divided into 3 stratigraphic units: Lower Zone (LZ), Main Zone (MZ), Upper Zone (UZ) capped by granophyre (Figure 12). The LZ has a thickness of up to 1000 m. It contains an ultramafic lower part composed of olivine- and chromite cumulate (dunite, peridotite) with variable amounts of orthopyroxene, clinopyroxene and intercumulus plagioclase. The ultramafic part is overlain by the so called contaminated gabbro, which grades upward into pyroxene-gabbros and microgabbros. The uppermost part of the LZ is composed of pyroxenite, which hosts the *Lower Chromitite* (LC) *layers*. The contact with the overlying Main Zone (MZ) is gradational through gabbronorite with

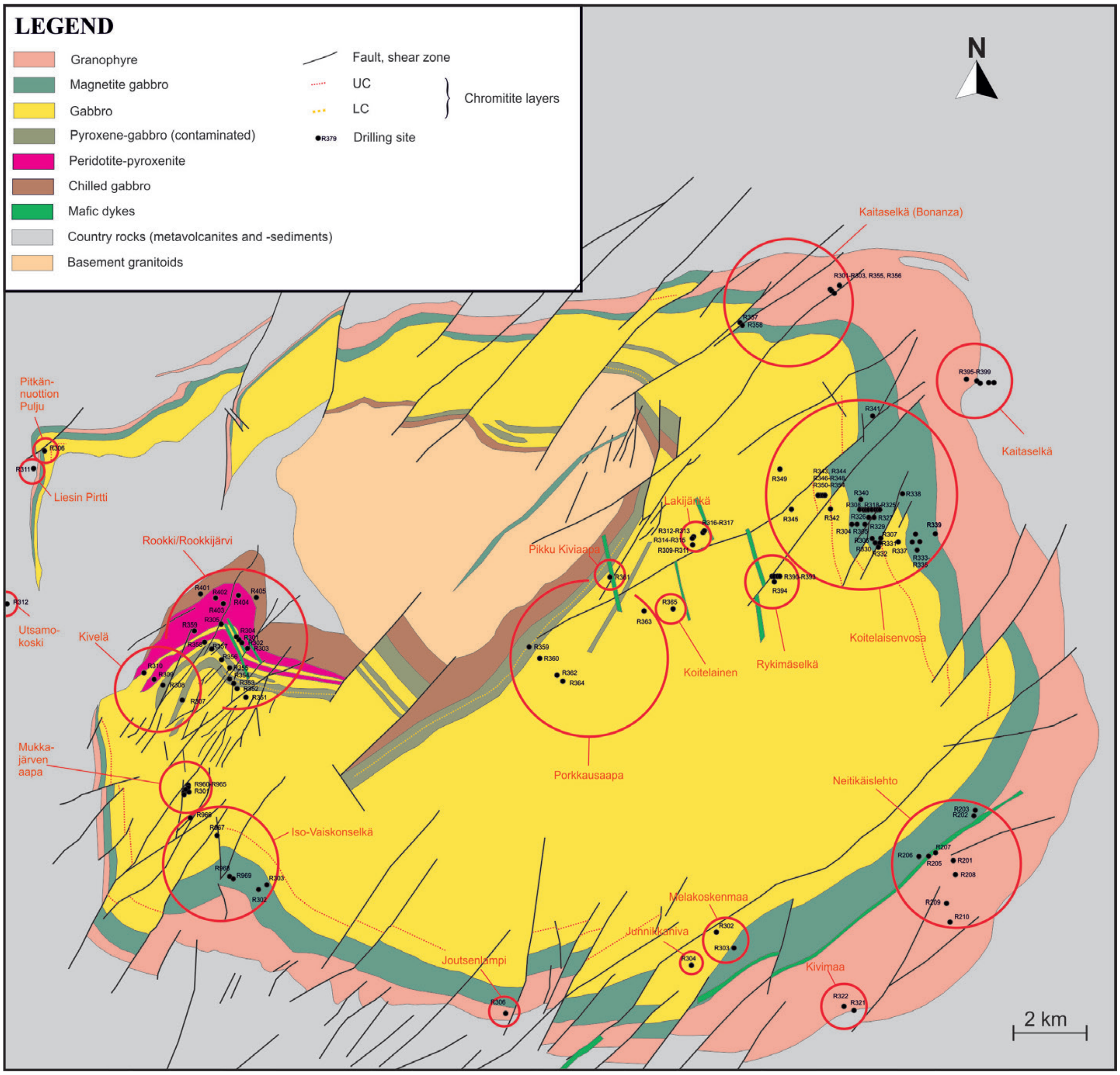


Figure 11. Geological map of the Koitelainen intrusion with GTK drill holes marked (after Mutanen 1997).

abundant thin (< 1 m) pyroxenite layers. The MZ is the thickest unit of the intrusion with an estimated thickness of 1500 m. This zone is mostly composed of gabbronorites. The 20-40 m thick contact between the MZ and the UZ is composed of heterogeneous anorthosite and chromitite layers of the *Upper Chromitite* (UC). The main part, i.e. ca. 200 m in thickness, of the UZ is composed of uralite-altered gabbros and anorthosites with the amount of anorthosite decreasing upward. The uppermost part of the UZ is composed of a ca. 100 m thick magnetite gabbro, which is separated from the gabbros below by a unit composed of spotted anorthosite containing ultramafic layers. The magnetite-rich zones are also enriched in vanadium, PGE and, in part, also with copper. (Mutanen 1997)

The *Lower Chromitite* (LC) *layers* have been intersected with four diamond drill holes in the Porkausaapa area where the dip of layering is 10° SE. Due to the small amount of drilling it is very difficult to connect individual chromitite layers in the area, but there are probably four to six chromitite layers more than 0.3 m thick, with chromite as the principal phase. The thickest section (>2.0 m) of chromitite in one drill core contains 21.2 wt.%. Cr_2O_3. In other diamond drill cores in the Porkausaapa area the Cr_2O_3 content ranges from 10.6 to 32.2 wt.%. In the Porkausaapa area,

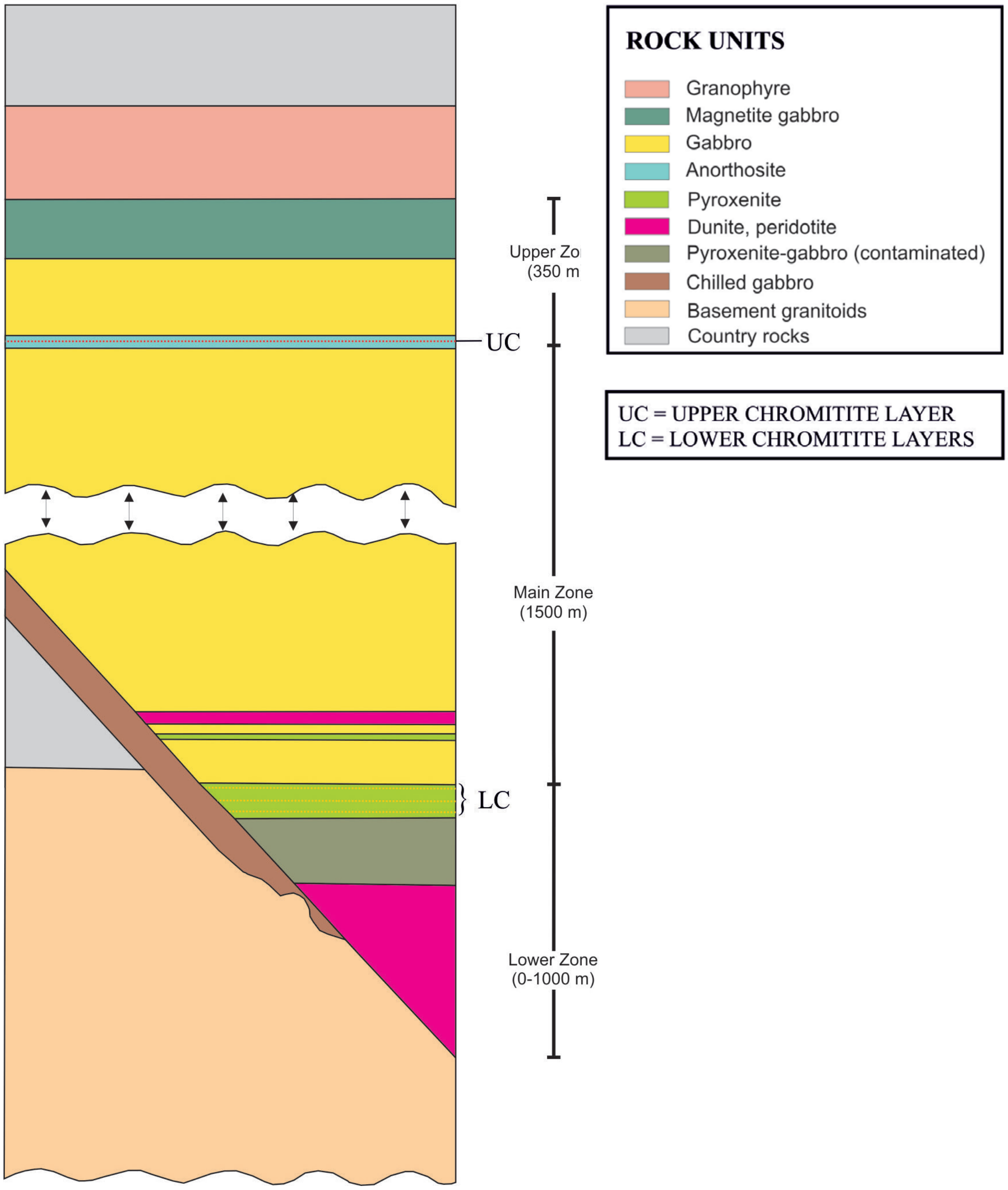


Figure 12. Stratigraphic column of the Koitelainen intrusion (after Mutanen 1997).

the LC has an average Pd+Pt content of 1.4 g/t. (Mutanen 1989). The LC layers have also been intersected in the Rookkijärvi area, located 10 km W of the Porkausaapa area. In this area, the LC layers were intersected with two drill cores in which the individual layers are from few tens of centimeters up to 2.3 meters in thickness. The Cr_2O_3 content in these layers are varies from 8.5 to 27.2 wt.%. The LC in these diamond drill cores also show high Pd+Pt grades, 0.2-1.8 g/t. (Hanski 1998). The locations of the Porkausaapa and Rookkijärvi areas are shown in Figure 11.

The *Upper Chromitite* (UC) *layer* was found during studies of the magnetite gabbro and has been intersected by 17 diamond drill holes (Mutanen 1979). According to these cores the UC is a laterally very uniform layer, 150-170 m stratigraphically below the magnetite gabbro. The layer is 1.3 m thick on average and contains 21.0 wt.% Cr_2O_3, 0.4 wt.% V and 1.1 g/t Pd+Pt. Mutanen (1989) estimated that the mineral resources of the UC are approximately 360 million tonnes of rock with 20.0 wt.% Cr_2O_3 and 1.1 g/t PGE (Pt+Pd+Rh+Ru+Ir+Os). This estimate is tentative, because it was made by assuming a constant dip of the layering and average compositions for the UC. The estimate was made down to a depth of 500 m from the surface.

AKANVAARA CHROMITITE LAYERS (LLC, LC, ULC AND UC)

Tuomo Karinen & Tuomo Törmänen (GTK)

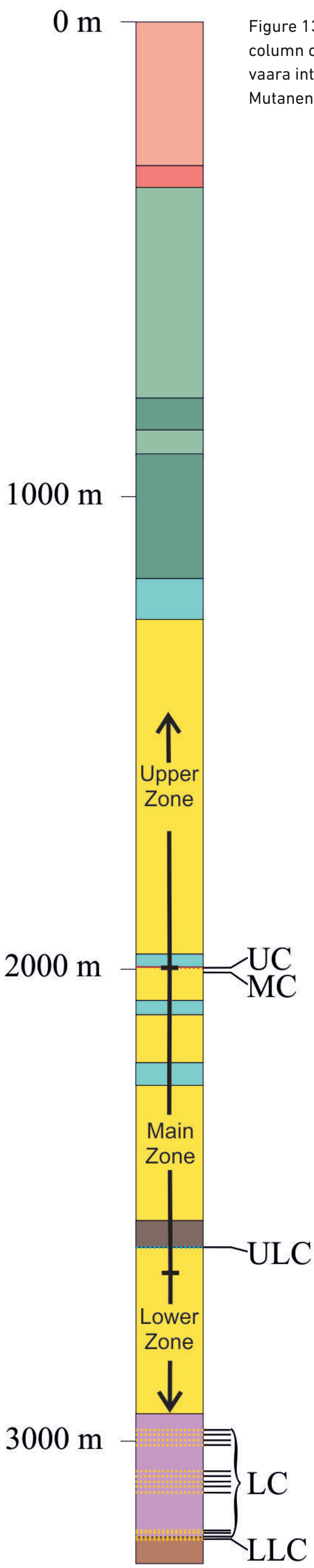
The Akanvaara layered intrusion (Figure 13) belongs to the same age group as the 2.45-2.44 Ga old intrusions that include e.g. the Koitelainen, Ahmavaara and Kemi intrusions (see more detailed descriptions of these intrusions in the chapter *Kemi Cr deposit*). The Akanvaara intrusion hosts a number of layers/zones enriched in various metals including at least 23 chromitite layers, some PGE/Au enriched zones and the V-enriched magnetite gabbro. Of the chromite-rich layers the LC, LLC, ULC and UC (see Figure 14) are the most significant economically (the MC is not considered economically important).

The Akanvaara intrusion is 15 km long and forms a curved north-trending, block-faulted monocline with a surface area of 50-55 km^2. The floor and roof contacts of the main part of the intrusion have been preserved, although the contacts are faulted in places. At the surface level the intrusion consists of two parts; the main intrusion block including magnetite-rich rocks and the smaller northern "wing", which does not contain similar magnetite-bearing rocks. The main intrusion block can further be divided into three smaller blocks (western, central and eastern), separated by faults (Figure 13). The estimated total stratigraphic thickness of the intrusion is ~3.1 km (Figure 14). Mutanen (1997) divided the layered sequence into three major units: the Lower, Main and Upper Zones, (abbreviated to LZ, MZ and UZ) which have stratigraphic thicknesses of ca. 640 m, 570 m, and 1900 m, respectively. The lower part of the LZ comprises several tens of meters of thick basal, fine-grained gabbro, which is probably the lower chilled margin of intrusion. The intrusion is overlain by a very thick (up to hundreds of meters) layer of granophyres.

The *Lowermost Lower Chromitite* (LLC) *layers* occur at the bottom of the LZ, within the heterogeneous subzone of gabbros and pyroxenites adjacent to the lower chilled margin. The *Lower Chromitite* (LC) *layers* occur in the homogeneous pyroxenitic rock above the heterogeneous part including LLC layers. In both the LLC and LC, the chromitite layers usually have sharp, faulted lower contacts and gradational upper contacts defined by narrow chromite-pyroxene intervals. The individual layers of LLC and LC generally occur as thin, pinch-and-swelled layers or pods showing varying thickness (from decimeters to meters). These layers cannot, therefore, be connected from drill hole to drill hole. The layers of LLC have a maximum thickness of ca. 2 meters. These layers appear also to be disturbed by crosscutting faults, and in some drill holes they are missing altogether. Cr_2O_3 grades in these layers vary generally between 10 to 24 wt.%. The thicknesses of the LC layers locally reach 4-5 m. Cr_2O_3 grades in these layers generally vary from 16 - 34 wt.% (weighted average 24.55 wt.% Cr_2O_3). Both LLC and LC layers are enriched in platinum-group elements (PGE), with typical grades of 200-900 ppb (the weighted average of LLC and LC is ca 600 ppb combined 6 PGE). The Pt/Pd ratio for the LLC is ca 1, and the order of abundance for the PGE and Au is Pd>Ru>Pt>Rh>Ir,Os>Au. The Pt/Pd ratio for the LC is much higher, with an average of 7.3, and the order of abundance for the PGE and Au is Pt>Ru>Os>Rh>Ir>Pd>Au.

The *Uppermost Lower Chromitite* (ULC) *layer* occurs close to the lower contact of the MZ, associated with a thin pyroxenite layer at its footwall (Figure 14). The thickness of this individual chromitite layer is usually only a few tens of centimeters: it is associated with highly fractured rock, resulting in high percentage of core loss. The weighted average Cr_2O_3 content is 22.3 wt.%: the layer has much lower contents of PGE than the LLC and LC (ca. 150 ppb PGE).

