


# Ore deposits, magmatism and precambrian geology of Finland

## Field trip guidebook

### **Educational Material**

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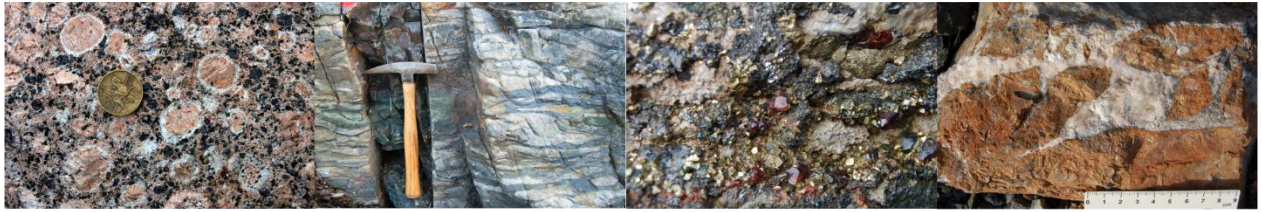
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# Ore Deposits, Magmatism and Precambrian Geology of Finland

## Field trip guidebook

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*Institute of Geochemistry and Petrology, ETH Zürich*  
*July 10-28, 2014*

*Field trip sponsored by:*

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*This Field Guide was assembled from contributions by participating student who take responsibility for correct referencing of data sources, to the best of their knowledge. In addition to the numerous company and government geologists who helped us before and during this field trip, we particularly acknowledge the rich information source by GTK, the Finnish Geological Survey, whose open-access data were extensively copied for this informal document in period May – September 2014.*

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## Program & map of the field trip stops

Day	Time	Locality	Settings & aims
Thu 10.7.	7:35 – 11:15 14:00	Travel ZH - HEL <b>Helsinki University</b>	Finnish bedrock geology - introductory lecture
Fri 11.7.	8:00	<b>Wiborg</b> rapakivi area	dimension stone quarries - guided tour
Sat 12.7.	10:00	<b>Luumäki</b> beryl pegmatite	gemstone production - quarry visit
Sun 13.7.	10:00	<b>Nunnanlahti</b> soapstone	quarry & production - guided tour
- group A	15:00	<b>Nilonsuo &amp; Lahtojoki</b> kimberlites	outcrop & test pit - heavy mineral sampling
- group B	15:00	<b>Koli</b> national park	guided geological hike
Mon 14.7.	10:00	<b>Keretti</b> Cu mine	museum - guided tour
	14:00	<b>Kylylahti</b> Cu mine	open pit mining (early stage) - geology guided tour
Tue 15.7.	9:00	<b>Siilinjärvi</b> P mine	open pit mining (developed) - geology guided tour
	14:00	<b>Talvivaara</b> Zn mine	heap leaching & metal recovery - production guided tour
Wed 16.7.	14:00	<b>Juomasuo &amp; Hangaslampi</b> Au prospects	test pits - mapping & explo strategies
Thu 17.7.	9:00	<b>Kevitsa</b> Ni mine	open pit mining (early stage) - mining & production guided tour
Fri 18.7.	9:00	<b>Kittila</b> Au mine	open pit mining - geology guided tour
Sat 19.7.		FREE DAY	Pallas-Yllästunturi NP
Sun 20.7.	10:00	<b>Hannukainen &amp; Sahavaara</b> Fe pits & prospects	closed mine & prospects - geology overview
Mon 21.7.	9:00	<b>Rompas</b> Au project	prospect (grass root) - exploration strategies lecture & tour
	14:00	<b>GTK Rovaniemi</b>	core storage facility - core logging practicals
Tue 22.7.	9:00	<b>Otanmäki</b> V project	closed mine & prospect - exploration guided tour
Wed 23.7.	9:00	<b>Pyhäsalmi</b> Zn-Cu mine	underground mining - mine visit & production tour
		Pyhäsalmi EMMA lab	center for physics - lecture
Thu 24.7.	9:00	<b>Länttä</b> Li deposit	prospect - exploration strategies
Fri 25.7.	9:00	<b>Vammala</b> Au processing plant	milling & flotation - guided tour
	14:00	Orogenic Au in Tampere area	outcrops
Sat 26.7.	11:00	<b>Olkiluoto</b> power plant	nuclear fuel repository - lecture
Sun 27.7.		Helsinki	city sightseeing
Mon 28.7.	7:55 – 9:40	Return HEL-ZH	



Schematic map of the field trip stops with starting and ending point in Helsinki.

## Logistics & general information

- Field Excursion Module Mineral Resources 651-4036-00L, jointly organized with SEG Student Chapter ETH Zürich
- Successful participants can be awarded 3 ECTS credits
- Date and duration: 10 – 28 July 2014 (18 days)
- Travel: direct flight AY2866 Zürich Airport – Helsinki Vantaa on 10.7.2014 at 7:35, return by AY0857 on 28.7.2014 at 7:55; local transport in Finland by 3 rented minivans (2 drivers per van)
- Accommodation: arranged in local camping facilities, hostels & holiday resorts
- Approximate cost: ca. 1600 Fr per person (50% covered by ETH Zürich, additional funding provided by SEG and AMIRA International)
- Field & personal equipment: good boots, rain gear (rain coat, umbrella), mosquito repellent and head net, hammer, camera, notebook and pencils, sleeping bag, sleeping mask (no sunset in areas behind the polar circle), waterproof jacket, warm & generally good field clothing, swimsuit (saunas & lakes), drivers bring comfortable shoes & licence
- Weather & climate: temperature during summer do not usually exceed 25°C, expect colder weather in northern parts (Lapland), possible morning frosts or persistent rain
- General information about Finland: member of EU, currency EURO, embassies and consulates located in the capital city – Helsinki, overall costs of living (food & housing) relatively high (rank as the 3<sup>rd</sup> most expensive country of EU, 5<sup>th</sup> in Europe), alcohol prohibition (possible to buy alcoholic beverages in special shops called Alko), no smoking at public places & most restaurants, official language Finnish and Swedish (Swedish minorities along western coast), easy communication in English.

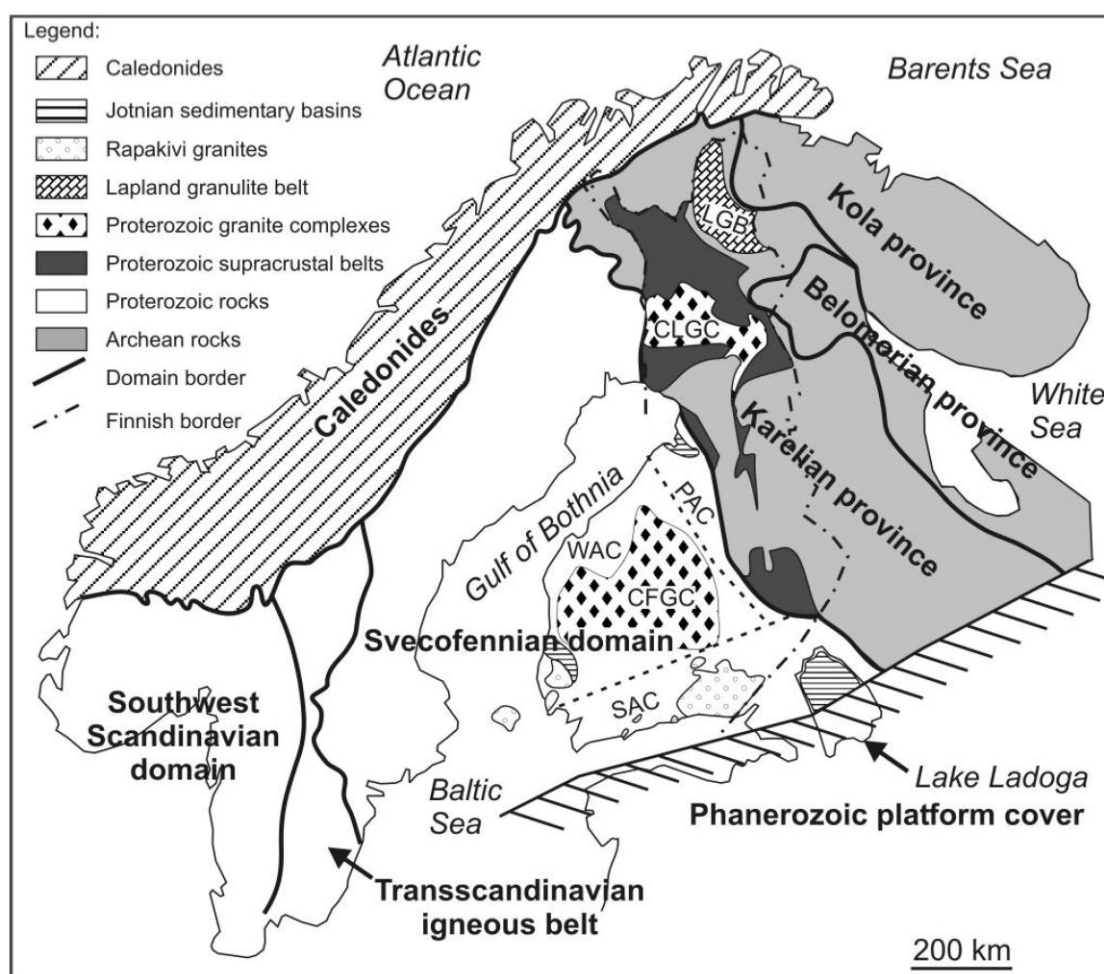
# Introduction: Geology of the Fennoscandian Shield

by Lisa Bieri

The following section was compiled and partly extracted from *Field trip guide 33 IGC excursion No. 15, August 15<sup>th</sup> to 21<sup>st</sup> 2008* and *Eurogranites 2005 – Proterozoic and archean granites and related rocks of the Finnish Precambrian*.

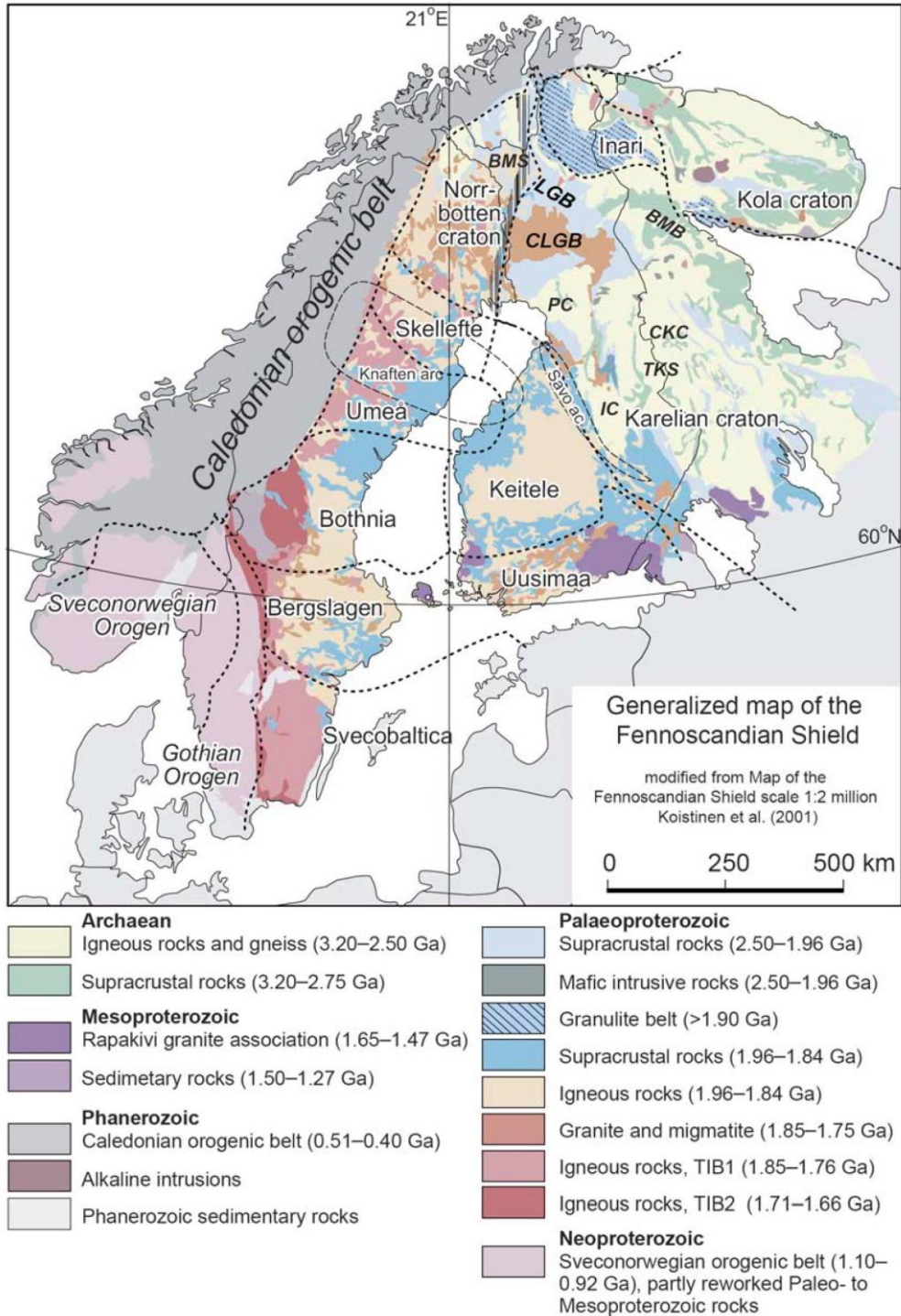
## Introduction

To understand the geology of Finland, we focus on the Fennoscandian Shield, which forms the north-western part of the East European craton (Fig. 1). The majority of the Fennoscandian Shield was formed during the Archean (3.85-2.5 Ga) and Paleoproterozoic (2.5-1.6 Ga).



**Figure A-1:** Geology and major structural units of Fennoscandian shield. PAC – Primitive arc complex; WAC – Arc complex of western Finland; SAC – Arc complex of southern Finland; CFGC – Central Finland granitoid complex; CLGC – Central Lapland granite complex; LGB – Lapland granulite belt. Right-diagonal ruling marks the northern edge of platform sediments. Simplified from Koistinen et al. (2001).





**Figure A-2:** Simplified geological map of the Fennoscandian Shield with major tectono-stratigraphic units. Map adapted from Koistinen et al. (2001), tectonic interpretation after Lahtinen et al. (2005). LGB = Lapland Greenstone Belt, CLGC = Central Lapland Granitoid Complex, BMB = Belomorian Mobile Belt, CKC = Central Karelian Complex, IC = Iisalmi Complex, PC = Pudasjärvi Complex, TKS = Tipasjärvi–Kuhmo–Suomussalmi greenstone complex. Shaded area, BMS = Bothnian Megashear.

## **The Fennoscandian Shield**

The Fennoscandian Shield is one of the most important mining areas in Europe, and the northern part, including Sweden and Finland, is intensely mineralized. Mineral deposit types include VMS, Kiruna-type apatite-iron ores, mesothermal (orogenic) Au ore, epigenetic Cu-Au ore, mafic and ultramafic-hosted Cr, Ni-(Cu), PGE and BIF. Unlike most other shield areas, the Fennoscandian Shield is more mineralized in its Paleoproterozoic than the Archean areas.

### **Archean**

The oldest preserved continental crust in the Fennoscandian Shield was generated during the Saamian Orogeny at 3.1–2.9 Ga (Fig. A1 and A2) and is dominated by the TTG series (gneissic tonalite, trondhjemite and granodiorite). Rift- and volcanic arc-related greenstones, subduction-generated calc-alkaline volcanic rocks and tonalitic-trondhjemitic igneous rocks were formed during the Lopian Orogeny at 2.9–2.6 Ga. Various intrusions cut the Archean basement due to deformation in a later stage at the end of this phase.

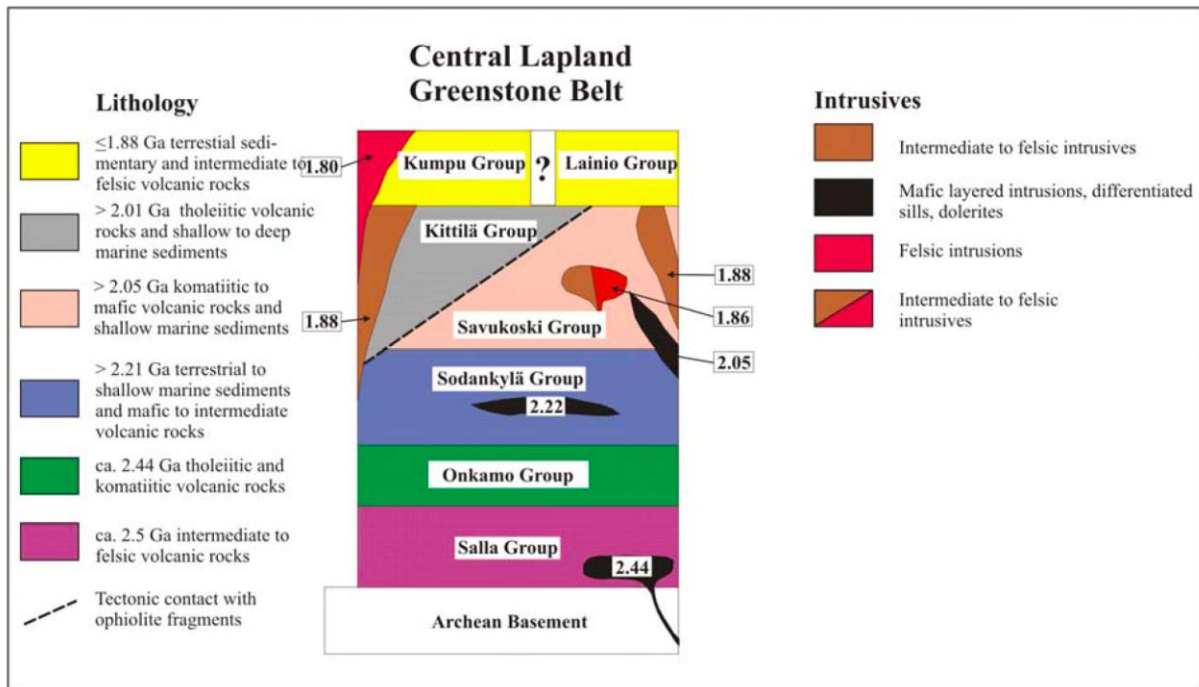
### **Paleoproterozoic**

Sumi-Sariolian (2.5–2.3 Ga) clastic sediments, intercalated with volcanic rocks varying in composition from komatiitic and tholeiitic to calc-alkaline and intermediate to felsic, were deposited on the deformed and metamorphosed Archean basement during extensional events. The beginning of this extensional setting between 2.51 and 2.43 Ga is indicated by the emplacement of numerous layered mafic igneous complexes (Alapieti et al. 1989, Weihed et al. 2005). The complete mafic series from high Mg-basalts, komatiites as well as pillow-lavas occurs whereas the series is incomplete in later extensional phases.

**The Paleoproterozoic Lapland greenstone belt (LGB)**, which overlies much of the northern part of the Archean craton, is the largest coherent greenstone terrain exposed in the Fennoscandian Shield (Fig A2). It extends for over 500 km from the Norwegian coast through the Swedish and Finnish Lapland into the adjacent Russian Karelia in the southeast and most likely represents a major tholeiitic province (Pharaoh, 1985). An originally continental rift setting is favored for these greenstones, which represent a major magmatic and rifting event at ca. 2.1 Ga with the final break up taking place at ca. 2.06 Ga (e.g. Pharaoh et al. 1987, Huhma et al. 1990, Martinsson 1997, Perttunen & Vaasjoki 2001, Rastas et al. 2001). It is believed that plume-generated volcanism led to the formation of the LGB (Martinsson 1997). The lithostratigraphy of the Finnish part of the Lapland greenstone belt, the Central Lapland greenstone belt, is presented in Fig A3.

Rifting culminated in extensive mafic and ultramafic volcanism and the formation of oceanic crust at approximately 1.97 Ga. This is indicated by the extensive komatiitic and basaltic lavas of the Kittilä Group of the CLGB in the central parts of the Finnish Lapland (Fig. A3). At the most extensive rifting, parts of the subcontinental asthenosphere are pulled out under the continent and are covered by shallow- to deep-marine sediments. Associated with the ultramafic material, there are carbonate rocks, graphite schist, iron formation and stratiform sulphide occurrences.

Fragments of oceanic crust were subsequently accreted onto the Karelian craton, as indicated by the Nuttio ophiolites in central Finnish Lapland and the Jormua and Outokumpu ophiolites further south (Kontinen 1987, Gaál 1990).



**Figure A-3.** Stratigraphy of the Central Lapland greenstone belt. Ages in Ga. Compiled by Tero Niiranen, after Hanski et al. (2001).

The up to 10 km thick pile of Paleoproterozoic volcanic and sedimentary rocks was multiply deformed and metamorphosed contemporaneously with the intrusion of the 1.89–1.87 Ga granitoids. Anatectic granites were formed during 1.82–1.79 Ga, during another major stage of deformation and metamorphism. Large-scale migration of fluids during the many stages of igneous activity, metamorphism and deformation is expressed by regional scapolitization, albitization and albite-carbonate alteration in the region.

The main period of the formation took place between 1.92 and 1.8 Ga, when the Svecofennian orogeny reworked and compiled the large parts of the Archean and Paleoproterozoic crust. The contractional setting led to the subduction of parts of the Paleoproterozoic below the Archean, and several volcanic arc complexes are accreted from the SW towards NE. It is assumed that the Fennoscandian Shield was tectonically reworked during five partly overlapping orogenies (Lahtinen et al. (2005)) with the amalgamation of several microcontinents and island arcs with the Archean Karelian, Kola and Norrbotten cratons and other pre-1.92 Ga components.

The following continental extension stage (1.86–1.84 Ga) was caused by extension of hot crust in the hinterlands of subduction zones located to the south and west and formed new juvenile crust with extensive granitoids in the northernmost Sweden and Finland.

After the extension, the Fennoscandian Shield went through another period of orogeny (Svecobaltic orogeny (1.84-1.80 Ga), Nordic orogeny (1.82-1.80 Ga)). After 1.45 Ga, a phase of stabilization and consolidation of the craton followed.

## Deformation and metamorphism

The Paleoproterozoic rocks in the northern part of the Fennoscandian Shield have undergone several phases of deformation and metamorphism. The metamorphic grade mainly is of low- to intermediate-pressure type, from lower-greenschist to upper-amphibolite facies. Granulite facies rocks only occur in the northern Finnish Lapland and on the Kola Peninsula with the arcuate Lapland Granulite Belt (Fig. A1).

Several of the crustal-scale shear zones are associated with abrupt changes in metamorphic grade, indicating that these zones have been active after the peak of regional metamorphism. Moreover, many of the epigenetic Au and Cu-Au deposits also show a strong spatial relationship with these major shear zones, although their local control are mainly the second- to fourth-order faults and shear zones. Structural evidence e.g. in the Kittilä region indicates close to syn-peak metamorphic timing for many of the epigenetic Cu-Au occurrences in Finland (Eilu et al. 2003). Au deposits such as the Suurikuusi in the Kittilä region occur mainly within the greenschist areas and indicate remobilization and concentration of the amphibolite derived fluids along shear zones.

## General metallogeny

**From: *Mineral deposits and metallogeny of Fennoscandia, Geological Survey of Finland, Special Paper 53, 2012.***

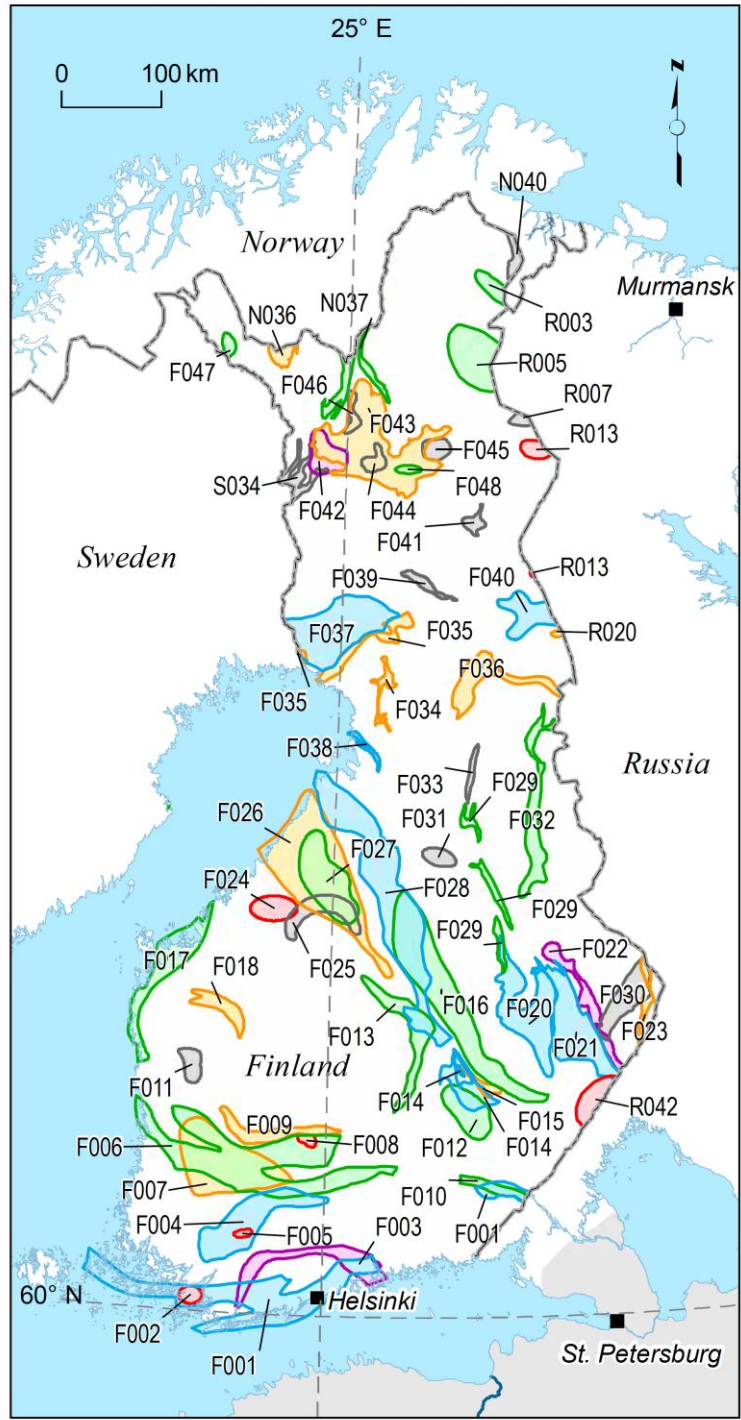
In total, 47 metallogenic areas have been identified in Finland. Ten areas are dominantly potential for ferrous metals (Fe, Ti, V, Cr), 11 for precious metals (Au, Pd, Pt), 11 for nickel, 8 for copper, zinc and/or lead, 4 for metals mostly used in advanced technologies ('hightech metals' Be, Li, Nb, REE, Ta), and 3 for uranium. In general, many of the metallogenic areas are potential for more than just one major group of metals. In total, the Finnish metallogenic areas include more than 30 different genetic types of metal deposits.

By past production and present resources, the most significant deposit types include: mafic intrusion-hosted Ti-Fe-V (e.g., Mustavaara deposit at Koillismaa), mafic to ultramafic hosted Cr (Kemi), IOCG-style Fe-Cu-Au (Hannukainen deposit in the Pajala-Kolari area), magmatic Ni-Cu-PGE (Portimo, Koillismaa, Hitura and Kotalahti areas, and Kevitsa and Sakatti deposits), orogenic gold (Kittilä), and VMS (Vihanti-Pyhäsalmi). Highly significant are also the unique deposit types of Outokumpu Cu-Co and Talvivaara Ni-Zn-Cu-Co.

In the Archean, only a few economic to subeconomic mineral deposits have been formed during the Lopian Orogeny related to rifting and building of a volcanic arc. These include orogenic gold (Ilomantsi), BIF and Mo occurrences, and ultramafic- to mafic-hosted Ni-Cu (Frietsch et al. 1979, Gaál 1990, Weihed et al. 2005). Minor Ni (Kuhmo) deposits occur in komatiite-related rocks.

Most of the known metal endowment of Finland though was formed during the Paleoproterozoic Era, during 2.45–1.92 Ga multi-stage rifting and the 1.9–1.8 Ga Svecofennian orogeny. The layered mafic igneous intrusions occurring at the culmination of the magmatic input due to rifting at 2.4 Ga mostly show Cr, Ni, Ti, V and/or PGE occurrences.

The most important post-Svecofennian metal deposit is the carbonatite-hosted Nb-REE at Sokli, dated to ca. 365 Ma.



- Base metals (Ni)
- Base metals (Co, Cu, Pb, Zn)
- Ferrous metals (Cr, Fe, Mn, Ti, V)
- Precious metals (Ag, Au, Pd, Pt, Rh)
- Special metals (Be, Li, Mo, Nb, REE, Sc, Sn, Ta, W, Zr)
- Energy metals (U, Th)

**Figure A-4:** The main metallogenic zones of Finland, from *Mineral deposits and metallogeny of Fennoscandia*, Geological Survey of Finland, Special Paper 53, 2012.

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# Diamonds in Europe?

## Finland's Kimberlites, Orangeites & Lamproites

by *Nico Küter*

### Introduction

Scandinavia is well known for some unique or world class ore deposits like Sweden's Kiruna magnetite ore or Finland's Siilinjärvi REE-phosphorus mine. Less known, however, is the high potential for diamonds in Finland and Sweden. Together with the western part of Russia, these countries lie partly on top of a shield called the Kola-Kuloi or Karelian Craton (Fig. B-1). The craton is cold enough to host ultrapotassic volcanism that originates from diamond-bearing subcontinental lithospheric mantle (SCLM) below 150 km depth. While Sweden's mining industry stays calm in diamond exploration, various prospects have been undertaken by several companies and the Finnish Geological Survey (GTK) in the central parts of the country, revealing different types of potential diamond host rocks. So far, no active diamond mine is present in Scandinavia, however, diamond-bearing dikes and pipes have been found and at least one of them (Lahtojoki) was close to mining. That the Scandinavian parts of Karelian Craton have the potential for major diamond deposits becomes plausible if one takes a look to the Russian equivalents in the nearby Arkhangelsk-district (Kuloi, White Sea; Fig. B-1); Here, economic diamond deposits are currently exploited like the AROSA's Lomonosov mine with estimated reserves of 220 million carats or LUKoil's Grib mine with estimates reserves of 98 million carats.

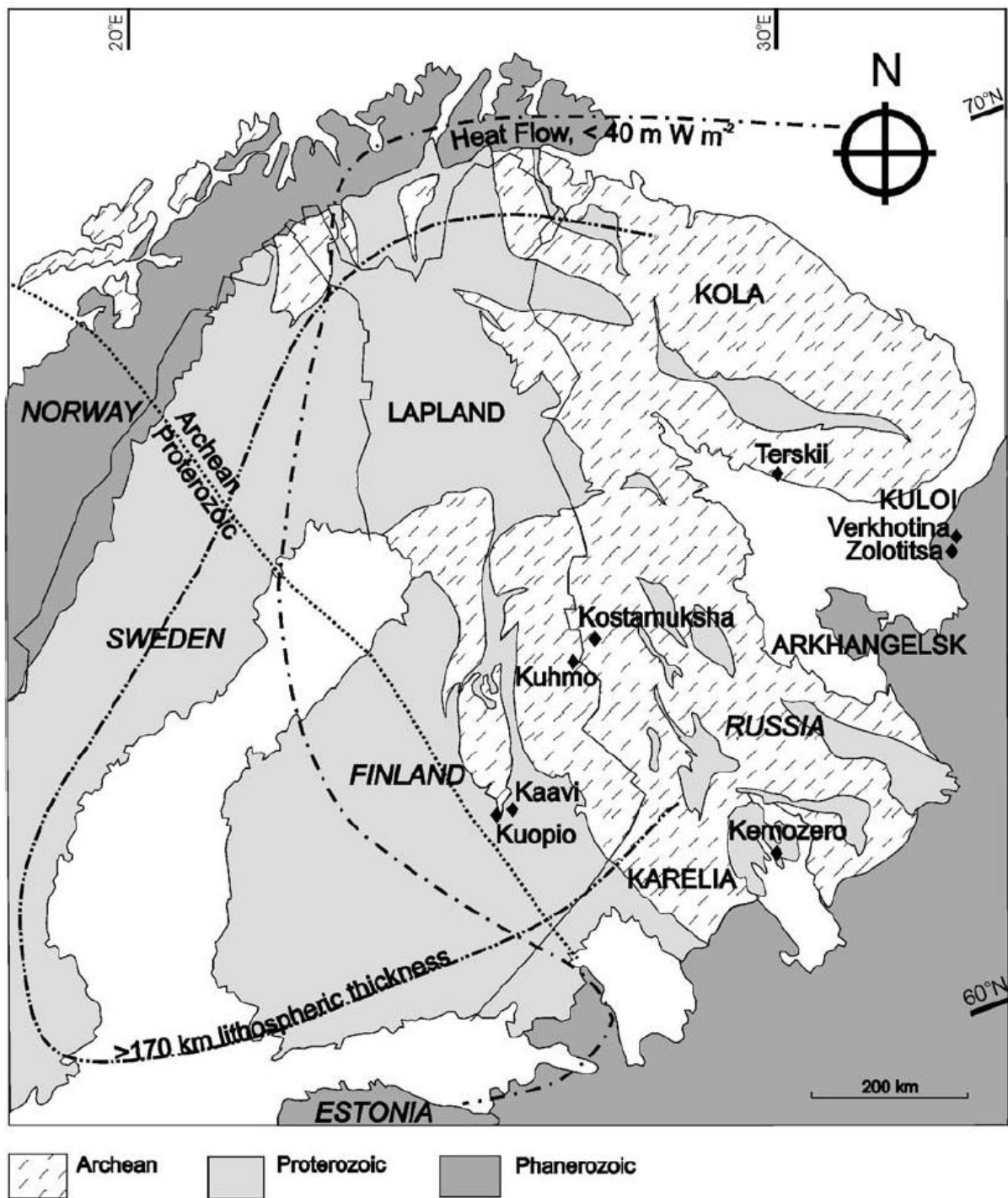
During our 2014 Finland excursion, we will pass by the two main diamond districts of Finland, namely the Kaavi-Kuopio and Lentiira area. The following few pages will give you a brief introduction about the anatomy of the Karelian Craton, diamond genesis and emplacement as well as exploration in glacial areas.

### Diamond Genesis and Surface Emplacement

Diamonds are far more abundant than commonly thought, being described from podiform chromitites in ophiolites (e.g. Yang et al., 2014), komatiites (e.g. Capdevila et al., 1999), ultrahigh pressure metamorphic rocks (e.g. Sobolev & Shatsky, 1990), impactites and meteorites (Koeberl et al., 1997; Daulton et al., 1996). However, diamond from these sources are commonly too small (micron-scaled) or too rare to be mined. Accordingly, the only known commercially valuable sources of gem quality and industrial diamonds are kimberlites, orangeites and lamproites.

The last two decades of diamond research revealed various, different processes of diamond formation within the mantle. And it is yet not fully understood when, how, where and at what timescales diamonds form in the mantle. The current state of science reveals that the Earth's mantle is comprized of different lithological domains, each with different carbon-oxygen-hydrogen- (COH-) fluids and specific oxidation state (oxygen fugacity.  $fO_2$ ). COH-fluid mixing or fluid-migration into domains of different oxidation state can precipitates diamonds, or can lea to its resorption (e.g. Rohrbach & Schmidt, 2011). The





**Fig. B-1.** Schematic overview on the Archean, Proterozoic and Phanerozoic buildup of northern Scandinavia and west Russia (Karelian Kraton). Area of high diamond-prospectivity are Archean parts with a low heat flow rate ( $< 40 \text{ m W m}^2$ ) and above a thick lithospheric crust, exceeding 170 km. Diamond-shaped spots and adjacent names highlight kimberlite (s.l.) provinces. Finland's Kuhmo corresponds to the Kuhmo-Lentiira area described in the text. From: Lehtonen et al. (2004).

crystallization of diamond requires at least 45 kbar (=150 km depth; Kennedy & Kennedy 1976) under Earth's conditions. Based on mineral inclusions and carbon isotope studies, it has been recognized that the majority of diamonds correspond to two types, a peridotitic and an eclogitic suite. The peridotitic diamonds are the far most abundant group with distinctive mineral inclusions

of olivine, pyrope and chromite are commonly  $\delta^{13}\text{C}$  values between -4‰ to -8‰ (with respect to VPDB). Eclogitic diamonds are characterized by commonly wider range of light  $\delta^{13}\text{C}$  values from +5‰ to -38.5‰ and kyanite, coesite, rutile, grossular or pyrope-almandine garnet as distinctive mineral inclusion suite (Cartigny, 2005; Tappert & Tappert 2010).

Internal zonation pattern, mineral inclusions and carbon isotopes indicate further complex and long-lasting processes of diamond growth and dissolution as well as diamond-migration due to mantle convection (Bulanova, 1995; Cartigny, 2005; Pearson et al. 2014).

Although strongly associated with kimberlite-type magmatism (*sensu lato*, including here orangeites and lamproites), diamonds usually do not form within these melts. In contrary, diamonds and kimberlite (s.l.) melts are commonly in disequilibrium resulting in the dissolution/destruction of diamond crystals within few days (Kozai & Arima 2000; Fedortchouk & Zhang, 2011). Indeed it seems that the oxidation potential of a carrier melt and the defragmentation-rate of xenoliths (or: the release of diamonds into the melt) are important factors, controlling the value of a kimberlite (s.l.). Accordingly, the more diamonds are released by fragmenting xenoliths into a very oxidizing environment, the less is the final amount of crystals sufficient in size and quality to make an economic deposit.

### **The Karelian Craton and their Kimberlites, Orangeites and Lamproites**

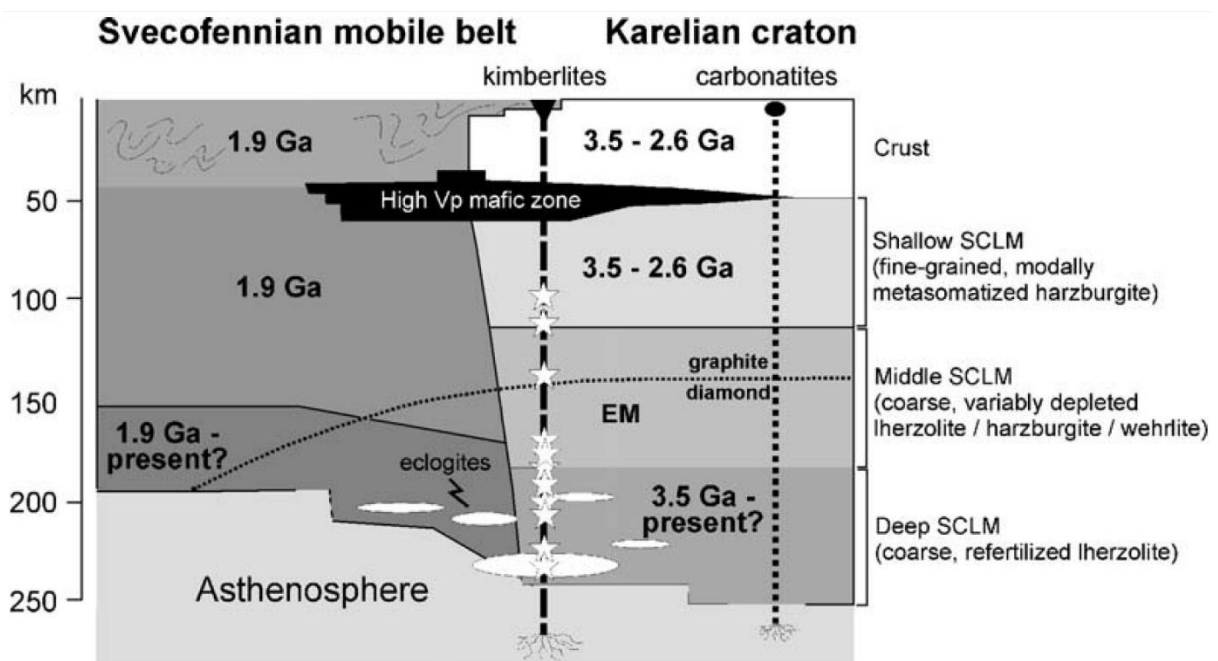
The strong association between diamond-bearing kimberlites and old, cold cratons was early recognized by Tom N. Clifford in 1966 and is until today, as we will see below, a valid and accepted theory in diamond-exploration (e.g. Janse 1994). As a result of Clifford's rule (economic) diamond-bearing volcanism is concentrated within cratonic areas with low heat-flow rates below 40 mW/m<sup>2</sup>. In comparison, the average heat flow rates for continental and oceanic crust are 65 mW/m<sup>2</sup> and 101 mW/m<sup>2</sup>, respectively (Pollack et al, 1993). Approximately ¼ of Finland lies on top of a low heat flow area that undershoots 40 mW/m<sup>2</sup> (Fig. B-1).

The buildup and the geotherm of a craton is investigated using geophysics as well as petrological and mineralogical studies on xenolith and xenocryst material recovered from ultrapotassic melts. Generally are cratonic roots geologically active places that can suffer various stages of melting and fluid alteration that can result in a profound change of chemistry, mineralogy and petrology (cf. O'Brien & Lehtonen, 2012). Based on the study of garnets and clinopyroxenes recovered from xenoliths, Lehtonen et al (2004) segmented the Kaavi-Kuopio craton into three parts (Fig. B-2):

- 1) 50 - 130 km deep, fine-grained and modally metasomatized harzburgite
- 2) 130 - 180 km deep, coarse and variably depleted assemblage of lherzolite, harzburgite and wehrlite and
- 3) 180 - >230 km deep refertilized lherzolite containing domains of highly diamondiferous mantle-eclogite (up to 90.000ct/ton, Peltonen et al., 2002)

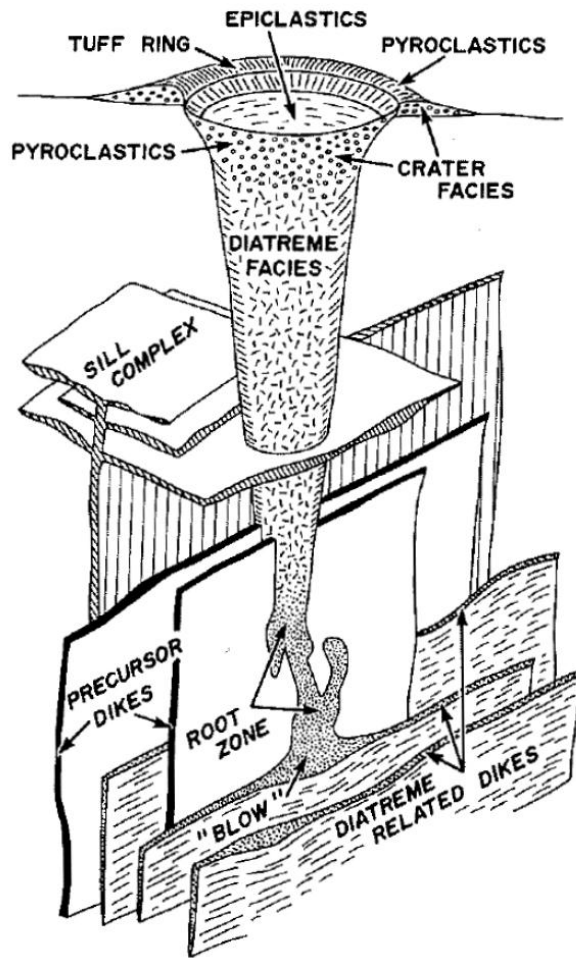
The emplacement of kimberlites (s.l.) within a craton is structurally controlled and happens within few hours to days. The presence of diamonds preserved in the oxidizing melts as well as the presence of up to ½ meter-sized mantle xenoliths (Stokes Law) are only two of a number of evidences for the fast travel of these mantle melts through the crust (e.g. Wilson & Head, 2007). Although not completely understood, the fast propagation of a melt through the cratonic lithosphere may be the result of depressurizing gas-exsolution (CO<sub>2</sub>, H<sub>2</sub>O; Champagne-effect of an

uncorked bottle), point-pressures and hydraulic fracking at the top of a propagating melt (Wilson & Head, 2007). Generally, high alkaline magmatism with high contents of mantle constituents is often associated to early rifting stages, as it can be found for example in the East African Rift or the Rhine valley. Especially in cratonic areas that experienced divergent stress can develop deep-going structural weaknesses, favoring the ascent of diamond-bearing melts. As result of the ascent along weakened lithosphere, kimberlites (s.l.) usually occur in local clusters as dikes, dikelets and diatremes (a.k.a. blows, pipes). The volcanic emplacement is usually short-lived but violent, creating Champaign-glass-shaped diatremes with different internal volcanic facies (cf. Smith et al., 2013; Fig. B-3). Besides the primary diamond content, the dilution by crustal xeno-material is an important factor on the diamond grade of a diatreme. Generally, the diamond-content within a diatremes can vary strongly but usually diamonds appear more concentrated in the lower parts of a diatreme where crustal contamination is at its lowest.



**Fig. B-2** Schematic cross section through the (...) edge of the Karelian craton showing the three distinct petrologic layers in the mantle inferred from pyrope and xenolith compositions. Figure and caption from Lehtonen et al (2004).

Two areas with diamond-bearing ultrapotassic volcanism have been discovered in Finland, namely the Kaavi-Kuopio (southwest-central Finland) and Lentiira Area (east-central Finland close to the Russian border). Each area represents a special, important type of diamond deposit: “True” kimberlites (after Mitchell, 1995; a.k.a. type I kimberlites) in Kaavi-Kuopio and orangeites (a.k.a. type II kimberlites) and lamproites in Lentiira. Both areas are described in more detail in locality-part of this guide.



**Fig. B-3** Scheme of a kimberlite (s.l.) complex after Mitchell (1986). Kimberlites (s.l.) can intrude in various ways, forming sill and dike structures. These intrusiva are commonly labeled as hypabyssal kimberlites. As volcanic facies can reach from almost hypabyssal types near the blow zone to highly fragmented, brecciated diatremes facies to lapilli-bearing pyroclastica of the crater facies.

### Diamond Exploration

As aforementioned, the Karelian Craton has potential to host economic diamond deposits (Fig. B-1). The finish diamond exploration history started after the accidental discovery of the Koskeniemi Pipe #1 in 1964 Kaavi-Kuopio area by the Finnish copper mining company Malmikaivos Oy. In collaboration-ship with the Australian company Ashton Mining Ltd. 24 kimberlites throughout whole Finland were discovered until the end of the last century; 16 of them diamond-bearing. However, regarding to the Finnish Geological Survey (GTK), the Karelian Craton remains strongly under-explored in terms of diamonds (O'Brien & Lehtonen, 2008).

The Karelian Craton is strongly affected by various glacial events and kimberlite and lamproite occurrences are nowadays buried under tens of meters glacial sand and till. For locating a diamond source, prospectors use a combination of geophysics and heavy mineral studies.

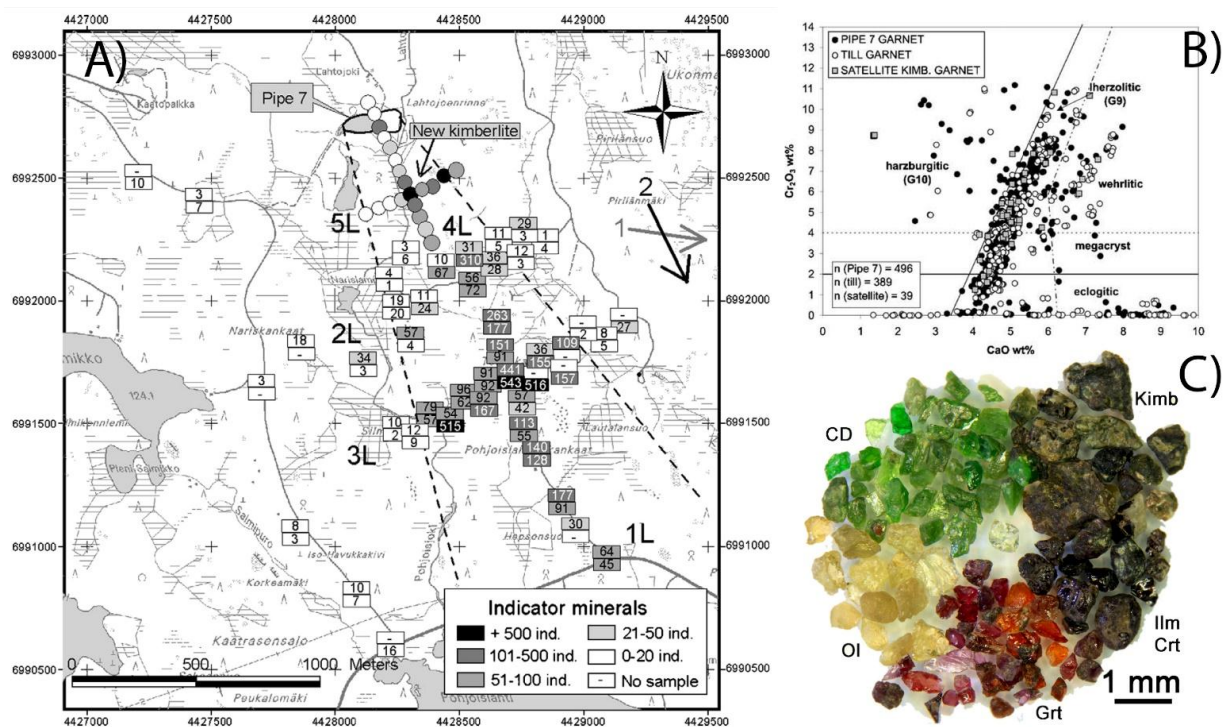
Airborne magnetic surveys highlight anomalies in the country rock that kimberlites (s.l.) commonly create after erupting and freezing of the magma. The magnetic orientation of the magma represents that of the Earth magnetic field at the time of eruption and hence fore it is usually distinct from the

orientation of the surrounding country rock. Such intrusions often appear as discrete anomalies in the magnetic maps (see geomagnetic map of Seitaperä in the Locality-section of this guide).

Complementary to a geophysical survey, large area till sampling focusses on the finding of mantle- and kimberlite-characteristic minerals, so called kimberlite indicator minerals (KIMs). This method follows the principle that KIMs have their highest concentration near their source and become dispersed with increasing distance. In combination with Quaternary geology, mapping of dispersion trails makes it possible to narrow a target area (Fig. B-4a). Further, this method allows tracing kimberlites that are hidden from aeromagnetic surveys by a thick glacial cover. Most commonly used KIMs are bright-greenish chrome diopside, orange grossular and purple pyrope, resorbed blackish chromites and pricroilminites (Fig. B-4c). They have the advantage to be magnitudes of order more abundant than the diamond itself. A prospect, as done for the Lentiira Area in Eastern Finland, requires a systematic sampling of 20 to 40 kg till samples at tens to hundreds different spots within a target area. The 0.25 – 2 mm size fraction of the samples are used for heavy mineral ( $d > 2.9 \text{ g/cm}^3$ ) separation. The heavy mineral concentrates are optically observed for KIMs. Separated grains are analyzed with EPMA or SEM for their chemistry, allowing a mineral-specific classification and a correlation to a potential diamond host.

Detailed analyses of certain minerals actually allow to pre-evaluate the diamond potential of a source. Especially garnet and chrome diopside are supportive minerals: Different empirically-based garnet classifications distinguishes between different lithological origins (e.g. Iherzolite-, eclogite- or kimberlite-hosted garnets), where some groups are highly favorable to be associated with diamonds (e.g. G9 and G10 garnets; cf. Schulze, 2003; Grütter et al., 2004; Fig. B-4b). Further, chrome diopsides allow the estimation of pressure and temperature at the time of crystallization, indicating whether the kimberlite/lamproite origins from the diamond-stability field below 150 km depth and whether they lie in the favorable low-heat-flow ( $< 40 \text{ mW/m}^2$ ) of a craton (Nimis & Taylor, 2000).

If the target, a pipe or a dike, has been localized, drilling and trench-excavating prospects are the next steps to map the size and outline of the intrusion and characterize its lithology. An important, final step is to evaluate the diamond load by bulk sampling of kimberlite (s.l.) soil and hard rock material. Bulk samples comprise of tens of tons of material that are processed in pilot plants. The evaluation of diamonds and estimation of the grade are the final critical factors before starting a mine.



**Fig. B-4** A) Kimberlite indicator mineral (KIM) distribution map from Lahtojoki Kimberlite Pipe #7. The amount of KIMs is increased along the SSE direction of glacier movement. KIMs-concentration beside the fan is almost negligible. B) Major element analyses on detrial garnets. The G-garnet classification (cf. Grütter et al., 2004) allows an allocation of the grains to a certain mantle lithology. Matches with the G9 and G10 garnet-fields are promising hints to a diamondiferous kimberlite source. C) Typical KIMs: CD = chrome diopsides, Ol = olivine, Grt = garnets (purple = pyropes, orange = grossulars), Ilm = ilmenites, Crt = chromites, Kimb = kimberlite fragments. The transparent crystal in the middle is a diamond. Fig 4 A & B from Lehtonen et al. (2005). Figure 4 C = Courtesy of the author.

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# Introduction to the Rapakivi granites and associated rocks of southeastern Finland

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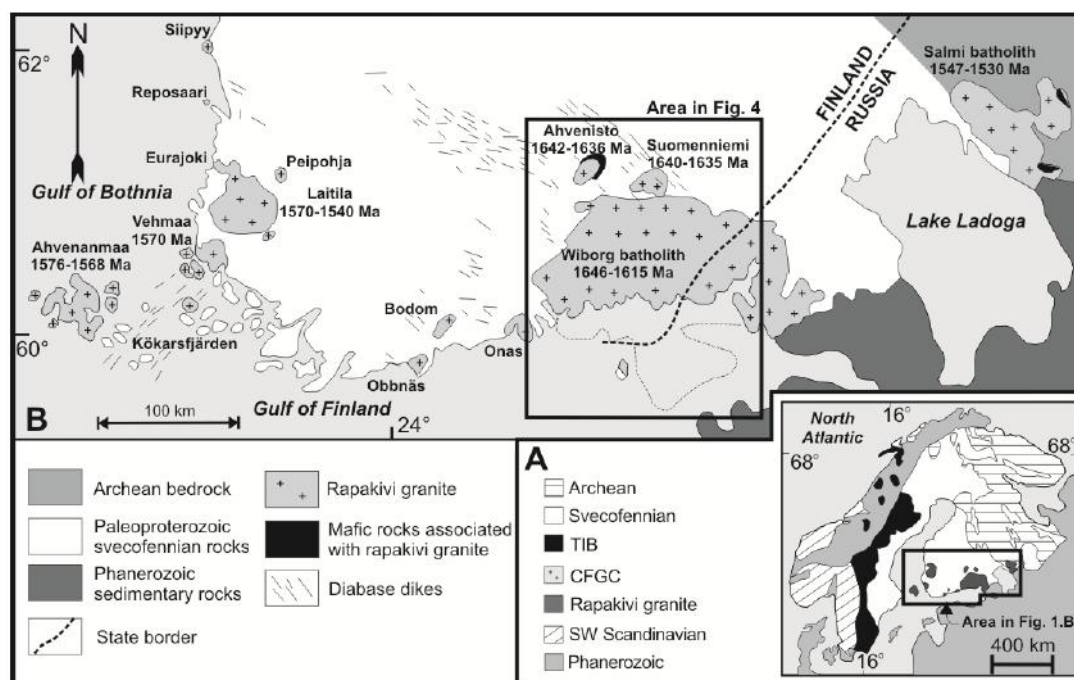
## Introduction

Southern Finland has been recognized as the type locality of rapakivi granites already in the late 19<sup>th</sup> century (Sederholm, 1891). Since then, research on rapakivi granites has constituted a considerable input to the field of granite research and particularly Finnish petrology. Regardless of the long-running research tradition, rapakivi petrogenesis still poses one of the key questions of granitology.

Finnish petrologic research can trace many of its advances especially to the southeastern parts of the country, where many of the actively studied rapakivi granite localities can be found. In addition to the granitic fundamentals, the area also hosts many peculiarities and petrologic specialities ranging from massif-type anorthosites and diverse hybrid rocks to the more evolved high-level hypabyssic rocks and rapakivi related volcanic rocks.

## Occurrence and age groups of the Finnish rapakivi suite

Proterozoic (1.67-1.54 Ga) rapakivi granites of southern Finland comprise four major batholiths (Wiborg, Ahvenanmaa, Laitila, and Vehmaa) and a group of smaller intrusions, which cross-cut sharply Paleoproterozoic (1.9- 1.8 Ga) Svecofennian country rocks (Fig. 1). The Finnish suite belongs to a vast magmatic province that spans from central Sweden (west) via Baltic countries and Poland (south) to Russia (east). The Finnish rapakivi granites have been emplaced in an extensional tectonic environment and they are regarded anorogenic (Rämö and Haapala, 2005) or distally orogenic (Åhäll et al. 2000) relative to contemporaneous orogenies. They can be divided into two age-groups, the older, 1.67-1.62 Ga, southeastern group and the younger, 1.59-1.54 Ga, southwestern group.



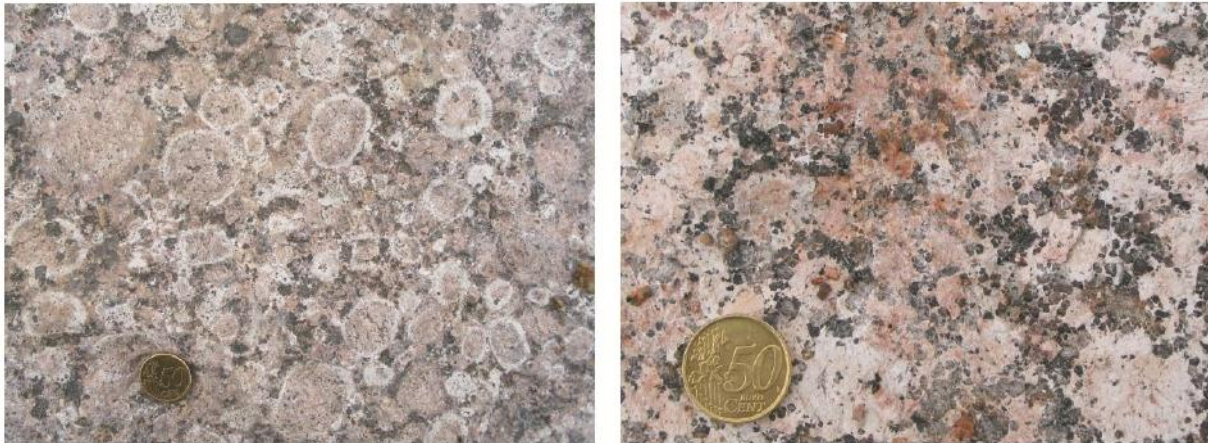
**Fig. C-1** A) The location of and B) generalized geologic map of the Finnish rapakivi province on the Fennoscandian shield. CFGC-Central Finland Granitoid Complex, TIB-Transscandinavian Igneous Belt (Map adapted from Heinonen et al., 2010a).



## Rock types, geochemistry and classification

Compositionally the Finnish rapakivi granites span from primitive fayalite-hornblende granite, through hornblende granite, biotite-hornblende granite, and biotite granite to evolved biotite granite and (locally topaz-bearing) alkali-feldspar granite. In field terms, rapakivi granites can traditionally be divided into two main categories according to the "maturity" of their rapakivi texture.

"Wiborgite", (Fig. 11-1-2) has a well-developed rapakivi texture with large (several cm in diameter) alkali-feldspar ovoids mantled with pronounced plagioclase rims. The majority of the Wiborg batholith consists of wiborgite and it is the type locality of this variety. "Pyterlite" (Fig. 11-1-2.) is a porphyritic rapakivi variety with less-pronounced plagioclase mantling of the alkali feldspar ovoids. The rims are not absent but sparse.



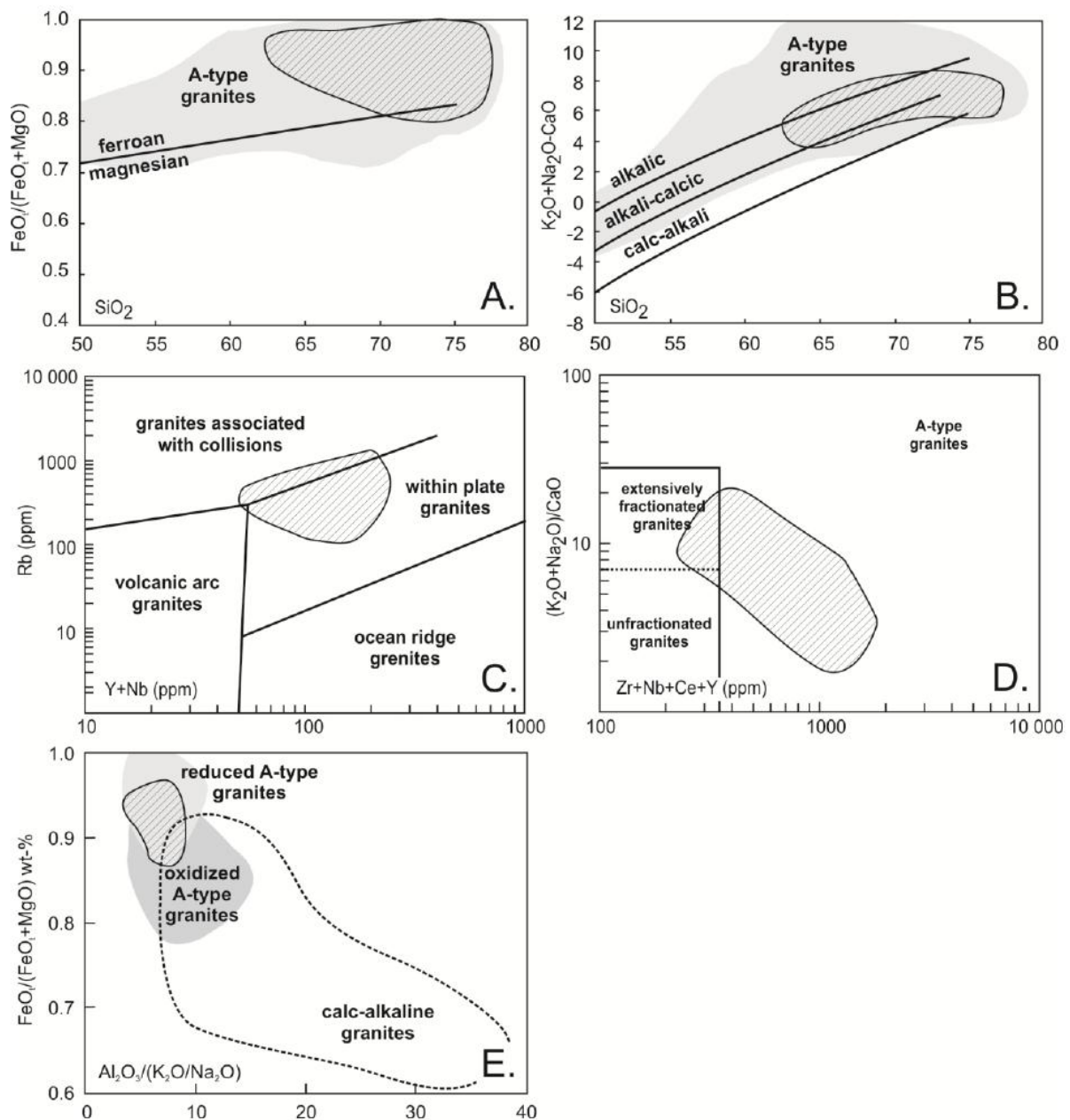
**Fig. C-2** Left: wiborgite (the rapakivi granite proper) with distinct plagioclase mantles surrounding ovoidal alkali feldspar from Summa. Right: pyterlitic rapakivi granite with drop-like quartz and ovoid alkali feldspar without plagioclase mantles from Virolahti. Photos: Tapani Rämö.

"Even-grained rapakivi granite" and "porphyritic rapakivi granite" are used to refer to rapakivi granites with normal igneous textures. In these varieties, alkali-feldspar ovoids are mostly absent or rare. "Rapakivi aplite" may be used for very fine-grained rapakivi varieties and "dark wiborgite" for wiborgite varieties including anorthite-rich plagioclase xenocrysts. The primitive, occasionally fayalite and hornblende bearing rapakivi granite varieties of southeastern Finland are called "tirilite". A common feature to all rapakivi varieties is the drop-like high-temperature quartz, which often serves as a diagnostic feature if the rapakivi texture cannot be detected.

The rapakivi granites are accompanied by anorthositic magmatism, which compared to similar localities for example in Labrador, eastern Canada (e.g., Emslie, 1978), is poorly exposed and mostly inferred from geophysical interpretations (Elo & Korja, 1993). The few outcropping localities in Ahvenisto (Alviola et al., 1999; Heinonen et al., 2010b), Kolinummi, and Ylämaa (Arponen et al., 2009) exhibit characteristics of the Proterozoic massif-type anorthosites (Ashwal, 1993), which makes the Fennoscandian rapakivi province a pronounced local occurrence of AMCG (anorthosite-mangerite-charnockite-granite) magmatism.

The Finnish rapakivi suite also features a host of associated hypabyssal rocks, diabase dike swarms (e.g., Lutinen et al., 2010) and quartz-feldspar porphyritic dikes (Rämö, 1991), as well as several localities of hybridized rocks (e.g., Rämö, 1991; Salonsaari, 1995; Alviola et al., 1999; Kosunen, 2004; Arponen et al., 2009;). Associated volcanic rocks are known but their occurrence is sparse and restricted to two localities, one of which is located in eastern Finland, and the other on the Russian island of Suursaari in the Gulf of Finland (Rämö et al., 2009).

