

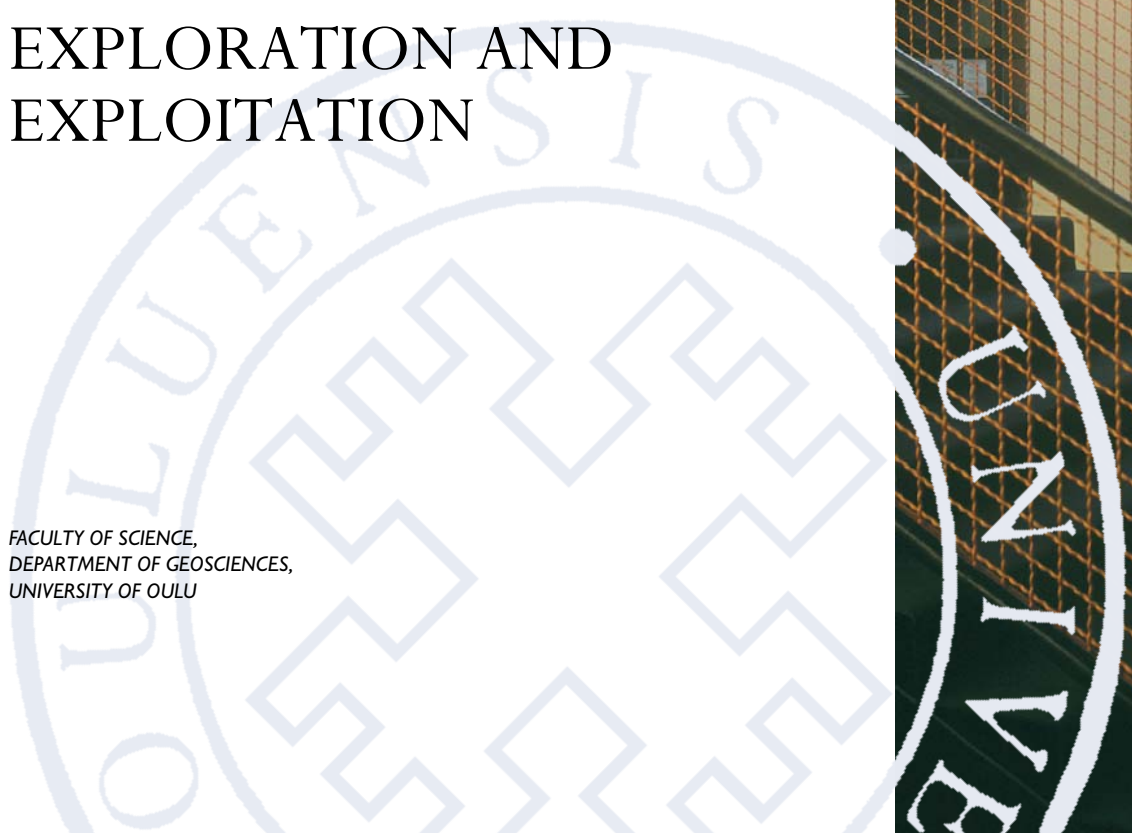
Tuomo Korkalo

GOLD AND COPPER
DEPOSITS IN CENTRAL
LAPLAND, NORTHERN
FINLAND, WITH SPECIAL
REFERENCE TO THEIR
EXPLORATION AND
EXPLOITATION

FACULTY OF SCIENCE,
DEPARTMENT OF GEOSCIENCES,
UNIVERSITY OF OULU

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TUOMO KORKALO

**GOLD AND COPPER DEPOSITS
IN CENTRAL LAPLAND,
NORTHERN FINLAND,
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EXPLOITATION**

Academic Dissertation to be presented with the assent of
the Faculty of Science, University of Oulu, for public
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Abstract

At least 30 gold deposits verified by means of one or more notable diamond drill hole results have been discovered in Central Lapland in the last 20 years, and these can be divided spatially into groups, between which the metal composition varies. The deposits contain varying amounts of sulphides and sulpharsenides as well as gold. Pyrite is the most common sulphide mineral in the gold deposits associated with volcanic rocks, and usually pyrrhotite in those associated with sedimentary rocks. The principal sulphide minerals in those connected with banded iron formations are pyrite and arsenopyrite. A separate group of formations consists of the palaeoplacer gold deposits associated with the molasse-like quartzites and conglomerates of Central Lapland.

The iron oxide-copper-gold deposits of Central Lapland, which are a significant potential source of copper and gold, are mostly associated with skarn rocks at the eastern contact of the acidic intrusive rocks of Western Lapland and with skarn rocks occurring as interlayers in metavolcanic and metasedimentary rocks.

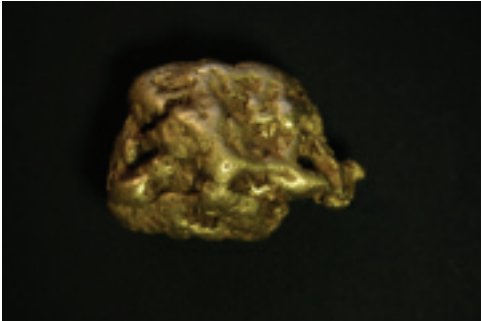
The gold deposits that have led to actual mining activities in Central Lapland are Saattopora in Kittilä and Pahtavaara in Sodankylä. Apart from the Laurinoja iron oxide-copper-gold ore body in Kolari, copper concentrate has been produced from the Saattopora gold ore deposit and the Pahtavuoma copper ore deposit. Only one gold ore in Central Lapland is being actively exploited at present, that of the Pahtavaara mine, which was worked in 1995–2000 and reopened in 2003.

The best starting point for successful gold ore exploration in Central Lapland can be achieved through a thorough knowledge of the deformation zones and their structures and alteration processes and the application of geochemical methods. Magnetic surveys can be of help in identifying and locating deformation zones of interest for exploration purposes and the majority of the associated shear zones and faults. Ore-critical zones usually feature graphite-bearing schists and iron sulphide-bearing sequences that can be traced by electrical methods and used as marker zones to verify the results of geological mapping. Geological, geophysical and geochemical techniques have been used in great diversity, and in particular till geochemistry and bedrock drilling have been methods by which the gold and copper deposits in Central Lapland have been discovered.

A total of 7.6 million tonnes of gold and copper ores, including the Laurinoja iron oxide-copper-gold ore, were extracted in Central Lapland over the period 1982–2000. The resulting production of gold during this period was 10 800 kg, together with 21 000 tonnes of copper in concentrates and 4500 kg of silver.

The gold and copper ores have been concentrated by gravity separation and/or flotation, since the ores so far taken into production has been of the free milling type. However, a substantial proportion of the deposits in the area contain copper, nickel, cobalt and arsenic as well, in the form of sulphides or sulpharsenides, so that the achievement of commercially saleable products calls for the use of different leaching processes. Deposits have also been found in Central Lapland that have consisted partly or entirely of refractory gold ore in which gold is lying in the crystal lattice of pyrite and/or arsenopyrite, the processing of which by the above-mentioned methods is not economic, as it requires pre-treatment by bio-oxidation or pressure oxidation in order to convert the gold to a cyanide-soluble form.

Keywords: concentrating, copper ores, exploitation, exploration, feasibility study, Finland, geochemistry, geophysics, gold ores, hydrothermal alteration, iron ores, Lapland, milling, mineral deposits, mining, schist belt, zinc deposits



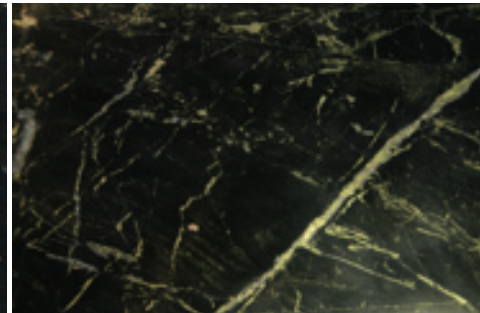
Gold nugget 393 g (replica)
Ivalo



Miniature gold bullion 100 g
Saattopora



Gold concentrate
Saattopora



Copper ore
Pahtavuoma

Fotos: Otto Korkalo (Gold nugget, Miniature gold bullion, Copper ore)
Esko Hänninen / Otto Korkalo (Gold concentrate)

Acknowledgements

This work was begun when I took partial retirement in 2000 and continued when I retired altogether in 2003, although I had nursed the idea of producing a publication on the gold and copper deposits of Lapland for a long time before that. In contrast to the numerous unpublished reports and memoranda produced by various companies and by the Geological Survey of Finland, few scientific papers have been published on these deposits.

Prof. Tuomo Alapieti of the University of Oulu showed immediate enthusiasm for the topic when I suggested that I should write a doctoral thesis on it, and I am extremely grateful to him for supervising and directing my work, as also to Mrs. Kristiina Karjalainen for drawing the figures and Mrs. Helena Saari for preparing the manuscript for publication.

The material was obtained mainly from the Outokumpu Company, and I would especially like to express my thanks to my superior, Markku Isohanni, Managing Director, for his interest and support, and also to the current manager of Outokumpu Mining Oy, Tuomo Mäkelä, for his encouragement throughout. Thanks also go to Prof. Elias Ekdahl and Dr. Ossi Leinonen, who refereed this work for publication, for their critical comments. I would also thank Prof. Ahti Silvennoinen, retired head of the Rovaniemi regional office of the Geological Survey of Finland, for the high quality and usefulness of the geological material obtainable on Lapland.

I owe a debt of gratitude to my numerous colleagues in the Outokumpu Company over a period of more than 30 years for the privilege of having been able to work with them on ore and mineral deposits and many other geological topics, not only in Lapland but throughout the country. I would in particular mention Juhani Aarnisalo, Lic.Phil., who was responsible for the various maps representing interpretations of the aerogeophysical data for Central Lapland that formed an important part of this work.

The manuscript was translated into English by Mr. Malcolm Hicks, M.A., whom I thank for his excellent work.

Finally, I would like to express my warmest thanks to my wife Pirkko and my children Katja and Otto for all the patience they have shown in encouraging me to complete this work.

Rovaniemi, May 2006

Tuomo Korkalo

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Abstract

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1 Introduction

1.1 Preface

The research reported on here is concerned with gold and copper deposits in Central Lapland, Northern Finland, their geological position, controlling factors, metal content, exploration and technical and economic exploitation possibilities. The focus is on mines and sites where geological, geophysical and geochemical investigations have been carried out, together with diamond drillings, and deposits have been discovered to the extent of at least one diamond drill hole result of economic or other significance.

The neutral term "deposit" will be used in most cases in this discussion, but more precise characterizations in economic terms will be provided where appropriate. Those deposits that have given rise to mining operations will be referred to as "ore deposits or ores", the best sites as "mineral deposits" and the others as "occurrences" or "showings", or simply as "prospects". Some notable ore and mineral deposits are described in more detail and are used as examples to create an overall picture of the gold and copper deposits of Central Lapland and the possibilities for discovering and exploiting them.

The author was engaged in ore prospecting fieldwork for Outokumpu Oy at more than ten sites in Central Lapland in 1970–1981, the most important of which were the company's Pahtavuoma copper, zinc and uranium deposits and the Saattopora gold and copper deposits. He subsequently worked as an ore geologist for the Outokumpu Oy Mining Technical Group, mainly in Finland but also abroad to some extent, before serving as director of the Outokumpu Finnmines Oy Saattopora and Laurinoja mines in 1989–1991. He was then head of exploration for Outokumpu Mining Oy in 1993–1999, with responsibility for the whole of Finland. He has participated in numerous economic and technical feasibility studies of gold and copper deposits in the area concerned here produced by the Mining Technical Group, among which particular mention should be made of the Saattopora (Au-Cu), Pahtavuoma (Cu-Ag, Zn, U), Kutuvuoma (Au) and Laurinoja (Fe-Cu-Au) deposits and of the Pahtavaara (Au) and Suurikuusikko (Au-As) deposits which were included in a bidding competition announced by the Ministry of Trade and Industry (MTI). He has also taken part in geological investigations and feasibility studies focused

on the Viscaria (Cu) ore deposit in Northern Sweden and the Bidjovagge (Au-Cu) ore deposit in Northern Norway.

In 1990 the Geological Survey of Finland presented the author with a 393 g solid gold replica of the largest gold nugget ever found in Lapland in recognition of his part in the discovery of the Saattopora gold ore, which led to the opening of Lapland's first bedrock gold mine. He has also received an award for the geological fieldwork that led to the discovery of the Pahtavuoma ore deposit.

The material employed in this work is based on numerous geological publications and unpublished sources and research reports dealing with Central Lapland and on the author's own field and other research data. Outokumpu Oy, Outokumpu Finmines Oy, Outokumpu Mining Oy (all of these referred to below simply as Outokumpu), Rautaruukki Oy and Otanmäki Oy, which was amalgamated with Rautaruukki Oy in 1967 (referred to collectively below as Rautaruukki) and the Geological Survey of Finland (GTK) have carried out major ore prospecting operations in the area over a period of several decades. The bedrock maps presented here are based to a great extent on geological mapping by GTK and basic research aimed at serving the purposes of ore prospecting. The lithostratigraphic classification is based on that proposed in the final report of the Lapland Volcanite Project, "Kittilän vihreäkivalueen geologia" (Summary: The stratigraphy, petrology and geochemistry of the Kittilä greenstone area, Northern Finland), a report in which use was made of research data from Outokumpu and Rautaruukki in addition to GTK material (Lehtonen *et al.* 1998).

The work of locating and interpreting the regional deformation, shear and fault zones made use of the freely available regional aeromagnetic, airborne electromagnetic and gravimetric maps published by GTK, in addition to which the various image maps produced by Juhani Aarnisalo, Phil.Lic., by processing GTK aeromagnetic data proved to be important tools for deducing the structural geological features controlling the deformation zones and gold and copper deposits.

At least 30 gold deposits of economic interest have been discovered in Central Lapland over the last two decades, three of which, Saattopora in Kittilä, Pahtavaara in Sodankylä and Kutuvuoma in Kittilä, a small satellite deposit of the latter, have led to the opening of a mine. Copper concentrate was produced from the Pahtavuoma copper ore and the Saattopora gold ore in the 1990s, although its production actually dates back to 1982, when Rautaruukki began to process the Laurinoja iron oxide-copper-gold ore from Hannukainen in Kolari into a gold-bearing copper concentrate at its Rautuvaara mine (Juopperi *et al.* 1982). All the above-mentioned mines have now been closed, Laurinoja in 1990, Pahtavuoma in 1993, Saattopora in 1995, Kutuvuoma in 1999 and Pahtavaara in 2000, although in this last case the mine was reopened in 2003.

1.2 Location of the Central Lapland area

Geographically, the Central Lapland area in Northern Finland as discussed here (Fig. 1) is about 30 000 km² in size and has a relatively low-lying topography, although it is also characterized in the north and west by chains of fells reaching a maximum height of

around 800 m. Bedrock exposure conditions are usually better on the hills than in the lower-lying peatland areas.

Geologically the area is part of the Palaeoproterozoic greenstone belt belonging to the Fennoscandian Shield. The majority of it is formed by the Central Lapland Greenstone Belt, which continues north-westwards into Sweden and Norway and south-eastwards into Russia, but there is also an area of acidic intrusive rocks in the west, the extensive Central Lapland granite area in the south and an area of Archaean gneisses in the east that runs on into Russia. The area borders on the Lapland granulite complex in the north-east.

Central Lapland is an exceptional area for Finland in terms of its Quaternary geology, and therefore also for ore prospecting, as several till beds differing in age have been identified (Hirvas 1991). It is also located almost entirely within the ice divide area, where the preglacial weathered crust is commonly presented.

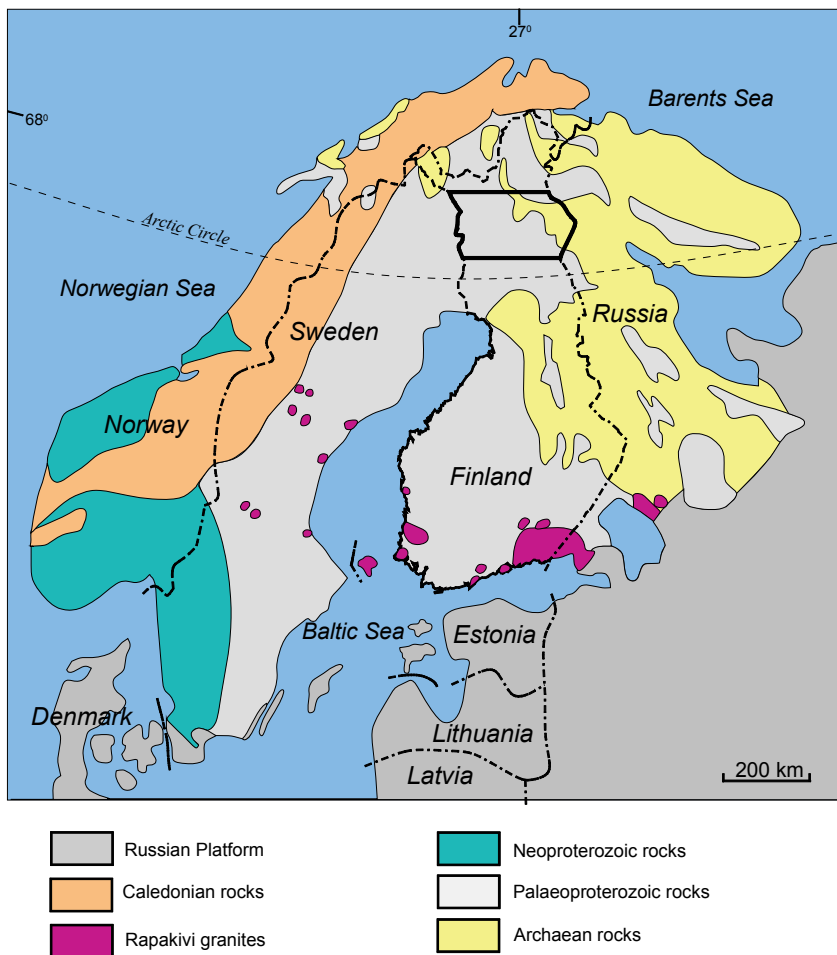


Fig. 1. General geology of the Fennoscandian Shield, outlining the major tectostratigraphic units. The Central Lapland area is indicated by solid black lines.