The *Upper Chromitite* (UC) *layer*, which occurs at the base of the UZ (Figure 14), is economically perhaps the most significant chromite-rich layer in the Akanvaara intrusion. Based on intersections of 30 diamond drill cores it is the most continuous, with thicknesses varying from 0.6 - 1.8 m. The average thickness of the massive part is ca. 1 m with an average grade of 22.79 wt.% Cr_2O_3. The UC is also enriched in vanadium (0.3-0.52 wt.%) which resides in chromite, and in PGEs (0.915 g/t). Mutanen (1998) estimated the mineral resources of the UC but his estimate must be considered as tentative, since it was made on the basis of a limited number of diamond drill cores. Thirty-eight holes were drilled (total 4994.1 m) targeting the UC layer along its known 6-7 km strike, and assuming the layering dipped at 30° down to 300 m below the surface. There is thus no actual data for the assumed deeper extensions of the UC. According to the estimate, the UC includes 18.1 million metric tons of rock containing 22.8 wt.% Cr_2O_3, 0.4 wt.% V and 0.912 g/t combined Pd+Pt+Ru+Os+Rh+Ir.



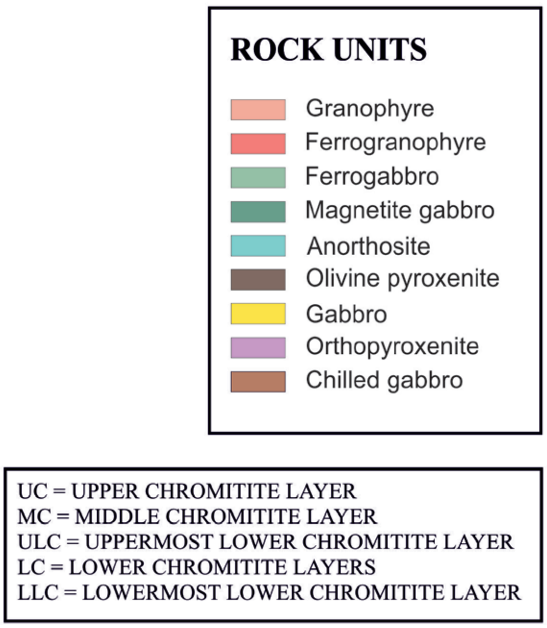


Figure 13. Stratigraphic column of the Akanvaara intrusion (after Mutanen 1997).

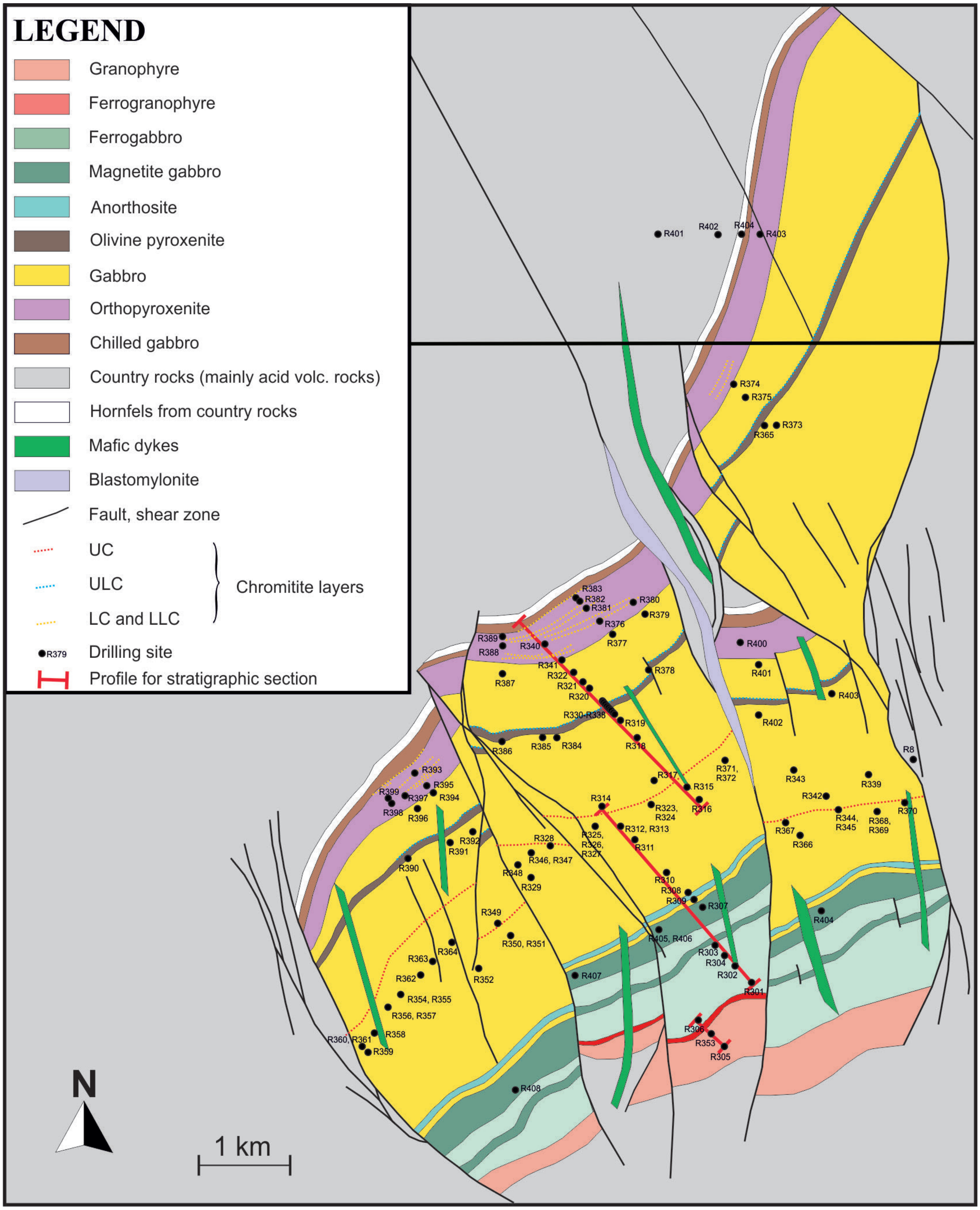


Figure 14. Geological map of the Akanvaara intrusion with GTK drill holes marked (after Mutanen 1997).

PORTIMO COMPLEX: KONTTIJÄRVI, AHMAVAARA AND SIIKA-KÄMÄ PGE-Cu-Ni DEPOSITS

Tapio Halkoaho & Hannu Makkonen (GTK)

The Portimo Complex belongs to the same Tornio-Näränkävaara Belt of ca. 2.44 Ga old mafic to ultramafic layered intrusions that include e.g. the Kemi intrusion (see more detailed descriptions of these intrusions in the chapter on the *Kemi Cr deposit*). This description of the Portimo Complex is based on several publications, including those by Alapieti & Lahtinen 1989, 2002, Alapieti et al. 1989, Huhtelin et al. 1989, Iljina et al. 1989, Lahtinen et al. 1989, Alapieti et al. 1990, Iljina 1994, 2005, Iljina & Hanski 2005, Perttunen & Vaasjoki 2001, Alapieti 2005, Halkoaho & Iljina 2012, Iljina et al. 2015.

The Portimo Complex is composed of four principal structural units: Konttijärvi, Suhanko, Narkaus intrusion (Lihalampi, Kilvenjärvi, Nutturalampi, Kuohunki and Siika-Kämä blocks) and Portimo Dykes (Figure 15). Each intrusion contains a marginal series and an overlaying layered series. The marginal series generally varies from ten to several tens of meters in thickness. In the Narkaus intrusion the marginal series is mainly composed of pyroxenite while the upper half of the Suhanko and Konttijärvi marginal series is composed of olivine cumulates. The layered series of the Narkaus intrusion contain up to three olivine-rich ultramafic cumulate layers (MCU I - MCU III), whereas the Suhanko and Konttijärvi intrusions contain only one, in the bottom of the layered series. The principal mineralisation types in the Portimo Complex are: 1) the PGE-enriched Cu-Ni-Fe sulphide disseminations in the marginal series of the Suhanko and Konttijärvi intrusions, 2) the massive pyrrhotite deposits located close to the basal contact of the Suhanko intrusion, 3) the Rytikangas PGE Reef in the layered series of the Suhanko intrusion, 4) the Siika-Kämä PGE Reef in the Narkaus layered series, and 5) the offset Cu-PGE mineralisation below the Narkaus intrusion.

The Konttijärvi Intrusion is 1.2 km long and 0.5 km wide at the surface section and dips 35-60^{o} N: its footwall and hanging wall rocks consist of Archaean migmatitic mica gneiss (Figure 15). The intrusion has been divided into two principal units: the marginal series and the layered series (Figure 16). The marginal series is ca. 40 m thick and the layered series ca. 120 m thick. The lower part of the marginal series is composed of pyroxenitic cumulates and the upper part of peridotitic olivine cumulates. The layered series is composed mainly of gabbronoritic cumulates with a ca. 25 m thick orthopyroxenite layer in the middle part of it.

The disseminated PGE-enriched, marginal series base-metal sulphide deposit of the Konttijärvi intrusion is generally 10–30 m thick (Figures 16 and 17, Table 1). It is, however, erratic and commonly extends from the lower peridotitic layer downwards for some 30 m into the basement gneiss (peridotite → pyroxenite → gabbro → basement gneiss). The PGE contents vary from only weakly anomalous values to 2 ppm but some samples contain > 10 ppm PGE (Figures 16 and 17).

The Suhanko intrusion is, at the surface, about 16 km long and 1 km wide, dipping 5-70^{o} to the NE, SW or W, depending on the part of the intrusion (Figure 15): its footwall rocks consist of Archaean diorite and felsic volcanic rocks. The hanging wall rocks, which are younger than the intrusion, include tonalitic migmatite, mafic vol-

Figure. 15. Generalised geological map of the Portimo Complex. Modified after Iljina 1994.

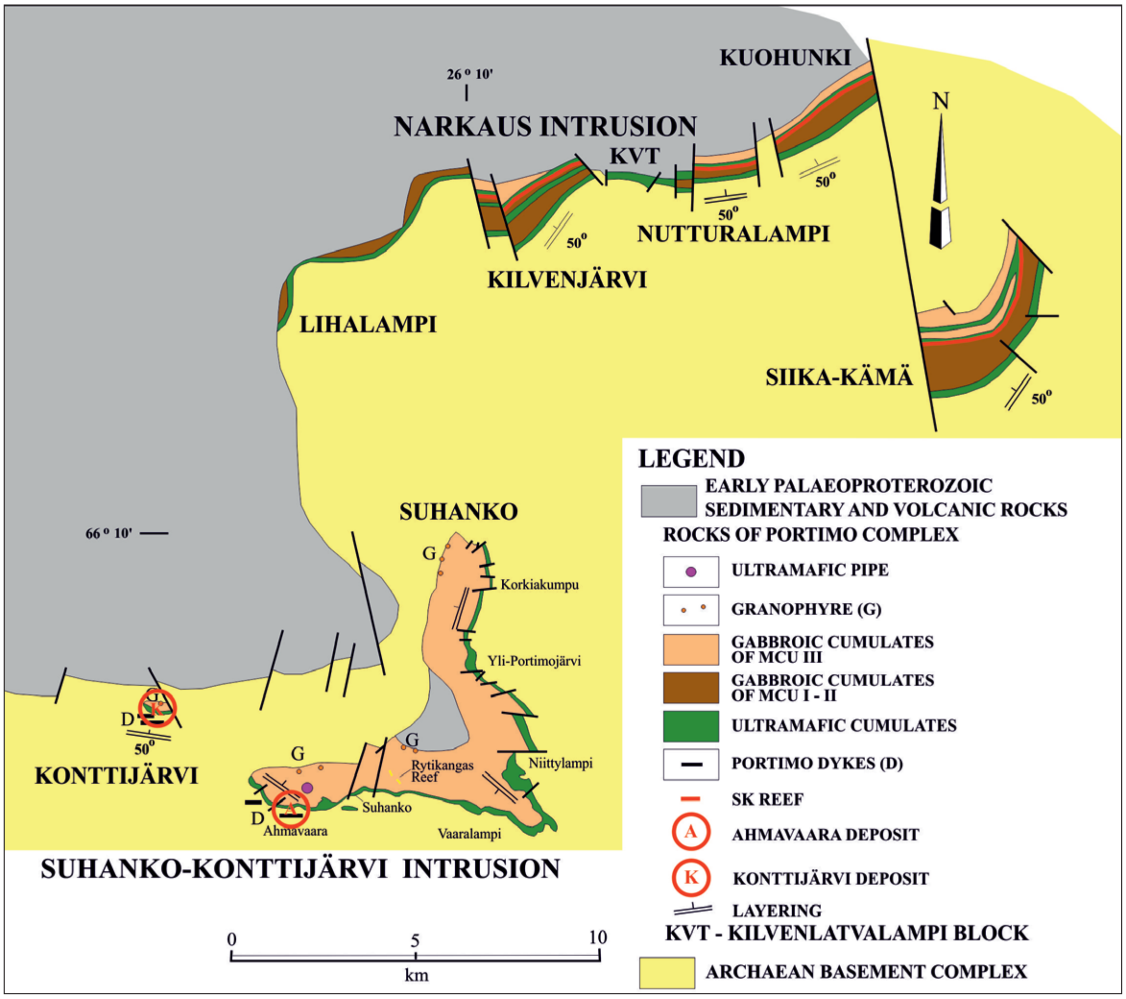
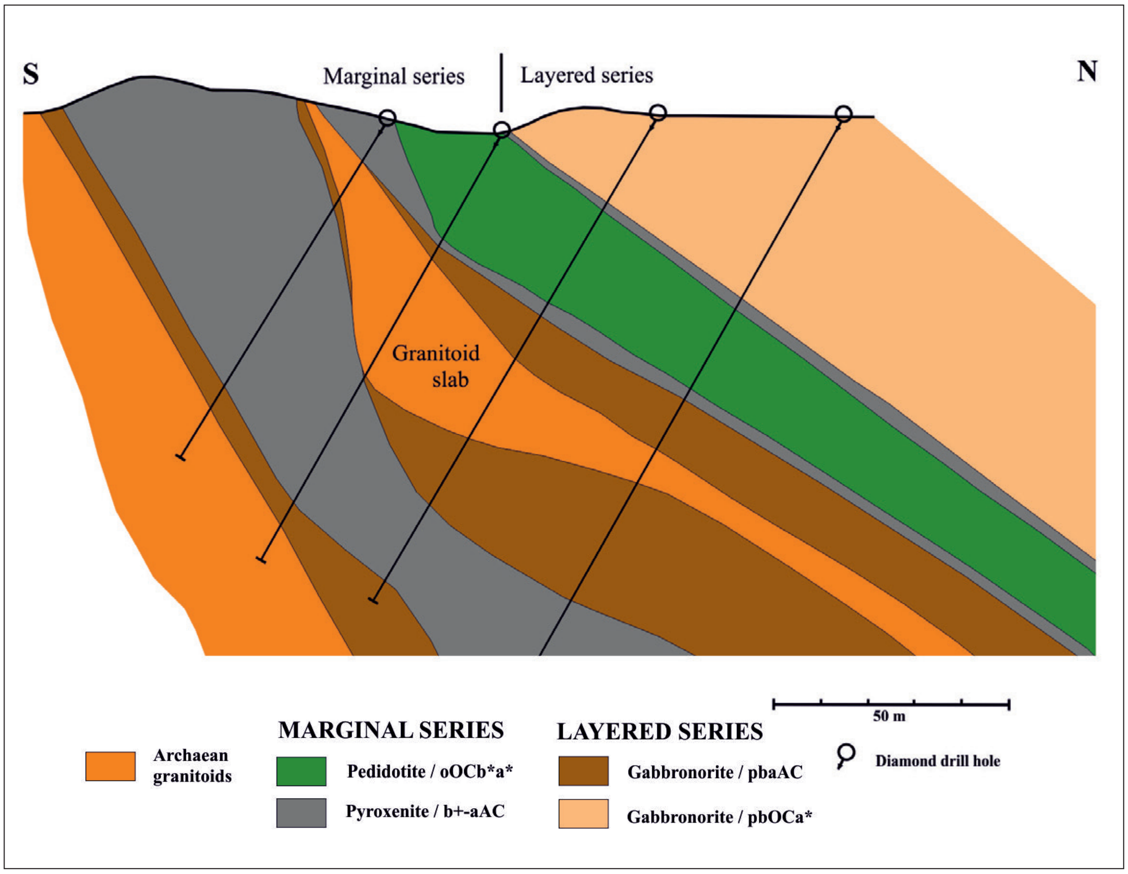


Figure 16. Generalised geological cross-section of the Konttijärvi layered intrusion. Modified after Iljina 1994.