Geochemically, the Finnish rapakivi granites are reduced (Dall'Agnol and de Oliveira, 2007), metaluminous (to marginally peraluminous) A-type (Whalen et al., 1987) within-plate (Pearce et al., 1984) granites with relatively high abundances of incompatible elements, high FeO/MgO and K<sub>2</sub>O/N<sub>2</sub>O ratios, and total alkalis (Rämö and Haapala, 2005). In the Frost et al. (2001) classification, the Finnish rapakivi granites are ferroan alkali-calcic granitoids (Fig. 11-1-3).



**Fig C-3** Finnish rapakivi granites (hatched fields) plotted on granite classification diagrams of A-B Frost et al. (2001), C Pearce et al. (1984), D Whalen et al. (1987), and E Dall'Agnol and de Oliveira (2007). Modified from Rämö and Haapala (2005) and Dall'Agnol and de Oliveira (2007).

### Southeastern Finnish rapakivi granites and associated rocks

The largest of the Finnish rapakivi intrusions is the Wiborg batholith (~18 000 km<sup>2</sup> at the current level of exposure) in southeastern Finland, and adjacent Russia, and also extending under the Gulf of Finland in the south (Fig. 11-1-4). The major rock type in the batholith is wiborgite, but it also hosts the pyterlitic and even-grained rapakivi varieties. The sole occurrence of rapakivi volcanics in Finland is located in the northeastern part of the Wiborg batholith in the Taalikkala region (Rämö et al. 2009). Associated gabbro-anorthositic rocks are inferred from seismic studies (Elo and Korja, 1993) to underlie the Wiborg batholith but they are exposed only as erratic xenoliths in the rapakivi granites of the Ylämaa region (Arponen et al., 2009) in the eastern part of the batholith (Fig. 11-1-4). In addition to the variety of anorthositic rocks (mainly leucogabbroanorthites and anorthosites hosting iridescent labradorite a.k.a. *spectrolite*) the xenoliths host a variety of hybrid rocks (Arponen et al., 2009). The most evolved phases within the batholith are the late stage topaz bearing granites in Kymi (Fig. 11-1-2), Artjärvi, and Säaskjärvi (Lukkari, 2007).



**Fig. C-4** Regional geology of the southeastern rapakivi province of Finland with localities mentioned in the text (Map adapted from Rämö and Haapala, 2005).

Two satellitic magmatic bodies - the Ahvenisto and Suomenniemi complexes - are located on the northwestern flank of the Wiborg batholith. The ~1640 Ma Ahvenisto complex is the prominent AMCG locality in the Fen- noscandian rapakivi suite (Alviola et al., 1999; Heinonen et al., 2010b). It comprises a concentric multiphase rapakivi granite batholith and a mafic arc complex with diverse anorthositic and monzodioritic rocks. The ~1640 Ma (Vaasjoki et al., 1991) Suomenniemi complex comprises a series of coarse- and even-grained rapakivi granites that grade from hornblende granites in the southeast to biotite granites in the northwest (Rämö, 1991).

Also a ~300 km swarm of diabase dikes spreads from the northern flank of the Wiborg batholith and its satellites to south central Finland (Fig. 11-1-1). These underformed, Subjotnian (~1.6 Ga) diabbases can roughly be divided into two geographic, compositionally overlapping groups, the western Häme swarm and the eastern Suomenniemi swarm. The diabbases are fairly evolved ( $\text{TiO}_2$  1.0-3.3 wt.%;  $\text{MgO}$  2.3-8.3 wt.%) continental tholeiites somewhat enriched in LREE and other highly incompatible elements with fractionated Nb/La ratios (0.3-0.6).

## Petrogenesis

Rapakivi granites are defined as A-type granites, characterized by the presence, at least in the larger batholiths, of granite varieties showing the rapakivi texture (Haapala and Rämö, 1992). So defined, and being an ubiquitous member of the granite clan all over the world, their genesis has also posed an integral dilemma in the quest for general A-type granite petrogenesis in general.

The Finnish rapakivi granites have traditionally been regarded as crustally derived (Rämö, 1991; Rämö and Haapala, 2005 and references therein; Haapala, 2010) as opposed to recent petrogenetic schemes devised for A-type granites, which emphasize the importance of a mantle component (e.g., Frost and Frost, 1997; Bonin, 2007) and consanguinity with the associated basic rocks (Frost and Frost, 2010).

The petrogenesis of the Finnish rapakivi granites was recently revisited by Heinonen et al. (2010a) who argued that despite presented rebuttals the two-source model is still the most favorable one for the Fennoscandian rapakivi suite. Based on Hf isotopic results, a model including a major crustal source component in the granites and a depleted MORB-source mantle as the source for the basic rocks was suggested.

## Economic significance

The economic significance of the rapakivi granites of southeastern Finland is not very high. Only local and low-grade polymetallic (Sn, W, Be, Zn, Cu, Pb) mineralizations associated with the late-stage granites are known (Haapala, 1995; Lukkari, 2007) and none of them are utilized commercially. In southeastern Finland these are restricted to the greisen-type mineralizations associated with the Kymi stock within the Wiborg batholith and the late-stage topaz-bearing granites of the Ahvenisto complex (Edén, 1991; Haapala, 1995). In Russian Karelia, skarn-type Sn-Be-Cu-Zn mineralizations associated with the (1.54 Ga) Salmi rapakivi batholith have been utilized commercially (Haapala, 1995). Recently Sundblad et al. (2010) have also reported some prominent indium occurrences related to the Pitkäranta skarn-deposits and some greisen localities in western Wiborg batholith.

Gem-quality beryl has been quarried from the Luumäki pegmatite in southeastern Wiborg batholith (Haapala, 1995; Rämö and Lahti, 2008) as well as topaz from the Kymi stock marginal pegmatite in the southern Wiborg batholith. The eastern Wiborg batholith *spectrolite* occurrences are also utilized as semiprecious stones even though their main use is as a prestigious dimension stone (Arponen et al., 2009). Several other Finnish rapakivi granite varieties and associated rock types are also utilized as dimension stone and shipped all over the world, which makes up to a significant local business in the region.

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## Field trip stops, Wiborg-Rapakivi area, 11.7.2014

**8:00-10:00/Drive: Helsinki (Kumpula)-Kymi (140 km, 1h 40 min)**

**10:00-11:30/STOP 1: Topaz quarries in the Kymi stock (6717 500, 3493 600)**

On the first stop of the day, we will examine the Kymi topaz granite stock. The stop is in the southwestern part of the Kymi stock ca. 10 km north of the town of Kotka, just east of Road 357. The stop consists of two quarries both in the topaz granites and the stockscheider pegmatite. The equigranular granite has been quarried for road materials and the pegmatite for gem-quality topaz.

In the first quarry we can see the two types of topaz granites of the stock as well as the contact between the granites. The contact is sinuous and fairly sharp, and some pegmatite-lined druses are found near the contact zone of these two granites. Inclusions of the porphyritic granite in the equigranular granite are visible on the northwestern wall of the granite quarry. The contacts of the enclaves are in places diffuse.

The stockscheider pegmatite, which rims the whole Kymi stock is visible on the second outcrop. The thickness of the stockscheider is normally 2 to 4 meters. The main minerals of the pegmatite are alkali feldspar, quartz, albite, biotite and topaz. More rare minerals include muscovite, fluorite, tourmaline, monazite, bastnaesite, arsenopyrite and molybdenite. Dendritic growth of biotite perpendicularly from the country rock contact to the interior of the stock is characteristic textural feature of the stockscheider.



**Fig. 11-1-1.** Kymi amazonite-pegmatite (photo A. Fiedrich).



**Fig. 11-1-2.** Miarolitic cavity near contact of the two granites (photo J. Sliwinski).

**11:30-11:45/Drive: Kymi-Summa (15 km, 15 min)**

**11:45-12:30/STOP 2: Summa wiborgite (6717 270, 3507 250)**

We will make a short stop to look at the main rock type of the batholith, wiborgite, at the Summa freeway ramp (circa 3 km west of downtown Hamina). The rock is loaded with ovoid alkali feldspar megacrysts, most of which are surrounded by sodic plagioclase mantles that have turned white because of post-glacial weathering. The diameter of the alkali feldspar ovoids is 1-10 cm, with the largest megacrysts being typically unmantled. Multiple rims are also present, as are mantled microgranite rock fragments. Quartz is present as euhedral high-quartz pseudomorphs (short prismatic crystals) and as anhedral interstitial grains. The main mafic silicate is Fe-enriched hornblende. Small pegmatitic pockets with alkali feldspar, quartz, biotite, fluorite, and apophyllite are also present in the wiborgite.

**12:30-13:30/Drive to the town of Hamina, Lunch break**

**13:30-14:15/Drive: Summa-Virolahti (40 km, 45 min)**

**14:15-15:15/Stop 3: Pyterlite at Virolahti**

On stop three we will examine an extensive pyterlite dimension stone quarry (Haikanvuori) by the bay of Virolahti ca. 5 km of the Russian border. This pyterlite is texturally similar to the wiborgite (Stop 2) with respect to the size and form of the alkali feldspar ovoids and the conspicuous drop quartz; only some of the alkali feldspar megacrysts are, however, mantled by oligoclase. The rock is also more silicic than the wiborgite of Stop 2 with biotite as the main mafic silicate. A characteristic feature of the Virolahti pyterlite are pegmatite bodies and miarolitic cavities (<1.5 m in diameter) that contain, besides alkali feldspar and quartz, biotite, fluorite, tourmaline, clevelandite, calcite, and some topaz and beryl, but no muscovite. Pyterlite at Virolahti has been quarried for dimension stone purposes since the 16<sup>th</sup> century; in the 19<sup>th</sup> century much of the rock was shipped to St. Petersburg. The current commercial name for the Virolahti pyterlite is Carmen Red.



**Fig. 11-3-1.** Virolahti outcrop, pyterlite type locality (photo: A. Fiedrich). **Fig. 11-3-2.** Ovoid in pyterlite (photo: A. Fiedrich).

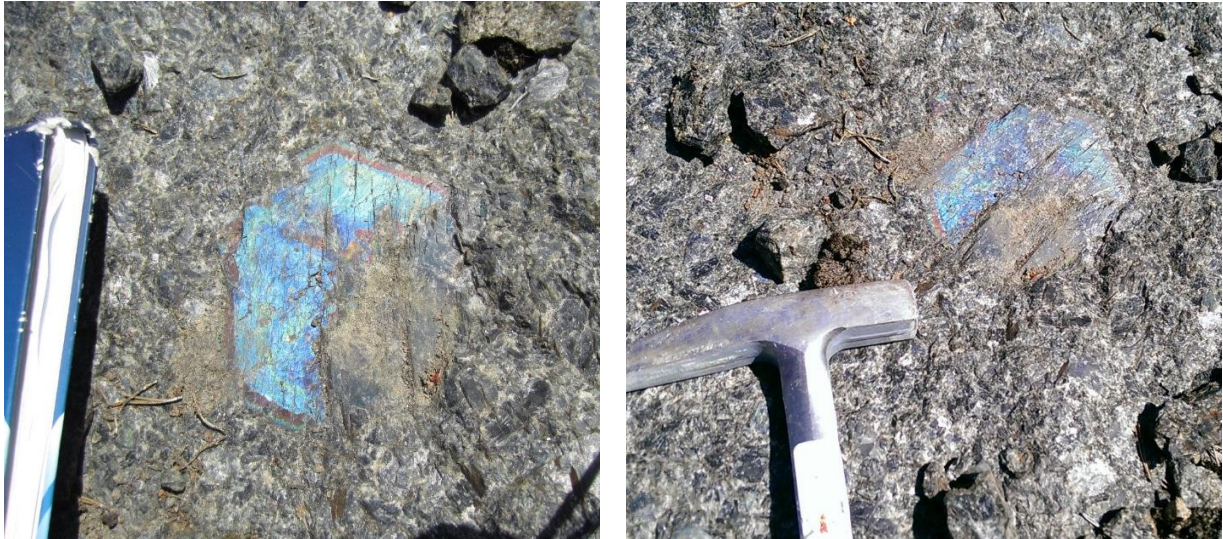
**15:15-16:15/Drive: Virolahti-Ylämaa (40 km, 45 min)**

**16:15-17:15/Stop 4: Ylijärvi spectrolite quarry**

The last stop of the day will be in the Ylämaa region in the south-central part of the Wiborg batholith where we will examine anorthositic rafts (xenoliths) found in wiborgite and in a greenish, fayalite-bearing equigranular rapakivi granite. Six anorthositic rafts (<2 km<sup>2</sup> in exposure) are known in Ylämaa. The plagioclase feldspar in them is profoundly iridescent ("spectrolite") and is utilized as precious and facing stone.

We will look at the anorthositic rocks in the Ylijärvi spectrolite quarry that is located on the western flank of the Ylijärvi anorthosite xenoliths that measures 1 km by 2 km at the current erosional level and is surrounded by wiborgite and relatively mafic green equigranular rapakivi granite. The quarry displays large lithologic variation with spectrolitic, plagioclase-megacrystic leucogabbro as the main rock type. This leucogabbro cuts (true) anorthosite, which is, overall, a rare rock type in the anorthositic rafts of the region. Further basic rock types include coarse leucogabbro and leucogabbro, both cut by the principal leucogabbro. No olivine-bearing gabbroic rocks are present in the Ylämaa region.





**Fig. 11-4-1.** Spectacular zoned spectrolite crystals. Photos: A. Fiedrich (left), D. Klimentyeva (right).

**17:15-17:30/Drive to the gem village (10 min)**

After visiting the quarry, we will stop at the Ylämaa gem village, where we can wrap the day up and take a look at some of the semi-precious stones produced from the local quarries.

**18:00/Departure to Lappeenranta/Helsinki**

<i>Date: July 12, 2014</i>	<i>STOP No.: 12-1</i>
<b>Locality name: Luumäki</b>	Kännätsalo
<i>Main commodity: gem beryl</i> <i>Geological setting or genetic model: pegmatitic dike</i> <i>Current development status: active mine</i>	
<b>WGS Latitude: 60.973209</b>	<b>WGS Longitude: 27.735833</b>
<i>Municipality: Luumäki</i>	
<i>Location &amp; access: 180 km northeast from Helsinki, less than 40 km from the Russian border. The quarry is situated along the road no. 6 at Luumäki which joins the village of Jurvala with the village of Tuukainen.</i>	
<i>Geological domain: Wiborg complex</i>	<i>Geological unit: rapakivi granites</i>
<i>Owner (2014): Karelia Beryl Oy, Mr. Timo Rönkä</i> <i>Address: Linnalantie 67, 54500 Taavetti</i>	

### Introduction

Karelia Beryl is a Nordic company quarrying various gemstones from Finland's ancient bedrock. Their main product is beryl in its many different forms: green beryl, golden beryl and aquamarine. The quarry, situated in Luumäki, South-Karelia, is the only one in Finland. [1]

The Kännätsalo beryl occurrence has been discovered next to a small road, when in 1982 a tiny topaz crystal was found during road construction work near Luumäki, Finland. Mineral enthusiast Kauko Sairanen identified the host of these crystals to be a pegmatitic dike, striking parallel to the road. Since this accidental discovery, the quarry was mined until 1995, when the sporadic delivery of gemstone quality beryl was no longer economic. In 2002 the claim owners of Karelia Beryl Mine have re-opened mining activity based on research work of Lahti and Kinnunen, 1993 [2].

### Geologic Situation

The quarry at Luumäki is situated in the core of a small pegmatitic dike, that has been formed due to an intrusion into the surrounding rock, a coarse-grained rapakivi granite of the northern part of the Viborg complex that covers an area of about 100 x 180 km from south-eastern Finland to nearby Karelia, Russia (Figs. 12-1-1 and 12-1-2) [2]. The different rapakivi granites in the region vary between 1.67 – 1.7 Ga [2], the gem pegmatites show radiometric ages from 2.5 to 1.65 Ga [7], of which only the latter is consistent with the field relations of the vuggy pegmatite intruding the Viborg Granite.

The pegmatite at Luumäki consists of a massive quartz core, about 10m wide, in the central part of the dike, which is surrounded by three feldspar-mica-quartz pegmatite zones, subdivided into intermediate, wall and border section (Fig. 12-1-4). From the fine-grained border zone nearest to the host granite the grain size of the pegmatitic material gradually increases towards the quartz core.

Common beryl occurs in the intermediate zone of the pegmatite, while gem beryl is found only in pockets, either associated with common beryl or embedded in the microcrystalline reddish quartz (jasper) that locally fills the pockets and fractures [2] near biotite-rich transition zone of the feldspar pegmatite to the quartz core, (Figs. 12-1-5 and 12-1-12). The largest and most attractive crystals found to date are shown in Figs. 12-1-7 and 12-1-8.

### Formation Process

Gem quality beryl crystals at Luumäki originate from miarolitic cavities near the center of granitic pegmatite bodies, at the biotite-rich transition to the quartz core. The crystals are formed in pockets as final products of the crystallization process of a parental granitic melt. At first feldspars and quartz are crystallized from a granitic melt. The residual melt is therefore enriched in elements excluded from these solidified phases. Volatile components are also increased in the granitic melt until the concentrations exceed solubility limits and an aqueous fluid gets exsolved from the melt. The principal formation

mechanism of miarolitic cavities in gemstone-bearing pegmatites is the decompression in an ascending volatile-rich magma. The decreasing pressure in the melt causes volatiles to exsolve. The resulting bubbles are trapped in the viscous, solidifying magma, forming miarolitic cavities, where nearly pure, gem-quality crystals are able to develop.

After Simmons et al. (2012), most beryl-topaz type pegmatites belong to the NYF-type pegmatite family (niobium-yttrium-fluorine-enriched, as opposed to the Li-Cs-Ta type pegmatites visited later on this excursion: Länttä). One gemological variety is represented by Heliodor beryl from Ukraine, which was found to be very similar to the Luumäki beryl by Lahti & Kinnunen (1993) [2].

### **Physical Appearance and Gemmological Properties**

The color of gem beryl ( $\text{Be}_3\text{Al}_2(\text{Si}_2\text{O}_3)_6$ ) varies from pale green to pale yellow-green, pale yellow to golden yellow, and pale blue (aquamarine). This variation is probably caused by ferric iron ( $\text{Fe}^{3+}$ ) that substitutes for aluminium in the structure of the mineral [2]. Gemmological properties of Luumäki beryl crystals were compared to gem beryls from other localities by Lahti & Kinnunen (1993). The specific gravity is slightly higher (2.685-2.688) than that given for pure  $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$  (2.62-2.66), but corresponds well to the values given for aquamarine and other pale beryls (2.628-2.730) with low alkali contents [2].

Parallel to the c-axis of the crystals examined by Lahti & Kinnunen (1993) internal tubular growth structures and corrosion tubes were found to be characteristic for Luumäki beryl crystals. Those tubes are also described as "trumpet-like" inclusions, as their diameter widens towards the surface of the crystal (Fig. 12-1-9). These structures were also found in pegmatitic beryls from the Ukraine and are thought to be secondary dissolution features.

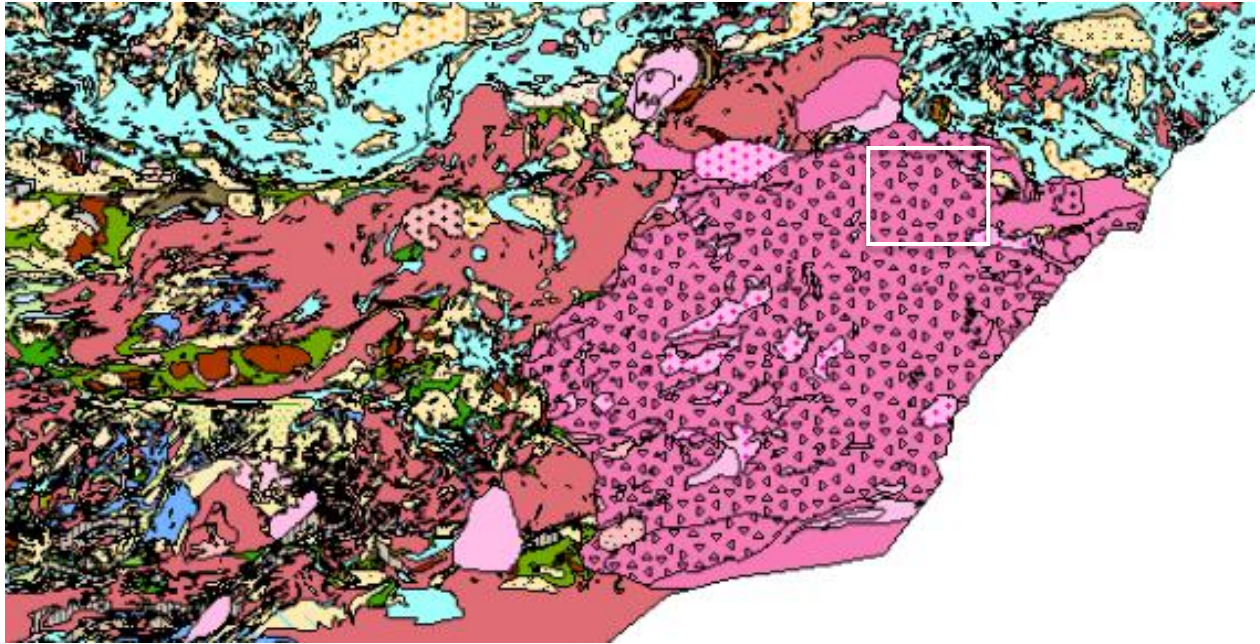
As second internal structures described by Lahti and Kinnunen also primary inclusions were examined. These are situated along former growth zones, in irregular cavities and in tube-like channels along the c-axis of the crystal. The primary fluid inclusions are commonly surrounded by networks of secondary micro-fractures; small cracks that formed during natural decrepitation and subsequently healed by recrystallization, thereby trapping small secondary fluid inclusions (Fig. 12-1-10) [2].

### **Conclusions**

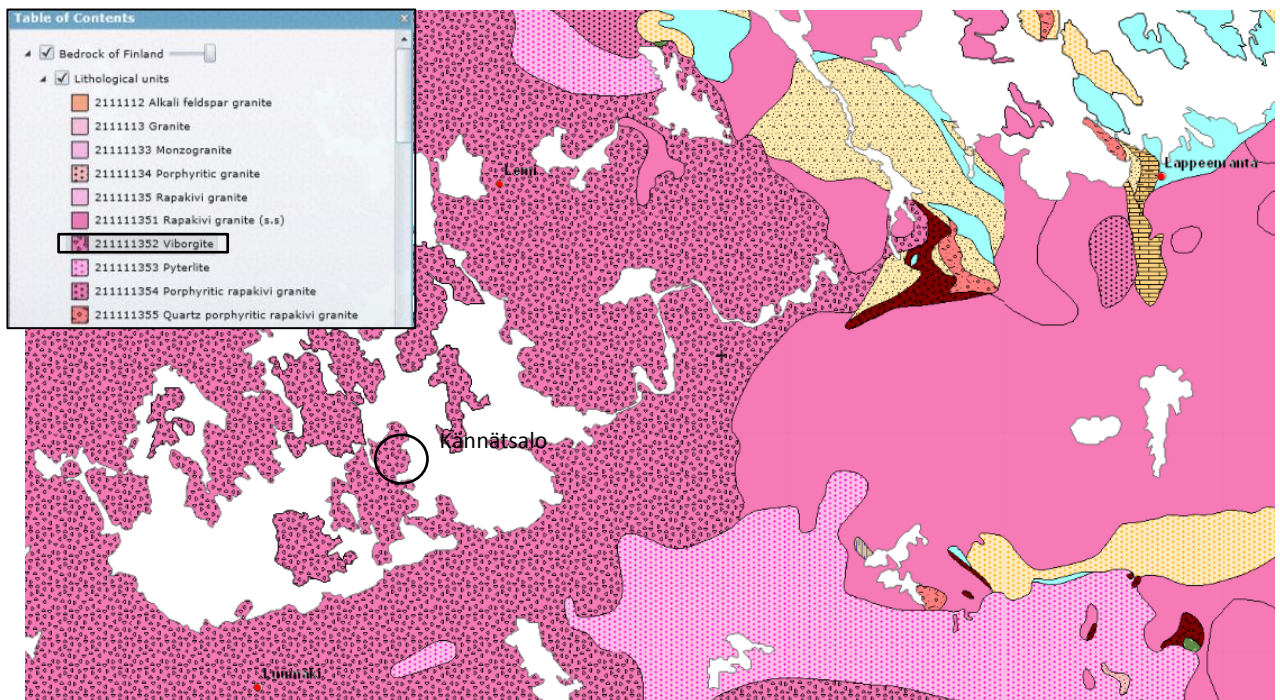
According to Lahti and Kinnunen (1993) the rapakivi intrusions have potential as a source of additional undiscovered gem minerals in Finland. The Luumäki pegmatite shows mineralogic and geologic similarities with the productive Ukrainian gem beryl and topaz pegmatites, which also occur in a rapakivi type granite of the same age. [2]

### **Field observation and interpretation**

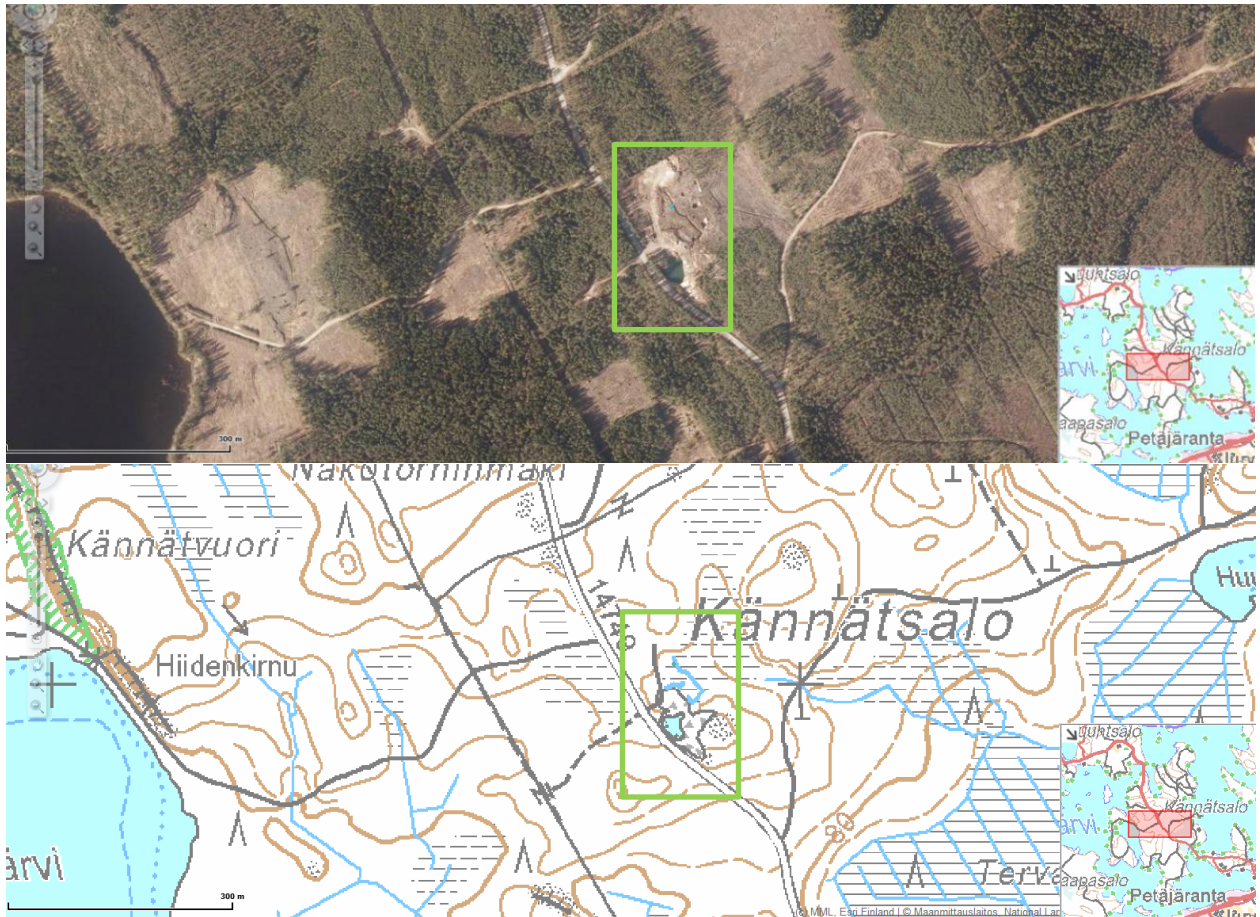
From an undercooled silicate melt common granite pegmatite including graphic quartz-feldspar intergrowths has been crystallized. Euhedral feldspars and biotites may mark the start of hydrous fluid saturation. Clevelandite (see Fig. 12-1-17), vug quartz including the quartz core of the pegmatite and the rare gem-quality beryls occurring in such vugs (not observed) all crystallized from aqueous fluid. The smoky color of the quartz near the contact was probably acquired during long-lasting U derived  $\alpha$ -radiation after pegmatite formation.



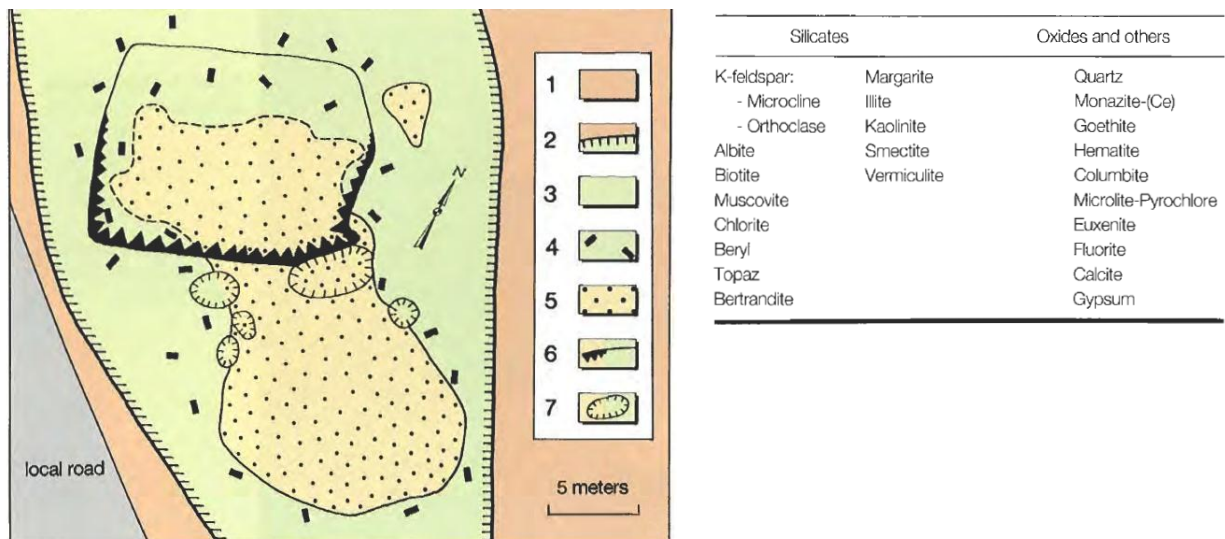
**Fig. 12-1-1.** Regional geological map of southern Finland showing in pink the Viborg batholith which intruded the surrounding Svecokarelian bedrock, 1.6 Ga ago. [6] Area shown in Fig. 2 indicated by rectangle.



**Fig. 12-1-2.** Smaller scaled geological map of the deposit area (Kännätsalo) and its surroundings, Luumäki to the south-west and Lappeenranta to the north-east. [6]



**Fig. 12-1-3.** Aerial photograph and base map showing the mining site Kännätsalo next to the road. [5]



**Fig. 12-1-4.** [2] Geologic map of the Luumäki gem beryl pegmatite. The colors represent: (1) rapakivi granite, country rock, (2) fine-grained border zone of the pegmatite dike, (3) wall zone of the pegmatite, (4) very coarse intermediate zone of the pegmatite, (5) quartz core, (6) gem beryl quarry, (7) larger cavities or crystal pockets observed on the surface. The road on the left joins village of Jurvala to the village of Tuukainen by the main road no. 6 at Luumäki, see also figure 3 above. The table on the left shows minerals identified in the intermediate zone of the Luumäki beryl pegmatite.



**Fig. 12-1-5.** The crystals are found in the massive reddish brown microcrystalline quartz (jasper). This yellowish green beryl crystal is of about 5cm length and shows a long cigar-shaped appearance. [2] Photo by Jari Väättäinen.



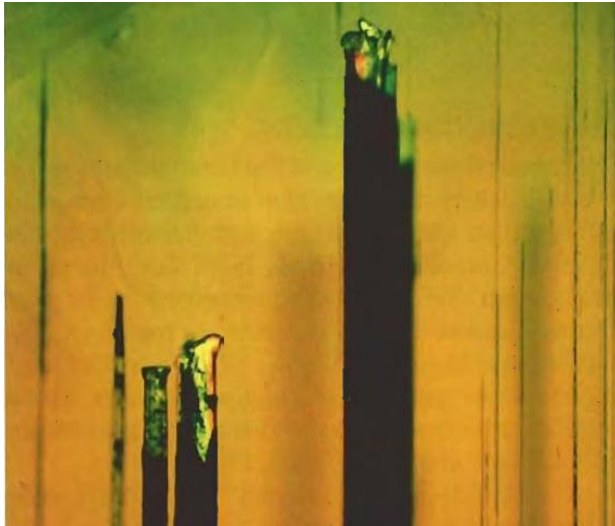
**Fig. 12-1-6.** Most of the Luumäki gem beryl from the May 2004 pocket consisted of relatively small fragments. The inset shows a green beryl weighing approximately 15 ct that was cut in Finland. [3] Photo by P. Lyckberg.



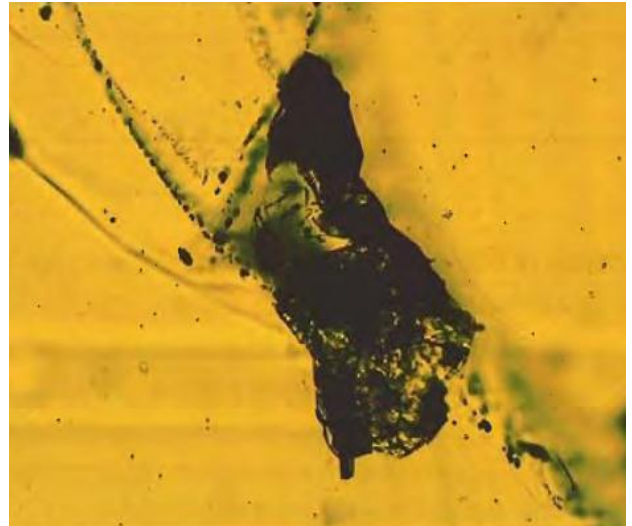
**Fig 12-1-7.** Green gem beryl crystals were found at the Luumäki pegmatite in May 2004. Some of the world-class crystals exceed 1kg. The crystal in this photograph is named 'Timo' by his finder, Timo Rönkä. [3] Photo by P. Lyckberg.



**Fig. 12-1-8.** This is Timo holding two of the biggest and most beautiful beryl crystals found in western Europe, both of around 15 cm length. The left one is called 'Jukkas beer bottle', the right one is called 'Erika', both of yellowish green color. [4]



**Fig. 12-1-9.** Those growing tubes are situated parallel to the *c*-axis of the crystal and are found to be characteristic of Luumäki beryl. Small syngenetic mineral inclusions (albite) can be seen here in the ends of the needles. Photomicrograph by Kari A. Kinnunen; transmitted crossed polarized light, magnified 20x. [2]



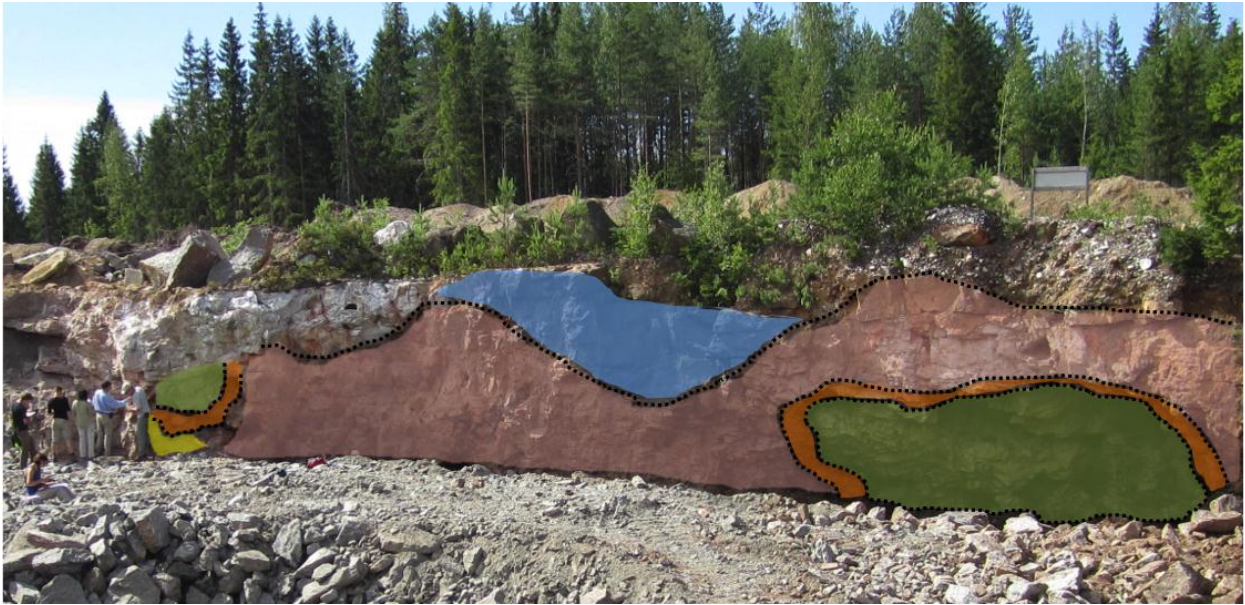
**Fig. 12-1-10.** Luumäki gem beryls show characteristic large, naturally decrepitated fluid inclusions, which originated from a healing process during recrystallization. Those small cracks are incorporated into the crystals and are of submicroscopic size. [2]



**Fig. 12-1-11.** The extraction of the beryl crystals has to be reduced to mining by hand to avoid any damage of the crystals. [3] Photo by P. Lyckberg.



**Fig. 12-1-12.** Open pit exposure of the Luumäki pegmatite showing feldspar-rich pegmatite (left and near water line), the biotite rich transition zone with small workings where beryl was presumably extracted (arrows), and the inner quartz core. Photo by T. Rönkä.



**Fig. 12-1-13.** Overview of zoned Luumäki pegmatite: red = granitic pegmatite, blue = wiborgite type rapakivi granites (see Fig. 14), yellow = graphic textured granite (see Fig. 15), green = quartz cores with euhedral biotite crystals (see Fig. 12 and 16), orange = cleveandite bearing zone (see Fig. 17). Photo by Alina Fiedrich



**Fig. 12-1-14.** Wiborgite type rapakivi granite showing characteristic plagioclase rims around K-feldspar crystals (see inset). Photo by Pilar Lecumberri Sanchez



**Fig. 12-1-15.** Graphic intergrowth of alkali feldspar and quartz ('Schriftgranit'), a characteristic texture indicating rapid crystallization from nucleus-poor granitic melt. Photo by Alina Fiedrich

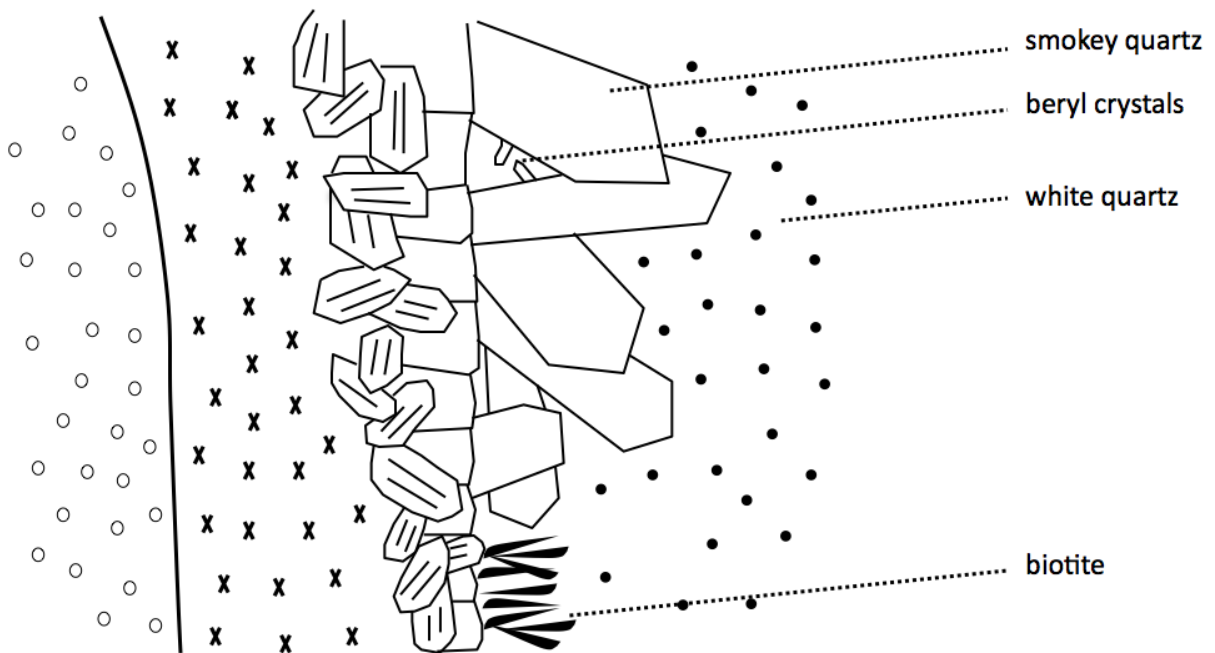




**Fig. 12-1-16.** Transition zone of large euhedral biotite and feldspar crystals, two stippled lines delineating the contact between the massive and partly graphic pegmatite (lower left) and the central quartz core of the pegmatite (top). Photo by Ch. Heinrich.



**Fig. 12-1-17.** At the contact between large euhedral feldspar (pink; lower left) and the quartz core a vug containing bladed albite ('clevelandite; arrow) and free-standing crystal surfaces has been observed. Photo by Ch. Heinrich



**Fig. 12-1-18.** Schematic illustration of the Viborg granite intruded by common feldspar pegmatite (black line) coarsening inward to large alkali feldspars with local graphic quartz intergrowth. The transition zone consists of inward-oriented bladed crystals of cleveandrite and euhedral plates of biotite, overgrown by euhedral smoky quartz grading inward to white massive quartz core. The occurrence of gem-quality beryl crystals in vugs is inferred, based on the location of diggings in this zone. Adapted from field sketch by Ch. Heinrich.

*References & online sources*

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**Compiled by: Seraina Holinger**

<i>Date: July 13, 2014</i>	<i>STOP No.: 13-1</i>
<b>Locality name: Nunnanlahti</b>	
<i>Main commodity: Soapstone</i>	
<i>Geological setting or genetic model: Ophiolite related</i>	
<i>Current development status: Active quarry</i>	
<b>WGS Latitude: 63.177313</b>	<b>WGS Longitude: 29.434378</b>
<i>Municipality: Juuka</i>	
<i>Location &amp; access: Located near the Nunnanlahti town</i>	
<i>Geological domain: Karelian domain</i>	<i>Geological unit: Nunnanlahti Green stone belt</i>
<i>Owner (2014): NunnaUuni Oy</i>	

### **Geology**

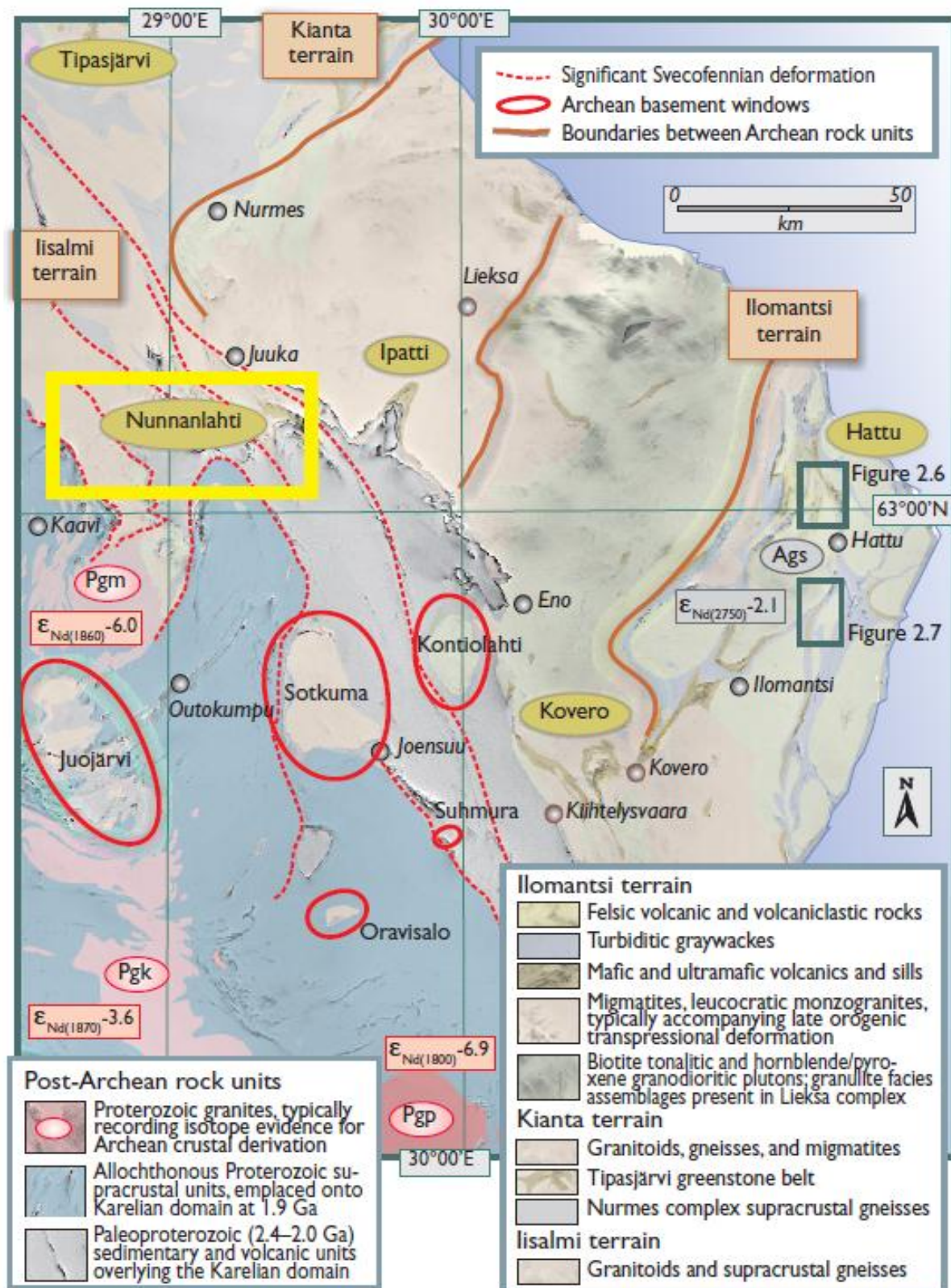
The Nunnanlathi Soapstone deposit is situated in the Nunnanlahti Green stone belt; this belt reaches a length of 15km and a width of maximal 3 km, and represents an allochthonous tectonic unit between Proterozoic and Archean rocks (Sorjonen-Ward, P., Rossi, T., 1997). The Nunnanlahti Green stone belt has a complex formation history, which is still not totally understood. The formation idea developed by Kohonen et al., (1991) is related to a thrust system which allowed the Nunnanlahti Green stone belt to be emplaced over proterozoic turbidites. In this region several lithologies are observable: ultramafic rocks, pillow basalt, felsic volcanic rocks, polytict schist and chert (Kohonen et al., 1989).

The formation age of the deposit is still unconstrained, due to the complex formation history and the strong straining that characterized the Nunnanlahti Green stone belt. In the Archean of Eastern Finland it is typical to find Paleoproterozoic dikes which crosscut archean sequences; regarding the Nunnanlahti belt, no dikes have been found crosscutting the soapstone, therefore it still remains unclear the period of alteration which led to the deposit formation (Sorjonen-Ward, P., Rossi, T., 1997).

The Soapstone deposit is related to ultramafic rocks alteration. Talc deposit generally forms by the addition of water (OH-) and silica to Mg-rich ultramafic rocks. Another frequent observable factor is the presence of shear zones (Pohl, 2011), in this case the Nunnanlathi shear zone. Metamorphic fluid in the Nunnanlathi region converted the Sveco-Karelian ophiolites into talc soapstone: serpentinites have been altered to talc-magnesite rocks.

The deposit is hosted by mafic rocks (mainly amphibolites). Between the soapstone and the surrounding amphibolites rocks there are several meters of a complex zone composed of mafic rocks, which contains some rich layers of actinolite and quartz  $\pm$  boudinaged veins. The lack of talc formation in this zone may be explained through a different composition of the mafic rocks, perhaps of basaltic composition. The mineralogy of the soapstone deposit consists mainly of Talc, Mg-carbonate, chlorite,  $\pm$ magnetite and amphiboles. The rocks show proterozoic foliation and probably have formed in amphibolites facies metamorphic conditions.

Soapstones are mainly used for cutting dimension stones, fireplaces and ovens. Thanks to the highly softness of the talc, the soapstone can be very easily extracted by sawing out cube of rock directly from the quarry ground. At present-day at the Nunnanlathi quarry, 70000 m<sup>3</sup> of soapstone are extracted per year. This leads to the production of 35000m<sup>3</sup> of waste rock, and the removal of 60000m<sup>3</sup> of overburden material (Sorjonen-Ward, P., Rossi, T., 1997).



**Fig. 13-1-1.** Map of the Nunnanlahti Green stone Belt (from *Precambrian geology of Finland: key to the evolution of the Fennoscandian shield*, 2006).



**Fig. 13-1-2.** Soapstone quarry and sawing machinery (www.flickr.com).



**Fig. 13-1-3.** Soapstone quarry (Photo: P. Lecumberri-Sanchez).



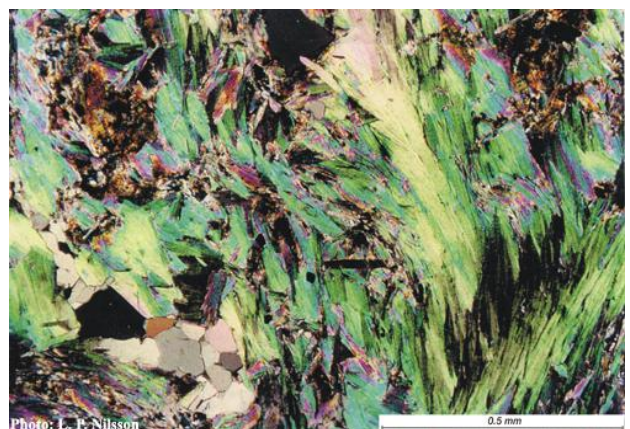
**Fig. 13-1-4.** Serpentine-rich magnetite-bearing lens within magnesite rich rock (Photo: P. Lecumberri Sanchez).



**Fig. 13-1-5.** Boudinaged vein with magnesite and magnetite (Photo: D. Klimentyeva).



**Fig. 13-1-6.** tourmaline vein in the soapstone (Photo: D. Klimentyeva).



**Fig. 13-1-7.** thin section showing talc in soapstone (Linnajavri area, <http://www.ngu.no>, Norwegian geological society).

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**Compiled by: Pietro Luraschi & Marco Verdon**

<i>Date: July 13, 2014</i>	<i>STOP No.: 13-2 (optional)</i>
<b>Locality name: Lahtojoki</b>	<b>Pipe #7</b>
<i>Main commodity: Diamonds</i> <i>Geological setting or genetic model: True Kimberlite (Type I)</i> <i>Current development status: test pit</i>	
<b>WGS Latitude: 63.028725</b>	<b>WGS Longitude: 28.574056</b>
<i>KKJ Northing: 6992911</i>	<i>KKJ Easting: 3580067</i>
<i>Municipality: Kaavi-Kuopio</i>	
<i>Location &amp; access: 8.8 km north of Kaavin Kunta, roas 5731 (Kortteisentie street), 1 km prior junction to Rasimäentie street) turn right into Nariskankaantie street and follow for 1 km.</i>	
<i>Geological domain: Outokumpu</i>	<i>Geological unit: Archean Karelian Craton</i>
<i>Owner (2014): unclear. JV of Mantle Diamonds Ltd (30%) &amp; Firestone Diamonds plc. (70%)</i>	

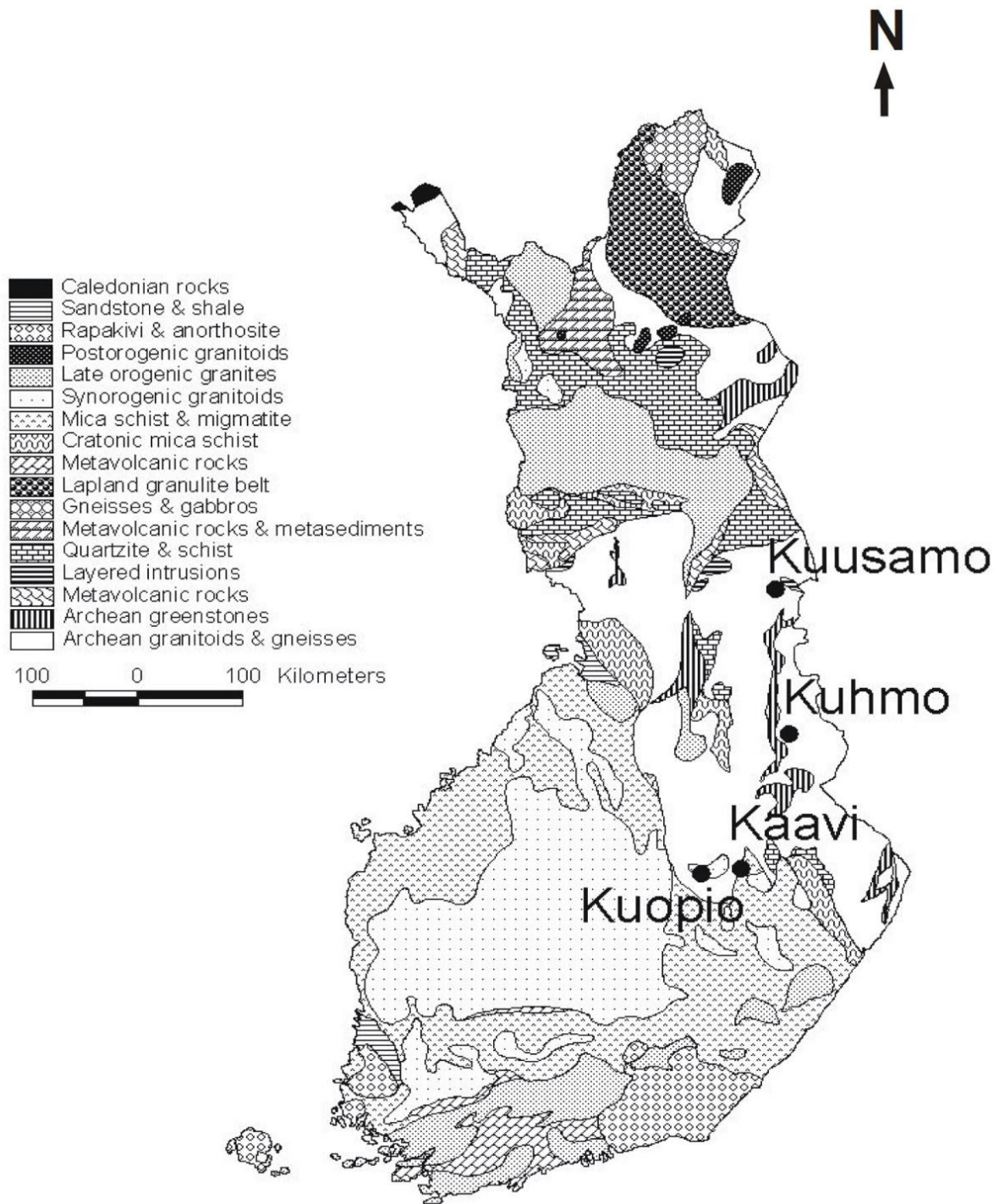
### **Geology**

The Kaavi-Kuopio kimberlites are represented by at least 20 kimberlites of 589 to 629 Ma emplacement age (U-Pb on perovskite, O'Brien et al. 2005). Trace element characteristics as well as petrographical and mineralogical appearance classify the occurrences as "true" Kimberlites (after Mitchell, 1995; a.k.a. Type I Kimberlites), similar to South African localities.

The kimberlites are present as up to 4 ha big diatremes, exposing different levels of their pipe (e.g. tuffistic upper parts, lower hypabyssal parts), and as dikes. However, erosion has removed the volcanoclastic crater-facies. Hypabyssal facies are described as dark-gray to blackish, dense porphyric (mainly Ol-macrocrysts) rock, which is rich in crustal and mantle xenoliths. Diatreme facies rocks appear more diverse and strongly weathered, yielding a wide spectrum of colors from gray to brown to dark red. Crystal and xenolithic content is usually covered a mixture of serpentine and carbonate shaping them to pelletoidal lapilli. Besides the calcite-serpentine matrix, the mineral content is typical for "true" kimberlites: The macrocrystic suite (0.5-10 mm) is made of forsterite, chromian diopside, pyrope garnet and picroilmenite. Kinoshitalite (Ba-Mica) is present in the matrix in all Kaavi-Kuopio kimberlites. Further mineral constituents are microphenocrystic (10-50  $\mu\text{m}$ ) monticellite (Ca-bearing Olivine  $\text{CaMgSiO}_4$ ), perovskite, and spinel.

During our field trip, we may have the chance to visit the Lahtojoki kimberlite pipe, which was the seventh pipe discovered in Finland. The pipe is 200 m (E-W) x 100 m (N-S) wide in cross section and dips 80° to the north. Drilling and test pitting revealed a tuffistic kimberlite breccia (upper diatremes facies) that is heavily diluted by crustal xenoliths.

Two test pittings in Lahtojoki revealed contradictory diamond grades of ~40 ct/100t (cpht) and only 5.7 cpht. Some eclogite xenoliths with extremely high diamond content were described by Peltonen et al. (2002), yielding grades up to 90.000 ct/t. However, the diamonds are mainly kimberlite hosted and therefore usually of resorbed appearance, the ratio of resorbed polyhedral to unresorbed octahedral stones is 9:1 (Kinnunen, 2001). The overall quality (color and clarity) appears to be good (O'Brien & Lehtonen, 2008). Lahtojoki Pipe #7 is the only Finish kimberlite locality that was close to mining.



**Fig 13-2-1.** Simplified geological map of Finland after Korsman et al. (1997), modified after Lehtonen (2005). Highlighted are the four kimberlite (s.l.) locations of Finland.





**Fig 13-2-2.** Google Earth™ image of Lathojoki test pitting. The actual pit is drown. Note the small size of the occurrence.



**Fig 13-2-4.** Lahtojoki pipe at time of exploitation. Image taken from [www.mantlediamonds.com](http://www.mantlediamonds.com).



**Fig 13-2-5.** Tuffistic kimberlite sample from Lahtojoki, rich in crustal xenoliths (e.g. red pebble at the bottom). Picture taken from O'Brien & Lehtonen (2008), no scale.



**Fig 13-2-6.** Lahtojoki diamonds (largest stone = 1ct). The diamonds appear clear but highly resorbed, sometimes with frosted surface (3<sup>rd</sup> diamond from the left). Exception is a little octahedron (yellow arrow) with no apparent resorption features. Picture from O'Brien & Lehtonen (2008).



**Fig. 13-2-7.** Heavy mineral sampling practical at Seitaperä. The search for Kimberlite Indicator Minerals (KIMs) is a commonly used tool in the exploration for diamonds. (photo D. Klimentyeva).

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Google Earth™

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*Previous field trip guides*

O'Brien & Lehtonen (2008) 9<sup>th</sup> IKC field trip guide.

*Comments: For general information on diamonds, the Karelian Craton and diamond exploration see previous introductory text.*

**Compiled by: Nico Küter**

<i>Date: July 14, 2014</i>	<i>STOP No.: 14-1 (museum)</i>
<b>Locality name: Outokumpu</b>	Keretti
<i>Main commodity: Cu (-Co-Zn)</i>	
<i>Geological setting or genetic model: ophiolite related</i>	
<i>Current development status: closed surface and underground mine</i>	
<b>WGS Latitude:</b> 62.730894	<b>WGS Longitude:</b> 29.005011
<i>KKJ Northing:</i> 6958200	<i>KKJ Easting:</i> 4448600
<i>Municipality: Outokumpu</i>	
<i>Location &amp; access: The deposit is located at the centre of the town Outokumpu</i>	
<i>Geological domain: Ophiolite tectonic complex, between the Archean basement (1.93 Ga) and the Svecofennian island arc domain schists (1.8 Ga)</i>	<i>Geological unit: Karelian Schist Belt</i>
<i>Owner (before closure): Outokumpu Oy</i>	

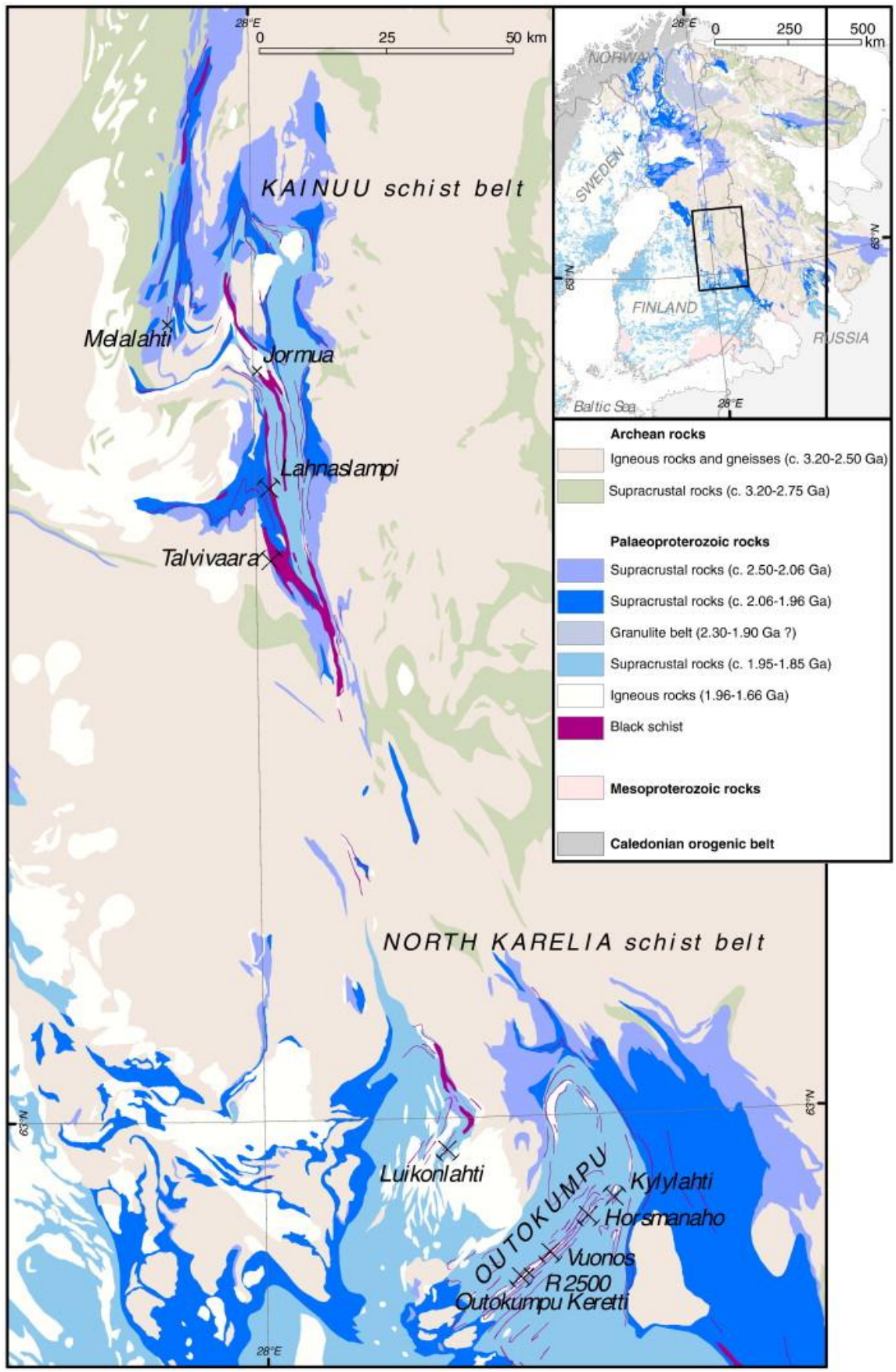
### **Geology**

The Outokumpu district belongs to the most important copper provinces of Finland. Economic grade ores include Cu, Zn, Co, Ni, Ag and Au. Finnish mining started in 1913 with the Keretti mine and was ongoing until a decrease in activity in the 1980s and 1990s. Outokumpu ore bodies are located at the boundary between Proterozoic and Archean rocks within the Karelian Schist Belt. The latter is situated between the Archean basement and the Svecofennian island arc domain schists, which are dated at 1.93 to 1.80 Ga [1]. The Outokumpu ore body is an assemblage of serpentinite and peridotite enveloped by Cr-bearing carbonate-quartz rocks which are fragments of a former ophiolitic ultra-mafic to mafic massif. They form a nappe of former ocean floor that was thrust onto the Karelian craton between 1.92 and 1.87 Ga. This led to intense multi-stage folding and amphibolite-facies metamorphism (peak temperature around 630°C) followed by faulting [5, 6].