1.3 Previous investigations

The earliest geological works to deal with Central Lapland were those of Hackman (1927) in the Kittilä area and the maps to a scale of 1:400 000 produced for the whole of the area concerned here by Mikkola (1937, 1941). The first geological maps of Central Lapland to a scale of 1:100 000 were published in 1967. A systematic aerogeophysical survey of Finland was commenced in 1951, and the first flights in this region took place in the Kolari area in 1955. A low-altitude aerogeophysical survey of the whole country began in 1972. Regional mapping of Quaternary deposits and geochemical investigations were initiated in Lapland in 1953, beginning in the Vuotso area of Sodankylä, and studies of surficial deposits in northern Finland for prospecting purposes were carried out in 1972–1976 (Hirvas *et al.* 1977). Regional geochemical mapping of the whole of Finland took place over the period 1982–1994 (Salminen 1995). A working group at the Rovaniemi office of GTK constructed a geological map of Central Lapland to a scale of 1:200 000 in 1983–1984 (Lehtonen *et al.* 1985), and the mapping work was continued by the Central Lapland Volcanite Project in 1984–1989 (Lehtonen *et al.* 1998), in which the main focus was on the stratigraphy, petrology and geochemistry of the Kittilä greenstone area. The joint Nordic undertaking known as the Nordkalott Project which began in 1980 and came to an end in 1986 (Bølviken *et al.* 1986) covered numerous aspects of geochemical, geophysical and geological research in Northern Fennoscandia.

The Finnish universities have also had significant projects dealing with the ore geology of Central Lapland. The stratiform iron ore project carried out by Åbo Akademi University at the instigation of the Ministry of Trade and Industry (MTI) examined the iron formations of Northern Finland in the years 1972–1975 (Lehto & Niiniskorpi 1977), while the University of Turku's nickel project examined the nickel ore potential of the ultramafic rocks of Lapland (Papunen *et al.* 1977), and the same university later had a Lapland volcanites project that focused on the sulphide deposits of the Kittilä greenstone area (Papunen *et al.* 1987) and a zinc project covering the whole country that studied the characterization of zinc deposits (Papunen 1990). The aim of the Kittilä ore project at the University of Oulu was to determine the geological nature and structure of the Kittilä greenstone area by geological and geophysical methods and to examine the nature of ore deposits in it and variations in their chemical composition (Paakkola *et al.* 1981). The Savukoski Archaean schist zones and their ore potential were examined in a research project on Archaean rocks at the same university (Pirainen 1985), and the University of Helsinki, together with GTK, worked on the nature of the post-orogenic granites of Lapland and the possibilities of the occurrence of porphyry copper deposits in connection with them (Front *et al.* 1989).

Among the most recent major geological projects to provide data on Central Lapland have been that concerned with radiometric age determinations from Lapland (Vaasjoki *et al.* 2001) and the Finnish Reflection Experiment 2001–2005, involving four seismic reflection lines (FIRE 1–4) for the whole of Finland, one of which consisted of a traverse from Southern to Northern Lapland (Kukkonen 2003). The most recent of all has been a study of metamorphism and deformation in the Palaeoproterozoic bedrock of Central Lapland (Hölttä *et al.* in press).

Ore prospecting in Central Lapland began in the 1940s, when Atri Oy conducted large-scale ore geological investigations in the Kittilä area in the hope of finding multimetal (Cu, Au, Ni, Co, As) deposits of the Sirkka type.

GTK began ore exploration for placer gold in Lapland in the 1940s and continued this work at varying intensities for several decades (GTK 1948–1960). The first major object of GTK research in Central Lapland was the Riikonkoski copper deposit in the 1970s (Puustinen 1985, Lång 1986), while its main investigation sites in the region since then have been layered intrusions and their associated PGE-bearing chromitite zones, and also nickel-copper-PGE-gold deposits (GTK 1971–2003). One area of particular interest in GTK exploration work in Central Lapland over the last twenty years has been the gold ore potential of the Kittilä greenstone area and the numerous gold deposits discovered within it (see Härkönen 1984, Keinänen *et al.* 1988, Härkönen & Keinänen 1989, Ward *et al.* 1989, Korkiakoski *et al.* 1989, Nurmi *et al.* 1991, Puustinen 1991, Korkiakoski 1992, Eilu 1994, Mänttari 1995, Eilu 1999, Eilu *et al.* 2003).

Outokumpu began ore exploration in Central Lapland in 1957, focusing at first on a search for base metals in the Kittilä greenstone area. The material gathered by Atri Oy and Vuoksenniska Oy was acquired by Outokumpu in 1966, and this enabled the company to continue research in the Kittilä area, whereupon its principal topics in the 1970s proved to be the Pahtavuoma copper ore deposit (Inkinen 1979) and the Saattopora copper(+gold) deposit (Korkalo 1982), both discovered during the 1970s. The Saattopora gold(+copper) ore, discovered by Outokumpu in 1985, and the research carried out on it heralded a substantial exploration programme directed at gold deposits in the Central Lapland area.

Rautaruukki exploration and mining in Central Lapland in 1959–1986 was concentrated mainly on the discovery and exploitation of iron ores, although one of the largest and most important of its sites was the Sokli carbonatite massif in Savukoski in the north-eastern part of the region (Vartiainen 1980). Meanwhile, the magnetite(+copper-gold) deposits of Rautuvaara in Kolari were described in meticulous detail by Hiltunen (1982) in his doctoral thesis "The Precambrian geology and skarn ores of the Rautuvaara area, northern Finland". Most of the magnetite and haematite deposits in Central Lapland were investigated by Rautaruukki, the best-known of these being the Rautuvaara formation with its iron deposits, the Porkonen-Pahtavaara iron formation and that of Jauratsi in Eastern Lapland. Prior to Rautaruukki, the Rautuvaara magnetite deposits and the Porkonen-Pahtavaara iron formation had been studied, among others, by Suomen Malmi Oy and Otanmäki Oy. Before abandoning its ore prospecting activities, Rautaruukki carried out a major survey of iron ore potential covering the whole of Finland together with Russian experts in 1980–1983, known as the Raetsu Project (Rautaruukki 1982). One part of this work was concerned with magnetite deposits in the Rautuvaara formation.

The interests of foreign mining and exploration companies in Central Lapland have been directed mostly at further studies and re-evaluations of already discovered, well-known deposits, such as the Pahtavaara, Suurikuusikko and Kuotko gold deposits and the Kevitsa nickel-copper-PGE-gold deposit.

1.4 A review of metallic ore mining in Finland

The Outokumpu copper ore in Eastern Finland, located in what was then the parish of Kuusijärvi, was discovered on 16th March 1910, when the third diamond drill hole intersected a rich copper ore body (9 m / Cu 6 wt%) at a depth of 20 m. This led the Finnish government together with Hackman & Co. to found a partnership company, Outokumpu Kopparverk, in 1914 to exploit this deposit. Exploitation had already begun on a small scale in 1913, and by 1916 the annual rate of extraction was 25 000 tonnes. The company Outokumpu Oy was founded in 1932, by which time the annual mining capacity had reached 150 000 tonnes, and it then took possession of the mine and assumed responsibility for its continuation and development (Kuisma 1989).

Exploitation of the Outokumpu ore and the associated metallurgic research effectively created the foundation for the mining and metallurgy industries in Finland. The crucial innovation as far as metallurgy was concerned was the flash smelting technique developed by Outokumpu, which was taken into use for the first time at the company's Harjavalta copper smelter in 1949. This technique later achieved worldwide success as a means for the further processing of copper concentrate.

Several decades were to pass, however, before any new base metal deposits were to be found in Finland in the quantities necessary for opening a mine. Apart from the Outokumpu ore, the main ore deposits to be discovered prior to 1950 were the Orijärvi copper-zinc-lead ore (in 1757), the Haveri gold-copper ore (1935), the Otanmäki iron-titanium-vanadium ore (1938), the Makola nickel ore (1939), the Ylöjärvi copper-tungsten ore (1940), the copper-zinc ores of Aijala (1945) and Metsämonttu (1946) and the Vihanti zinc-copper ore (1946). One of the earliest mines to exist in the whole country was that of Jussarö on the south coast, where iron ore was extracted for the first time in the 1830s.

Apart from Outokumpu, Otanmäki and Vihanti, the most important deposits of metal ores in Finland were discovered only in the 1950s and 1960s, the most notable among them being the iron ores of Raajärvi (in 1955) and Rautuvaara (1956), the Pyhäsalmi zinc-copper ore (1958), the Kemi chrome ore (1959), the nickel ores of Kotalahti (1954), Vammala (1961) and Hitura (1963), the copper ores of Virtasalmi (1964), Vuonos (1965), Luikonlahti (1965) and Hammaslahti (1966) and the Mustavaara vanadium-iron ore (1968).

Deposits discovered in the 1970s and 1980s that led to the opening of a mine were the Pahtavuoma copper ore (in 1970), the Laurinoja iron-copper-gold ore and Kuervaara iron ore (1974), the Enonkoski nickel ore (1980) and the Mullikkoräme zinc ore (1989). The last significant discovery took place in 1996, when a new zinc-copper ore lens was found below the existing ore body at Pyhäsalmi, the extraction of which is expected to add more than fifteen years to the life of the mine, which has already been operating for several decades.

Many of the copper ore deposits proved to contain gold as well, which, as a by-product of the copper concentration process, did much for the cash flows of the mines. By far the best case in this respect was the Outokumpu copper ore, which yielded altogether more than 18 tonnes of gold during the mine's lifetime, while other producers have included Pyhäsalmi (still in production) and Laurinoja.

The first deposits of bedrock gold in Finland to lead to the opening of a mine were those at Haveri in the south of the country, where a gold-copper ore was discovered in

1935, and Kivimaa in Southern Lapland, where a small gold-copper ore body was found in 1964. Of the gold deposits discovered in the 1980s and 1990s, those at Orivesi in Southern Finland (in 1981) and Saattopora (1985) and Pahtavaara (1985) in Central Lapland and the small satellite deposit of the latter at Kutuvuoma (1993) are the only ones to have led to mining. The main gold deposits in Finland that have not yet been mined are those of Suurikuusikko and Kuotko in Central Lapland, Oijärvi in Southern Lapland, Juomasuo in Kuusamo (and others in the area), Laivakangas in Western Finland, Pampalo, where development and test mining has taken place, Pirilä and Osikonmäki in Eastern Finland and Jokisivu in South-Western Finland.

The mines in Finland being worked for metal ores at present are the chrome mine at Kemi, the zinc-copper mine at Pyhäsalmi, the nickel mine at Hitura and the gold mine at Pahtavaara. In spite of the marked growth in ore prospecting, not a single metal ore deposit has been discovered over the last 35 years that has led to mining activities on the scale of those that began in the 1950s and 1960s or earlier. Those discovered between 1970 and 2005 that have led to mining are the above-mentioned Enonkoski, Mullikkoräme, Saattopora, Pahtavuoma and Kutuvuoma, together with the deep extension to the Pyhäsalmi ore deposit, all by Outokumpu, Laurinoja and Kuervaara discovered by Rautaruukki, Orivesi discovered by Lohja Oy, Pahtavaara and Pampalo (test mine) discovered by GTK.

1.5 The discovery of gold and copper deposits in Central Lapland

The first definite observation of gold in Finnish Lapland consisted of two gold-bearing dolomite boulders discovered in the estuary of the Kemi River in Southern Lapland by the chief of police in the area, J. G. Boucht, in 1836 (Stigzelius 1986). Later, placer gold was found at Äimäkoski on the Teno River and at points on the lower reaches of the Ivalo River, both in Northern Lapland, in 1867 and 1868, respectively. It was these placer gold finds that led to the legendary Lapland gold rush that lasted for over a century and can in a sense be said to be still going on today, although at a lesser intensity.

The copper-gold-nickel deposit identified by Atri Oy at Sirkka in Kittilä in the 1940s was the first in Central Lapland to give rise to plans for a mine. The deposit eventually turned out to be of only modest proportions, and in spite of the company's considerable prospecting efforts, no new deposits were found that would have justified mining operations. Later, in the 1980s and 1990s, Outokumpu and GTK carried out large-scale research into the zones of metasedimentary and metavolcanic rocks in the southern and central parts of the Kittilä greenstone area, in the course of which most of the currently known gold deposits were discovered.

At the same time as the "modern gold rush" was beginning in Finland in the 1980s, Outokumpu was examining the possibility of reopening the Bidjovagge copper mine in Northern Norway. New investigations revealed, however, that the gold in the Bidjovagge ore was of greater value for mining purposes than the copper, and once the company had gained the rights to exploit this deposit, mining was resumed in 1985. Altogether 1.94 million tonnes of ore with an Au content of 3.7 g/t and a Cu content of 1.3 wt% was extracted over six years (Anttonen R 1995). The new investigations carried out at Bidjo-

vagge and the promising results obtained provided more encouragement for gold prospecting in Central Lapland.

The first bedrock gold deposit in Central Lapland that led to mining operations was the Saattopora ore body in the southern part of the Kittilä greenstone area, which was discovered thanks to an analogy with the Bidjovagge ore deposit (Korkalo 1987). Again a copper(+gold) deposit was already known at the site, dating back to 1972, and diamond drill cores from an extension to this were re-examined in 1985 and found to contain substantial amounts of gold, the best drill core having a mean gold content of 6 g/t over a core length of 15 m and a copper content of 0.3 wt%. These drill holes were located only a few hundred metres from the previously identified Saattopora copper(+gold) deposit.

The second gold deposit in Central Lapland to be mined was that of Pahtavaara, discovered by GTK in 1985 in connection with regional till surveys and bedrock mapping (Korkiakoski 1992).

The Kutuvuoma gold ore deposit, located about 50 km west of the Pahtavaara mine, was discovered by Outokumpu in 1993 as a result of more detailed investigations into a gold anomaly revealed in GTK's regional till survey and of subsequent diamond drilling.

The first gold deposit to be found in the middle part of the Kittilä greenstone area was that of Sukseton, discovered by Outokumpu in 1981. Later a number of gold-arsenic deposits were located in the area, the most significant being those of Suurikuusikko and Kuotko, discovered by GTK in 1986.

The majority of the approximately 30 currently known gold deposits in Central Lapland were discovered within a period of just over ten years after the Saattopora and Pahtavaara finds, whereas the main copper deposits, including the copper-dominated gold deposits, had already been identified in the early 1970s.

About 90% of the known gold deposits in Central Lapland were discovered in the 1980s, since when the number of finds has declined markedly. The main ones dating from the 1990s are those of Kettukuusikko, Loukinen and Ruoppapalo, discovered by GTK, and Hanhimaa and Kutuvuoma, discovered by Outokumpu.

The first copper deposit of any significance to be found in Central Lapland was that of Riikonkoski in Kittilä, discovered by GTK in 1969, while Outokumpu discovered a silver-bearing copper ore deposit at Pahtavuoma in Kittilä in 1970. Part of the Pahtavuoma ore body was mined in connection with exploitation of the Saattopora gold ore and processed at the Rautuvaara mine. In 1972 Outokumpu discovered a relatively large but low-grade copper deposit at Saattopora in connection with its Pahtavuoma investigations. The only significant copper deposit to be found outside the Kittilä greenstone area is that of Vesilaskujänkkä in the eastern part of Central Lapland, discovered by Rautaruukki in 1981.

The numerous magnetite-copper-gold deposits associated with the Rautuvaara formation in Kolari, the most important of which are Laurinoja, Cu Rautuvaara, Rautuoja and Kuervitikko, were almost without exception discovered by Suomen Malmi Oy and Rautaruukki. Outokumpu did find a skarn sequence in the volcanic rocks close to the Yllästunturi quartzite area east of the Rautuvaara formation in 1979 which had similar magnetite-copper-gold deposits associated with it to those in the Rautuvaara formation itself.

1.6 Production of gold and copper ore in Central Lapland

The first attempt to exploit a gold-copper deposit in Central Lapland on an industrial scale was the establishment of a test mine at Sirkka in Kittilä in 1955 (Räisänen 2001). This did not prove profitable, however, and the mine was closed in 1956. Altogether about 3000 tonnes of ore were extracted.

Gold and copper production in Central Lapland began in 1982, when Rautaruukki added a flotation plant to its magnetic separation-based processing facility at Rautuvaara in order to process gold-bearing copper concentrate from the Laurinoja magnetite-copper-gold ore (Juopperi *et al.* 1982). Altogether some 3.26 million tonnes of magnetite ore were extracted from the open pit Laurinoja mine in 1982–1988, from which both iron concentrate and gold-bearing copper concentrate were produced (Rautaruukki 1988).

A total of 2.12 million tonnes of gold-copper ore were extracted from the Saattopora gold mine in 1988–1995 and processed at Rautuvaara, and during this period the closed Laurinoja mine was reopened to provide a further 0.21 million tonnes of copper and gold-bearing magnetite ore, in addition to which 0.02 million tonnes of low-grade ore was taken from the old waste rock heaps at Rautuvaara and Laurinoja for processing. At the same time 0.26 million tonnes of copper ore were extracted from Pahtavuoma, again for processing at the Rautuvaara concentrating plant, together with a consignment of 0.01 million tonnes of copper ore from the product of test mining at Pahtavuoma in 1974–1976 (Korvuo 1995).

Open pit mining at the Pahtavaara gold mine in Sodankylä was commenced in 1995 and lasted until 2000, during which time 1.70 million tonnes of ore were extracted. The site was then reopened for mining towards the end of 2003. About 0.01 million tonnes of ore have been extracted from the satellite deposit of Kutuvuoma, about a half of which has been processed at the Pahtavaara concentrating plant (Puustinen 2003). The production of gold and copper ore in Central Lapland is given in Table 1.

Table 1. Production of gold and copper ore in Central Lapland.

Mine	Company	Tonnes	Au g/t	Cu wt%	Years of mining	Reference
Sirkka test mine (1)	AB Vuoksenniska Oy	(3000)			1955–1956	Räisänen (2001)
Laurinoja (2)	Rautaruukki	3258000	0.25	0.45	1982–1988	Rautaruukki (1988)
Saattopora	Outokumpu	2115000	3.29	0.28	1989–1995	Korvuo (1995)
Laurinoja	Outokumpu	207000	1.01	0.93	1990	Korvuo (1995)
Laurinoja	Outokumpu	18000	0.32	0.33	1989	Korvuo (1995)
Total Au-Cu ore		5598000	1.43	0.40		
Pahtavaara (3)	Terra Mining Oy	1697000	2.14		1995–2000	Puustinen (2003)
Kutuvuoma	Terra Mining Oy	6000	5.00		1999	Puustinen (2003)
Total Au ore		1703000	2.15			
Pahtavuoma	Outokumpu	261000		1.08	1993	Korvuo (1995)
Pahtavuoma	Outokumpu	13000		1.01	1974–1976	Korvuo (1995)
Total Cu ore		274000		1.08		
Placer gold	Mainly privates	(2)			1868–	Stigzelius (1986)

1) No precise information is available on the metal content of the ore obtained from the Sirkka deposit, although channel and grab samples were reported by Mikkola and Sandström (1964) to have a Cu content of 0.66 wt% and samples of crushed ore from the concentrating plant 0.34 wt% Cu. Nothing was said of the Au content of the ore.