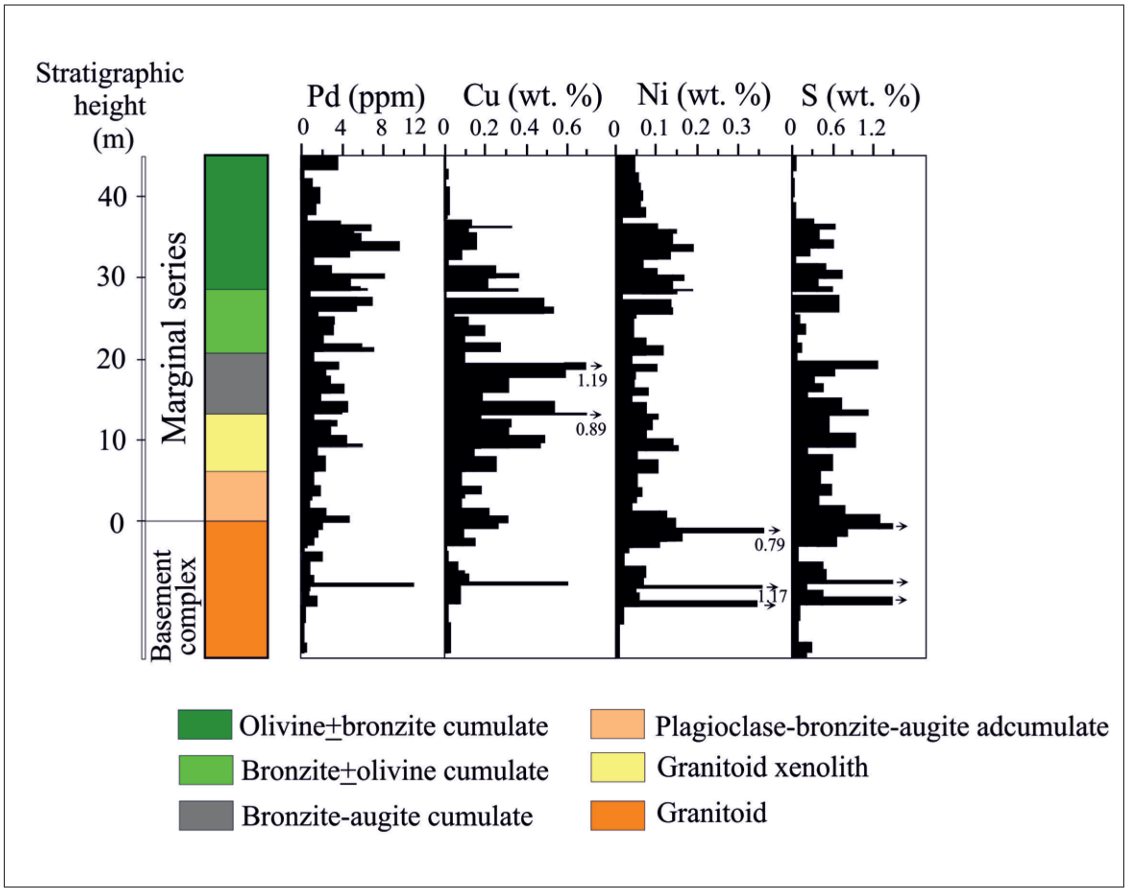


Figure 17. Stratigraphic sequence of the Konttijärvi marginal series showing variations in bulk Pd, Cu, Ni and S in diamond drill hole KO-3. Modified after Alapieti et al. 1989.

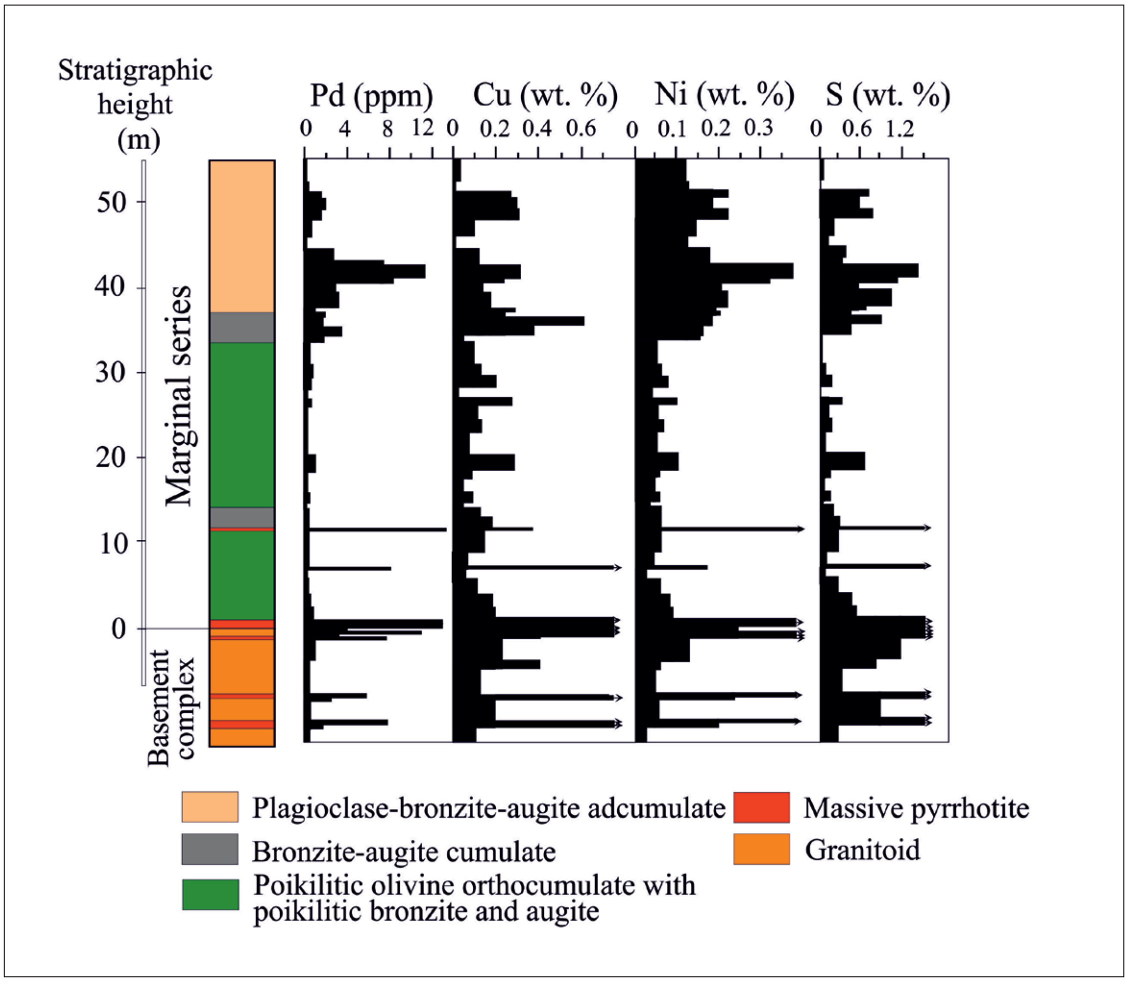


Figure 18. Stratigraphic sequence of the Ahmavaara marginal series showing variations in bulk Pd, Cu, Ni and S in diamond drill hole YP-143. Modified after Iljina et al. 1989.

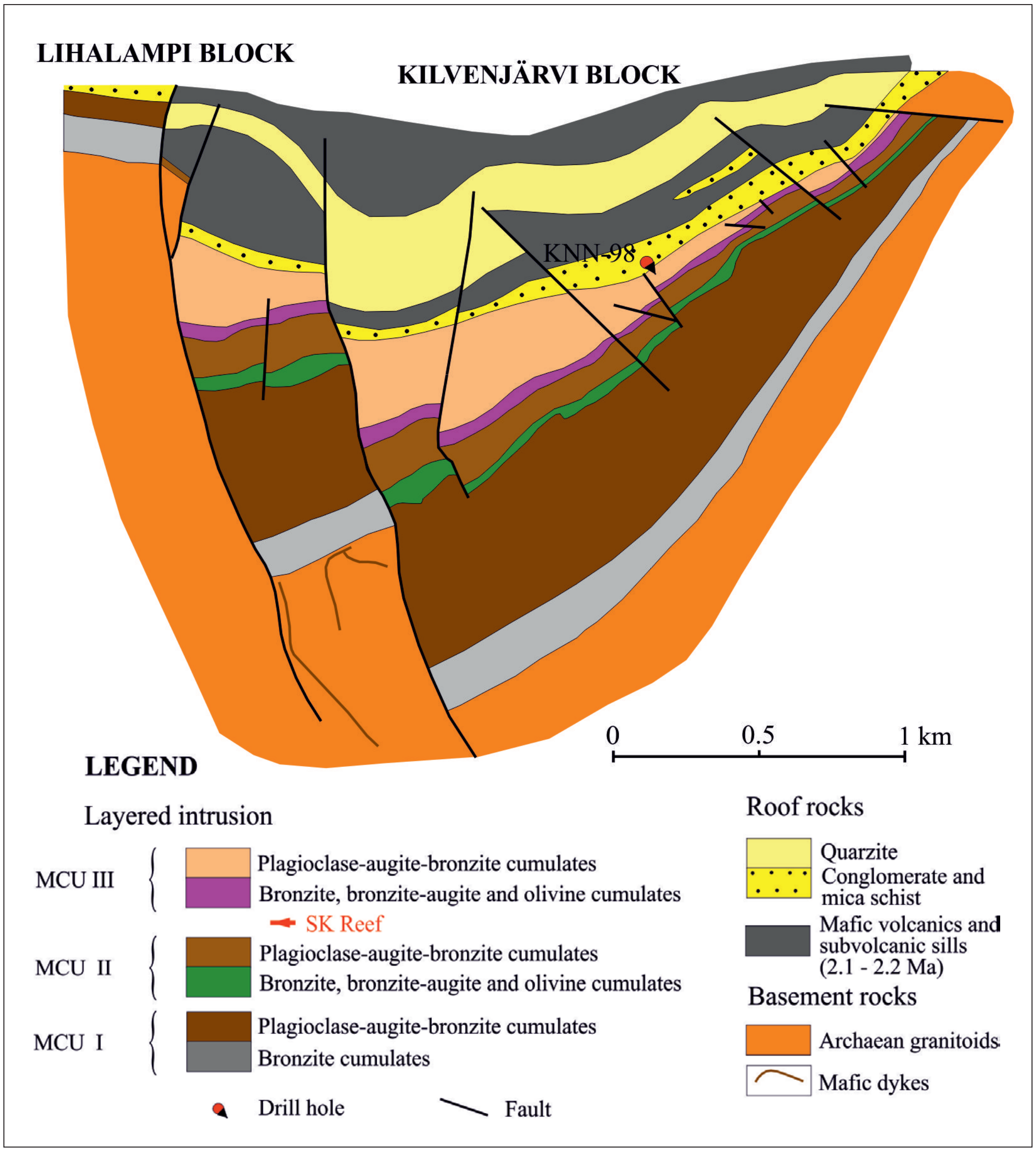


Figure 19. Geological map of the Kilvenjärvi block of the Narkaus Intrusion. Modified after Huhtelin et al. 1989.

canic rocks, conglomerates and quartzites. The intrusion has been divided into two principal units: the marginal series and the layered series. The marginal series is 10-60 m thick (see Figure 18) and the layered series about 500 m thick. The lower and middle parts of the marginal series are composed of pyroxenitic and gabbronoritic cumulates and the upper part of peridotitic olivine cumulates. The layered series is composed mainly of gabbronoritic and anorthositic cumulates.

Massive sulphide mineralisations occur in the Suhanko intrusion as dykes and plate-like bodies conformable to the layering. The thickness of the massive sulphide mineralisations varies from 0.2 - 20 m: they are located within the interval of 30 m below the basal contact of the intrusion and 20 m above it (see Figure 18, Table 1). The Ahmavaara sulphide paragenesis is composed of pyrrhotite, chalcopyrite and pentlandite. Normally the massive pyrrhotite deposits of the Suhanko Intrusion show low PGE values (max. a few ppm Pt + Pd). The PGE concentrations are generally much higher in the Ahmavaara deposit (up to 20 ppm).

The Narkaus intrusion (Lihalampi, Kilvenjärvi, Nutturalampi, Kuohunki and Siika-Kämä blocks) is about 22 km in total length, up to 2.5 km in width and its footwall rocks consist of Archaean granitoids. The hanging wall rocks, which are younger than the intrusion, include

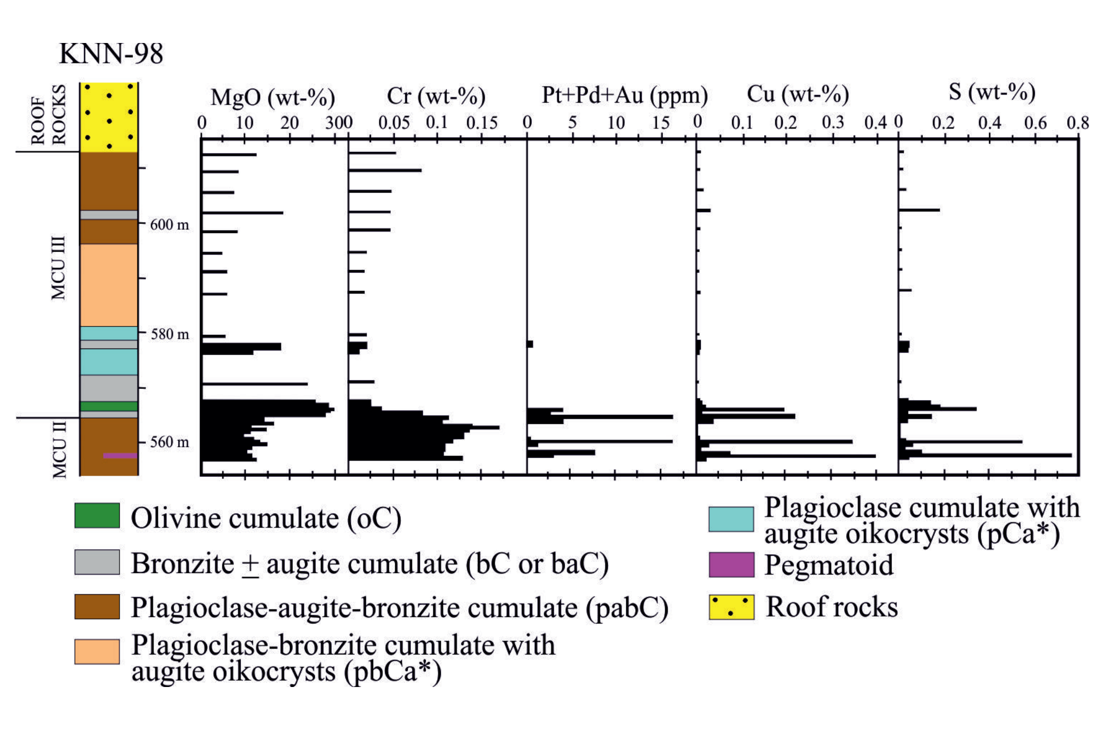


Figure 20. Whole-rock chemical variation in the Siika-Kämä PGE Reef. Modified after Huhtelin et al. 1989.

mafic volcanic rocks, conglomerates, quartzites, mica schists and Archaean granitoids as in the case of Siika-Kämä block. The intrusion has been divided into two principal units: the marginal series and the layered series. The marginal series of the Kilvenjärvi block (Figure 19), about 10 m thick, is composed of gabbronoritic and bronzititic cumulates and partly melted floor-rock xenoliths. The layered series, about 860 m thick, is composed of alternating sequences of ultramafic, gabbronoritic, gabbroic and anorthositic cumulates and it has been divided into megacyclic units I - III, starting from the base and abbreviated as MCU I – MCU III. The chemical composition of megacyclic units I – II is boninitic (Cr-rich) and of megacyclic unit III tholeiitic (Cr-poor) (see Figure 20). These variations are interpreted as being attributable to repeated influxes of new magma into the Narkaus chamber during solidification.

The Siika-Kämä PGE Reef (Table 1) of the Narkaus intrusion is located at the contact zone between the gabbronorite of MCU II and the ultramafic cumulates of MCU III, most commonly at the base of MCU III, but in places it may lie somewhat below that or in the middle of the olivine cumulate layer of MCU III (Figure 20). The Siika-Kämä Reef has been identified in the Kilvenjärvi, Nutturalampi, Kuohunki and Siika-Kämä intrusion blocks (Figure 15). Chlorite-amphibole schist is the most common host rock for the Siika-Kämä Reef. Normally the reef contains weak base metal sulphide disseminations, but locally also chromite seams or chromite disseminations. The thickness of the reef varies from less than one meter to several meters: many drill holes penetrate a number of mineralised layers. The reef PGE concentration varies from several hundred ppb to tens of ppm.