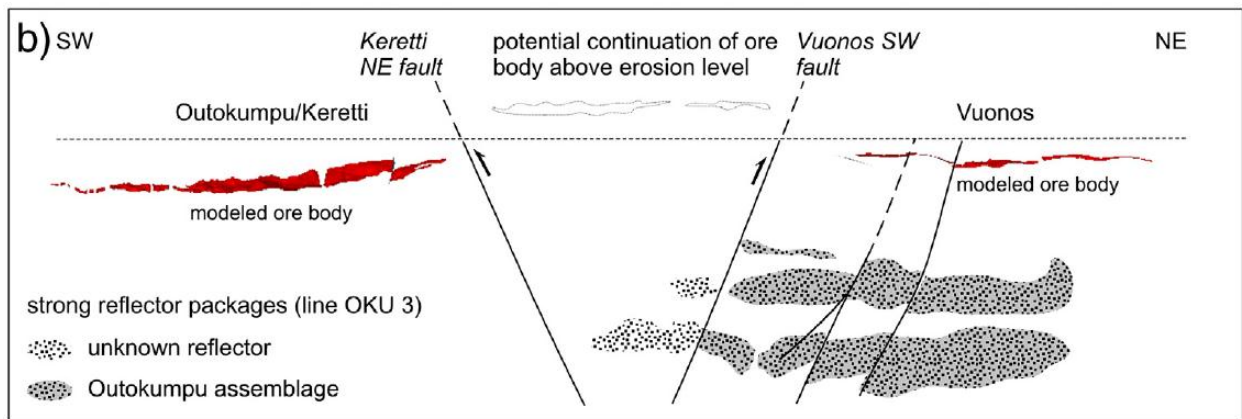
The ore body originally contained a single lens, which was then cut by faults into three bodies. These were produced by the mines of Keretti (the main Outokumpu ore body), Luikonlahti 27 km to the NW, as well as Vuonos 4 km to the NE. [1, 2]. The massive ores of Keretti and Vuonos occur in stockworks within the Outokumpu assemblage. They contain enrichments in Cu, Co, Zn and Ni and diagnostic minerals such as chalcopyrite, sphalerite, pyrrhotite and pentlandite [5]. Local alterations include quartz, diopside and tremolite. The Keretti deposit itself is located within a serpentinite assemblage >10 km in length and 1-1.5 km in width, enclosed in carbonate (skarn)-quartz rocks [2].

The genesis of the Cu-ore with primary mineralization during regional deformation and secondary remobilization and mineralization along the quartz rock-basalt schist boundary close to ultramafic bodies. A second remobilization by fluids led to a short transport through fault zones and emplacement close to the quartz units [2].

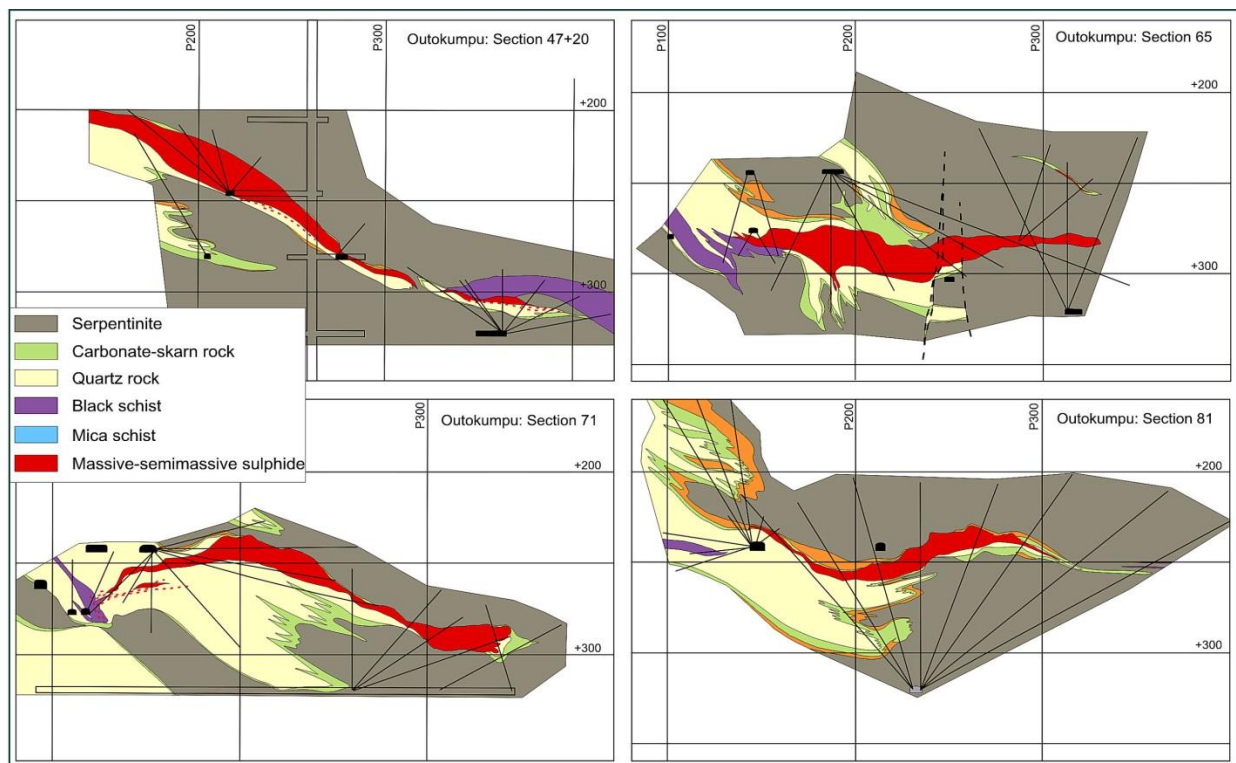
The Keretti mine was closed 1989 after 79 years of mining. It had a production of: 28.5 Mt with 3.8% Cu, 0.24% Co, 1.07% Zn, 0.8 g/t Au, 8.9 g/t Ag, 0.12% Ni, 25.3% S, 28.11% Fe [1]. The deposit was discovered through a glacial boulder of Cu-mineralization whose provenance was traced back to the oxidized outcrop which now sits in the centre of the town Outokumpu. Today the former mine is used as art gallery, restaurant and museum.



**Fig 14-1-1.** Regional map of the Outokumpu ore bodies, note the Keretti mine in the south of the Outokumpu region. [4]



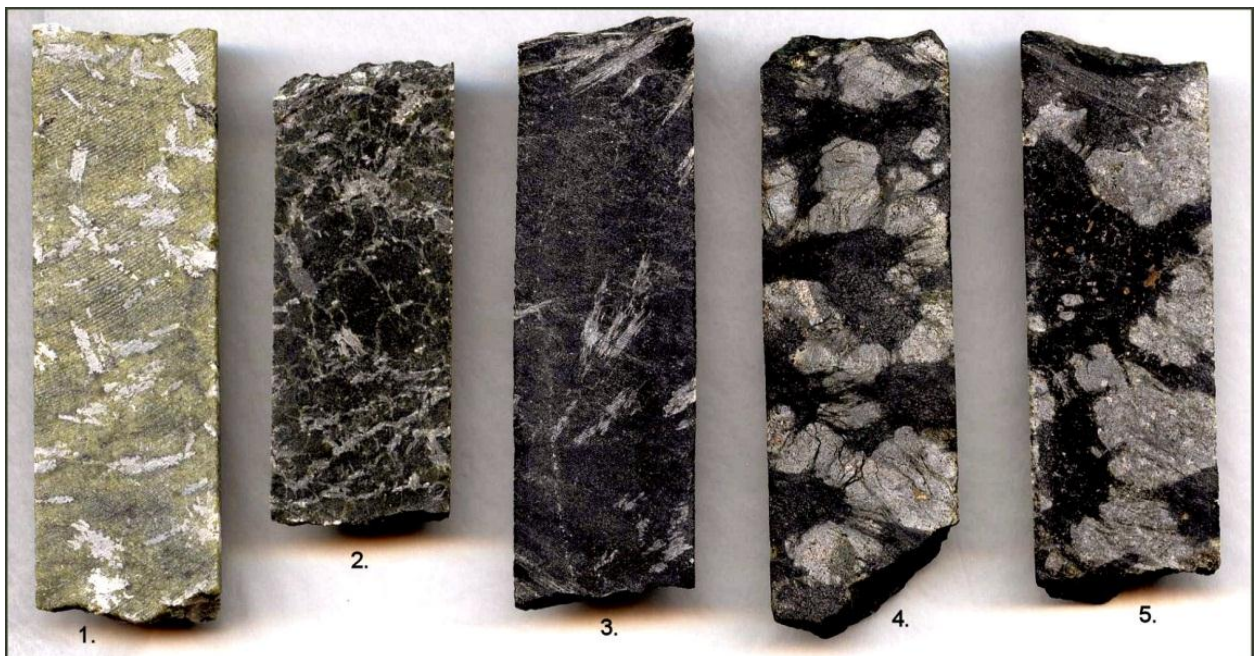
**Fig 14-1-2.** Along-strike cross-section of the Keretti and Vuonos ore body. The area between the NE-striking Keretti-fault and SW-striking Vuonos-fault has been interpreted as pop-up-structure that explains the absence of any ore body between the two. The grey lenses at depth are based on latest geophysical research that indicates further ore bodies which have not been drilled yet. [6]



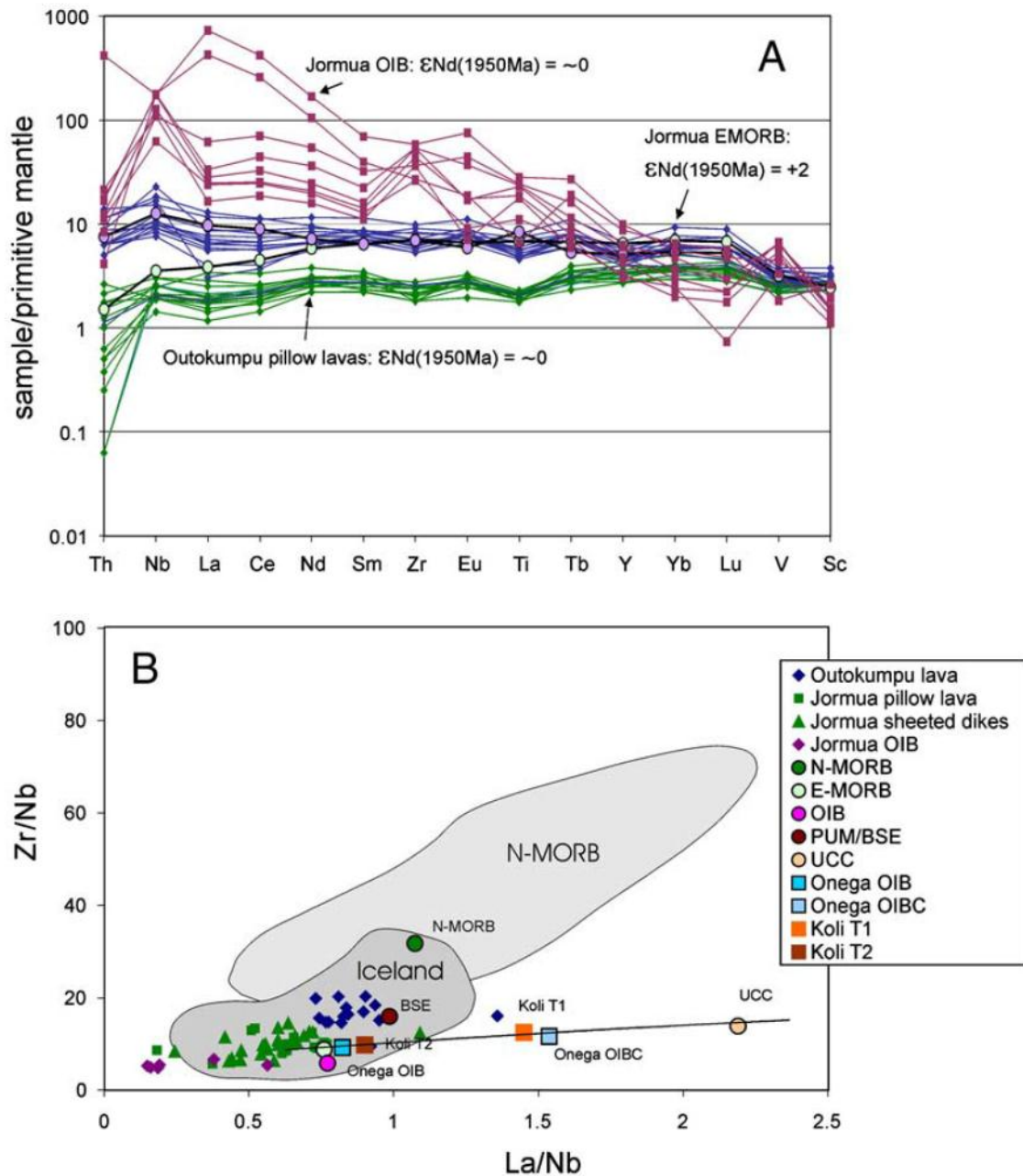
**Fig 14-1-3.** Vertical cross-sections across the Outokumpu ore body, profiles 47+20, 53, 65, 68+20, 71, 81, 83. Kontinen et al., 2006 [2].



**Fig 14-1-4.** Keretti copper mine shaft (built 1954, closed 1989, now a protected structure). Photo: NBA. ([http://msi.lms.lt/ihp/gateway/fi/pict\\_big/det4\\_1.html](http://msi.lms.lt/ihp/gateway/fi/pict_big/det4_1.html))



**Fig 14-1-5.** Main types of serpentized metaperidotite in the Outukumpu peridotite massif: 1. talc-olivine; 2. antophyllite-talc-olivine; 3. antophyllite-olivine; 4. antophyllite-enstatite-olivine and 5. antophyllite-tremolite-enstatite-olivine metaperidotite. Olivine is serpentized extensively to chrysotile-lizardite in all samples. Kontinen et al., 2006 [2].



**Fig 14-1-6.** Isotope signatures as indicators of origin for ultramafic material, e.g. basaltic rocks within serpentinite massifs. The authors interpreted these data as evidence for plume origin with a component of recycled oceanic crust. Crustal or lithospheric mantle contamination can be excluded.

A) Mantle-normalized extended REE plot for Outokumpu (Losomäki) and Jormua Ophiolite metabasalts with additional data for Jormua OIB, average N-type MORB (black line with light green dots) and E-MORB (black line with lavender dots). The Outokumpu basalts have significantly lower REE, suggesting similar source but higher degree melting for Outokumpu basalts.

B)  $Zr/Nb$ – $La/Nb$  diagram showing the fields of Icelandic plume related basalts and N-MORB. Outokumpu and Jormua Ophiolite metabasalts plot in the field of the Icelandic basalts that are thought to be plume related. For comparison averages of the 2.1 Ga Koli T1 and 1.96 Ga T2 tholeiite dikes, 2.0 Ga OIB-type Onega plateau basalts (OIB=non-contaminated, OIBC=contaminated), N-MORB, E-MORB, OIB, primary mantle (BSE), and upper continental crust (UCC) are shown. Note that crustal contamination that is apparent for the Koli T1 and Onega (OIBC), is not indicated for Outokumpu and Jormua basalts.” [7]



**Fig. 14-1-7.** *Cr-diopside in serpentinite-metaperidotite (photo: L. Gilsbach).*

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**Compiled by: Julia Krawielicki**



<i>Date: July 14, 2014</i>	<i>STOP No.: 14-2</i>
<b>Locality name: Kylylathi</b>	
<i>Main commodity: Cu (-Co)</i>	
<i>Geological setting or genetic model: ophiolite related</i>	
<i>Current development status: underground mine under construction</i>	
<b>WGS Latitude: 62.855752</b>	<b>WGS Longitude: 29.345232</b>
<i>KKJ Northing: 6972600</i>	<i>KKJ Easting: 4466820</i>
<i>Municipality: Polvijärvi</i>	
<i>Location &amp; access: 400 km NE of Helsinki (Northern Karelia) and Outokumpu ca. 25 km to the southwest; Access to the area via west of the centre of Polvijärvi on the highway 502. Open access to a car park and then through a security gate to the mine (underground via a decline tunnel named the Vesanto Decline).</i>	
<i>Geological domain: Karelian</i>	<i>Geological unit: Archean Ophiolite complex</i>
<i>Owner (2014): Altona Mining Limited / Kylylahti Copper Oy.</i>	

### **Geology**

The Outokumpu deposits in eastern Finland are situated within the North Karelia Schist Belt (NKS) which is located between the Karelian Craton in the southwest and Paleoproterozoic Svecofennian domain in the northeast. The latter consists of 1.93-1.88 Ga old island-arcs while the Cratonic domain mostly contains Archean gneisses. The NKS rocks are 2.5-1.9 Ga old and dominated by amphibolites grade metasedimentary rocks which underwent multiple folding. The older quartz-sandstone unit (2.5-2.0 Ga) has been interpreted as autochthonous shallow-water cratonic to epicratonic sediment while the younger unit (2.0-1.9 Ga) contains allochthonous deep-water turbidite sequences [5].

The Kylylathi deposit is located at a zone of black schists and serpentinite lenses, which host the Cu-Co-Zn sulphides. The region was shaped by intense tectonic activity. Kylylahti is located at a SW-NE trending, SW-plunging synformal structure (Viinijärvi synform) and several SW-NE to SSW-NNE and NW-SE-trending faults separate and displace the fold-attached deposits of the Outokumpu area [2, 6].

Outokumpu deposits are attached to three geological units ("Outokumpu Association"):

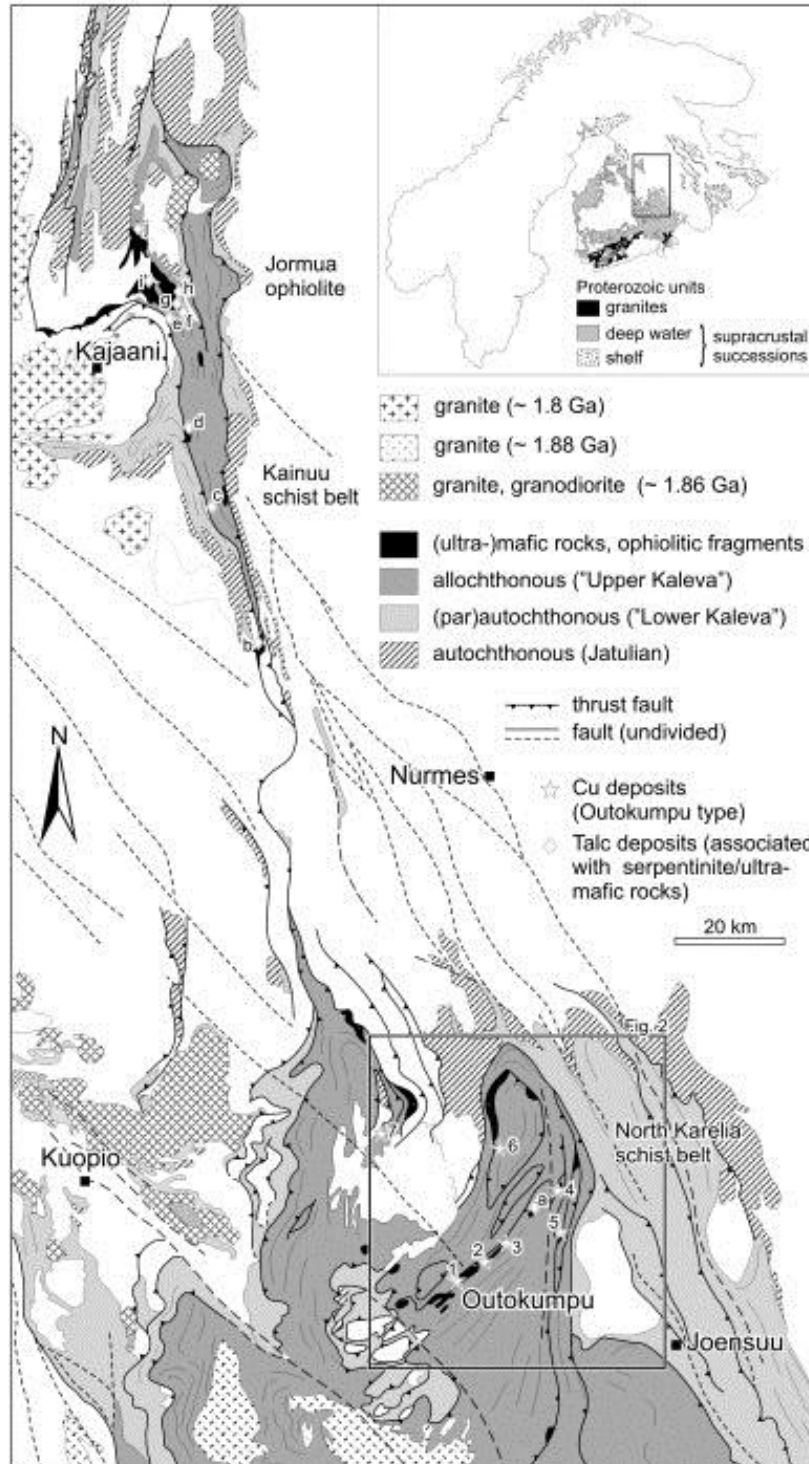
- a) Serpentinite lenses originating from peridotite including talc schist and soapstone
- b) Carbonate-skarn-quartz rocks with minor black schist ("transition zone") which are relicts of the strongly altered margin to the serpentinite [6]
- c) Ore body (Cu sulfide zone) between serpentinite and transition zone adjacent to shear zones.

The length of the Kylylahti ore bodies varies between 1.5 and 4 km [2, 6].

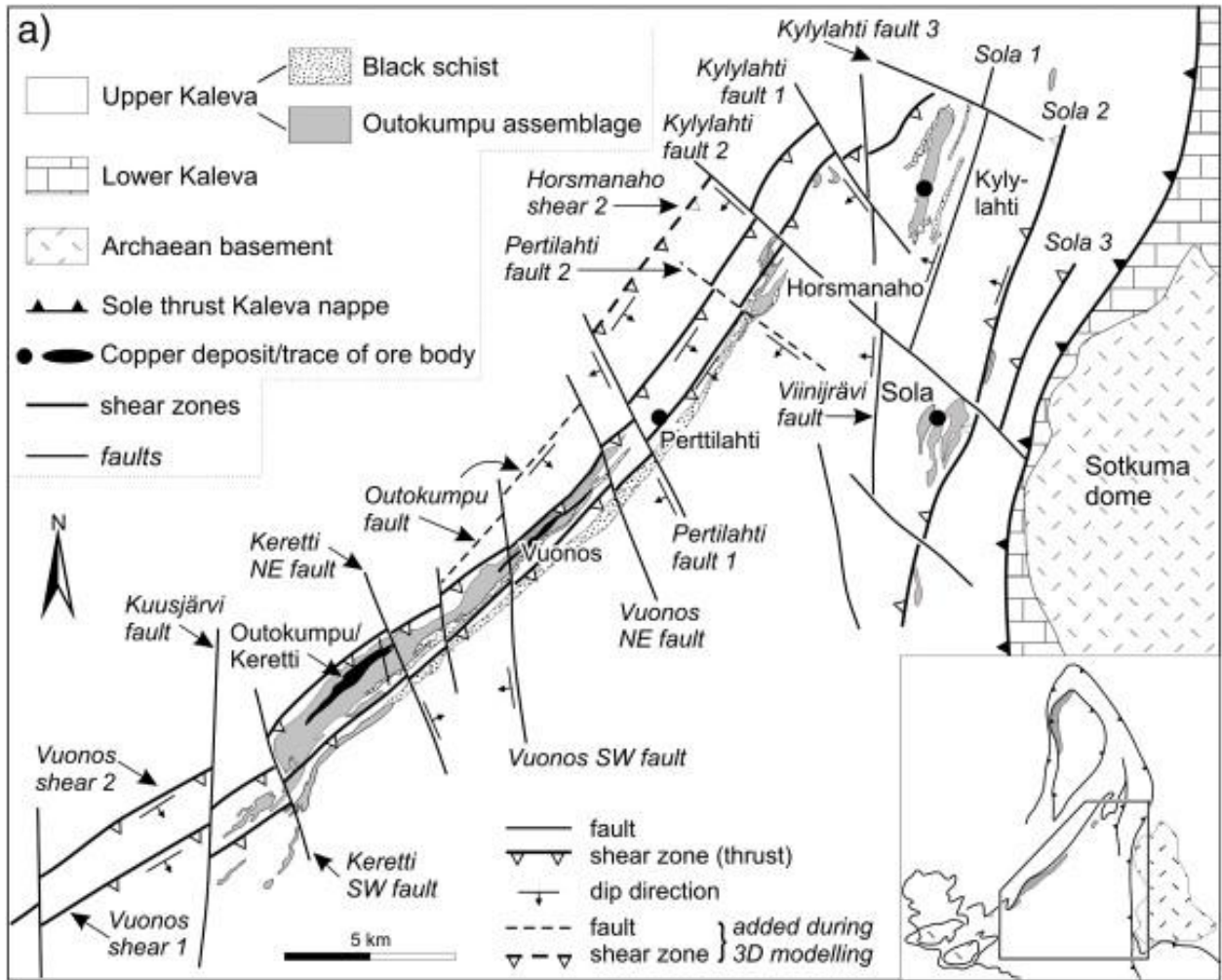
The mineralization history is a highly discussed topic. Mass-balance and isotope signals give evidence for a polygenetic origin. First, venting of high T-low-pH hydrothermal fluids led to Cu-Zn-Co-Ag-Au-sulphide deposition on a serpentinized ultramafic seafloor. Second, an additional Ni-source enriched this deposit about 40 Myrs afterwards. The deposition was likely related to chemical interaction between obducting peridotite massifs and adjacent black schists ("listwaenite-birbirite type carbonate-silica alteration") [7]. Third, the "proto-ore" was remobilized by fluids flowing along thrust sheets that separate lens-shaped metaperidotite bodies. These sheets were then themselves divided into several pieces by intense regional faulting (fig. 2) [6, 7].

The overall resources of the Outokumpu area, including Kylylahti, Saramäki, Vuonos, Hautalampi, Riihilampi, are estimated to 15.9 Mt of Cu (+ mineralization with Au, Ni, Zn, Co), 156'200 t Co and 32'300 t Ni. Kylylahti has resources of 8.8 Mt with 1.33% Cu, 0.24% Co, 0.22% Ni, 0.54% Zn and 0.78% Au (see table). Analysing the areas of Kylylahti, three domains of estimations have been set: "semi-massive sulphides" (Cu>0.8%), "disseminated sulphide" (Cu>0.4%) and "halo domain" (Cu<0.4%). In terms of economic value it is only marginally feasible, which means rising prices for Cu, Co and Zn make the construction of a mine useful in the near future.

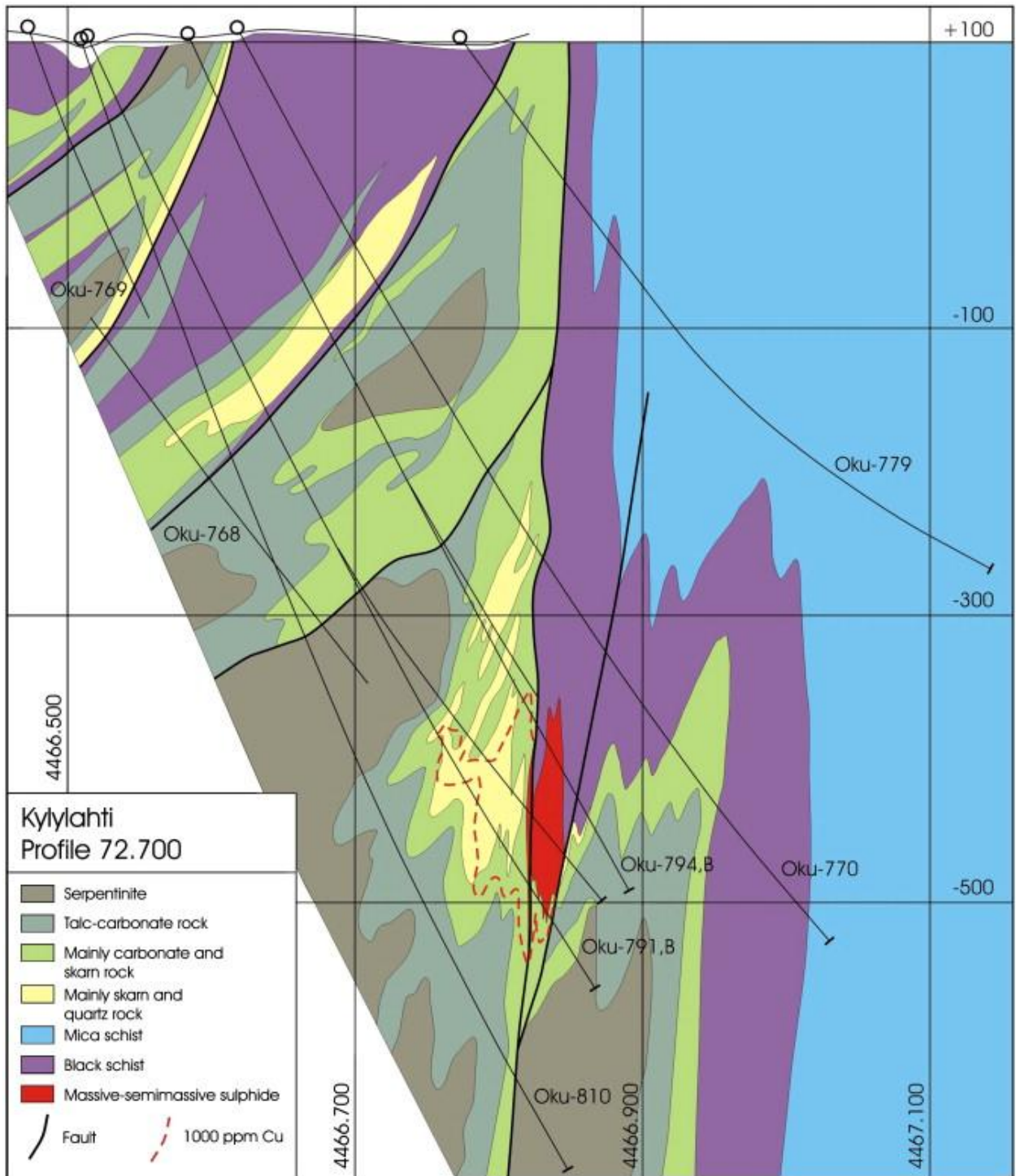
The Outokumpu area has been mined since 1914 but the Kylylahti deposit was not discovered before 1984. Between 2005 and 2008 new test works and drilling were done and since 2012 new techniques such as stoping were applied [1]. The rock containing ores is transported out by road trucks to the Luikonlahti mill. The tunnel system goes down to 583 m below surface (March 2014) with a length of 4.5 km. The goal is to reach 800 m depth in 2015 and 1.1 km in the near future. [2]



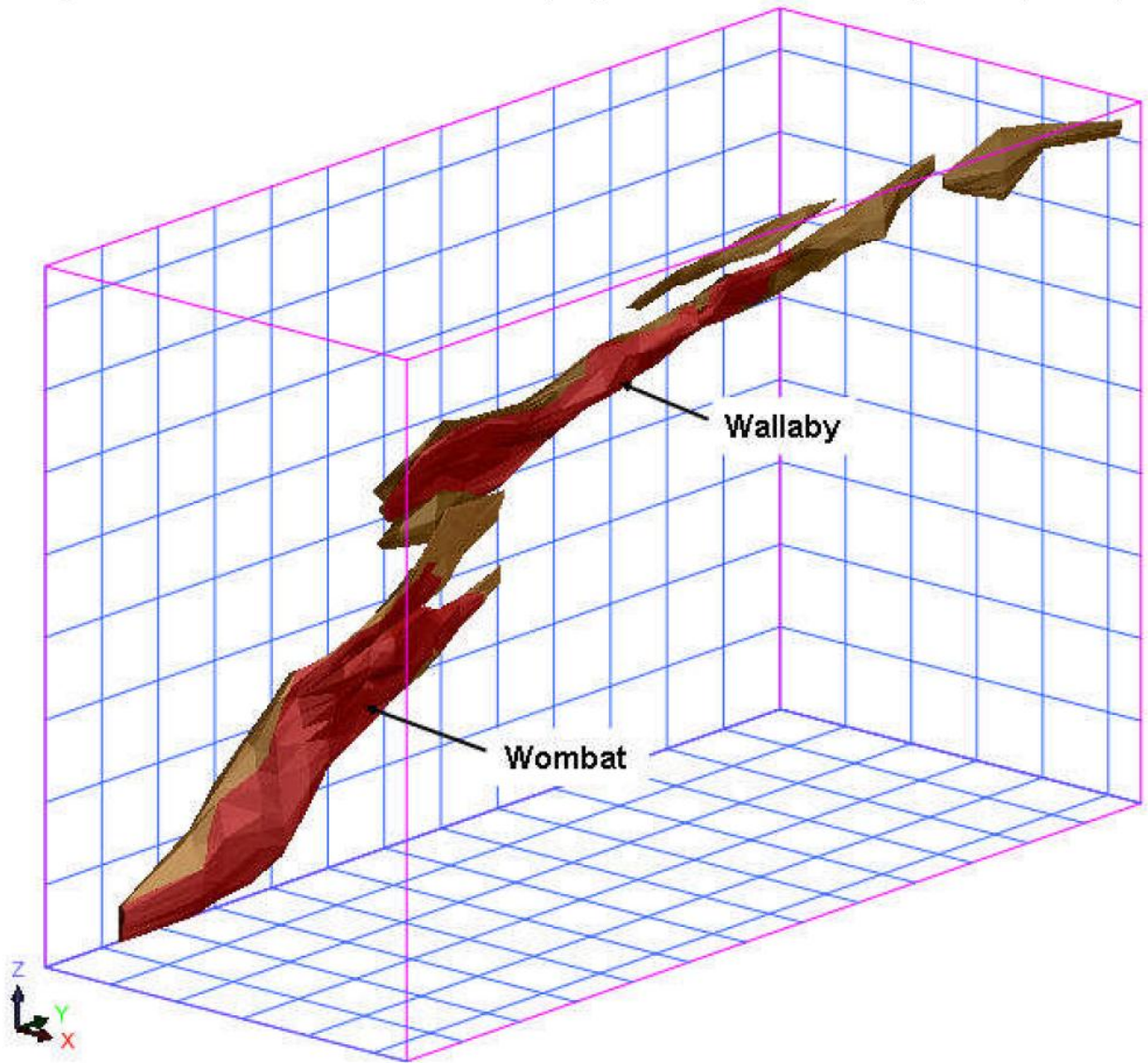
**Fig 14-2-1.** Regional geology of Kainuu and North Karelia schist belts showing the Jormua ophiolite and Outokumpu ore deposits. The numbers relate to the following Cu-deposits: **Outokumpu/Keretti (1)**, Vuonos (2), Perttilahti (3), **Kylylahti (4)**, Sola (5), Saramäki (6), Luikonlahti (7). [6]



**Fig 14-2-2.** Outokumpu ore zone (location see fig. 1) and its main mineralization bodies as well as tectonic deformation. Faults have been identified by geophysical mapping and 3D-modeling [6].



**Fig 14-2-3.** Cross-section of the Kylylahti-deposit showing the ore body with the highest Cu-Co-Zn (-Au)-sulphide mineralization (1000 ppm Cu) [7].



**Fig 14-2-4.** 3D-cross section of the Kylälahti ore body looking northwest showing the distribution of semi-massive (red) and disseminated sulphides (brown). The grid represents 100 m cubes. To understand the areas between Wallaby and Womat (mineralization zones), directional drilling and electromagnetic prospecting is in use. [4]

### Kylylahti Mine Mineral Resource and Ore Reserve Estimates

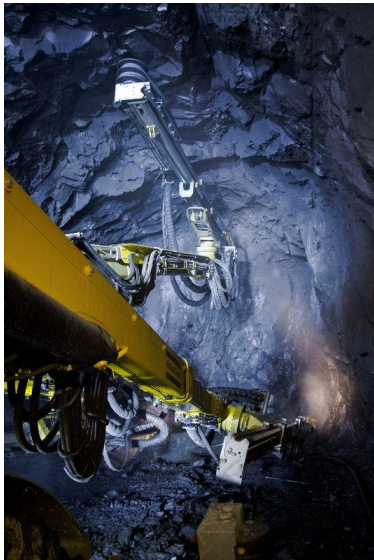
	Tonnes (m)	Cu (%)	Au (g/t)	Zn (%)	Co (%)	Ni (%)
<b>MINERAL RESOURCES</b>						
Measured	1.20	1.19	0.48	0.56	0.22	0.19
Indicated	7.20	1.35	0.77	0.53	0.24	0.23
Inferred	0.50	1.38	1.71	0.54	0.27	0.24
<b>Total</b>	<b>8.80</b>	<b>1.33</b>	<b>0.78</b>	<b>0.54</b>	<b>0.24</b>	<b>0.22</b>
Contained metal (tonnes)	-	117,480	222,600oz	47,400	21,350	19,680

	Tonnes (m)	Cu (%)	Au (g/t)	Zn (%)	Cu (t)	Au (oz)
<b>ORE RESOURCES</b>						
Proven	0.57	1.43	0.66	0.66	8,100	12,000
Probable	3.98	1.70	0.86	0.61	67,600	110,000
<b>Total</b>	<b>4.55</b>	<b>1.66</b>	<b>0.83</b>	<b>0.62</b>	<b>75,651</b>	<b>122,000</b>
Mining Inventory	0.20	1.75	0.54	0.63	4,475	4,415

See ASX releases dated 29 August 2013, 26 March 2014 and 7 May 2014 for JORC 2012 Compliance. Mineral Resources are inclusive of Ore

**Fig 14-2-5.** Kylylahti resource estimations. [2]



**Fig 14-2-6.** Drilling in Kylylahti decline (tool: "Jumbo"). [2]

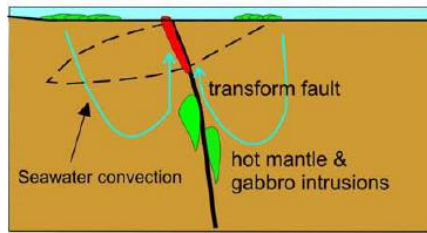


**Fig 14-2-7.** Kylylahti mine site with temporary offices, water storage ponds under construction and decline entrance. [2]

**Ultramafic ocean floor stage, 1950 Ma:**

Inhalative, fault-controlled deposition of hydrothermal sulphides at oceanic ridge or transform fault zone.

**Cu proto-ore formation**

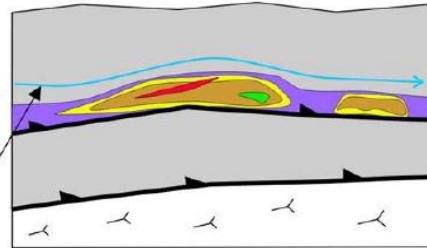


**Obduction stage, 1900 Ma:**

Low-T (100 - 200 °C) listwaenite-birbrite-type carbonate-quartz alteration of peridotite body margins > Ni sulphide disseminations.

**Ni proto-ore formation**

Early metamorphic carbonic-aqueous fluids, focussed by thrust faults



- Mantle peridotite
- Sulphides
- Gabbro stocks, lavas and dikes
- Black schists
- Silicified and carbonated peridotites (incl. nickel sulphide disseminations)
- "Upper Kaleva" turbidites
- Archaean basement gneisses

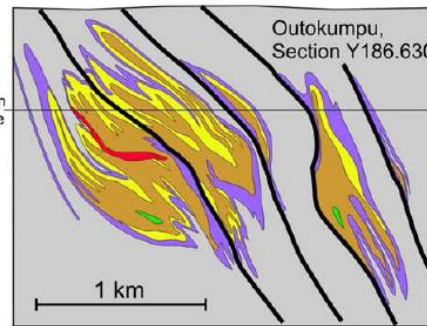
**Regional deformation stage, 1880 Ma:**

Syntectonic remobilisation:

**Mixing of the Cu- and Ni- proto-ore components**

Peak metamorphic (ca. 630 °C) static recrystallisation: textural upgrading

Retrogression



**Fig 14-2-8.** Sketch of a three-stage-genetic model for Outokumpu ore deposits with emphasis on Ni dissemination. [7]



**Fig. 14-2-9.** Deformation and brecciation structures in drill core (photo: D. Klimentyeva).

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**Compiled by: Julia Krawielicki**



<i>Date: July 15, 2014</i>	<i>STOP No.: 15-1</i>
<b>Locality name: Siilinjärvi</b>	
<i>Main commodity: Phosphor</i>	
<i>Geological setting or genetic model: Intrusive carbonatite</i>	
<i>Current development status: open pit mining</i>	
<b>WGS Latitude: 63.11111</b>	<b>WGS Longitude: 27.75778</b>
<i>Municipality: Siilinjärvi</i>	
<i>Location &amp; access: 20 km North of Kuopio, 4.8 km NE from Siilinjärvi town by Nilsiantie/route 75</i>	
<i>Geological domain: Archean Karelian-Kola craton</i>	<i>Geological unit: Iisalmi granite gneiss</i>
<i>Owner (2014): Yara Suomi Oy</i>	
<i>Address: Nilsiantie 501, P.O. Box 20, 71801 Siilinjärvi</i>	

### **Geology**

The Iisalmi granite gneiss area extending some 100 km to the North from Siilinjärvi represents a very old peneplain of sub-Karelian land surface. Much granitic material was added to the basement rocks by plutonic intrusions. The Siilinjärvi complex has intruded the Southern end of this relatively stable basement gneiss area close to the north of the Lake Ladoga-Central Bothnia mobile deep fracture zone (Puustinen, 1971). The area of Siilinjärvi represents the intersection area of the deep fracture and a northerly aligned fracture, which has been favorable to magma intrusions from deep levels of the Earth's crust or mantle. The complex is a subvertical tabular body, roughly 16 km long with a maximum width of 1.5 km and a surface area of 14.7 km<sup>2</sup>, with dips varying 70-90° W. It also conforms to the general north-south strike of schistosity of the surrounding basement (Puustinen, 1971). The rocks of the complex comprise (from the oldest to the youngest) glimmerite (phlogopite), syenite and carbonatite. Although not strictly zoned, cross-cutting relationships and xenoliths suggest that, at least at the present level of exposure, some of the syenites formed early, followed by relatively carbonate-poor ultramafic magmatic pulse that created the majority of the phlogopite rocks, finally culminating in a carbonate-dominated pulse (O'Brien, 1980).

White-green medium grained pure carbonatite formed during the carbonate-dominated pulse is relatively rare and in general true carbonatite (>50 modal % carbonates) is a relatively minor rock type at Siilinjärvi (O'Brien, 1980). The vast majority of the central body is formed of phlogopite-rich rocks ranging from almost pure glimmerite (biotite) via carbonate glimmerite to silicocarbonatites and finally to carbonatites (O'Brien, 1980). The overall mode of the carbonatite-glimmerite portion of the complex, as indicated by the average composition of the Siilinjärvi ore (Härmälä, 2001), is 65% phlogopite, 20% carbonates (with a 4:1 calcite:dolomite ratio), 5% richterite and 10 % apatite (equivalent to 4 wt.% P<sub>2</sub>O<sub>5</sub> in the whole rock). Other, relatively rare accessory minerals at Siilinjärvi include barite, strontianite, monazite, pyrochlore, baddeleyite, ilmenite, magnetite, pyrite, pyrrhotite and chalcopyrite. Fenites surrounding the carbonatite-biotite central core developed as a result of sodium and potassium metasomatism of the surrounding granite gneiss country rock (O'Brien, 1980). The main minerals in the fenites are microcline, amphibole and pyroxene but there exists a wide variety of syenite types including: pyroxene, amphibole, carbonate quartz, aplitic, and quartz-aegirine syenites. The development of H<sub>2</sub>O- and alkali-rich late-stage fluids that formed the fenite halo was a direct consequence of the early crystallization of predominantly carbonate and apatite.

Even though all varieties of this magmatic pulse contain apatite, apatite is nonetheless concentrated in the carbonate-rich rocks. Apatite occurs as gray to greenish yellow prisms and also as irregular, inclusion-

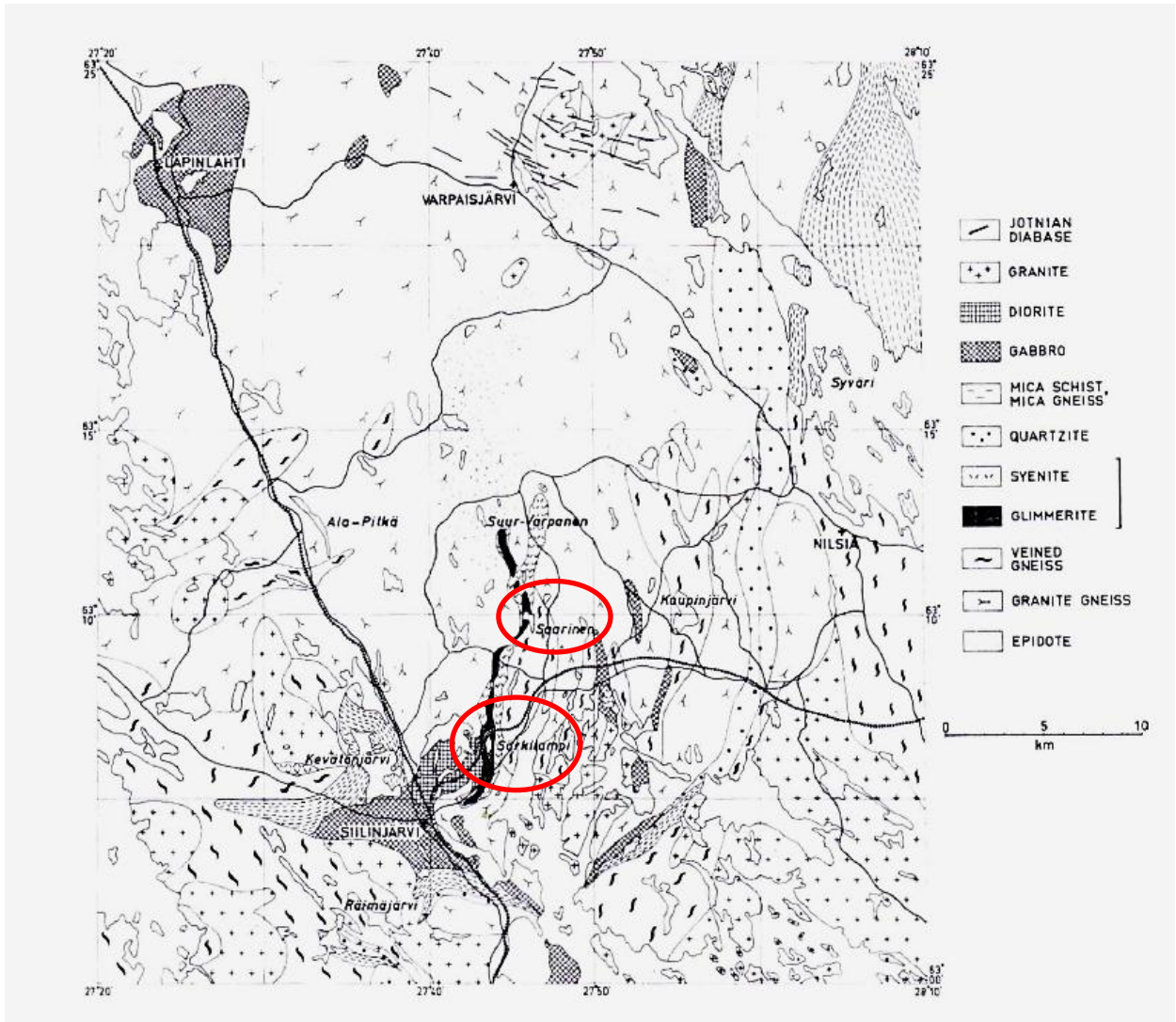
free grains in the glimmerite-carbonatite rocks (Puustinen, 1971).

A concordant zircon U-Pb age of  $2609 \pm 6$  Ma (Lukkarinen et al., 2003) shows that Siilinjärvi is one of the oldest carbonatites in the world and hence represents the first carbonatite discovered in the Precambrian of Finland (O'Brien 1980. and Puustinen 1971).

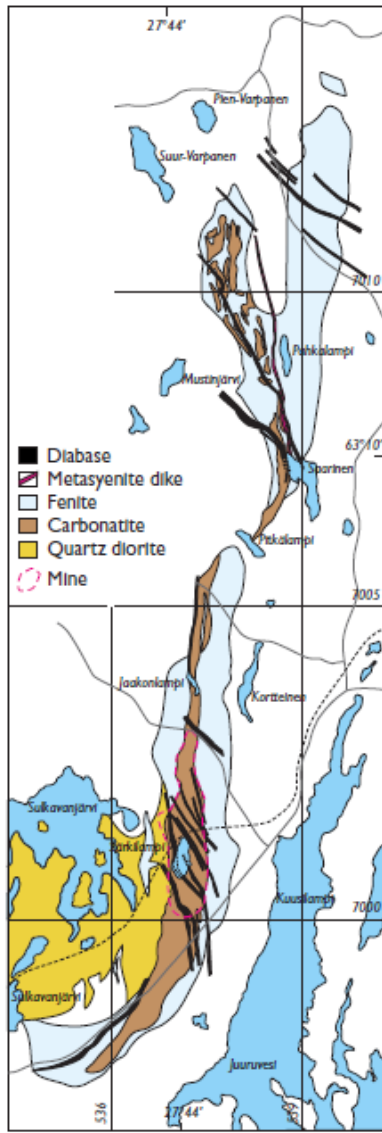
Carbonatites are known to contain the highest concentrations of rare earth elements (REE) of any igneous rocks. Kapustin (1966) established that most primary minerals (calcite, dolomite, apatite i.e.) are strongly enriched in REE, with enrichment factors increasing steadily from Lu to La. The REEs reside mainly in the Ca-bearing phases (i.e. carbonates, apatites, Ca-Nb-oxides and Ca-silicates) where they substitute with  $\text{Sr}^{2+}$  for  $\text{Ca}^{2+}$  (Hornig-Kjarsgaard, 1997).

Siilinjärvi represents one of the largest phosphates reserve in Finland having estimated reserves of 2.35 billion tonnes of ore grading 24%  $\text{P}_2\text{O}_5$  (Wikipedia). The mine produces 9.81 Mt of apatite ore, from which ~ 860 000 tonnes of apatite concentrate were recovered as the main product for fertilizer production, as well as the by-products, carbonate based products (~135000 t) for other agricultural/environmental uses. Mica concentrate production, ~ 8000 t, for mica pigment and other purposes, is owned by Swedish-based Minelco Oy. Gypsum, a by-product of Siilinjärvi's phosphoric acid (~ 290 000 t  $\text{P}_2\text{O}_5$ ) production, is gaining market share as a paper pigment (~ 105 000 tpa). Raw materials for these products are mined from the Archean (2609 Ma) Siilinjärvi carbonatite (gtk.fi).

Exploration drilling began 1958 and continued along with laboratory and pilot plant work until 1979 when an open pit mine for phosphorus ore was commissioned (Fig. 15-1-5). Present production at the Siilinjärvi mine is about 9.2 Mt of ore per annum (O' Brien, 1980).



**Fig 15-1-1. Geological Map of the Siilinjärvi mine (Puustinen 1971).**



**Left: Fig. 15-1-2.** Geological map of the Siilinjärvi carbonatite complex after Puustinen 1971 from Lehtinen et al. (2005).



**Fig. 15-1-3.** Open pit mining at Siilinjärvi mine.



**Fig. 15-1-4.** Siilinjärvi mine. Both photos: [www.nhm.ac.uk](http://www.nhm.ac.uk).



**Fig. 15-1-5.** Glimmerite-carbonatite within open pit at Kemira Oy Siilinjärvi apatite mine. Proterozoic mafic dikes truncating vertical banded fabric, indicating limited Proterozoic tectonic overprint in western part of Iislami terrain. From Lehtinen et al (2005).



**Fig. 15-1-6.** Medium-grained calcite carbonatite with apatite (greenish) and one 3-cm-wide phlogopite book. From Lehtinen et al (2005).



**Fig. 15-1-7.** Panoramic view of the Siilinjärvi mine (photo: M. Schnyder).



**Fig. 15-1-8.** Centimetre-sized apatite crystal within carbonatite (photo: L. Gilsbach).



**Fig. 15-1-9.** Pervasively fenitized (alkali-metasomatized) country rock gneiss, invaded by veins filled with large salmon-colored potassium feldspar and minor alkali amphibole (dark green). Fenitization is caused by alkali-rich fluids or salt melts expelled by the crystallizing carbonate magma, which is only stable as a magmatic melt thanks to these fluxing components (photo: Ch. Heinrich).



**Fig. 15-1-10.** Internal magmatic contact within the Siilinjärvi carbonate, showing earlier banded phlogopite carbonate (also called glimmerite if carbonate content is less than a few percent; right side of photo). This magmatic banding is truncated by later intrusion of weakly biotite-bearing but apatite-rich carbonatite composed of 60% cream-colored calcite and 30% pale green apatite. (photo: Ch. Heinrich).

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**Compiled by: Lea Menn**

<i>Date: July 15, 2014</i>	<i>STOP No.: 15-2</i>
<b>Locality name: Talvivaara</b>	Sotkamo
<i>Main commodity: Ni-Cu-Co-Zn</i> <i>Geological setting or genetic model: precipitation from anoxic/euxinic seawater</i> <i>Current development status: open pit mining</i>	
<b>WGS Latitude: 63.99314</b>	<b>WGS Longitude: 28.05693</b>
<i>KKJ Northing: 7099650</i>	<i>KKJ Easting: 3551900</i>
<i>Municipality: Sutkamo</i>	
<i>Location &amp; access: 28 km SSE from Kajaani town. Regional road 6 southwards, turn right onto 870 and right again on 8714</i>	
<i>Geological domain: Archean gneiss greenstone belt</i>	<i>Geological unit: Proterozoic Kainuu Schist Belt</i>
<i>Owner (2014): Talvivaara Mining Company Plc.</i> <i>Address (if applicable, e.g. mine site): Talvivaarantie 66, 88120 Tuhkakylä, FINLAND</i>	

### **Geology**

The Talvivaara (Sutkamo) deposit is a low-grade but large sulfidic Ni-Zn-Cu-Co deposit hosted by highly sulfidic-graphitic muds and turbiditic wackes. It is (by volume) the largest black-shale-hosted deposit in the world containing 1550 Mt of ore averaging 0.22% Ni, 0.13% Cu, 0.49% Zn and 0.02% Co. The precursors of the metamorphosed and recrystallized host rocks were deposited 2.1-1.9 Ga ago in a stratified marine basin. The mineralization is stratabound, C- and S-rich black schists. Ore-minerals are pyrrhotite, pyrite, sphalerite, chalcopyrite and pentlandite (Kontinen, 2012; Loukola-Ruskeeniemi and Lahtinen, 2013)

The Talvivaara deposit is divided into two ore-bodies, Kuusilampi and Kolmisoppi (Fig. 15-2-2). Both are 2.5- 2.8 km long, between 30 and 600 m wide and extend to depths of up to 800 m. The deposit is part of the much larger Talvivaara Ni-Zn-Cu zone (Fig. 15-2-1), which is located in the N-S trending Paleoproterozoic Kainuu Schist Belt stretching over 150 km. The deposits occurring in the zone are low-grade sulfide deposits hosted in C-rich black schists (Kontinen, 2012; Loukola-Ruskeeniemi and Lahtinen, 2013).

The Kainuu Schist Belt is characterized by 3 main components (Kontinen 1986b, 1987, Laaioki, 2005): (1) cratonic and epicratonic, dominantly quartz-arenite sequences of the Sumi-Sariola and Jatuli stage (2.5-2.1 Ga); (2) rift-related wacke-pelite sequences of the lower Kaleva stage (2.1-1.95 Ga); (3) deep-water turbidite-wackes and pelites of the Upper Kaleva stage (1.95-1.9 Ga). The latter stage is considered allochthonous, carrying fault-related ophiolitic fragments (Peltonen et al. 2008). After deposition the Kainuu Belt was subject to multiple low- to medium P-T deformation and metamorphic events during the Svecofennian orogenesis (1.91-1.78 Ga; Kontinen, 2012).

Talvivaara-type deposits are associated with sulfide- and metal-rich carbonaceous sediments. Occasional carbonaceous sediments occur in the Jatuli sequence but the majority is hosted in the two Kaleva stages. Today the original sediments are metamorphosed to graphite- and sulphide-rich metasediments. The metasediments in the Kaleva sequences are strongly enriched in the base metals Cu, Zn and Ni as well as in the redox-sensitive elements As, Fe, Mo, Sb, Se, V and U (Luokola-Ruskeeniemi, 1999). The metal enrichment is comparable to that in Phanerozoic metal-rich black shales deposited in large oxic-anoxic, stratified, restricted marine basins with the seawater as the ultimate source of metals. (Kontinen, 2012)

The Ni-mineralization in the Talvivaara zone is stratabound and stratigraphically controlled and is often

associated with very graphitic (5-15 wt% C) and sulfidic (5-30 % S) units. Increased Ni-contents (>0.1 %) in the Talvivaara black schists is often correlating with Mn-rich layer (>0.8 %; Kontinen, 2012).

The Talvivaara Sutkamo deposit is the only deposit currently in operation. The deposit is located in the central part of the Talvivaara belt and has an exposed strike of about 12 km. One or two <50 m thick, strongly metal-enriched mud-layers are intercalated with cm- to m-scale thinly bedded to laminar pyritic muds and carbonate rock now metamorphosed to coarse-grained carbonate-diopside-tremolite calc-silicate rocks (Luokola-Ruskeeniemi and Heino, 1996).

Post-mineralization folding and reverse faulting increased the volumes of mineable material by thickening and stacking the mineralized units (Fig. 15-2-3). Occurring sulphides are pyrrhotite, pyrite, sphalerite, chalcopyrite, pentlandite and alabandite (Figs. 15-2-4 to 15-2-7). The Ni is hosted in pyrrhotite and its pentlandite exsolutions with the Co mainly hosted in the pyrite (Kontinen, 2012). Sulfides occur both as fine-grained disseminations and coarse grains or aggregates (Fig. 15-2-4, 15-2-6 and 15-2-7). Chalcopyrite mainly occurs in joint surfaces and quartz-sulfide. The majority of the economically important Ni is located in pyrrhotite and pentlandite exsolutions in pyrrhotite. In Fig. 15-2-4 synsedimentary lamination occurs with mineralized spheroidal pyrite cross-cut by later quartz-sulfide veins characterized by euhedral pyrites. The veins are considered to be syndeformation (later than disseminated pyrite) indicating different stages of Ni-mineralization or remobilization (Loukola-Ruskeeniemi and Lahtinen, 2013).

Suggested genetic models for the Ni-deposit are: (1) hydrothermal systems on the seafloor; (2) a meteorite impact into the Talvivaara restricted seawater basin; (3) association with ultramafic magmatic rocks as in the nearby Outukompu-region; (4) precipitation from anoxic/euxinic seawater enriched in Ni and other base metals. (Loukola-Ruskeeniemi and Lahtinen, 2013; Kontinen, 2012)

Recent contributions to the discussion strongly favor the latter genetic model on the basis of homogenous metal contents and ratios over big scales and on the basis of sulphur isotopic analyses. However, the influence of ultramafic rocks is still debated. During metamorphism and deformation, remobilization and local enrichment of metals might have occurred. (Loukola-Ruskeeniemi and Lahtinen, 2013; Kontinen, 2012)

Mining at Talvivaara Sutkamo started as a non-selective bulk open-pit operation in 2008. Once in full production, an annual Ni output of 50,000 t was envisaged. This mine was the first place where bio-heap leaching was tested and it is still applied to this day making the exploitation of low-grade Ni-Zn sulphide ore bodies economic (Loukola-Ruskeeniemi and Lahtinen, 2013).

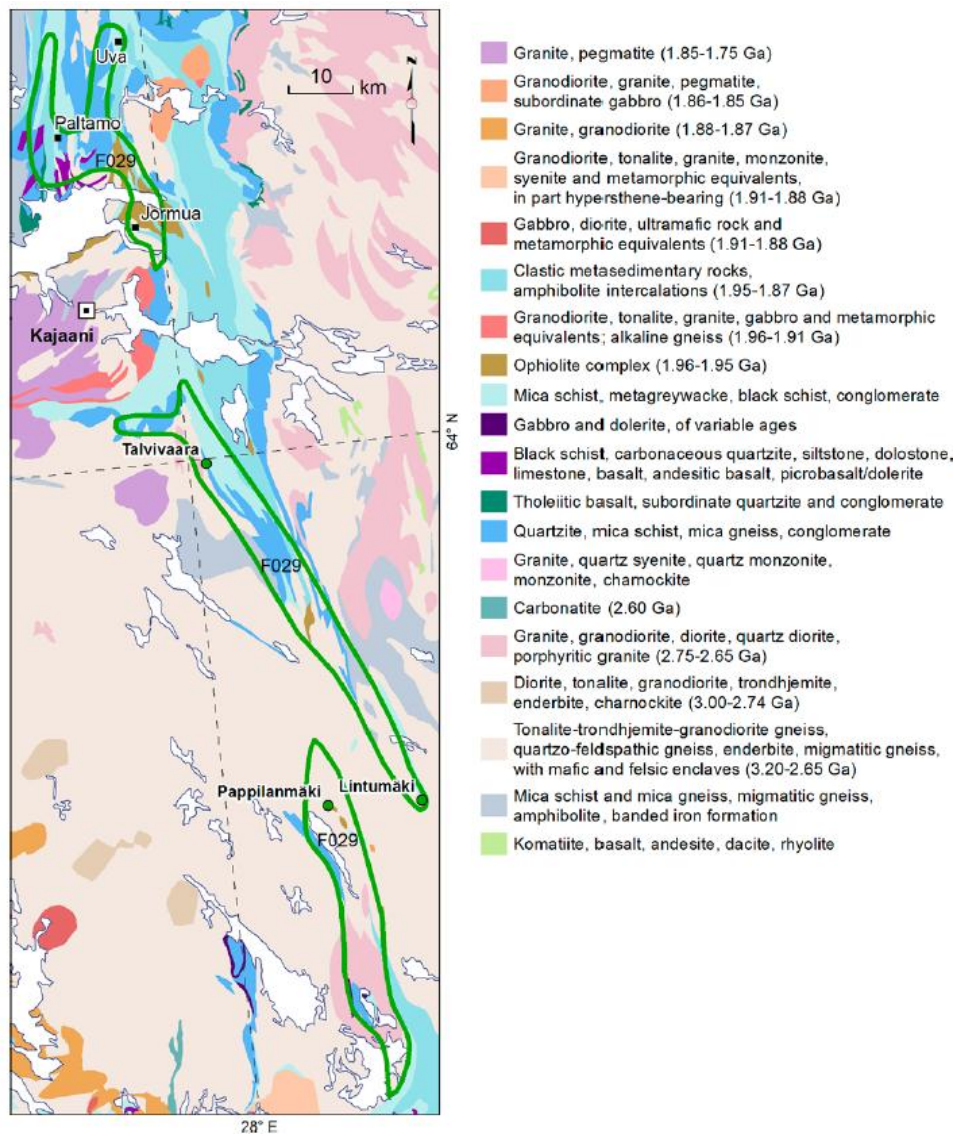
For the bio-heap leaching process the mined metasediments are piled up and reworked by endemic bacteria. Then an acidic solution (pH 3) containing H<sub>2</sub>S is added to the 'pregnant' heap leading to the precipitation of first Cu, followed by Zn and Ni. The precipitated elements are then filtered to gain the metal products ready for sale. Before precipitation the solution contains 1-3 g/L Ni while the concentration is reduced to 30 – 50 mg/L after precipitation. The used solution is purified and used again for heap irrigation which leads to a higher recovery. The process is also working at the very low temperatures encountered in central Finland during winter as the oxidation of pyrite is liberating enough heat energy to increase the local fluid temperature to up to 50°C.

Each pad needs about 14,000 m<sup>3</sup>/hr of H<sub>2</sub>S running through it as the residence time is only a few hours.