2) The Hannukainen deposits are represented in the calculations by the Laurinoja ore, the only FeOx-Cu-Au deposit in the Rautuvaara formation from which copper concentrate has been produced. Mean copper and gold concentrations have been calculated for the concentrate obtained from the ore extracted by Rautaruukki, the total of 48 600 tonnes of concentrate being said to contain 22.6 wt% Cu and 9.78 g Au /t (Rautaruukki 1988). The calculations also take into account the recovery percentages of the copper and gold, and an estimate is given for the Cu and Au content of the crushed rock removed before processing.

3) The ore from Pahtavaara does not take account of that extracted since the reopening of the mine in 2003.

2 The regional geological setting of Central Lapland

2.1 General

The bedrock of Finland forms part of the Fennoscandian Shield and is composed mainly of the Archaean (3100–2500 Ma) migmatites, granitoids and greenstone belts of Eastern and Northern Finland, the Palaeoproterozoic (2500–1650 Ma) granitoid complexes and sedimentary and volcanogenic rocks occupying the majority of the country and the Lapland granulite complex. Younger than 1650 Ma are the anorogenic rapakivi granites of Southern and South-Western Finland, the clay and sandstones of South-Western Finland and the Oulu region, the extensive Salla and Laanila diabases, sedimentary strata in the north-western arm of Lapland, the Oulu region and South-Western Finland, the kimberlite pipes of Eastern Finland, the Caledonian rocks of the north-western arm of Lapland and the Sokli carbonatite massif and the Iivaara alkaline rocks of Eastern Lapland.

The Central Lapland area studied here (Fig. 2), which is almost coincident with the Central Lapland Greenstone Belt, consists chiefly of Palaeoproterozoic metasedimentary and metavolcanic rocks, granitoid areas, a granulite complex and Archaean formations. The extensive Kittilä greenstone area occupies the western and central parts of the Central Lapland Greenstone Belt, while metasedimentary rocks are in the majority in the eastern part, which also features an Archaean granitoid complex with associated Archaean metasedimentary and metavolcanic rocks. The north-eastern corner of the area borders onto a granulite complex. There are several layered intrusions in the central and eastern parts of the area and numerous mafic intrusions and metadiabases along the southern edge, while the western part possesses synorogenic granitoids and the northern and southern parts late orogenic granites. Post-orogenic granitoids are to be found in a NE-SW-trending deformation zone. Among the youngest rocks in Central Lapland are the Salla (NW-SE-oriented) and Laanila (NE-SW-oriented) diabase dykes running parallel to the deformation zones and the Sokli carbonatite massif in the north-east.

The deformation zones, which are typical of the Central Lapland area, are composed of a number of separate, practically parallel shear zones and are intersected by younger faults and shear zones. The principal directions of deformation are NW-SE, from Muonio to Salla, and almost perpendicular to this, NE-SW, from Ivalo to Kolari. These in turn

intersect with a NNW-SSE-trending fracture zone running in virtually a straight line from Northern Norway to Lake Onega in Russia, having a gravity anomaly associated with it.

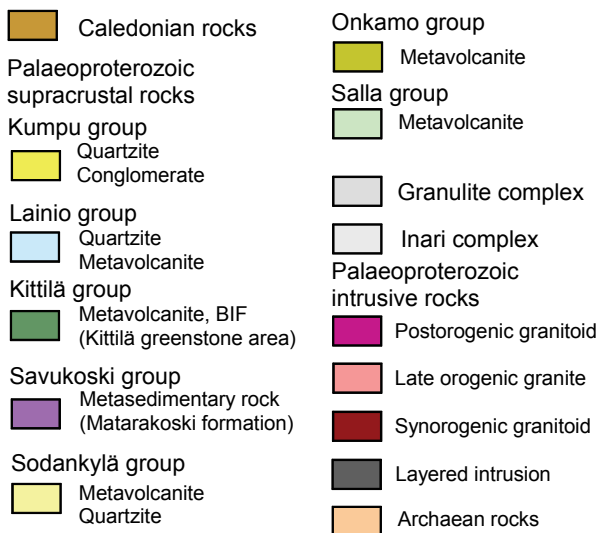
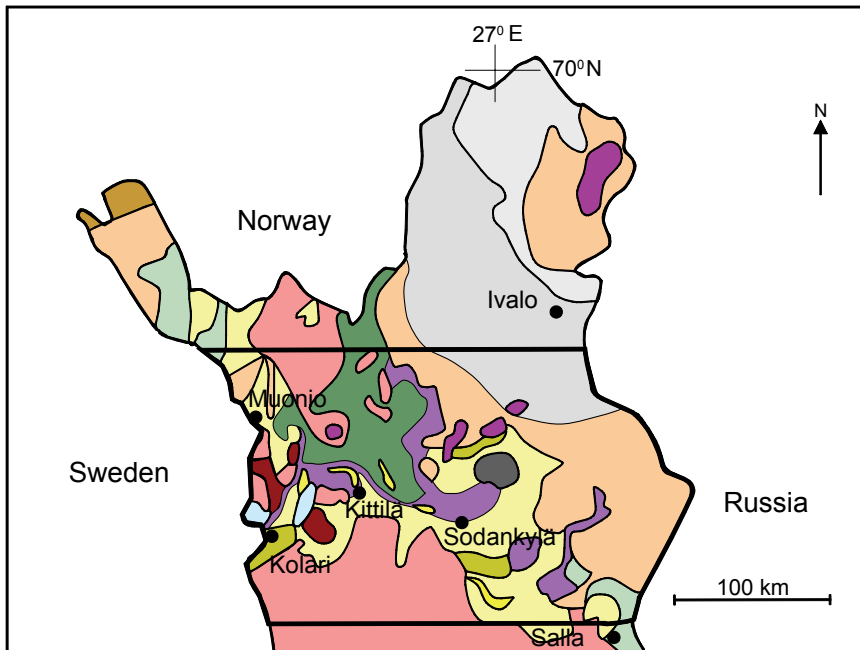


Fig. 2. The bedrock of Northern Finland, simplified from Lehtonen *et al.* (1998). The Central Lapland area studied here is delimited with thick lines.

2.2 Archaean rocks

The Archaean formations of Central Lapland are of age 2830–2680 Ma, although one gneiss dome has been dated to over 3000 Ma (Hanski *et al.* 2001). The extensive domain of Archaean rocks in the eastern part of the area is composed of granitoid complexes, paragneisses and metavolcanite zones, the granitoids being principally tonalites, granodiorites and granitic gneisses, the paragneisses quartz-feldspar gneisses and mica gneisses, the metavolcanites amphibolites and the ultramafic rocks frequently metakomatiites (Juopperi 1994). Unusual gold-bearing garnet-amphibole-cordierite-quartz rocks belonging to the silicate facies of an iron formation have been observed in connection with the paragneisses (Inkinen 1988). The central part of the Central Lapland Greenstone Belt contains Archaean granitoids and migmatites in the form of domes surrounded by Palaeoproterozoic formations. Granodioritic and tonalitic gneisses for which an age of 2600 Ma has been obtained (Väänänen & Lehtonen 2001) occur in the western part of the greenstone belt.

2.3 Palaeoproterozoic metasedimentary and metavolcanic rocks

The interrelations between the lithostratigraphic units formed by the Palaeoproterozoic metasedimentary and metavolcanic rocks overlying the Archaean basement in Central Lapland were studied in the 1920s to 1940s (Hackman 1927, Sederholm 1932, Mikkola 1941), and it was Sederholm who gave the name Lapponian schists to the metasedimentary rocks and overlying greenstones of Central Lapland. Mikkola (*op. cit.*), in turn, was of the opinion that the Kumpu-Oraniemi sequence of quartzites, conglomerates and mica schists represented a molasse facies that had been deposited discordantly on top of the Lapponian schists.

The most recent interpretation of the lithostratigraphy of the Central Lapland Greenstone Belt is based on the results of the GTK Lapland volcanite project, in which the supracrustal rocks of the area were grouped stratigraphically and labelled according to international recommendations (Lehtonen *et al.* 1998). This meant that seven groups of metavolcanic and metasedimentary rocks were recognized (from oldest to youngest): the Salla, Onkamo, Sodankylä, Savukoski, Kittilä, Lainio and Kumpu groups. These were in turn divided into lithostratigraphic type formations named after well-known geographical sites where they are exemplified.

The stratigraphy of the Central Lapland Greenstone Belt (Fig. 2) is in broad outline as follows (Lehtonen *et al.* 1998, Keinänen & Salmirinne 2003):

The oldest unit, the Salla group (2520–2440 Ma), is composed of intermediate to felsic metavolcanites, including a volcanic conglomerate, andesitic, dasitic and rhyolitic pillow lavas and pyroclasts.

Somewhat younger is the Onkamo group (2440–2400 Ma), composed of tholeiitic and komatiitic metavolcanites. The metavolcanites have the composition of pyroclastic komatiites and mafic and intermediate lavas.

Above the Onkamo group in the stratigraphy is the Sodankylä group (2400–2200 Ma), which is widely distributed over the southern and eastern parts of the Central Lapland

Greenstone Belt. This group is composed of conglomerate overlain by quartzites, mica schists and mica gneisses. Its youngest rock unit comprises albitized metasedimentary rocks and mafic to felsic metavolcanites.

Slightly younger than this is the Savukoski group (2200–2050 Ma), which is represented over extensive areas throughout Central Lapland. The lower part of this rock sequence is composed of phyllites, black schists, dolomites, tuffites and metatuffs, overlain by metavolcanites of a basic or ultrabasic composition.

The next unit is the Kittilä group (2050–2000 Ma), composed principally of metavolcanites. This begins with Fe-tholeiitic metavolcanites, which are followed by iron sulphide and iron carbonate schists and banded iron formations. Still younger are the Mg-tholeiitic metavolcanites and the mica schists and greywackes located above them.

The Lainio and Kumpu groups (1930–1850 Ma) are the youngest formations in the area. The lower part of the Lainio group consists of intermediate to felsic lamprophyric metavolcanites, with quartzites, conglomerates and mica schists above them, and the youngest unit in the stratigraphy is the Kumpu group, comprising quartzites, silts and conglomerates.

The gold and copper occurrences in Central Lapland are with only a few exceptions located in the metasedimentary, metavolcanic and metamorphic ultramafic rocks of the Savukoski group or in banded iron formations associated with the metavolcanic rocks of the Kittilä group. Some of the iron oxide-copper-gold occurrences are associated with metasedimentary rocks of the Savukoski group and some with skarn zones associated with lamprophyric metavolcanites of the Lainio group.

2.4 Palaeoproterozoic intrusive rocks

Acidic intrusive rocks of varying age and composition are to be found in Central Lapland. According to Hanski *et al.* (2001), these can be divided into three age groups: acidic plutonic rocks of age 1920–1910 Ma, a synorogenic plutonism of age c. 1880 Ma and granitoids of age c. 1800 Ma. The ages of the most extensive acidic intrusions in the area, such as the Central Lapland granite complex and the Hetta complex in the north, are not known for certain in all respects, on account of the limited amount of geological research carried out there, but Hanski *et al.* (2001) suggest that at least some of these must belong to the 1800 Ma age group. The youngest acidic intrusive rocks in this age group are the post-orogenic Nattanen-type granite intrusions associated with the NE-SW-trending deformation zone, while the synorogenic montzonites occurring mainly in the western part of Central Lapland belong to the middle age group.

Large numbers of mafic intrusions of various kinds and both mafic and acidic dykes are also to be found in the area, most of these being of age 2430–2000 Ma (Hanski *et al.* 2001). The most significant layered intrusions are the Koitelainen, Kevitsa and Akanvaara intrusions in the eastern part, while the dykes are mainly composed of diabases, lamprophyres and both mafic and acidic veins. Diabases and gabbros are encountered mainly on the southern edge of the area. The orientations of the lamprophyres and acidic and mafic dykes coincide with the principal trends of the deformation zones, NW-SE and NE-SW, while the quartz-carbonate veins usually run N-S.

The largest dykes are the Salla diabase dyke swarm in the east, c. 150 km in length, and the Laanila diabase dyke in the north-east, c. 100 km. Both are oriented in accordance with the principal deformation zones, the Salla dyke NW-SE and the Laanila dyke NE-SW.

Serpentinites are encountered on the eastern edge of the Kittilä greenstone area, where they occur in conformable lenses in a zone of length c. 70 km within a belt composed of mafic lavas, tuffites and black and graphite schists (Lehtonen *et al.* 1998). This serpentinite zone runs parallel to the NNW-SSE gravity anomaly that crosses the Fennoscandian Shield. The chemical composition, environment and mode of occurrence of the serpentinites indicate that they are derived from fragments of old ophiolite (Paakkola *et al.* 1981, Hanski 1997). They differ in metal content from the other ultramafic rocks of the Kittilä greenstone area, e.g. in that there is no evidence of the gold occurrences typical of the greenstone area in connection with them, whereas chromite has been encountered in them although it is rare elsewhere in the Kittilä greenstone area.

2.5 The granulite complex

Part of the arc formed by the Northern Lapland granulite complex is visible in the north-eastern corner of the area. The origins and petrology of this complex have been described by a number of authors (e.g. Meriläinen 1976, Huhma & Meriläinen 1991). It is chiefly composed of garnet-plagioclase-quartz gneisses formed by regional metamorphic high temperature and pressure processes in a granulite facies and includes parts that are of a mafic, pyroxene-bearing plutonic character. The granulite has undergone folding and metamorphism as a consequence of a NE-SW overthrust movement, leading to gently sloping arc-shaped shear zones.

2.6 The structural setting

The regional fracture and deformation zones of Central Lapland have been studied by authors such as Mikkola and Niini (1968), Tuominen *et al.* (1973), Mikkola and Vuorela (1977), Aarnisalo (1978), Kuosmanen *et al.* (1978), Tuominen and Aarnisalo (1978), Aarnisalo *et al.* (1982) and Gáal *et al.* (1989), chiefly on the basis of satellite images, air photographs and high-altitude magnetic maps to a scale of 1:400 000. The most recent research into the structural geology of the area has included that of Härkönen and Keinänen (1989), Ward *et al.* (1989), Gáal and Sundblad (1990), Korhonen (1992) and Väisänen (2002). These works have, among other things, demonstrated the significance of fault and shear zones as factors controlling the occurrence of gold in Central Lapland.

Mikkola and Vuorela (1977) and Aarnisalo (1978) had already noted that the oxide and sulphide deposits in Central Lapland were mainly associated with WNW-ESE, NNW-SSE and NE-SW fracture zones, although the only sulphide deposits known in the area at that time were the Pahtavuoma, Riikonkoski and Saattopora copper deposits and the multitemporal occurrence at Sirkka, while the best-known iron oxide deposits were those of Rautu-

vaara, Hannukainen, Porkonen-Pahtavaara and Jauratsi. The first actual gold deposits were not discovered until the 1980s or later.

According to Colvine *et al.* (1988) deformation zones are usually discordant with the surrounding lithology and thus contain different rock types. In addition, the rocks in a deformation zone tend to be highly tectonized, crushed and altered and contain carbonate and water-bearing minerals. The deformation zones themselves are composed of numerous practically parallel shear zones and are characterized by both brittle and plastic deformation structures. Syntectonic and post-tectonic intermediate dyke swarms are to be found in the shear zones, and alluvial and fluvial metasediments are also typical of deformation zones (*op. cit.*).

The structural geology of the deformation zones in Central Lapland conforms well with the above description. The principal such zones, running NW-SE and NE-SW, comprise clearly distinguishable parallel or diverging shear and fracture zones, they cut across the lithology and they contain various rocks that are typical of the Central Lapland Greenstone Belt. Pronounced tectonization and hydrothermal alteration are common, especially in areas where gold occurrences have been identified. They also contain numerous intermediate and acidic dykes or dyke swarms of various types running parallel or almost parallel to the zones themselves, notably diabases, albite diabases, lamprophyres and acidic veins. Saverikko *et al.* (1985) have noted that the ultramafic rocks of the Kummitsoiva explosion crater in the eastern part of the area and the Sattasvaara metakomatiite are similarly connected with a NW-SE-oriented deformation zone. Alluvial and fluvial formations are represented by the quartzites and conglomerates of the Kumpu group occurring in the same deformation zone.

Northern Fennoscandia is crossed by certain relatively straight regional fracture zones (Figs. 3A and 3B) that depart in orientation from the deformation zones described above. These were first pointed out in the 1970s (Tuominen *et al.* 1973, Aarnisalo 1978, Kuosmanen *et al.* 1978). They are clearly visible in satellite images, where they are seen to cross the Fennoscandian Shield for a considerable distance. The most prominent of these (Fig. 3A) is a NNW-SSE lineament extending from Malangen fjord in Northern Norway to Lake Onege in Russia (Tuominen *et al.* 1973), which is also visible as a gravity anomaly (Fig. 4). The various individual greenstone belts of Northern Fennoscandia and Russian Karelia are closely related to this lineament and have longitudinal axes that conform to it in direction. A second gravity anomaly can be detected in the the Kittilä greenstone area, running perpendicular to the NNW-SSE anomaly. The Kittilä greenstone area is located at the intersection of two gravity anomalies and is cross-shaped (Fig. 4). This geometrical form can also be clearly discerned on the map of Bouguer anomalies for the whole of Finland (Elo 1997).

The NNW-SSE gravity anomaly mentioned above is of exactly the same orientation as the Raahe-Ladoga suture that crosses Central Finland, which also has a gravity anomaly associated with it (Kahma 1978).

Gravity anomalies occurring on a shield scale are usually features that extend to the mantle and represent major access channels for magmatic activity (Eisenlohr *et al.* 1989, O'Driscoll 1990).

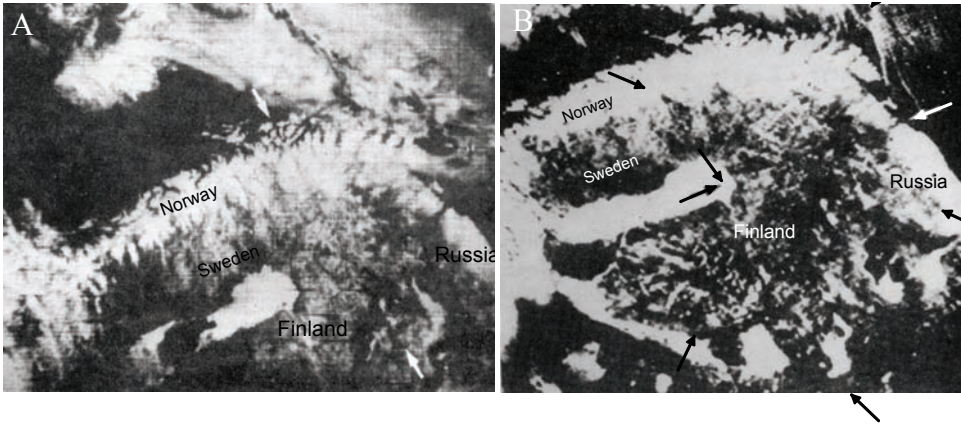


Fig. 3. A. Satellite image showing the lineament (white arrows) extending from Malangen fjord in Norway into Russia (Tuominen *et al.* 1973). B. Satellite image showing other lineaments (arrows) crossing Northern Fennoscandia (Kuosmanen *et al.* 1978).