Occurrence	Tonnage (Mt)	Pd g/t	Pt g/t	Cu %	Ni %	Au g/t	Deposit subtype	References
Konttijärvi	75.3	0.95	0.27	0.1	0.05	0.07	Contact	Puritch et al. (2007)
Ahmavaara	187.8	0.82	0.17	0.17	0.09	0.9	Contact	Puritch et al. (2007)
Siika-Kämä	43.1	2.7	0.72	0.11	0.08	0.08	Reef	Gold Fields (2003)

Table 1. PGE±Cu-Ni deposits with a resource estimate in the Portimo Complex area.

MUSTAVAARA V-Fe-Ti OXIDE DEPOSIT

Tuomo Karinen & Tuomo Törmänen (GTK)

The Mustavaara V-Fe-Ti oxide deposit is hosted by the Koillismaa Intrusion, which is a part of the ca. 2440 Ma Tornio-Näränkävaara Intrusion belt (see more detailed description of these intrusions in the chapter *Kemi Cr deposit*). The ore in the Mustavaara deposit is defined by the oxide-rich lower part of the magnetite gabbro layer within the upper part of the Koillismaa Intrusion ("magnetite-rich cumulates" in Figure 21, see also Figures 22 and 23). This block is one of the largest blocks of the intrusion, and it has been modelled gravimetrically to extend to a depth of ~ 2000 m. The block is 20 km long and 4 km thick with an exposed area of ~ 80 km^2. The magnetite gabbro layer is uniform and can be traced in almost every block of the Koillismaa Intrusion. The layer is, however, thicker in the Porttivaara block area than in the other intrusion blocks and in the Mustavaara deposit area it reaches a thickness of 240 m (Juopperi 1977, Ruotsalainen 1977, Piirainen et al. 1978, Alapieti 1982, Iljina & Hanski 2005, Karinen et al. 2015).

Sample	1	2	3	4	5
wt %					
SiO_2	34.99	42.72	38.99	44.76	3.12
TiO_2	2.79	2.00	2.11	2.06	7.50
Al_2O_3	10.44	12.27	12.49	14.69	1.16
Fe_2O_3	19.81	11.63	16.49	8.73	54.20
FeO	15.61	11.08	12.85	9.56	30.40
MnO	0.21	0.17	0.17	0.21	0.30
MgO	3.17	5.18	4.28	5.90	0.75
CaO	7.31	9.21	8.61	10.88	1.17
Na_2O	2.32	2.48	2.47	2.53	0.04
K_2O	0.89	0.35	0.34	0.30	0.03
ppm					
V	3800	2200	2600	1500	9180
Cr	130	30	20	20	60
Ni	290	140	110	90	220
Cu	610	760	780	320	70
Co	130	100	130	180	180

Table 2. Composition of different sub-layers of the Mustavaara deposit. Data of 1–4 collected from Juopperi (1977), and 5 from the annual report 1982 of Rautaruukki Company (Rautaruukki Oy, 1982).

According to Juopperi (1977) and Karinen et al. (2015) the Mustavaara deposit comprises a ca. 80 m thick succession of ilmenomagnetite-rich sub-layers in the lower part of the magnetite gabbro layer. The grades of the ore in these layers correlate with the amount of the ilmenomagnetite, an oxide phase which originally crystallised as titaniferous magnetite, but which later, in a subsolidus stage reacted to form composite grains of fine ilmenite lamellae in a V-bearing magnetite host (Table 2, Figures 22 and 23). The dip of the ore layer in the area of the deposit is 40° N, but steepens to 60° east of the old open pit, where the layer also becomes narrower, being only 20 m thick. Depending on the amount of ilmenomagnetite, the deposit is divided into distinct sub-layers comprising, from the bottom upwards: the Lower Ore Layer (LOL; 5 m thick; 20–35 wt.% ilmenomagnetite), the Middle Ore Layer (MOL; 15–50 m thick; 10–15 wt.% ilmenomagnetite), the Upper Ore Layer (UOL; 10–40 m thick; 15–25 wt.% ilmenomagnetite) and the Disseminated Ore Layer (DOL; <10 wt.% ilmenomagnetite).

The history of mining in the Mustavaara deposit dates back to the mid 1950s when a local man observed compass interferences in the area adjacent to the deposit. This encouraged him to send samples from the area to different mining companies. The samples led the Otanmäki Company to launch an exploration project in the area. The decision was also facilitated by the aeromagnetic anomalies that were detected in the area during

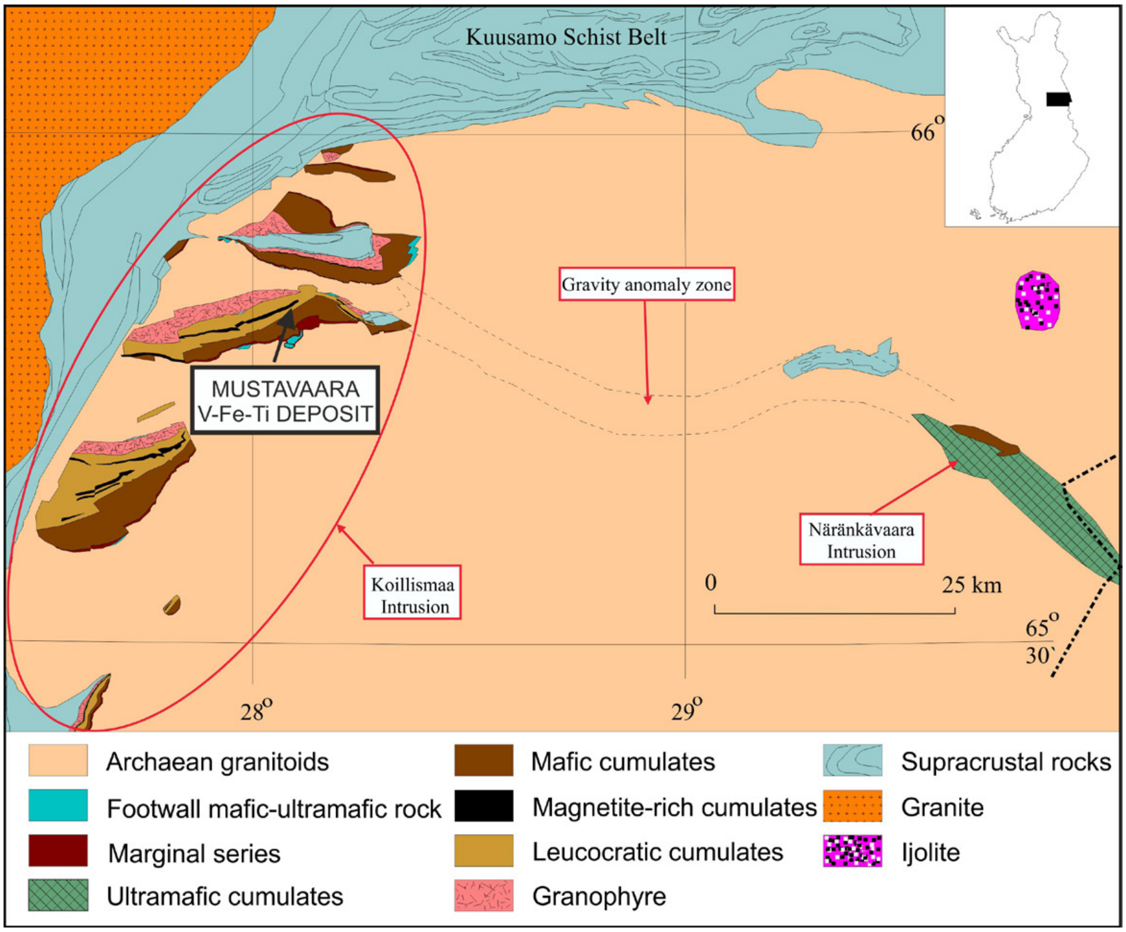


Figure 21. Generalised geological map of the Koillimaa-Näränkävaara Layered Complex. Modified from Karinen (2010).

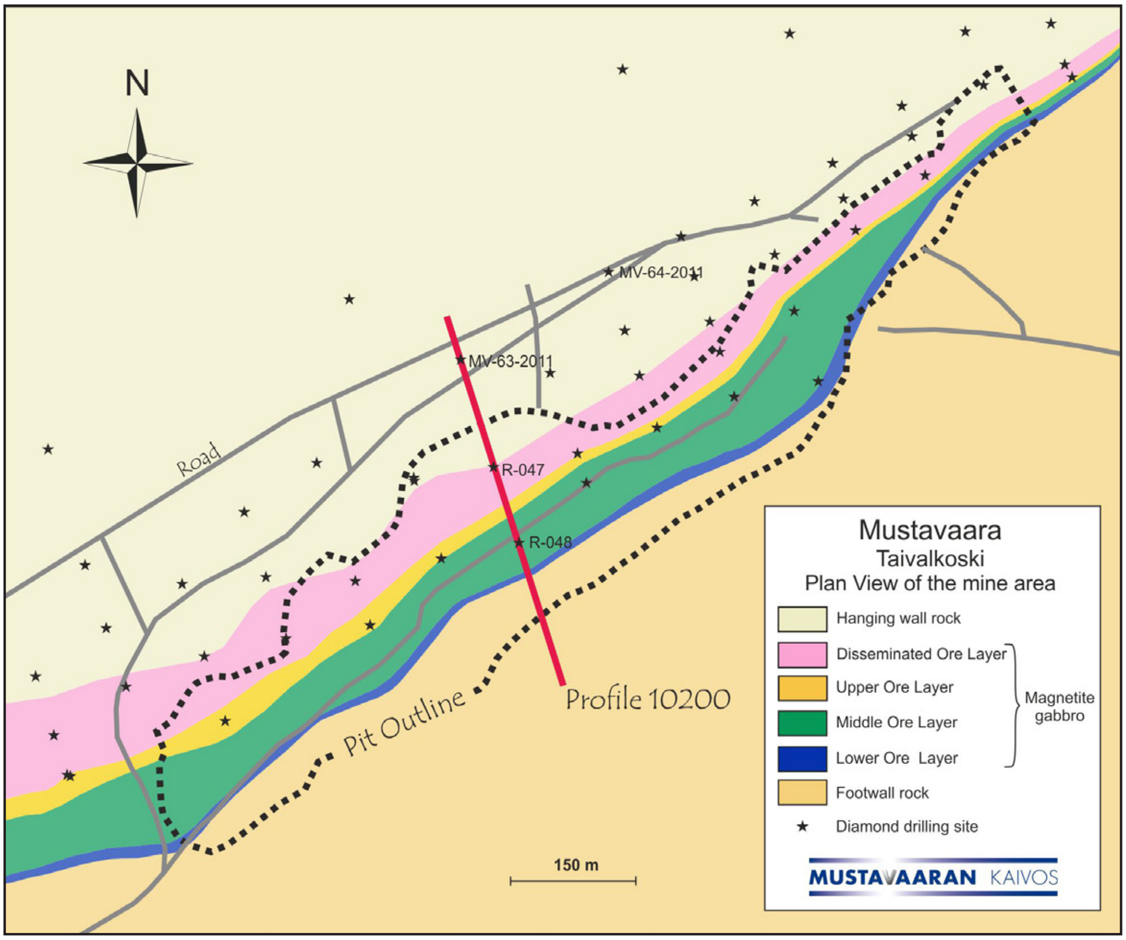


Figure 22. Plan view of the Mustavaara open pit area showing the ore layers projected to surface.

the high altitude survey program carried out by the Geological Survey of Finland (GTK) (1951–1972). The measurements showed that the samples represent a coherent high anomaly layer in the Mustavaara area. During the following years, the Otanmäki Company explored the area. In 1967 this work led to the discovery of a V-bearing magnetite gabbro layer in the upper part of the Porttivaara block of the Koillismaa Intrusion. (Isokangas 1957, Juopperi 1977, Markkula 1980).

The decision to open a mine in the Mustavaara area was made by the Rautaruukki Steel Company in 1971 (the Otanmäki Company was merged with Rautaruukki in 1968). Open-pit mining began in 1976, but was terminated in 1985 due to the low price of vanadium. The ore reserves of the Mustavaara Mine were 38 Mt at 16.8 wt.% ilmenomagnetite concentrate, with a cut-off value of 11.9 wt.% (Paarma 1971). The reserves were estimated to 100 m below the surface. During its operational life, the mine produced 13.45 million tons of ore and 1.97 million tons of ilmenomagnetite-rich concentrate averaging 0.91 wt.% V. During the operation of the mine, one significant challenge to overcome was the optimisation of the production line to gain the maximum V-grade with minimum amount of ilmenite lamellae in the magnetic concentrate. The annual production was approximately 240,000 tons of concentrate and 2,500–3,000 tons of V_2O_5 (1400–1700 t V), accounting for 6–9 % of the global production of vanadium at that time (Juopperi 1977, Puustinen 2003).

The mine area has recently been re-evaluated for additional ore potential by Mustavaara Mine Ltd. A drilling programme by the company has outlined a down-dip continuation of the magnetite gabbro. A new ore reserve estimate has been calculated to a depth of 250 m down from the topographic surface. The current reserves are 99 million tons of ore grading 14.0 wt.% ilmenomagnetite with a vanadium content of 0.91 wt.%. The reserves include 64 million tons in proven and 35 million tons in the probable class. These estimates were calculated using an ilmenomagnetite cut-off value of 8.0 wt.% (Mustavaaran Kaivos Oy, 2013).

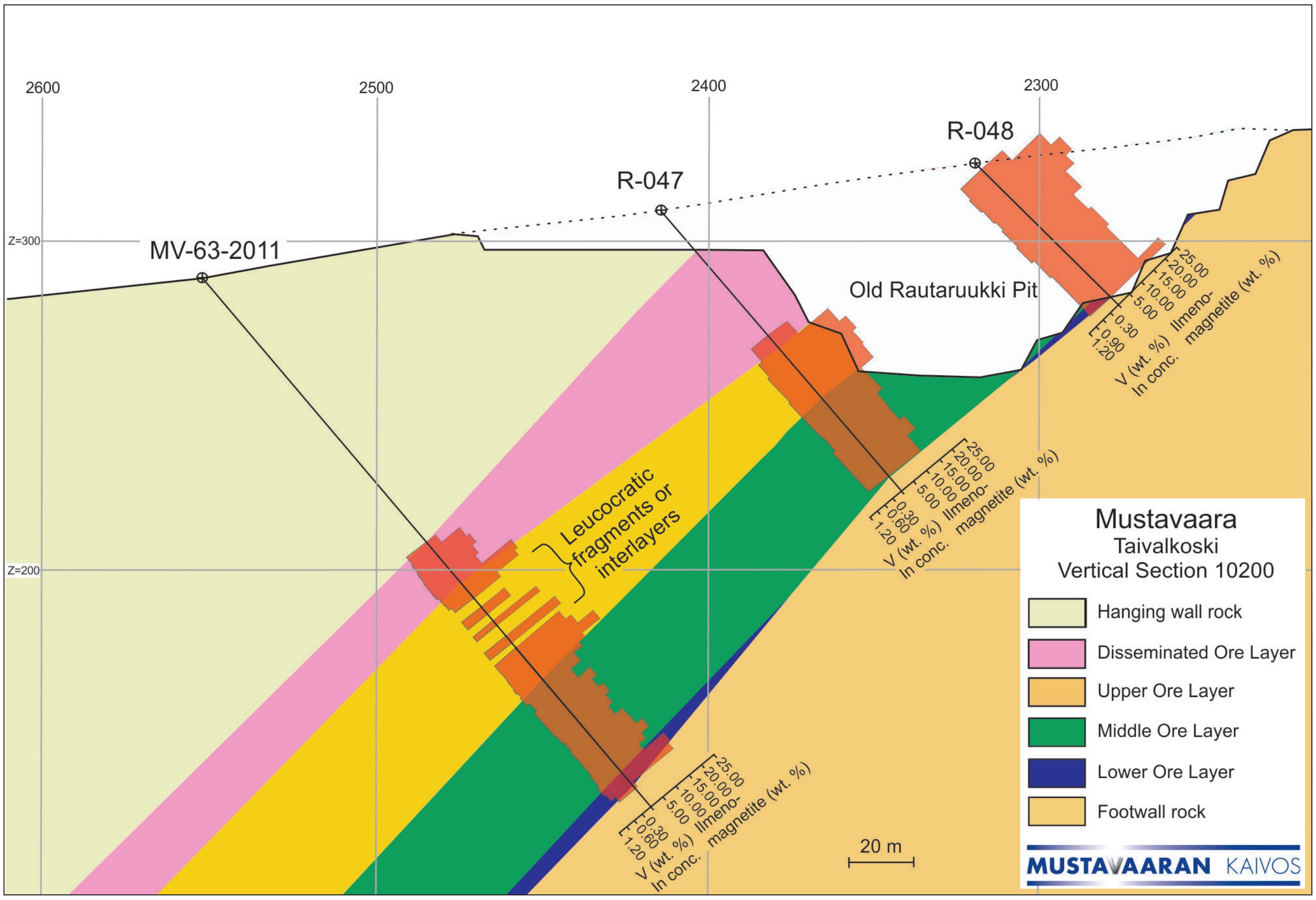


Figure 23. Vertical cross section of the ore of the Mustavaara Deposit along profile 10200. See location of the profile in Fig. 22.