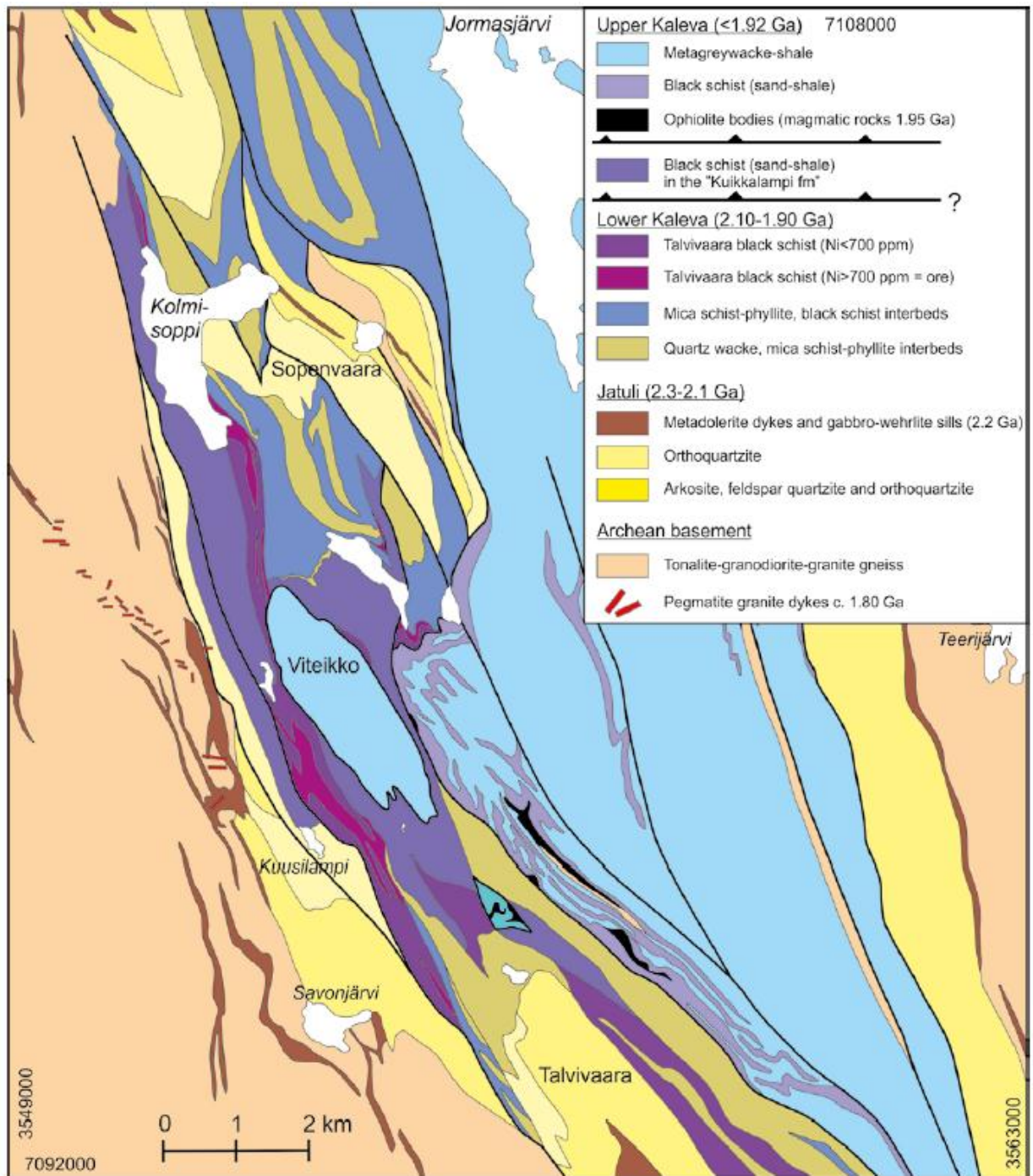


After starting a new pile sufficient metal concentrations of the leaching fluids are reached after 3-6 months. Ore is first stored on the primary pad which yields a recovery of 70%. Later it is transferred to a secondary pad with the final recovery reaching 90-95%.

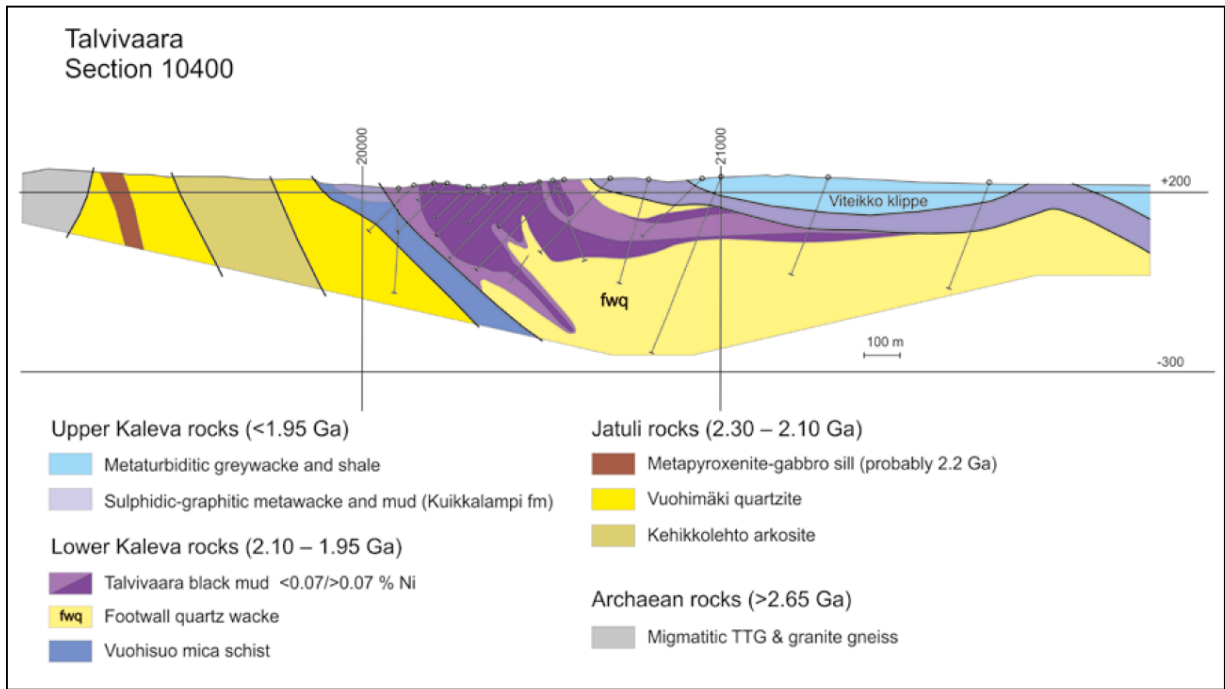
A major point of debate is the potential connection to the Outokumpu-style deposits. As described before, two explanations for the genesis of the mineralisation at Talvivaara are the precipitation from Ni-enriched seawater and secondly, the association with ultramafic rocks as suggested in the Outokumpu-district (VMS). In the Outokumpu district the general genetic model involves an early VMS-style Cu-mineralization and later obduction of the whole rock suite. The ultramafic rocks are pre-enriched in Ni and during deformation the two 'proto-ores' are remobilized with metals being mixed and reprecipitated. However, the ultramafics at Keretti are directly overlain by black shales. This opens up the possibility of a Ni and Cu pre-enrichment by precipitation from seawater as suggested for Talvivaara. The enriched sediments are then obducted and they contribute a certain quantity of metal for the later remobilization process.



**Fig 15-2-1.** Regional Map of the Talvivaara area. F029 delineates the area which is known to host Talvivaara-type deposits (Kontinen, 2012).



**Fig 15-2-2.** District scale map with the two orebodies (Kuusilampi and Kolmisoppi) located in the light purple lithology (Kontinen, 2012).



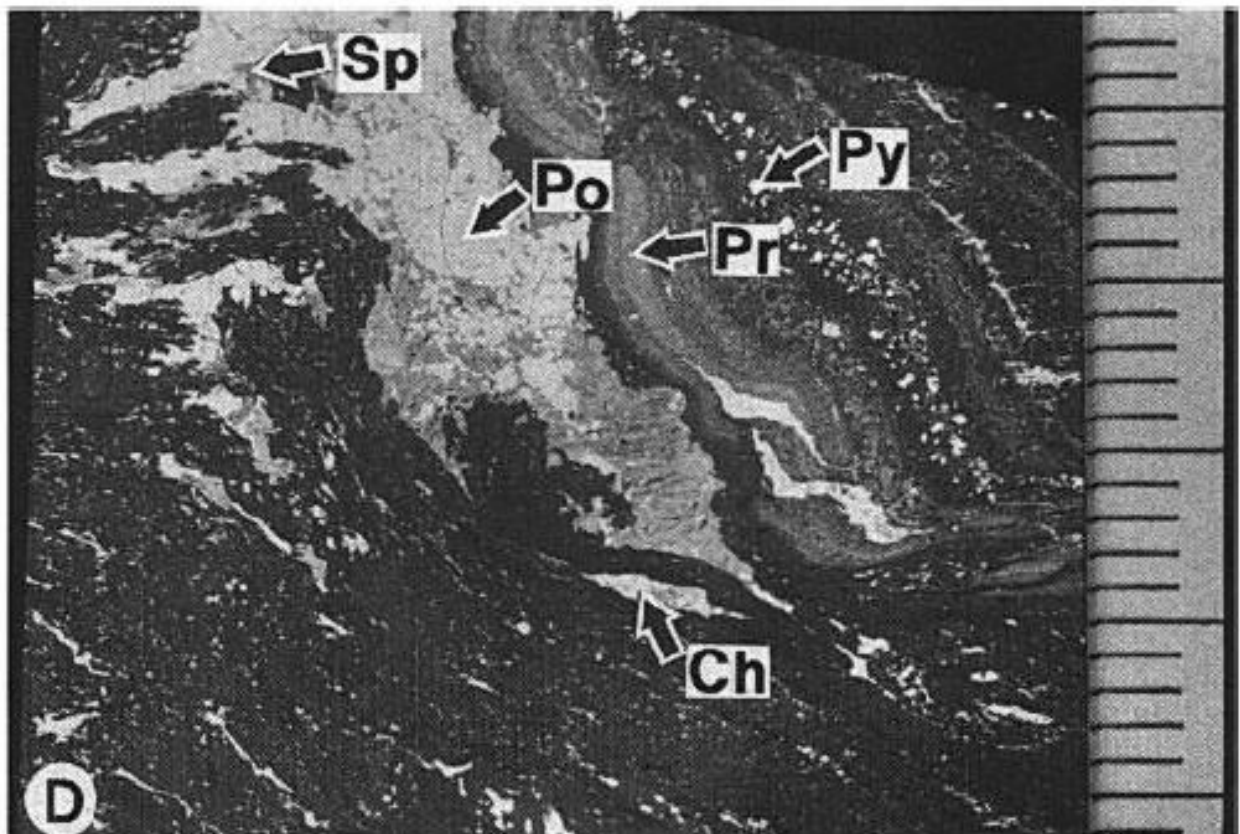
**Fig 15-2-3.** Cross-section across the Kuusilampi ore body, view from NNW (Kontinen, 2012).



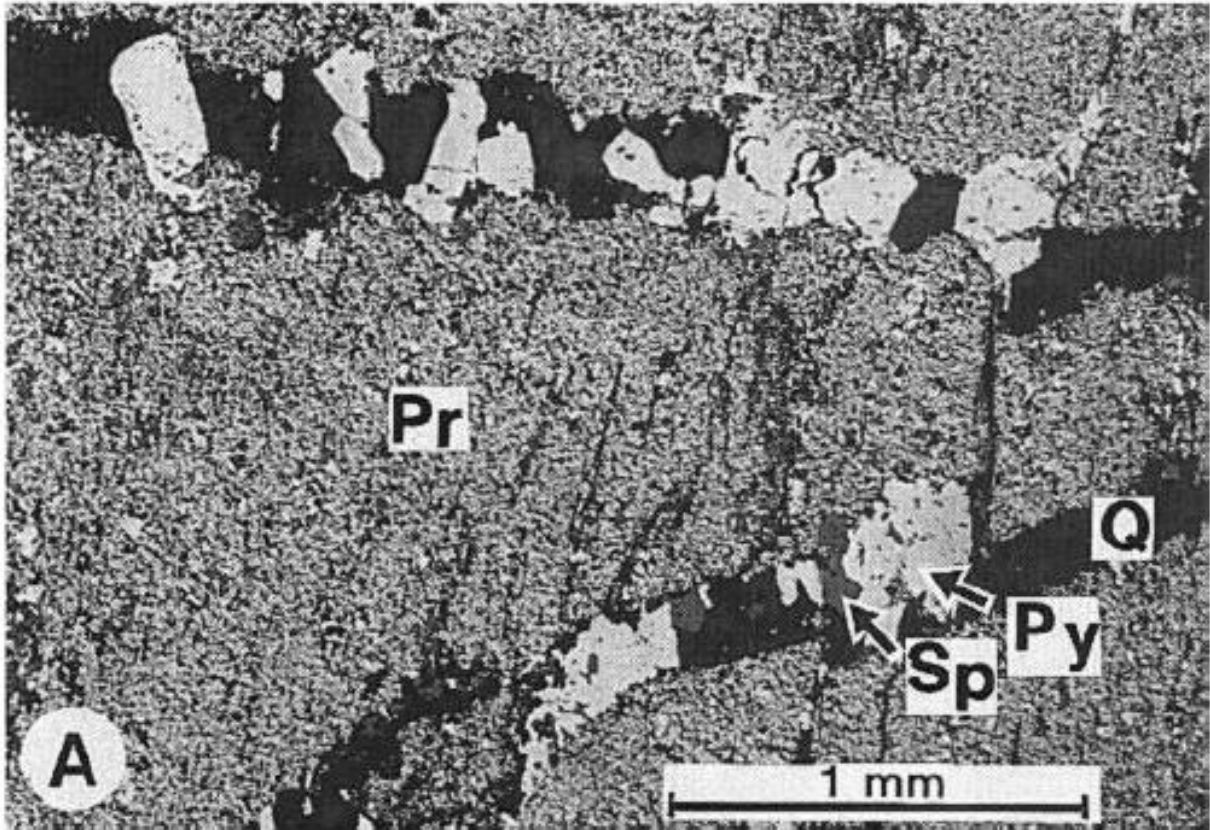
**Fig 15-2-4.** Synsedimentary/syndiagenetic laminae in black schist rich in graphite and spheroidal fine-grained pyrite. The lamination is cut by quartz-sulphide veins with coarse-grained pyrite. The width of the core section is 3 cm (Loukola-Ruskeeniemi and Lahtinen, 2013).



**Fig 15-2-5.** A black metacarbonate rock with abundant tremolite, sulphides and graphite. The black metacarbonate rocks occur as 0.5- to 3.0-m-thick intercalations in black schist. The width of the core section is 3 cm (Loukola-Ruskeeniemi and Lahtinen, 2013).



**Fig 15-2-6.** Ni-rich black schist containing both fine-grained sulfide material (Pr), including the other sulfides in addition to pyrite (Py), and coarse grained sulfides in veins (Sp sphalerite; Ch, chalcopyrite; Po, pyrrhotite), scale in mm (Loukola-Ruskeeniemi and Heino, 1996).



**Fig. 15-2-7.** Dense fine-grained pyrite dissemination (Pr) cut by quartz-sulfide veins (P, pyrite; Sp, sphalerite; Q, quartz; Loukola-Ruskeeniemi and Heino, 1996).



**Fig. 15-2-8.** Talvivaara open pit panorama (currently under water; photo: S. Holinger).



**Fig. 15-2-9.** *Bioleaching heaps stage I (photo: K. Schlöglöva).*

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- Kontinen, A., 2012. F029 Talvivaara Ni-Zn-Cu, GTK Special Paper 53, 276-280.

**Compiled by: Simon Large**

<i>Date: July 16, 2014</i>	<i>STOP No.: 16-1 (optional)</i>
<b>Locality name: Seitaperä</b>	Pipe # 16
<i>Main commodity: Diamonds</i>	
<i>Geological setting or genetic model: Orangeite to Lamproite</i>	
<i>Current development status: Exploration</i>	
<b>WGS Latitude: 64.246703</b>	<b>WGS Longitude: 29.796497</b>
<i>Municipality: Lentiira - Kostamuksha</i>	
<i>Location &amp; access: Road 912 between Kuhmo and intercept of road 912 with road 89, 20 km NE of Kuhmo. Lefthandside, between road and Lake Kylmalahti (a.k.a. Lentua).</i>	
<i>Geological domain: Outokumpu</i>	<i>Geological unit: Archean Karelian Craton</i>
<i>Owner (2014): Karelian Diamond Resources plc.</i>	

### **Geology**

#### *Lentiira area - Kostamuksha Orangeites and Lamproites*

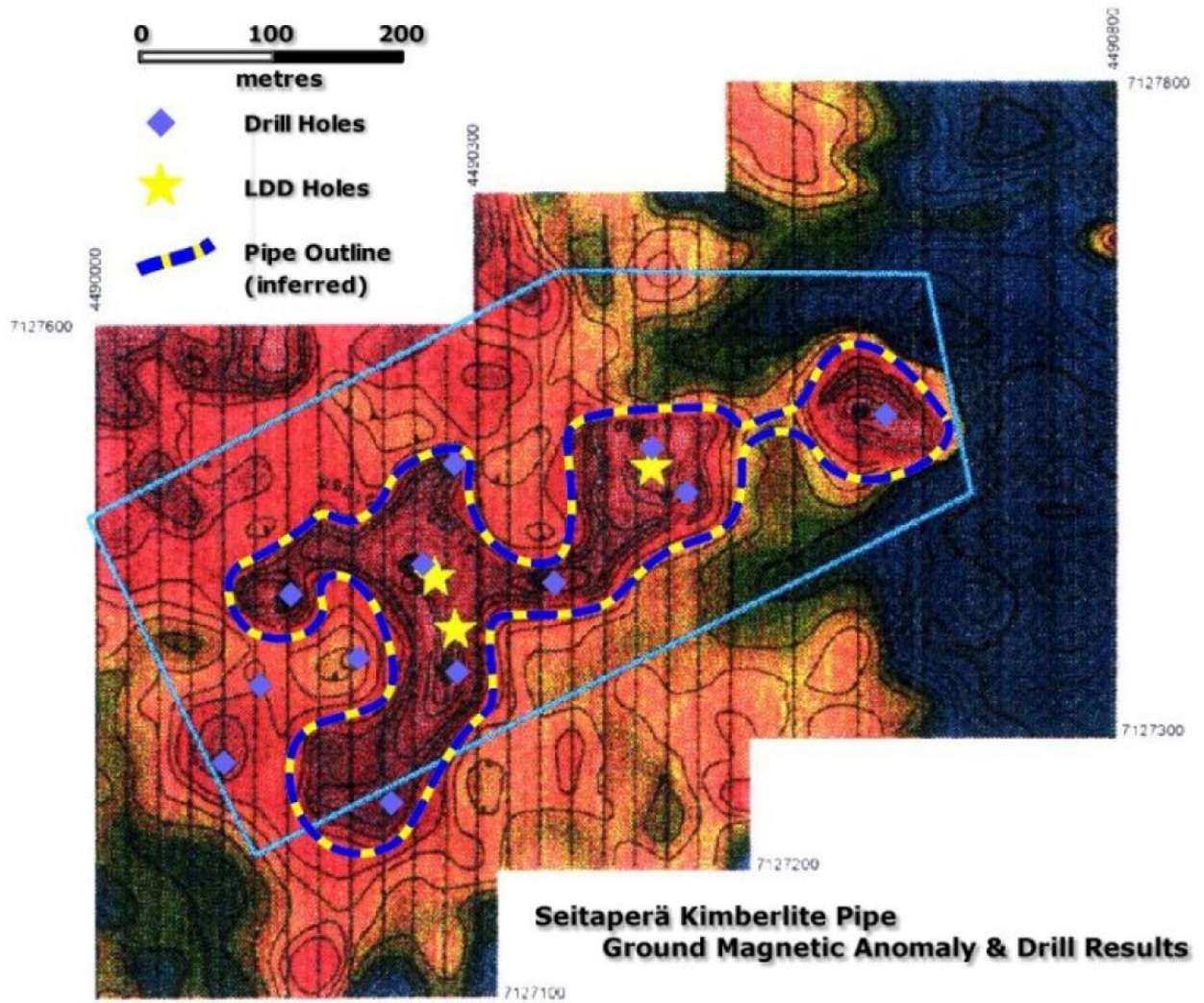
The orangeites and lamproites of the Lentiira area are located within a strongly deformed, up to amphibolite-facies granitoid-greenstone belt of 2800 – 2650 Ma. Rb-Sr mineral isochron ages and Ar-Ar ages constrain an emplacement age of 1230 – 1200 Ma (Belyatsky, 1995; O'Brien et al. 2007) that is double the age of the Kaavi-Kuopio kimberlites. The classification of these intrusiva is difficult due to variable mineralogy resembling either orangeites (after Mitchell, 1995; a.k.a. Type II Kimberlites) or lamproites. However, a distinction to “true” kimberlites (Type I) like those from the Kaavi-Kuopio area can be made by the abundance of Ti-phlogopite, low-Ti tetraferriphlogopite (anomalously Fe-rich) and K-richite (amphibole) as well as indirectly by the absence of monticellite. A further feature of orangeites and lamproites is their high volatile content dominated by H<sub>2</sub>O species and the ultrapotassic character which separates them from the commonly CO<sub>2</sub> dominated, less potassic type I kimberlites (Mitchell, 1995; O'Brien & Lehtonen, 2008).

Lamproites and orangeites likely originate from highly metasomatized SCLM regions which is reflected by their load of xenolithic peridotite content that often is enriched or completely composed of hydrous minerals. A special xenolithic assemblage are so called MARID (Mica, amphibole, rutile, ilmenite and diopside) are interpreted as parts of metasomatized SCLM (Dawson & Smith, 1977; Konzett et al., 1998).

In occurrence and shape, lamproites and orangeites appear similar to kimberlites forming diatremes or dikes. They are explored in the same way with the exception that indicator minerals (see below) a less abundant.

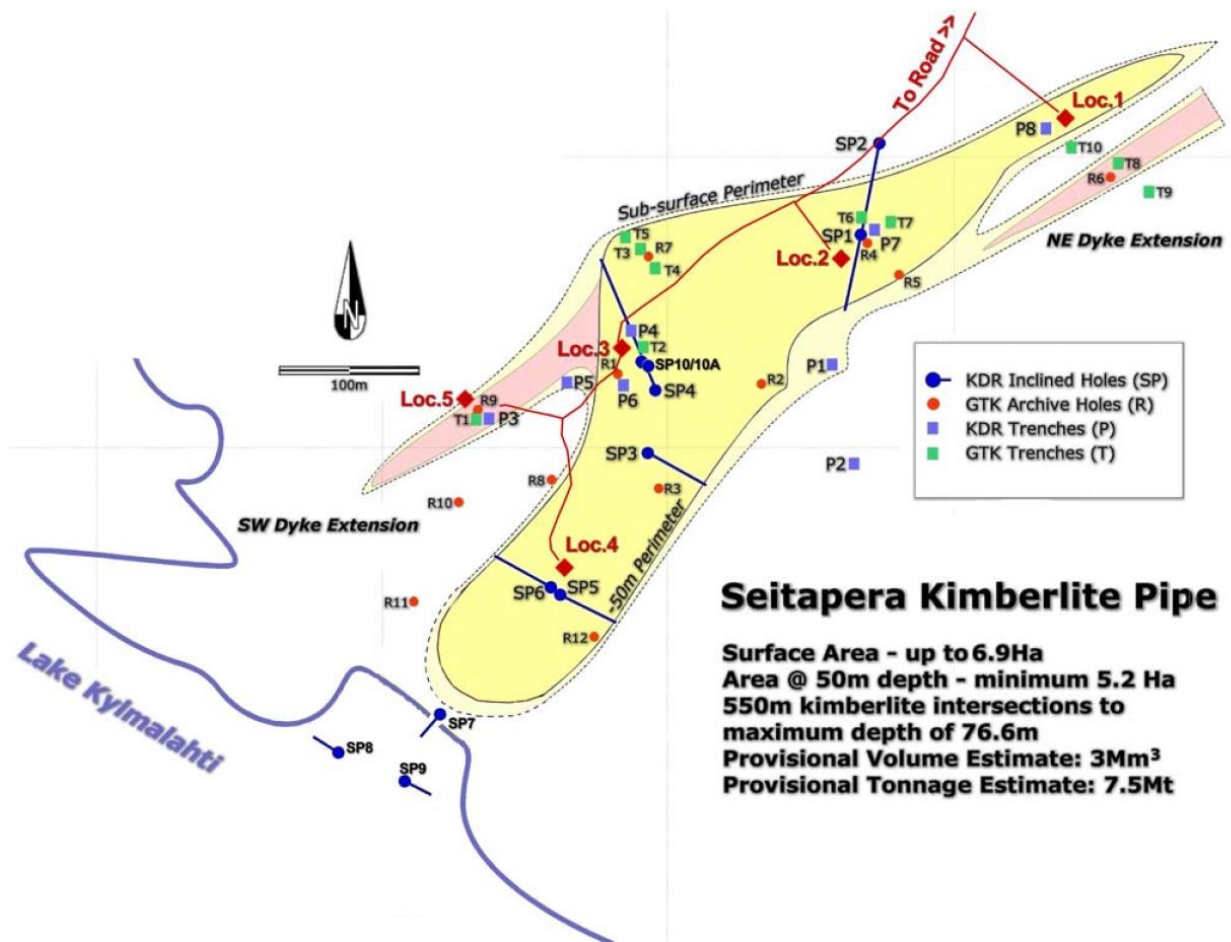
During our trip, we may have the chance to visit the **Seitaperä** diatremes which are the largest known intrusions of the Lentiira – Kostamuksha area. Seitaperä is the 16<sup>th</sup> body discovered by Ashon-Malmikaivos Oy in 1993. The locality is a composite of numerous smaller diatremes that follow an echelon fault-structure in WSW – ENE direction and covers an area of approximately seven hectares surface area. The diatremes and their rock content are not directly visible, however, a 1200 m wide depression between pronounced granite-gneiss ridges outlines the intrusion. We may have luck and can find rock material in pit excavations. Ashon-Malmikaivos Oy confirmed the presence of micro- and macro-diamonds of Seitaperä. Karelian Diamond Resources plc. regularly reports finding diamonds in drill core material. However, no information is published about the economic value of Seitaperä.

**Regional Geology:** See Fig. 14-3-1.



**Fig. 16-1-1.** Ground magnetic map of the Seitaperä pipes. The undulous outline is due to several different pipes lying close to another. Accordingly, different volcanic facies have been recognizes at the different oarts of the occurrence, ranging from hypabyssal porphyric dikes to kimberlite breccia. From Grimmer & McNulty (2008).





**Fig. 16-1-2.** Map of Seitaperä kimberlite highlighting its outline and indicating the location of drilling campaigns and trenching. Figure from Grimmer & McNulty (2008).

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*Previous field trip guides*

Grimmer & McNulty (2008), 9<sup>th</sup> IKC field trip guide.

O'Brien & Lehtonen (2008); 9<sup>th</sup> IKC field trip guide.

*Comments:* For general information on diamonds, the Karelian Craton and diamond exploration see previous introductory text.

**Compiled by: Nico Küter**

<i>Date: July 16, 2014</i>	<i>STOP No.: 16-2</i>
<b>Locality name: Juomasuo</b>	
<i>Main commodity: Au-Co-Fe-U</i>	
<i>Geological setting or genetic model: orogenic gold / IOCG</i>	
<i>Current development status: test pit</i>	
<b>WGS Latitude: 66.28882</b>	<b>WGS Longitude: 29.19952</b>
<i>KKJ Northing: 7355400</i>	<i>KKJ Easting: 4464230</i>
<i>Municipality: Kuusamo</i>	
<i>Location &amp; access: 37 km N from Kuusamo town by road E63/5 then 950, gravel road to the site</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Kuusamo Schist Belt</i>
<i>Owner (2014): Dragon Mining OY</i>	

### **Geology**

The Juomasuo deposit is located in the Kuusamo supracrustal belt (Fig. 16-2-1) which is a volcanic-sedimentary formation located in eastern Finland. It was deposited discordantly on an Archean Gneiss complex 2.5 to 2 Ga ago in a Paleoproterozoic rift environment (Vanhanen, 2001). Hydrothermal alteration and green schist facies metamorphism occurred during the Svecofennian orogeny 1.9-1.8 Ga ago (Nikkola, 2014). The Kuusamo supracrustal belt hosts over 30 sulphide deposits which resulted from mineralization related to pervasive hydrothermal alteration (Pankka, 1992).

Juomasuo, the largest Au-Co-U deposit in the Kuusamo supracrustal belt, is hosted in the Sericite Quartzite Formation in an epigenetic shear zone in the NE-trending Käylä-Konttiaho Anticline. The deposit is hosted in felsic metavolcanic rocks, mafic metavolcanic rocks, metasedimentary rocks and meta-ultramafic rocks (Hanes and Schlöglóvá, 2013). The host rocks are heavily altered, where the succession from chloritization, sericitization, carbonatization to albitization (Fig. 16-2-6) (Vanhanen, 2001) resulted in a zoned alteration (Fig. 16-2-2 and 16-2-3) with sharp contacts. Weakly altered rocks still show sedimentary structures such as graded bedding and banding (Fig. 16-2-7).

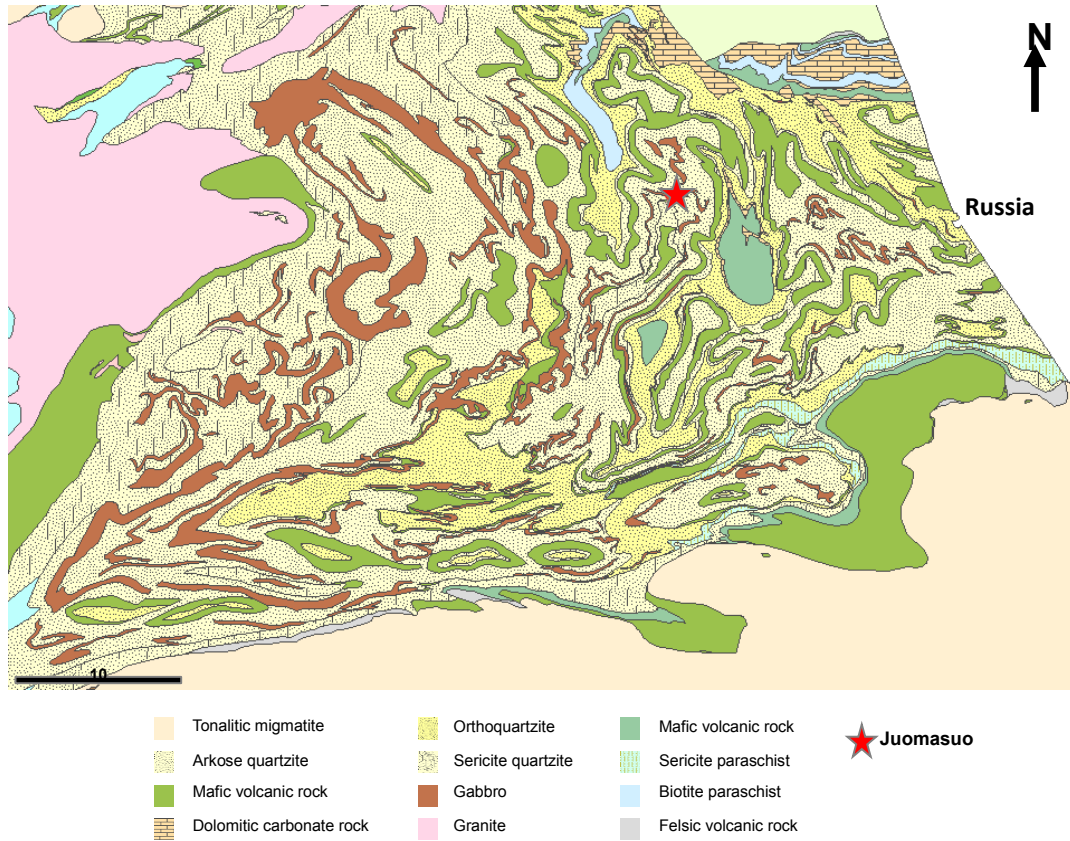
The sulphide mineralization is mainly hosted in sericite-chlorite rocks with the ore zone along a ductile shear (Fig. 16-2-3). In addition, the mineralization is distinctively strata bound along a mildly folded horizon of volcanic and sedimentary rocks which is enveloped by ultramafic rocks (Hanes and Schlöglóvá, 2013). The most common minerals are pyrrhotite (as elongated seams or veins) and pyrite (as cubic porphyroblasts or disseminations), and to a lesser extent cobaltite and cobaltpentlandite. Gold occurs as inclusions in pyrite (Fig. 16-2-4), uraninite and cobaltite or as grains in association with tellurides and Bi minerals (Fig. 16-2-5) (Pankka, 1992). Rare earth elements occur as minerals allanite, monazite and bastnasite and Uranium primarily occurs as discrete grains of uraninite.

The main resource of the Juomasuo deposit is gold with a 2,371,000 tons grading 4.6 g/t gold (347,000 ounces). In addition and separate to the gold resource, an indicated and inferred mineral resource for cobalt totaling 5,040,000 tonnes grading 0.12% cobalt and 0.1 g/t gold has been defined. (Dragon Mining Ltd., 2014). Furthermore, the deposit is also enriched in Ag, Cu, Mo, Ni, REE and U. After several drilling campaigns to evaluate the Juomasuo ore deposit it was assessed to be technically, economically and environmentally feasible is now under development (Nikkola, 2014).

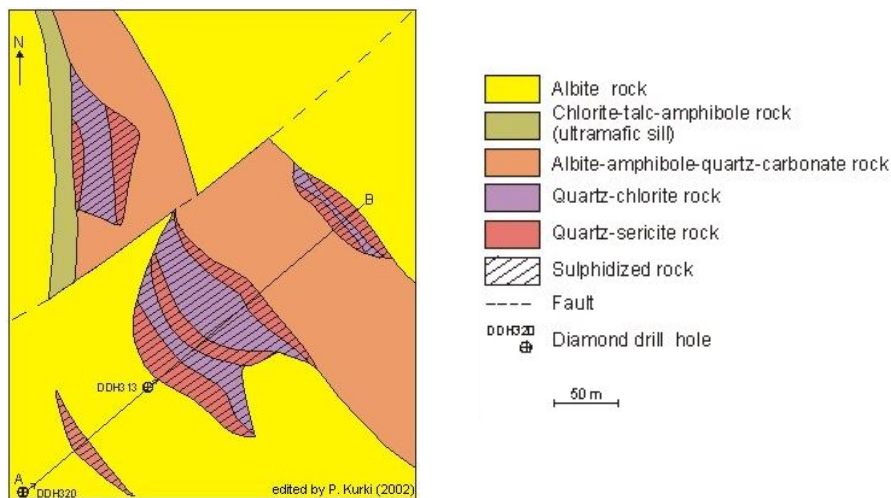
### **Discussion**

In the field, it is almost impossible to distinguish the different rock types without previous knowledge. But the alteration zones are clearly visible and the contacts between different alteration types can be traced throughout the test pit. This reveals a folding of the different alteration horizons. The altered meta-ultramafic rocks are barren and envelop the ore-bearing altered metavolcanic and metasedimentary rocks which can be recognized by the occurrence of pyrrhotite and pyrite.

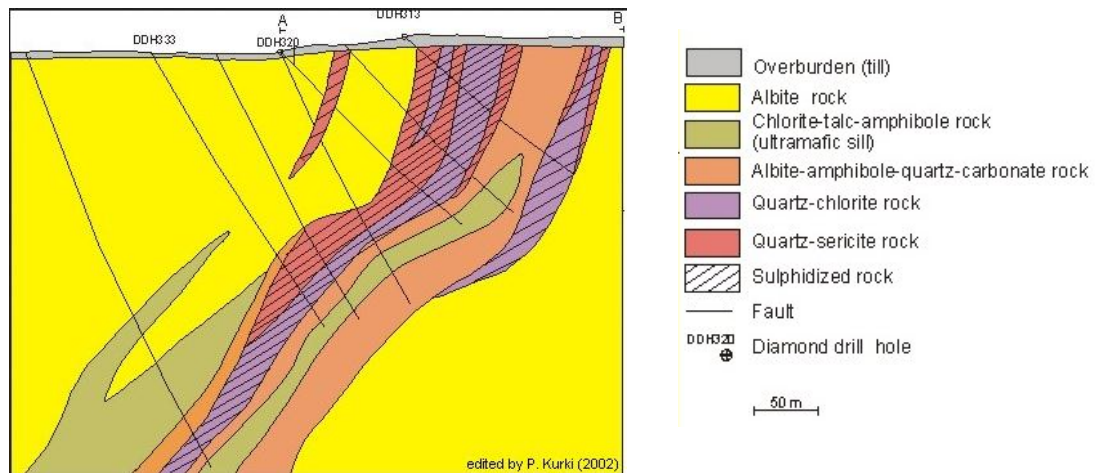
The ore shoots are pencil-shaped and are located in the fold hinges showing that, apart from being structurally controlled on a regional scale, the mineralization is limited to specific horizons making it also strata bound on a local scale. The more impermeable meta-ultramafic rocks trapped the hydrothermal fluids and focused them within the more permeable metavolcanic and metasedimentary rocks. In the fold hinges, where the rocks were most strongly fractured, the ore shoots formed along the cracks. (Schlöglová, personal communication, 2014).



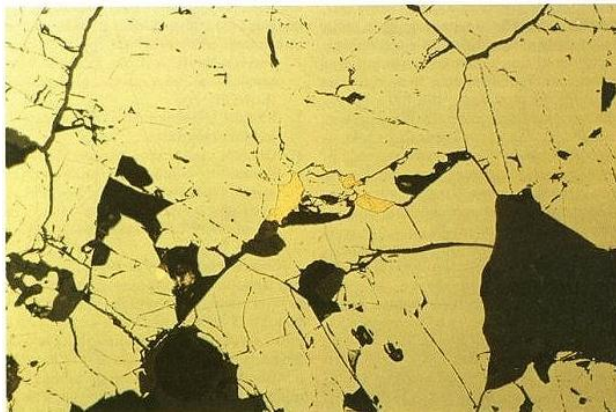
**Fig. 16-2-1.** Simplified map of the Kuusamo supracrustal belt showing lithologies and location of the Juomasuo deposit (after bedrock map 1:200000 of the Geological Survey of Finland).



**Fig. 16-2-2.** Ground surface geology of Juomasuo (after Pankka, 1992; edited by Kurki, 2002).



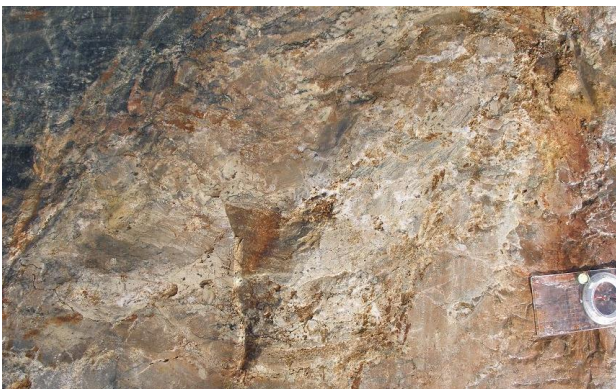
**Fig. 16-2-3.** Cross section of the Juomasuo deposit (after Pankka, 1992; edited by Kurki, 2002).



**Fig. 16-2-4.** Gold inclusions in pyrite (from Pankka, 1992).



**Fig. 16-2-5.** Veinlets of gold, tellurides and Bi minerals in sericite-quartz rock (from Pankka, 1992).



**Fig. 16-2-6.** Albitization of fine-grained sedimentary rock (Photo by P. Eilu, 2006).



**Fig. 16-2-7.** Deformed primary banding in sedimentary rock (Photo by P. Eilu, 2006).



**Fig. 16-2-8.** Juomasuo test pit: Contact of felsic metavolcanic rocks and their carbonate alteration (photo: D. Klimentyeva).

**Fig. 16-2-9.** Juomasuo test pit: Contact between altered metasediments and metavolcanic rocks (photo: D. Klimentyeva).

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**Compiled by: Matthias Sieber**

<i>Date: July 16, 2014</i>	<i>STOP No.: 16-3</i>
<b>Locality name: Hangaslampi</b>	
<i>Main commodity: Au-Co-Fe-U</i>	
<i>Geological setting or genetic model: orogenic gold / IOCG</i>	
<i>Current development status: prospect</i>	
<b>WGS Latitude: 66.28077</b>	<b>WGS Longitude: 29.20357</b>
<i>KKJ Northing: 7354500</i>	<i>KKJ Easting: 4464400</i>
<i>Municipality: Kuusamo</i>	
<i>Location &amp; access: 36 km N from Kuusamo town by road E63/5 then 950, gravel road to the site</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Kuusamo Schist Belt</i>
<i>Owner (2014): Dragon Mining OY</i>	

### **Geology**

The Hangaslampi deposit is located 1 km south of Juomasuo. Hence, regional geology, alteration and mineralization processes are the same as at Juomasuo. For details see *Juomasuo* (Stop 16-2).

The deposit is located in the contact zone between mafic metavolcanic rocks of the tholeiitic Greenstone Formation II and metasedimentary rocks of the Sericite Quartzite Formation (Fig. 16-3-2 and 16-3-3) (Vanhanen, 2001). It is a moderately dipping body of mineralization that remains open along the strike.

The major mineral at Hangaslampi is Pyrite with gold grains (up to 10 µm) as inclusions. Gold can also be found at grain contacts between sulphides and silicates as well as between quartz, chlorite and sericite grains (Vanhanen, 2001). Minor minerals include pyrrhotite, uraninite, cobaltite and cobaltpentlandite.

The resource for gold at Hangaslampi is 403,000 tons grading 5.1 g/t gold (66,100 ounces). Separate from the gold resource, the total resource for cobalt is 180,000 tons grading 0.09%. In addition to the reported gold and cobalt, the Hangaslampi deposit also contains uranium and rare earth elements at low quantities (Dragon Mining Ltd., 2014). The majority of the updated resource occurs within 80 m of the natural surface level.

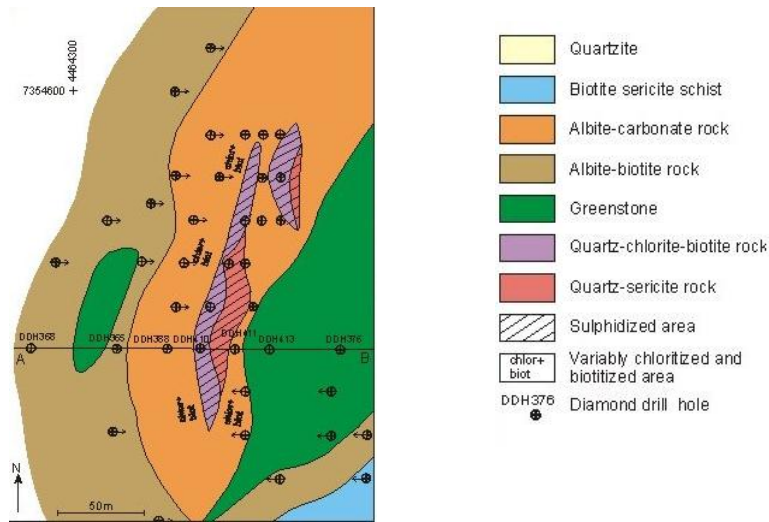
Recently, there have been four drilling campaigns (50 holes) at Hangaslampi and in the vicinity of the deposit in order to evaluate the extent and geometry of the identified mineralization. Both recent and historical drilling has focused on the near surface portions of the deposit.

### **Discussion**

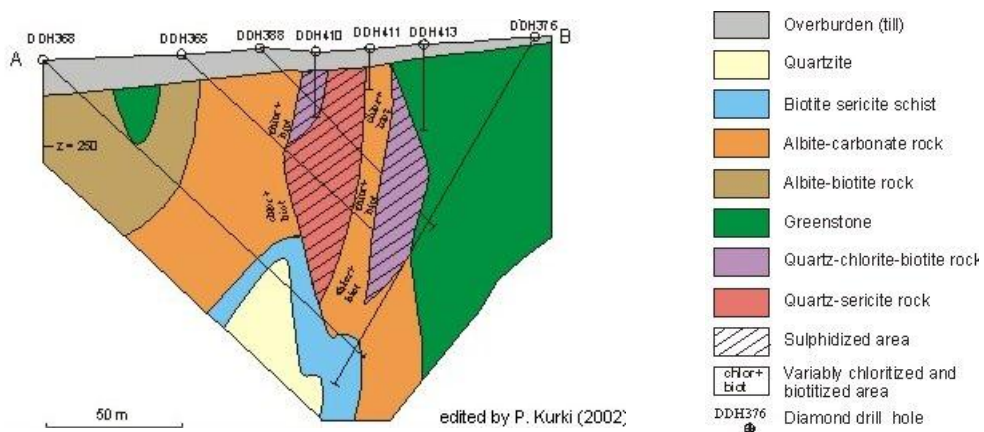
The metasedimentary rocks, mainly quartz-sericite rock and quartz-chlorite-biotite rock, are hosting the sulphides at Hangaslampi. Pyrite, the major sulphide at Hangaslampi, can be found throughout the test pit as cubic porphyroblasts (up to a few cm) or fine grained within the metasediments. Additionally, magnetite can be found in association with carbonate veins, which crosscut the metasediments. From our field observations we could not determine whether these veins were formed during the main phase of sulphide mineralization 1.9-1.8 Ga ago or if they represent a later stage of fluid activity.

In contrast to the Juomasuo deposit, the metasediments are dominated by chloritization and no clear zonation of the alteration is visible. It appears that the Hangaslampi deposit is solely structurally controlled. However, a detailed lithochemical study for the Hangaslampi deposit has yet to be completed in order to obtain a better understanding of the distribution of gold within the ore body and its relation to the host rocks.

**Regional geologic map:** See Fig. 16-2-1.



**Fig. 16-3-1.** Surface geology of the Hangaslampi deposit (after Vanhanen, 2001; edited by Kurki, 2002).



**Fig. 16-3-2.** Cross-section of the Hangaslampi deposit (after Vanhanen, 2001; edited by Kurki, 2002).



**Fig. 16-3-3.** Hangaslampi test pit: cm-sized pyrite and magnetite (photo: D. Klimentyeva).

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Dragon Mining Ltd, 2014. ASX announcement, 19 June 2014: Resource update for the Hangaslampi deposit, Kuusamo gold project. June 2014

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Vanhanen, E.J., 2001. Geology, mineralogy and geochemistry of the Fe-Co-Au-(U) deposits in the Paleoproterozoic Kuusamo schist belt, Northeastern Finland. Geological Survey of Finland, Bulletin 399, 229 p.

**Compiled by: Matthias Sieber**



<i>Date: July 17, 2014</i>	<i>STOP No.: 17-1</i>
<b>Locality name: Kevitsa</b>	
<i>Main commodity: Ni-Cu-PGE</i>	
<i>Geological setting or genetic model: ultramafic intrusion-related</i>	
<i>Current development status: active mine, production started in 2012</i>	
<b>WGS Latitude: 67.698601</b>	<b>WGS Longitude: 26.965247</b>
<i>KKJ Northing: 7512400</i>	<i>KKJ Easting: 3498700</i>
<i>Municipality: Sodankylä</i>	
<i>Location &amp; access: Highway E75 from Rovaniemi (the provincial capital of Lapland; lies 180 km to the south of Kevitsa) to the village of Petkula and then by by-road across the Vajukoski dam followed by forest road. The nearest town is Sodankylä. The mine lies about 140 km north of the Arctic Circle.</i>	
<i>Geological domain: Karelian</i>	<i>Geological unit Kittilä Greenstone Belt/ Sodankylä Group</i>
<i>Owner (2014): First Quantum Minerals Ltd.</i>	

### **Geology**

The Kevitsa ultramafic intrusion in northern Finland hosts the Kevitsa deposit, which was formed by igneous activity that started ~ 2.05 Ga ago (Malehmir et al., 2012). It is situated within the Central Lapland Greenstone Belt (Koivisto et al., 2012). The intrusion measures about 3.5 km (N-S) and 5 km (E-W). It is approximately circular in plan view (3). The intrusion is surrounded by older mica schists and other pelitic rocks. Some komatiitic volcanic rocks and calcareous and carbonaceous sedimentary rocks are also found in these pelites (4) (Fig. 17-1-1, 17-1-2).

The intrusion has internal layering, which is made by changes in composition resulting from successive pulses of magma, and not simple differentiation of a single pulse (Malehmir, 2012). In the northeast, there are basic olivine pyroxenites and metaperidotites. Gabbro is found in the west and the central areas, whereas in the south there is a granophyre. (3)

The deposit is located in the olivine-pyroxenite of the ultramafic zones and contains mostly olivine and orthopyroxene (3).

The basal contact of the Kevitsa intrusion to the host rocks dips about 50-60° to the south in the northern part of the complex. The bedding of the metasediments in the south dips in different directions with an angle of 50-60°, suggesting that the fabric is affected by folding or buckling (Koivisto et al., 2012).

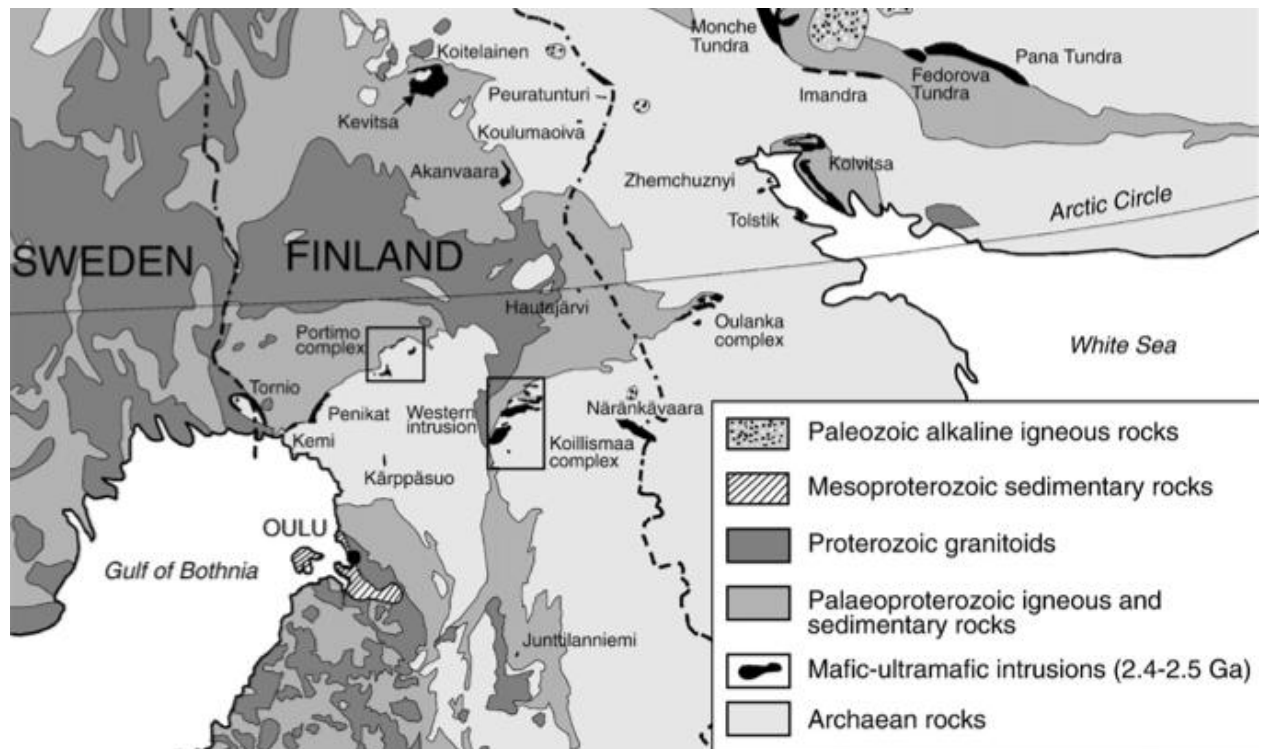
The eastern part of the deposit was affected by the Satovaara Fault Zone at about 1.9-1.8 Ga. The resources have therefore been affected by structures, which offset the disseminated mineralization. However, there is no evidence that the deposit is structurally controlled (Koivisto et al., 2012).

Rocks near the contact to the Kevitsa intrusion have been altered to hornfels, and regionally the rocks underwent amphibolite facies metamorphism (Koivisto et al., 2012).

The intrusion contains up to 5 % sulfide (pyrrhotite, troilite, chalcopyrite, pentlandite, cubanite, millerite and heazlewoodite), which mostly occur as granular masses interstitial to the cumulate silicate mineral grains. They are finely disseminated and 100-500 mm in size. (3) There are two main types of ores. First, the 'normal' ores contains 2-6 vol% disseminated sulfides and an average of Ni and Cu grades of 0.3 and 0.42 wt %, respectively (Ni/Cu < 1). Second, the 'Ni-PGE' ore is characterized by similar sulphide contents, but a higher Ni grade and lower Cu grade (No/Cu reaches 15). A geochemical special pattern of the Ni-PGE ore is that the olivine contains much more Ni than they do in other mafic-ultramafic rocks globally

(Fig. 17-1-8). This second type of ore occur as irregular, discontinuous, lense-like bodies in the ultramafic rocks (Yang et al., 2013).

The mineral property of Kevitsa was acquired in 2008 by First Quantum Minerals Ltd (5). Kevitsa is an open pit mine mining Ni, Cu and some Au. The reserves are estimated to be of 240 million tonnes and they are expected to support mine life of over 20 years. However, there is potential to extend the mine life for another decade and to increase the volume mined. The average production is estimated to be 10'000 tonnes of Ni grading almost 12 % Ni and 20'000 tonnes of Cu grading almost 28 % Cu (5).



**Fig 17-1-1.** General geological map (Rasilainen et al., 2010).

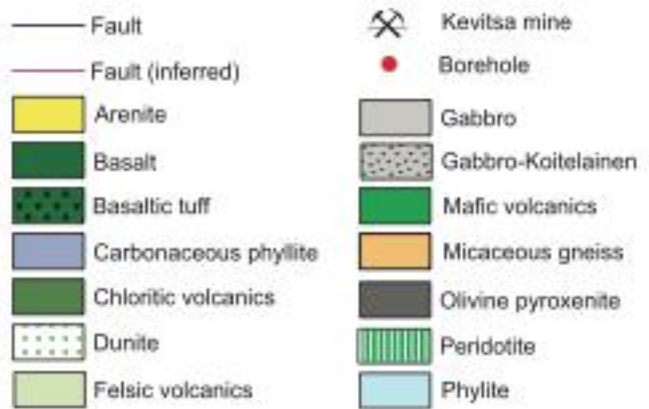
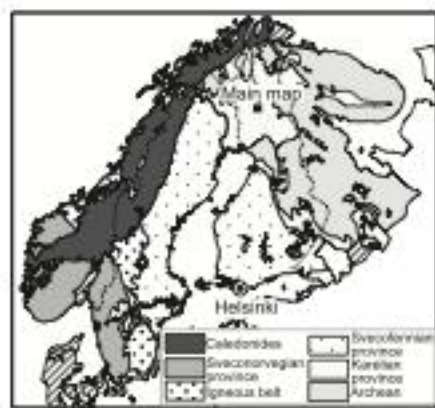
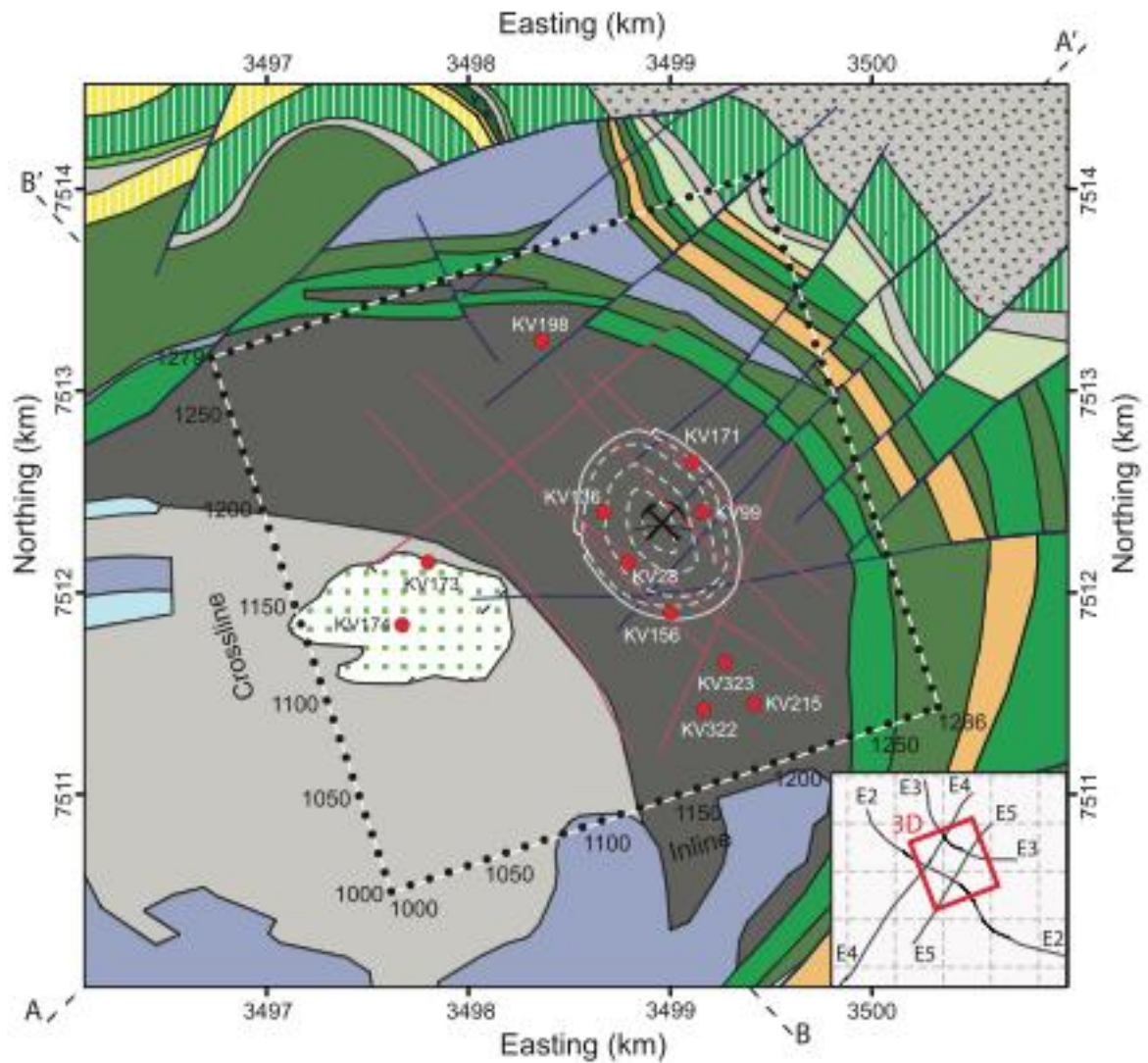
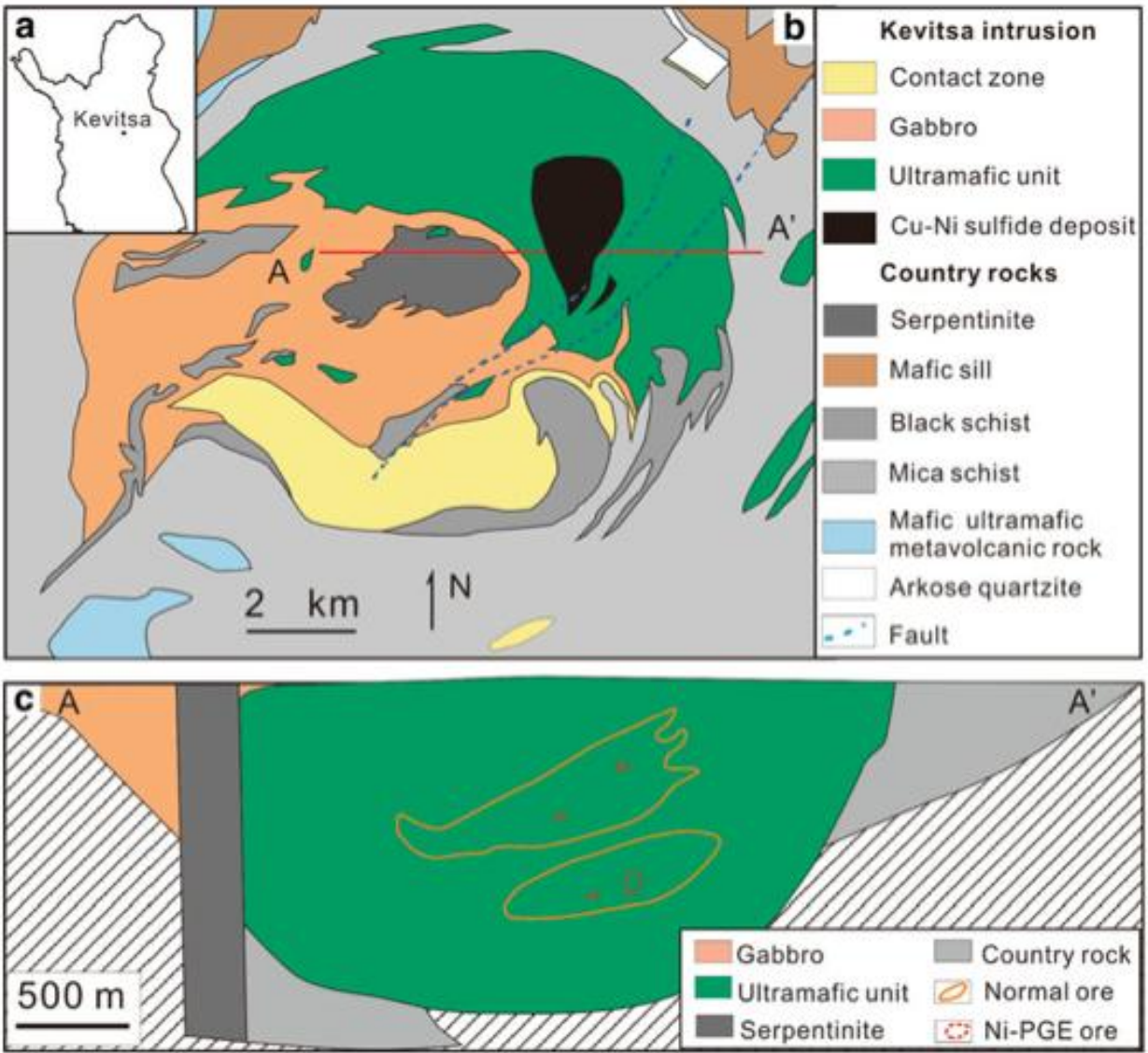


Fig 17-1-2. Geologic map (Malehmir et al. 2012).



**Fig 17-1-3.** Deposit scale geological map (Yang et al., 2013).

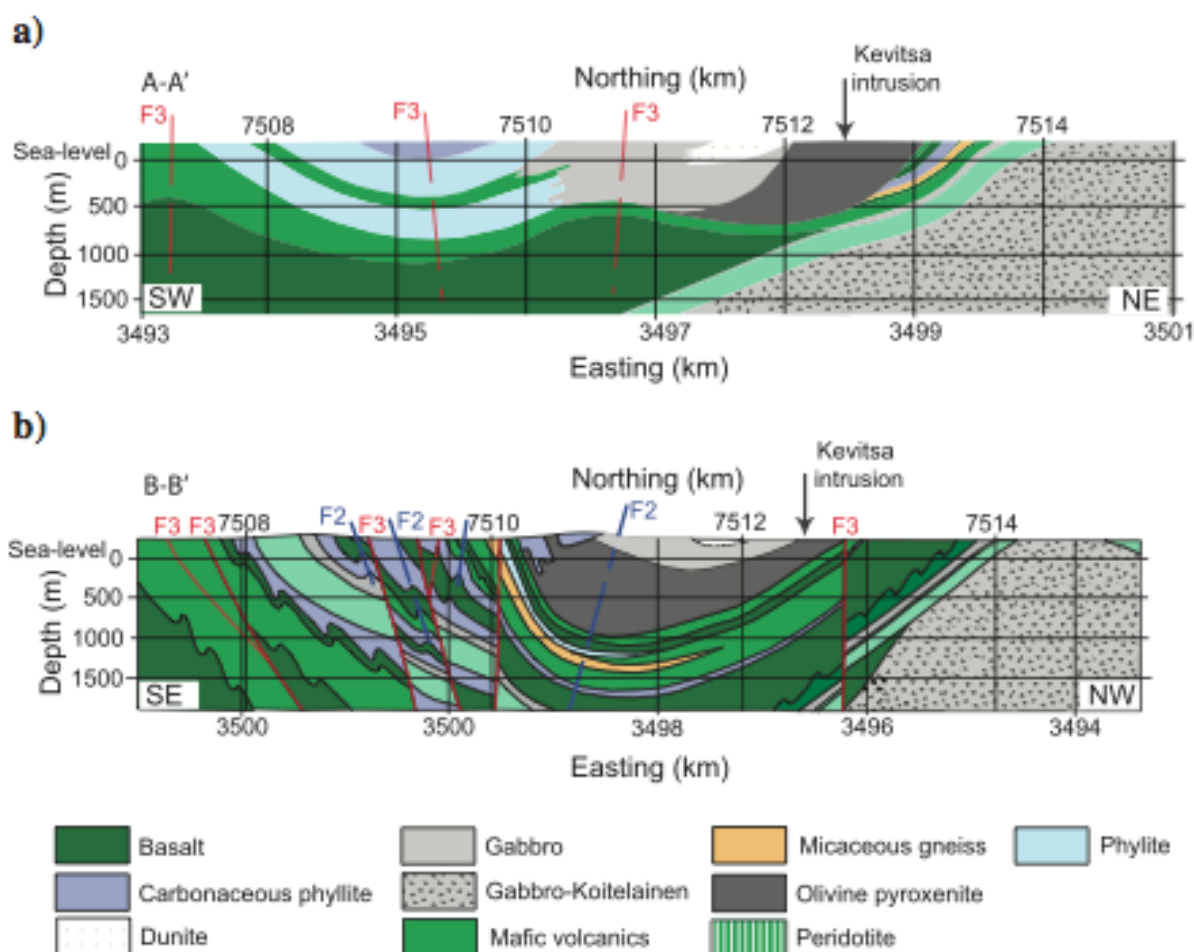


Figure 2. Simplified geologic cross sections along (a) northeast–southwest and (b) southeast–northwest directions, showing expected geometry of the main Kevitsa intrusion (an oval shaped intrusion flattening toward the southwest) and fault systems (courtesy of First Quantum Minerals Ltd.). The geologic cross sections are longer than the geologic map shown in Figure 1.

Fig 17-1-4. Geological cross-sections of the Kevitsa deposit (Malehmir et al., 2012).