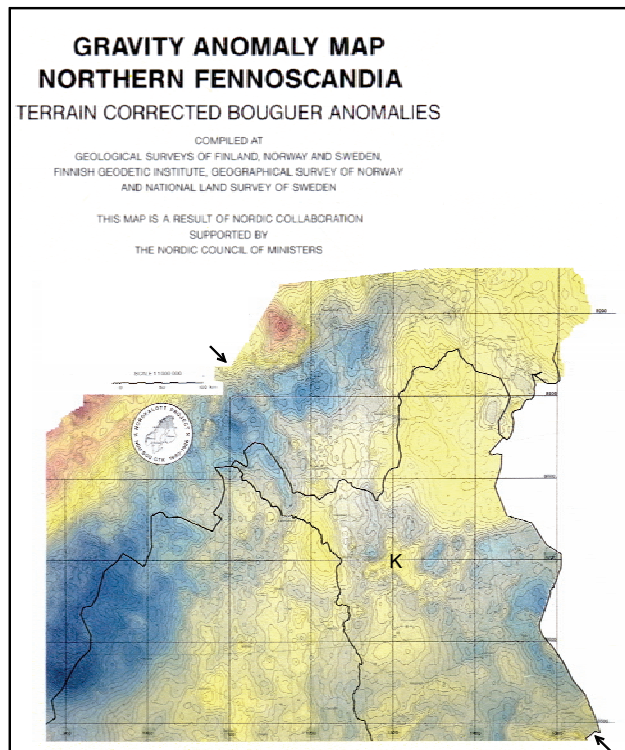


Fig. 4. Gravity anomaly map of Northern Fennoscandia (Bølviken *et al.* 1986). The gravity anomaly stretching from Malangen fjord into Russia is indicated with black arrows (see also Fig. 3A). The Kittilä greenstone area is marked K.

3 Classification of gold deposits

Gold is one of the oldest-known metals in the world, having been used as a form of currency as far back as the fifth millennium B.C. The discovery of large placer gold deposits in North America led to the famous Gold Rush to California in 1848, Colorado in 1858 and the Klondike in 1896, and gold was also found in Australia, Brazil and Russia during the same century. The first find of placer gold in Finland was beside the Teno River in Northern Lapland in 1867 (Stigzelius 1986).

The world production of gold at the present time is around 2000 tonnes per year, of which mines in Finland and imported raw materials accounted for 6.2 tonnes in 2004 according to Söderholm (2005). The majority of the world's gold comes from orogenic gold ores connected with Archaean greenstone belts, from palaeoplacer ore deposits and from deposits in very much younger Mesozoic and Tertiary formations (Woodall 1988). The largest sources of gold in the world are the ore deposits associated with the Witwatersrand quartzites and conglomerates in South Africa and the ores contained in the greenstone belts of Australia, Canada, India and Africa, in addition to which some is to be found as a main product or by-product in sulphide, porphyry copper and iron oxide-copper-gold ores of various types.

The gold deposits of the Fennoscandian Shield are associated with three tectonic-stratigraphic units (Nurmi *et al.* 1991): 1) the Late Archaean greenstone belts of Eastern Finland, 2) the intracontinental Palaeoproterozoic Lapland greenstone belt in the northern part of the shield, and 3) the Palaeoproterozoic, juvenile Svecofennian complex in South-western Finland and Southern Sweden. The gold deposits of Central Lapland belong to the second group in this classification.

The genetic classification of gold deposits has been somewhat confused for decades. Lindgren (1933) divided the hydrothermal deposits, to which gold deposits are regarded as belonging, into three groups on the basis of the depth of the formation in which they are located, epithermal (1–2 km), mesothermal (2–3 km) and hypothermal (3–5 km), and this classification is in principle still in use, although in a somewhat modified form. Phillips *et al.* (1984) divided gold deposits connected with greenstone belts into two general types, a dyke type to be found in metavolcanic and metasedimentary rocks and a stratiform type found in banded iron formations. These two can be distinguished both spatially and temporally, although they exist in close proximity to each other in some areas. The

work "Gold Metallogeny and Exploration" (ed. Foster 1991) recognises seven types of gold deposit:

- Archaean lode gold deposits
- Phanerozoic gold deposits at tectonically active continental margins
- epithermal gold deposits in volcanic terrains
- intrusion-related gold deposits
- Carlin-type gold deposits
- auriferous hydrothermal precipitates on the modern sea floor
- ancient placer gold deposits

Other terms that have also been used to describe gold deposits include lode gold, mesothermal, greenstone-hosted, slate-belt hosted, turbidite-hosted, Mother Lode-type, and gold-only deposits (Groves *et al.* 1998). The complexity and indeterminacy of the situation is in part a consequence of the epigenetic character of the deposits, as the host rock can be almost any volcanic, sedimentary or ultramafic rock that can be found in a greenstone belt.

The classification of Eckstrand *et al.* (1995) distinguishes placer gold deposits, gold contained in massive volcanogenic sulphide deposits, porphyritic copper-gold deposits, skarn gold and iron oxide-copper-gold deposits, while Poulsen and Hannington (1995) divide lode gold into epithermal gold, quartz-carbonate vein gold, iron formation-hosted strata-bound gold and disseminated and replacement gold.

In the opinion of Groves *et al.* (1998), all the above-mentioned types with the exception of ancient placer deposits and gold obtainable from sulphide ores form a consistent genetic group with a single origin, "orogenic gold deposits", as all of them are linked in one way or another with an orogenic compressional or transpressional deformation process. These orogenic gold deposits can then be divided on the basis of their depth of formation into epizonal (< 6 km), mesozonal (6–12 km) and hypozonal (> 12 km) types.

With only a few exceptions, the gold deposits to be described here are of this orogenic kind. Since the term "orogenic gold deposit" carries virtually no useful information from a prospecting point of view, the author prefers, however, to classify the Central Lapland gold deposits into subregions based mostly on geological features such as the host rock, ore mineral paragenesis and resulting metal composition.

4 Gold deposits of Central Lapland

4.1 General

The NW-SE-oriented Palaeoproterozoic Northern Fennoscandian greenstone belt contains several dozen deposits with a significant gold content, the main ones among which, i.e. ones that have led to the opening of a mine, are the Aitik and Pahtohavare copper-gold ores in Northern Sweden, the Bidjovagge gold-copper ore in Northern Norway and the Saattopora gold-copper ore, the Pahtavaara gold ore and the Hannukainen iron oxide-copper-gold ore of Central Lapland in Finland. With the exception of Aitik and Pahtavaara, however, all the mines have subsequently been closed down, either because of exhaustion of the ore or for some other reason. The largest known gold deposit in Finland in terms of both size and gold reserves and resources is that of Suurikuusikko in the middle part of the Kittilä greenstone area in Central Lapland.

The majority of the gold deposits in Central Lapland are associated with the southern and middle parts of the Kittilä greenstone area, being located in or immediately adjacent to subsidiary shear and fault zones within regional deformation zones. They are characterized almost without exception by pronounced hydrothermal alteration in the host and wall rocks.

The gold deposits will be described here as a group characterized mainly by a set of similar geological features and ore mineral parageneses and resulting metal compositions. The iron oxide-copper-gold (FeOx-Cu-Au) deposits will be dealt with later as a separate ore type. Geographically, the gold deposits may be said to be distributed between the following areas (Fig. 5):

Gold deposits hosted by metasedimentary or metavolcanic rocks:

Saattopora-Muusanlammet area	Au-Cu, (Ni, As)
Sirkka-Jerusalemjänkkä area	Au, Cu, Ni, Co, As
Isomaa-Karesselkä area	Au, Cu, (Ni, As)
Pahtavaara area	Au

Gold deposits hosted by banded iron formations:

Suurikuusikko-Rovaselkä area	Au-As
Archaean gold deposits	Au

Palaeoplacer gold deposits	Au
Placer gold deposits	Au

The gold potential of the major banded iron formations of Central Lapland, the Porkonen-Pahtavaara formation in Kittilä and the Jauratsi formation in Pelkosenniemi, will also be considered here, although no actual gold deposits are yet known to exist in them.

The Saattopora-Muusanlammet area, the westernmost gold cluster in Central Lapland (no. 1 in Fig. 5), comprises five copper-bearing gold deposits belonging to a geological zone dominated by metasedimentary rocks. Only the Saattopora gold(+copper) ore deposit has been mined so far. The principal sulphide minerals in the deposits are pyrrhotite and chalcopyrite and the host rock is an albitized metasedimentary rock.

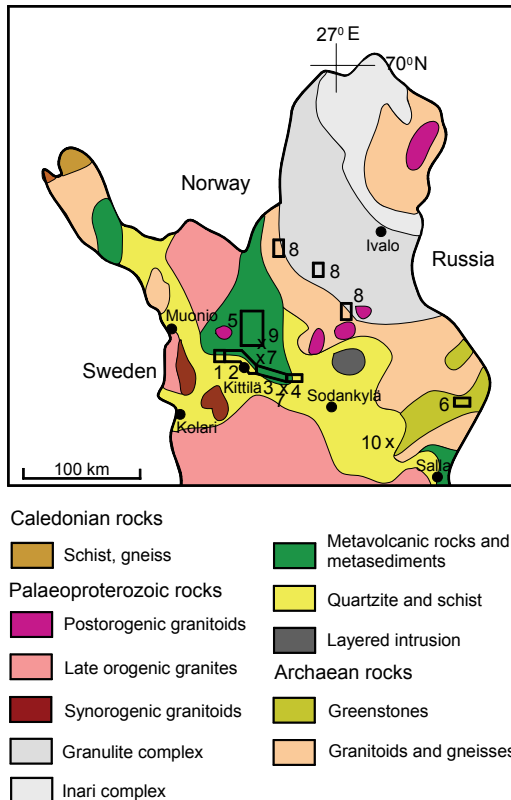


Fig. 5. The bedrock of Lapland, simplified from GTK (2004). Sub-areas with gold deposits added by the author. Sub-areas with gold deposits: 1) Saattopora-Muusanlammet, 2) Sirkka-Jerusaleminjängkä, 3) Isomaa-Kaaresselkä, 4) Pahtavaara, 5) Suurikuusikko-Rovaselkä, 6) Archaean gold deposits, 7) Palaeoplacer gold deposits, and 8) Placer gold deposits. Iron formations: 9) Porkonen-Pahtavaara, and 10) Jauratsi.

The eight gold deposits located in a zone of metasedimentary and ultramafic rocks to the east of the Saattopora-Muusanlammet area form a separate group of their own, in which

the Sirkka deposit has been an object of test mining. With only a few exceptions, these deposits of the Sirkka-Jerusalemjänkkä area (no. 2 in Fig. 5) have, unusually, relatively high nickel, cobalt and arsenic concentrations, and the area possesses large amounts of komatiitic ultramafic rocks, in connection with which most of the deposits are to be found. The main ore mineral in the gold deposits of this area is usually pyrite, or in places gersdorffite.

Further east, in a schist zone lying between the Kittilä greenstone area and the Central Lapland granitoid, is the heterogenic Isomaa-Kaaresselkä cluster (no. 3 in Fig. 5), comprising nine gold deposits, some of which are copper-bearing. Among these, the small Kutuvuoma gold deposit has been mined to some extent. These occurrences are connected with a local east-west deformation zone containing highly albitized metasedimentary rocks, mafic and felsic metavolcanic rocks and mafic intrusions. Their principal sulphide minerals are pyrite and pyrrhotite, with albitized metasedimentary or ultramafic metavolcanic rocks as the host rock, with only a couple of exceptions.

The easternmost gold deposit in the southern part of the Kittilä greenstone area is that of Pahtavaara (no. 4 in Fig. 5), which is still being mined. This is associated with the extensive, continuous Sattasvaara formation composed mainly of komatiitic metavolcanic rocks. The principal ore minerals are magnetite and pyrite, and the host rock is metakomatiite (Korkiakoski 1992). The small Hookana gold occurrence south of Pahtavaara also belongs to the same ultramafic area.

The seven most significant gold deposits in the Suurikuusikko-Rovaselkä area are situated in the middle part of the Kittilä greenstone area (no. 5 in Fig. 5). The area as a whole consists mainly of metavolcanic rocks and quartz-banded iron formations, with granitoid areas to the north. The gold deposits are associated with a sulphide facies in an iron formation, although some gold has also been detected in the rocks of the oxide facies. The principal ore minerals in the deposits are pyrite and arsenopyrite, whereas the nickel and cobalt sulpharsenides that are typical of many of the gold deposits in the southern part of the Kittilä greenstone area are virtually absent here.

Two small gold occurrences connected with iron formations have been found in the eastern part of Central Lapland (no. 6 in Fig. 5), where the host rock is evidently an Archaean iron formation (Inkinen 1988).

Two palaeoplacer gold deposits are known in Central Lapland (no. 7 in Fig. 5), both associated with quartzites and conglomerates of the Kumpu group (Härkönen 1986).

A number of placer gold deposits from which gold has been panned for more than 100 years are known to exist in the contact area between the Archaean gneisses and the granulite complex (no. 8 in Fig. 5).

The Porkonen-Pahtavaara banded iron formation in the Kittilä greenstone area (no. 9 in Fig. 5) and that of Jauratsi in Eastern Lapland (no. 10 in Fig. 5) are described here as areas with a gold potential.

4.2 Gold deposits hosted by a volcano-sedimentary succession

4.2.1 General

Numerically the majority of gold deposits in Central Lapland are located in the Matarakoski formation, belonging to the Savukoski group, which forms the southern edge of the Kittilä greenstone area (Fig. 5). They are mostly connected with albitized metasedimentary and metavolcanic rocks and contain varying amounts of sulphides, principally pyrrhotite, pyrite and chalcopyrite, while some also include sulpharsenides such as arsenopyrite, gersdorffite and cobaltite. Their copper content is of commercial significance as well as the gold, but the other metals present are of little economic value.

4.2.2 The Saattopora-Muusanlammet area

The Saattopora-Muusanlammet area, located east of Lake Äkäsjärvi, 25 km north-west of Kittilä, belongs to the almost east-west-oriented Matarakoski schist formation. This formation is composed of metasedimentary rocks and tuffites (Fig. 6) and also contains albite diabases and ultramafic rocks. To the north of this schist area are Mg-tholeiitic metavolcanites of the Kittilä group, and to the south-west Fe-tholeiitic metavolcanites of the Savukoski group (Lehtonen *et al.* 1998). The quartzites and conglomerates of the Kumpu group to the south-east of the Saattopora-Muusanlammet area are the youngest rock units in the region.

The main gold deposits in the Saattopora-Muusanlammet area are Saattopora I (Au-Cu), the copper-dominated Saattopora II (Cu-Au), Harrilompolo, Aakenusvaara and Muusanlammet (Fig. 6, Table 2). There are also several less thoroughly investigated gold-copper showings connected with albitized phyllite zones west of Saattopora, e.g. a 5 m drill core intersection with Au 2.22 g/t and Cu 0.15 wt%. It should also be noted that the Pahtavuoma copper ore is located only about 10 km west of Saattopora in the same Matarakoski formation. The difference, however, lies in the fact that the Saattopora deposits are associated with the Matarakoski metasedimentary rocks close to the contact with the Kittilä metavolcanic rocks, whereas the Pahtavuoma deposit also lies in the Matarakoski metasedimentary rocks but close to the Savukoski metavolcanic rocks.

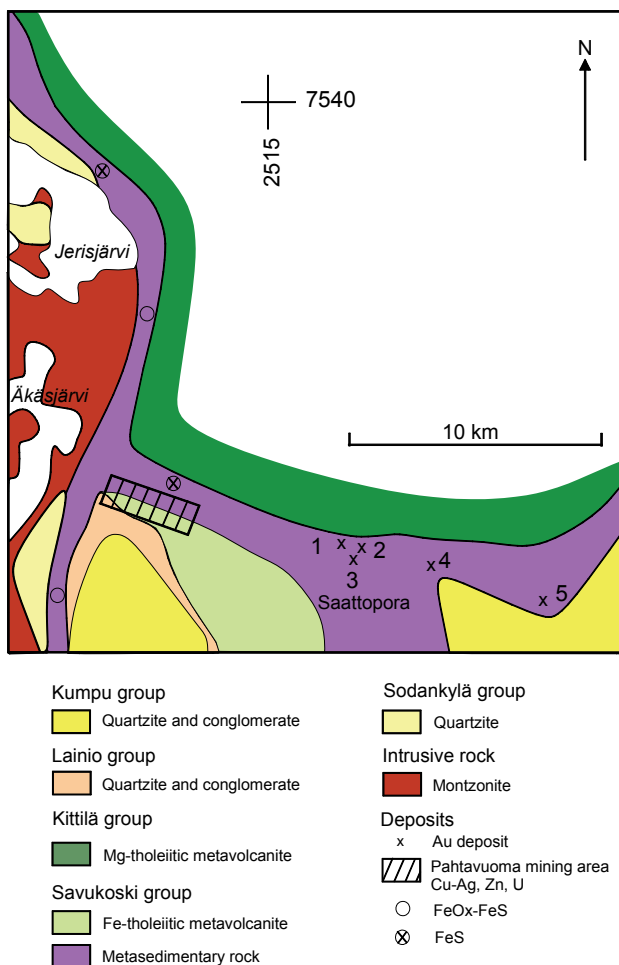


Fig. 6. Geology of the Saattopora-Muusanlammet area, simplified from Lehtonen *et al.* (1998). Data on gold and other deposits added by the author. Gold deposits: 1) Saattopora I (Au-Cu), 2) Saattopora II (Cu-Au), 3) Harrilompolo, 4) Aakenusvaara, 5) Muusanlammet.

Table 2. Gold deposits of the Saattopora-Muusanlammet area.

Deposit	Status	Mt	Diamond drill core m	Au g/t	Cu wt%	References
Saattopora I (Au-Cu) A and B ore bodies	mine (closed)	2.24		3.40	0.31	Korvuo (1995)
Saattopora II (Cu-Au)	deposit	11.6		0.25	0.62	Korkalo (1982)
Harrilompolo	occurrence		5.5	2.70	0.07	Korvuo (1997)
Aakenusvaara	occurrence		18.0	1.12	0.36	Anttonen (1994)
Muusanlammet	occurrence		6.6	2.41	0.48	Reino (1976)

4.2.2.1 Saattopora I (Au-Cu)

The Saattopora I gold-copper ore deposit was discovered by Outokumpu in 1985 as a consequence of its analogy with the Bidjovagge gold-copper ore deposit in Northern Norway (Korkalo 1987). After three years of intensive investigations, the company decided in August 1988 to open a mine for production purposes (Anttonen *et al.* 1989). The feasibility study indicated that it was more economic to transport the ore 55 km by road to the Rautaruukki concentrating plant at Rautuvaara in Kolari than to build a separate concentrating plant at Saattopora (Korkalo *et al.* 1987, Korkalo *et al.* 1988), especially since it was known that Rautaruukki intended to close the Rautuvaara mine in 1988, and that only small modifications to the plant would be necessary for processing the Saattopora I gold-copper ore.