THE KEVITSA AND SAKATTI Ni-Cu-PGE DEPOSITS

Tuomo Törmänen & Tuomo Karinen (GTK)

The Kevitsa and Sakatti Ni-Cu-PGE deposits are located within the Central Lapland greenstone belt (CLGB) in northern Finland. The CLGB consists of volcano-sedimentary sequences, spanning a time interval from the 2.44 Ga Salla Group felsic-intermediate metavolcanic rocks to ca. 1.88 Ga molasse-type metasediments of Lainio and Kumpu Groups (Hanski & Huhma 2005). Mafic magmatism within the CLGB is recorded by a number of intrusive phases. The oldest mafic intrusive phase is represented by the 2.44 Ga mafic layered intrusions of Koitelainen and Akanvaara (Figure 24). At 2.20 Ga a suite of differentiated mafic sills intruded into the southern part of the CLGB. 2.15 Ga gabbroic sills and dykes occur in the central and south-eastern part of the schist belt. The last major mafic intrusive phase is represented by the 2.05-2.0 Ga Kevitsa-type layered intrusion and sills, as well as minor gabbroic intrusions and dykes (Rastas et al. 2001; Räsänen & Huhma 2001; Hanski & Huhma 2005). The 2.44 Ga layered intrusions host a number of meter-scale chromitite (±PGE) horizons as well as V-enriched magnetite gabbros. The only known magmatic Ni-Cu-PGE deposits are hosted by the 2.05 Ga Kevitsa intrusion and some of the small ultramafic intrusions, of unknown age, in the Sakatti area (Figure 24).

Kevitsa deposit

The Kevitsa Ni-Cu-PGE deposit is located in northern Finland, 170 km N of the Arctic Circle, within the Paleoproterozoic Central Lapland greenstone belt (CLGB). The deposit was originally discovered by the Geological Survey of Finland in 1987 (Mutanen 1997), with continued exploration until mid 1990s. The deposit was subsequently explored by Outokumpu Ltd, Scandinavian Minerals, and finally by First Quantum Minerals Ltd. (FQM), which started production in 2012. The current (2012) mineral resource is 240 Mt at 0.3 % Ni, 0.41 % Cu, 0.21ppm Pt, 0.15ppm, Pd, and 0.11ppm Au (Santaguida et al. 2015).

The disseminated Ni-Cu-PGE mineralisation is hosted by the 2.06 Ga (Mutanen & Huhma 2001) layered or composite Kevitsa intrusion. The intrusion consists of ultramafic, gabbroic, and granophyric parts with locally developed magmatic layering. The ultramafic part, which hosts the mineralisation, occurs at depth and in the NE-part of the intrusion. It is mostly composed of olivine websterite, olivine clinopyroxenite and minor plagioclase-bearing (olivine) websterite, and a pyroxenite zone between the ultramafic and gabbroic parts of the intrusion (Santaguida et al. 2015). The cumulate rocks of the ultramafic part are variably altered to amphibole-chlorite-serpentine-bearing assemblages. Gabbroic rocks (gabbro, olivine gabbro, and gabbronorite) form the upper (SW) part of the intrusion. The granophyre zone, according to Mutanen (1997), forms the southern part of the intrusion, but this has not been encountered in the FQM drill holes. The marginal zone of the intrusion is made up of pyroxenite and gabbro with a gradational contact to olivine websterite. A km-sized ultramafic body occurs in the central part of the intrusion. Mutanen (1997) describes this as a serpentinised dunite xenolith, unrelated to the intrusion. Numerous ultramafic and sedimentary xenoliths occur throughout the intrusion and especially in the mineralised part of the intrusion (Mutanen 1997; Santaguida et al. 2015). The immediate country rocks of the intrusion consist of mafic volcanic rocks, phyllite with graphite- and sulphide-rich interlayers, arkosic quartzite, and carbonate-bearing schists (Mutanen 1997; Santaguida et al. 2015).

The irregularly shaped disseminated Ni-Cu-PGE deposit is concentrated in the central (ultramafic) part of the intrusion. It extends from the surface to a depth of approximately 400 metres. Mutanen (1997) recognised four different types of sulphide mineralisation: the regular ore, which makes up the bulk of the Ni-Cu-PGE mineralisation, Ni-PGE ore, transitional ore, and false ore. In the current FQM classification the Ni-PGE and transitional ore types are classified as Ni-PGE ore (Santaguida et al. 2015). The regular ore is composed of interstitial, disseminated sulphides, mainly pyrrhotite, pentlandite and chalcopyrite, with a Ni tenor from 4-7 % and <1 ppm PGE. The regular ore has Ni/Cu ratios of ca. 0.5 and Pt/Pd ratios >1: Ni-Cu concentrations vary, however, at local and deposit scale with more Ni-rich zones occurring at depth and in the southern part of the deposit, and Cu-rich zones in the central parts of the deposit. Ni-PGE ore, which constitutes approximately 5 % of the resource, occurs as discordant zones within the regular ore. It has a higher Ni tenor (>10 %) and higher PGE contents. It is also typified by the presence of heazlewoodite, millerite, and pyrite as additional sulphide minerals. False ore generally contains more sulphides, varying from heavy disseminations to net-textured to semi-massive pyrrhotite-rich ore with only minor pentlandite and chalcopyrite resulting in a low Ni tenor of 2-3 % (Mutanen 1997; Santaguida et al. 2015).

Sakatti deposit

The Sakatti Ni-Cu-PGE deposit is located in northern Finland, 150 km N of the Arctic Circle, within the Paleoproterozoic Central Lapland greenstone belt (CLGB). Regional exploration by Anglo American led to the discovery of the deposit in 2009 (Coppard 2011).

Currently, three separate mineralised ultramafic bodies are known to occur in the area: The main body, NE-body and SW-body. The main body subcrops in a ca. 250x500 m area. It forms an irregular, 200-400 m wide, NW-plunging, tubular intrusion with a known depth extent of approximate 1200 m (Brownscombe et al. 2015). The intrusion consists mostly of serpentinised peridotite (olivine cumulate with interstitial clino- and orthopyroxene) and subordinate dunite (olivine adcumulate) at depth. On a regional scale, the ultramafic bodies are surrounded by quartzites of the Sodankylä Group (≥2.2 Ga) and pelitic metasediments of the Savukoski Group (ca. 2.06 Ga Matarakoski Formation). The immediate wall rocks to the main intrusion, however, are not easily classified into either of the aforementioned groups. The most prominent wall rock is a fine grained, aphanitic unit, which is composed of small olivine and plagioclase phenocrysts in a fine grained plagioclase-pyroxene-olivine groundmass. Close to the contact with the intrusion it contains mm- to cm-scale fingers or veins of intrusion peridotite. Based on mineralogical and textural features, it is thought to be volcanic in origin, compositionally resembling komatiite-picrite. In the SW part of the deposit, wall rocks include a heterogeneous package containing mafic volcanic rock, scapolite-biotite schist and gabbroic sills intruding the mafic volcanite and scapolite-biotite schist (so called mafic suite). Upwards in the stratigraphy, the aphanitic unit and the mafic suite are followed by a 100-300 m thick hematite-carbonate-albite-talc altered polymictic breccia unit. Uppermost in the wall rock sequence there is a 600 m thick phyllitic unit (Brownscombe et al. 2015).

The sulphide mineralisation consists of disseminated sulphides, sulphide veins, and semi-massive to massive sulphides.

<u>Disseminated sulphides</u> extend from the subcropping SE-part of the intrusion, through the central part of the intrusion to the deeper parts, although the whole of the intrusion is not mineralised. The disseminated sulphides are mainly composed of chalcopyrite with minor pyrrhotite, pentlandite, and pyrite. The disseminated sulphides tend to be more Cu-rich in the shallower parts and Cu-poor in the deeper parts (Brownscombe et al. 2015). Typical grades along thick intersections are 0.51 % Cu, 0.23 % Ni, 0.44 ppm Pt, 0.22 ppm Pd, and 0.13 ppm Au (62.70 m in DDH 08MOS8007) (Coppard et al. 2013).

<u>Massive to semi-massive sulphide veins</u> occur predominantly in the shallow and central parts of the intrusion (together with disseminated sulphides). They are Cu-rich, Au-enriched (compared to disseminated and massive sulphides) and typically 5-20 cm thick (Brownscombe et al. 2015; Coppard et al. 2013).

<u>Massive sulphides</u> occur as stacked lenses in the

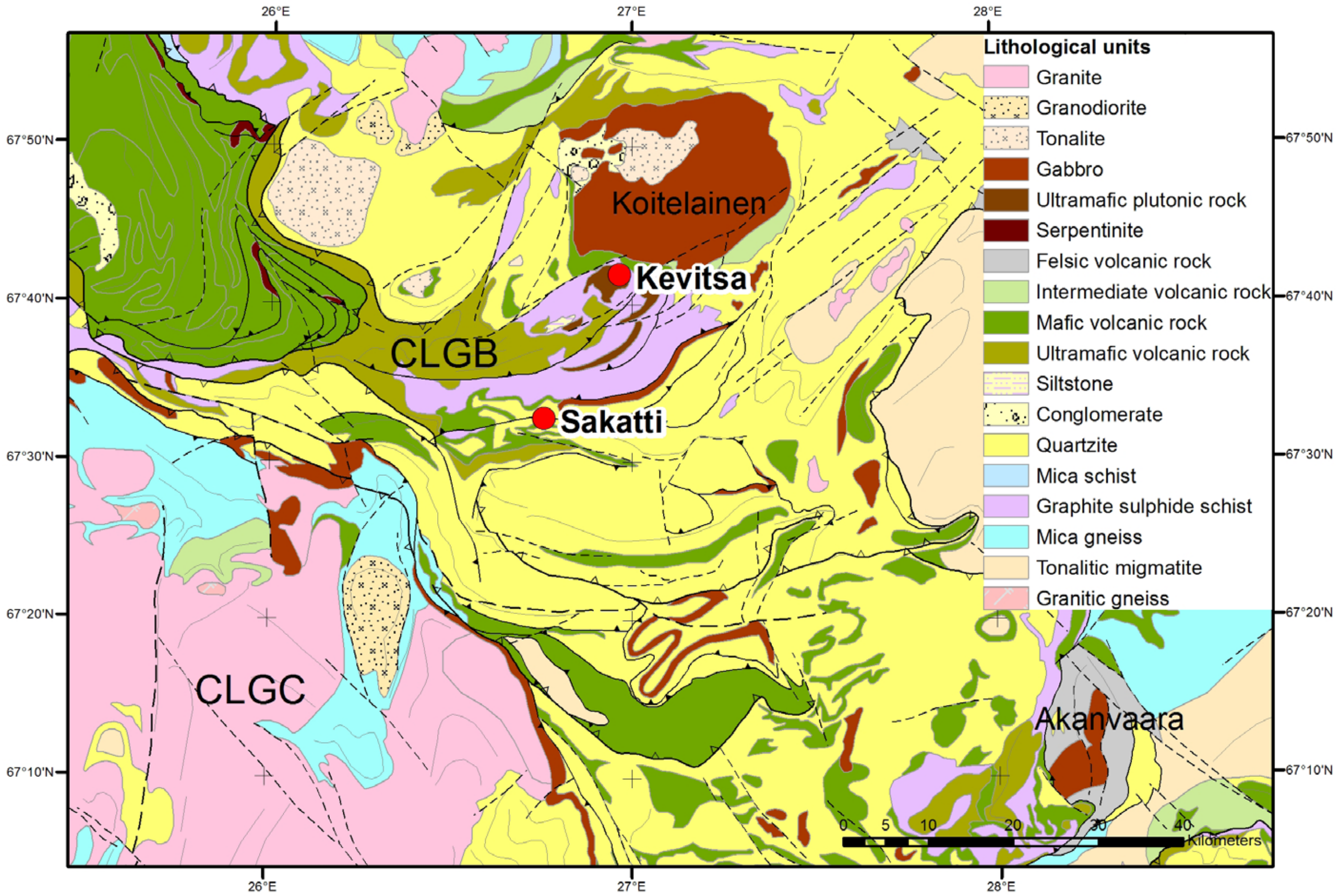


Figure 24. Location of 2.44 Ga layered intrusions (Koitelainen, Akanvaara) and the Kevitsa and Sakatti Ni-Cu-PGE deposits within the Central Lapland Greenstone Belt (CLGB). 2.2 Ga layered sills occur in the Kevitsa-Sakatti area and at the contact between CLGB and the Central Lapland Granitoid Complex (CLGC).

central part of the intrusion, extending up to 150 m into the aphanitic sidewall. The lenses are up to 25 m thick in the central part, thinning down to 0.5 m towards NW and SE. A 26.5 m interval of massive sulphides (DDH 11MOS8049) contained 3.69 % Cu, 4.16 % Ni, 0.18 % Co, 1.10 ppm Pt, 1.27 ppm Pd, and 0.24 ppm Au (Coppard et al. 2013). Disseminated and vein sulphides have low Ni/Cu ratios and high Pt/Pd ratios of <1 and 2, respectively. The massive sulphides show highly variable Ni/Cu ratios, with high ratios (Ni/Cu>10) in the deeper part of the intrusion and more Cu-rich in the upper parts of the intrusion (Ni/Cu<0.1). Platinum dominates over palladium in the disseminated and vein-style mineralisations with Pt/Pd ratios of ca. 2. In the massive sulphides, Cu-rich parts are Pt-rich, whereas Ni-rich parts are more Pd-rich (Brownscombe et al. 2015). No grade-tonnage estimates have been published for the Sakatti deposit(s) but based on published data it is potentially a world-class deposit, if not giant or even super giant.

OTANMÄKI Fe-Ti-V

Janne Hokka & Akseli Torppa (GTK)

The Otanmäki Fe-Ti-V oxide deposits are hosted by a mafic to anorthositic intrusion complex (2065 ± 4 Ma) which is situated along with alkaline granitoids (2050 Ma) at the boundary between the Archaean Pudasjärvi and Iisalmi blocks, immediately W of the Palaeoproterozoic Kainuu schist belt (Talvitie & Paarma 1980, Kontinen et al. 2013a). In addition to ferrous metals, the area is a potential source for REE, Zr and Nb in gneissic alkaline granitoids. The belt of intrusive alkaline granitoids extends a few tens of kilometers to the east (Figure 25).

The Otanmäki ferrous-metal deposits are orthomagmatic magnetite-ilmenite ores that have undergone a complex deformation and metamorphism. For most parts, the Otanmäki and Vuorokas intrusions are tectonised and show strong metamorphic fabrics (foliation). The gabbros are layered, and well developed magmatic differentiation is only seen in untectonised parts of the deposits. The oxide ore is located in the heterogeneous gabbro-anorthosite unit which is the stratigraphical Upper part of the intrusion. The Lower part is mainly seen in Vuorokas: it consists predominantly of gabbronorites, olivine gabbronorites and bronzite cumulates (Nykänen 1995).