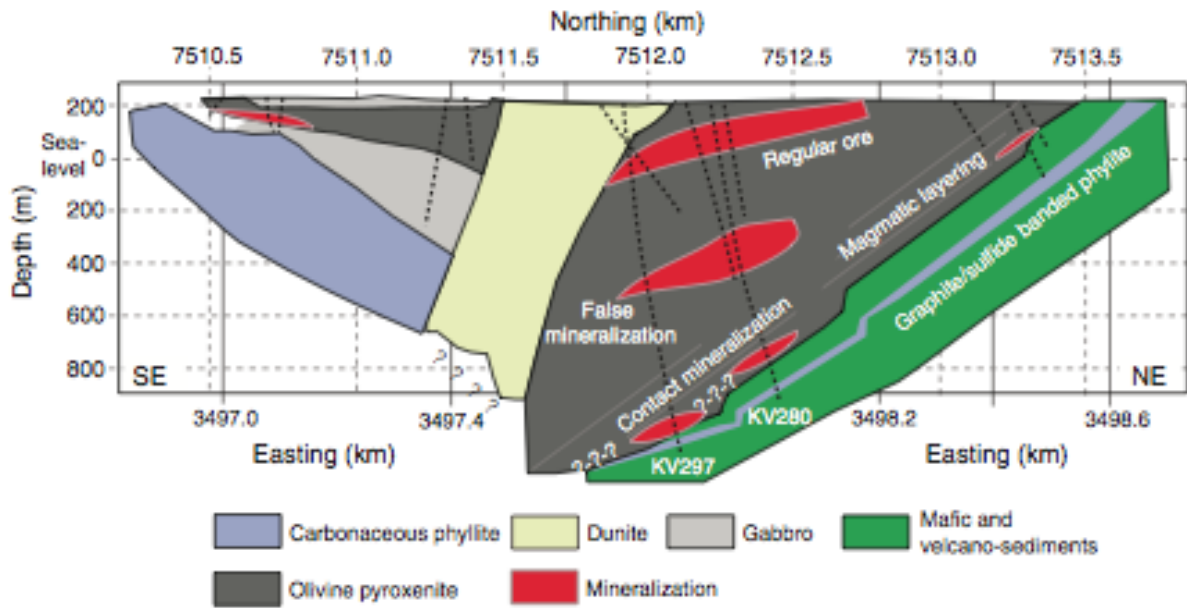


Figure 3. Schematic cross section constrained by deep magnetotelluric and borehole data, showing the main Kevitsa intrusion (hosting the main mineralization-regular ore) and proven massive sulfide mineralization occurring as false and contact mineralization in the study area.

Fig 17-1-5. Schematic cross-section. Mineralizations in red (Malehmir et al., 2012).

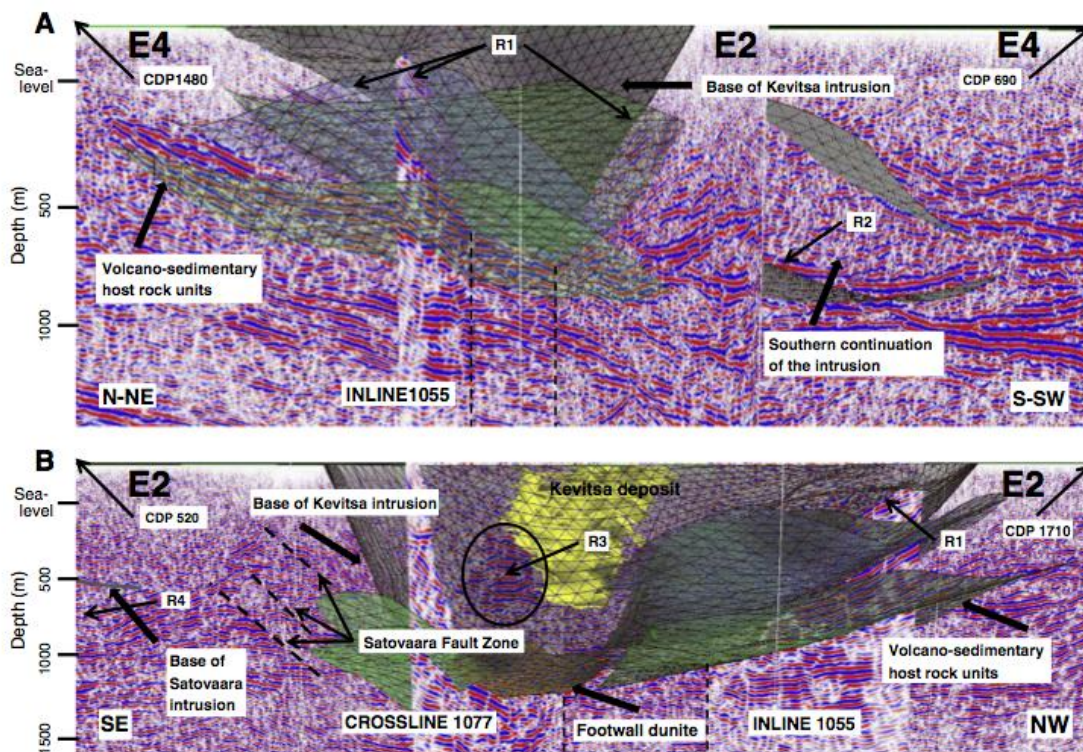
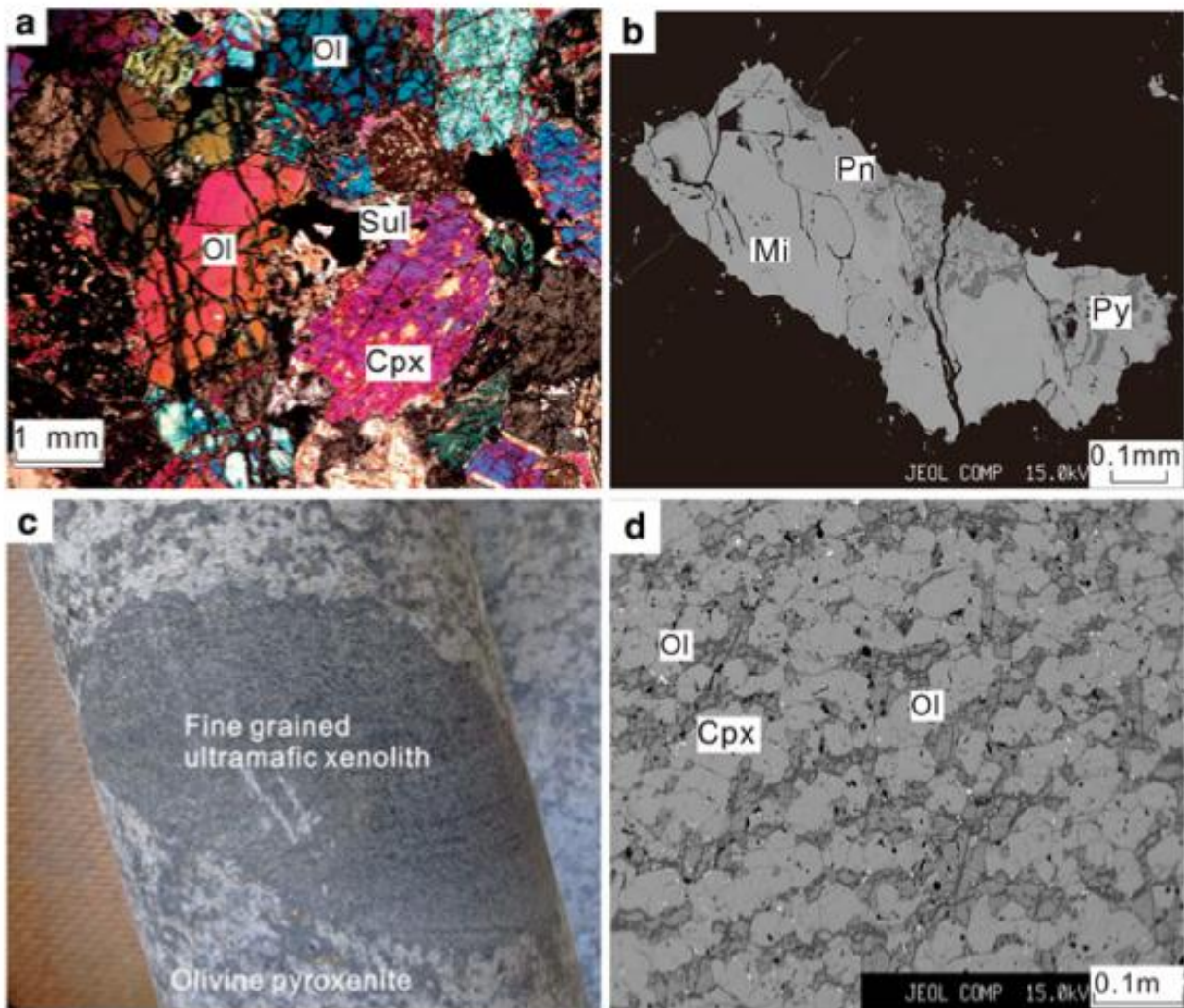
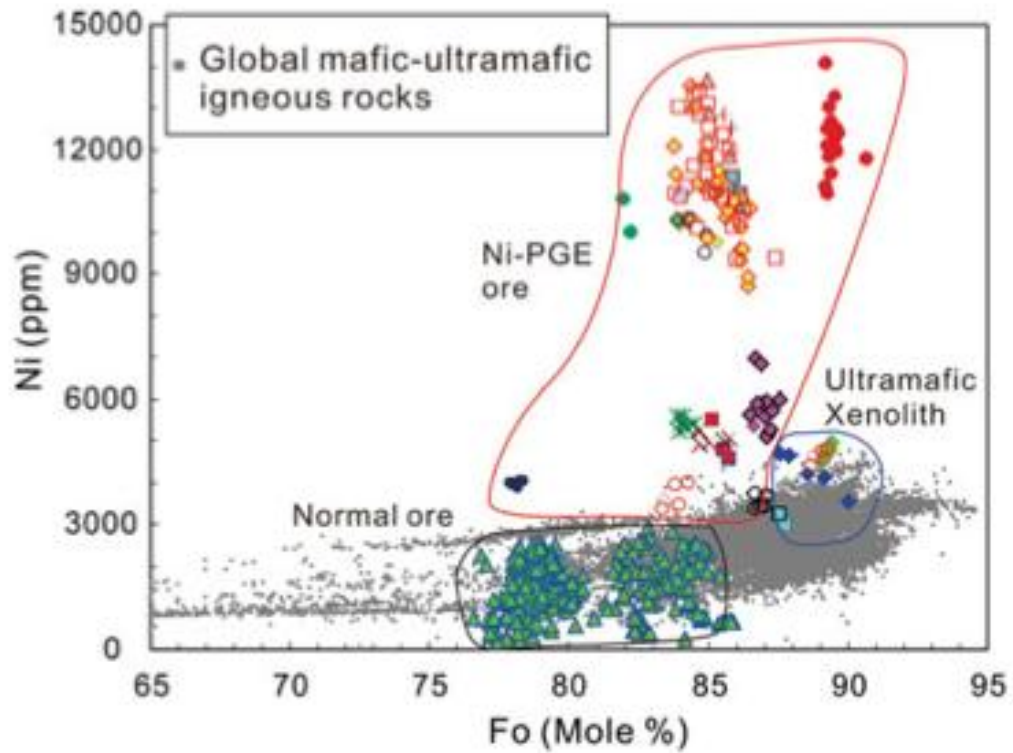


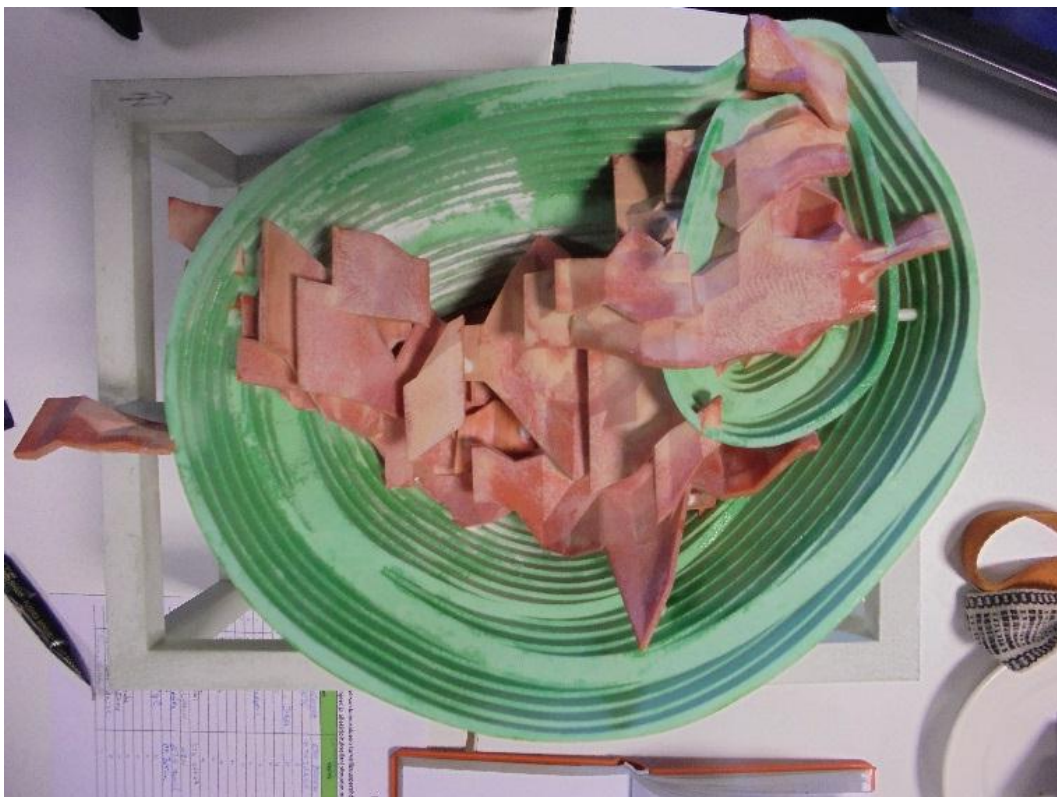
Fig 17-1-6. 3D visualization of Kevitsa (Malehmir et al., 2014).



**Fig 17-1-7. A** Microscope image of olivine and pyroxenite; **B** back-scattered electron images of sulfide minerals in the Ni-PGE ore of Kevitsa; **C** drill core containing fine-grained ultramafic xenolith; **D** back-scattered electron images of the fine-grained ultramafic xenolith. Ol: olivine; Cpx: clinopyroxene; Mi: millerite; Pn: pentlandite; Py: pyrite (figure and legend from Yang et al., 2013).



**Fig 17-1-8.** Composition of olivine in Kevitsa normal ore, Ni-PGE ore, and ultramafic xenoliths, compared to olivines from other igneous rocks globally (Yang et al., 2013).



**Fig. 17-1-9.** Kevitsa mine model with ore body outline (pink) and final extent of mine when completely mined (green) (photo: Ch. Bovier).





**Fig. 17-1-10.** selected area for following blasting in the open pit (photo: Ch. Bovier).

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*Contributions to Mineralogy and Petrology*, Vol. 166, Issue 1, pages 81-95

(1) <http://www.first-quantum.com/Careers/our-locations/finland/operations-at-kevitsa/default.aspx>

(2) <http://en.gtk.fi/ExplorationFinland/Moreinfo/kevitsa.html>

(3) <http://www.infomine.com/minesite/Kevitsa.html>

(4) <http://en.gtk.fi/information/services/commodities/Nickel/kevitsa.html>

(5) <http://www.first-quantum.com/Our-Business/operating-mines/Kevitsa/default.aspx>.

**Compiled by: Christelle Bovier**

<i>Date: July 18, 2014</i>	<i>STOP No.: 18-1</i>
<b>Locality name: Kittilä</b>	<b>Alternative name: Suurikuusikko</b>
<i>Main commodity: Au</i> <i>Geological setting or genetic model: IOCG/orogenic Au</i> <i>Current development status: active mine. Open pit and underground operation</i>	
<b>WGS Latitude: 67.90154</b>	<b>WGS Longitude: 25.391019</b>
<i>KKJ Northing: 7535700</i>	<i>KKJ Easting: 2558600</i>
<i>Municipality: Kittilä</i>	
<i>Location &amp; access: 50 km NE from Kittilä. 3 km from a sealed road, a public gravel road adjacent to the area.</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Kittilä Greenstone Belt</i>
<i>Owner (2014): Agnico-Eagle</i>	

### **Geology**

In 1986, coarse visible gold was discovered along a road cut. During the following five years, the Geological survey of Finland conducted regional exploration programs. From 1999 to 2005, the property was explored by Riddarhyttan Resources AB. In 2005, the property was acquired by Agnico-Eagle, a Canadian company, which decided to construct an open pit, an underground mine and a mill (Scales, 2008). Ore production in the open pit started in May 2008 and was exhausted in 2012. The production underground started in 2010 and is expected to last till 2034. The production 2013 was of 146'421 oz gold. The proven and probable reserves contain 4.7 million ounces (32 million tonnes at 4.6 g/t gold) as of December 31, 2013. There is still exploration going on, both on the site of the mine and further away on the Suurikuusikko Trend (5).

The deposit is located within the Kittila Greenstone Belt (2 Ga), which is oriented nearly vertical. The region consists of mafic volcanic and sedimentary rocks (5). The orogenic gold deposit is hosted by Mg-tholeiitic and Fe-tholeiitic basalts of a volcano-sedimentary unit, which also contains graphite-bearing volcanic tuffs (Fig. 18-1-2 ,18-1-4). The mineralization underwent strong albitization, carbonitization and sulphidization (Kojonen and Johanson, 1999). The mine area is underlain by greenschist facies (chlorite-carbonate) mafic volcanic assemblages (Scales, 2008).

A 100- to 200-metre-thick structural zone, the 'Suurikuusikko Trend', hosts the Kittila deposit. Mineralized zones have been found over a strike length of more than 25 km (5). Figure 18-1-3 shows five main zones of the known gold reserves and resources on which most of Agnico Eagle's work has focused. These in total about 4.5 km long segments are located on the Suurikuusikko Trend (5). The mineralized domain in the shear zone is subvertical (2).

There is no visible gold in the Kittila ore. The gold is tied up with arsenopyrite, which contains about 73 % of the gold, and arsenic-rich pyrite, which contains about 23 % of the gold (Figs. 18-1-8, 18-1-9, 18-1-10). The remaining 4 % occur as free extremely small grains in pyrite. (Scales, 2008). Occasionally, gold may also occur in gersdorffite (2). The 'free' gold is found in the outer, oxidized or eroded sections of the ore (5). Au-rich arsenopyrite and pyrite occur disseminated in microfractures, shear fabrics, and stylolitic features. Pyrite + arsenopyrite ± gersdorffite intergrowths are characteristic and these commonly from larger aggregates (2). Only 4 % of the gold is relatively easy to extract, the free gold. The rest is called refractory (5). Gangue minerals are albite, quartz, K feldspar, calcite, ankerite, siderite, micas and chlorite (2).

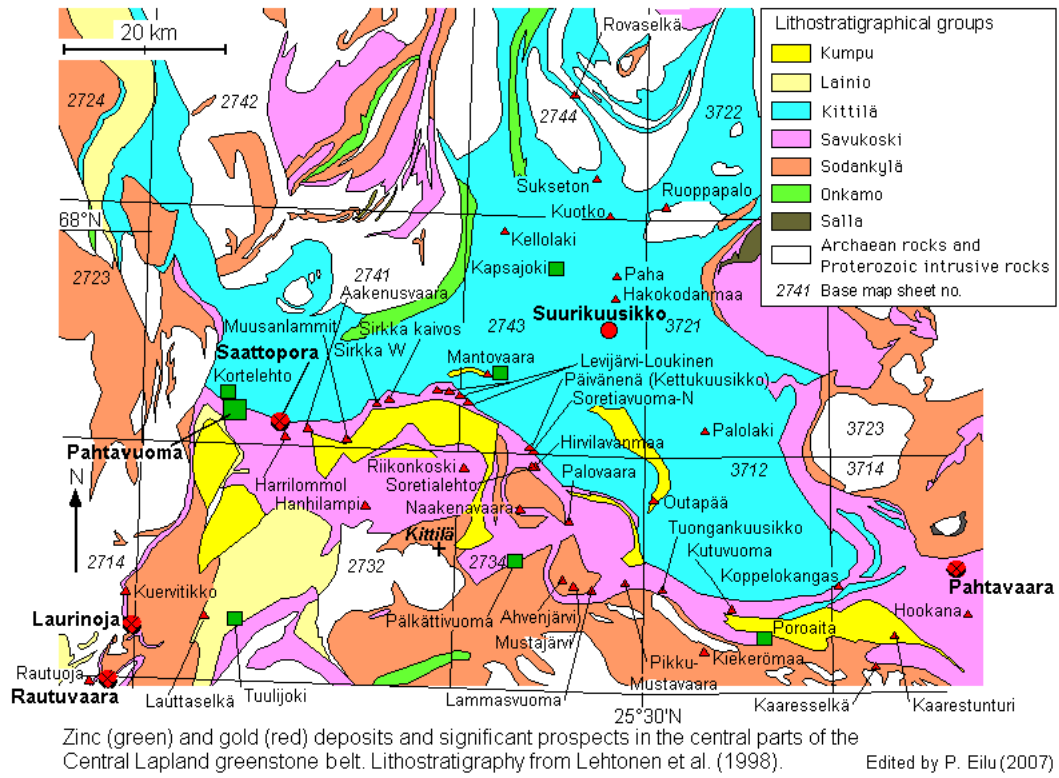


Figure 18-1-1. Regional geological map (1).

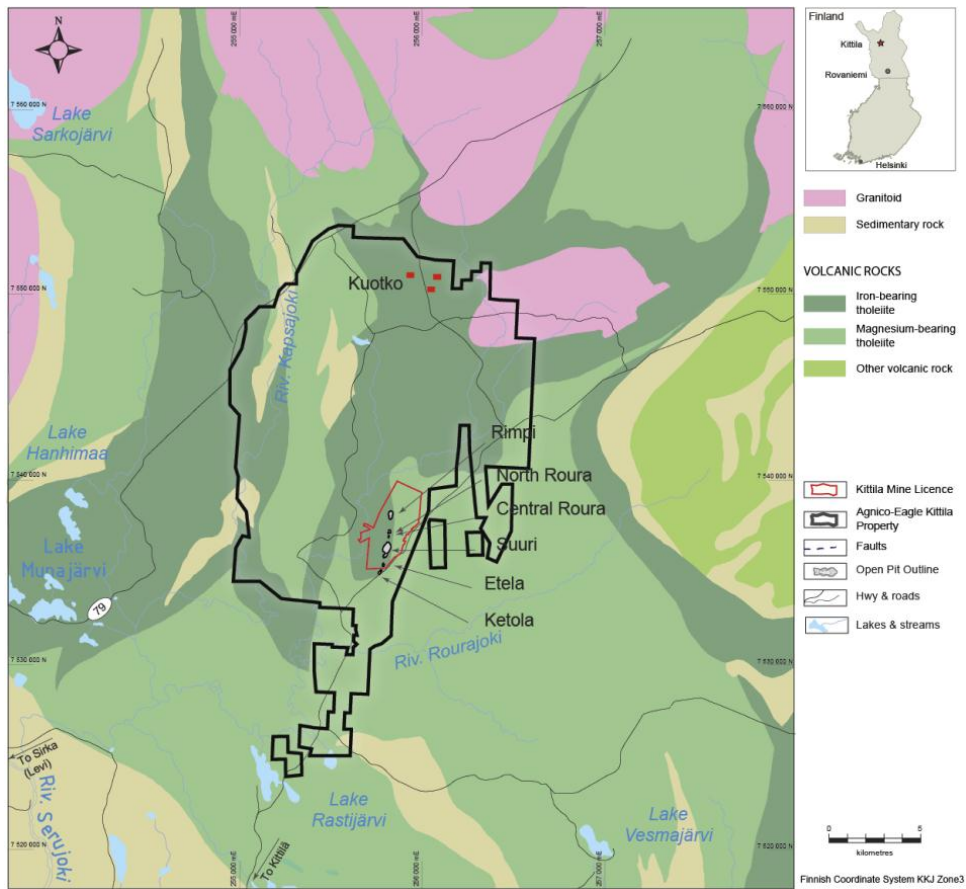


Figure 18-1-2. Surface geology of the mine (6).

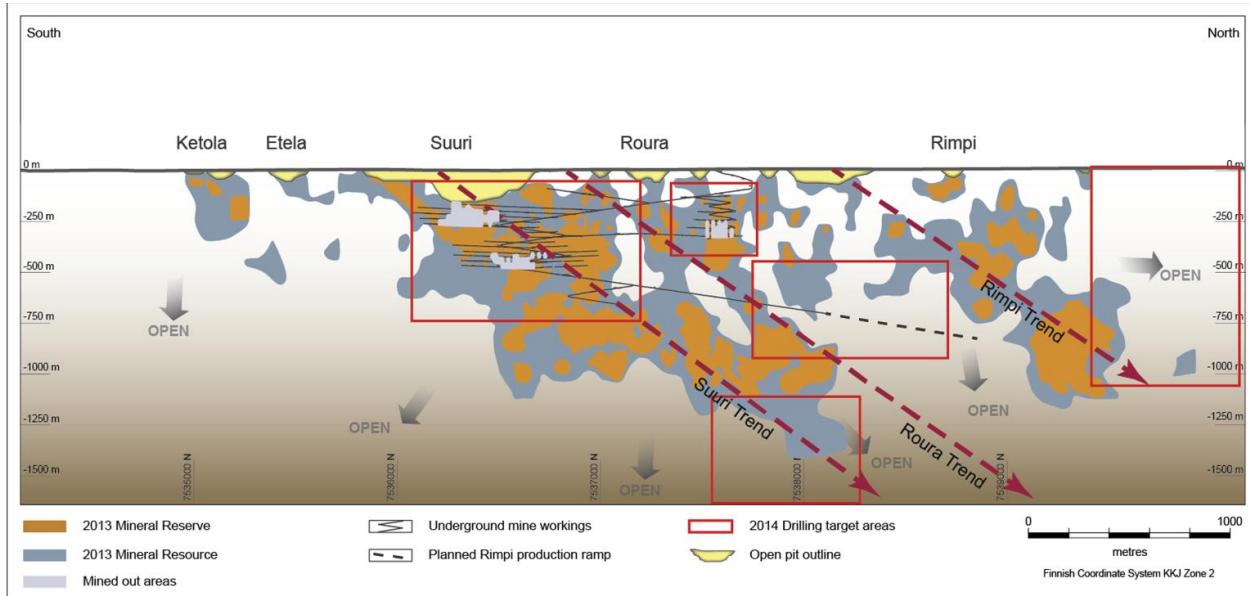


Figure 18-1-3. Composite Longitudinal Section of Kittila Mine (7).

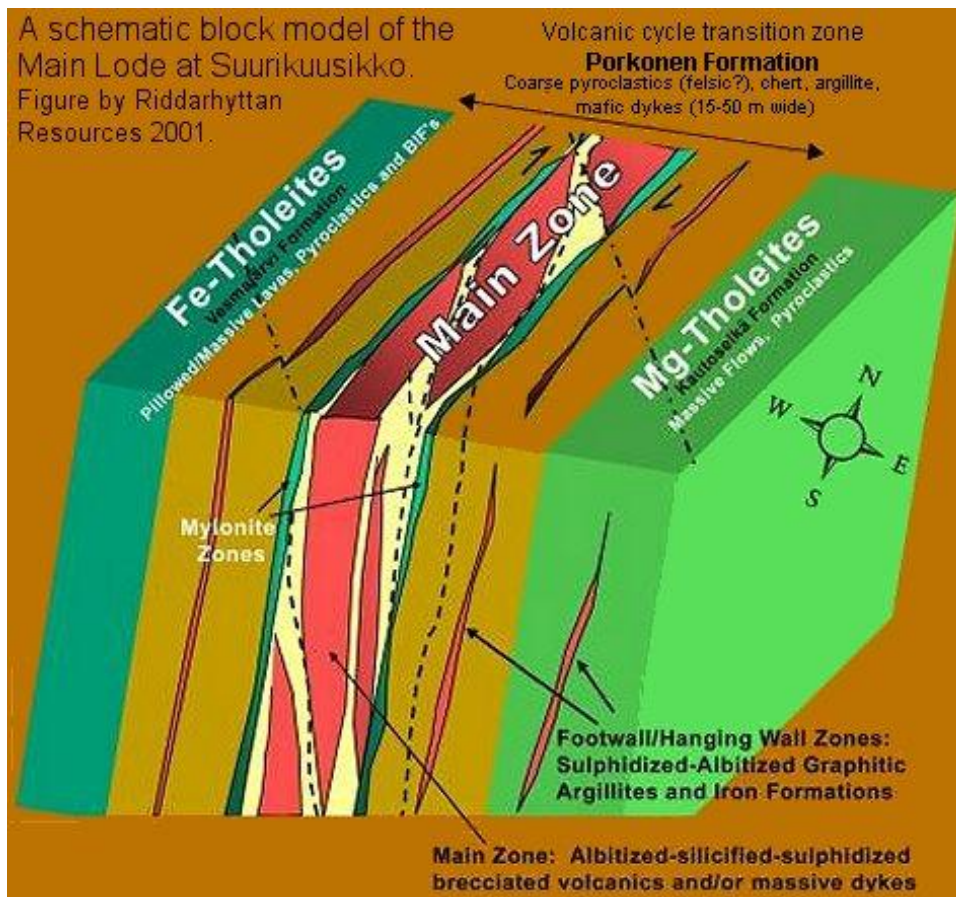
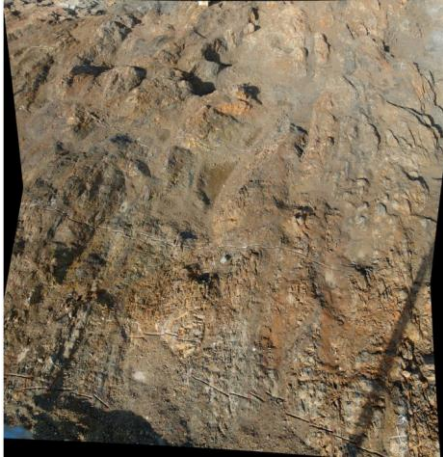


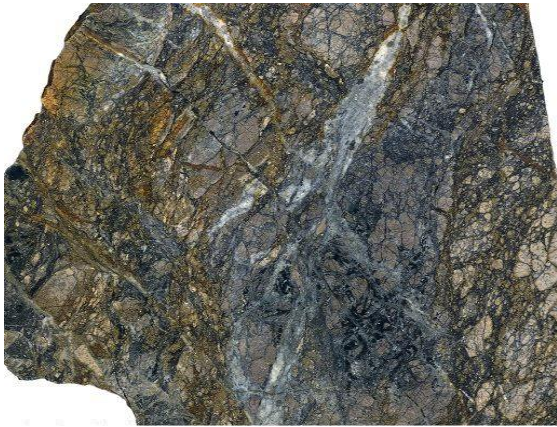
Figure 18-1-4. An older cross-section (2001) (9).



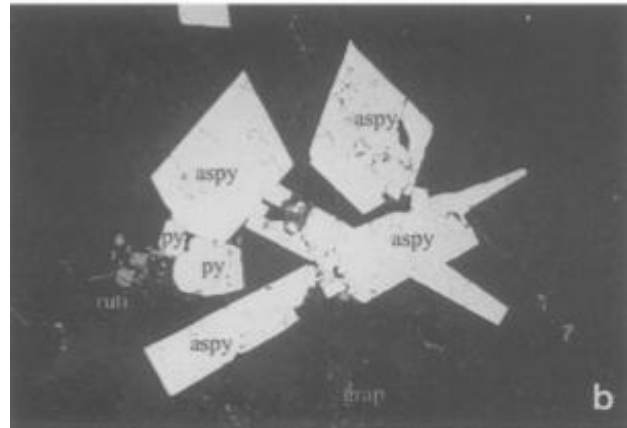
**Figure 18-1-5.** Ore-outcrop surface, planview, North up (Photo: Juhani Ojala, 2007) (10).



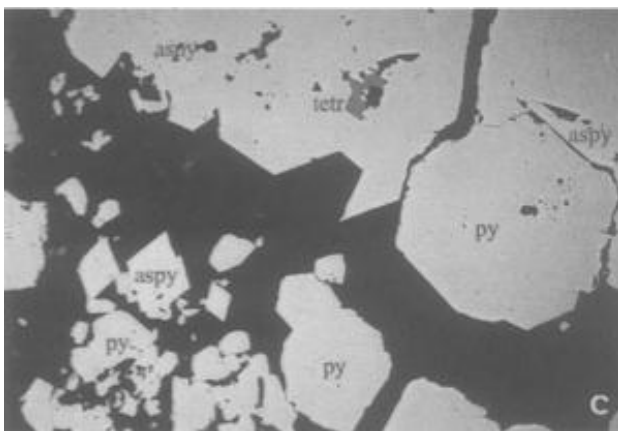
**Figure 18-1-6.** Typical brecciated ore at Suurikuusikko (Photo: Ridarhyttan AB, 2001) (8).



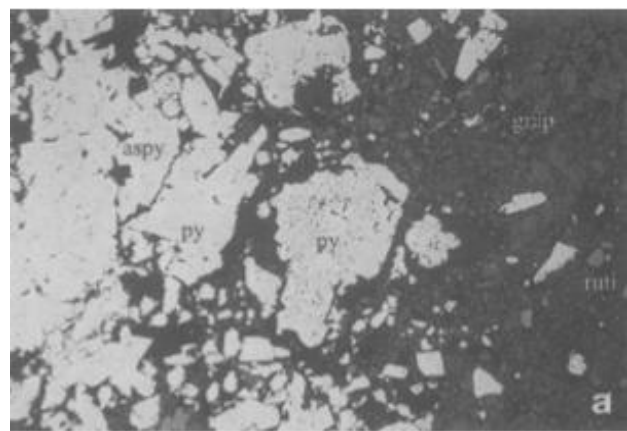
**Figure 18-1-7.** High-grade ore: intense multi-stage brecciation and leaching, abundant arsenopyrite and pyrite. Host rock is a graphitic phyllite or graphitic tuffite of intermediate primary composition. Field of view 6 cm (11).



**Figure 18-1-8.** Euhedral arsenopyrite (aspy) and pyrite (py), disseminated fine-grained graphite and rutile (ruti); the length of the picture is 0.75 mm (Kojonen and Johanson, 1999).



**Figure 18-1-9.** Arsenopyrite (aspy), pyrite (py) and tetrahedrite (tetr); the length of the picture is 0.378 mm (Kojonen and Johanson, 1999).



**Figure 18-1-10.** Arsenopyrite (Aspy), pyrite (py) and graphite (grap); the length of the picture is 0.75 mm (Kojonen and Johanson, 1999).



**Figure 18-1-11.** Aerial view of Kittilä mine in september 2007 (4).



**Fig. 18-1-12.** Open-pit of Kittilä: Wedging out of the ore body on the opposite wall of the pit (photo: Ch. Bovier).



**Fig. 18-1-13.** Kittilä high-grade ore in drill core (photo: Ch. Bovier).

**Fig. 18-1-14.** Boudinaged and foliated veins in Kittilä drillcore (photo: D. Klimentyeva).



**Fig. 18-1-15.** Remnants of pillow basalt in Kittilä drill core (photo: D. Klimentyeva).

*References & online sources*

Kojonen, K. and Johanson, B. (1999). Determination of refractory gold distribution by microanalysis, diagnostic leaching and image analysis. *Mineralogy and Petrology*. Vol 67, pages 1-19

Scales, M. (2008) *Flying toward the Finnish line - Kittila gold mine readied for September startup*. *Canadian Mining Journal*, Vol. 129, Issue 5, pages 32-35

(1-4), (8-11) <http://en.gtk.fi/information/services/commodities/Gold/suurikuusikko.html>

(5-7) <http://www.agnicoeagle.com/en/Operations/Our-Operations/Kittila/>

**Compiled by: Christelle Bovier**

<i>Date: July 20, 2014</i>	<i>STOP No.: 20-1</i>
<b>Locality name: Hannukainen</b>	<i>Alternative name: Laurinoja</i>
<i>Main commodity: Fe</i> <i>Geological setting or genetic model: IOCG</i> <i>Current development status: definitive feasibility study</i>	
<b>WGS Latitude: 67.539810</b>	<b>WGS Longitude: 23.97931</b>
<i>KKJ Northing: 2499300</i>	<i>KKJ Easting: 7496350</i>
<i>Municipality: Pajala</i>	
<i>Location &amp; access: 25 km NE of Kolari. One km to a sealed road, gravel roads to the mine site</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Central Lapland Greenstone Belt</i>
<i>Owner (2014): Northland Resources</i>	

### **Geology**

According to the definitive feasibility study that was finalized by Northland resources in March 2014, measured and indicated resource of Hannukainen are 187 Mt grading 30% Fe total, 0.18% Cu and 114 ppb Au (Northland website).

The ore mineral assemblage at Hannukainen contains magnetite, pyrite, pyrrhotite and chalcopyrite, bornite, gold, molybdenite, and uraninite (guide and references wherein).

Five types of alteration assemblages are identified at Hannukainen:

- early albitization
- scarn alteration (clinopyroxene-actinolite-magnetite), main mineralization stage
- potassic alteration (biotite, K-feldspar,  $\pm$ magnetite, clinopyroxene-actinolite)
- sulphidization (Cu-Au minerals, second generation of magnetite)
- carbonation (calcite).

Age of the main mineralization stage is  $\sim$ 1.8 Ga (Niiranen et al., 2007) based on U-Pb age of zircons in scarn ( $1797\pm 5$  Ma) and metamorphic titanite in altered wallrock (1810-1780 Ma).

Based on fluid inclusions data, two different stages were defined for the Hannukainen ore-bearing fluids (Niiranen et al. 2007). The first stage H<sub>2</sub>O fluids contained 12-22 weight percent of NaCl<sub>eq</sub>, were Fe-bearing and with Na-Ca  $\pm$  K, suggested temperature interval is 450–550°C. The second stage fluids were highly saline (32–56 wt.% Na-Cl<sub>eq</sub>) H<sub>2</sub>O-CO<sub>2</sub>, and differed from the first stage fluids by the absence of Fe, temperature was 290–370°C (Niiranen, 2011).



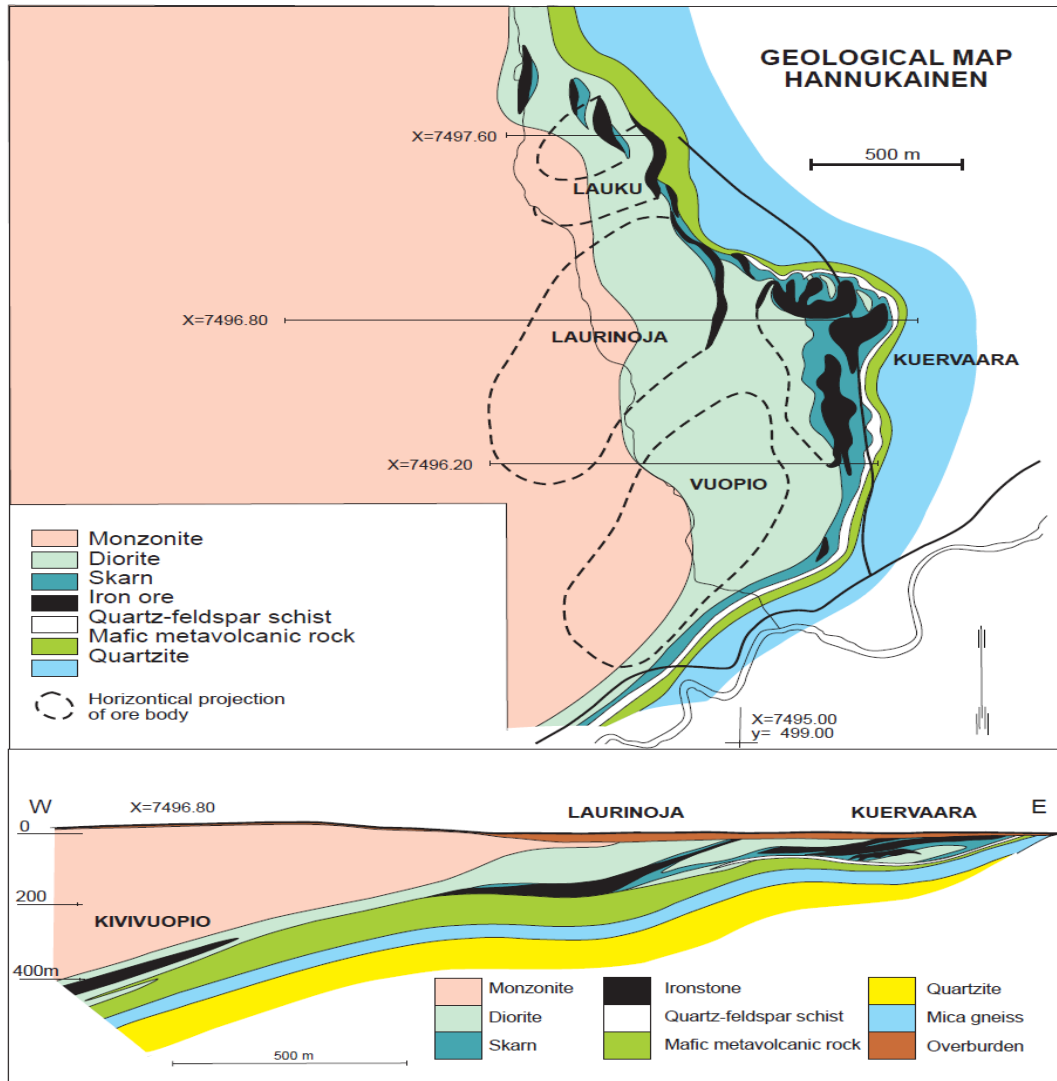
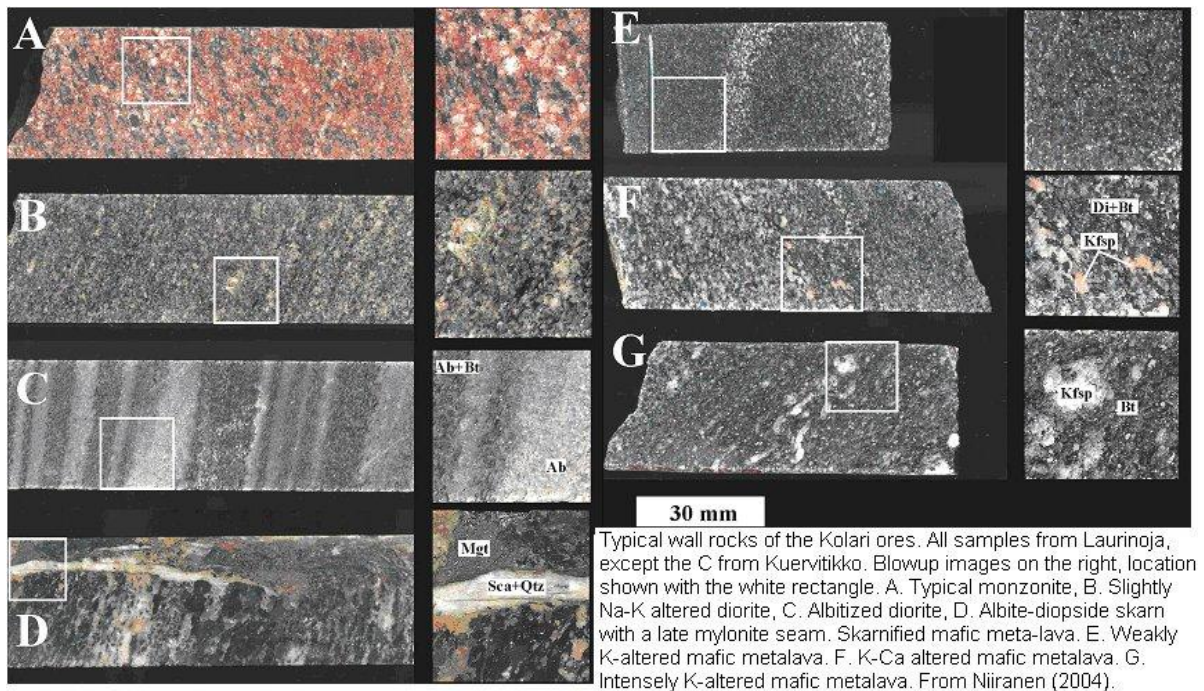


Fig. 20-1-1. Geology and cross section of Hannukainen deposit (Niirainen, 2011; from GTK website).



Fig. 20-1-2. The Laurinoja open pit at Hannukainen (Photo by Pasi Eilu, 1985; from GTK website).



**Fig. 20-1-3.** Drill core samples from Hannukainen (from GTK website).



**Fig. 20-1-4.** Hannukainen: Banded amphibole-rich metasediments with high-temperature alteration and big magnetite crystals at contact (photo: D. Klimentyeva).



**Fig. 20-1-5.** Hannukainen: Scapolite crosscutting the foliation. Scapolite is stabilized at high *S* fugacity (photo: D. Klimentyeva).

*References & online sources*

- Niiranen, T. 2004. Locality 2. Hannukainen. In: Eilu, P. (ed.) Iron oxide-copper-gold excursion and workshop, Northern Finland and Sweden 31.5.–4.6.2004. Geol. Surv. Finland, Report M 10.3/2004/1/10. 42–57.
- Niiranen, T., Poutiainen, M., and Mänttari, I., (2007). Geology, geochemistry, fluid inclusion characteristics, and U–Pb age studies on iron oxide–Cu–Au deposits in the Kolari region, northern Finland. *Ore Geology Reviews*.
- Niiranen, T., 2011. IOCG and Porphyry-Cu deposits in Northern Finland and Sweden (25th International Applied Geochemistry Symposium 2011, Excursion guide). Day 1, Stop 1, page 21.
- <http://northland.eu/en-us/projects/hannukainen>
- <http://new.gtk.fi/export/sites/en/information/services/commodities/Gold/hannukainen.html>

**Compiled by: Dina Klimentyeva**

<i>Date: July 20, 2014</i>	<i>STOP No.: 20-2</i>
<b>Locality name: Sahavaara</b>	
<i>Main commodity: Fe</i> <i>Geological setting or genetic model: IOCG</i> <i>Current development status: production</i>	
<b>WGS Latitude: 67.36666</b>	<b>WGS Longitude: 23.29999</b>
<i>Municipality: Pajala</i>	
<i>Location &amp; access: 80 km from Kolari</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Central Lapland Greenstone Belt</i>
<i>Owner (2014): Northland Resources</i>	

### **Geology**

The deposits of Sahavaara group, as well as Hannukainen deposit, are located on the margin of the Central Lapland greenstone belt (CLGB; Fig. 20-2-1). Rifting of the Archean basement commenced the CLGB evolution at the Archean-Proterozoic boundary.

The main structural feature related to these deposits is the Pajala shear zone (or Pajala-Kolari shear zone, PSZ), which is a 50 to 100 km wide, NNE-SSW trending complex that was active during Svecofennian orogeny between 1.98-1.79 Ga. Initiated by continent-continent collision of the Norbotten and Karelian craton at 1.89-1.86 Ga, the lineaments of PSZ were reactivated during a later orogenic events between 1.83-1.79 Ga (Baker and Lepley, 2010). Three deformation stages mark the development of CLGB (Vaisanen, 2002). Peak metamorphic conditions (upper greenschist to upper amphibolite facies) were achieved during the second stage.

Bedrock units in the area include:

- 2.44-1.91 Ga Karelian sequence: tholeiitic volcanic rocks and marine sediments
- <1.88 Ga Svecofennian sequence: quartzites, phyllites, mica schists, conglomerates, minor felsic intrusions

Intrusions:

- 1.89-1.86 Ga Haparanda suite, mafic to felsic,
- 1.82-1.77 Ga granitoids (Niiranen, 2011).

### **Sahavaara deposit**

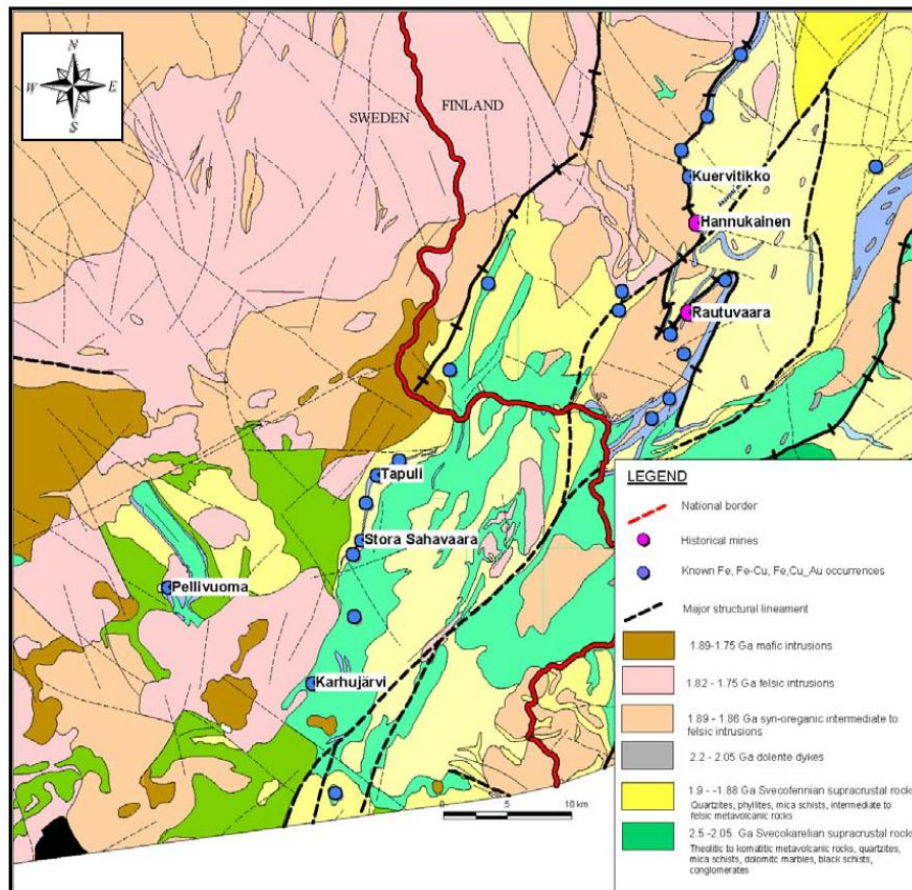
Sahavaara deposit includes two tabular ore bodies of magnetite skarn mineralization. In total, Södra Sahavaara and Stora Sahavaara have a combined measured and indicated resource estimate of 86.8 Mt, grading 39.8% Fe (Northland technical report, 2010).

Main ore minerals at Sahavaara are magnetite, pyrrhotite, and pyrite (Fig. 20-2-3). Gangue minerals are serpentine, tremolite, diopside, and chlorite. Two-stages of skarn alteration are dominant within the ore zone; early diopside-tremolite stage and late retrograde serpentine stage (Fig. 20-2-4). The alteration horizon extends to 200 below the ore zone. Clay alteration is observed within the faults in the skarn zone.

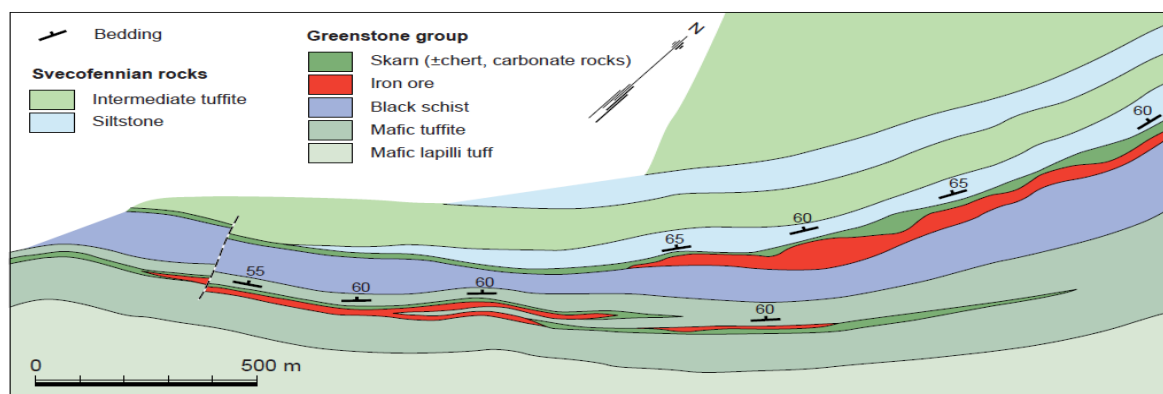
Hanging wall to the west of the skarn unit consists of graphitic phyllite, quartzitic phyllite, and quartzite. The footwall rock immediately below the skarn is graphitic schist with fine-grained quartz, scapolite, graphite, biotite, tremolite with pyrrhotite-pyrite and chalcopyrite mineralization.

Traditionally the deposits in the Pajala area have been defined as "skarn iron ores", the ores

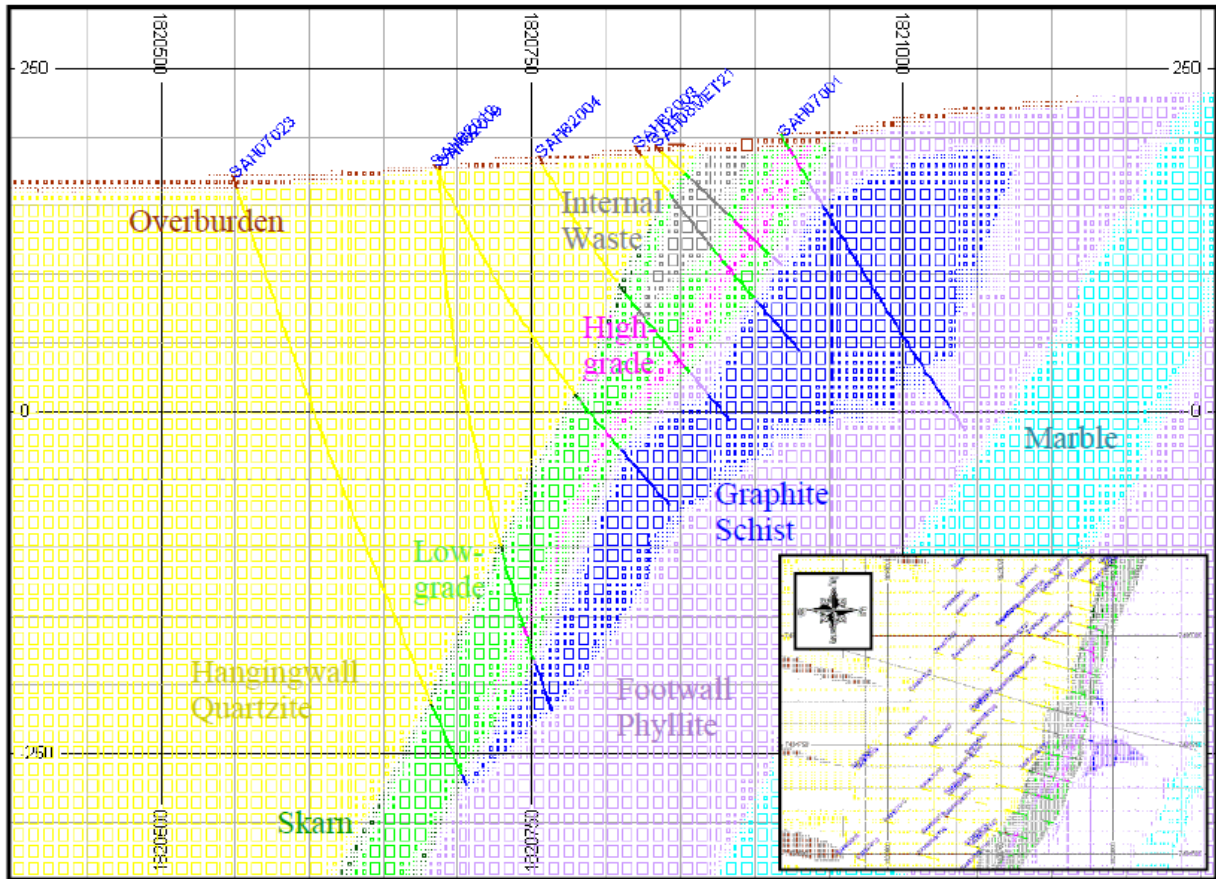
considered syn-genetic, based on spatial association of orebodies to the contacts of intrusion. However, the U-Pb zircon and titanite ages from the intrusions and altered rocks at Kolari indicate that the mineralization post-dates the magmatism of hanging wall diorite and monzonite at Hannukainen by ~60 Ma. This evidence, together with similarities to the IOCG deposits in Cloncurry district, Australia, led to the hypothesis that Kolari deposits are examples of IOCG mineralization (Niiranen, 2011).



**Fig. 20-2-1.** Mineral occurrences and deposits in Pajala-Kolari shear zone (from Baker and Lepley, 2010).



**Fig. 20-2-2.** Geology of Stora Sahavaara deposit (from Niiranen, 2011).



**Fig. 20-2-3.** Cross-section through Sahavaara deposit (from Baker and Lepley, 2010).



**Fig. 20-2-4.** Sahavaara: Secondary mineralization of zeolite (photo: D. Klimentyeva).



**Fig. 20-1-5.** Sahavaara skarn mineral assemblage with epidote and actinolite (photo: D. Klimentyeva).

#### References

- Abongwa, P. 2009. Mineral texture and composition of magnetite in the Sahavaara IOCG deposit, Pajala area. Master's thesis, Lulea University of Technology.
- Baker, H., Lepley, B. (SRK Consulting). 2010. Mineral resource estimate for the Sahavaara iron deposit.
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- Ojala, V. J., Weihed, P., Eilu, P., Iljina, M. 2007. Metallogeny and tectonic evolution of the Northern Fennoscandian Shield: Field trip guidebook. Geological Survey of Finland, Guide 54. Day 4, Stop 1, page 73.
- Väisänen, M. 2002. Structural features in the *central Lapland greenstone belt*, northern Finland. Geol. Surv. Finland, Report K 21.42/2002/3.

**Compiled by: Dina Klimentyeva**

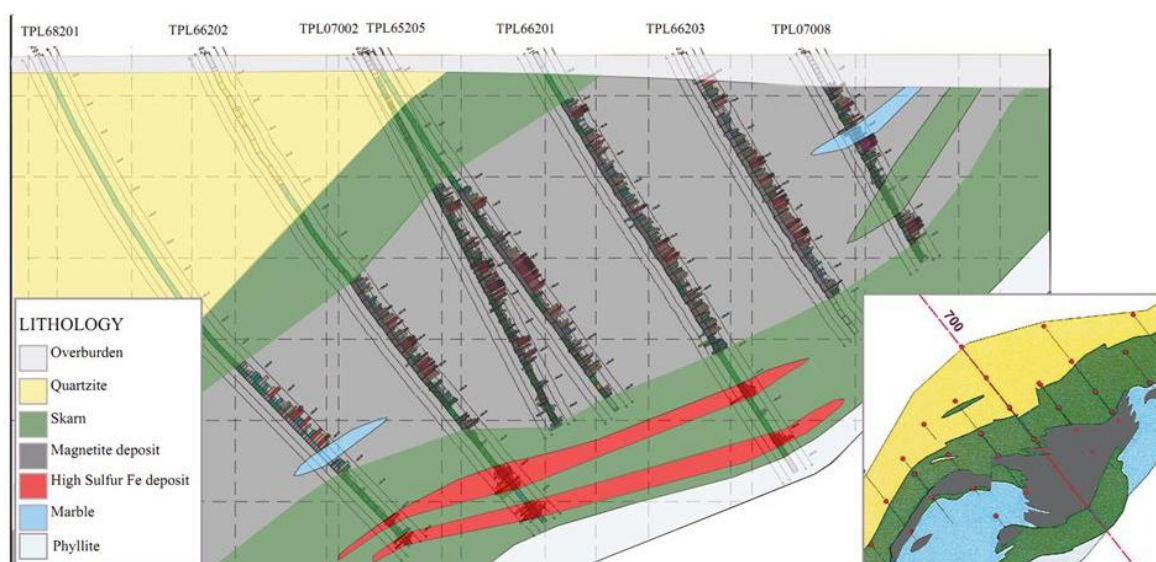
<i>Date: July 20, 2014</i>	<i>STOP No.: 20-2b (not visited)</i>
<b>Locality name: Tapuli</b>	
<i>Main commodity: Fe</i> <i>Geological setting or genetic model: IOCG</i> <i>Current development status: production</i>	
<b>WGS Latitude: 67.441594</b>	<b>WGS Longitude: 23.422223</b>
<i>Municipality: Pajala</i>	
<i>Location &amp; access: 3.5 km from Sahavaara</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Central Lapland Greenstone Belt</i>
<i>Owner (2014): Northland Resources</i>	

### Geology

The Tapuli deposit is located 3.5 km NE of Sahavaara and is similar to Sahavaara in wallrock and structure. Total measured resources are 52.8 million tonnes, with an average grade of 27 % Fe (Baker, 2010). Slightly elevated concentrations of S, Co, and Cu are observed in sulfur-rich parts of the deposit. The deposit occurs as a semi-continuous mineralized zone beneath an average of 11 m of till and includes 7 mineralized lenses dipping 45-60° to the WNW and NW.

The sole ore mineral in Tapuli is magnetite, with only traces of pyrite and pyrrhotite. Clinopyroxene, tremolite, actinolite, serpentine, and carbonates are gangue. Majority of mineralization is breccia-style: irregularly shaped magnetite patches, actinolite and biotite brecciate the host rock.

Alteration is classified into three assemblages (Niiranen, 2011): clinopyroxene-tremolite alteration (pre-dating the mineralization), magnetite-actinolite alteration (mineralization event), and serpentine alteration (post-dating mineralization, possibly increasing the ore grade).



**Fig. 20-2b-1.** Cross-section through the Tapuli deposit (from Baker and Lepley, 2010).





**Fig. 20-2b-2.** Tapuli drill core (from Baker and Lepley, 2010).

*References*

Baker, H., Lepley, B. (SRK Consulting). 2010. Mineral resource estimate for the Tapuli iron deposit, Pajala municipality, Norbotten county, Sweden.

*Previous field trip guides*

Niiranen, T., 2011. IOCG and Porphyry-Cu deposits in Northern Finland and Sweden (25th International Applied Geochemistry Symposium 2011, Excursion guide). Day 1, Stop 5, page 22.

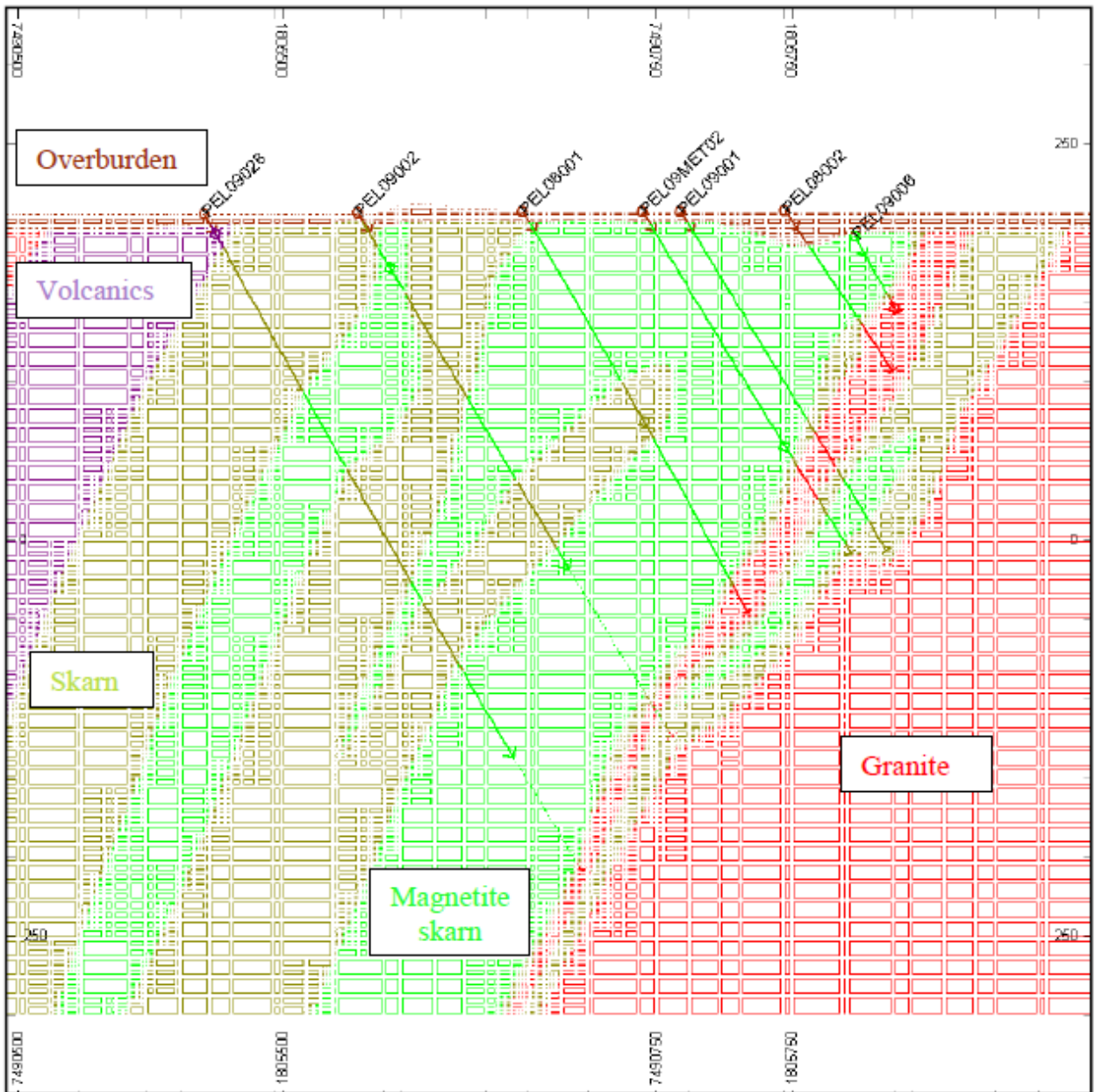
**Compiled by: Dina Klimentyeva**

<i>Date: July 20, 2014</i>	<i>STOP No.: 20-3 (optional)</i>
<b>Locality name: Kaymajarvi</b>	<i>Alternative name: Pellivuoma</i>
<i>Main commodity: Fe</i> <i>Geological setting or genetic model: IOCG</i> <i>Current development status: production</i>	
<b>WGS Latitude: 67.396162</b>	<b>WGS Longitude: 22.941394</b>
<i>Municipality: Pajala</i>	
<i>Location &amp; access: around 30 km from Sahavaara, first along road 99, then gravel road.</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Central Lapland Greenstone Belt</i>
<i>Owner (2014): Northland Resources AB</i>	

### **Geology**

Total measured and indicated resources amount to 57.34 Mt of ore, with an average grade of 30% Fe. Bedrock and the general setting are similar to Sahavaara, except for the presence of a granite intrusion. The deposit contains several mineralized lenses conformable with the contact between granite and the footwall. Three alteration assemblages, similar to Tapuli, define skarn mineralization (Baker and Lepley 2010).