Saattopora I lies in a schist zone belonging to the Matarakoski formation, which is composed of metasedimentary rocks (Fig. 6), and itself contains mainly phyllites, mica schists, albite schists, tuffites and ultramafic rocks. Graphite-bearing interlayers are common in this zone. To the north of the zone are the Mg-tholeiitic metavolcanites of the Kitilä group. Saattopora I is located in a W-E-oriented deformation zone, together with a number of narrow (< 1 m) shear zones running parallel to it. The deformation zone is in turn intersected by NE-SW and N-S-oriented shear and fault zones, so that the whole area is broken up into characteristic lozenge-shaped blocks.

Saattopora I is composed of two ore lenses, A and B, about 200 m apart, which are associated with two parallel albite schist zones (Fig. 7) separated by ultramafic and metasedimentary rocks. Both lenses have as their host rock an albite schist containing varying amounts of accessory quartz and biotite, and also tourmaline in places. At the point of the gold deposit the albite schist is intersected perpendicularly by N-S-oriented carbonate-quartz veins, which are the main gold-bearing units in the deposits. The carbonate in these veins is of an extremely coarse-grained texture, with single grains measuring several centimetres in diameter, and the veins themselves vary in width from a few millimetres to almost a metre. The veins also intersect with a marginal zone of ultramafic rock in the footwall of ore body A, but not with any other rock type. The carbonate has the composition of an iron-rich dolomite (Sotka & Hänninen 1987).

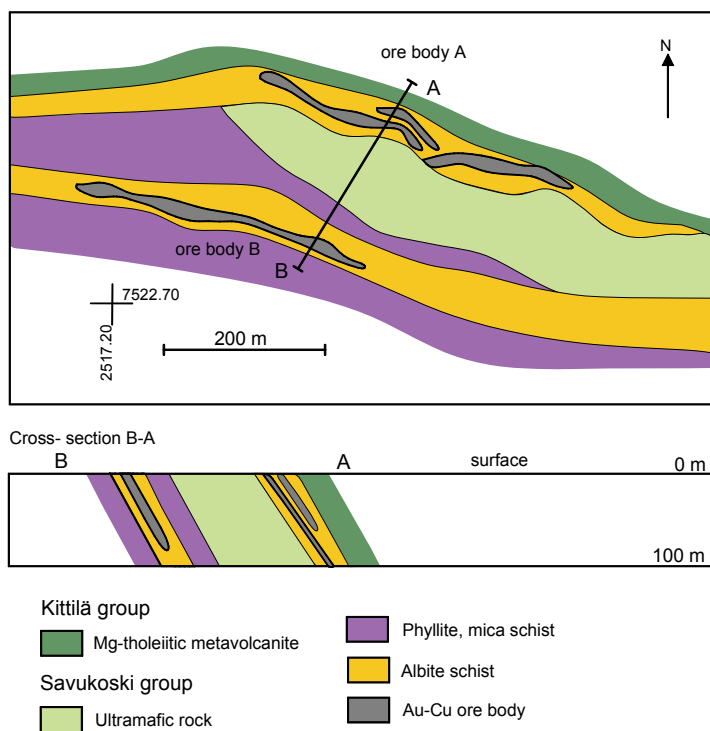


Fig. 7. Geology of the Saattopora I area, simplified from Korkalo (1989, in Anttonen *et al.* 1989).

The hanging wall of ore body A is composed of tuffites with graphite-bearing interlayers and criss-cross calcite veins a few mm thick. Unlike the dolomite veins intersecting the ore, these calcite veins contain neither sulphides nor gold. Towards the north the tuffites grade to mafic metavolcanites. The footwall of ore body A is a talc-chlorite schist, and there is a zone several metres wide at its edge which contains albite and carbonate in addition to talc and chlorite.

The hanging wall of ore body B is chiefly composed of albitized metasedimentary rocks, i.e. albite-biotite and albite-sericite schists with graphite-phyllite interlayers. The footwall consists chiefly of albitized phyllites.

The principal ore minerals in both ore bodies are pyrrhotite and chalcopyrite, with gold, pyrite, gersdorffite, cobaltite, pentlandite, arsenopyrite and tellurides as the main accessory ore minerals.

The boundaries depicted for the ore bodies are mostly based on analyses which showed the albite schist zones with a gold content of over 1.5 g/t to be 400 m in length and to vary between 1 m and 20 m in width. Ore body A continues to a depth of at least 120 m below the bedrock surface, and the albite schist zone broadens with depth, but at the same time its Au content deteriorates ($\text{Au} < 1 \text{ g/t}$), falling below the level of economic feasibility for mining.

Ore body A consists of a low-grade part, with an Au content of 1.5–5 g/t, and a number of narrower high-grade zones located inside this, with Au concentrations of 5–10 g/t. The gold is to be found in a relatively coarse-grained form (grain size up to some 100 μm) together with sulphides in the quartz-carbonate veins and in clusters of grain sizes 20–50 μm in the carbonate-rich albite schist. The sulphides form fine-grained disseminations and patches, and the chalcopyrite in particular can be found in fracture-fill veins less than 1 mm in width that intersect with the direction of schistosity.

The average metal composition of ore body A is Au 3.40 g/t (uncut value 5.65 g/t), Cu 0.37 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.06 wt%, Co 0.02 wt%, Fe 8.89 wt%, As 0.02 wt% and Ag 0.1 g/t. The S content is 3.98 wt% (Sotka & Hänninen 1987). These results are weighted means of 28 core samples of average length 2 m derived from 8 drill holes. The corresponding figures for ore body B are Au 3.10 g/t, Cu 0.80 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.11 wt%, Co 0.02 wt%, Fe 6.91 wt%, As 0.13 wt%, Ag 0.6 g/t and S 8.44 wt% (Sotka 1989), based on means for samples of length 1 m from six drill holes. Thus ore body B has markedly higher Cu, Ni, As and S concentrations than ore body A.

Ore body A at Saattopora I was overlain by a 1–2 m thick till cover resting on 0.5–1.5 m of preglacial weathered crust. Six analyses performed on a sample of 100 kg of weathered bedrock pointed to a mean Au concentration of 5.7 g/t (Anttonen 1988), but the gold was unevenly distributed in the material and varied in concentration according to the gold content of the bedrock itself. Some of the weathered bedrock was taken to the concentrating plant at Rautuvaara for further processing along with the ore proper, but unfortunately the high proportion of fines contained in it caused difficulties in the flotation process.

A conventional estimate of the ore reserves obtainable from ore body A at Saattopora I by open pit mining at the time of deciding to commence mining was 0.68 million tonnes, with an Au content of 3.60 g/t and a Cu content of 0.28 wt% (cut-off Au 1.5 g/t, specific gravity of the ore 2.93 g/cm³). No production plans were drawn up for ore body B at that stage. The total mineral resources estimate for ore body A was 1.18 million tonnes, with an Au content of 4.4 g/t (uncut value). The mining capacity was placed at 0.29 million tonnes per annum, so that the estimated operation time of the mine was 2.5 years. (Korkalo *et al.* 1988.) Further conventional and percussion drilling carried out during mining operations raised the estimated ore reserves to 2.24 million tonnes (Au 3.40 g/t, Cu 0.31 wt%) and extended the life of the mine to 6 years (Korvuo 1995).

Ore body A had been investigated to a depth of 100 m and ore body B to 50 m prior to the decision to commence mining, with 3–5 drill holes per cross-section and intervals of 25 m between the cross-sections. The reliability of the drilling density was tested geostatistically for ore body A, yielding the result that the interval between cross-sections was adequate for estimating the mean gold content (Ekberg 1992). It nevertheless became apparent early in the mining operations that the drilling density had not been sufficient relative to the quantity of ore involved.

The preliminary estimate for the Au content of the whole of ore body A had been 4.4 g/t before cutting, i.e. reduction of all Au grades greater than 20 g/t to exactly 20 g/t, which gave a new mean estimate of 3.6 g/t, virtually the same as the eventual observed mean concentration (Korkalo *et al.* 1988).

Both open pit and underground mining took place at Saattopora I (Fig. 8), and a total of 1.05 million tonnes of ore was extracted from ore body A and 0.19 million tonnes from ore body B by the former method and 0.57 and 0.31 million tonnes, respectively, by the latter (Korvuo 1995). Thus the total quantity of ore mined was 2.12 million tonnes. Given a total of 3.50 million tonnes of waste rock extracted, the ratio of ore to waste rock was 1 / 2.82 in open pit mining.

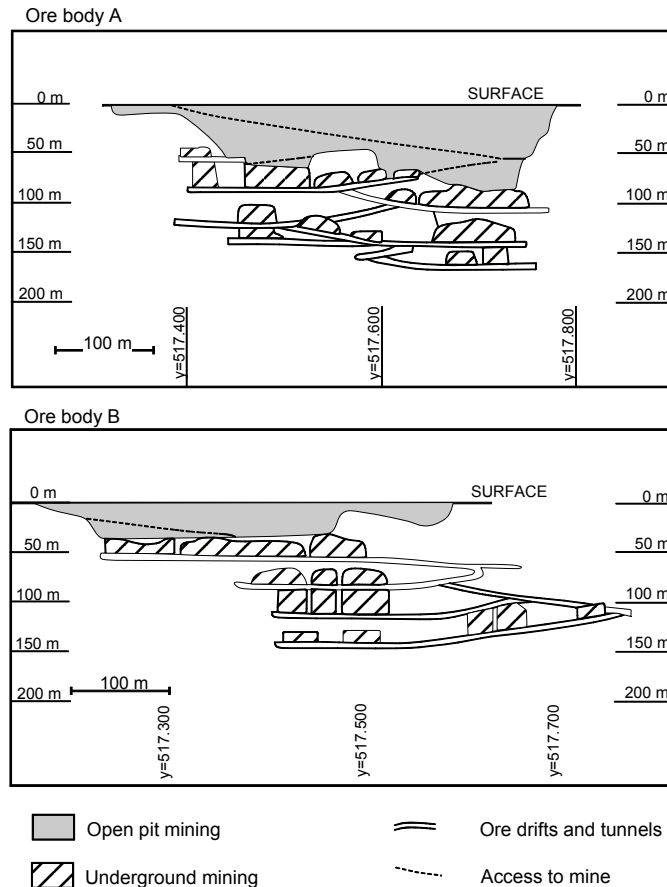


Fig. 8. Mining operations in ore bodies A and B at the Saattopora I (Au-Cu) mine, longitudinal projection. Modified from Korvuo (1995).

The ore extracted from the Saattopora mine was transported a distance of 55 km by road to the concentration plant at Rautuvaara in Kolari for mineral processing, which involved crushing, grinding, gravity separation and flotation. The gravity separation cycle consisted of two Reichert cone separators, eight Reichert spiral separators and a shaking table (Anttonen *et al.* 1989). Gold recovery in the gravity concentrate was 32.1%, corresponding to a total of 2255 kg of gold, the gold grade of the gravity concentrate being 3.18 wt%. The subsequent flotation process then gave a sulphide concentrate with a gold

content of 45.6 g/t and a recovery of 57.2 %. Since the sulphide concentrate contained 4023 kg gold, the total quantity of gold recovered was 6278 kg. The mill recovery for copper in the flotation process was 92.1%, the copper grade of the concentrate 5.86 wt% and the total amount of copper produced 5177 tonnes (Korvuo 1995).

4.2.2.2 Saattopora II (Cu-Au)

Saattopora II, located about 0.5 km east of the Saattopora I gold-copper ore bodies (Fig. 6), was discovered by Outokumpu during investigations close to the Pahtavuoma copper ore deposit in 1972 (Korkalo 1982). Outokumpu had already carried out an extensive stream sediment survey in Western Lapland in 1964–1965, in which a broad copper anomaly had been identified in the Saattopora area, but the follow-up investigations at that time had failed to reveal the deposit.

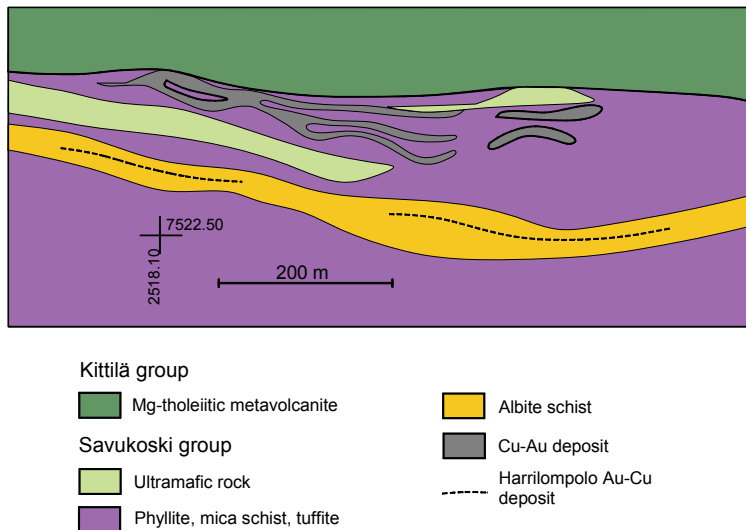


Fig. 9. Geology of the Saattopora II area, simplified from Korkalo (1982).

Saattopora II is associated with an E-W-oriented schist zone of metasedimentary and ultramafic rocks, where the metasedimentary rocks are albitized phyllites, mica schists and tuffites (Fig. 9). The copper-gold deposit is located in this schist zone, close to its contact with Kittilä group Mg-tholeiitic metavolcanites. To the south of this deposit lies the albite schist zone with which the Saattopora I ore body B and the Harrilompolo gold-copper occurrence are associated (Fig. 11).

The hanging wall rocks of Saattopora II are metasedimentary rocks and metavolcanites with graphite-bearing interlayers, and the footwall is composed of albitized metasedimentary rocks, which in their current form are mostly albite-biotite schists. There are also some ultramafic rocks in the footwall and a small talc-chlorite-carbonate lens in the east-

ern part of the hanging wall. The albitization of the metasedimentary rocks is not as intensive as in Saattopora I, but carbonatization is extremely pronounced, as seen from the occurrence of carbonate both in a network of veins and as individual grains in the albitized metasedimentary rocks. The carbonate veins do not have as clear a N-S orientation as at Saattopora I and tend to vary in direction, with NW-SE the most common, although some N-S veins are encountered.

The Saattopora II copper-gold deposit is discontinuous and composed of a number of zones of varying copper and gold content. The host rock is a brecciated, microfolded, both albitized and carbonatized, locally graphite-bearing phyllite or mica schist, and the strike of the deposit is E-W and the dip 50–60° to the north. The deposit is 1200 m long and 1–20 m wide and has been shown by diamond drilling to extend to a depth of at least 230 m below the bedrock surface (Fig. 10).

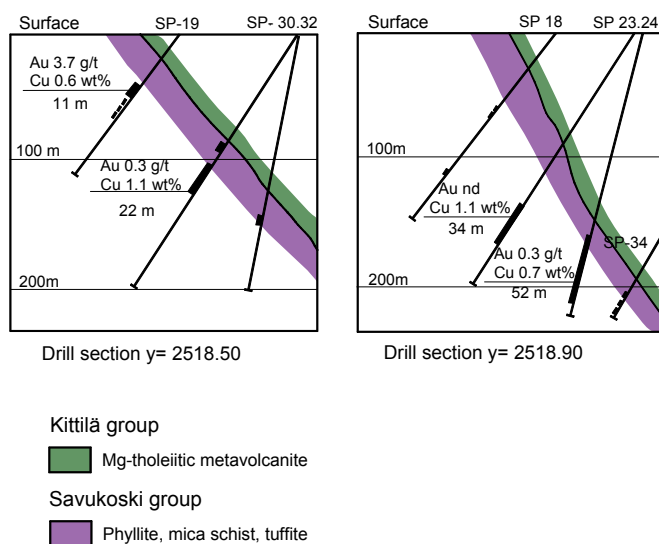


Fig. 10. Saattopora II drill sections, simplified from Korkalo (1982).

The principal ore minerals in the Saattopora II copper-gold deposit are pyrrhotite and chalcopyrite, with accessory gersdorffite, arsenopyrite, pyrite (secondary), pentlandite and gold. Other occasional minerals include uraninite, tucholite, niccolite, cobaltite and bismuthinite. The mean metal composition of the deposit is Cu 0.75 wt%, Au 0.25 g/t, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.10 wt%, Co 0.01 wt%, Fe 10.06 wt%, As 0.04 wt% and Ag 2 g/t. The mean S concentration is 3.43 wt%. These results are means, weighted by the core lengths analysed, of a total of 451 m of cores from 40 drill holes analysed at intervals of about 2 m. Sulphur isotope studies showed the sulphur to be of volcanic origin (Mäkelä & Tammenmaa 1978).

Gold occurs sporadically throughout the zone containing sulphides, but the gold and copper concentrations are not directly correlated. One drill core of length 22 m had a

mean Au content of 0.88 g/t and Cu content of 0.18 wt%, while another core of length 52 m had Au 0.32 g/t and Cu 0.67 wt%. The uneven distribution of gold in the deposit is also reflected in some high concentrations, e.g. 6.30 g/t over a core length of 3 m with a Cu content of 0.19 wt%. The high gold concentrations were frequently found in markedly albited metasedimentary rocks.

The Saattopora II deposit also contains vein-like sulpharsenide clusters, principally in the form of gersdorffite. These are most common in the hanging wall, where the mean metal composition of twenty such veins (cut-off As 0.1 wt%, drill core lengths 0.6–3.0 m) was Cu 0.23 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.78 wt%, Co 0.04 wt%, Fe 8.86 wt%, As 0.44 wt% and Ag 2 g/t and the mean S content 2.07 wt%. One of the best veins in terms of metal content was 1.65 m wide and had Cu 0.14 wt%, Ni 4.27 wt%, Co 0.46 wt% and As 2.22 wt%. Although Au concentrations in these veins were not analysed systematically, the mean for four core samples was 0.70 g/t. Saattopora II resembles some of the gold occurrences in the Sirkka-Jerusalemijänkkä area in term of its metal composition.

The mineral resource estimate for Saattopora II was based on a series of cross-sections mostly comprising 1–3 diamond drill holes at intervals of 50 m (or 100 m in places), the most important sections being composed of 4–5 drill holes. Employing a cut-off of 0.3 wt% Cu and a specific gravity of the ore of 2.93 g/cm³, an estimate of 11.6 million tonnes with a Cu content of 0.62 wt% and Ni 0.09 wt% was obtained (Korkalo 1982). This estimate applied to three inhomogeneous sulphide-bearing zones separated by areas where the Cu content is < 0.3 wt%. Analyses of the most important drill hole cores suggested an Au content 0.25 g/t for the whole deposit.