The Otanmäki mine operated from 1953–1985 (Vuorokas Mine 1979–1985). In total, 30 Mt of ore grading of 32-34 % Fe, 5.5-7.6 % Ti and 0.26 % V was mined (Puustinen 2003). The processing plant in Otanmäki produced magnetite (7.6 Mt), ilmenite (3.8 Mt), sulphur (0.2 Mt) concentrates and vanadium pentoxide (55 545 t) from the vanadium plant. Vanadium pentoxide (V2O5) was the main product for most of the

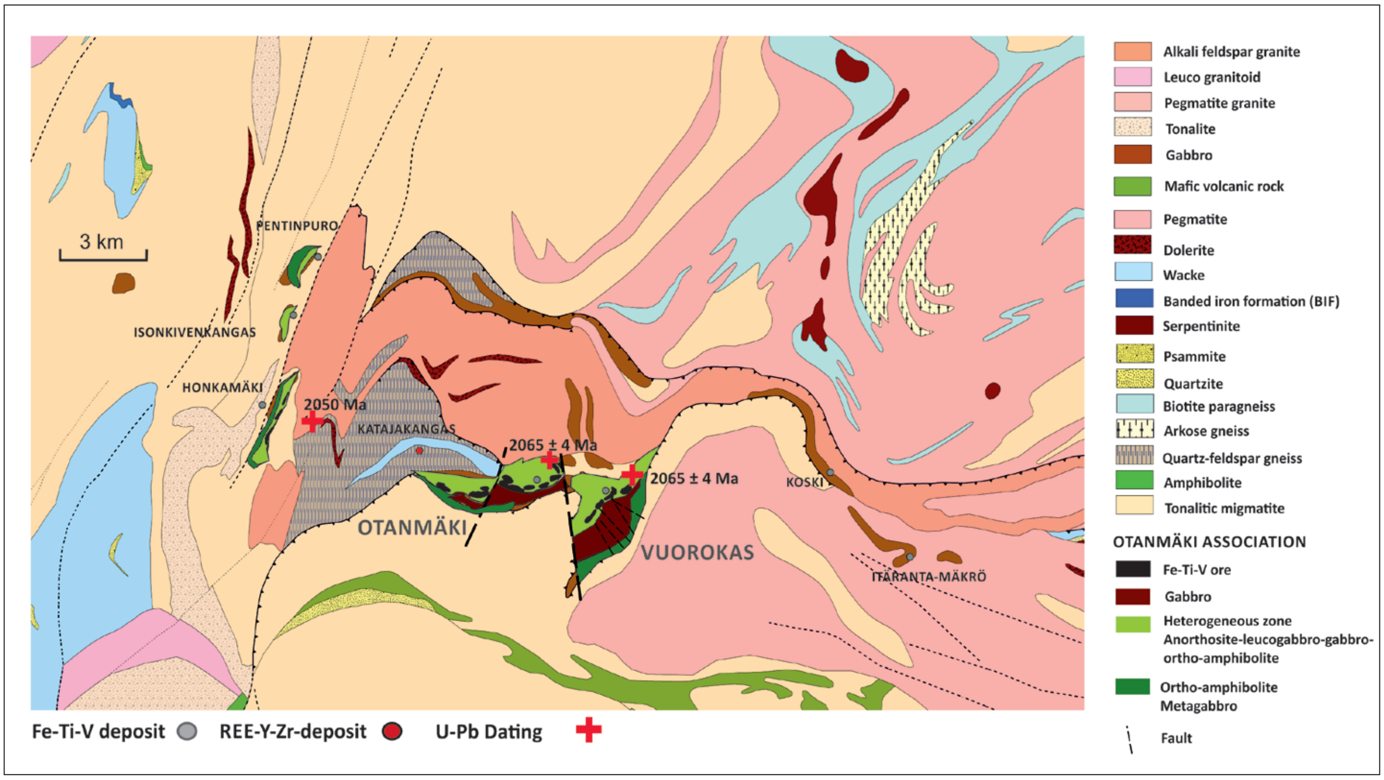


Figure 25. The Otanmäki area consists of several separate intrusions that host the vanadium-bearing magnetite-ilmenite mineralisations (Otanmäki, Vuorokas, Honkamäki, Pentinpuro, Isonkivenkangas, Koski and Itäranta-Mäkrö). Modified after GTK digital bedrock database.

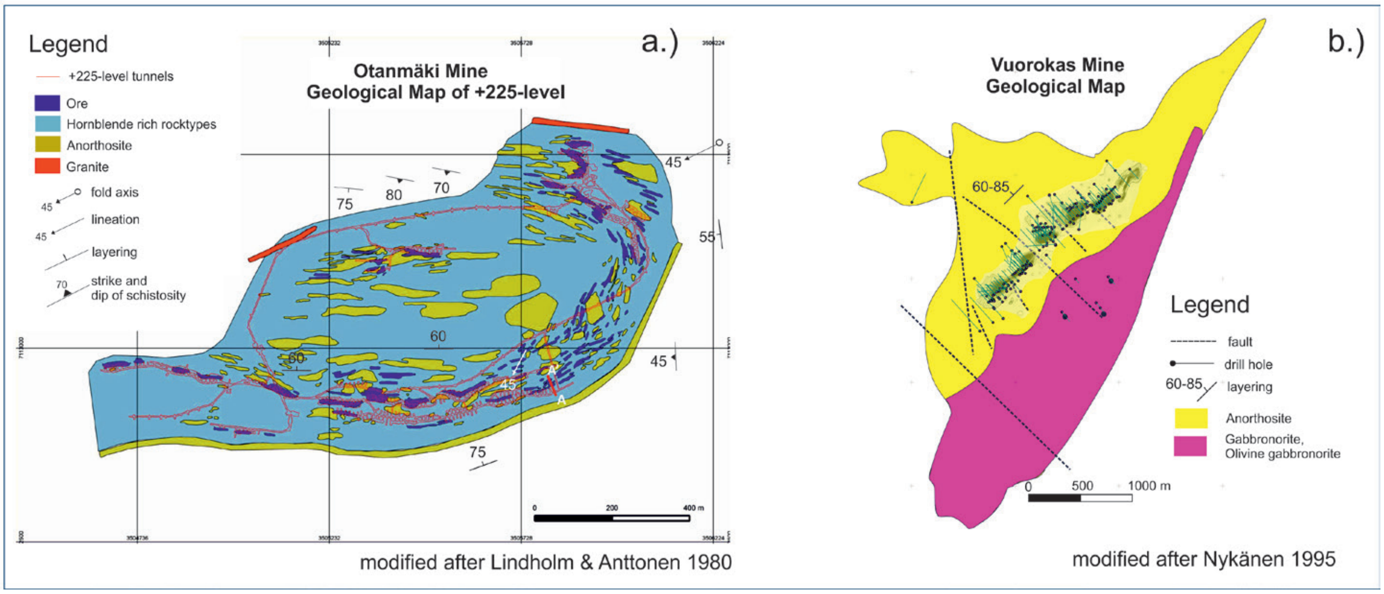


Figure 26. a.) Geological map of Otanmäki Mine (+225 level) shows that the ore consists of hundreds of individual lens-like ore bodies (blue). The deposit is at 64.117°N, 27.100°E. b.) The Vuorokas intrusion (right) comprises gabbro-norites in the lower part and gabbro-anorthosites in the upper part of the intrusion. The oxide ore is located at the contact zone of heterogeneous anorthosites and amphibolites (Nykänen 1995).

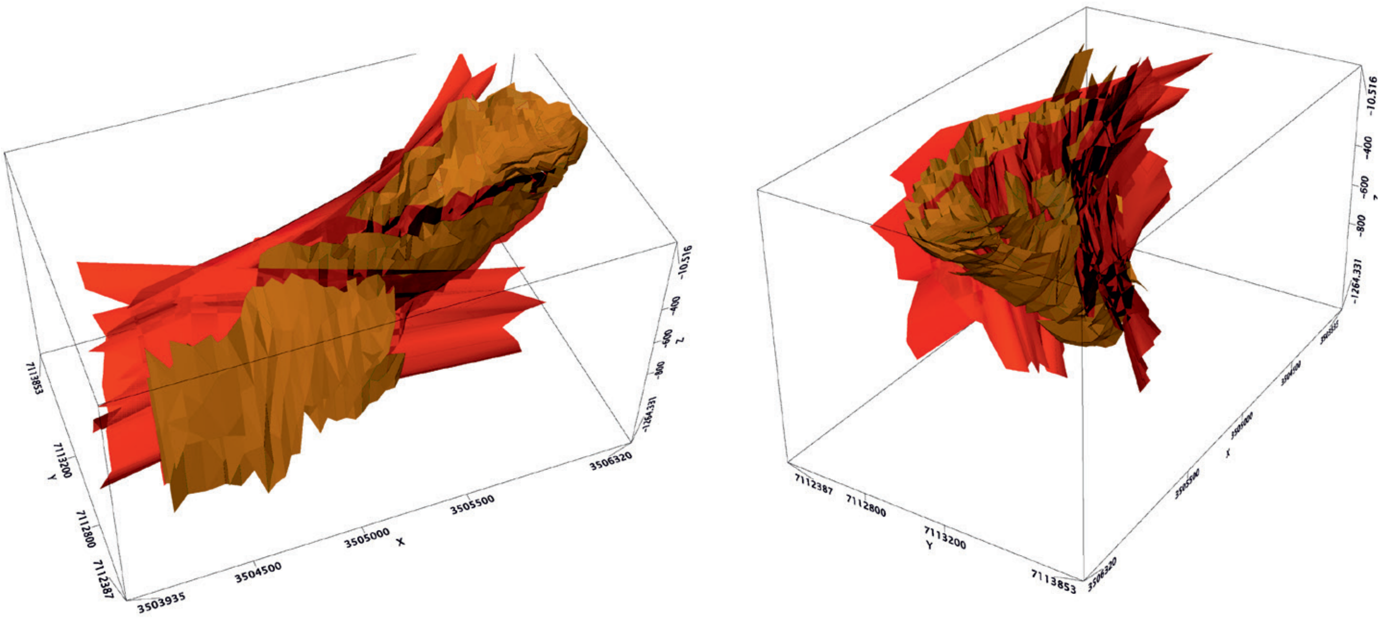


Figure 27. The NE syncline structure has a plunge of ca. 40°–60° to SW-W and the ore zone is concordant with the fold axes. Modified after Parkkinen 2013.

mine life (Illi et al. 1985). The mine consists of three separate shafts (Otanmäki, Suomalmi, and Vuorokas), and 125 kilometers of tunnels. The deepest level in Otanmäki reaches down to the +675 level (485 m above sea level).

The heterogeneous nature of the Otanmäki deposit is clearly seen in its many unequally sized and irregularly shaped ore lenses (Figure 28) which contain abundant gangue inclusions. The lenses are subvertical, 2–200 m long and 3–50 m thick, strike E-W and dip at 70°- 90° N. The mineralised zone (Figure 26 a) is roughly 3 km long and 0.5 km wide, and it forms a semicircle-shaped syncline structure (Figures 26 and 27) at its eastern end. The syncline structure has a plunge of ca. 40°–60° to SW-W and the ore zone is plunging along the fold axes. Foliation cuts the primary magmatic layering normally in 1–20° angles. The magmatic layering is mainly controlling the ore but due to the deformation axis of individual lenses tends to face the line-

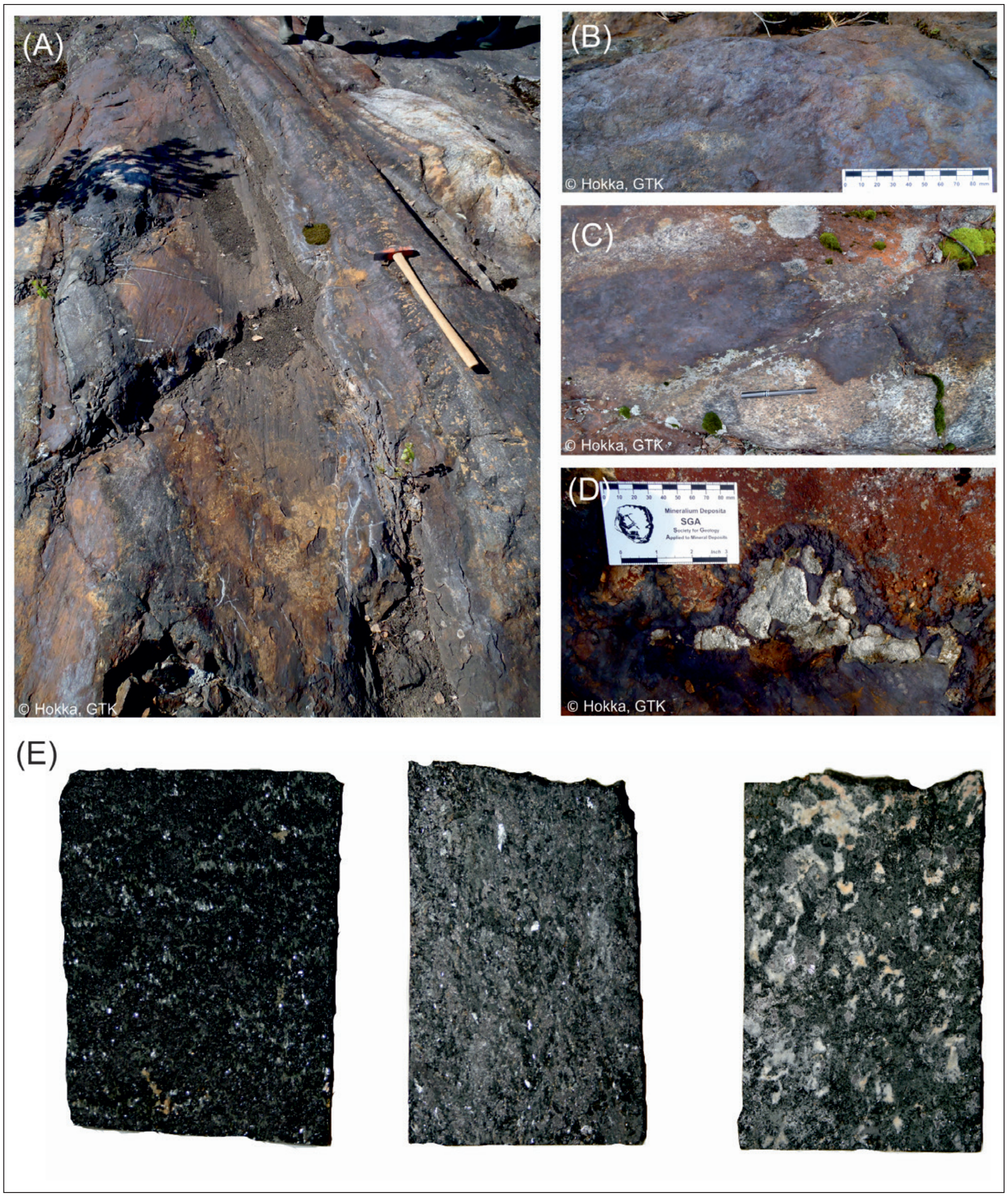


Figure 28. (A) Massive, first class ore from the Metsämalmi outcrop area; (B) & (C) First class ore is distinguished by its sharp contacts to the wall rock and unique rainbow-like colours at weathered surface; (D) massive pyrite inclusions in leucogabbro; (E) The main ore types in Otanmäki.

ation (Kerkkonen 1979). The ore zone is open at depth but is known to extend to >800 m (Lindholm & Anttonen 1980).

The average mineralogy of the Otanmäki (Figure 29) high-grade ore consists of magnetite (35–40 wt. %), ilmenite (25–30 wt. %) and sulphides (1–2 wt. %). The main gangue minerals are chlorite, hornblende and plagioclase. Magnetite and ilmenite occur mainly as granoblastic textured, separate 0.2–0.8 mm grains (Kerkkonen 1979, Pääkkönen 1956). In parts, ilmenomagnetite is predominant, containing ilmenite and spinel as exsolved lamellae and inclusions in magnetite (Figure 29) (Kerkkonen 1979).

The vanadium content in the magnetite is 0.80–1.18 % V_2O_3 (~ 0.62 wt. % V) and varies slightly between the ore bodies (Kerkkonen 1979, Pääkkönen 1956).