The main ore mineral is magnetite. Sulfide mineralization also occurs, represented by pyrite, pyrrhotite, and chalcopyrite. Gangue minerals are dominated by serpentine, especially in the ore-rich areas. Cross-section through the deposits is shown on Fig. 20-3-1. The age of the granite intrusion is ~1.8 Ga. A several-meter thick phlogopite-chlorite-garnet alteration zone occurs at the contact with granite.



**Fig. 20-3-1.** Cross section through Pellivuoma deposit (from Baker and Lepley, 2010).

**References**

Baker, H., Lepley, B. (SRK Consulting). 2010. Mineral resource estimate for the Pellivuoma iron deposit, Pajala municipality, Norbotten county, Sweden.

**Compiled by:** Dina Klimentyeva

<i>Date: July 21, 2014</i>	<i>STOP No.: 21-1</i>
<b>Locality name: Rompas</b>	<b>Alternative name: Rajapalot</b>
<i>Main commodity: Au-Co-Fe-U</i> <i>Geological setting or genetic model: orogenic gold / IOCG</i> <i>Current development status: prospect</i>	
<b>WGS Latitude:</b> 66.150219	<b>WGS Longitude:</b> 24.942269
<i>Municipality: Ylitornio</i>	
<i>Location &amp; access: 45 km WSW of the city of Rovaniemi. Highway E75 (4) southwesterly for 24 km to the junction of highway 930, just past the town of Muurola. Heading westerly on highway 930 for about 28 km. Property is accessed via a secondary/tertiary gravel road that heads northerly from the village of Kaitajärvi</i>	
<i>Geological domain: Lapland</i>	<i>Geological unit: Peräpohja Schist Belt</i>
<i>Owner (2014): Mawson Resources Ltd</i>	

### **Geology**

High grade gold and uranium was recently discovered in the Rompas area. It lies a few kilometer south of the arctic cycle in the municipality of Ylitornio in northern Finland. There are two styles of mineralization. In the first style, gold and uranium are found in a hydrothermally mineralized veins mostly located in metabasalts. A second mineralizing system occurs at Rajapalot, 8km east of Rompas, where sulfidic and disseminated gold occurs in a replacement deposit.

On a regional scale, the discoveries are located the Paleoproterozoic Peräpohja Schist Belt (PSB) which is part of the mostly Archean Karelian Province. The Karelian Province comprises the oldest rocks of the Baltic shield, with an age of 3.1-2.9 Ga (corresponding to the Saamian orogeny).

The PSB sedimentary and volcanic rocks range in age from 2.3 to 1.92 Ga. The belt is composed of a supracrustal sequence of quartzites, mafic volcanics and volcanoclastics, carbonates, and black shales which are overlain by micaschists, phyllites and greywackes. Metamorphic grade ranges from greenschist in the south to lower amphibolites facies conditions in the Rompas area. The rocks unconformably overly Archean basement at the southern side of the PSB. The basement consists mainly of granitoids, layered intrusions and remnants of a greenstone belt. In the north the PSB is bordered by the high grade metamorphic (partly migmatized) Central Lapland Granitoid Complex (CLGC). Mostly likely a fault separates these two units. The rocks of the PSB are thought to represent a failed intra-continental rift with 500 Ma history of active evolution near the paleo-equator. Later in their history the rocks of the PSB was cut by diabase sills and dikes (2.2-2.1 Ga) and mainly granodioritic plutons (1.88-1.9 Ga), limiting their age to 1.9 Ga

Generally the strain within the PSB is heterogeneous. In the southern part it is very weak at we can still find pillow lavas and vesicles in mafics rocks. In the north, strain intensity increases and initial rock textures are difficult to recognize.

The western part of the Rompas area is underlain by medium-coarse grained schistose and tightly folded quartzites of the CLGC. To the east in the central part of the claims occur rocks of the Martimo formation, composed of carbonate and calc-silicate rocks, black schists and meta-volcanics. The meta-volcanics are mainly basalts dated at ~2.25 Ga. Central to this unit but normally north and south of Rompas the

Martimo formation also contains mica schists, conglomerates and arkosites.

In the south eastern part of the claim, the calc-silicates and meta-volcanics are in contact with mafic and felsic meta-volcanics. Further south these meta-volcanic join the Jouttiaapa Formation which is made up of amygdaloidal basalts containing quartz, chlorite, epidote and calcite amygdules

Structural features in the Rompas area are dominated by upright, N-trending isoclinal folds (D2) which are refolded by E-trending upright folds (D3). The foliation of the D2 folds is variable in intensity but generally increasing southward. This leads to the complete destruction of original rocks textures in the mafic volcanic rocks. Amphibolite-facies metamorphism accompanied the formation of the D2 foliation. The fabric is defined by biotite and hornblende. Biotite is seen as an evidence of early potassic alteration. Later cummingtonite-anthophyllite amphiboles overgrow the D2 foliation. Deformation is thought to have occurred ~1.8 Ga.

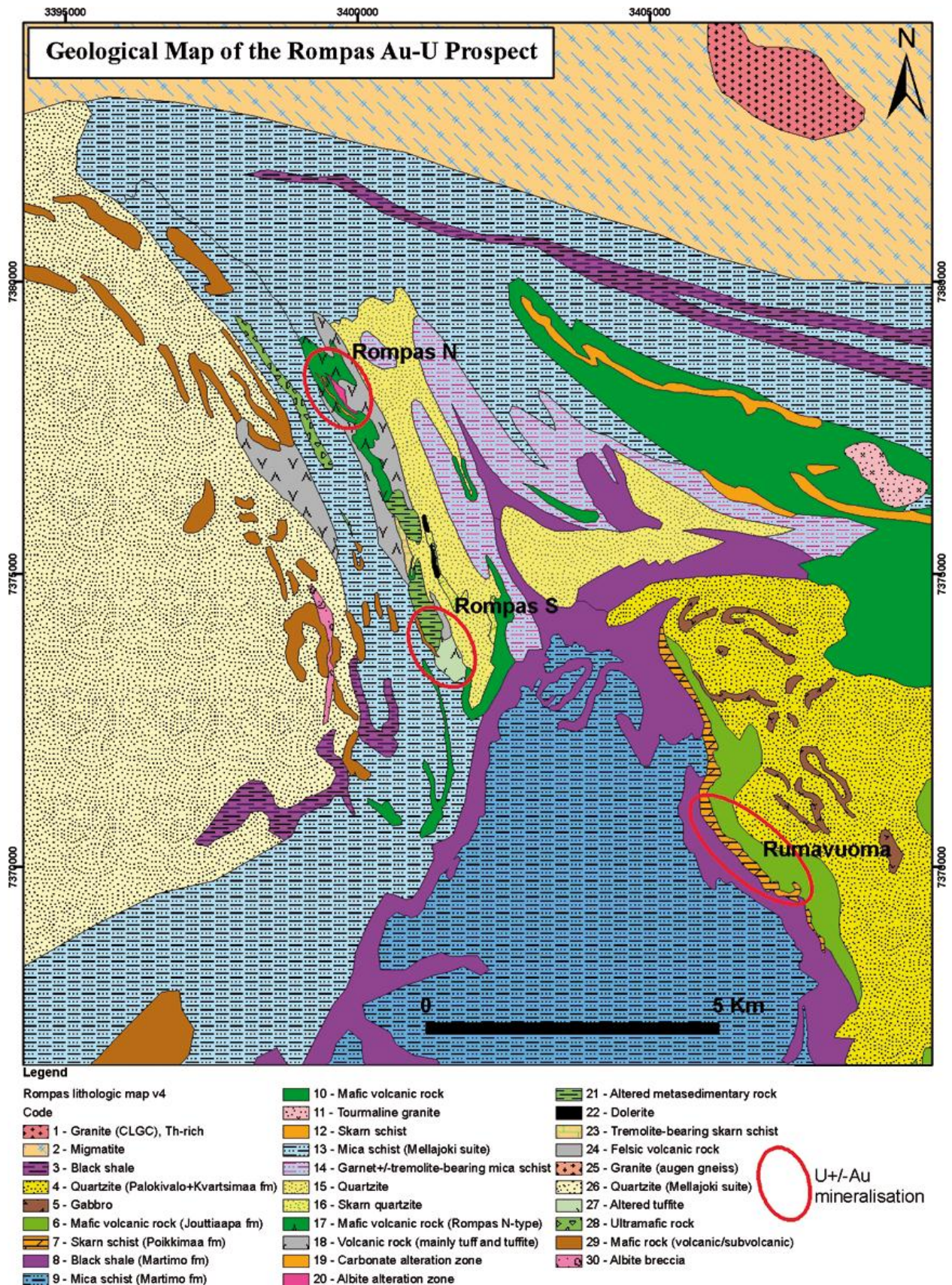
With an average gold grade in channel samples of 203.66g/t Au and 0.73% U, Rompas is a promising discovery of bonanza-type ore, wherein U is mostly present as uraninite and gold is commonly native.

At Rompas the mineralized host rock mainly consists of meta-basalts. Gold and uraninite occur within or close to carbonate or calc-silicate veins. The host rocks are partly skarnitized. Veining also occurs in the adjacent hornfels metasediments but there the veins do not contain any Au or U. This implies that fluid-rock interaction with basalt play a key role in forming this deposit. The Au occurs mainly in cracks in the uraninite and seems to post-date uraninite formation. Au also occurs as free gold close to the uraninite grains. No sulphides are associated with the mineralization, which shows only minor amounts of oxides like magnetite.

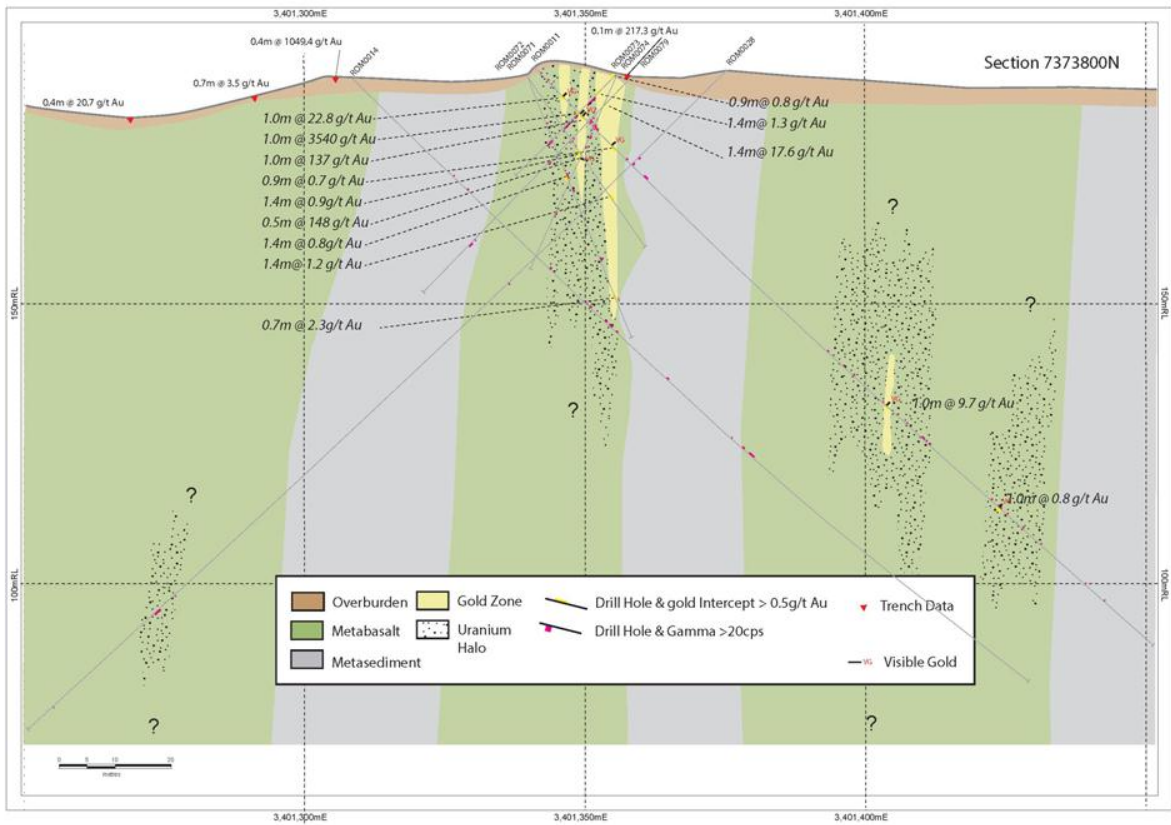
Mineralized structures include shears, jogs, boudins and veins. In some places structures appear to show an en echelon pattern and the mineralization is clearly structurally controlled. Gold seems to be correlated with uranium concentrations.

The nature of the mineralization is probably epithermal and may be related to a buried intrusive. This intrusive might correlate with the CLGC directly in the north. The mineralization has a widespread alteration footprint and shows multiple stages of mineralization.

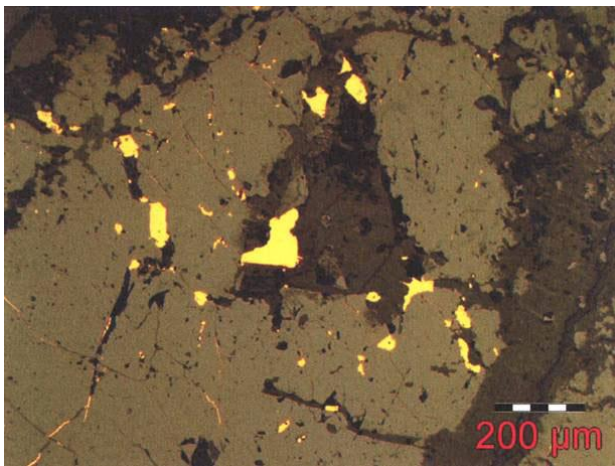
Because Rompas was discovered recently, little is known about the formation and genetic model of this deposit. A PhD thesis dealing with that topic was written in 2014 but was not yet accessible at the time of writing. Currently Rompas is in the exploration stage of development, and geochemical exploration as the main tool for tracing gold mineralization is carried out.



**Fig. 21-1-1.** Geological map of the Rompas region  
(from [http://www.iags2011.fi/25thIAGS2011\\_E1\\_net.pdf](http://www.iags2011.fi/25thIAGS2011_E1_net.pdf)).



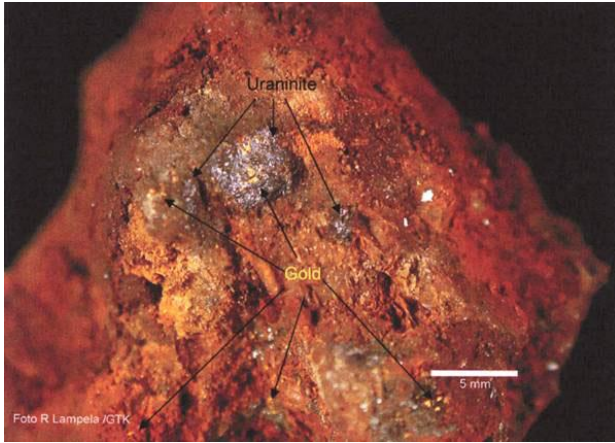
**Fig. 21-1-2.** Cross-section from northern drill block in south Rompas (from Mawson Resources website, newsrelease).



**Fig. 21-1-3.** Uranite (grey) gold(yellow) in and Carbonate (dark grey) from Rompas (from From Mawson Resources website).



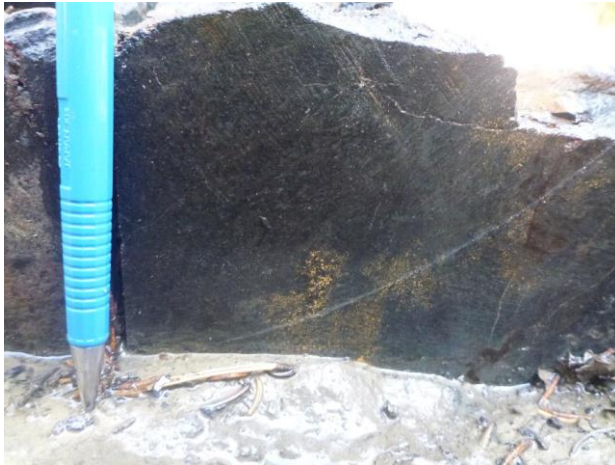
**Fig. 21-1-4.** Massive Uranite Vein from Rompas (from From Mawson Resources website).



**Fig 21-1-5.** Gold grains and uraninite in partly weathered carbonate from Rompas (from Mawson Resources website).



**Fig. 21-1-6.** Mineralized section in drill core (from Mawson Resources website).



**Fig. 21-1-7.** Native Au in greenschist-amphibolite facies metabasaltic rocks in Rompas area. Au is often associated with high U-content in the rocks and occurs also in fractures of uraninite. Bonanza type Au concentrations are found in some parts of the area but currently no comprehensive mineralization model exists (photo: L. Gilsbach).



**Fig. 21-1-8.** Field occurrence of Qtz-carbonate vein with halo of presumably chlorite-albite alteration overprinting the magmatic hostrock. Boudinage and offsets indicate that the emplacement of these veins occurred early before or during regional amphibolite facies metamorphism. The veins are ubiquitous and only locally mineralized with U and Au and sometimes armoured by tremolite/diopside/cummingtonite. Some veins show tourmaline and albite rims. This vein did not show elevated U radioactivity (photo: Ch. Heinrich).





**Fig. 21-1-9.** High-grade U-Au mineralized breccia containing clasts of dark presumably chlorite-altered mafic rock that already contain boudinaged quartz-carbonate veins (right end of core). These textural relations and the restricted occurrence of high-grade Au and U indicate that economic mineralization postdates and is independent of the more regionally-extensive quartz-carbonate veining in the Rompas area (photo: Ch. Heinrich).

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<http://www.mawsonresources.com/s/Rompas.asp>

[http://www.mawsonresources.com/s/NewsReleases.asp?ReportID=584964&\\_Title=Mawsons-Rompas-High-Grade-Gold-Project-Finland-Project-Update](http://www.mawsonresources.com/s/NewsReleases.asp?ReportID=584964&_Title=Mawsons-Rompas-High-Grade-Gold-Project-Finland-Project-Update)

[http://www.youtube.com/watch?v=LVN\\_JYBGDnQ](http://www.youtube.com/watch?v=LVN_JYBGDnQ)

[http://www.iags2011.fi/25thIAGS2011\\_E1\\_net.pdf](http://www.iags2011.fi/25thIAGS2011_E1_net.pdf)

*Previous field trip guides*

International Applied Geochemistry Symposium Field Excursion. - Active and ongoing gold exploration and mining in Northern Finland. Page 36.

**Compiled by: Lucas Gilsbach**

<i>Date: July 22, 2014</i>	<i>STOP No.: 22-1</i>
<b>Locality name: Otanmäki</b>	
<i>Main commodity: Fe-Ti-V</i>	
<i>Geological setting or genetic model: layered mafic intrusion</i>	
<i>Current development status: closed mine, to be reopened in 2017-2019</i>	
<b>WGS Latitude: 64.11669</b>	<b>WGS Longitude: 27.1001</b>
<i>KKJ Northing: 7112999</i>	<i>KKJ Easting: 3505049</i>
<i>Municipality: Vuolijoki</i>	
<i>Location &amp; access: 39 km E from Pyhäntä town by road 28, 42 km W from Kajaani town by road E63, 28</i>	
<i>Geological domain: Talvivaara-Kuusamo</i>	<i>Geological unit: Otanmäki Belt, Karelian</i>
<i>Owner (2014): Otanmäki Mine Oy (Vuorokas Oy)</i>	
<i>Address: Veteraanitie 1, nr. 9, FI-88200 Otanmaki, Finland</i>	

### **Geology**

The Otanmäki deposit is located in the Otanmäki belt in Central Finland. It belongs to the Karelian supergroup (Lehtinen et al., 2005). Prominent rock units (Figs. 22-1-1, 22-1-4) are: (a) Archean basement, consisting of 2.6-2.8 Ga old banded gneisses (Fig 22-1-5), (b) supracrustal schist and metavolcanics, (c) ca. 2060 Ma old layered gabbro and anorthosite with magnetite-ilmenite ore (Figs. 22-1-6 to 22-1-8), (d) alkaline, metasomatic gneiss, and (e) microcline granite (Lindholm and Anttonen, guide book).

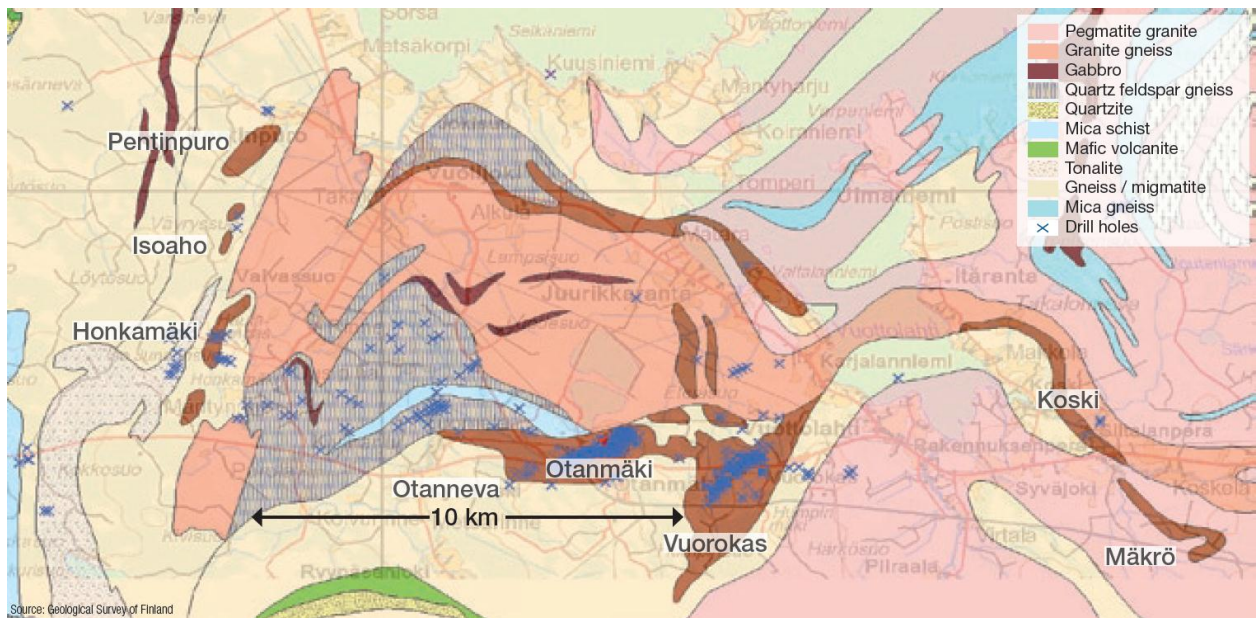
Main ore minerals (Figs. 22-1-6 to 22-1-8) are magnetite (40 %), ilmenite (19 %), and sulfides (1-2 %) (Otanmäki Mine Oy, 2012). Main gangue minerals (Fig. 22-1-6) are chlorite, hornblende, and plagioclase. After Pääkkönen (1956), first class ore (50-80 % ore minerals) occurs together with chlorite, chloritized hornblende, clinozoisite, and epidote. Second class ore (35-50 % ore minerals) occurs with hornblende and plagioclase (Pääkkönen, 1956). The ore forms bands flowing around brecciated gabbro and anorthosite (Lindholm and Anttonen, guide book). It should be noted that earlier authors describe different textures of the mineralization (\*).

The Otanmäki mineralization dips 40-60° SW (Fig. 22-1-3) and reaches > 200 m depth (Otanmäki Mine Oy, 2012, Pääkkönen, 1956). According to Pääkkönen (1956), the Otanmäki area is related to the Karelian folding zone. In the W' part an early folding in E-W, and in the central part a later one in NW-SE direction is imprinted in the rock. The general strike of the Otanmäki region is N-S, and it dips steeply to the E or W. Its curved shape is due to later deflection, with the W' Archean crustal segment acting as resistance area during tectonic movement. Intrusion of granite occurred into the cores of large folds. The Archean basement gneiss was sheared and metamorphosed before the end of folding. In contrast, clearer schistosity in granite and gabbro points to shearing in the latest phase of folding in these rocks (Pääkkönen, 1956). The preferred genetic model for the ore formation is magmatism. The deposit represents a layered mafic intrusion. Later metamorphism at ca. 560 °C lead to purification of the ore (Lindholm and Anttonen, guide book).

The Otanmäki deposit itself comprises several hundred ore lenses (Hokka, 2013, see Fig. 22-1-2). Otanmäki Mine Oy (2012) estimates its resource to 11 Mt indicated and 3 Mt inferred. It consists of 40 % Fe, 7.6 % Ti, and 0.26 % V. Close to Otanmäki there are other ore occurrences like Vuorokas, Pentinpuro, Isoaho, Honkamäki, Mäkrä, and Koski. Together, the resource estimate is 21.5 Mt indicated and 15.1 Mt inferred. The planned new production for Otanmäki is 480 kt/yr Fe pellets, 250 kt/yr ilmenite

concentrate, 4.3 kt/yr  $V_2O_5$ , and 9.7 kt/yr pyrite concentrate. The average Otanmäki ore holds 36.8 %  $Fe_{tot}$ , 13.5 %  $TiO_2$ , and 0.38 %  $V_2O_3$ . It is diluted by 16.3 %  $SiO_2$ , 10.3 %  $Al_2O_3$ , 3.4 %  $CaO$ , 4.2 %  $MgO$ , and other minor components (Otanmäki Mine Oy, 2012). Magnetite contains 0.8-1.05 %  $V_2O_3$ , 0.03 %  $Cr$ , and 0.06-0.12 %  $Zn$  (Pääkkönen, 1956).

The Otanmäki deposit was discovered in 1937/38 by airborne, surface, and underground magnetic exploration (Rautaruukki Oy, 1980, field guide). Positive anomalies are caused by magnetite-ilmenite ore related to mafic intrusion (Lindholm and Anttonen, guide book). Further exploration consisted in diamond core and percussion drilling. The mine was active from 1953 till 1985 and is planned to be reopened between 2017 and 2019 (Otanmäki Mine Oy, 2012). The mining technique was sublevel open stoping in the past and will be open pit as well as underground mining in the future. Currently, exploration is conducted to validate historical data. It comprises re-surveying of drillholes, susceptibility measurements, saw channel sampling, in-situ XRF analyses, and trenching. Continuation of the ore zone towards the SW was encountered (Hokka, 2013).



**Fig. 22-1-1.** Regional geology of the Otanmäki area. Brown color probably represents fragments of mafic intrusion. Otanmäki Mine Oy (2012).

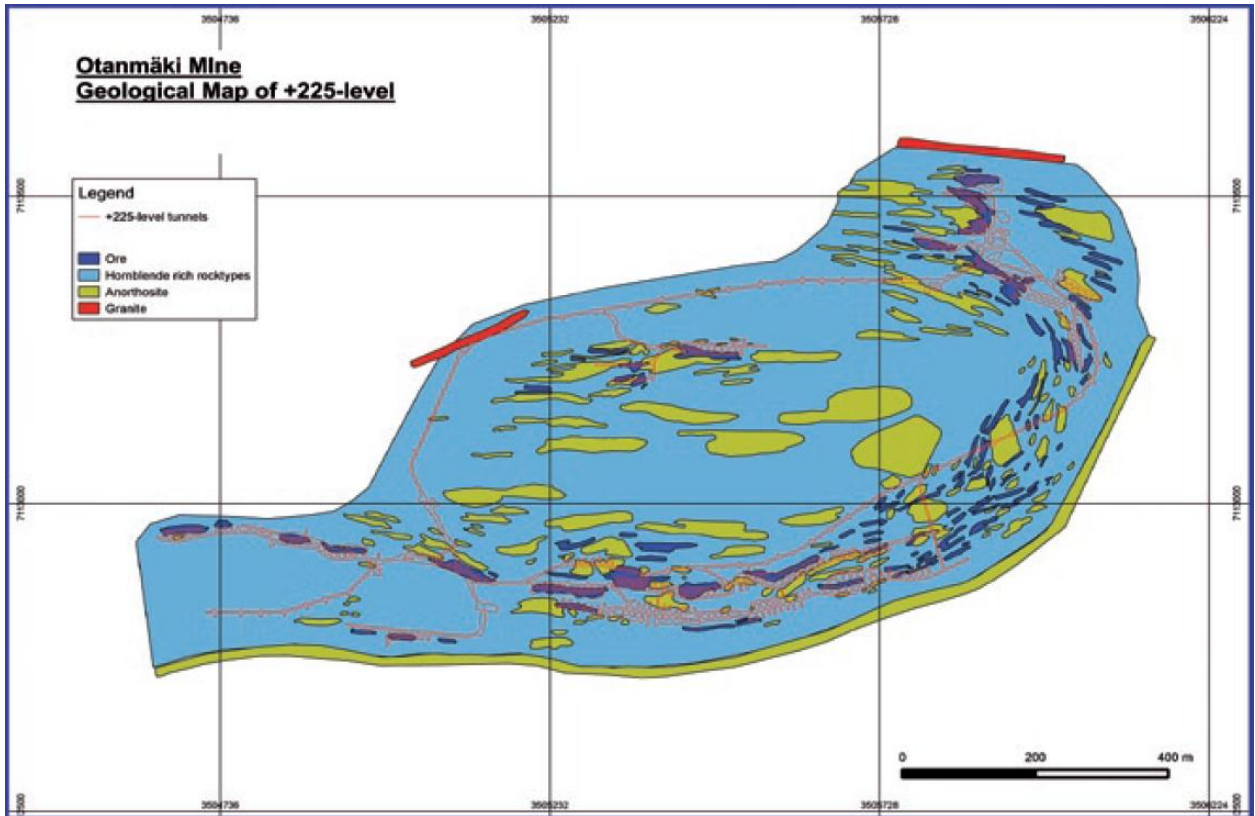


Fig. 22-1-2. Geology of the Otanmäki mine. Otanmäki Mine Oy (2012).

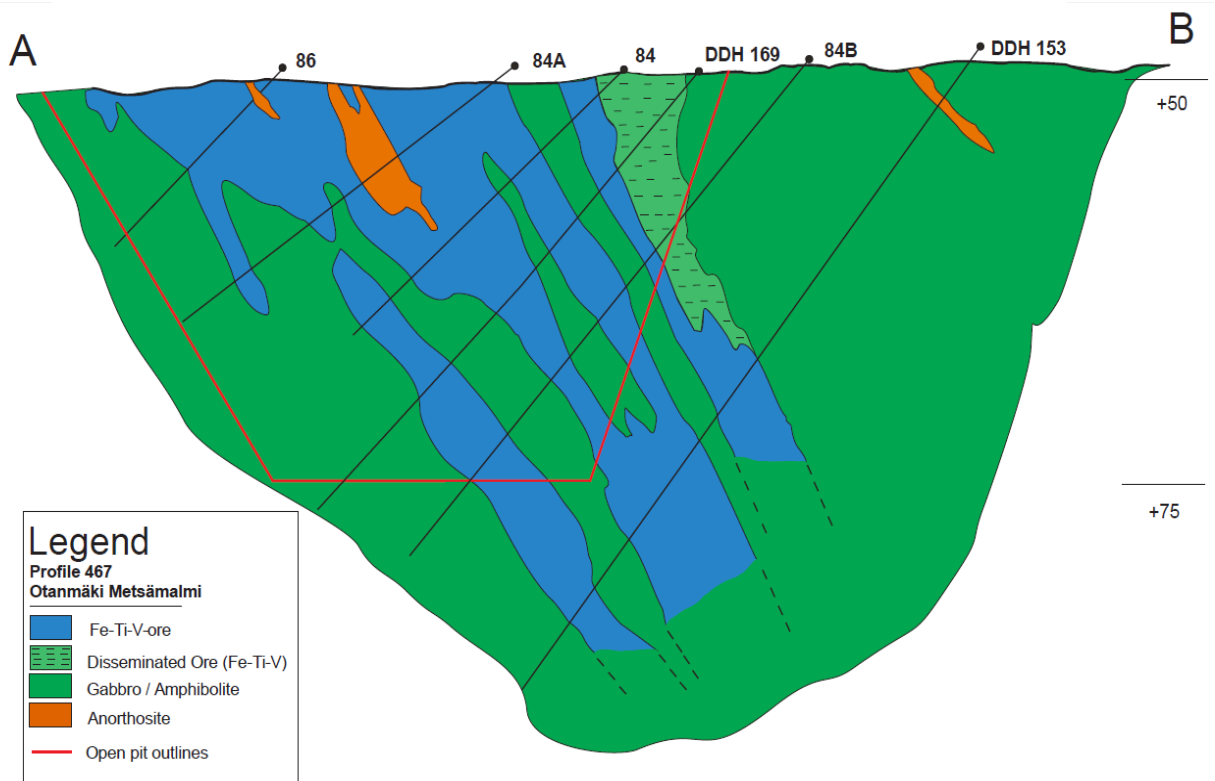


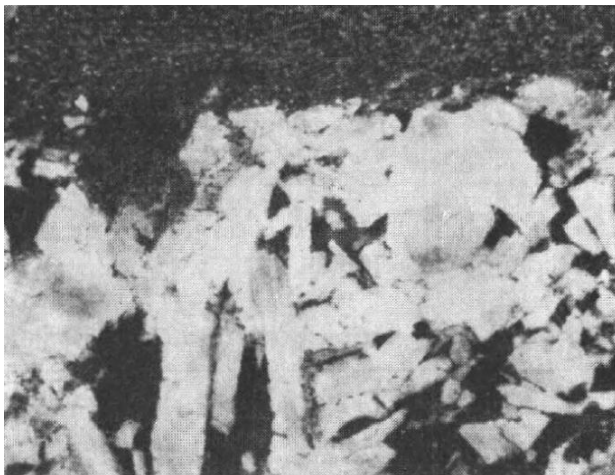
Fig. 22-1-3. Simplified cross-section. Dip of mineralization: 40-60° SW. Hokka (2013).



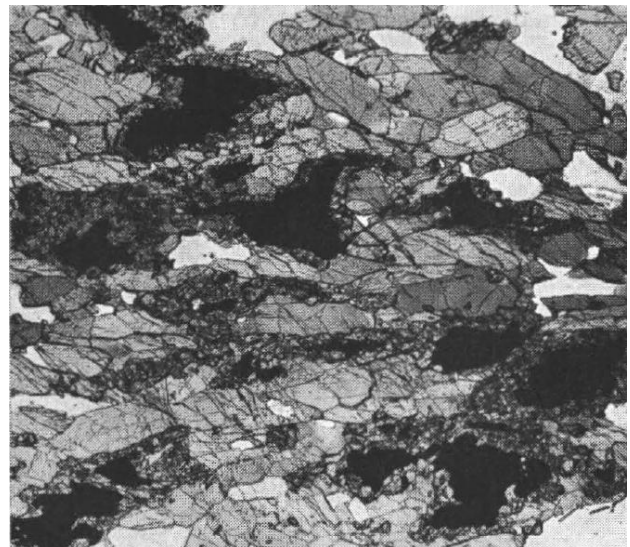
**Fig. 22-1-4.** Rock complex in the area of striped gneiss. Railway SW of Pikku-Otanmäki hill. Ca. 1/100 of natural size. a = amphibolite, b = mica gneiss, c = granite, d = glacial deposits. Pääkkönen (1956).



**Fig. 22-1-5.** Folded striped and banded gneiss. Light bands are mostly plagioclase and dark stripes are rich in biotite. Railway SW of Pikku-Otanmäki. Ca. 1/6 of natural size. Pääkkönen (1956).



**Fig. 22-1-6.** Coarse-grained anorthositic gabbro in contact with fine-grained amphibolite. Light grains are plagioclase ( $An_{30}$ ), dark grains are hornblende. Pikku-Otanmäki. Natural size. Pääkkönen (1956).



**Fig. 22-1-7.** Dark amphibolite. Ilmenite and magnetite are black, and hornblende is dark grey. Greyish-dotted plagioclase appears to be older than smaller grains. Magn.  $6\frac{1}{2}x$ . Pääkkönen (1956).



**Fig. 22-1-8.** Otanmäki ilmenite ore. GTK.



**Fig. 22-1-9.** decimetre- to m-scale folds in banded rocks along train tracks (photo: K. Schlöglöva)



**Fig. 22-1-10.** Old test pit and likely future mining pit. Deposit was originally discovered by boulder hunting and magnetic surveys. Plagioclase- to hornblende-rich rocks: anorthosite, anorthosite-gabbro, gabbro. Distinction of ore classes with susceptibility and geochemistry: hand-held susceptibilitymeter and portable XRF. Rhythmic layering, banded structures, metamorphic textures (several fold generations and schistosity) due to later Svecofennian orogeny (photo: K. Schlöglöva).



**Fig. 22-1-12.** Layered intrusives: Magmatic layering (probably also overprinted and modified) at ca. 30° to schistosity, visible in hornblende orientations (photo: A. Fiedrich).



**Fig. 21-1-11.** cm-scale crenulation cleavage (photo: D. Klimentyeva).

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Lindholm, O., Anttonen, R.: Geology of the Otanmäki Mine, second day, p. 25 – 33.

*Comments* (\*) Publications from different times do not match entirely. Lack of description of alteration.

**Compiled by:** Alina Fiedrich



# Otanmäki Excursion Guide Book

Otanmäki Mine Oy

J. Hokka, GTK & J. Jylänki, Otanmäki Mine Oy

7/21/2014





## 1. INTRODUCTION

The Otanmäki area is defined by several vanadium-rich magnetite-ilmenite deposits in a Paleoproterozoic belt of orthoamphibolite- gabbro-anorthosite intrusives and alkaline granitoids along the boundary between the Archean Pudasjärvi and Iisalmi blocks, immediately to the west of the Paleoproterozoic Kainuu schist belt (appendix 1.). 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 kilometres to the east.

In 1937, two glacial boulders of magnetite-ilmenite (1. 53.66 % Fe, 9.90 % Ti and 50.86 % Fe, 10.40 % Ti) rock were found in Sukeva by two field assistants of Geological Survey of Finland (GTK), about 40 km southeast of Otanmäki. In 1938, their source was located on the basis of magnetic ground survey by GTK. Further studies revealed several smaller magnetite-ilmenite deposits within a radius of 10 km around Otanmäki (appendix 1.). The state-owned company Otanmäki Oy was founded to exploit the ore deposit. Later Otanmäki Oy was amalgamated with Rautaruukki Oy, the major steel producer in Finland. During their lifetime, Otanmäki and Vuorokas were major vanadium producers in the world.

The Otanmäki mine operated from 1953 till 1985, and it mined total of 30 Mt of ore grading of 32-34% Fe, 5.5-7.6% Ti, 0.26% V. Total production was 7.6 Mt iron concentrates, 3.8 Mt ilmenite, 0.2 Mt sulphur concentrates and 55 545 t  $V_2O_5$ . Otanmäki mine consists of 975 kilometers of drilling, three shafts (Otanmäki, Suomalmi, and Vuorokas), and 125 kilometers of tunnels.

## 2. REGIONAL GEOLOGICAL SETTING

Due to the flat topography and extensive cover of swamps, till and hillocks in Otanmäki area, it is generally poorly outcropping. Thus the geological map relies heavily on geophysical surveys carried out at the height of 30-50 meters and diamond drilling conducted in Otanmäki area (Lindholm & Anttonen 1980).

According to Zelt (1974) the regional metamorphic grade was generally in amphibolite facies. The smaller gabbro intrusions, Honkamäki and Pentinpuro, were altered to amphibolites. For instance, larger intrusive bodies like Otanmäki and Vuorokas are more schistose from the margins and primary textures are more preserved in centre parts of the intrusion (Kerkkonen 1979).

### 2.1. Otanmäki rock units

The lithological units in Otanmäki region have been classified as follows: pre-Svecokarelian basement, Otanmäki association, alkali gneiss, supracrustal rocks, and microcline granite. Stratigraphically, the pre-Svecokarelian basement rocks represent the oldest lithological unit in the area. The age of the basement rocks haven't been determined radiometrically, but compared with U-Pb datings of similar rocks elsewhere in eastern Finland, age of 2600 – 2800 Ma is indicative. U-Pb data on zircons of Otanmäki and Vuorokas gabbros show an age of 2058 Ma and 2063 Ma, respectively. The U-Pb age of alkalic gneiss at Honkamäki is  $2018 \pm 3$  Ma (Hytönen & Hautala 1985).

It's still uncertain whether these are the ages of formation or metamorphism of these rocks. In any case, the alkalic gneiss intersects the ore bearing zone at Otanmäki (Lindholm & Anttonen 1980). Supracrustal rocks of Otanmäki schists are stratigraphically top of alkalic gneisses. The lowermost part of meta-sedimentary sequence, the quartz-feldspar schists, have been affected by metasomatic processes (Puumalainen 1986).

## **2.2. Pre-Svecokarelian basement**

Structurally heterogeneous unit of Archean tonalite migmatite or striped gneiss (Pääkkönen 1956) in the southern and western part of Otanmäki, represents the typical pre-Svecokarelian basement complex rocks. The rock varies in texture from fine- to medium-grained gneissose granite to strongly compressed and contorted veined gneiss. Commonly it contains inclusions of amphibolites, veins of pegmatitic granite and fragments of mica gneiss (Pääkkönen 1956, Lindholm & Anttonen 1980).

## **2.3. Supracrustal rocks**

The supracrustal rocks seem to form a triangle shaped basin structure. The rocks association consists of banded layers quartz-feldspar schists, mica schists, metavolcanics, and metaturbides of Katajakangas (Puumalainen 1986). Metasomatically altered, quartz-feldspar schist hosts the Katajakangas and Kontioaho REE-Nb-Zr deposit (Hugg 1985a, Hugg 1985b, Al-Ani et al. 2010).

## **2.4. Otanmäki association**

Otanmäki association consists of several separate gabbro-anorthosite intrusives that host the vanadium bearing magnetite-ilmenite ores (Otanmäki, Vuorokas, Honkamäki, Pentinpuro, Isonkivenkangas). The gabbros are partly layered and well developed magmatic differentiation is seen in the rocks in Otanmäki and Vuorokas. The ore zone is located at the heterogeneous gabbro-anorthosite unit which is at the top layered gabbros. Unit is mostly altered to amphibolites. Also ortho-amphibolite zone is used in literature to describe the unit. The gabbros are of the uralitic variety and the main mineral composition is plagioclase and hornblende. Occasionally, relicts of pyroxene and olivine can be seen (Lindholm & Anttonen 1980).

## **2.5. Alkalic gneiss**

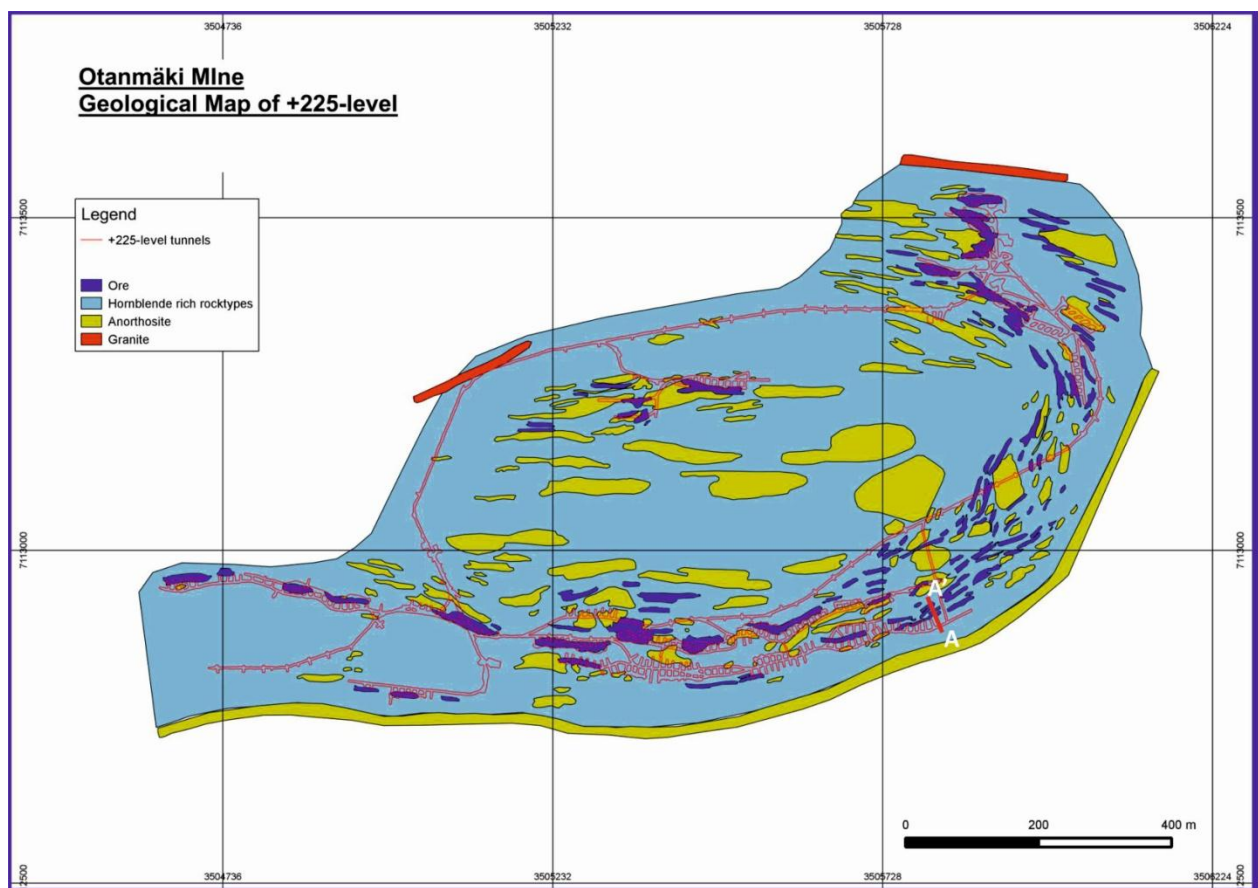
This rock unit was first described as "reddish hornblende granite" containing darker gneissic hornblende-rich bands (Wilkman 1931). Later on the rocks were studied by Pääkkönen (1956) who called it gneissose granite. The more used name was given by Otanmäki mine geologist Lindholm & Anttonen (1980) who termed the same rock as alkali gneiss with metasomatic features. If the rock is regarded as plutonic, the name microcline-albite quartz syenite should be used (Streckeisen 1974). It is believed to be formed metasomatically from Archean granite gneisses (Puumalainen 1986). The main minerals of the rock are microcline, albite, quartz, aegirine and riebeckite (Hytönen & Hautala 1985). There is also potential source for REE, Zr and Nb in gneissic alkaline granitoids. The belt of intrusive alkaline granitoids extends a few tens of kilometres to the east and can be significantly larger (Kuivasaari et al. 2012).

## 2.6. Microcline granite

The granite rocks are situated in the eastern part of Otanmäki area and are parts of the microcline granite intrusion, the Kajaani granite suite, extending towards east and bounded by the Karelian schist belt (Lindholm & Anttonen 1980).

## 3. OTANMÄKI DEPOSIT (Fe-Ti-V)

Otanmäki deposit lies on the northern flank of a large hornblende gabbro intrusion in a heterogeneous zone of metagabbros, gabbros and anorthosites. It is limited in the north by alkalic gneiss and in the south it is in contact with banded gneiss. The mineralized zone (horizontal plane section) is roughly 3 kilometers long and 0.5 kilometers wide, and it forms a semicircle-shaped structure at its eastern end (Fig.1.).

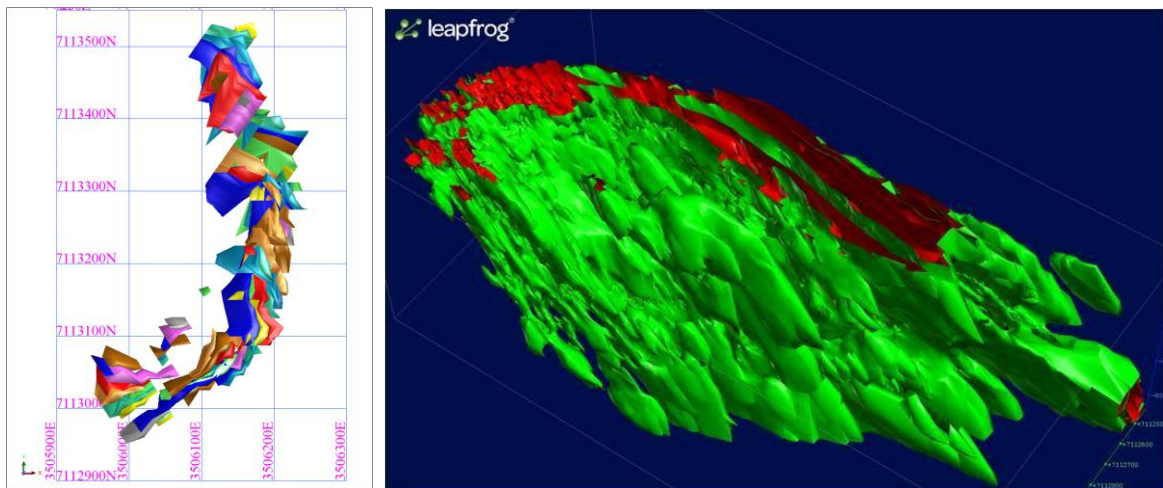


**Fig.1.** The Otanmäki Mine geological map of +225-level shows the semicircle-shaped structure at the eastern end of the Otanmäki deposit. Several hundred known ore lenses are spread over a large zone (modified after Lindholm & Anttonen 1980).

The ore zone is open at depth but it's known to extend to over 800 meters. The ore zone doesn't form a continuous and homogeneous package – quite the contrary, it comprises irregular, partly

elongated swarm of lenses of variable size (Fig. 2.-3.). The individual ore lenses can vary from 20 to 200 meters in length and from 5 to 30 meters in width (Lindholm & Anttonen 1980).

Most of the lenses are E-W oriented and elongated parallel to the strike of the schistosity, although, there are several separate ore bodies which have very indefinite direction of elongation, and some ore veins are also situated in vertical position (Pääkkönen 1956). The lenses are deeply dipping 70°-90° to the north and south and the ore zone as a whole has a plunge of ca 40° to the west but the individual ore lenses have slightly deeper plunge of 45°- 60° to the west. In many cases the ore lenses aren't elongated in any particular direction (Lindholm & Anttonen 1980).



**Fig. 2.** The different colored solids represent ore bodies of Otanmäki deposit (right). Otanmäki ore bodies are deeply dipping to the north and south and plunge is to the west. The left picture is a bird's eye view from east (Parkkinen 2013).

### 3.1. Genesis of Otanmäki

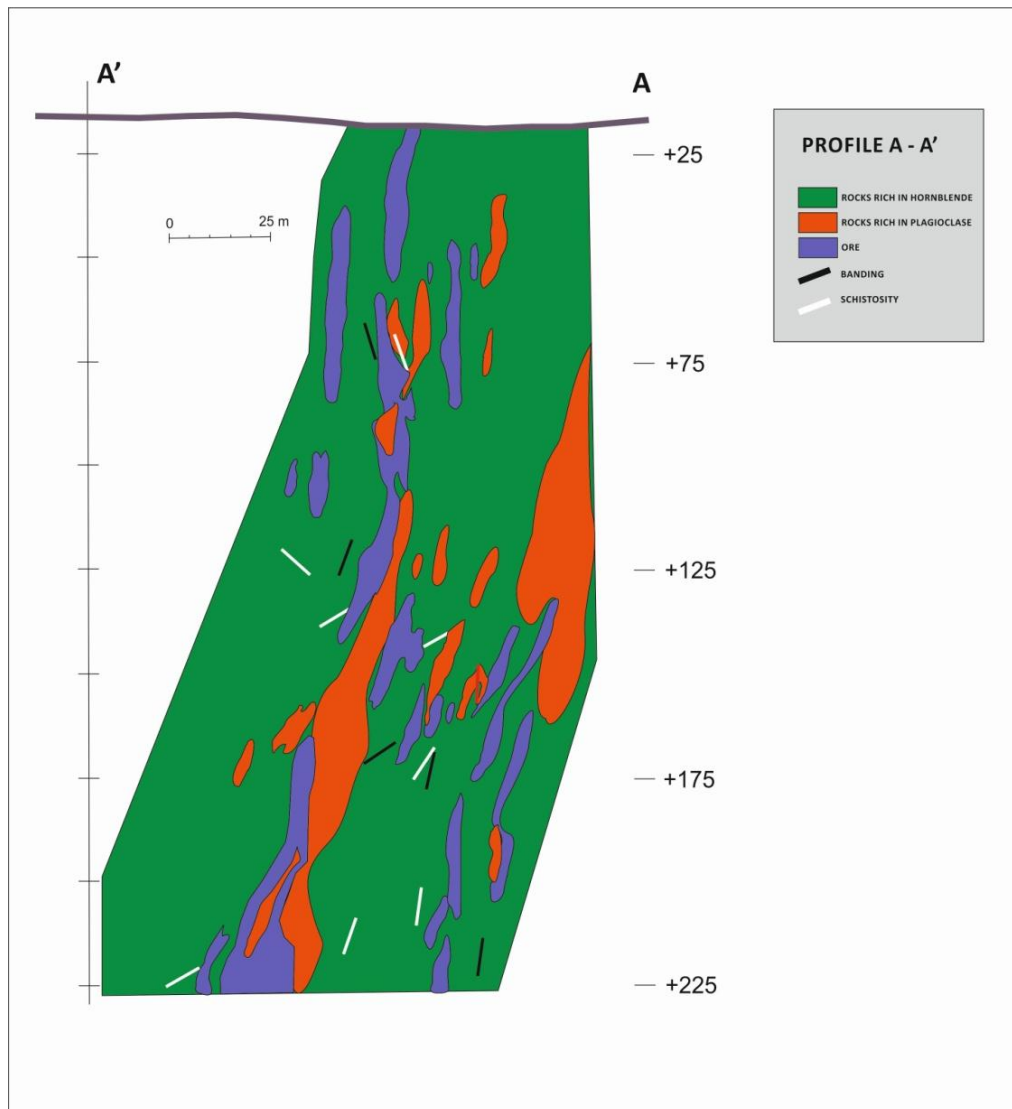
A major rifting event and continental breakup of prolonged Archean crust (presumed supercontinent) took place in northern Fennoscandia at 2.1 – 2.04 Ga. The event was fertile for ore formation of Cr, PGE, Ni, Cu, Ti and V (Lahtinen et al. 2008).

Otanmäki is an orthomagmatic deposit that undergone complex deformation and metamorphism. There are still many controversies in explaining the genesis of orthomagmatic Fe-V deposits and what mechanisms crystallized and accumulated millions of tones of oxides to form large-scale Fe-Ti deposits (Zhou et al. 2005). One of the key questions is whether an iron-rich immiscible liquid is separated from crystallizing silicate magma or whether magnetite nucleated and grew in the magma, to be concentrated by gravitational settling. When looked at Skaergaard intrusion, the current and most predominant theory is deposition of crystals from convecting magma (Irvine 1987, Irvine et al. 1998) via in-situ nucleation and crystal growth in a solidification front at the interface between the convecting magma and the semi-consolidated cumulate pile (McBirney and Noyes 1979). According to Juopperi (1977) and Mutanen (1989) the iron-rich immiscible liquid was separated from magma due to tholeiitic-type differentiation, where crystallization of plagioclase and Mg-rich silicates resulting in enrichment of Fe in the residual liquid, and crystallized as an intercumulus phase.

According to Pääkkönen (1956) the ore formation of Otanmäki is explained by metamorphism (metamorphic differentiation) and its stress action towards the titanium and iron oxide rich gabbroic rocks. This seems unlikely because there is no evidence of tectonic control on Fe-Ti-V deposition. Although, metamorphism have affected the migration of silicate phase (lineation of hornblende, chlorite lenses), it have not enriched oxides in the system (Kerkkonen 1979). Nevertheless, basis for the discussion of the genesis of Otanmäki deposit is that it is regarded as magmatic intrusion and the ore formation is related to mafic magma and its fractional crystallization (Kerkkonen 1979, Lindholm & Anttonen 1980, Papunen 1986). Due to the regional metamorphism and complex deformation, it is difficult to determine if the ore bodies were originally emplaced as horizontal position and tilted after deformation. In that case, the banding structures would represent primary layered features. Other possibility is flow differentiation, where intrusion would have been placed and crystallized almost in its original position (Papunen 1986).

Banded structures are found in Otanmäki ore, the bands flow around fragments with turbulent features. Also plagioclase has a weak flow lamination (Kerkkonen 1979). The ore zone contains abundant variable size anorthositic and gabbroic bodies and fragments which impart an appearance of breccias to the zone (Lindholm & Anttonen 1980). These observations support the theory of flow differentiation (Papunen 1986). Banded second-class ore has graded bedding where the top parts are more hornblende rich. That's evidence supporting the gravitational differentiation during the magma flow.

Late-stage regional metamorphism affected the mineralogy by purifying magnetite and ilmenite at a temperature of ca. 560 °C. Otherwise, metamorphism didn't play any role in the ore formation processes in general.



**Fig.3.** The profile A'-A (see figure 1.) shows the heterogeneous nature of Otanmäki deposit. Lenses are unequal size; irregular shaped and contain abundant gangue inclusions. Mining geology has to provide an exceptionally large amount of detailed information for high confidence resource estimations and stope design (modified after Lindholm & Anttonen 1980). Very distinct feature of the ore zone is foliation of the intrusive rocks. The schistosity cuts banding commonly in an angle of  $1 - 20^\circ$  and it is best seen in host rocks and occasionally in high-grade ore. When banding and schistosity have nearly the same strike and dip, it is almost impossible to determine if the layering and inclusions features are magmatic or metamorphic. The lamination of plagioclase laths support the magmatic layering but it is certain that there exists tectonic banding in Otanmäki as well (Kerkkonen 1979).

## 3.2. Otanmäki rock types

### 3.2.1. Hornblende rock

Fine to medium-grained, often contains ore impregnation and sulphide segregations. Typically, hornblende rocks occur within ore zone as lenses or bands. Grain size varies. Rocks are commonly sheared (table 1.).

### 3.2.2. Ortho-amphibolite (amphibolite)

Fine to medium-grained, granoblastic or schistose Amphibolite and hornblende rocks are the main gangue rock type within the ore zone. Typically, the rock contains 10-35 % of plagioclase. Common accessories are ilmenite, sphene, and sulphides.

### 3.2.3. Metagabbro (gabbroic amphibolites)

Fine to medium-grained, schistose or orientated (lineation). Granoblastic plagioclase is often zoned. Typically, metagabbro contains 35-50 % of plagioclase. Ilmenite-sphene impregnations are common.

### 3.2.4. Gabbro

Typically coarse-grained rock. Plagioclase is usually euhedral. Sometimes ophitic, distinct laminations are possible. In some varieties plagioclase is very dark. Ilmenite-sphene impregnations are common.

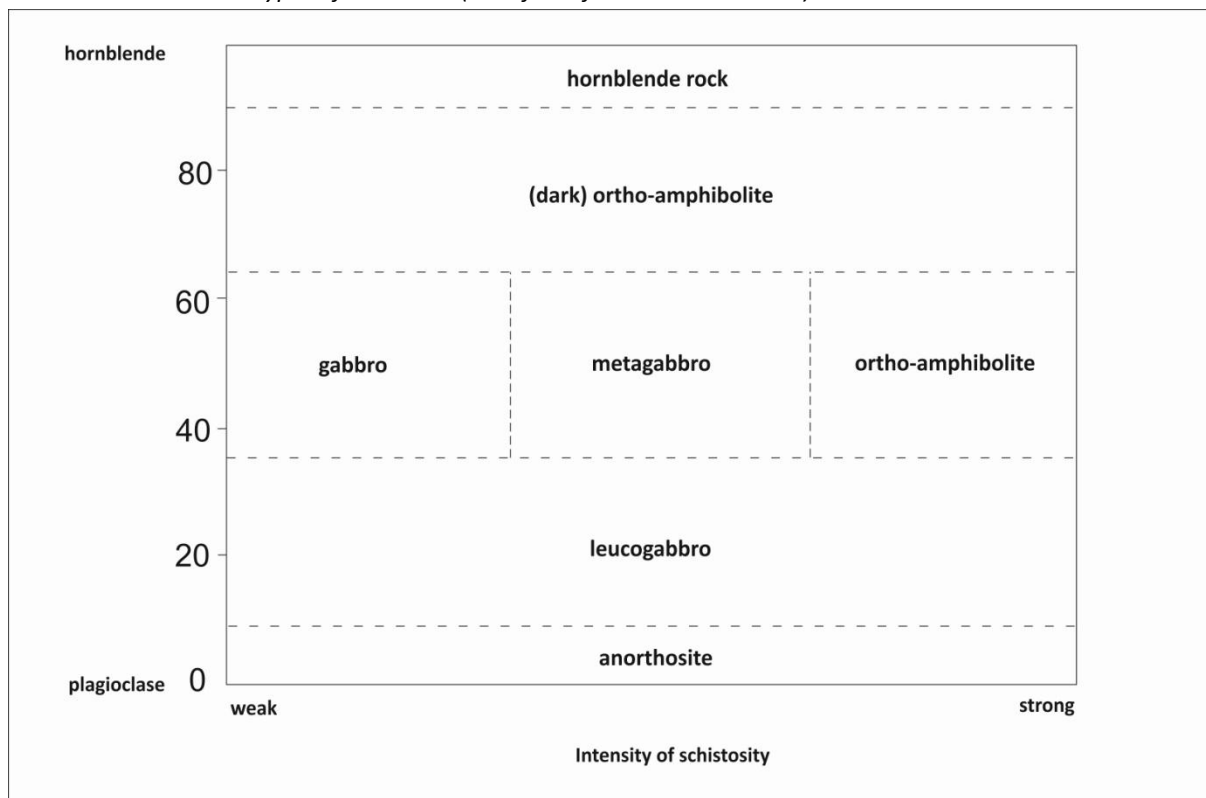
### 3.2.5. Anorthosite gabbro (leucogabbro)

Medium to coarse-grained rock, commonly seen as 0.1-0.2 meters wide layers. Plagioclase occurs as euhedral and anhedral grains and commonly altered into epidote, sericite and saussurite. In sheared type, micas are common. Common accessories are ilmenite-sphene, pyrite, and chalcopryite.

### 3.2.6. Anorthosite

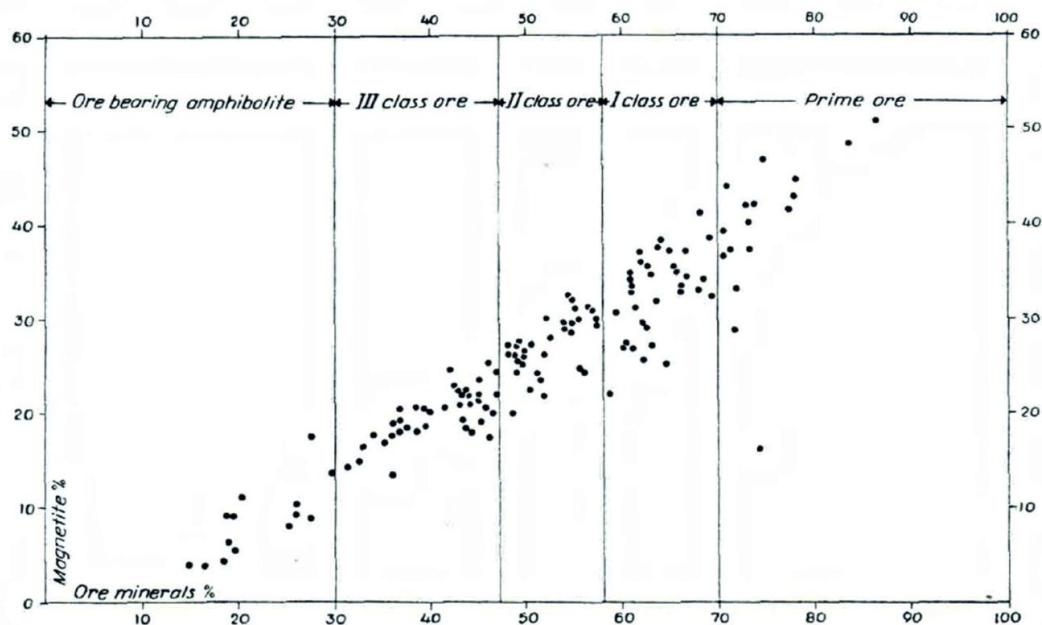
Coarse-grained rock that occurs only as inclusion. Plagioclase often altered into epidote, sericite, and saussurite (reddish color). Occasionally, carbonate (prehnite) rich parts.

**Table.1.** The main rock types of Otanmäki (modified after Kerkkonen 1979).



### 3.2. Otanmäki ore

The ore minerals at Otanmäki are vanadium-bearing magnetite and ilmenite. The gangue minerals (table 2.) are chlorite in high-grade ore, and hornblende with minor plagioclase in disseminated, low-grade ore. It's clearly visible, when moving towards low grade ore, that hornblende becomes more prevalent as gangue mineral at the expense of chlorite, and pyrrhotite becomes more dominant at the expense of pyrite. The relative amounts of hornblende and plagioclase show extensive variation in the disseminated ore. The content of magnetite and ilmenite varies as in the diagram (Fig.4.).