4.2.2.3 Harrilompolo

The Harrilompolo gold-copper occurrence, located about 100 m south of Saattopora II (Fig. 11), was discovered by Outokumpu as a consequence of a till geochemical survey of the surroundings of Saattopora. As in the case of the Saattopora deposits, the gold-bearing schist zone is associated with metasedimentary rocks of the Matarakoski formation, which have zones rich in graphite and iron sulphides as interlayers. The deposit is located in the same albite schist zone as ore body B at Saattopora I (Fig. 11), and there are similar W-E-oriented shear zones with associated ultramafic lenses.

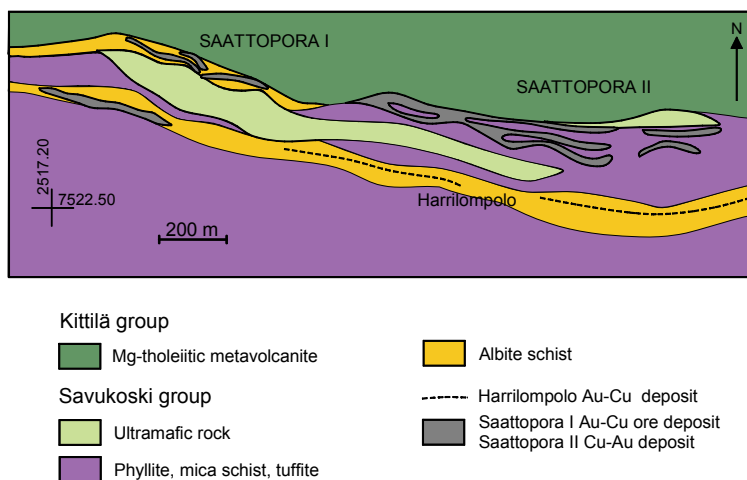


Fig. 11. Geology of the Harrilompolo area, map compiled from Figs. 7 and 9.

The gold-bearing zone at Harrilompolo is discontinuous and somewhat scattered. The Au content is 2–7 g/t in samples of length 1–2 m from the best drill holes, with a Cu concentration of 0.2 wt%, and there is another sample of length 12 m that has an Au content of 0.51 g/t and Cu 0.16 wt% (Korvuo 1997). It was nevertheless not possible to demonstrate any economically exploitable gold occurrence at Harrilompolo at the time when the Saattopora mine was working.

4.2.2.4 Aakenusvaara

The Aakenusvaara gold-copper occurrence, lying east of the Saattopora and Harrilompolo deposits (Fig. 6), was discovered, like Harrilompolo, as a result of the till geochemical survey carried out by Outokumpu and the subsequent diamond drilling. This occurrence, too, is associated with the albitized metasedimentary rocks of the Matarakoski formation, the host rock being a carbonate-bearing albite schist that contains graphite in places. Small ultramafic lenses oriented in parallel to the zone itself are to be found in the metasedimentary rocks north of the occurrence.

Although no less than 42 holes were drilled at the Aakenusvaara site, and in spite of some potential Au concentrations, there is insufficient evidence on which to base any reliable estimate of the mineral resources, on account of the scattered nature of the deposit. One 7.0 m core, for instance, had an Au content of 5.80 g/t and another of length 4.8 m a content of 2.76 g/t. The means for eight drill holes (combined core length 58 m, weighted according to the lengths of sample analysed) were Au 1.32 g/t and Cu 0.45 wt%. The Aakenusvaara occurrence is associated with the same W-E deformation zone as the Saattopora deposits, a zone that is intersected by a N-S-oriented fault at Aakenusvaara.

4.2.2.5 *Muusanlammet*

The copper-dominated gold occurrence at Muusanlammet, about 7 km east of Saattopora (Fig. 6), was discovered by Atri Oy in the 1940s on the basis of a 2.9 m drill core intersection with Cu 1.1 wt%. The site is connected with a sequence of metasedimentary rocks belonging to the Matarakoski formation lying between quartzite of the Kumpu group to the south and metavolcanic rocks of the Kittilä group to the north. The zone is composed of carbonate-bearing phyllites, sericite schists, chlorite schists, greywackes and talc-chlorite lenses.

Outokumpu drilled 7 holes into an electromagnetic zone with a copper anomaly in the till (max. Cu 0.29 wt%) in 1975. These drill holes passed through a sulphide and graphite-bearing phyllite-tuffite zone with brecciated parts containing pyrrhotite and chalcopyrite. The Cu content of the best intersection was 1.0 wt% over a core length of 4.8 m in one core. Gold was not analysed systematically in the drill cores, but some 1.5 m core samples had Au concentrations of 2–7 g/t and Ag concentrations of 5–14 g/t, the latter being higher than those normally found in gold deposits in Central Lapland, which are generally < 2 g/t. Ag concentrations of the same order have also been observed in the Sirkka W, Loukinen and Sirkka gold deposits to be described below.

Like the other gold-copper deposits of the Saattopora-Muusanlammet group described above, the Muusanlammet occurrence is associated with a deformation zone, while another dominant structural feature at this site is a very distinct NE-SW-oriented fault line that crosses the whole of the Central Lapland area.

4.2.3 *The Sirkka-Jerusalemjänkkä area*

The Sirkka-Jerusalemjänkkä area possesses a number of gold deposits containing varying amounts of copper, nickel, cobalt and arsenic as well as gold. These are again connected with the Matarakoski formation located between the metavolcanite of the Kittilä group and the quartzite of the Kumpu group, and in places that of the Sodankylä group (Fig. 12). The area is composed primarily of a phyllite-black schist-dolomite-tuffite association together with ultramafic rocks. The host rock for the gold deposits is usually a komatiitic ultramafic rock, metasedimentary rock or a network of quartz-carbonate veins, the main sulphide mineral being pyrite, and in places also pyrrhotite and gersdorffite. There are a number of chrome-marble occurrences in this area that have been interpreted as altered ultramafic rocks (Lahtinen 1981, Riikonen 1997), which are rare elsewhere in Central Lapland. The eight best-known gold deposits in the area (Fig. 12, Table 3), are those of Sirkka W, Sirkka, Loukinen (Jänkkäjärvi), Lälleänvuoma (Kettukuusikko, Päivänenä), Soretiavuoma N, Hirvilavanmaa, Soretialehto and Jerusalemjänkkä (Palo-vaara).

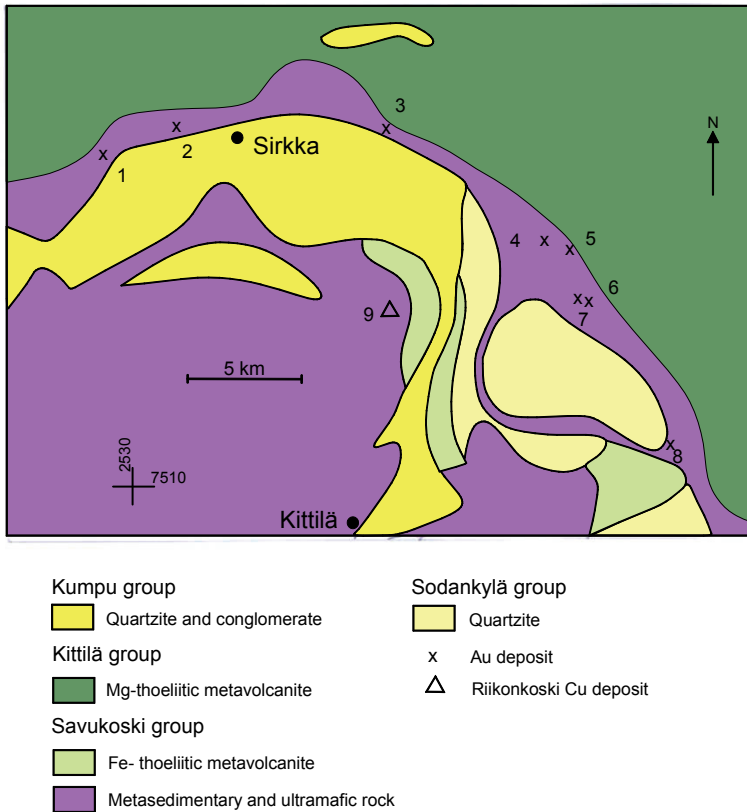


Fig. 12. Geology of the Sirkka-Jerusalemjänkkä area, simplified from Lehtonen *et al.* (1998). Gold deposits: 1) Sirkka W, 2) Sirkka, 3) Loukinen (Jänkkäjärvi), 4) Lälleänvuoma (Kettukuusikko, Päivänenä), 5) Soretiavuoma N, 6) Hirvilavanmaa, 7) Soretialehto and 8) Jerusalemjänkkä (Palovaara). Copper deposit: 9) Riikonkoski.

Table 3. Gold deposits of the Sirkka-Jerusalemjänkkä area.

Deposit	Status	Tonnes	Diamond drill core m	Au g/t	Cu wt %	References
Sirkka W	occurrence		11.6	0.5	0.5	Hugg (1987)
Sirkka	test mine	10 000			0.34	Mikkola & Sandström (1964)
Loukinen						
Levijärvi deposit (Jänkkäjärvi)	deposit	114 000		0.5	0.5	MIT (2002)
Lälleänvuoma (Kettukuusikko, Päiväneva)	deposit		28.7 m/10 drill holes	3.99		Keinänen & Salmirinne (2003)
Soretiavuoma N	occurrence		3.0	5.0		Eilu (1999)
Hirvilavanmaa	deposit	110 000		2.9		ScanMining (2005)
Soretialehto	occurrence		8.0	3–4		Eilu (1999)
Jerusalemjänkkä, (Palovaara)	occurrence		13.0	2.74	0.08	Outokumpu (2004)

4.2.3.1 *Sirkka and Sirkka W*

Investigations into the multimetal (Cu, Au, Ni, Co, As) deposit at Sirkka began with the discovery of an auriferous boulder at the mouth of the River Levijoki, west of the village of Sirkka, in 1939. This one sample led to a sizeable ore prospecting operation in the area that lasted more than ten years and was focused mainly on the Sirkka deposit, leading later to some test mining. The work was begun by Atri Oy in 1939 and continued by Vuoksenniska Oy in 1953. In addition to geophysical surveys, Atri Oy made over 300 diamond drill holes into the schist zone, following the southern edge of the Kittilä greenstone area eastwards for a distance of nearly 40 km from Muusanlammet. Vuoksenniska Oy set up a test mine in 1955 which consisted of a vertical shaft, 650 m ore drifts running mainly along the deposit and a small concentrating plant (Räisänen 2001), but it was decided that profitable mining was out of the question because of the small size and scattered nature of the ore body combined with processing problems. Thus the mine was closed early in 1957. About 3000 tonnes of ore had been extracted and processed within that time (Mikkola & Sandström 1964). Outokumpu acquired the mining rights for the Sirkka deposit in 1966 and made four further diamond drill holes extending below the known deposit, but the results were poor and the site was abandoned.

The Sirkka deposit is associated with the Matarakoski formation, which consists of metatuffs and tuffites together with metasedimentary rocks with graphite-rich interlayers (Fig. 12). The formation also contains talc-chlorite-carbonate rocks. The metasedimentary rocks are overlain unconformably by quartzites, siltstones and conglomerates of the Kumpu group that have been interpreted as a molasse (Mäkelä 1968, Lehtonen *et al.* 1998). At the contact between the metasedimentary rocks and the Kumpu group quartzites both of these rock types are intersected by sulphide and gold-bearing quartz-carbonate veins (Vormisto 1969, Outokumpu 1989).

The Sirkka deposit is located on the edge of an overthrust surface formed by the metasedimentary rocks of the Matarakoski formation and the quartzite of the Kumpu group and intersected by two distinct fault zones, one oriented NE-SW and running through practically the whole of the Central Lapland greenstone belt, passing to the west of the Sirkka deposit, and the other oriented NNW-SSE and also several tens of kilometres in length, passing to the east of the deposit.

The Sirkka deposit comprises two separate quartz-carbonate vein swarms, Kuukeri and Monttu 5 (Trench 5), which are connected with breccia in a shear zone. The deposits can be divided into two main types by reference to their ore mineralogy, one with sulphide minerals dominant and the other sulpharsenides (Vesanto 1978). The former mineral paragenesis contains varying amounts of chalcopyrite, pyrite and pyrrhotite, while the latter has arsenopyrite, gersdorffite and cobaltite. The gold is associated with the sulpharsenides, and silver with the chalcopyrite.

No precise details are available on the size of the Sirkka deposit or its metal content, but Mikkola and Sandström (1964) calculated that there were some 10 000–20 000 tonnes of sulphide-bearing rock contained in one vein down to a depth of 30 m and estimated its composition on the basis of processing samples at Cu 0.34 wt%, Ni 0.52 wt% and Co 0.11 wt%.

Substantial concentrations of certain metals are to be found in individual veins in places. Drill holes passing through the Kuukeri vein have given concentrations of

Au 8.3 g/t and Cu 1.95 wt% over a core length of 0.51 m, Ni 5.17 wt% for 1.97 m and Co 1.82 wt% for 1.31 m, while a drill hole in the Monttu 5 vein gave a Cu content of 3.9 wt% for a sample length of 3.00 m and an Au content of 30 g/t for 1.00 m (Vormisto 1969). Another drill hole in the same deposit gave a high Ag content of 203 g/t over a core length of 1.4 m, a figure which deviates vastly from the level of < 2 g/t usually recorded for gold deposits in the Central Lapland greenstone area.

Although some sites of preglacial weathering have been encountered at the contact between the Matarakoski formation and the Kumpu group in the Sirkka area that extend downwards for several tens of metres, scarcely any signs of tectonization or weakness zones have been seen in the drill holes intersecting this almost vertical contact (Vormisto 1969). The same situation also prevails in the area of the Pahtavuoma copper deposit, where several drill holes have passed through the contact between the quartzite of the Kumpu group (and possibly that of the Lainio group) and the metasedimentary rocks of the Matarakoski formation.

The Sirkka W occurrence, located SW of the test mine, was discovered by Outokumpu in 1988 on the basis of their geochemical investigations and subsequent diamond drilling. It is associated with carbonatized ultramafic rocks in the metasedimentary zone and is again highly discontinuous. Its Au and Cu concentrations are reflected well in a 11.6 m drill core that has been shown to contain Au 0.5 g/t and Cu 0.5 wt%, while the ultramafic rock intersected by another drill hole had a mean Au content of 0.8 g/t over a core length of 40 m. The Kumpu quartzite close to the contact between the Matarakoski formation and the Kumpu group contains iron sulphides and gold-bearing quartz-carbonate veins in the same way as the Sirkka deposit (Hugg 1987, Outokumpu 1989).

4.2.3.2 Loukinen (Jänkkäjärvi)

When Atri Oy extended their Sirkka investigations further east, into the Loukinen and Jänkkäjärvi areas (Fig. 12), the latter known then as "Hossa", they made 44 drill holes altogether and observed a number of high metal concentrations in the Jänkkäjärvi area, albeit over short core intersections, e.g. Au 5 g/t, Cu 0.5 wt%, Ni 0.21 wt%, As 1.16 wt% and Ag 12 g/t over a core length of 1.74 m (Atri Oy, quoted by Lahtinen 1981).

On the strength of the Atri Oy material, Outokumpu began an extensive geochemical survey of its own in the area in 1976, leading to the discovery of a gold and copper-bearing zone of metasedimentary rocks containing ultramafic lenses near the contact between the quartzites of the Kumpu group and the metavolcanites of the Kittilä group.

When GTK began explorations in the area in 1994 following the discovery of a gold-bearing gersdorffite boulder, this work pointed to a multimetal deposit at Loukinen, close to the above Jänkkäjärvi site. The area concerned is composed of komatiitic and tholeiitic metavolcanites and graphite-bearing phyllites, and the host rocks of the gold deposit are metakomatiite and graphitic phyllite. The principal ore mineral is pyrite and the accessory minerals chalcopyrite, gersdorffite, pyrrhotite, pentlandite and gold. The best drill core contains 0.5 g/t Au and 1.25 wt% Cu over a core length of 12 m. The former occurs as native gold and in places as inclusions or in solid solution in pyrite or gersdorffite (Keinänen V 19.8.1998 and 23.12.1998, quoted by Eilu 1999).

As described in the call for tenders issued by MTI (2002), the Loukinen gold-nickel-copper deposit comprises four sites, of which the Levijärvi deposit, for instance, has a preliminary estimate of 114 000 tonnes for its mineral resources, with an Au content of 0.5 g/t and an Ni content of 0.45 wt%.

4.2.3.3 *Lälleänvuoma (Kettukuusikko, Päiväneva) Soretiavuoma N, Hirvilavanmaa and Soretialehto*

This cluster of four gold deposits, comprising, from north to south, Lälleänvuoma, Soretiavuoma N, Soretialehto and Hirvilavanmaa, is associated with a NNW-SSE zone of ultramafic and metasedimentary rocks of the Matarakoski formation belonging to the Savukoski group (Fig. 12). Outokumpu referred to the Lälleänvuoma site as Päivänenä, and GTK used the name Kettukuusikko (Keinänen & Salmirinne 2003). Both of these names thus indicate in part the same deposit as Lälleänvuoma here.

Research in the area goes back to the 1940s, when Atri Oy carried out a programme of geophysical measurements and diamond drilling in the Soretialehto area etc. on the basis of its analogy with deposits of the Sirkka type. The geochemical investigations performed by Outokumpu in the late 1970s pointed to significant copper-nickel-cobalt till anomalies, which then led to the discovery of the first gold deposit, that of Lälleänvuoma mentioned above. The best diamond drilling intersection gave an Au content of 6.6 g/t over a core length of 4.3 m.

Further investigations by GTK in the 1980s led to the identification of the other known gold occurrences in the area, although the extensions of the Lälleänvuoma deposit (Kettukuusikko) were detected only in 2003, upon re-analysis of the geophysical and geochemical data (Keinänen & Salmirinne 2003).

According to Keinänen & Salmirinne (2003) the above gold deposits are located in the Matarakoski formation, composed chiefly of highly altered ultramafic rocks and lying in a NNW-SSE-oriented zone about 1.5 km in breadth between the Mg-tholeiitic metavolcanites of the Kittilä group and quartzites of the Sodankylä group. The ultramafic rocks are metakomatiites, now in the form of talc-chlorite-amphibole and talc-chlorite-carbonate schists and carbonate-quartz-fuchsite rocks. Some albite rocks are also to be found, and locally graphite-bearing phyllites that border on the ultramafic rocks. The host for the deposits is a talc-chlorite rock, and also a graphitic phyllite in places in Soretialehto. The principal ore mineral is pyrite and the accessory minerals are gold, chalcopyrite, magnetite, pyrrhotite, arsenopyrite, gersdorffite, millerite and violarite. The gold in the Lälleänvuoma (Kettukuusikko) deposit occurs in the form of small, free grains as inclusions in the host rock and fracture fillings in pyrite (op. cit.).