Another style of metallic mineralization within

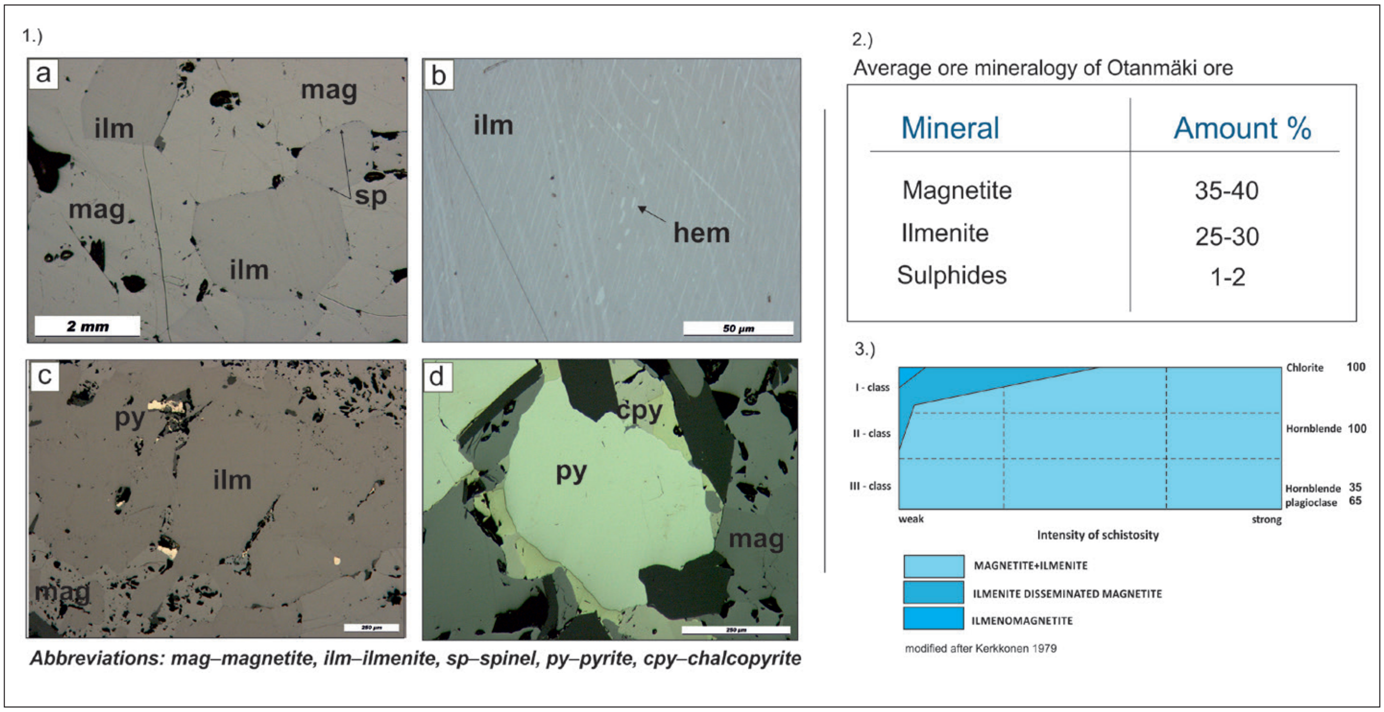


Figure 29. Representative photomicrographs, displaying typical associations of oxide minerals and exsolution textures. 1a) Granoblastic texture of ilmenite and magnetite grains (0.2–0.8 mm). Due to re-crystallisation, grains occur mainly as discrete, separate grains. Also spinel granules along the grain boundary; 1b) Dust-like particles of hematite exsolution and twinning in ilmenite; 1c-d) Pyrite and chalcopyrite together with magnetite. 2 The average ore mineralogy of Otanmäki first class ore. 3 The associations of oxide minerals in Otanmäki ore depend on the intensity of schistosity and ore grade. Modified after Kerkkonen 1979.

the area is defined by rare metal and REE prospects, mainly associated with alkaline gneisses. The Katajakangas Nb-REE prospect (0.46 Mt at 2.4 % RE_2O_3, 0.31 % Y_2O_3, and 0.76 % NbO) is a narrow mineralised zone hosted by sheared quartz-feldspar gneisses with riebeckite and alkaline pyroxene (Hugg 1985a, Puumalainen 1986, Al-Ani et al. 2010). The main ore minerals are fergusonite, allanite and columbite (Hugg 1985a). The fergusonite is characterized by a high content of radioactive elements such as Th and U. Katajakangas has clearly a metasomatic origin (Al-Ani et al. 2010, Sarapää et al. 2013). The Kontioaho occurrence, another REE mineralisation in the Otanmäki area, contains 1.62 Mt at 3.3 % ZrO_2, 0.66 % Ln_2O_3, 0.18 % Y_2O_3, and 0.14 % Nb_2O_5. Kontioaho is situated 1.3 km NNE of Katajakangas. The surface projection of the mineralized zone is approximately 400 x 600 m and it forms a 12 m thick stratiform vein-like body at the basal contact of quartz-feldspar schist (Hugg 1985b). The main ore mineral assemblage includes fergusonite, allanite, and xenotime (Hugg 1985b).

In general, the Katajakangas and Kontioaho mineralisations contain fergusonite (Nb, Y, HREE), allanite (LREE), columbite (Nb), and xenotime (Y). In addition, titanite in Kontioaho contains high amounts of yttrium (Äikäs 1990).

LUMIKANGAS AND PERÄMAA DEPOSITS

Niilo Kärkkäinen (GTK)

Lumikangas Fe-Ti-P gabbro

The Lumikangas gabbro is the northernmost intrusion of the Kauhajoki Fe-Ti-P gabbro field (Peräkorpi Ti metallogenic area in Eilu et al. 2012) situated between synkinematic (ca. 1.88 Ga) and postkinematic (ca. 1.87 Ga) granitoids in the western part of Central Finland Granitoid Complex (Figure 30). The Geological Survey of Finland (GTK) found and studied the Lumikangas Fe-Ti-P gabbro using geophysical surveys and drilling during the period 2002-2004. The reasons for initiating these studies were 5 km long aeromagnetic and regional gravity anomalies in an unexposed area with a 30-70 m thick Quaternary soil cover (Sarapää et al. 2005). The Fe-Ti-P Kauhajoki gabbros and the Lauhanvuori granite probably belong to a post-orogenic bimodal magmatic suite (Kärkkäinen and Appelqvist 1999, Rämö et al. 2001, Peltonen 2005b).

The Lumikangas intrusion is layered with a basal part composed of dark medium-grained gabbronorite, hornblende gabbro and olivine gabbro, and an upper part of medium to coarse-grained leucogabbro and monzogabbro. The layers have a gentle dip, 30° to the east. Ilmenite occurs as separate grains, in anhedral to subhedral granular aggregates with magnetite and as exsolution lamellas in magnetite. (Chernet et al. 2004). The vanadium content of the magnetite varies from 0.3 - 1.6 % V. The Lumikangas gabbro is characterised by rather high K_2O and low Cr contents, a high alkali feldspar component in normative feldspar, and coeval crystallisation of apatite, Fe-Ti oxides and mafic silicates (Sarapää et al. 2005).

The Lumikangas gabbro contains disseminated ilmenite, apatite and Ti-magnetite, in total averaging 18–22 wt.%, distributed with slightly variable amounts throughout the intrusion (Sarapää et al. 2005). Magnetic and gravity surveys indicate that the Lumikangas deposit extends to a depth of 300 - 500 m: the total length of the anomalies is 5 km. The possible resources include 230 million tons of oxide gabbro containing an average of 18 % ore minerals: 8.4 % (max. 21 %) ilmenite, 4.3 % (max. 17 %) magnetite and 5.0 % (max. 13 %) apatite. The estimate is based on geophysical interpretation and two drilling sections (totalling 1308 m), according to which the Fe-Ti oxide rich block (with specific gravity 3.2 t/m^3) is 1200 m long, 300 m wide and 200 m deep.

Perämaa Fe-Ti-P gabbro

The Perämaa gabbro is the major potential source of iron, phosphorus and titanium in the Kauhajoki Fe-Ti-P gabbro field (also called the Peräkorpi Ti metallogenic area in Eilu et al. 2012) (Figure 30). It was found by drilling an aeromagnetic anomaly within the western part of the Central Finland Granitoid Complex. Several Fe-, Ti- and P-rich mafic intrusions rim the postorogenic Honkajoki pluton which consists of potassium-rich granites, forming a bimodal magmatic suite with the Fe-Ti-P gabbros (Rämö et al. 2001, Peltonen 2005b).

Exploration in the Perämaa area has been limited. During the discovery drilling (totalling 411 m) by the Geological Survey of Finland (GTK) the major interest was in iron and titanium. In the early 1980s the possibility of mining phosphorus ore was studied by Kemira Oy in co-operation with GTK (ground geophysics, 2845 m drilling, beneficiation tests) (Pakarinen 1984, Ervamaa 1986).

The low-grade Perämaa Fe-Ti-P deposit is composed of disseminated and thin semi-massive layers of ilmenite, titaniferous magnetite and

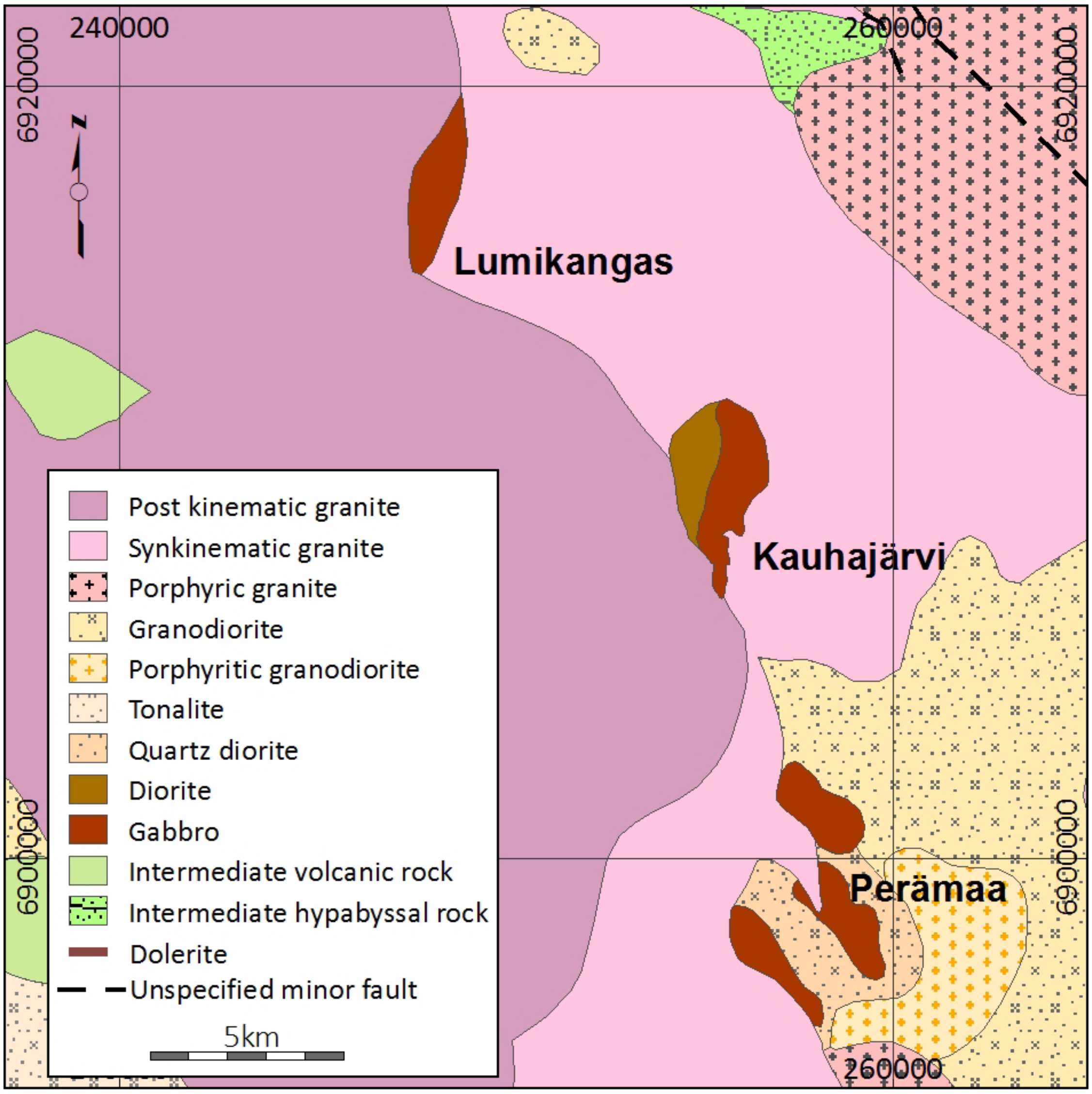


Figure 30. The location of the Kauhajoki Fe-Ti-P gabbro field within the Svecofennian Mid-Finland Granitoid Complex (modified from Bedrock of Finland-DigiKP database of GTK)

apatite in rhythmically layered peridotites, olivine gabbronorites, gabbronorites and gabbros, in which the layering is almost vertical (Pakarinen 1984, Rämö 1986). Ilmenite occurs both as separate grains and as lamellae in magnetite (ilmenomagnetite). In the Perämaa intrusion, there are three Fe-Ti-P-mineralised ultramafic-mafic blocks, which are estimated to contain 200-300 million tons mineralised rock containing about 2.5 % P_2O_5, 5 % TiO_2 and 10 % magnetite (with 0.5 % V) down to depth 60-120 m (Ervamaa 1986, Pakarinen 1984). The depth of the intrusion is interpreted, on the basis of gravity and magnetic surveys, to be more than 400 m. The Perämaa Fe-Ti-P gabbro can thus be rated as a potential future resource for apatite, ilmenite, iron and vanadium.

SIILINJÄRVI

Esa Heilimo (GTK)

The Archaean Siilinjärvi carbonatite-glimmerite complex is located in the Archaean Karelia province near the boundary of the Palaeoproterozoic Svecofennian domain. It is the oldest carbonatite to be mined for phosphate fertilizer as well as being one of the oldest carbonatites on Earth.

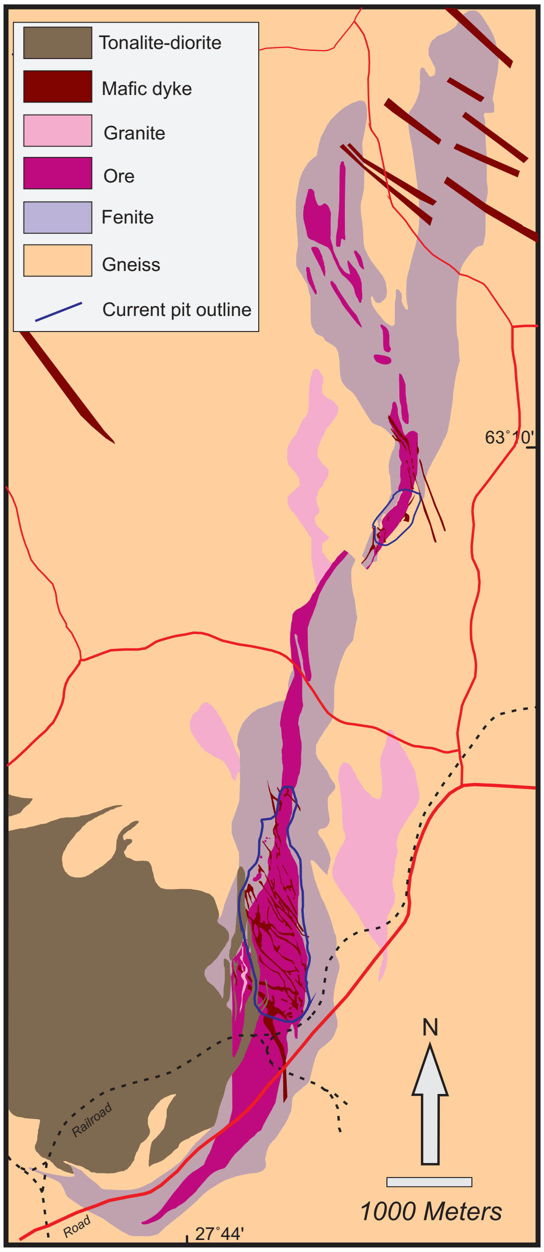


Figure 31. Geological map of the Siilinjärvi carbonatite-glimmerite complex.

The complex is a steeply dipping lenticular body roughly 16 km long with a maximum width of 1.5 km and a surface area of 14.7 km². The carbonatite-glimmerite occurs as tabular bodies of glimmerite and carbonatite intruded into Archaean basement gneiss, which shows a fenitised halo around the bodies (Puustinen 1971). Two of the carbonatite-glimmerite bodies are currently being mined for apatite, the main pit Särkijärvi in the south (see Figures 31 and 32) and the satellite pit Saarinen, in the north. The abundant zircon found in all the rock types in the complex has allowed several U-Pb age determinations to be made for the Siilinjärvi carbonatite-glimmerite, giving reliable ca. 2.61 Ga age results (e.g. Kouvo unpublished; Rukhlov & Bell 2010, Tichomirova et al. 2013, Zozulya et al. 2007).

The carbonatite and glimmerite are intimately mixed, varying from nearly pure glimmerites (tetraferriphlogopitites; Puustinen 1974) to nearly pure carbonatites. Well-developed sub-vertical to vertical lamination can be observed throughout the main lithologies. Apatite is observed in all rock varieties. Although the complex is not distinctly zoned, the volume of carbonatite is greatest near the center of the intrusion. Glimmerites near the outer edges of the body can be nearly carbonate-free, but still contain ore-grade amounts of apatite (Table 3). Two types of carbonatite can be observed; an apatite-bearing type (with a 4:1 calcite:dolomite ratio) and a younger, transecting apatite-poor type (with a 4:1 calcite:dolomite ratio; O'Brien et al. 2015). The compositions of both carbonatites are relatively pure calsio-carbonatite. Light green to grayish apatite forms rounded grains or euhedral hexagonal rods, up to several centimetres long. All the apatite found at Siilinjärvi is fluoropatite, containing 0.75 - 4 wt. % F (Hornig-Kjarsgaard 1998, O'Brien et al. 2015).