**Fig. 4.** In the first-class ore the magnetite/magnetite+ilmenite ratio is commonly 0.40-0.60 and in third-class ore the ratio is 0.30-0.50. The constant ratio of magnetite and ore minerals helped in developing alternative methods to map the ore bodies. A calibrated three-component magnetometer survey conducted from drill holes (diamond core drilling and extension steel drilling) was cost saving technique and assured a sufficient geological information from the challenging ore zone (Pääkkönen 1956).

The high-grade ore contains 30-40% magnetite and 28-30% ilmenite which generally occur as discrete isometric crystals. The mutual relations of magnetite and ilmenite change as the total volume of oxides in the rock decreases: the disseminated ore contains even twice as much ilmenite as magnetite. For example, if magnetite disappears from the rock it may still contain up to 8-10 % of ilmenite. Pyrite, pyrrhotite and chalcopyrite also were economically significant during mining and accounted for up to 1-2 % of the volume of the ore and host rock (Kerkkonen 1979).



**Table. 2.** The Otanmäki ore is divided in three main ore classes based on the amount of magnetite and ilmenite in the rock. The first ore class is easily distinguished from the second class because of the absence of hornblende that gives the rock more compact appearance (Pääkkönen 1956). The difference between the second and third class ore is not as distinct because there is no change in habit, only the amount of ore minerals decreases from 35 to 20 % in third class. The amphibolites that have higher oxide mineral content than normal amphibolites are classified in third class ore. Third class ore occurs typically as disseminated ore and generally exploited when it is situated in the marginal zone of higher grade ore. Also a compact ore type is found that do not contain any silicate minerals at all. It occurs as veins in very small amounts so it's insignificant for exploitation in general. It's easily distinguished by its sharp contact between the wall rock and unique rainbow-like colors at weathered surface (Pääkkönen 1956).

<b>ORE CLASS</b>	<b>MAGNETITE+ILMENITE %</b>	<b>GANGUE</b>
<b>I - class</b>	<b>&gt; 55</b>	<b>Chlorite</b>
<b>II - class</b>	<b>30 - 55</b>	<b>Hornblende</b>
<b>III - class</b>	<b>&lt; 30</b>	<b>Hornblende + plagioclase</b>

Intergrowths of magnetite and ilmenite are rare. This and the mode of occurrence of pyroxene and olivine indicate that some metamorphism took place. Most likely, magnetite and ilmenite exsolved from each other under the amphibolite facies metamorphic conditions. The first class ore which have been tectonized, magnetite and ilmenite occur as separate grains and in untectonized counterpart ilmenite is mainly in magnetite as inclusions and lamellae (Kerkkonen 1979). No evidence of mobilization of ore is found in Otanmäki. The percentage of vanadium in magnetite is around 0.80-1.05 %  $V_2O_3$  but fairly constant at 0.90 %  $V_2O_3$ . The layering is not affecting the vanadium content.

## 3.4. Mineralogy of Otanmäki ore

### 3.3.1. Magnetite

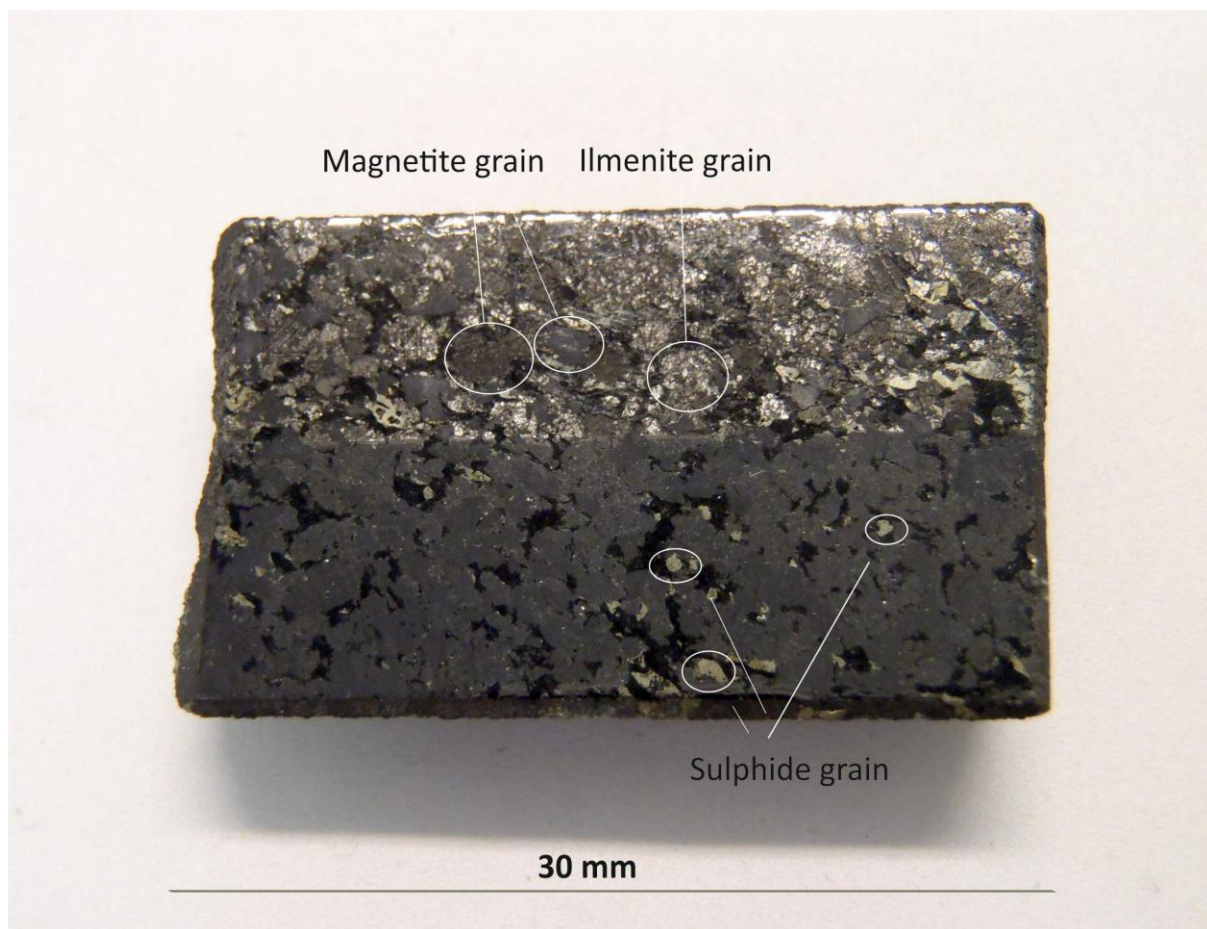
The size of the magnetite grains (Fig. 5.) varies from average of 0.2 – 0.8 mm and in some parts of the high grade ore the grain size well over 1 mm. A typical medium grained magnetite crystal contains 5-20 exsolution lamellae which are 1-2 microns wide and less than 60 micron long. Exsolution lamellae are lacking from small magnetite crystals. Magnetite may contain ilmenite inclusions 0.002-0.06 mm in diameter (Lindholm & Anttonen 1980).

### 3.3.2. Ilmenite

The ilmenite grains (Fig. 5.) are usually a diameter of 0.2 – 0.3 mm and form typically small clusters. Lamellar twinning of ilmenite and hematite inclusions and exolutions are very common. Sometimes Ilmenite occurs as inclusions or lamellae in magnetite (Kerkkonen 1979). Also small silicaste inclusions are found as well, but no magnetite is seen in the ilmenite (Pääkkönen 1956).

### 3.3.3. Sulphides

The sulphides ( pyrite, pyrrhotite and chalcopyrite) is mainly found in small amounts, typically as grain clusters but also as small compact veins. Its content of total ore and host rock is average of 1-5 % and its economically viable due to cobalt in pyrite (Kerkkonen 1979).



**Fig.5.** A polished minidrill (OT59) sample of Otanmäki ore where magnetite and ilmenite occur as separate grains. When etching the sample with hydrochloric acid, magnetite turns to various brown colors and ilmenite turns pale (Kerkkonen 1979).

### 3.3.4. Silicates

The main silicates are plagioclase, hornblende, biotite, clinopyroxene and olivine. The pyroxenes and olivine are rarely found due to metamorphism. Some metagabbros contain olivine-pyroxene relicts and pseudomorphs (Papunen 1986). There are clear indications on pyroxenes from level +425 (Itämalmi ore) where small pyroxene-hornblendite inclusions have been found. Also occasional

ilmenite dissemination in hornblende grains is an evidence of pyroxene in oxide rich rocks (Kerkkonen 1979).

#### 4. REE-BEARING MINERALS IN OTANMÄKI ALKALINE ROCKS

The first indications of elevated Nb-lanthanide concentrations were observed in 1960's and during the exploration in 1970's it was concluded that it's related to Honkamäki and Otanmäki type metasomatic alkaline rocks. Not until 1983 more focused exploration began following the identification of REE-bearing boulder trains by GTK and led to a discovery of Katajakangas and Kontioaho deposits (Hugg 1985a, Hugg 1985b). A total of 59 diamond drill holes for a total of 8,862 metres have been drilled in the area (Hugg 1985b).

Katajakangas mineralization is located at the middle part of Otanmäki supracrustal rocks and is hosted by quartz-feldspar schist. The main rocktypes found in Katajakangas includes amphibolite-biotite gneiss, quartz-feldspar gneiss and quartz-amphibolite-carbonate rocks, and alkaline-gneiss. The mineralized veins are stratiform with the main rock package and the average thickness is 0.5 meters but some veins can go up 1.4 meters in width. The NE-SW trending mineralized body is roughly 850 meters long (Hugg 1985a). Mineral assemblage consist primary of quartz, biotite, calcite, plagioclase, amphibolites, epidote, and muscovite. Allanite- (Ce), which has an idealized formula  $(\text{Ce,Ca,Y})_2(\text{Al, Fe}^{3+})_3(\text{SiO}_4)(\text{OH})$  and Fergusonite  $\text{Y}(\text{Nb, Ta})\text{O}_4$ , are the most abundant and widespread REE-bearing minerals in the Otanmäki alkaline rocks. Also some columbite  $(\text{Fe, Mn})(\text{Nb, Ta})_2\text{O}_6$  is found as accessory mineral. Fergusonite is characterized by high content of radioactive elements as Th and U. The REE has obviously mobilized in metasomatic processes (late-stage hydrothermal alteration); redistributed in the host minerals and trapped by epidote, which forms a complete solid solution series ranging from REE-free epidote to allanite-Ce (Al-Ani et al. 2010). In 1985, Rautaruukki Oy reported a resource estimate at Katajakangas of 0.46 million tonnes at 2.71% TREO, 0.76% Nb<sub>2</sub>O<sub>5</sub>, and 1.13 ZrO<sub>2</sub> (TREO = total rare earth oxide). The resource estimate is based on 14 diamond drill holes, drilled in 7 profiles 850 metres along strike and has been calculated to a vertical depth of 150 metres (Hugg 1985a).

Kontioaho deposit Kontioaho is situated 1.3 kilometers to the north-northeast of Katajakangas. The mineral assemblage consists of quartz, microcline, plagioclase, zircon and magnetite. The main REE minerals are allanite, fergusonite and xenotime. The deposit is hosted by altered quartz-feldspar schist which is approximately 7-12 meters wide northwest trending zone (Hugg 1985b).

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## APPENDIX

### LOCALITY/STOP DESCRIPTION

#### STOP 1.

##### Honkamäki (V-Ti-Fe) deposit and Otanmäki association rocks

Honkamäki deposit is situated 12 kilometers west of Otanmäki (see map). Geologically, it represents a typical vanadium-rich magnetite-ilmenite deposit of Otanmäki type (Kinnunen 1980). The trench has been excavated during the field season of 2013.



**Fig. 1.** The trench outlines in Honkamäki (left) and leucogabbro (right).

#### STOP 2.

##### Alkalic gneiss (Pikku-kallio rock quarry)

Alkalic gneiss surrounds the supracrustal rocks (see map). It is characterized as heterogeneous rock containing microcline, albite, quartz, aegirine and riebeckite.



**Fig. 2.** Alkalic gneiss (Honkamäki granite).

#### STOP 3.

##### The striped gneiss (Railway SW of Pikku-Otanmäki)

Banded gneiss is of the pre-Svecokarelian basement complex (ca 2.8-2.6 Ga) and represents the oldest rock type in the region. Structurally, the gneiss is very heterogeneous and contains inclusions of amphibolites, veins of pegmatitic granite and fragments of mica gneiss (Lindholm & Anttonen 1980). The main mineral composition is quartz, plagioclase ( $An_{10}$ ), microcline, epidote, chlorite, and apatite.



**Fig. 3.** The Archean striped gneiss (Tonalitic migmatite).

#### **STOP 4.**

##### **Otanmäki gabbro (Pikku-Otanmäki)**

The gabbro is usually medium- to coarse grained and the typical rectangular habit of greenish or reddish grey plagioclase (An<sub>55</sub>) grains and the fringe-like form of hornblende are the most distinct features. The main minerals are plagioclase and hornblende with ilmenite, magnetite, epidote, apatite, sphene, and pyrite are common accessory minerals. Hornblende is always present but seldom as the predominant mineral. In some places the remnants of colorless monoclinic pyroxene grains are surrounded by grains of uralitic hornblende. The twinning lamellae of the plagioclase laths are often bent and have sometimes an undulatory extinction (Pääkkönen 1956).



**Fig. 4.** Otanmäki gabbro at Pikku-Otanmäki outcrop.

#### **STOP 5.**

##### **Trench 1, Otanmäki association rocks**

The trench has been excavated during the field season of 2013.

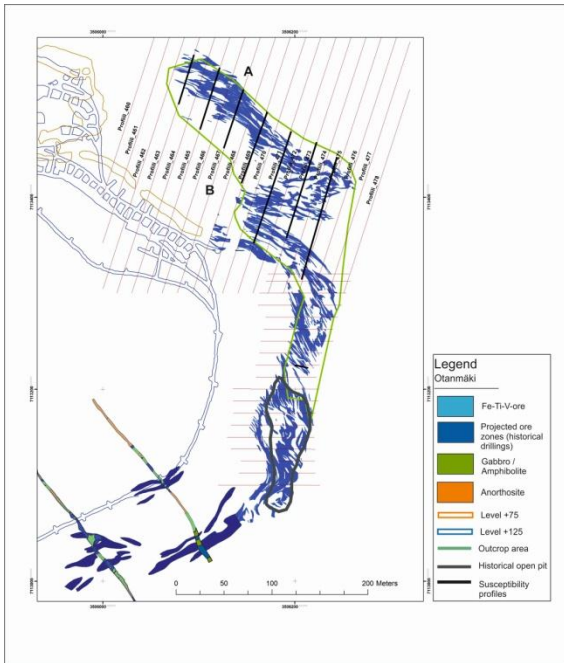
#### **STOP 6.**

##### **Metsämalmi outcrop area**

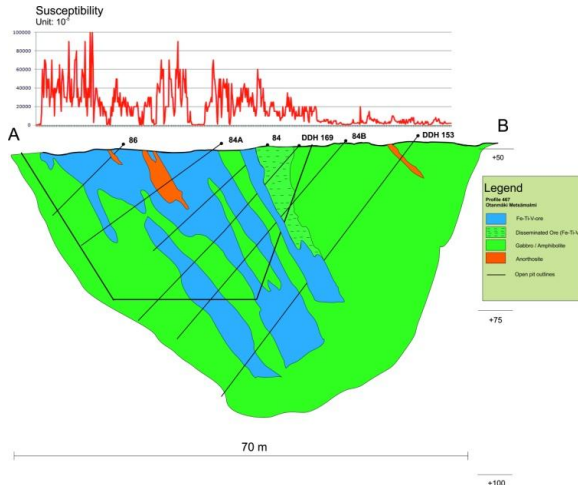
Otanmäki association rocks. 250 x 200 meters sized outcrop area of Metsämalmi which Rautaruukki Oy had initial plans to open-pit mine in 1980's. For that purpose the overburden was removed and now this area gives a spectacular view to the geological features.



**Fig. 5.** The Metsämalmi outcrop area (upper). The main ore types and different micro-structures seen in outcrops of Metsämalmi (lower).



**Fig.6.** Otanmäki ore consists of hundreds of individual lens-like ore bodies. Trenching confirms that the main ore zone is continuing towards SW. Susceptibility measurements were conducted at 30 metres spacing along the historical profile lines (black lines).

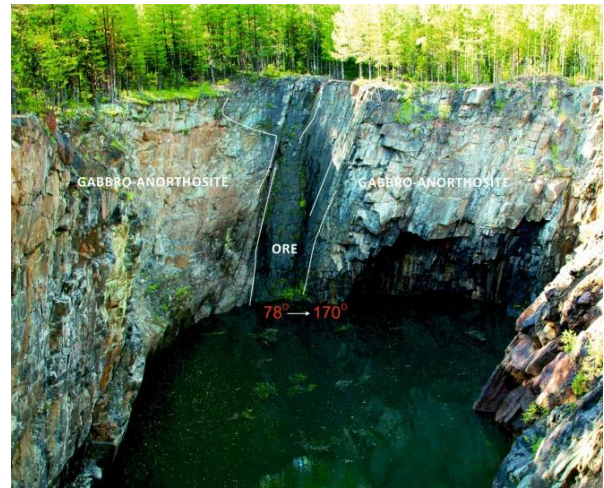


**Fig.7.** A cross-section A-A' of Metsämalmi ore.

**STOP 7.**

**Suomalmi cave-in pit**

The uppermost tunnel was blasted for the risk of cave-in. Now it gives a good sight to the ore dimension.

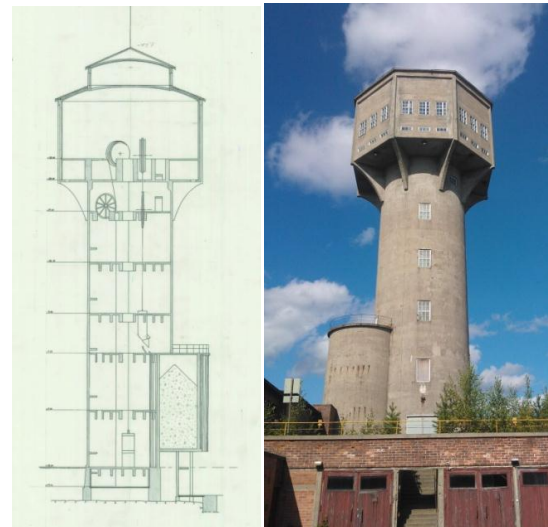


**Fig. 8.** The ore zone visible in the cave-in pit.

**STOP 8.**

**The main shaft of Otanmäki**

Challenge yourself and climb up to the old mine tower of Otanmäki and experience the old mining spirit.



**Fig. 9.** The main shaft of Otanmäki.

**STOP 9.**

**The Otanmäki association rocks (bomb shelter)**



## STOP 10.

### Vuorokas mine (rock quarry)

Vuorokas mine is situated about 3 km eastward from Otanmäki main shaft. The deposit was discovered in 1939, a year later than Otanmäki deposit. The deposit comprises a 2 km long ore zone (SW-NE) including at least 6 separated ore bodies. Geologically, it represents a typical vanadium-rich magnetite-ilmenite deposit of Otanmäki type (Kinnunen 1980).

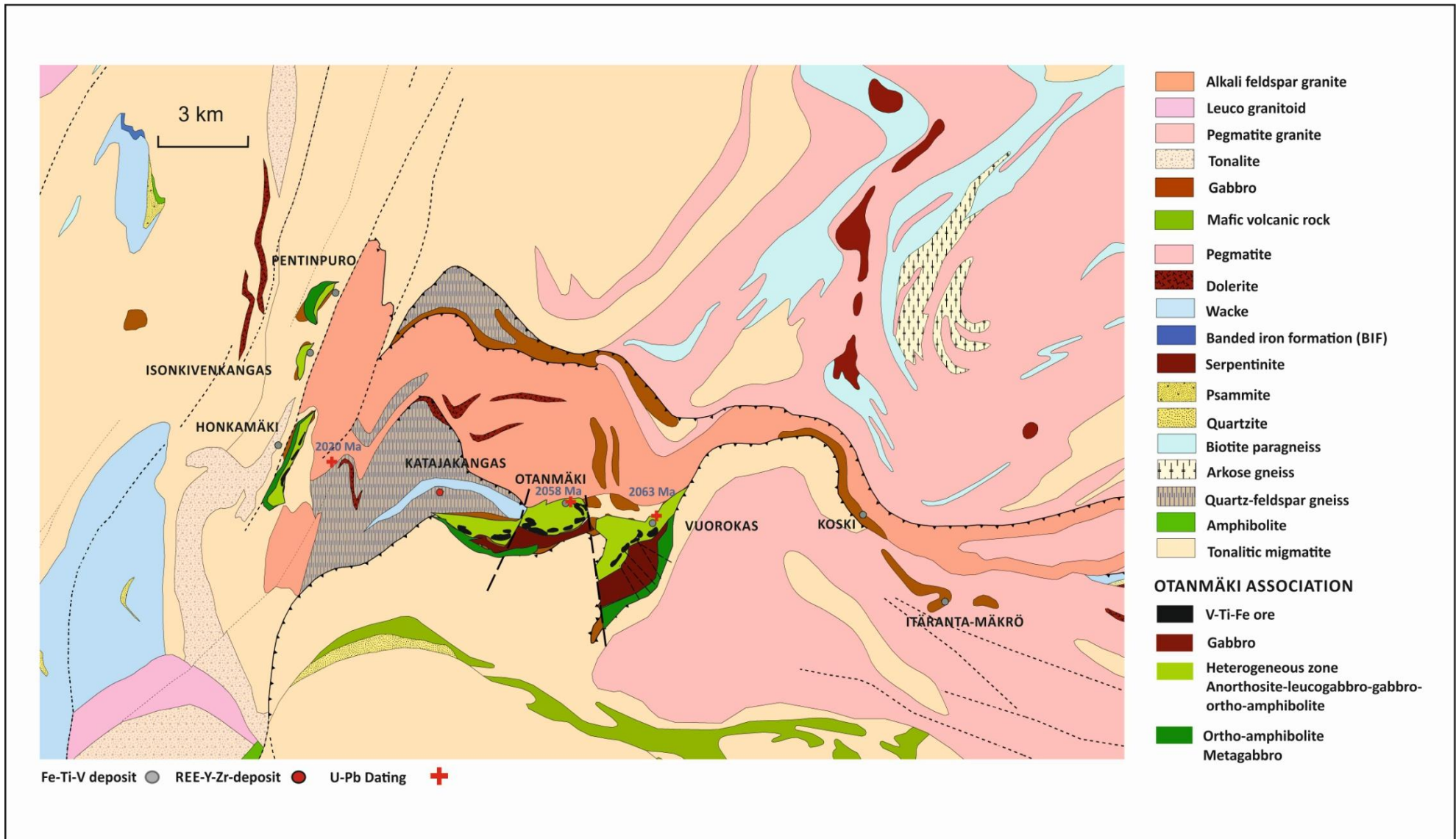


Fig.10. Vuorokas rock quarry.

## MAP OF EXCURSION STOPS



# GEOLOGICAL MAP OF OTANMÄKI REGION



modified after *Bedrock of Finland –DigiKP*

<i>Date: July 23, 2014</i>	<i>STOP No.: 23-1</i>
<b>Locality name: Pyhäsalmi</b>	
<i>Main commodity: Cu-Zn</i>	
<i>Geological setting or genetic model: VMS</i>	
<i>Current development status: underground mine</i>	
<b>WGS Latitude: 63.65948N</b>	<b>WGS Longitude: 26.04611E</b>
<i>KKJ Northing: 7062380</i>	<i>KKJ Easting: 3452930</i>
<i>Municipality: Pyhäjärvi</i>	
<i>Location &amp; access: 5 km SE from Pyhäsalmi, 150 km S of Oulu. Railway and a sealed road to the mine; 3 km from the Highway no. 27.</i>	
<i>Geological domain: Svecofennian</i>	<i>Geological unit: Raahe–Ladoga suture</i>
<i>Owner (2014): First Quantum Minerals</i>	

### **Geology**

The Pyhäsalmi deposit is a stratabound massive Zn-Cu-pyrite deposit. It was formed syngenetically with silicic volcanics and was exposed to several phases of deformation. It is mined in an underground operation and has total reserves of close to 60 Mt.

The Pyhäsalmi deposit is located in the Vihanti-Pyhäsalmi district (Fig. 23-1-1). The district situated on the NE corner of the Svecofennian domain, which is characterized by the Raahe-Ladoga suture (Västi, 2012). The highly metamorphosed and tectonized Raahe-Ladoga zone is part of the Svecofennian domain (1.95-1.80 Ga) stratigraphically between Archean basement complexes in the east and the Central Finland Granitoid Complex (1.88 Ga) in the southwest (Luukas and Kuosa, 2012).

The Vihanti-Pyhäsalmi district is about 300 km long and 10-40 km wide and hosts several sub-economic to economic base metal deposits. The district has historically been one of the most significant base metal mining areas in Finland and used to be called the Main sulphide ore belt. Metavolcanic rocks, or occasionally metasedimentary rocks, formed in an island arc environment host most of the sulfide deposits in the district. In the vicinity of the main Pyhäsalmi deposit the volcanic succession is characterized by extensional continental margin felsic volcanism followed by rifted marine mafic volcanism. Close to the centers of mafic volcanism large scale-hydrothermal alteration occurred. This was followed by more calc-alkaline volcanism (Västi, 2012).

The only currently mined deposit in the volcano-sedimentary Pyhäsalmi group is the Pyhäsalmi massive Zn-Cu-pyrite deposit (Fig. 23-1-2, 23-1-3), with reported total reserves (past and present) of just under 60 Mt at 0.95 % Cu, 2.41 % Zn, 37.5 % S, 0.4 g/t Au and 14 g/t Ag. Three minor nearby deposits were also mined during the operation of the mine. The Ruostesuo deposit (0.24 Mt), the Kangasjärvi deposit (0.086 Mt) and the Mullikoräme deposit (1.15 Mt). The main Pyhäsalmi deposit is hosted in a bimodal volcanic sequence altered by a characteristic sericite-cordierite-antophyllite alteration. The deep zones of the ore body were tectonically displaced and are now surrounded by unaltered mafic and felsic volcanic rocks. Furthermore, pegmatite and diabase dikes as well as plutonic intrusives occur in the deposit area (Luukas

and Kuosa, 2012).

The ore at Pyhäsalmi is composed of massive pyrite with variable amounts of chalcopyrite and sphalerite. Accessory ore minerals are pyrrhotite, galena, arsenopyrite, magnetite and tetrahedrite-tennantite (Fig 23-1-3 to 23-1-6). Typical gangue minerals are quartz and barite with occasional calcite. In the transitional zone between the ore and country-rock, disseminated sulfides occur which are considered to be replacing minerals of the host rock. Ores containing pyrrhotite were considered to post-date fracturing and tectonic events by early studies, implying different phases of mineralization or remobilization (Helovuori, 1979). To depths of about 1000 m, the center of the ore body is enriched in sphalerite while the outer margins are chalcopyrite-rich. Below that, the center is characterized by a low-Cu/Zn massive pyrite centre bordered by chalcopyrite-rich ore and sphalerite-rich rocks at the outer margins (Saltikoff, Puustinen and Tontti, 2006).

The ore is conformable with its environment and most of it is considered syngenetic to the metavolcanics. It is classified as a VMS-type deposit. In plan view the orebody extends for 650 m and is up to 80 m wide. The deepest mining level is at 1400 m below surface. The complicated shape of the ore body reflects several deformation events, some of which were associated with remobilization of sulfides (Helovuori, 1979).

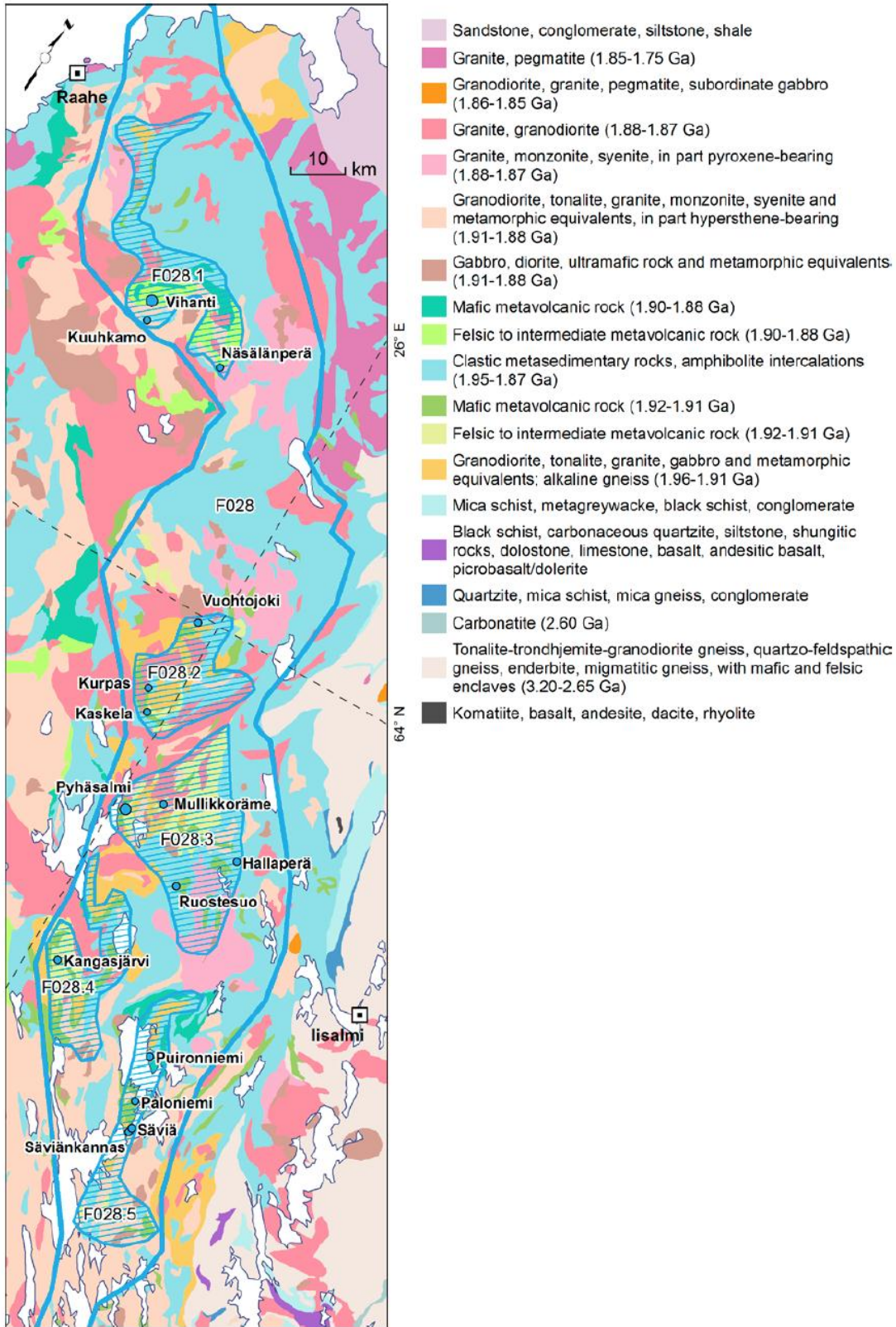
The ore deposit was discovered in 1958 by a farmer drilling a hole in his yard for a new well. Production commenced a few years later and has been continuously ongoing since. A curiosity about this deposit is the cosmic-ray experiment facility at the lowest levels of the mine.

### **Discussion**

The cordierite-schists associated with the ore-body were point of discussion by the visiting group. The original location relative to the sulfide-bearing rock units is not easily reconstructable but the general idea was that the Mg-Fe-rich ore-forming fluids precipitate the Fe together with the sulfides while the Mg is precipitated in the host rocks leading to Mg-alteration. The amphibolite to granulite facies metamorphism during the fennoscandian orogeny then led to the formation of the cordierite schists. Furthermore, the absence of galena in the deposit suggests that no continental crust was leached by the convecting fluids. This argument is strengthened by the fact that the local rock suite is characteristic for an oceanic crust sequence.

The origin of the unusual form of the orebody has not been circumstantially explained in openly published, English literature. The only explanation for the vertically elongated, tube-like shape of the upper part of the deposit and the so called 'potato-shape' in the bottom part are metamorphic processes. The most reasonable explanation that our group discussed was the downward sinking of the previously deposited sulfide-rich lithologies due to gravitational processes, which could lead to a similar shape. Sulfide-bearing rocks have a much higher specific gravity than the country-rocks, which would explain the 'sinking' in relation to the country rocks.

The zonation of massive pyrite in the centre of the 'potato' and sphalerite and chalcopyrite-rich units at the margins can also be explained by their rheology. Chalcopyrite and sphalerite are more ductile than pyrite and might therefore surround the more brittle massive pyrite core after the deformation process.



**Fig. 23-1-1.** Regional map of the Pyhäsalmi deposit (from Västi, 2012).

# SURFACE PLAN OF THE PYHÄSALMI ORE

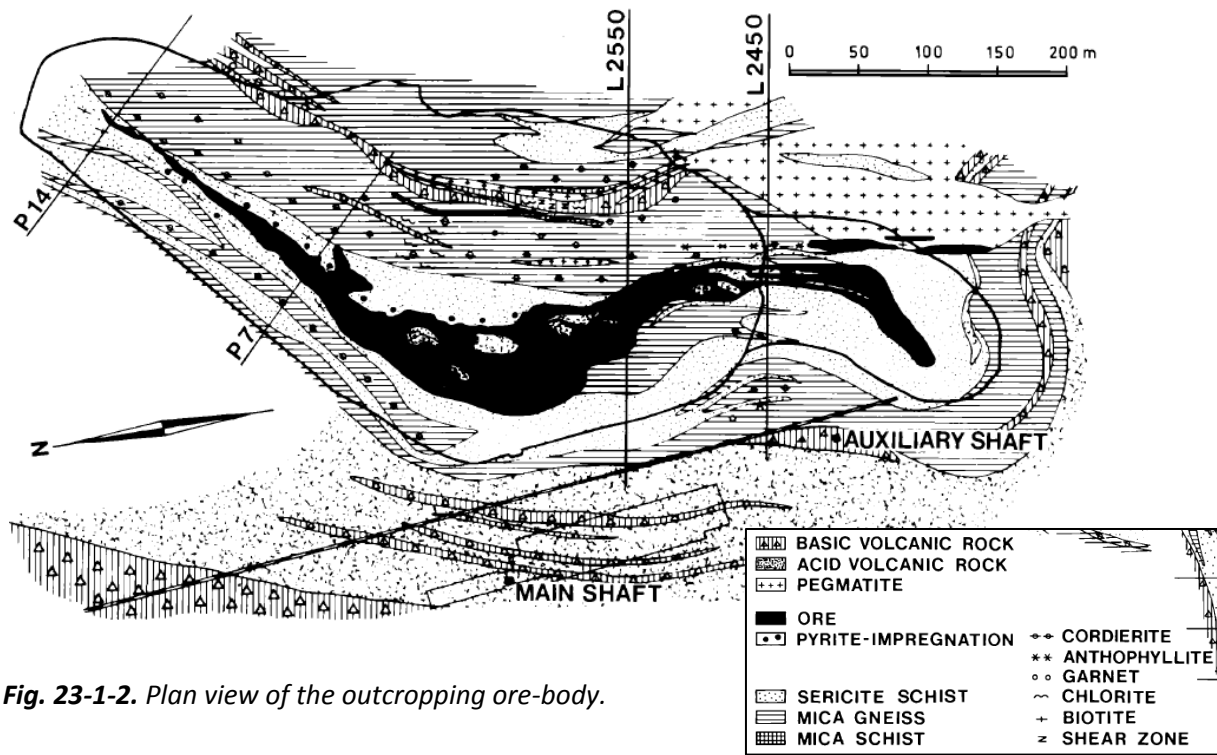


Fig. 23-1-2. Plan view of the outcropping ore-body.

# Pyhäsalmi ore deposit

Modified from Mäki & Luukas (2001)  
by K. Västi

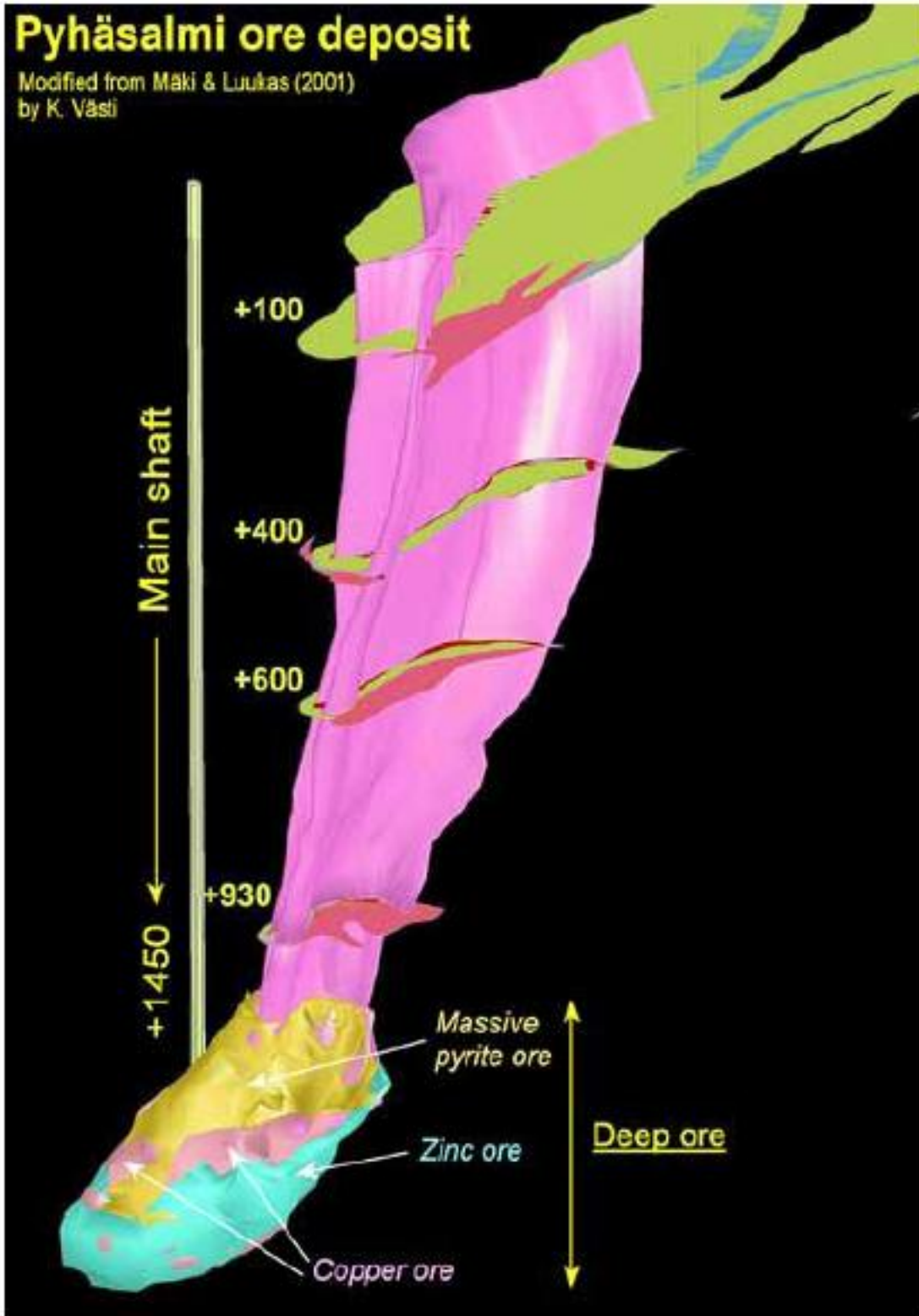
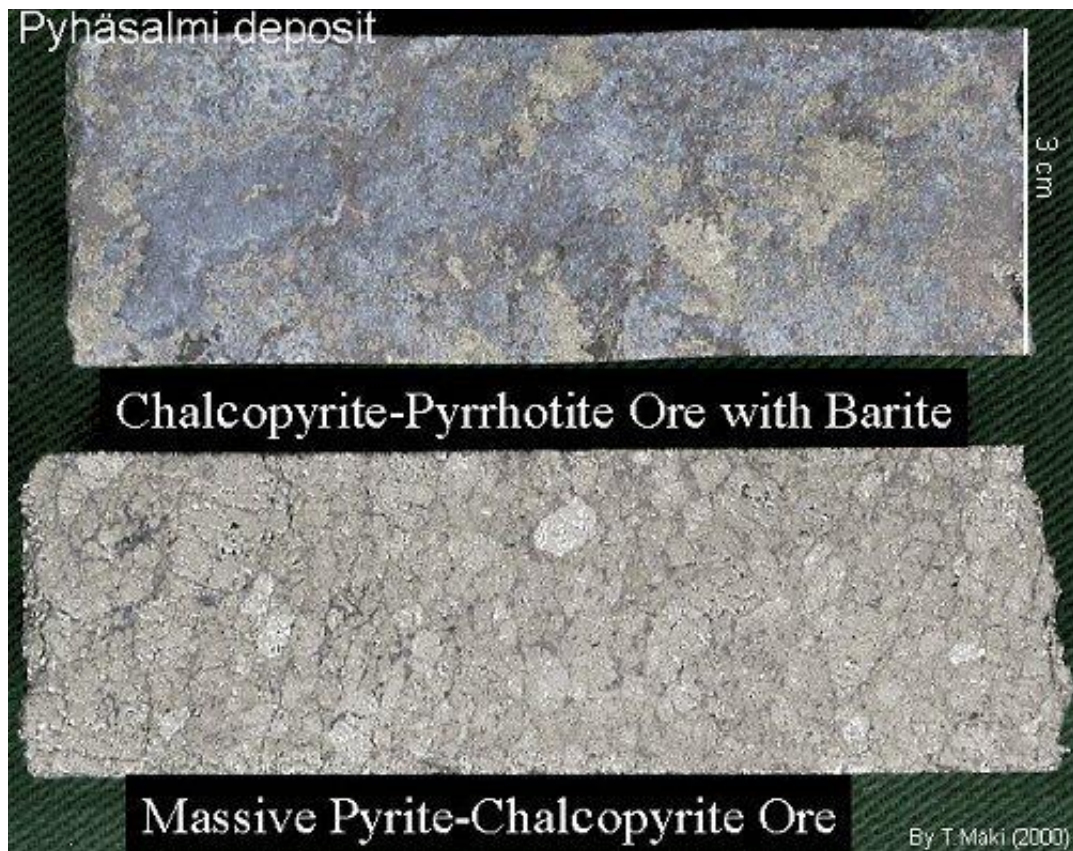
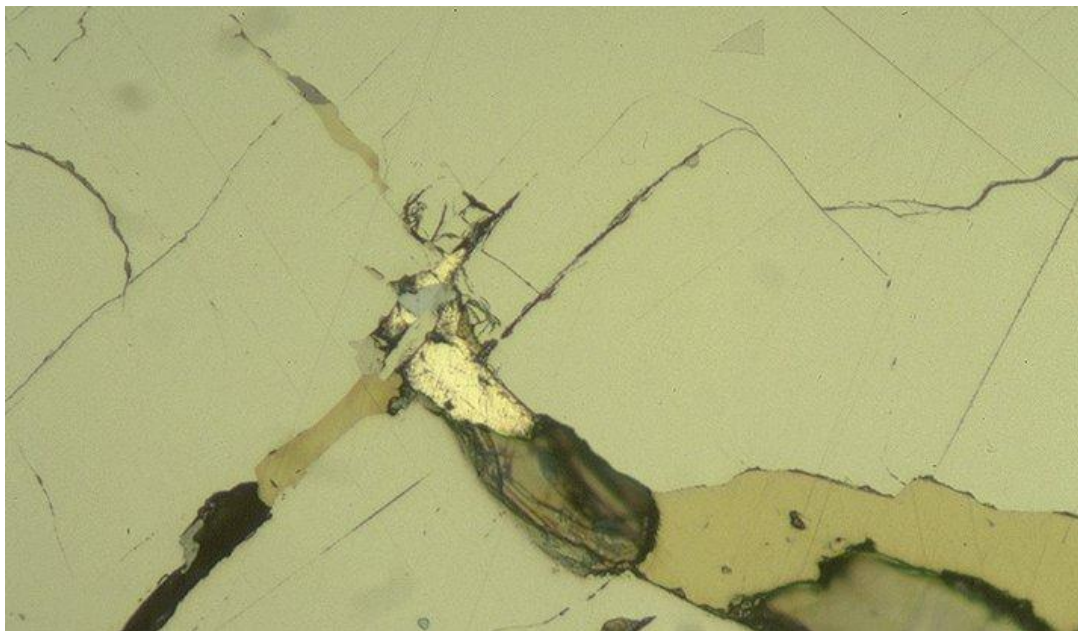


Fig. 23-1-3. 3D-model of the Pyhäsalmi deposit (from Västi, 2012).

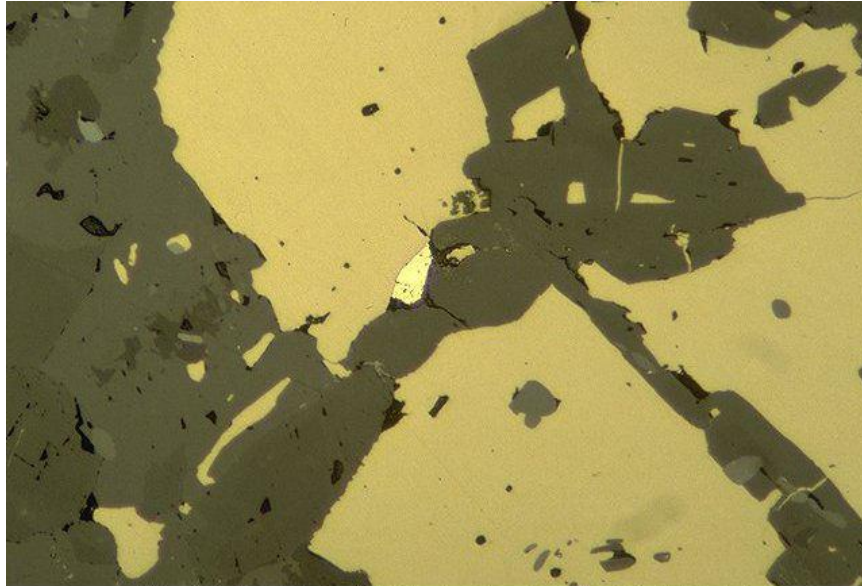


**Fig 23-1-4.** Different ore-types of the Pyhäsalmi deposit (from GTK website).



**Fig. 23-15.** Native silver, chalcopyrite, pyrrhotite and galena in pyrite fractures. Field of view 0.5 mm, photo: Pasi Eilu (from GTK website).





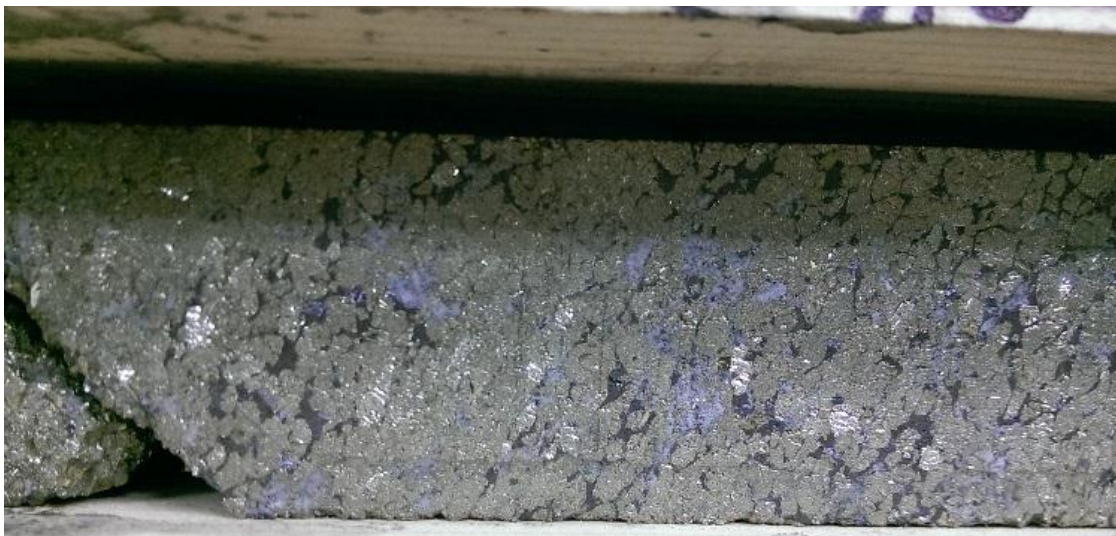
**Fig. 23-1-6.** *Electrum with chalcopyrite in high-grade ore . Field of view 1 mm, photo: T. Maki (from GTK website).*



**Fig. 23-1-7.** *Outer contact of the deep massive sulfide orebody. Highly disharmonic folding of quartzite (grey to white competent lithology: former exhalative chert; note continuous lamination) and Bt-Cpy-gneiss (dark brown ductile material squeezed into fold hinges; exhalative sulfide and former clay minerals on ocean floor). Was this intense local deformation caused by gravitational sag of massive sulfide orebody during high-grade metamorphism? (photo: Ch. Heinrich; photo corresponds to scale of about 2 m x 1.2 m).*



**Fig. 23-1-8.** *Folded pyrite-chalcopyrite vein in talc-chlorite-muscovite schist. Interpreted as original stockwerk vein in the footwall of a massive sulfide deposit, where upwelling heated seawater caused intense Ms-silicate alteration of submarine volcanics and subsequently led to massive sulfide exhalation onto the seafloor (photo: Ch. Heinrich).*



**Fig. 23-1-9.** *Pyhäsalmi massive reworked pyrite ore with preferred orientation (photo: D. Klimentyeva).*

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<http://en.gtk.fi/ExplorationFinland/Moreinfo/pyhasalmi.html>.

**Compiled by: Simon Large**

<i>Date: July 24, 2014</i>	<i>STOP No.: 24-1</i>
<b>Locality name:</b> Länttä	<i>Alternative names:</i> Syväjärvi (Kaustinen)
<i>Main commodity:</i> Li	
<i>Geological setting or genetic model:</i> Spodumene Pegmatite	
<i>Current development status:</i> Pre-feasibility stage	
<b>WGS Latitude: 63.661517</b>	<b>WGS Longitude: 23.807067</b>
<i>Municipality:</i> Kaustinen and Ullava, Central Ostrobothnia	
<i>Location &amp; access:</i> Länttä: by Kaustinen take the road 63; Syväjärvi: Between Länttä and Kaustinen	
<i>Geological domain:</i> Central Finland Granite Complex	<i>Geological unit:</i> Pohjanmaa schist belt
<i>Owner (2014):</i> Keliber Oy, Toholammintie 496, 69600 Kaustinen	

### **Geology**

The Kaustinen Lithium province has an area of 500 km<sup>2</sup> and is part of the Svecofennian Pohjanmaa schist belt, which is located between the Central Finland Granite Complex (mostly granite and Granodiorite with an age between 1.89-1.87 Ga) and the Vaasa Migmatite Complex.

Starting in the 1960s using boulder fans, diamond drillings, till sampling and geophysical surveys, dozens of spodumene pegmatite veins were found in this region. Most of the Rare-elements bearing granitic pegmatite of the Kaustinen Region belong to the LCT (Li, Cs, Ta) family, only one deposit shows NYF (Nb, Y, F), elements enrichment. The veins are beryl pegmatite, spodumene pegmatite, or albite-spodumene pegmatite.

The pegmatite forms as a residual melt of granitic intrusions. Regarding the Kaustinen region it is still not clear to which intrusion those veins are related. The U-Pb ages obtained from LCT pegmatite are between 1.79 and 1.82 Ga. Those values indicate that the pegmatites have a different magmatic origin than the culmination (1.88Ga) of the Svecofennian orogeny (Alviola, 2001).

The Pohjanmaa schist belt is mainly composed of mica schist and greywackes. In some cases sulphide bearing black schist sans volcanic rocks are also present. The metamorphic grade of this belt varies between low amphibolite conditions in the eastern part, and high amphibolites conditions near the Vaasa Granite Complex (Alviola, 2001)

The only economic mineral in those deposits is spodumene, no lepidolite was found. The average Li<sub>2</sub>O (wt-%) concentration varies from 0.74% to 1.18%, which means a normative content of 10% to 15% of spodumene (see table 24-1-1).

The pegmatites are mineralogically similar to each other; the main minerals are plagioclase (albite), quartz, K-feldspar (very big reddish crystal up to >6cm), spodumene and muscovite. Spodumene minerals are typically coarse grained elongated lath-shaped crystals, the size can vary from 0.5cm to more than 12cm. The color can vary from greenish to grey, but it can in some cases appear reddish depending on the iron content. The Kaustinen Pegmatites are as usual zoned and show enrichment of the incompatibles elements towards the core of the dike, where the highest spodumene concentration

can be found.

Two of the most interesting sites in the Kaustinen area are the Länttä and the Syväjärvi deposits, together they are supposed to contain 5.5 Mt of Lithium with an average concentration of 0.95%.

**Länttä:** The Länttä resource represents an example of homogenous albite-spodumene pegmatite. The deposit consists of two, partly boudinaged veins, with a maximum vein width of about ten meters. Also small parallel veins exist in connection to these main veins. The host rock is mainly intermediate-mafic volcanic rock with some mica schist. The vein strike is SW-NE and dips 70° to SE with close to vertical lineation. Overburden averages 4 m at Länttä varying from almost 0 to 7 m and is almost totally till with some peat on the surface.

**Syväjärvi:** The spodumene pegmatite exists in the form of main dikes of a maximum thickness of 30 m that split in two in places and in a few narrow parallel dikes. The host rock in the area is a blend of mica schist and greywacke, with some volcanic rocks such as tuffs, lapilli tuffs, agglomerates and plagioclase porphyrites that are also present.

Table 1. Mineral assemblages and the average Li<sub>2</sub>O-, Ta<sub>2</sub>O<sub>5</sub>-, Nb<sub>2</sub>O<sub>5</sub>- and BeO contents of the Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites.

Deposit	Main minerals (in abundance order)	Accessory minerals	Li <sub>2</sub> O %	Ta <sub>2</sub> O <sub>5</sub> ppm	Nb <sub>2</sub> O <sub>5</sub> ppm	BeO ppm
Leviäkangas	Albite, Quartz, K-feldspar, Spodumene, Muscovite	apatite, cassiterite, cookeite, garnet, graphite, Mn-Fe phosphate, montebrasite, Nb-Ta oxides, sphalerite, tourmaline, zeolite	0.74	72	87	185
Syväjärvi	Albite, Quartz, K-feldspar, Spodumene, Muscovite	apatite, arsenopyrite, garnet, Nb-Ta oxides, sphalerite, tourmaline	1.00	26	36	148
Rapasaaret	Albite, Quartz, Spodumene, K-feldspar, Muscovite	andalusite, apatite, arsenopyrite, beryl, calcite, chlorite, fluorite, garnet, Mn-Fe phosphates, Nb-Ta oxides, pyrite, pyrrhotite, tourmaline, zinnwaldite	1.18	53	58	502

Table 2. The known lithium resources of the Kaustinen area.

Deposit	Tonnage (Mt)	Li <sub>2</sub> O wt%
Emmes	1.1	1.3
Länttä	2.95	0.92
Leviäkangas	2.1	0.7
Syväjärvi	2.6	0.98
Rapasaaret	3.7	1.02

Tables 24-1-1 & 24-1-2. From Ahtola and Kuusela (2013).

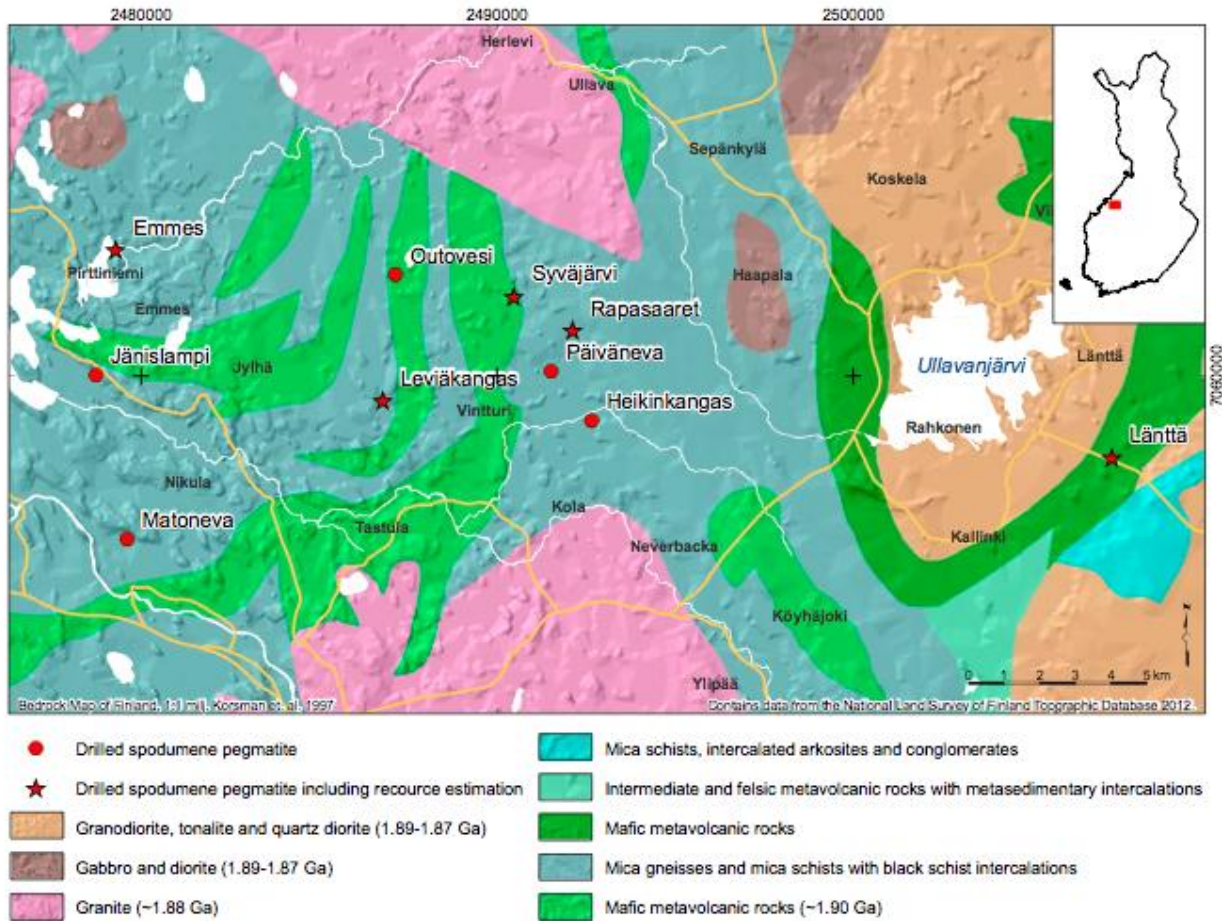


Fig. 1. Regional geological map of the Kaustinen Li province after Korsman et al. (1997), showing the locations of the drilled spodumene pegmatites.

Fig. 24-1-1. From Ahtola and Kuusela (2013).

# The Lithium province of Central Ostrobothnia

- the most important known lithium deposits

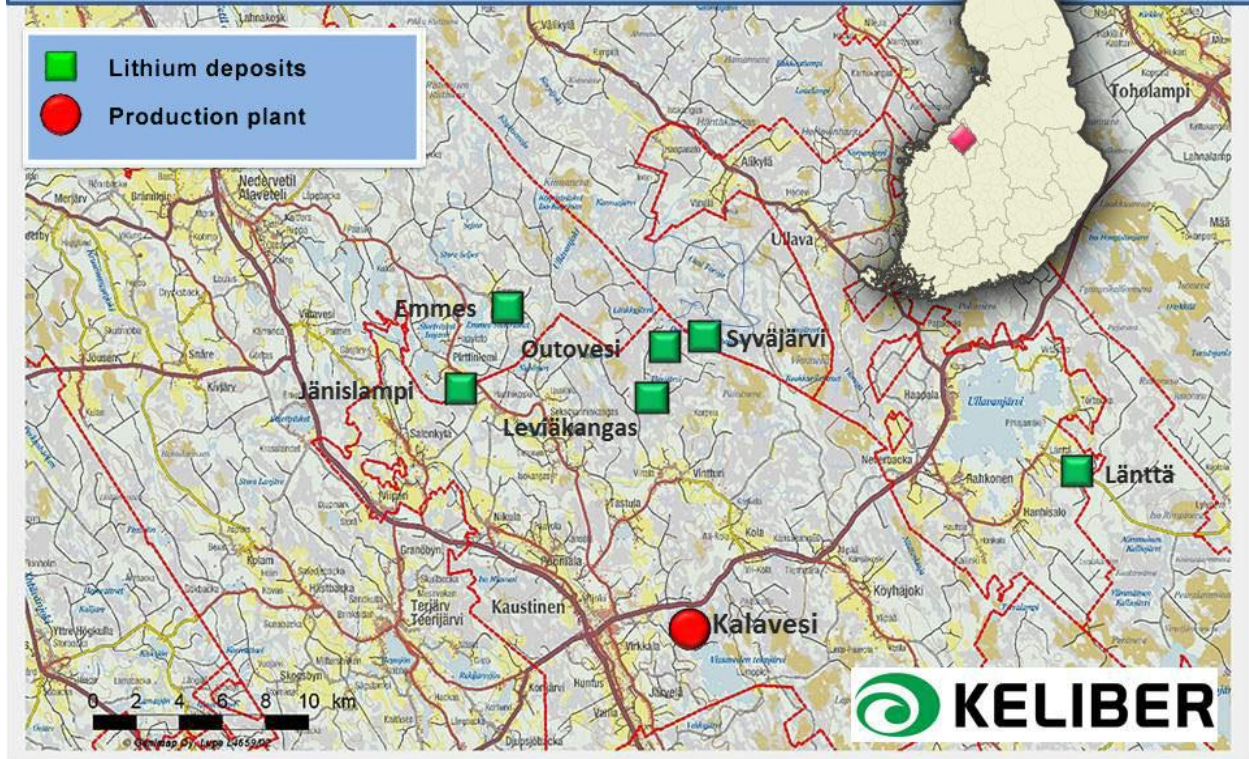


Fig 24-1-2. Map of the Kaustinen Lithium deposit (From keliber website).

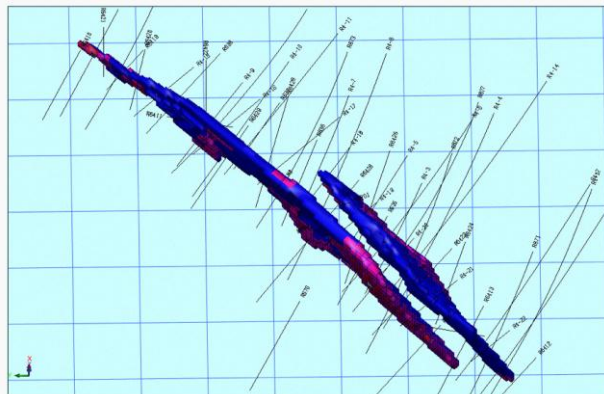


Fig 24-1-3 Länttä deposit (From keliber website).

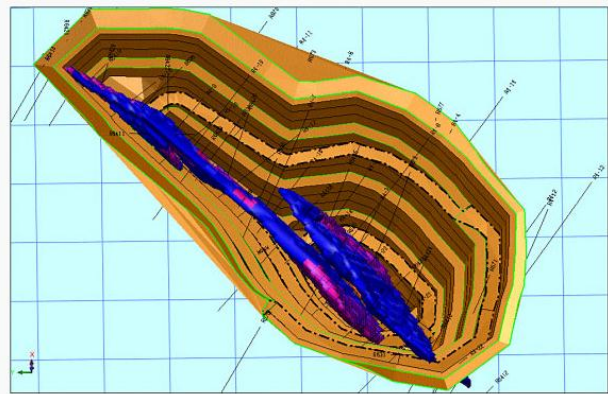
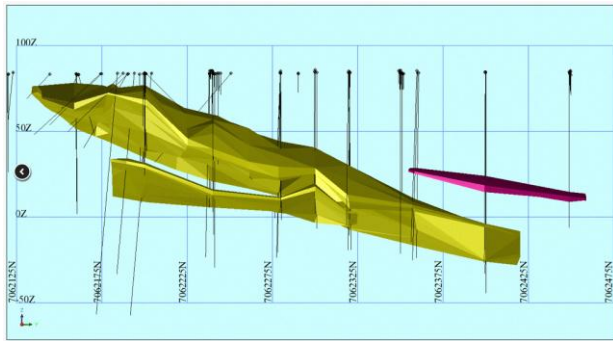
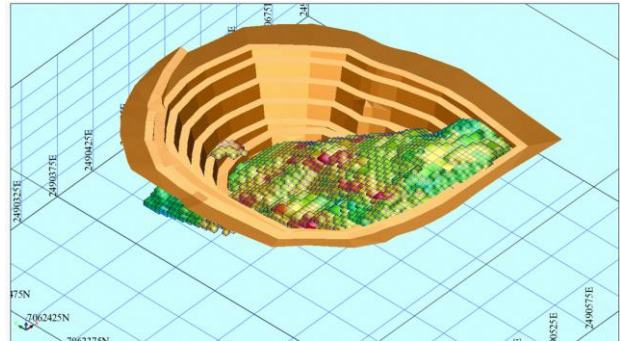


Fig 24-1-4 Länttä deposit (From keliber website).



**Fig. 24-1-5** Lanttä deposit (From keliber website).



**Fig. 24-1-6** Lanttä deposit (From keliber website).



**Fig. 24-1-7.** Lanttä spodumene pegmatite: feldspar pegmatite with blade-shaped spodumen crystals growing perpendicularly inward (up), away from the intrusive contact against the amphibolite host rock (bottom). Wavy contact and concordant foliation in amphibolite indicates that pegmatite intruded before or during regional metamorphism. (photo: Ch. Heinrich).