The metal concentrations in the deposits are well reflected in those of a 7.3 m drill core from Lälleänvuoma in which the Au content was 4.27 g/t, Cu < 0.01 wt%, Zn 0.02 wt%, Pb 0.01 wt%, Ni 0.11 wt%, Co < 0.01 wt% and Fe 6.31 wt%, with an S content of 1.31 wt%. The Cu content is highest at Soretiavuoma N, 0.19 wt%. Zn and Pb concentrations are < 0.01 wt% in all four deposits, and As, Ni and Co are again highest in Soretiavuoma N, where they are 0.11 wt%, 0.24 wt% and 0.04 wt%, respectively (Nurmi *et al.* 1991,

Outokumpu 2004). A combined sample of total length 52.9 m from 10 drill holes at Ket-tukuusikko had an Au concentration of 2.96 g/t (Keinänen & Salmirinne 2003).

4.2.3.4 Jerusaleminjänkkä (Palovaara)

It was GTK that discovered Jerusaleminjänkkä (Fig. 12), in 1987, in connection with dia-mond drilling for bedrock mapping purposes. The area again belongs to the Matarakoski formation and is composed of metatuffs, metasedimentary rocks, mafic metalavas and ultramafic metavolcanic rocks, with some albite diabases and lamprophyres present. Pro-nounced hydrothermal alteration is typical of the area (Eilu 1994, Lehtonen *et al.* 1998).

The host rock is mainly composed of albitized schists, and the principal ore mineral is pyrite together with occasional haematite. Gold is distributed in a sporadic manner, but there are a number of core samples 1–2 m in length in which it reaches concentrations of 1.1–5.3 g/t (Anttonen 1993).

4.2.4 The Isomaa-Kaaresselkä area

The gold deposits of the Isomaa-Kaaresselkä area are located in an albitized schist zone between the Kittilä greenstone area and the Central Lapland granite area. The better known deposits are nine in number: Isomaa (Ahvenjärvi), Mustajärvi, Lammasvuoma, Pikku Mustavaara, Tuonganoja (Tuongankumpu, Tuongankuusikko), Kutuvuoma, Kie-kerömaa, Rimpelä (Koppelokangas) and Kaaresselkä (Fig. 13, Table 4). Although there are large quantities of ultramafic rocks belonging to the schist zone, the host rock of the deposits is with only a few exceptions either highly albitized phyllite, tuffite or metatuff. There have been few observations of arsenic-bearing minerals in the area other than at Tuonganoja and Rimpelä, where gersdorffite occurs in places.

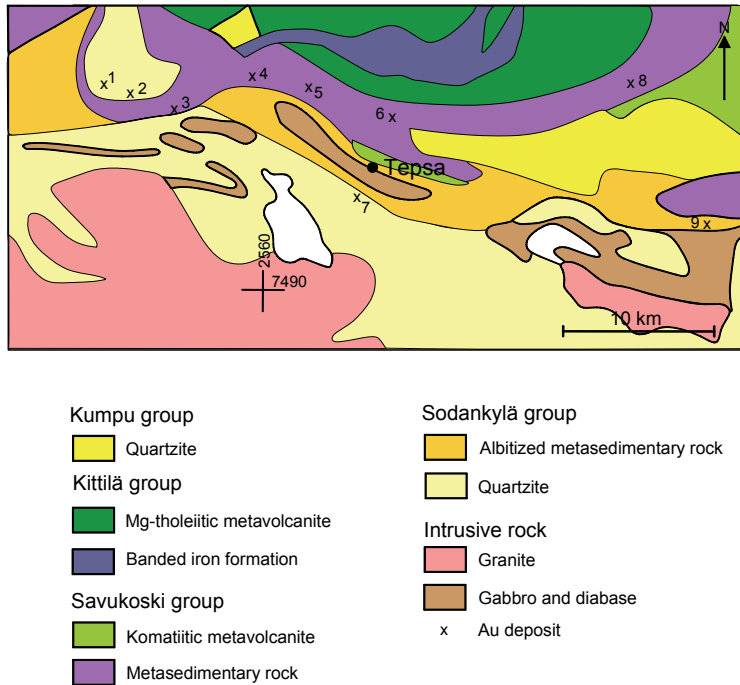


Fig. 13. Geology of the Isomaa-Kaaresselkä area, simplified from Lehtonen *et al.* (1998). Gold deposits: 1) Isomaa (Ahvenjärvi), 2) Mustajärvi, 3) Lammasvuoma, 4) Pikku Mustavaara, 5) Tuonganoja (Tuongankumpu, Tuongankuusikko), 6) Kutuvuoma, 7) Kiekerömaa, 8) Rimpelä (Koppelokangas) and 9) Kaaresselkä.

Table 4. Gold deposits of the Isomaa-Kaaresselkä area.

Deposit	Status	Mt	Diamond drill core m	Au g/t	Cu wt %	Reference
Isomaa (Ahvenjärvi)	prospect		5.00	1.3		Eilu (1999)
Mustajärvi	occurrence		2.70	14.6	<0.01	Outokumpu (2004)
Lammasvuoma	occurrence		15.50	0.80	<0.01	Outokumpu (2004)
Pikku Mustavaara	occurrence		5.0–8.0	2.8	0.55	Keinänen (1990)
Tuonganoja (Tuongankumpu, Tuongankuusikko)	deposit		28.51	0.41	1.36	Outokumpu (2004)
Kutuvuoma	mine (closed)	0.07		7.3	0.1	Anttonen RS (1995)
Kiekerömaa	prospect		5.0	5.8		Outokumpu (1986)
Rimpelä (Koppelokangas)	prospect		sample	2.93		Outokumpu (1990)
Kaaresselkä	occurrence		see text	1–10	0.1–2	Pulkkinen (1999)

4.2.4.1 *Isomaa (Ahvenjärvi)*

The Isomaa prospect, located on the southern edge of a quartzite zone belonging to the Sodankylä group (Fig. 13), was discovered by GTK in 1984 directly from an exposure in connection with bedrock mapping. The host rock is albitized and sericitized quartzite, and chromium-nickel anomalies in the till of the area point to the existence of ultramafic rocks as well. The principal ore mineral is pyrite, with gold, Au-Ag tellurides and molybdenite as accessory minerals. The best intersection achieved by diamond drilling has been a 5 m sample with an Au concentration of 1.3 g/t, although a boulder with an Au concentration of 8.5 g/t has been discovered in the area (Ilvonen 1994, Keinänen V 20.8.1998 and 23.12.1998, quoted by Eilu 1999).

4.2.4.2 *Mustajärvi*

Like Isomaa, the gold occurrence at Mustajärvi, identified by Outokumpu on the basis of geochemical till sampling in 1991, is located on the southern edge of the Sodankylä group quartzite zone, where there is evidence of albitization, quartzization and in places kaolinization (Fig. 13). The host rock is an albite-rich schist and the principal ore mineral is pyrite. The gold is associated with sulphide-bearing quartz-tourmaline-carbonate veins, and there are also gold-bearing lumps of quartz within the kaolin (Hugg 1996).

The best diamond drill core sample was obtained in the iron sulphide zone, where the Au content was 14.6 g/t over a core length of 2.70 m, while a 12 m long drill core sample of weathered rock containing kaolin and lumps of quartz gave an Au concentration of 2.70 g/t, together with Cu, Zn, Pb, Ni and As concentrations of < 0.01 wt%, Co and S concentrations of 0.01 wt% and an Fe concentration of 5.77 wt% (Outokumpu 2004).

4.2.4.3 *Lammasvuoma*

The Lammasvuoma gold occurrence is connected with the Matarakoski formation at a point close to the contact between the Savukoski and Sodankylä groups (Fig. 13). It was discovered by Outokumpu in 1989 on the basis of a gold anomaly zone revealed by a till survey. A number of basal till and weathered bedrock samples gave Au concentrations of 1–5 g/t.

According to Huhtelin (1991), basic and ultrabasic pyroclastic rocks are typical of the area, as also are ultrabasic metalavas, which have been altered to chlorite-talc schists in some places and occasionally contain magnetite. The area also possesses metasedimentary rocks, carbonate rocks, albitites, albite fels and albite diabases. All in all, the rocks of this area are markedly albitized, talcized and chloritized.

The gold occurrence is to be found in the albite fels, close to its contact with the talcized ultramafic rock, the albitized host rocks being found to contain ankerite and calcite veins. Pyrite is virtually the only ore mineral in this case (Huhtelin 1991). The occur-

rence has a dip of only 20–30°, causing it to stand out from all the others in Central Lapland, which are practically vertical in orientation.

Apart from just a few more continuous enrichments, the gold is widely scattered in the occurrence. A number of diamond drillings have yielded cores with Au concentrations of 0.85–2.88 g/t over lengths of 11–15 m. The metal concentrations of the occurrence as a whole are well represented by the analysis of one 15 m core sample: Au 0.85 g/t, Cu, Zn, Pb < 0.01 wt%, Ni 0.02 wt%, Co 0.01 wt%, Fe 6.14 wt%, As < 0.01 wt%, Ag < 0.01 wt% with S 1.13 wt% (Outokumpu 2004).

4.2.4.4 *Pikku Mustavaara*

The Pikku Mustavaara gold occurrence, at the contact between volcanic schists of the Savukoski group and sedimentary graphite schists (Fig. 13), was discovered by GTK in 1980 directly from an outcrop in connection with bedrock mapping (Keinänen 1990). The host rocks are carbonate and quartz-carbonate veins causing brecciation in albite and black schists, and the ore minerals are pyrrhotite, pyrite and chalcopyrite, with arsenopyrite, gersdorffite and gold as accessory minerals. The copper concentration of the occurrence is conspicuous, as witnessed by an 8 m diamond drill core that has Cu 0.55 wt%. An Au concentration of 2.8 g/t is recorded for one 5 m length of drill core (op. cit.).

4.2.4.5 *Tuonganoja (Tuongankumpu, Tuongankuusikko)*

The Tuonganoja area possesses three gold deposits, known as Tuonganoja, Tuongankumpu and Tuongankuusikko, located about a kilometre apart. The whole area will be referred to here simply as Tuonganoja.

The first reports of a copper (gold) deposit at Tuonganoja (Fig. 13) date from 1968, when Rautaruukki obtained a drill core with a 2.5 m zone having a Cu concentration of 1.3 wt% and an 18 m drill intersection having a mean concentration of 0.45 wt% (Rautaruukki 1969). Outokumpu carried out investigations in the same area in 1968–1969 and identified a low-grade gold-copper-nickel deposit there. The company then returned to the site in 1990 and discovered a new, more significant gold-copper deposit.

The gold-copper and gold-copper-nickel deposits mentioned above are associated with the contact between the Matarakoski formation and the albitized metasedimentary and metavolcanic rocks of the Sodankylä group, which are somewhat older than the latter. The rocks of the Matarakoski formation are chiefly albitized or quartzized phyllites containing graphite-bearing interlayers, in addition to which albite schists and ultramafic rocks are also to be found. The deposits contain varying amounts of sulphides, of which the most significant are pyrrhotite and chalcopyrite, and also gersdorffite in places. The host rock is either graphitic phyllite or albite schist.

The metal composition of the gold-copper deposit is perhaps best reflected in a 28 m drill core which gave mean concentrations (weighted by sample length) of Au 0.41 g/t, Cu 1.36 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.14 wt%, Co 0.04 wt%, Fe 8.88 wt%,

As 0.17 wt% and Ag < 0.01 wt%, with S 7.67 wt%. The corresponding results for a 2.7 m length of drill core passing through the gold-copper-nickel deposit were Au 1.33 g/t, Cu 2.66 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 1.07 wt%, Co 0.08 wt%, Fe 3.47 wt%, As 1.40 wt% and Ag < 0.01 g/t, with S 3.47 wt% (Outokumpu 2004). Both ore types are copper-dominated and resemble the gold-copper deposits of Saattopora and some of the gold-copper-nickel deposits of the Sirkka-Loukinen area.

4.2.4.6 *Kutuvuoma*

The Kutuvuoma gold ore deposit, situated in the south-eastern corner of the Kittilä greenstone area, about 30 km west of the Pahtavaara mine in Sodankylä, was discovered by Outokumpu in 1993 on the basis of a geochemical gold anomaly and subsequent drilling operations. Terra Mining Oy extracted some 9000 tonnes of ore with an Au concentration of 5 g/t from the site in 1999, of which 6000 tonnes was processed at the Pahtavaara concentration plant (Puustinen 2003).

Kutuvuoma is associated with the albitized metasedimentary rocks with graphite-bearing interlayers of the Matarakoski formation (Fig. 13), the host rock being a brecciated brownish albite schist and the country rocks black schists and mafic to ultramafic, typically carbonatized, albitized and quartzized metavolcanic rocks. The ore deposit itself, which is bounded at both ends by N-S-oriented fault zones, consists of two E-W-oriented lenses that are in a practically vertical position and lie about 150 m apart. The principal ore minerals are pyrrhotite and in places pyrite, with accessory chalcopyrite and gold (Anttonen RS 1994, 1995).

Bulk samples have shown the metal composition of the deposit to be Au 3.63 g/t, Cu 0.13 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.09 wt%, Co 0.01 wt%, Fe 28.8 wt%, As < 0.01 wt% and Ag < 3 g/t, with S 10.10 wt%. The best gold concentrations were found in sulphide-bearing zones. Although the mean copper concentration over the whole deposit was only 0.1 wt%, significant concentrations were recorded in individual drill holes, e.g. a sample of length 7 m with Cu 0.87 wt% (Outokumpu 2004).

The conventional estimate for the mineral resources contained in the Kutuvuoma ore deposit, employing a cut-off value of Au 1.0 g/t and a cutting point of 20 g/t Au, is 68 000 tonnes, with a mean Au concentration of 7.3 g/t and Cu concentration of 0.1 wt%. The Au concentration without cutting was 9.5 g/t. The estimate was based on 47 drill holes arranged in cross-sections at intervals of 20 m and comprising 4–5 drill holes each (Anttonen RS 1995).

There are no bedrock exposures in the Kutuvuoma area, the weathered bedrock crust (mainly clastic weathering) being overlain by an average of 2.5 m of cover till. Investigations into the gold content of the weathered material showed a 5 litre sample of till and clastic material to contain some 2000 microscopic Au nuggets. A small number of these represented coarse grains, the largest being 600 µm in size. The Au content of the fine fractions of the heavy mineral samples was in the range 6–93 g/t. There is one N-S-oriented weathered fault zone in the eastern part of the area that gives high Au concentrations, e.g. 9.1 g/t over a 14 m core length (Anttonen RS 1995).

4.2.4.7 *Kiekerömaa*

The Kiekerömaa gold prospect, in a quartzite zone belonging to the Sodankylä group (Fig. 13), was located by Outokumpu in 1996 as a result of diamond drilling following the observation of till anomalies. The highly weathered bedrock is composed of albitized and carbonatized quartzite and magnetite-bearing diabase dykes. The prospect has been intersected for distances of 1–5 m by a number of drill holes, giving Au concentrations of 1.0–8.9 g/t (Outokumpu 1986).

4.2.4.8 *Rimpelä (Koppelokangas)*

Outokumpu investigated the Rimpelä area in the 1970s on account of the discovery of chalcopyrite in an albite-carbonate bedrock exposure, but drillings revealed only sporadic occurrences of this chalcopyrite. The Rimpelä prospect is associated with highly albitized metasedimentary rocks of the Matarakoski formation which are nowadays in the form of albite-carbonate rocks (Fig. 13). Other alteration processes noted are sericitization and quartzization. With the increased interest in gold prospecting in the 1980s, the old drill cores were re-examined and found to contain Au-bearing sequences, whereupon further drill cores were obtained, but the results failed to come up to expectations.

4.2.4.9 *Kaasselkä*

The Kaasselkä occurrence was discovered by GTK in 1987 on the basis of an observation made in a bedrock exposure (Pulkkinen 1999). The site is located at the contact between a gabbro-diabase intrusion and albitized metasediments and metatuffs of the Sodankylä group (Fig. 13). According to Pulkkinen (op. cit.) the gold has become enriched in shear zones at the rock type contacts in the brecciated sulphide-carbonate zone, with chalcopyrite and pyrite-bearing quartz veins. Gold is to be found together with carbonate in connection with pyrite, arsenopyrite and chalcopyrite. There are several separate occurrences in the Kaasselkä area, two of which have a combined volume of around 160 000 m³ (op. cit.). Since these are partly composed of weathered gold-bearing rock, it is difficult to estimate their weight in tonnes, but their Au concentrations vary in the range 1–10 g/t and Cu 0.1–2 wt%.

4.2.5 *The Pahtavaara area*

The Pahtavaara area is located in the south-eastern part of the Kittilä greenstone area, north of Sattasvaara and about 25 km north-west of the village of Sodankylä (Fig. 5). The Pahtavaara gold ore was discovered by GTK in 1985 during till investigations, when visi-

ble gold was found in a metakomatiite exposure (Karvinen 1990). A detailed, annotated description of the gold ore and its geology has been produced by Korhikoski (1992). Also belonging to the Pahtavaara area is the small Hookana gold prospect to the south of Sattasvaara.

4.2.5.1 Pahtavaara

The Pahtavaara gold ore belongs to the komatiitic metavolcanites of the Sattasvaara formation in the Savukoski group (Fig. 14). The Sattasvaara metakomatiite occupies an area about 40 km in length and 15 km in width and is composed chiefly of ultramafic to mafic metalavas and metavolcanic rocks. The ultramafic metavolcanites are chemically komatiitic amphibolite-chlorite rocks that are usually abundant in magnetite and breccia structures (Korhikoski 1992).

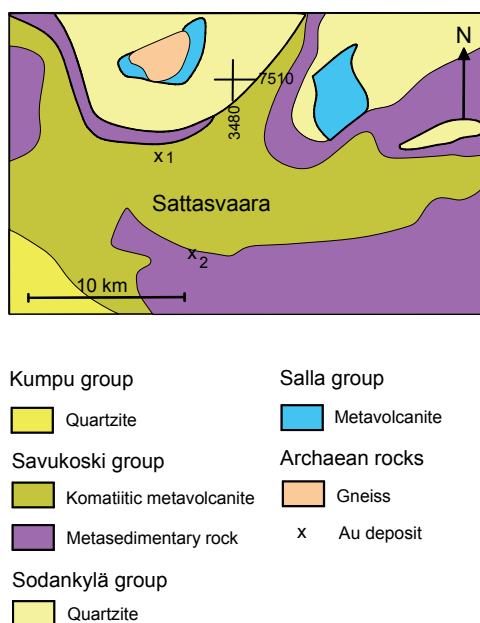


Fig. 14. Geology of the Pahtavaara area, simplified from Lehtonen *et al.* (1998). Gold deposits: 1) Pahtavaara, 2) Hookana

The Sattasvaara metavolcanite formation bears signs of a volcanic crater located in the same NW-SE-trending fault system as the Kummitsoiva volcano close to the Russian border (Saverikko *et al.* 1985).