Figure 32. Aerial photograph of Siilinjärvi mine main pit Särkijärvi. Source: Yara Suomi Oy.

	Ore[1]	Glimmerite	Carbonatite, apatite-bearing	Carbonatite, apatite-poor
Micas[2]	65.0	81.5	14.7	1.7
Amphibole	5.0	4.5	0.6	0.2
Calcite	15.0	1.6	61.2	86.8
Dolomite	4.0	0.9	13.4	10.6
Apatite	10.0	10.4	9.9	0.8
Accessories	1.0	0.7	0.1	0.4
SiO_2 (wt. %)	30.2	37.5	7.8	1.3
TiO_2	0.3	0.5	0.1	<0.1
Al_2O_3	7.0	8.8	1.8	0.2
Fe_2O_3t	7.1	8.3	3.0	1.6
MnO	0.1	0.0	0.1	0.2
MgO	18.3	20.8	8.1	4.6
CaO	13.9	6.8	38.6	47.0
Na_2O	0.2	0.2	0.1	0.1
K_2O	6.2	7.6	1.6	0.2
P_2O_5	4.2	4.1	4.5	0.5

Table 3. Siilinjärvi ore zone rocks, modal mineralogy, and major elements chemistry after O'Brien et al. (2015).

1) Average ore composition; significant variation from block to block. 2) Mainly tetraferriphlogopite.

Several younger intrusions crosscut the entire Siilinjärvi complex. Northwest–southeast or NNW-SSE trending mafic dykes, with widths that range from few centimetres to several tens of metres, transect the ore. The southwestern margin of the main ore body has been intruded by mafic dykes and bodies of Paleoproterozoic tonalite-diorite displaying mingled texture. These are associated with disruption and N-S shearing of carbonatite-glimmerite ore (O'Brien et al. 2015).

The Siilinjärvi mine is currently the only operating phosphorus mine in Western Europe, the closest competing operator in the Arctic being in the Kola alkaline province of the northwest Russia. The Siilinjärvi complex was discovered in the 1950 after a local mineral collector sent a sample of carbonatite to the Geological Survey of Finland (GTK).

Exploration drilling was carried out from 1958 by several companies, including Lohjan Kalkkitehdas Oy, Typpi Oy, and Apatiitti Oy. In 1968, Kemira and its subsidiaries took over the claims and commenced laboratory and pilot plant studies. The open pit mine has been active since 1979. A change of the ownership occurred in 2007, when Kemira sold the mine and plant to Yara Suomi Oy. The main pit, Särkijärvi, is approximately 250 m deep, with a bench height of 28 m in 2015. Current production is ca. 11 Mt of ore per year with an average in situ grade of 4.0 wt.% of P_2O_5. The overall blast rate at the mine is 600,000 t per week (total from both pits). Ca. 400 Mt of rock has been mined since the start of the operation, 260 Mt of which being ore. A mine optimisation plan from 2010 gives ore reserves until the year 2035 of 234 Mt with 157 Mt of waste rock, stockpiled separately.

SOKLI

Laura Lauri (GTK)

The Sokli carbonatite intrusion in northeastern Finland was discovered in 1967 by Rautaruukki Oy during their exploration for iron. It belongs to the Devonian (ca. 360–380 Ma) Kola alkaline province, which hosts several large phosphate deposits and the most known REE deposits in the Fennoscandian Shield (Kramm et al. 1993). The Sokli intrusion (Figure 33) is a multi-stage, funnel-shaped pluton ca. 5 km in diameter that intrudes the local Archean crust. The intrusion consists of a magmatic carbonatite core concentrically surrounded by metacarbonatite, metasomatically altered ultramafic rocks, and a wide fenite aureole (Vartiainen 1980, 2001; O'Brien et al. 2005). Late-stage carbonatite dikes cross-cut the older intrusion phases and the fenite zone. The intrusion is capped by a ca. 26 m thick regolith that constitutes the main phosphate ore. In addition to phosphate ore the deposit contains Nb, Ta, Zr and some U. The main ore minerals at Sokli are apatite, pyrochlore, magnetite, ancylite, rhabdophane, baddeleyite, zirconolite, fersmite and lueshite. The Sokli carbonatite complex is estimated to contain in total 190.6 Mt of P ore grading 11.2 wt.% P_2O_5. The ore comprises lateritic P ore (36.7 Mt @ 18.7 wt.% P_2O_5), silicate-apatite P ore (19.3 Mt @ 11.0 wt.% P_2O_5), weathered crust P ore (57.6 Mt @ 14.1 wt.% P_2O_5), and Kaulusrova ore (75.2 Mt @ 5.6 wt.% P_2O_5, 0.2 wt.% Nb_2O_3 and 1.9 Mt Nb-Ta ore @ 1.9 wt.% P_2O_5, 0.6 wt.% Nb_2O_3), which are all considered as soft rock ores (Siirama 2009, Pöyry Environment Oy 2009). Siirama (2009) also reports hard rock ores that comprise 3000 Mt in the magmatic core, 110 Mt Nb ores, 500 Mt Arch ore (situated on the SE side of the carbonatite core), 1800 Mt of metacarbonatitic ores and 6800 Mt of metasomatite ores, which altogether yield a total of 12 210 Mt of P-ores in hard rock. The so far unexploited phosphate deposit is currently under a mining license held by Yara Suomi Oy. Recent investigations by GTK indicate that late-stage carbonatite ring dykes surrounding the intrusive complex contain REE carbonates such as ancylite-(Ce) and bastnäsite-(Ce). The Sokli project of Yara Suomi was suspended in autumn 2015 due to economic reasons.

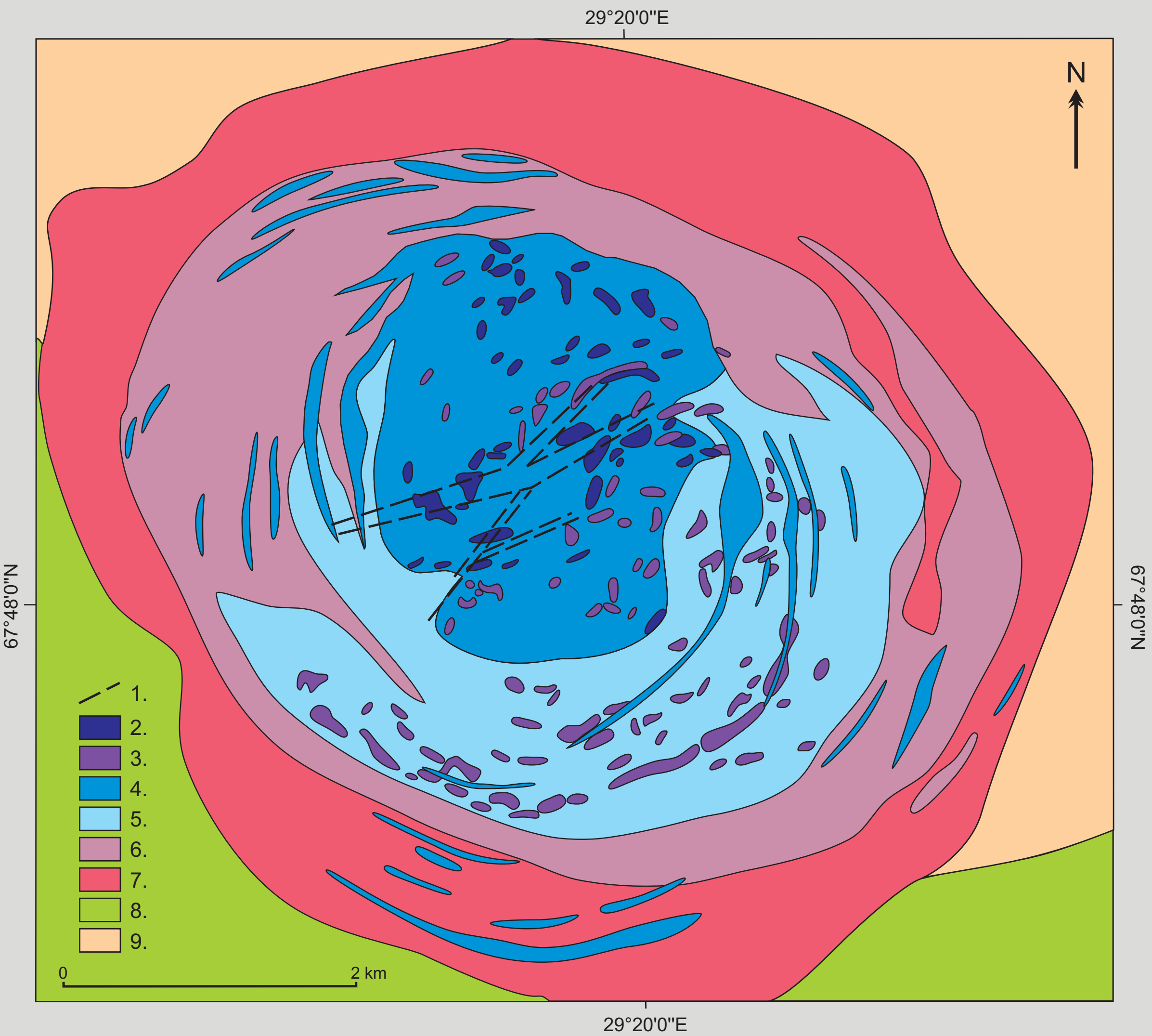


Figure 33. Geological map of the Sokli carbonatite complex (modified after Vartiainen 1980). Legend: 1-central fracture zone, 2-magmatic phoscorite, 3-metaphoscorite, 4-magmatic sövite and silicosövite, 5-metasilicosövite, 6-metasomatite, 7-fenite, 8-amphibolite, 9-tonalite gneiss.

THE LAHTOJOKI KIMBERLITE PIPE

Marja Lehtonen & Hugh O'Brien (GTK)

Kimberlites and related rocks occur in three major provinces in eastern Finland, (1) Kaavi-Kuopio, (2) Lentiira-Kuhmo and (3) Hossa-Kuusamo. Provinces 1 and 3 contain archetypical kimberlites, whereas only olivine lamproite-orangeite hybrids are known from province 2. Altogether, there are approximately 40 known kimberlitic/lamproitic bodies in Finland. Over half of the bodies are proven to contain diamonds; mostly, however, only microdiamonds. The most diamondiferous kimberlite found so far, is the Lahtojoki Kimberlite pipe that belongs to the Kaavi-Kuopio province.

The Kaavi–Kuopio province consists of two kimberlite fields, located only ~ 50 and ~ 30 km from the southwestern margin of the Karelian craton. The kimberlites are characterised by abundant macrocrysts of olivine, in a matrix of euhedral olivine, monticellite, perovskite, magnesian ulvöspinel-magnetite, Ba-rich phlogopite-kinoshitalite mica, apatite, calcite, and serpentine (O'Brien & Tyni 1999). Their major and trace element contents as well as Sr, Nd, and Pb isotopic compositions are similar to those of other Group I kimberlites globally. Age determinations by ion microprobe of U-Pb in perovskites from four pipes have resulted in ages ranging from 589–626 Ma (O'Brien et al. 2005).

The Kaavi-Kuopio kimberlites range from hypabyssal dikes to volcaniclastic kimberlite and volcaniclastic kimberlite breccias formed in diatremes. The bodies are rather small, ranging from < 1 m dykes to diatreme-facies pipes up to 4 ha in surface area. None of the pipes have crater-facies materials preserved due to erosion. Many of the pipes are diamondiferous, several having reasonable diamond grades (14 – 41 ct/100 t; Tyni 1997).

The Lahtojoki Kimberlite is the best studied of all the kimberlites due to its high diamond content. It is located in Kaavi municipality (63° 1' 50.3"N, 28° 34' 39.2"E). The pipe was discovered by Malmikaivos Oy by sampling of glaciogenic deposits followed by magnetic survey and drilling in 1989. The Lahtojoki diatreme is suboval in plan, measuring approximately 200 m (E–W) × 100 m (N–S), with approximately 2 ha of surface area. It is located in a swamp and covered by 13–20 m of glacial deposits and peat. Drill core information suggests that at the – 100 contour, the pipe plunges 80° toward the south, and is still nearly 2 ha in cross section.

The Lahtojoki kimberlite is mainly composed of macrocrystal tuffisitic kimberlite and subordinate tuffisitic kimberlite breccia with relatively rare hybabyssal kimberlite. The degree of weathering varies in the upper part of the pipe. Locally there is a several metres thick soft weathered kimberlite horizon whereas in other areas the weathered kimberlite has been removed by glacial erosion exposing fresh kimberlite.

Mini-bulk sampling of the pipe by Malmikaivos Oy/Ashton Mining Ltd, totalling at 23.3 t, suggests an average grade of 26 carats/100 t for diamonds > 0.8 mm in diameter (Tyni 1997). However, the 1000 t bulk sample collected by the company returned only 5.7 c/100 t. The large discrepancy between the results is probably due to the high country rock dilution of the volcaniclastic kimberlite breccia that formed a significant portion of the bulk sample. In contrast, the volcaniclastic diatreme material that was sampled for mini bulk testing, has a much lower country rock content overall. The notable variations within the mini-bulk results may, however, be related to the fact that diamonds in the Lahtojoki kimberlite occur not only as xenocrysts in the matrix, but also as a rock-forming mineral in some of the eclogite xenoliths (Peltonen et al. 2002).

Figure 34. Volcaniclastic kimberlite breccia from the Lahtojoki kimberlite. Photo: Niko Auvinen, GTK.

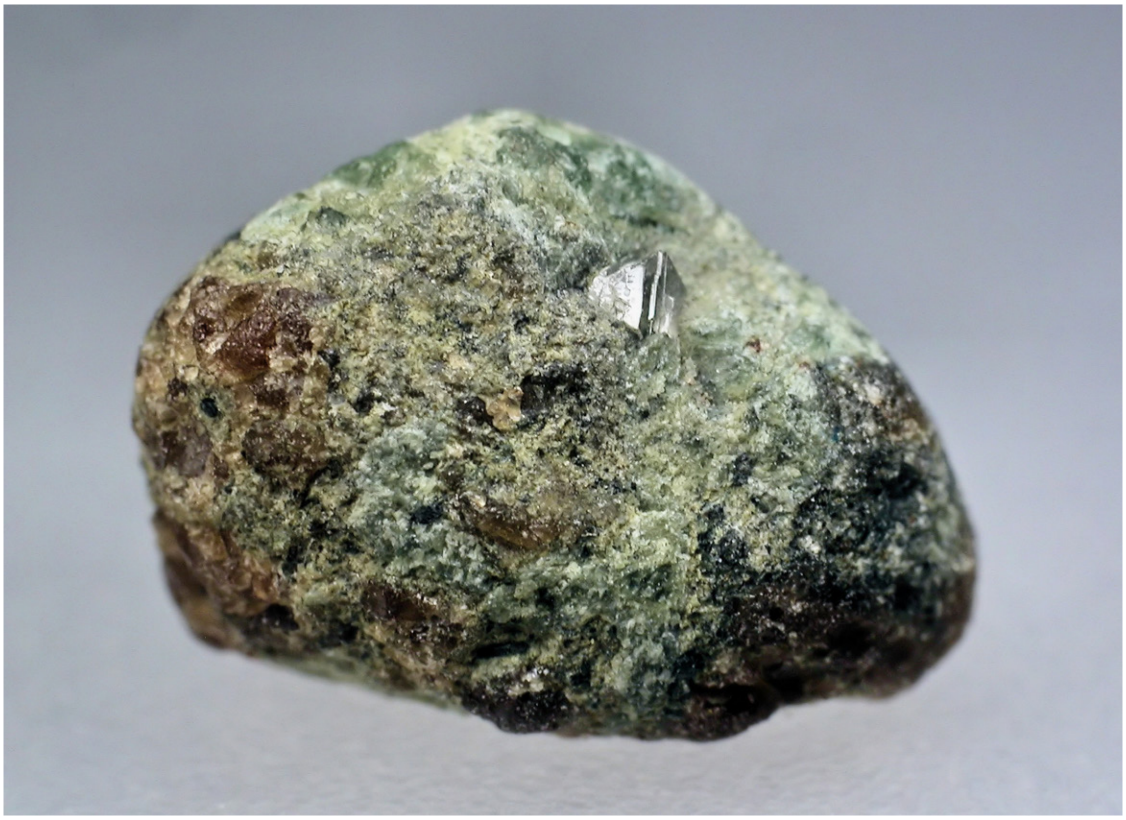


Figure 35. An eclogite xenolith from Lahtojoki hosting a diamond crystal. The diameter of the diamond is 1 mm. Photo: Kari A. Kinnunen, GTK.

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