**Fig. 24-1-8.** Lanttä spodumene pegmatite: Closeup of high-grade Li ore composed of albite + quartz + pink laths of spodumene (photo: Ch. Heinrich).



**Fig. 24-1-9.** Typical sample of amphibolite-facies metamorphosed turbidite of the Pohjanmaa Schist Belt, representing former deep-water sedimentation related to the intra-oceanic arc that formed the juvenile Svecofennian crust during Paleoproterozoic (~ 1.9 Ma) times (photo: Ch. Heinrich).



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- <http://www.nordicmining.com/keliber-lithium/category290.html>

**Compiled by: Pietro Luraschi and Marco Verdon**

<i>Date: July 25, 2014</i>	<i>STOP No.: 25-1 (optional)</i>
<b>Locality name: Kalliojärvi</b>	
<i>Main commodity: Au Ag, As, Au, Cu, S.</i>	
<i>Geological setting or genetic model: orogenic</i>	
<i>Current development status: prospect</i>	
<b>WGS Latitude: 61.32422</b>	<b>WGS Longitude: 23.69790</b>
<i>KKJ Northing: 6809400</i>	<i>KKJ Easting: 2484000</i>
<i>Municipality: Lempäälä</i>	
<i>Location &amp; access: About 15 km SSW of the city of Tampere. Four km from a sealed road and railway, a gravel road across the area.</i>	
<i>Geological domain: Svecofennian</i>	<i>Geological unit: Vammala Migmatite Zone</i>
<i>Owner (2014): Björkdalsgruvan – North American Gold JV (since 2004)</i>	

### ***Svecofennian orogeny***

The bedrock of southwestern Finland was chiefly formed during the composite Svecofennian orogeny at 1.9–1.8 Ga (Grönholm and Kärkkäinen, 2012). The orogeny evolved through accretion and attempted collapse to collisional stages. The bedrock of southwestern Finland essentially comprises, from south to north, the Uusimaa, Häme, Pirkanmaa and Tampere, and the southern part of the Pohjanmaa supracrustal belts with syn- to late-orogenic intrusion (Fig 1). In addition, the SW part of the Central Finland Granitoid Complex occupies a large area between the Tampere and Pohjanmaa belts. The oldest stages of plate-tectonic evolution in the area relate to microcontinent accretion with an Archean craton to the northeast and the simultaneous northward subduction of an igneous arc (Tampere belt) and an accretionary complex (Pirkanmaa or Vammala Belt) under a microcontinent (Central Finland Granitoid Complex) during 1.91–1.89 Ga (Grönholm and Kärkkäinen, 2012). Eilu (2012) described the tectonic evolution in southern Finland. Almost contemporaneously, during 1.90–1.87 Ga, the Tampere–Pirkanmaa igneous arc–accretionary complex also subducted to the south under the Bergslagen microcontinent, that is, under the Häme and Uusimaa belts. Subduction of the Tampere and Pirkanmaa belts towards the north ended at 1.89 Ga. This was followed, during 1.89–1.87 Ga, by the first major stage of deformation, regional metamorphism and N-S shortening in southern Finland. After an interlude of attempted orogenic collapse, the second major orogenic stage, with extensive magmatism, high-T metamorphism and transpressional deformation followed during 1.84–1.79 Ga. The latter stage was related to continent–continent collision in the southeast during 1.84–1.82 Ga and in the west during 1.82–1.80 Ga. The orogenic evolution of southern Finland (and Central Sweden) during 1.84–1.79 Ga could be not merely continent–continent collision, at least partly, also be related to a southward retreating Andean-type active margin system. Most of the active orogenic evolution of the area, including all ductile deformation, ended by 1.79 Ga (Eilu, 2012).

### ***Gold deposits in SW Finland***

The types of gold mineralization detected or suspected to occur in SW Finland include: 1) Au-rich VMS, 2) epithermal gold, 3) porphyry and/or other types of granitoid-related Au-Cu, and 4) orogenic gold. Orogenic gold occurrences in SW Finland are all hosted by rocks metamorphosed under amphibolite-facies conditions. Their location is structurally controlled: they are in secondary to tertiary shear zones hosted by the locally most competent lithological units (Eilu, 2012). They are gold-only deposits and the main ore minerals typically include, in decreasing order, pyrrhotite, arsenopyrite, pyrite, and löllingite. Gold occurs in native grains associated with gangue and the sulphides, in quartz veins and in the host rock.

All hosts to gold in the region are within the age range of 1.9–1.8 Ga. Some mineralization appear to be syngenetic, many postdate the intrusion or extrusion of the igneous hosts and at least the earliest deformation, and all predate the post-1.79 Ga brittle structures (Eilu, 2012). Eilu (2012) mentioned that there are two possible periods for orogenic gold mineralization in SW Finland: the main deformation and metamorphic stages of 1.89–1.87 Ga and 1.84–1.80 Ga. But there is obscurity whether all mineralization took place during the 1.89–1.87 Ga accretionary stage of the Svecofennian evolution, whether there was also significant mineralization during the 1.84–1.80 Ga collisional stage, or whether it all took place during 1.84–1.80 Ga (Eilu, 2012).

### ***Vammala Migmatite Belt (VMB)***

Vammala Migmatite Belt is a belt of migmatized mica gneisses and schists south of Tampere trends EW and is up to 50 km wide (Fig 2). It is part of a belt extending to east and west that has been given various names in the literature (Rutland et al., 2004), including Vammala Migmatite Belt (Kähkönen et al., 1994), Pori-Vammala-Mikkeli Migmatite Zone (Kilpeläinen, 1998), Mica gneiss-migmatite Belt (Lahtinen, 1994; 1996), Psammitic migmatite zone (Korsman et al., 1999), Tonalite Migmatite Zone (Koistinen et al., 1996), Tonalite- Trondhjemite Migmatite Belt (Mouri et al., 1999) and Pirkanmaa Belt (Nironen et al., 2002). The belt is considered to be one part of widespread pre-1.91 Ga metamorphic complexes in the Svecofennian domain.

Kilpeläinen (1998) explained that the Pori-Vammala-Mikkeli Migmatite Zone is characterized by intensely migmatized turbiditic greywacke and the synkinematic granitoids crosscutting them, but the presence of volcanic is rare in this zone. The metamorphic grade was already high (670 °C, 5-6 kb) at the initial stage of structural development, before the intrusion of synkinematic tonalites, and the high intensity of the hydration reactions at the retrograde stage is typical of porphyroblastic rocks in the zone (Kilpeläinen et al. 1994). The gradual and fault controlled boundary between the Tampere Schist Belt and the Vammala Migmatite Belt (Fig 3) south of it is characterized by migmatitic metasedimentary rocks and synkinematic granitoids and are commonly conformable with migmatite structures (Kilpeläinen, 1998).

### ***Geology of Kalliojärvi***

Kalliojärvi is located close to the northern margin of the Vammala Migmatite Zone between Tampere and Hämeenlinna, in a sequence of mica gneisses and tonalitic intrusions.

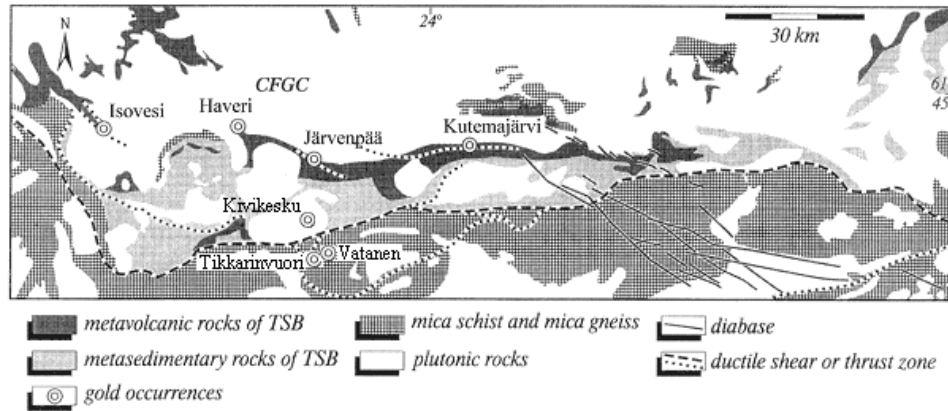
The following information about the prospect is taken from the GTK website.

The mineralization is hosted by mica gneiss and metagreywacke. It comprises a set of subparallel, E-W trending mineralized zones along strike of minor shear zones in a shallowly west-plunging synform. The metamorphic mineral assemblage within the metagreywacke consists of garnet-cordierite. The geotectonic environment is arc-accretionary. Granite and granitic pegmatites dikes are abundant and postdate, cut across the mineralized zones. Native gold possibly associated with arsenopyrite.

The local structural trend is E-W shear zones and, possibly, the more competent units of the host rock. The veins in Kalliojärvi are quartz and quartz-hematite veins. Oldest, S1, foliation detected as orientation within K-fsp phenocrysts and remains of crenulation; the dominant S2 foliation is folded by F3 which dominates the regional picture; the latter is overprinted by N-S trending F4. Gold predates D3 of is related to post-D4 brittle deformation.

The extent of mineralization reach 250 m long, 50–60 m wide, 2–5 m thick, subhorizontal, E–W trending, with a shallow plunge to the E. The best section is Kalliojärvi prospect is a set of synformal, subparallel, E-W trending mineralized zones from <1 to 10 m wide. 4.8 m @ 6.5 ppm, 4.3 m @ 7.2 ppm, 3 m @ 5.6 ppm, 1 m @ 15.7 ppm Au. 5 @ 0.5 ppm Au, 950 ppm As; 1 m @ 1.48 ppm Au. The first indications were anomalous Au values in regional till survey and numerous auriferous boulder and outcrop samples detected by amateur prospectors. Both ground magnetic and IP anomalies reflect the local structures of the mineralized setting. The strong local IP anomalies are related to a graphitic mica schist and an

intensely sheared and sulphidized granitoid both of which appear to be barren on gold.



Simplified geological map of the Tampere schist belt (TBS; modified after Koistinen, 1994).

CFG = Central Finland Granitoid Complex.

From Poutiainen and Grönholm (1996).

Edited by P. Eilu (1999)

Fig. 25-1-1. from GTK website.

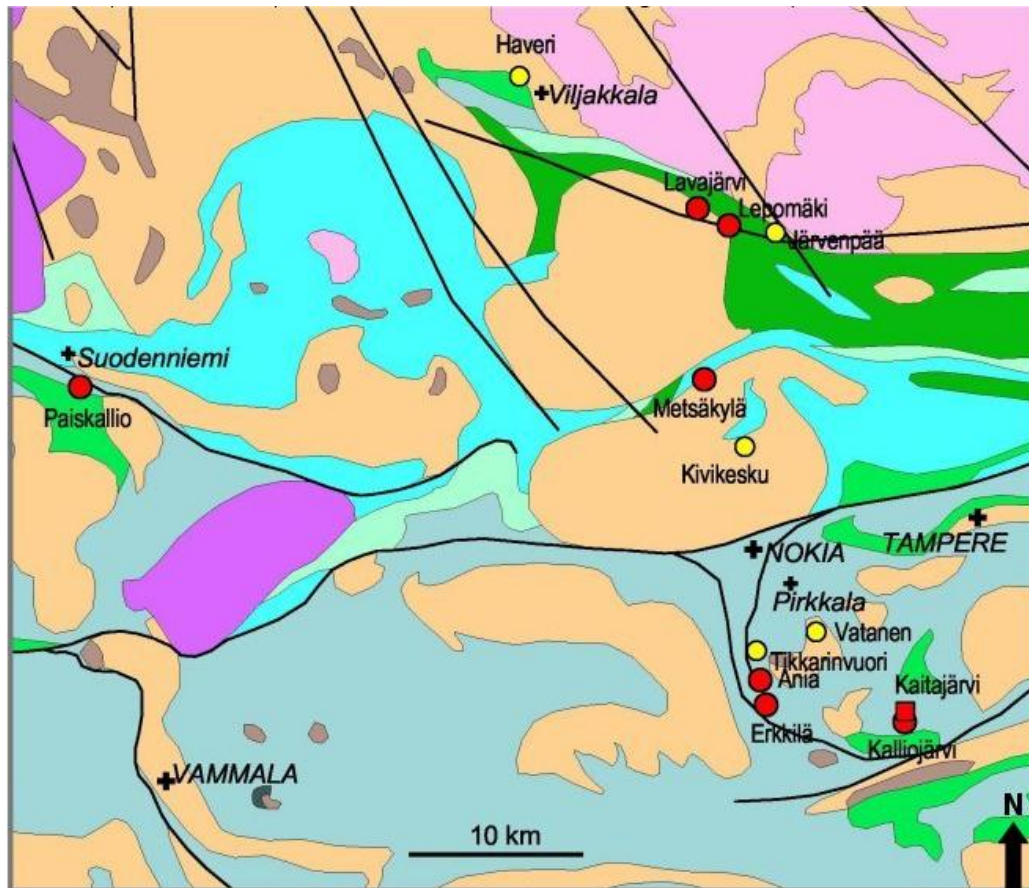
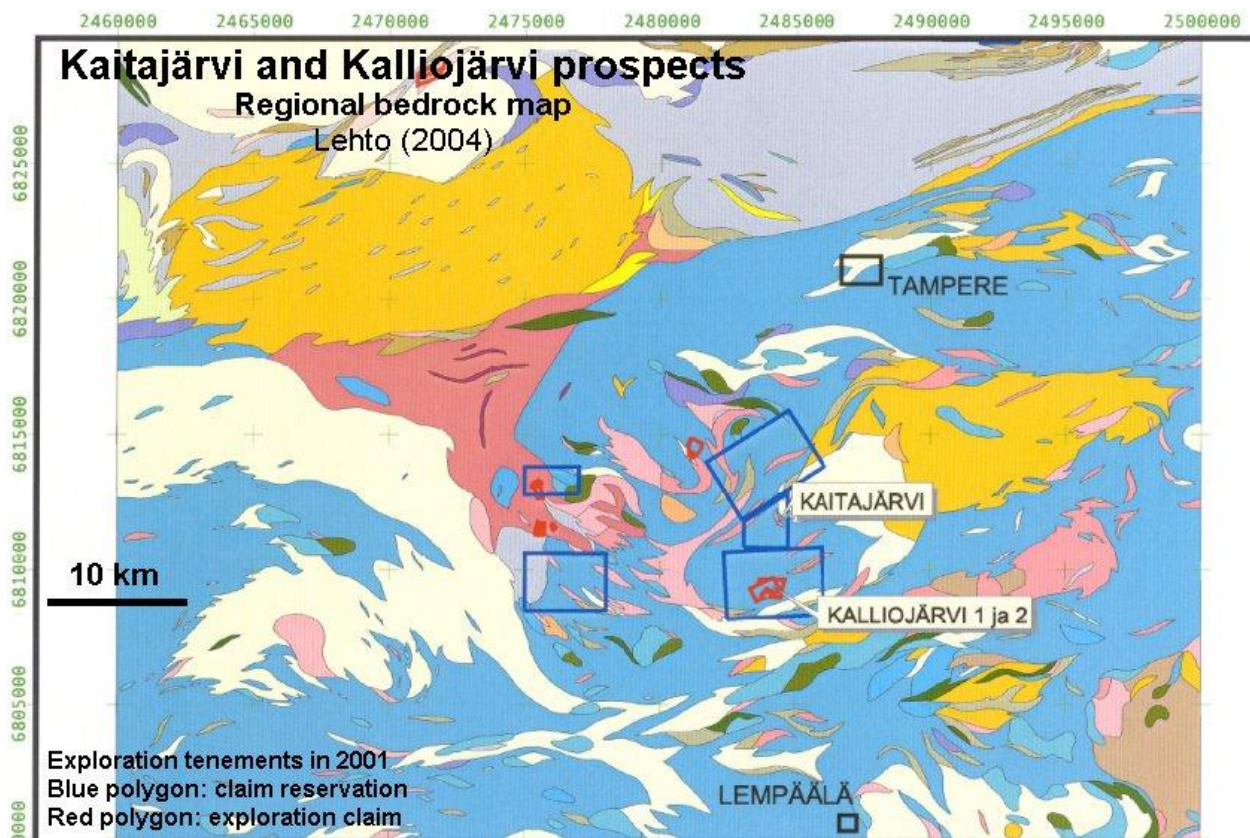


Fig. 25-1-2. Western part of the Tampere Schist Belt and Vammala Migmatite Zone (Kärkkäinen et al., 2003, from GTK website).



**Fig. 25-1-3.** from GTK website.

References & online sources

<http://new.gtk.fi/information/services/commodities/Gold/kalliojarvi.html>

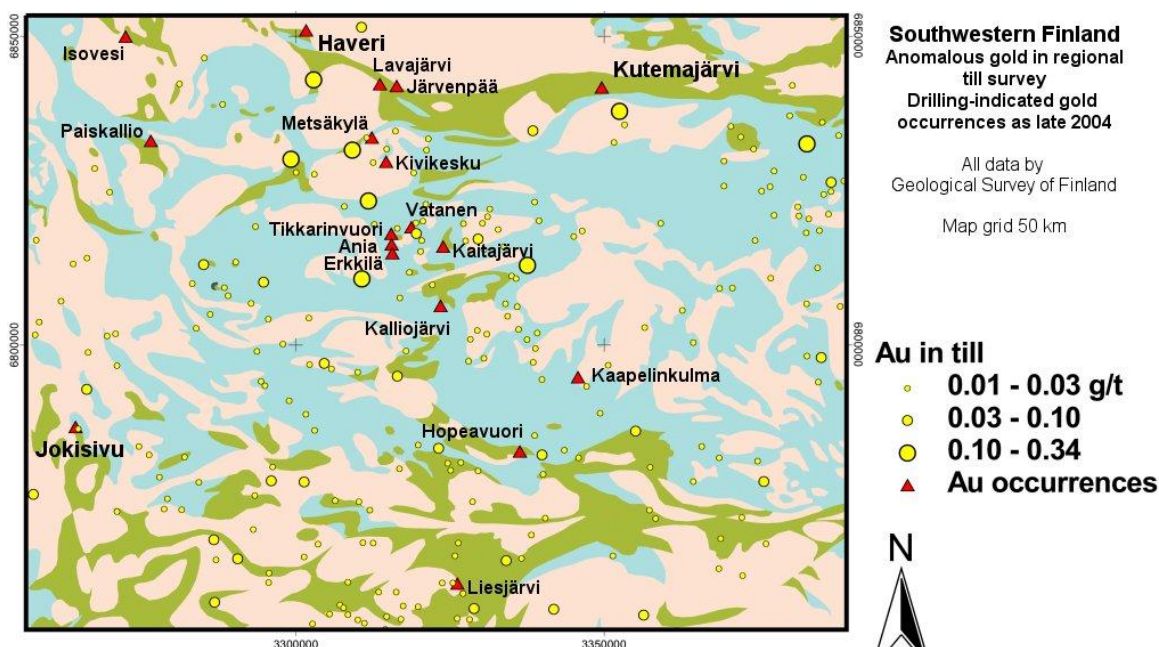
**Compiled by:** Windeati Argapadmi

<i>Date: July 25, 2014</i>	<i>STOP No.: 25-2 (optional)</i>
<b>Locality name: Kaitajärvi</b>	
Main commodity: Au Geological setting or genetic model: orogenic Current development status: prospect	
<b>WGS Latitude: 61.41082</b>	<b>WGS Longitude: 23.69707</b>
KKJ Northing: 6811450	KKJ Easting: 2484000
Municipality: Lempäälä	
Location & access: 15 km S from the city of Tampere. Five km to a sealed road, gravel roads to the area, four km to railway, seven km to airport.	
Geological domain: Svecofennian	Geological unit: Vammala Migmatite Zone
Owner (2014): N/A	

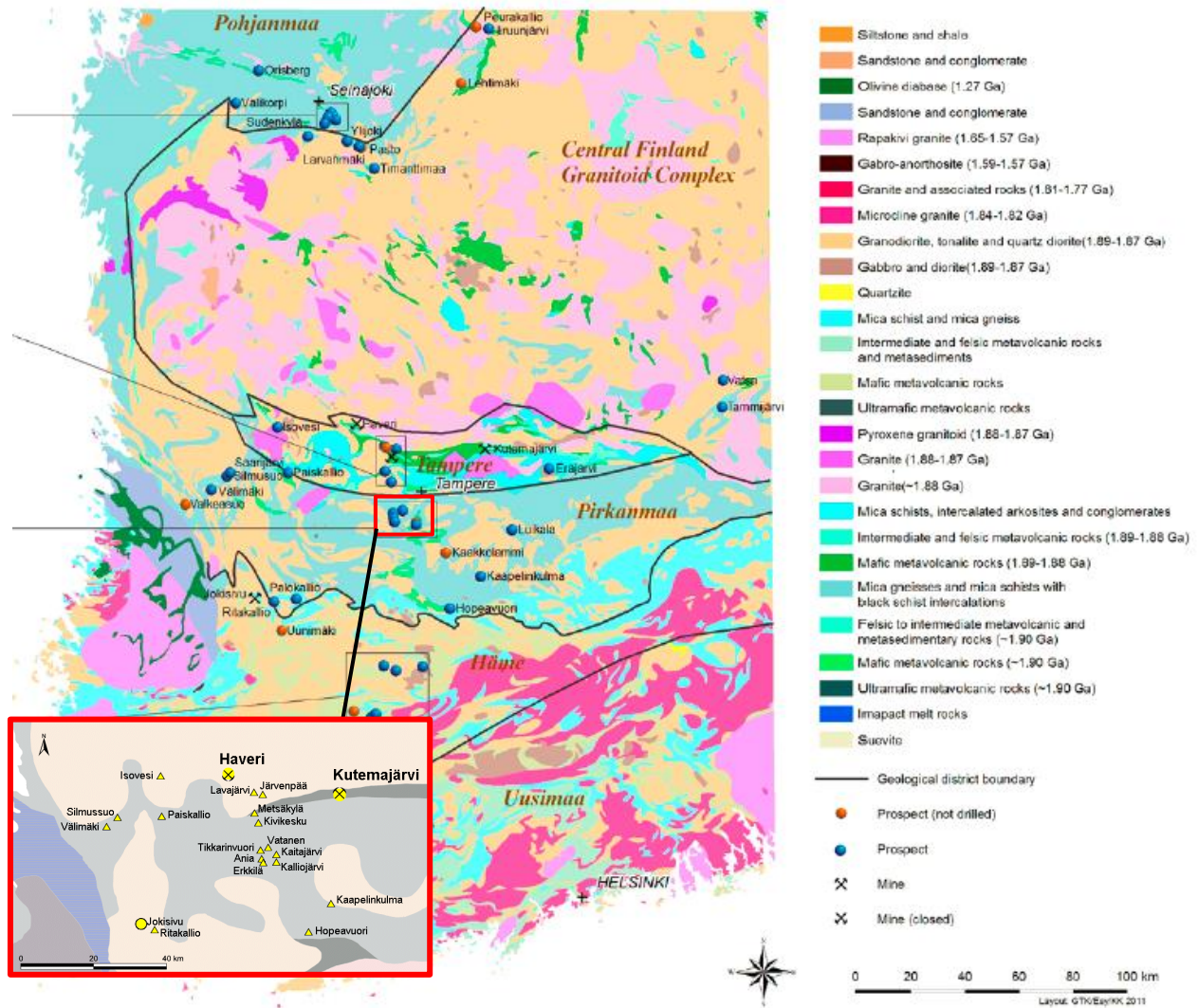
### Geology

Kaitajärvi is a Paleoproterozoic orogenic gold occurrence with no resource estimate available. It is hosted by mica gneiss, defined by auriferous quartz veins, and is controlled by minor WSW-trending shear zones branching from a larger NW-trending shear zone. There is some local granite pegmatite dikes.

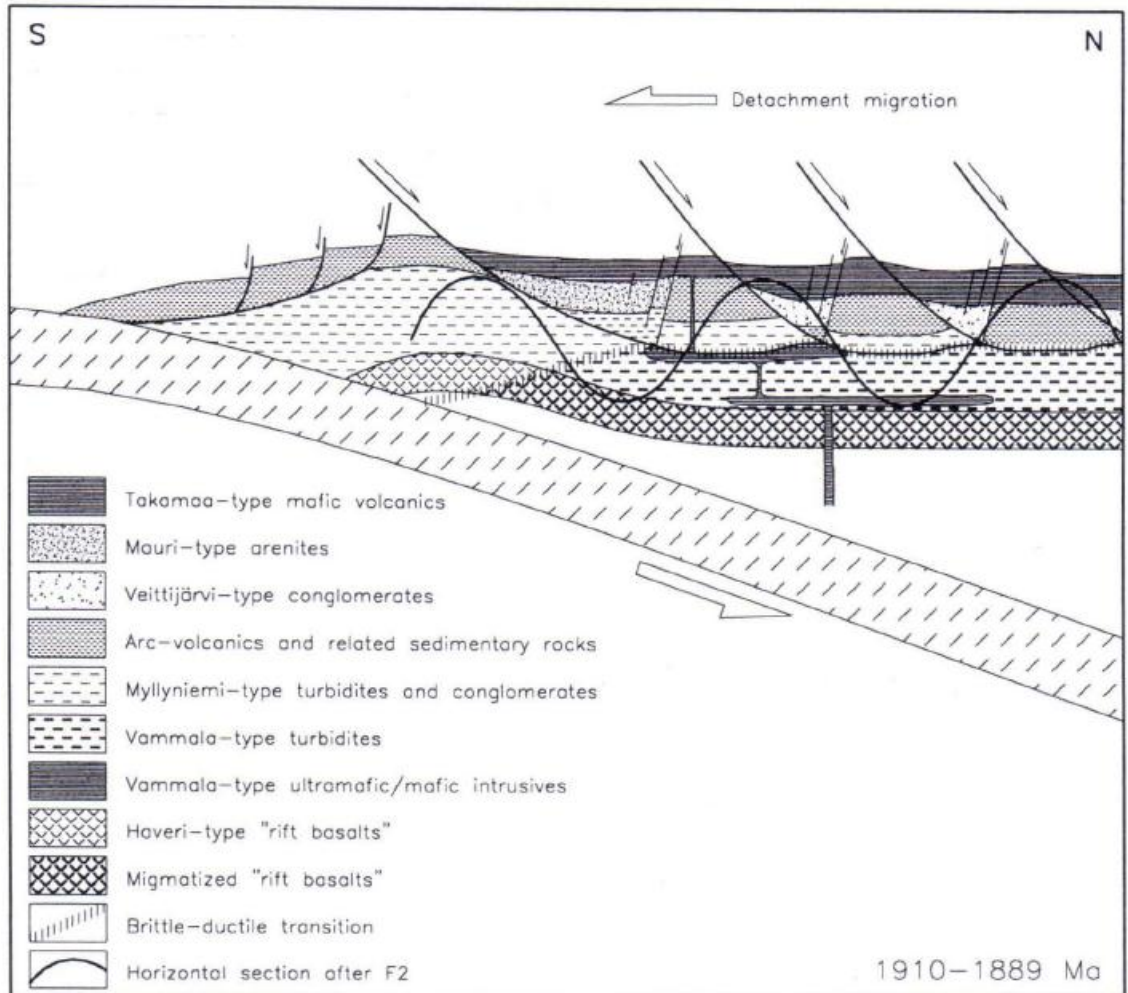
The structural style in Kaitajärvi is seen from the magnetic anomaly body forming subvertical, ENE-trending shear zones branching from a larger NW-trending shear zone. There is also presence of abundant quartz veins. GTK exploration activity revealed a 100–400 m wide magnetic anomaly, and a weak IP anomaly due to the presence of pyrrhotite dissemination. As, Au, S and possibly Zn anomalies in bedrock are related to the gold occurrence. The best section in Kaitajärvi prospect is 1 m @ 0.6 ppm Au (Fig 3).



**Fig. 25-2-1.** Geological map of SW Finland with gold anomaly distribution. (<http://en.gtk.fi/information-services/commodities/Gold/vatanen.html>.)



**Fig. 25-2-2.** Geology of southwestern Finland and gold deposits and occurrences detected in SW Finland (Grönholm and Kärkkäinen, 2012). The red box shows the Kaitajärvi area.



**Fig. 25-2-3.** Schematic cross section of Tampere-Vammala area (Kilpeläinen, 1998).

*References & online sources*

<http://en.gtk.fi/information/services/commodities/Gold/vatanen.html>

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Rutland, R.W. R., Williams, I. S. and Korsman, K. 2004. Pre-1.91 Ga deformation and metamorphism in the Paleoproterozoic Vammala Migmatite Belt, southern Finland, and implications for Svecofennian tectonics. Bulletin of the Geological Society of Finland, Vol. 76, 2004, pp. 93–140.

**Compiled by: Windeati Argapadmi**



<b>Date: July 25, 2014</b>	<b>STOP No.: 25-3</b>
<b>Locality name: Ania</b>	
Main commodity: Au Geological setting or genetic model: orogenic gold Current development status: Prospect	
<b>WGS Latitude: 61.41002</b>	<b>WGS Longitude: 23.54017</b>
KKJ Northing: 6811410	KKJ Easting: 2475620
Municipality: Pirkkala	
Location & access: 15 km SW from the city of Tampere. Sealed road next to the area, 14 km to railway, 12 km to airport.	
Geological domain: Svecofennian	Geological unit: Vammala Migmatite Zone
Owner (2000): Geological Survey of Finland (GTK)	

### **Geology**

The gold-bearing quartz veins at Ania and Tikkarinvuori lie in the Vammala Migmatite Zone, which is part of the Svecofennian domain. The Vammala Migmatite belt (VMB) is a zone of migmatized mica-shists and gneisses. It is part of a metamorphic complex in the Svecofennian domain older than 1.91 Ga Metagreywacke and meta-basaltic rocks of a former rift or marginal basin that were deposited at around 1.98 Ga constitute most of this zone (Rutland et al., 2004). Synorogenic compression that (1.89-1.80 Ga) during the Svecofennian orogeny was followed by orogenic gold mineralization in this area. The svecofennian orogenic gold deposits mostly formed under amphibolite facies conditions (Eilu et al., 2003).

Ania, in the Vammala Migmatite Zone, is an orogenic gold occurrence of presumably Paleoproterozoic age (Kärkkäinen et al., 2007). There is no resource estimate available. It is hosted by mica gneiss, and is located in the contact zone between tonalite and metagreywacke. Alteration around the vein is 1-5 m broad and mostly holds disseminated arsenopyrite. Native gold can be found as free grains in gangue and as inclusions in arsenopyrite (Kärkkäinen et al., 2007). Gold was most likely remobilized during deformation and recrystallization from 1.84 to 1.80 Ga (Eilu et al., 2003).

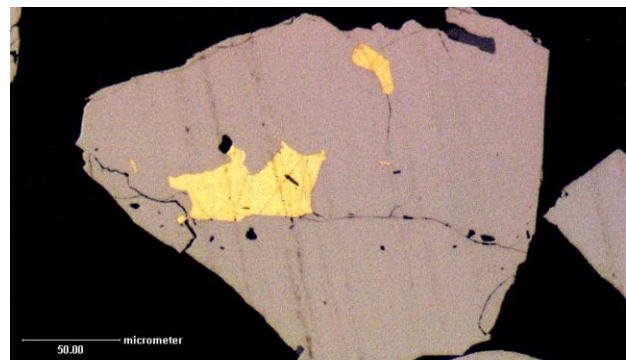
**Regional geological map** - see Fig. 25-1-2.



**Fig. 25-3-1.** Ania exploration site in October 2006, Kärkkäinen et al., 2006 (from GTK website).



**Fig. 25-3-2.** Ania: visible gold in quartz vein, scale in cm, Kärkkäinen et al., 2006 (rom GTK website).



**Fig. 25-3-3.** Native gold as inclusion in arsenopyrite. (Kärkkäinen et al., 2007).

*References & online sources*

- R.W. Roye Rutland, Ian S. Williams and Kalevi Korsma. Pre-1.91 Ga deformation and metamorphism in the Paleo-proterozoic Vammala Migmatite Belt, southern Finland, and implications for Svecofennian tectonics Bulletin of the Geological Society of Finland, Vol. 76, 2004, pp 93-140
- N. Kärkkäinen, P. Huhta, K. Karttunen, M. Pelkkala 2007, Tutkimustyöselostus Pirkkalan Kunnassa Valtausalueilla Ania 1 Ja Ania 2 (Kaiv Rekro 7001/1 JA 7001/2) Suoritetuista Malmitutkimuksista
- P. Eilu, P. Sorjonen-Ward, P. Nurmi, T. Niiranen, A Review of Gold Mineralization Styles in Finland. Economic Geology, Vol 98, 2003, pp. 1329-1353
- <http://new.gtk.fi/informationsservices/commodities/Gold/aniam.html>

**Compiled by: Ulrich Aerne**

<i>Date: July 25, 2014</i>	<i>STOP No.: 25-4</i>
<b>Locality name:</b> Tikkarinvuori	
<i>Main commodity:</i> Au	
<i>Geological setting or genetic model:</i> orogenic gold, mesothermal	
<i>Current development status:</i> Prospect	
<b>WGS Latitude:</b> 61.42553	<b>WGS Longitude:</b> 23.53769
<i>KKJ Northing:</i> 6813140	<i>KKJ Easting:</i> 212305
<i>Municipality:</i> Pirkkala	
<i>Location &amp; access:</i> 15 km SW from the city of Tampere. 500 m from a sealed road.	
<i>Geological domain:</i> Svecofennian	<i>Geological unit:</i> Vammala Migmatite Zone
<i>Owner (2007):</i> Erkki Kreivi	

### **Geology**

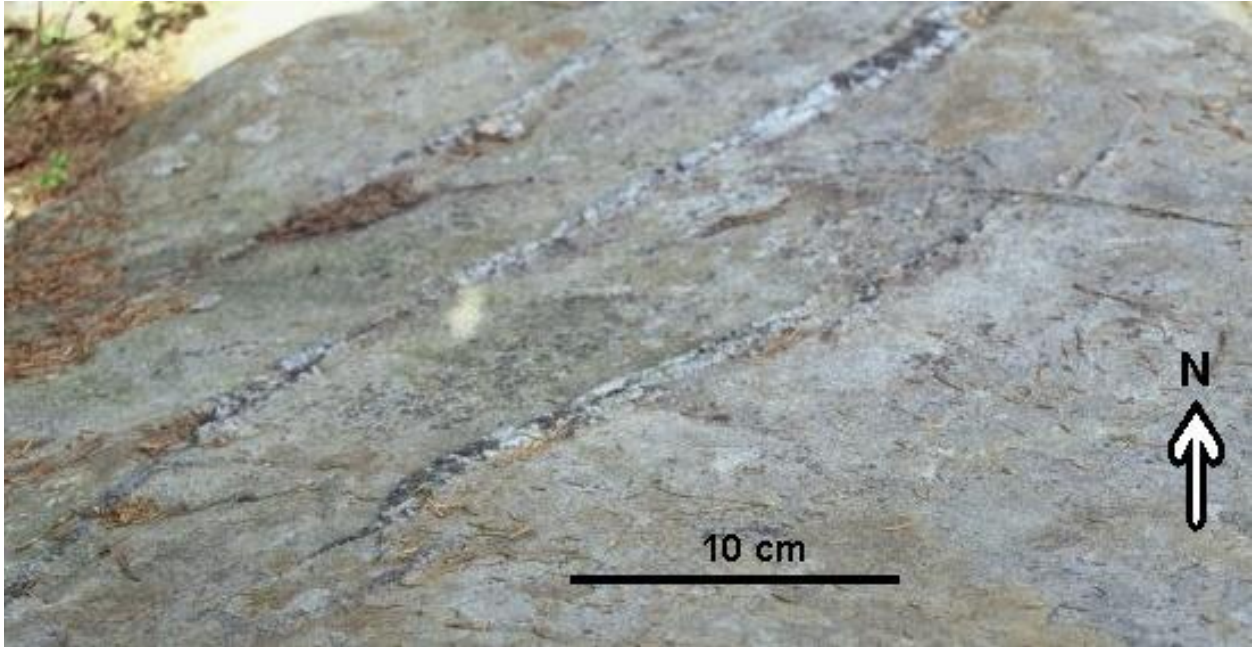
The deposit is a Paleoproterozoic orogenic gold occurrence with no resource estimate available. Small (few centimeters) en echelon veins hosted in gneissic, amphibolite facies metagreywacke that are thought to be controlled by a dextral D4 shear zone. (Rosenberg, 1998). Gold can be found mainly at quartz vein margins. Arsenopyrite is as well present (GTK, 2007).

The structural setting and mineralogy is similar to the larger Jokisivu deposit.

**Regional geological map** - see Fig. 25-1-2.



**Fig. 25-3-1.** Visible gold in quartz vein from Tikkarinvuori, photo: Pasi Eilu (from GTK website).



**Fig. 25-3-2.** Auriferous en echelon quartz veins with dextral shear sense in metagreywacke. (Photo Pasi Eilu 2002).

*References & online sources*

Rosenberg, P. 1998. Pirkkalassa vuosina 1992–1995 suoritetut kultatutkimukset. Geol. Surv. Finland, Report M 19/2123/-98/1/10. 18 p.

<http://new.gtk.fi/informationsservices/commodities/Gold/tikkarinvuori.html>

**Compiled by: Ulrich Aerne**

<i>Date: July 25, 2014</i>	<i>STOP No.: 25-5 (optional)</i>
<b>Locality name: Vatanen</b>	
<i>Main commodity: Au</i> <i>Geological setting or genetic model: orogenic "mesothermal"</i> <i>Current development status: prospect</i>	
<b>WGS Latitude: 61.43631</b>	<b>WGS Longitude: 23.59731</b>
<i>KKJ Northing: 6814320</i>	<i>KKJ Easting: 2478690</i>
<i>Municipality: Pirkkala</i>	
<i>Location &amp; access: 10 km SW from the Tampere city centre. A gravel road to the area, 1 km to a sealed road.</i>	
<i>Geological domain: Svecofennian</i>	<i>Geological unit: Vammala Migmatite Zone</i>
<i>Owner (2014): N/A</i>	

### **Geology**

Vatanen, in Vammala Migmatite Zone, is a Paleoproterozoic orogenic gold occurrence with no resource estimate available. It has an undefined shape, is comprised of sets of Au- and As-rich quartz veins, and is hosted by tonalite (GTK website). The metamorphic mineral assemblage within the granodiorite intrusion consists of plagioclase-hornblende-quartz-biotite±diopside. Free native gold with quartz, native gold as inclusions in arsenopyrite. The granodioritic intrusion clearly predates gold mineralization.

Sets of quartz veins in a synorogenic dominantly tonalitic to quartz dioritic body that is, possibly, a subvolcanic intrusion; the intrusion is surrounded by mica gneisses which predate the intrusion (GTK website).

Structural style in Vatanen is auriferous-arsenopyriteic-quartz veins with 0.1-3 cm wide. The general trends of these veins are N, NNW, NW and W trends. Oldest, S1, foliation detected as orientation within K-fsp phenocrysts and remains of crenulation; the dominant S2 foliation is folded by F3 which dominates the regional picture; the latter is overprinted by N-S trending F4. Gold is related to post-D4 brittle deformation.

The extension of Vatanen prospect reaches a few hundreds of metres long and about 100 m wide with best section is approximately 10 m @ 0.5 ppm Au. The exploration activity conducted by GTK revealed the regional anomaly is 20x60 km, the extent of the local Au anomaly is about 300x300 m and the local As anomaly is 200x300 m.

**Regional geological map** - see Figs. 25-1-2, 25-2-1 and 25-2-3.

### *References & online sources*

<http://en.gtk.fi/information/services/commodities/Gold/vatanen.html>

Eilu, P. 2012. Gold mineralization in southwestern Finland. Geological Survey of Finland, Special Paper 52, 11–22, 1 figure and 1 appendix.

Grönholm, S. & Kärkkäinen, N. (eds.) 2012. Gold in Southern Finland: Results of GTK studies 1998–2011. Geological Survey of Finland, Special Paper 52, 276 pages, 185 figures, 23 tables and 6

appendices.

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Rutland, R.W. R., Williams, I. S. and Korsman, K. 2004. Pre-1.91 Ga deformation and metamorphism in the Paleoproterozoic Vammala

Migmatite Belt, southern Finland, and implications for Svecofennian tectonics. Bulletin of the Geological Society of Finland, Vol. 76, 2004, pp. 93–140.

***Compiled by: Windeati Argapadmi***

<i>Date: July 25, 2014</i>	<i>STOP No.: 25-6 (optional)</i>
<b>Locality name: Kivikesku</b>	
<i>Main commodity: Au</i> <i>Geological setting or genetic model: orogenic "mesothermal"</i> <i>Current development status: prospect</i>	
<b>WGS Latitude: 61.52944</b>	<b>WGS Longitude: 23.51002</b>
<i>KKJ Northing: 6824730</i>	<i>KKJ Easting: 2474110</i>
<i>Municipality: Nokia</i>	
<i>Location &amp; access: 5 km to Nokia, 12 km from Tampere city centre. A gravel road to the area, 3 km to the Highway 11.</i>	
<i>Geological domain: Svecofennian</i>	<i>Geological unit: Tampere Schist Belt</i>
<i>Owner (2014): N/A</i>	

### **Geology**

Kivikesku, in the Tampere Schist Belt, is a Paleoproterozoic orogenic gold occurrence with no resource estimate available. It comprises sets of 1-5 m wide lodes and is hosted by metagreywacke. Free native gold, and 1-micron gold inclusions in arsenopyrite.

An Au-rich boulder found by an amateur prospector, this led to discovery of a number of similar boulders and, later, bedrock mapping, investigation of Au and scheelite distribution in till, and drilling led to the mineralization (Lindmark, 1995).

A volcano-sedimentary association, in the western part of the Tampere Schist Belt, intruded by a granodiorite; the deposit is in metagreywacke that is, partially, a large inclusion (xenolith) in the granodiorite, parallel and near the contact between the metasedimentary rock and the granitoid (Lindmark, 1995). (from GTK website)

**Regional geological map** - see Figs. 25-1-2 and 25-1-2.

### *References & online sources*

<http://new.gtk.fi/information/services/commodities/Gold/kivikesku.html>

Lindmark, B. 1995. Tutkimustyöselostus Nokian kaupungin valtausalueella Koukkujärvi 1

(kaivosrekisterinro 4890/1) suoritetuista kultatutkimuksista vuosina 1990–1994. Geol. Surv.

Finland, Report M06/2123/-95/1/10. 7 p.

**Compiled by: Windeati Argapadmi**

<i>Date: July 26, 2014</i>	<i>STOP No.: 26-1</i>
<b>Locality name: Onkalo</b>	<i>Alternative name:</i> Olkiluoto Nuclear Power Plant
Nuclear Waste Repository	
<b>WGS Latitude: 61.238295</b>	<b>WGS Longitude: 21.455725</b>
<i>Municipality: Eurajoki</i>	
<i>Location &amp; access: Main Road number 8 between Eurajoki and Rauma, take Road number 2176 six km after Eurajoki to the right.</i>	
<i>Geological domain: Paleoproterozoic Bedrock</i>	<i>Geological unit: Migmatitic Gneiss</i>
<i>Owner (2014): TVO (Teollisuuden Voima)</i>	

### **Geology**

After the Finnish Nuclear Energy Act was amended in 1994 to specify that all nuclear waste produced in Finland must be disposed of in Finland, Olkiluoto (located in the municipality of Eurajoki, W-Finland) was selected in 2000 as the site for a very long-term underground storage facility for Finland's spent nuclear fuel. This facility named ONKALO ("Onkalo" means "cave" or "cavity" in Finnish) is located within the Olkiluoto Nuclear Power Plant, about five km east from the power plants. It is a deep geological repository for the final disposal of spent nuclear fuel, the first such repository in the world. The facility is currently under construction, run by the company Posiva, which is owned by the two existing producers of nuclear power in Finland, Fortum and TVO. (Wikipedia)

The principle behind the final disposal is to use multiple release barriers that help to ensure that no nuclear waste will be released to living nature or is accessible to people (Fig. 26-1-4). This so called KBS-3 Concept was developed by SKB, the company responsible for nuclear waste management in Sweden. The different release barriers are:

- **State of Matter of the Fuel:** The ceramic state of the fuel forms the first release barrier itself. The uranium is solid and dissolves in water only slowly, which diminishes the rate of release of radioactive substances.
- **Final disposal Canister:** Spent nuclear fuel will be stored in massive metal canisters. The interior is made of nodular graphite cast iron, the exterior is made of copper. Cast iron has been selected because it is strong enough to resist the mechanical stress (e.g. earthquakes, glaciers) that the canister is subjected to. The outer part made of 5 cm thick copper is to protect the insert and the fuel assemblies from the corrosive effect of groundwater.
- **Bentonite Barrier:** The canister is isolated from the surrounding rock with a number of blocks of tightly compressed bentonite. These blocks serve as buffer material between the canisters and the surrounding bedrock. Due to its expanding character when coming into contact with water, the bentonite fills the space surrounding the canisters and prevents water from coming anywhere near the copper canisters.
- **Bedrock:** The bedrock provides the canister and bentonite with conditions where changes are slow and predictable. Deep in the bedrock, the canisters are protected from any changes occurring above ground such as future ice ages, and kept away from people's normal living environment.



Posiva's current plan is to place the final disposal canisters inside vertical holes drilled in the final disposal tunnels. They are also exploring the possibility to place the canisters in horizontal final disposal holes. After the canisters and the buffer material have been installed, the final disposal tunnels are filled up with clay blocks and pellets. The advantages of clay are its low water conductivity and its long-term chemical and mechanical stability. At the end of the final disposal operations, the technical facilities, the access tunnel and the shafts will also be backfilled.

The purpose of the final disposal facility is to take care of packing the spent nuclear fuel assemblies in canisters and to dispose them permanently into the bedrock. It consists of two sections:

- Encapsulation Plant: Spent nuclear fuel is packed in transportation casks and delivered to the receiving area of the encapsulating plant. The cask and the final disposal canister are then docked tightly inside the fuel-handling cell, where the fuel is transferred from the transportation cask first to the drying station and then to the final disposal canister. When all fuel assemblies have been transferred to the canister, it is filled with argon gas and then tightly closed with an inner steel cover. From the handling cell, the filled canister is transferred to a welding station where the canister lid is sealed with electron beam welding. After an inspection of the tightness of the weld, the canister is then transferred by the access tunnel to the repository (Fig. 26-1-3).
- Repository: The repository is located deep inside the bedrock, in which the most important section are the tunnels where the encapsulated spent nuclear fuel is disposed of. The deposition tunnels are located at a depth of about 400-450 metres and the final disposal canisters will then be placed in vertical holes (6 to 8 m deep) drilled in the floor of those tunnels.

The main rock type in Olkiluoto bedrock is migmatitic gneiss. The bedrock in the area is approximately 1800 to 1900 million years old. There are various types of structures in the rock, some of them water conductive. The final disposal tunnels and the disposal holes for the canisters will be positioned inside the bedrock in such a manner that any major water-conducting structures will be avoided (Fig. 26-1-5).

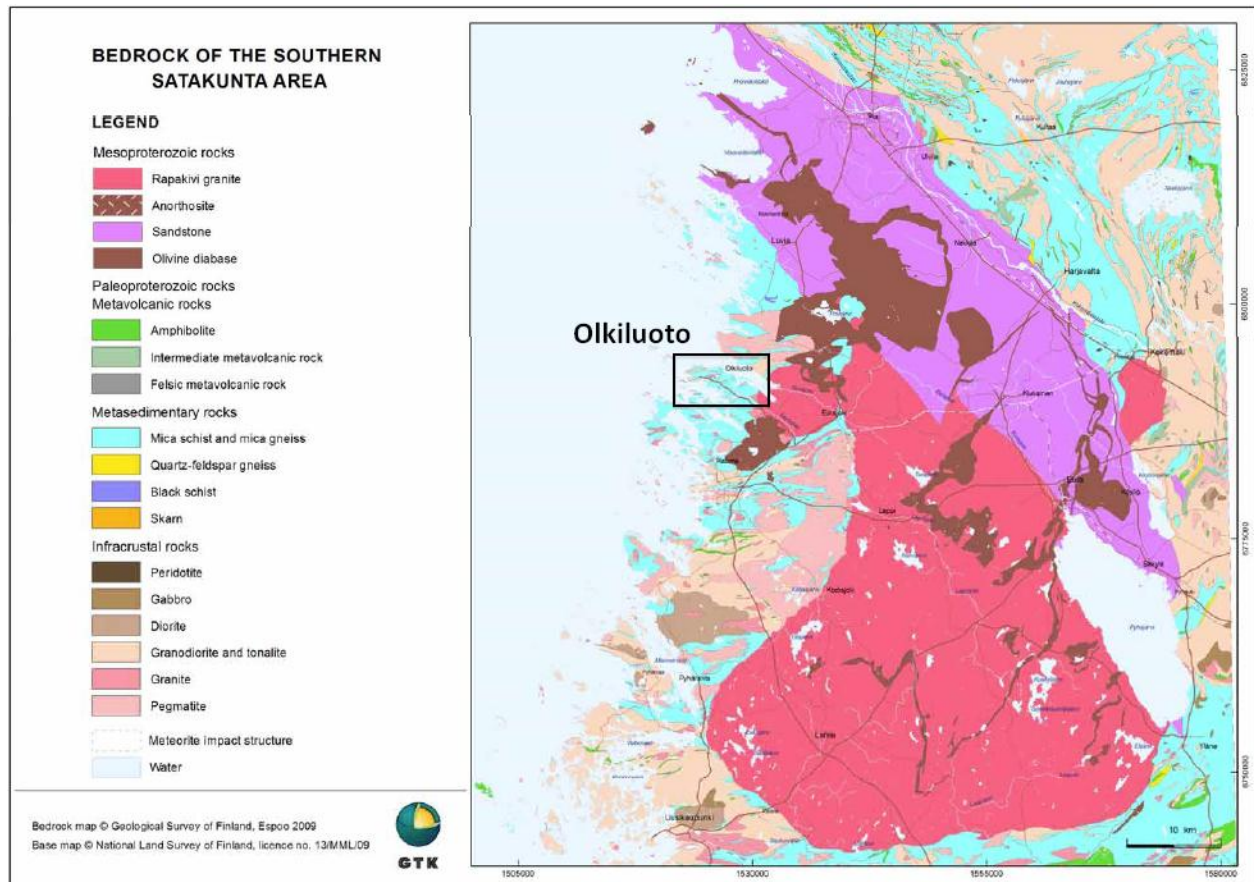
"The facility's construction plans are divided into four phases:

- Phase 1 (2004-2009): focused on excavation of the large access tunnel to the repository, spiraling downward to a depth of 420 metres.
- Phase 2 (2009-2011): continued the excavation to a final depth of 520 metres. The characteristics of the bedrock were studied in order to adapt the layout of the repository.
- Phase 3: construction of the repository, is expected to begin around 2015.
- Phase 4: the encapsulation and burial of areas filled with spent fuel, is projected to begin around 2020." (Wikipedia)

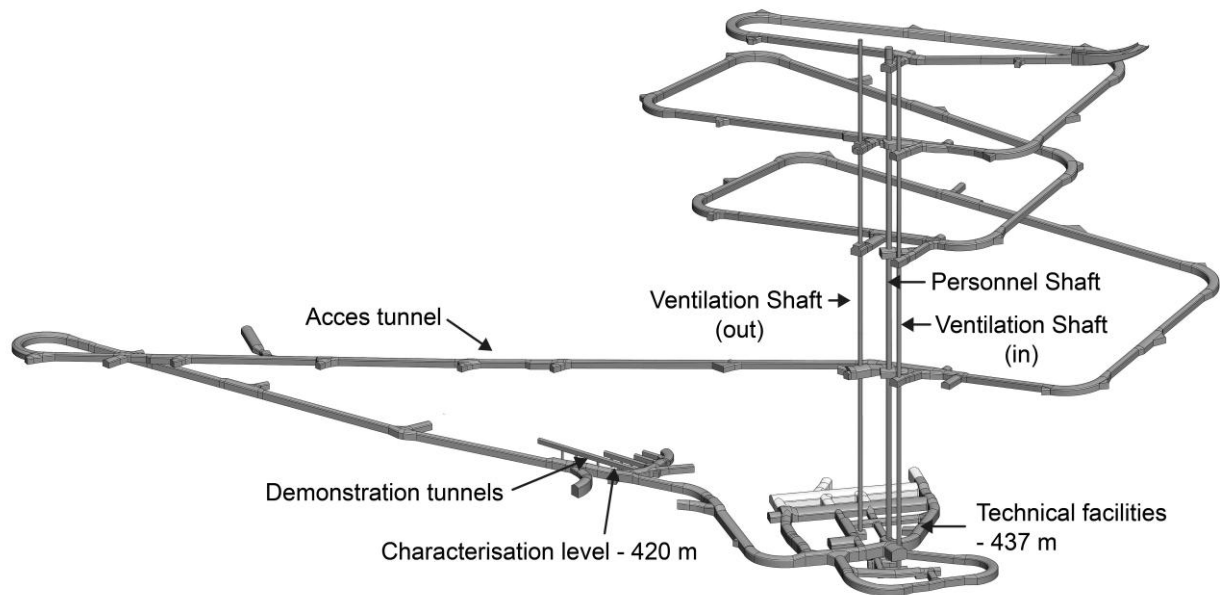
The access tunnel is excavated by drilling and blasting. Cemented anchor bolts made of ribbed steel bars as well as shotcrete are used to strengthen the rock. The associated three shafts in ONKALO (personnel shaft, supply air shaft and exhaust air shaft) are constructed with the raise boring method where first a pilot hole is drilled down and then a reamer bit is installed to the drill, which is then pulled up while the bit is rotating. This leads to a diameter of 4.5 m for the passenger shaft and to a diameter of 3.5 m for the air shafts (Fig. 26-1-2).

The ONKALO repository is expected to be large enough to accept canisters of spent fuel for around one

hundred years, i.e. until around 2120. This equals an amount of about 5500 t U. The volume of rock to be excavated for the facility is approximately 1.3 million cubic metres. The total length of the tunnels has been calculated to be 42 kilometres, located within an area extending over 2 to 3 km<sup>2</sup>. The estimated costs of this project are in the range of €900 million to €1 billion. The whole facility is built for very high mechanical and chemical resistance and to remain leak-tight inside the bedrock for at least 100 ka.



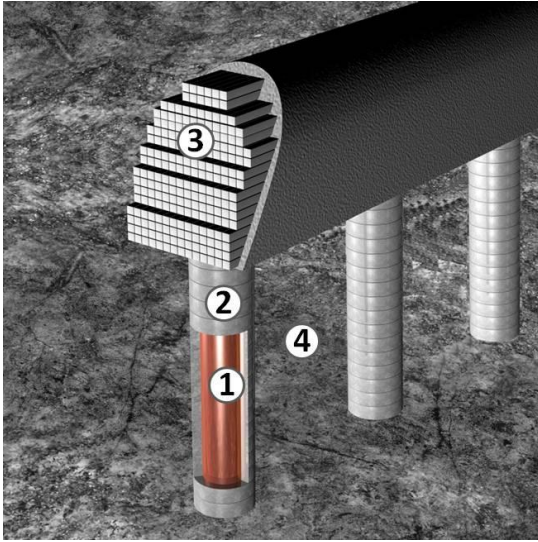
**Fig. 26-1-1.** Regional Geology of Olkiluoto (Posiva Working Report 2010-70).



**Figure 26-1-2.** Schematic of the research tunnel and the shafts (Posiva Oy, website).



**Fig. 26-1-3.** Longitudinal Section of the encapsulation plant (Posiva Oy, website).



**Fig. 26-1-4.** Schematic of the Release Barriers: **Fig. 26-1-5.** Bedrock (Posiva Oy, website).  
 1) Final disposal canister, 2) Bentonite buffer, 3) Tunnel backfill, 4) Bedrock (Posiva Oy, website).



**Fig. 26-1-5.** Large Cu tubes (left) as used for longterm storage of fuel rods in steel casing (right), the power plant exhibition (photo: Ch. Heinrich).

**References & online sources**

[http://www.posiva.fi/en/final\\_disposal/onkalo#.U5gjOiiv7Fj](http://www.posiva.fi/en/final_disposal/onkalo#.U5gjOiiv7Fj)

[http://en.wikipedia.org/wiki/Onkalo\\_spent\\_nuclear\\_fuel\\_repository](http://en.wikipedia.org/wiki/Onkalo_spent_nuclear_fuel_repository)

Aaltonen et al.: Geological Model of the Olkiluoto Site, Version 2.0; Posiva Working Report 2010-70.

Comments: Check out the documentary “Into Eternity” by Danish director Michael Madsen.

**Compiled by: Marc Schnyder**

## Ore Generation in Archean-Proterozoic Units of Finland

*A synthesis of metallogeny observed during the fieldtrip – by Jakub Sliwinski & Juliana Troch*

Ore deposition occurs in a variety of geotectonic regimes throughout Finland, and is intimately linked to the geodynamic history of the Karelian craton and later Svecofennian orogeny. Ore-forming processes in the region can be roughly subdivided into six geotectonic events which, thanks to detailed mapping and geochronology, are both spatially and temporally well-constrained (See the Figure). (1) The original assembly of the Archean TTG basement and subsequent deformation formed the foundation of the craton, which was followed by (2) rifting and generation of Proterozoic greenstone belts. (3) Exhumation of the mantle comprized the end of the extensional period, which was followed by (5) compressional tectonics during the Svecofennian orogeny. (5) Extension and partial melting of the crust, which emplaced the world-famous Rapakivi granites occurred before the continent was consolidated and cratonized. Finally, (6) late alkali/carbonatitic intrusions and kimberlite pipes intruded along the margins of the Karelian craton.

The core of the Fennoscandian Shield is formed by the Kola, Belomorian and Karelian cratons (3.1-2.5 Ga), which collectively form the Kola Peninsula and eastern boundary of Finland. The oldest rocks encountered on this field excursion are Archean TTG gneisses (2.8-2.6 Ga), forming the host rock of the younger Otanmäki Fe-Ti-V deposit. Intense structural deformation at this time is coincident with numerous intrusions, including the Silinjärvi P-carbonatite (2.61 Ga).

Following deformation and intrusion, the region started undergoing an extensional period, forming many of the NW-SE trending Paleoproterozoic greenstone belts in eastern Finland (2.45-2.0 Ga). Ore deposits associated with this era are of several varieties: 1) the Vaaralampi soapstone, which formed during the serpentinization of most likely komatiitic protolith (~2.1 Ga) and subsequent hydrothermal and structural alteration to a talc-schist; 2) the Kevitsa intrusion (2.05 Ga) in northern Finland, which comprises a layered ultramafic intrusion hosting Ni-Cu-PGE in disseminated sulfides; and 3) the Otanmäki intrusion into Archean basement (2.0 Ga), which hosts V-Ti-Fe in magnetite, ilmenite and sulfides.

Initiation of a passive margin by mantle exhumation facilitated the creation of several volcanic/exhalative deposits between 1.97 and 1.93 Ga at the boundary of the Karelian craton: (1) The Kylylahti Cu-Au VMS deposit, formed originally at the contact of altered ultramafic material and a metaturbidite/blackschist, then later obducted with the onset of compressional tectonics; (2) The Outokumpu Cu-Zn complex (2.06 Ga), initiated by ophiolitic sulfide mineralization and (3) the Talvivaara 'sedex' Ni-Cu-Zn deposit, formed in reducing black shales.

Compressional tectonics between 1.92 and ~1.8 Ga led to the formation of intraoceanic arc complexes as well as the prominent Svecofennian orogeny and several dominantly IOCG deposits hosted in orogenic shear zones: (1) the Sahavaara and Hanukainen Fe IOCG deposits, formed by interaction of granitic rock with evaporitic sediments; (2) the Pyhäsalmi Cu-Zn VMS deposit hosted in volcanics within the Savo schist belt and subsequently remobilized and concentrated (1.89 Ga); (3) The Kittilä/Suurikuusikko orogenic Au deposit precipitated from amphibolite-grade fluids and focused along shear zones; (4) the Kuusamo Au-Co-U-Fe IOCG (1.9 Ga); (5) the uraninite-associated Rompas Au prospect and finally, (6) the

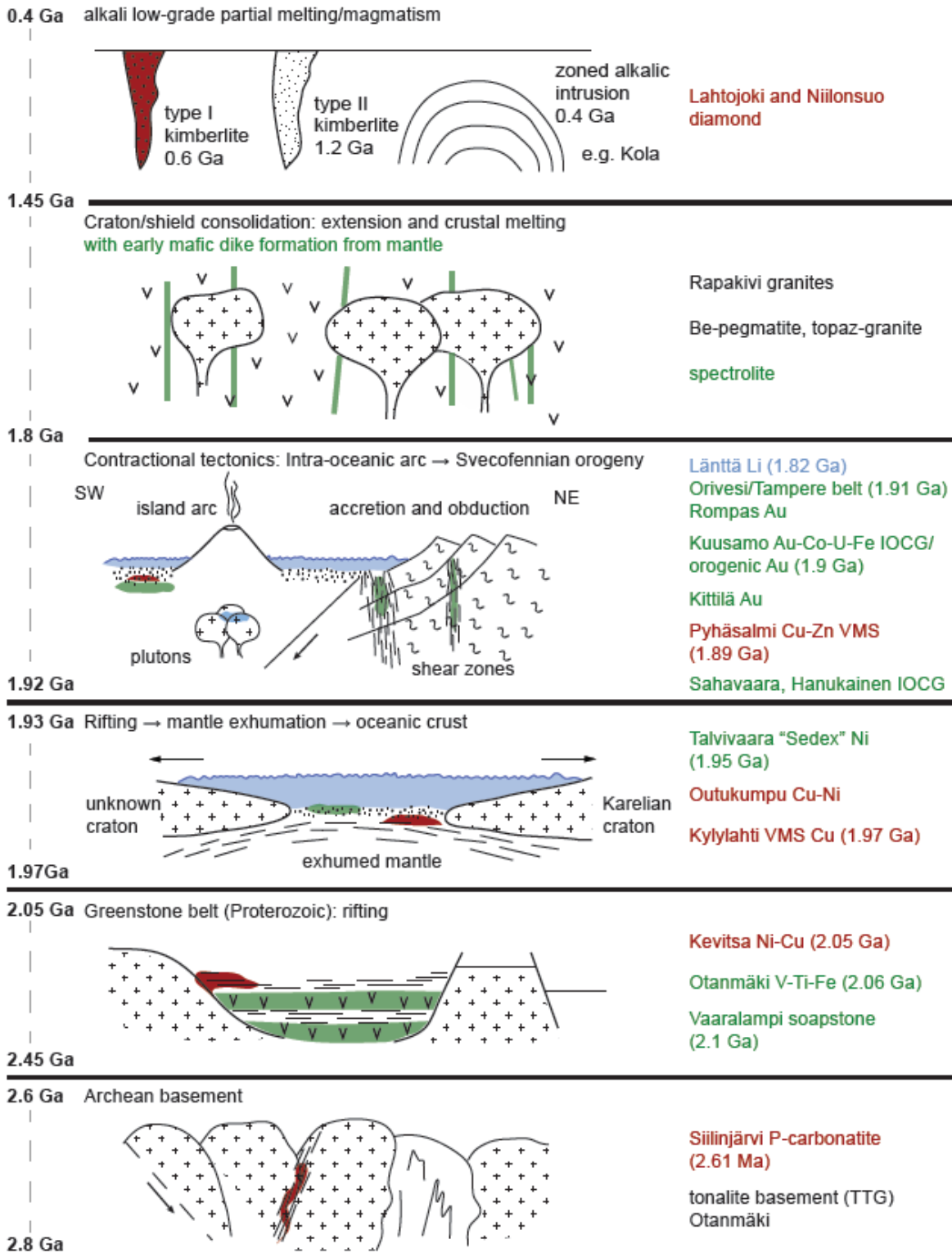
Länttä Li-pegmatite related to late-orogenic granites. It should be noted that the compressional regime in this era worked to remobilize many earlier mineralizations, increasing their grade.

Newly-initiated rifting between 1.8 and 1.45 Ga led to the emplacement of numerous granites of variable economic importance: (1) early mafic dikeing emplaced spectrolitic plutons; (2) the main phase of plutonism in this era comprized the Rapakivi granites, now valued as dimension stones; (3) finally, high degrees of fractionation generated pegmatites, including the Luumaki beryl-pegmatite and Kymi topaz-granite.

Following extensive plutonism, cratonization of the continent took place, effectively halting regional tectonics and allowing only minor late intrusions of kimberlitic and alkalic affinities. Notable in this time are two phases of kimberlite: (1) the Lahtojoki Kimberlite (0.6 Ga, type I diamondiferous) and (2) the Niilonsuo kimberlite (1.2 Ga, non-diamondiferous). Late zoned alkalic intrusions, notably in the Kola peninsula, intrude as late as 0.4 Ga.

**TIME GEOTECTONICS**

**FIELDTRIP LOCATIONS/  
DEPOSITS**



**Fig. D-1.** Metallogenic epochs of Finland (Re-drafted based on field sketches by Ch. Heinrich).

## Acknowledgements

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Hospitality of one of the most prominent ore deposit districts in Europe – Finland, made our trip successful and enjoyable. We believe that this event helped young geology students and graduates to find their interest in exploration and mining and set their step onto a successful future career.



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## Group picture



*Field course participants at the Otänmäki vanadium prospect with Jouko Jylänki (CEO of Otänmaki Mine Oy, front right) and Janne Hokka (geologist, GTK Kuopio office, front left).*

*From left: Matthew Steele-MacInnis, Juliana Troch (in the back), Pilar Lecumberri-Sanchez, Christoph Heinrich, Dina Klimentyeva, Christelle Bovier, Windeati Argapadmi, Ulrich Aerne, Szandra Fekete (in the back), Jakub Sliwinski, Lucas Gilsbach, Alina Fiedrich (standing), Simon Large, Katerina Schlöglova, Tobias Schlegel, Nico Küter, Pietro Luraschi (standing), Seraina Holinger, Lisa Bieri (standing), Julia Krawielicki, Marco Verdon, Matthis Sieber (standing), Marc Schnyder, Lea Menn.*

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