According to Korhikoski (1992) the host rock of the Pahtavaara gold ore is a variously altered pyroclastic metakomatiite from which two alteration products have emerged: a biotite schist containing talc, carbonate and in places pyrite veins, and a

coarse-grained massive amphibolite with quartz and baryte veins. The principal ore minerals are magnetite and pyrite and the main accessory ore minerals chalcopyrite and gold.

The Pahtavaara ore gave the following metal analysis results: Au 8.40 g/t (higher than the mean for the whole deposit), Cu < 0.01 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.09 wt%, Co 0.05 wt%, Fe 14.13 wt%, As < 0.01 wt% and Ag 0.10 g/t, with S 3.18 wt% (Nurmi *et al.* 1991). Of the other metals present, mention should be made of barium, with a mean concentration of 1.29 wt%, quite a different order from the mean figure of only 0.03 wt% for the other gold deposits in Central Lapland. No substances are present that would be detrimental to processing of the ore, e.g. the Te concentration is only 0.01 g/t and As < 0.01 wt% (op. cit.).

Production began at the Pahtavaara mine in 1996 and came to an end in 2000, but the mine was re-opened late in 2003. Prior to re-opening a total of 1.7 million tonnes of ore had been extracted by open pit mining, together with 6.8 million tonnes of country rock with a ratio of ore to waste rock of 1/4. The head grade of the gold for the concentrating plant was 2.14 g/t, with concentration taking place by both gravity separation and flotation. The only metal of economic interest was gold, of which 3814 kg was produced over the period 1996–2000 (Puustinen 2003).

The estimated proven and probable ore reserves of the Pahtavaara mine before extraction began amounted to 1.8 million tonnes, with an Au content of 3.06 g/t (William Resources Inc. 1997).

4.2.5.2 *Hookana*

The Hookana prospect south of Pahtavaara was discovered by GTK in 1986 following the observation of a gold-bearing boulder in the course of geochemical investigations (Pulkkinen E 21.8.1998, quoted by Eilu 1999). The prospect is connected with a zone of metatuffs and metasedimentary rocks belonging to the Matarakoski formation lying south of the Sattasvaara metakomatiite complex (Fig. 14). The host rock is an albitized diabase, and the principal ore minerals are pyrite and chalcopyrite, with accessory pyrrhotite and gold (Pulkkinen *et al.* 1986).

4.3 Gold deposits hosted by banded iron formation

4.3.1 *General*

The term iron formation has been used for stratigraphic units of banded, bedded or laminated rocks of all ages that contain 15% or more iron, in which the iron minerals are commonly interbanded with quartz, chert and/or carbonate (Gross 1995). Iron formations may be divided into SiO₂ and Al₂O₃-dominated types, of which the former typically occur in greenstone belts and the latter in areas of metasedimentary rocks. Depending on the

physico-chemical conditions under which they emerged, iron formations may be composed of four facies: oxide, carbonate, silicate and sulphide.

The iron formations of the Kittilä greenstone area, including those of the Jauratsi area in Eastern Lapland, are of the SiO_2 type, while the others in Central Lapland are of the Al_2O_3 type. The gold deposits of the central and northern parts of the Kittilä greenstone area are associated with banded iron formations of the SiO_2 type.

Considerable gold deposits have been found worldwide in connection with iron formations, the largest, e.g. Morro Velho in Brazil and Homestake in the USA, being of the order of 100 million tonnes in size and having an initial gold content of around 1000 tonnes. The most famous ore deposit in Canada, the Lupin deposit, has ore reserves of some 10 million tonnes, with an Au concentration of 10.75 g/t. Gold deposits connected with iron formations generally have a high Au concentration (Kerswill 1995).

Gold deposits hosted by iron formations are classified as either syngenetic, in which the gold was deposited in the same sedimentation process as the quartz, epigenetic, in which it was derived from a hydrothermal solution, or hybrid. Most gold deposits of this kind are located in rocks of the sulphide facies (Fripp 1976, Phillips *et al.* 1984, Kerswill 1993, 1995, Gross 1995).

At least 100 iron formations are known to exist in the Central Lapland Greenstone Belt, most of which possess oxide and sulphide facies and some also carbonate and silicate facies (Paakkola 1971, Lehto & Niiniskorpi 1977, Hugg 1979). The majority of these formations are located in the Kittilä greenstone area or in Eastern Lapland, and practically all of them feature the chert layers typical of quartz-banded iron formations. The main gold deposits connected with these iron formations are to be found in the middle part of the Kittilä greenstone area (no. 5 in Fig. 5). Although no gold deposits have yet been discovered in the largest of the iron formations in Central Lapland, the Porkonen-Pahtavaara formation in the SE part of the Kittilä greenstone area and that of Jauratsi in the eastern part of the Central Lapland Greenstone Belt, they will be described here as being potential sites for gold deposits.

On the other hand, the magnetite(\pm copper-gold) deposits in the Rautuvaara and Ylläs formations will not be included amongst the true iron formation deposits here, but will be treated as representing a separate FeOx-Cu-Au ore type. Similarly the gold deposits described above are not in the author's opinion associated with true banded iron formations but rather with sulphide-bearing schists or ultramafic rocks.

4.3.2 Suurikuusikko-Rovaselkä area

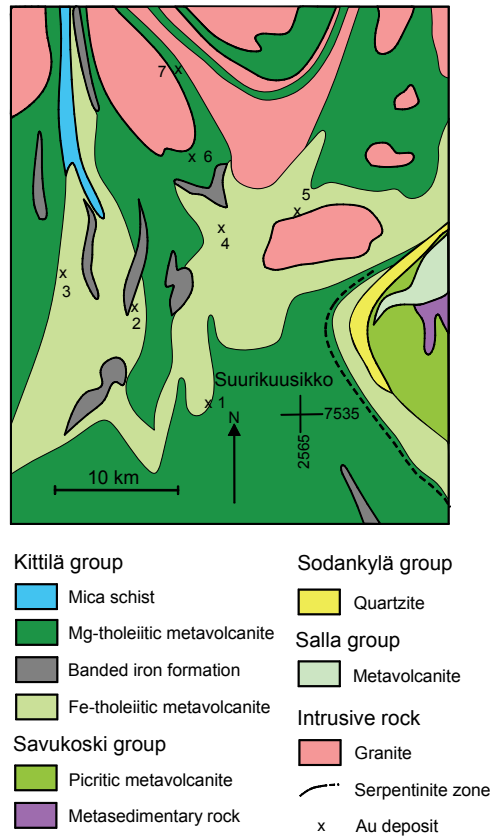


Fig. 15. Geology of the Suurikuusikko-Rovaselkä area, simplified from Lehtonen *et al.* (1998). Gold deposits: 1) Suurikuusikko, 2) Kapsajoki, 3) Hanhima, 4) Kuotko (Iso-Kuotko), 5) Ruoppapalo, 6) Sukseton, and 7) Rovaselkä.

The gold deposits hosted by banded iron formations in the middle part of the Kittilä greenstone area are: Suurikuusikko, Kapsajoki, Hanhima, Kuotko (Iso-Kuotko), Ruoppapalo, Sukseton and Rovaselkä (Fig. 15, Table 5). These typically have low copper (except Sukseton), nickel and cobalt concentrations but usually a high arsenic concentration.

Table 5. The gold deposits in the Suurikuusikko-Rovaselkä area.

Deposit	Status	Mt	Diamond drill core m	Au g/t	Cu wt %	As wt %	References
Suurikuusikko	deposit	17.7 (1)		5.3	< 0.01 (2)	0.49 (2)	Riddarhyttan Resources AB (2005)
Kapsajoki	occurrence		2.25	0.62	0.13	0.62	Outokumpu (2004)
Hanhimaa	deposit		10.6	4.86			Dragon Mining NL (2003)
Kuotko (Iso-Kuotko)	deposit		(3)	7.9	0.07	2.72	Härkönen <i>et al.</i> (2001)
Ruoppapalo	prospect		4.0 (4)	2.7			Eilu (1999) (5)
Sukseton	occurrence		6.48	0.35	0.61	0.18	Outokumpu 2004
Rovaselkä	prospect		1.30	0.35	0.05	0.11	Nurmi <i>et al.</i> (1991)

1) Ore resources: 17.7 million tonnes (indicated + inferred), (2) Nurmi *et al.* (1991) a drill core 8 m, (3) Laboratory test sample 300 kg, (4) Channel sampling on an outcrop, (5) Härkönen 1 24.08. 1998 and 17.09. 1998, quoted by Eilu 1999.

4.3.2.1 Suurikuusikko

The Suurikuusikko gold deposit, located near the centre of the Kittilä greenstone area (Fig. 15), was discovered by GTK in 1986 in connection with investigations into the gold ore potential of Central Lapland, when visible evidence of gold was observed in the adjacent bedrock (Härkönen 1992). The deposit is associated with a sulphide-rich schist zone in an iron formation situated between two Kittilä group metavolcanites of different composition (Härkönen & Keinänen 1989), the younger being of the Mg-tholeiitic type and the older of the Fe-tholeiitic type (Lehtonen *et al.* 1998).

The host rock to the Suurikuusikko gold deposit is a basic metatuff or metalava with interlayers of graphite schists, cherts and iron formation sulphide facies. The principal ore minerals are arsenopyrite and pyrite, with accessory pyrrhotite and gold and sporadic chalcopyrite. The Suurikuusikko deposit is a refractory ore in which gold is mostly lying within the arsenopyrite or pyrite (Härkönen 1992, MTI 1997).

The metal composition of the Suurikuusikko deposit, as indicated by a 9 m diamond drill core, is Au 6.2 g/t, Cu < 0.01 wt%, Zn 0.01 wt%, Pb < 0.01 wt%, Ni 0.02 wt%, Co < 0.01 wt%, Fe 6.90 wt%, As 0.49 wt% and Ag 1.4 g/t, with an S concentration of 3.0 wt% (Nurmi *et al.* 1991). The total ore resources (indicated and inferred) are 17.7 million tonnes, with an Au concentration of 5.3 g/t (Riddarhyttan Resources AB 2005).

The gold deposit is connected with a NE-SW-oriented deformation zone intersected by a N-S shear zone that controls the location of the deposit (Härkönen & Keinänen 1989). The Lälleänvuoma (Kettukuusikko), Soretiavuoma N, Hirvilavanmaa and Soretialehto gold deposits lie at the southern end of the same zone.

4.3.2.2 *Kapsajoki*

The Kapsajoki gold occurrence, about 10 km NW of the Suurikuusikko deposit (Fig. 15), was discovered by Outokumpu during regional mapping in 1980. It is located at the southern end of a 10 km N-S-oriented iron formation.

According to Eeronheimo (1981) the geology of the Kapsajoki area consists of basic and intermediate volcanic and sedimentary zones intersected by quartz-feldspar porphyries. The volcanites are basic metalavas, metatuffs and tuffites in composition, with associated narrow chert, graphite schist and pyrrhotite-rich interlayers. Pronounced albitization and epidotization is typical of the area.

The metavolcanites of the area contain pyrrhotite and in places also chalcopyrite (Cu 0.1–0.2 wt%), and gold (0.16–0.67 g/t) has been encountered in the cherts of the interlayers. The highest Au concentrations (1 g/t) have been recorded in pyrite veins within the chert. The deposit also has arsenic-bearing lenses (As approx. 1 wt%) in which there are Au concentrations > 1 g/t. Anomalous Zn concentrations of 0.1–0.35 wt% are to be found in the massive pyrrhotite layers. The most pronounced fault and shear zones in the area run NE-SW and NW-SE.

4.3.2.3 *Hanhimaa*

Discovered by Outokumpu in 2003, Hanhimaa is the most recent addition to the list of Central Lapland gold deposits. It lies at the contact between Mg and Fe-tholeiitic metavolcanic rocks of the Kittilä group, i.e. at a corresponding contact to the Suurikuusikko deposit (Fig. 15). The mean Au concentration for the 7 drill core samples of length 1.00–10.60 m from separate drill holes intersecting this deposit is 4.29 g/t, with the best core, that of length 10.60 m giving a concentration of 4.86 g/t (Dragon Mining NL 2003).

4.3.2.4 *Kuotko (Iso-Kuotko)*

The Kuotko deposit, situated in a NE-SW-oriented deformation zone (Fig. 15), was discovered by GTK in 1986 on the basis of a gold anomaly observed in the course of regional till investigations (Härkönen 1994). The local bedrock is composed of basic metatuffs, tuffites and pyroclastic rocks such as agglomerates and volcanic breccias. The local shear zone contains abundant acidic porphyries, granophyres, ankerite veins and lamprophyres.

The Kuotko gold deposit lies in a sulphide-bearing quartz-carbonate vein system associated with tholeiitic metavolcanic rocks, and its ore minerals are pyrrhotite, pyrite and arsenopyrite. Mineralogical investigations have shown that 80% of the gold is in free milling form, the rest mainly lying within arsenopyrite and pyrite in refractory ore (GTK 2001). The Kuotko deposit in fact comprises a number of ore bodies, one of which

amounts to 170 000 tonnes with an Au concentration of 4.3 g/t and another to 121 000 tonnes at 2.7 g/t (op. cit.).

The mean metal concentrations in the deposit, based on a 10 m drill core, are Au 1.4 g/t, Cu 0.02 wt%, Zn 0.01 wt%, Pb < 0.01 wt%, Ni < 0.01 wt%, Co < 0.01 wt%, Fe 12.1 wt%, As 1.10 wt% and Ag 0.7 g/t. The S concentration is 2.48 wt% (Nurmi *et al.* 1991).

4.3.2.5 Ruoppapalo

This prospect identified by GTK in 1986 on the basis of geochemical investigations lies at the contact between a granite and a mafic metavolcanite (Fig. 15). The host rock is obviously an albitite intersected by quartz-carbonate veins. The ore minerals are pyrite and to a lesser extent arsenopyrite, and the gold is in free milling form. The gold concentration, obtained by sampling a channel of length 1–4 m, is 2.7–3.2 g/t (Härkönen I 24.8.1998 and 17.9.1998, quoted by Eilu 1999).

4.3.2.6 Sukseton

The copper-bearing gold occurrence known as Sukseton, located about 25 km north of Suurikuusikko (Fig. 15), was discovered by Outokumpu in 1981 in the course of bedrock mapping. The main rocks in the area are basic to intermediate metalavas and pyroclastics of the Kittilä group together with acidic lapilli tuffs and agglomerates, in addition to which fine-grained massive cherts mainly composed of quartz are also to be found. Felsic porphyry veins such as quartz-feldspar and plagioclase porphyrites commonly occur amongst the metavolcanic rocks and run parallel to the NE-SW-oriented deformation zone.

The host rocks are predominantly felsic agglomerates and lapilli tuffs, with narrow interlayers of graphite-bearing schists, cherts and rocks representing the oxide and sulphide facies of the iron formation. The principal ore minerals are pyrrhotite and arsenopyrite, although pyrite and chalcopyrite are also encountered. The gold is found in free milling form in association with the arsenopyrite, sometimes in coarse grains of the order of 100 µm.

The sulphide-bearing zone at Sukseton is more than 100 m wide and several hundred metres long, with Au and Cu concentrations distributed unevenly within it. One 95 m drill core, for example, had a mean Au concentration of 0.1 g/t and Cu 0.15 wt%, but contained massive arsenopyrite sections some 1–2 metres in length with Au 2–5 g/t and As 0.5–3.0 wt%. The mean metal concentrations obtained for the occurrence in 13 analyses performed on a 25 m drill core were Au 0.35 g/t, Cu 0.17 wt%, Zn 0.01 wt%, Pb < 0.01 wt%, Ni 0.01 wt%, Co < 0.01 wt%, Fe 7.28 wt% and As 0.22 wt%, with S 4.02 wt% (Outokumpu 2004).

4.3.2.7 Rovaselkä

The Rovaselkä prospect is located in a narrow zone of Mg-tholeiitic metavolcanic rocks of the Kittilä group about 1 km wide running between two synorogenic granites (Fig. 15). The site was discovered by Outokumpu in 1984 in connection with geological mapping and geochemical investigations, when an Au anomaly was identified in the till of a volcanite area connected with an electromagnetic zone. The host rock at the granite contact is a sulphide-rich schist. An iron formation with a magnetite-bearing chert layer is connected with the same schist zone 5 km further south (Lehto 1975). The metal composition of the Rovaselkä deposit, as determined from a drill core of length 1.30 m, was Au 0.35 g/t, Cu 0.05 wt%, Zn <0.01 wt%, Pb < 0.01 wt%, Ni 0.04 wt%, Co < 0.01 wt%, Fe 27.77 wt%, Ag 0.32 g/t and As 0.11 wt%, with S 13.9 wt% (Nurmi *et al.* 1991).

4.3.3 The Porkonen-Pahtavaara area

The Porkonen-Pahtavaara metavolcanite zone and the associated manganese-bearing iron formation in the south-eastern part of the Kittilä greenstone area (no. 9 in Fig. 5) is composed of lava-derived and both pyroclastic and chemical metasedimentary rocks (Paakkola 1971). The iron and manganese in the iron formation were precipitated under physico-chemical conditions corresponding to an oxide, carbonate or sulphide facies, depending on the depth of the sea at the time, the rocks of the sulphide facies being in the lowest stratigraphical position and those of the oxide facies in the highest. The main sulphide mineral in these zones is pyrrhotite, with pyrite present in places, but chalcopyrite occurs only sporadically.

The Porkonen-Pahtavaara iron deposits have been estimated to amount to between 42 and 88 million tonnes, with Fe concentrations varying from 35 to 40 wt% (Paakkola 1971). Otanmäki Oy (later Rautaruukki) obtained a mean Mg concentration of 3.9 wt% for the manganese siderite schists when assessing the possibility of using this material as a manganese ore, the corresponding Fe concentration being 20.5 wt% (*op. cit.*).

With the boom in gold ore exploration in the 1980s, the iron formations of Central Lapland began to be regarded in general as potential localities for such ores, and the Porkonen-Pahtavaara area became one of the most important sites. Outokumpu, for instance, studied gold-critical features of the iron formation in 1984 and 1987 by re-analysing a total of some 600 old drill core samples, paying attention to both the oxide and sulphide facies. The results for the sulphide facies did point to certain gold anomalies (Au 0.01–0.02 g/t), in which anomalous Cu concentrations were also recorded (0.1–0.2 wt%), with corresponding Fe and S concentrations of 20 wt% and 15 wt%, respectively.

The banded iron formations of Mustavaara and Karjalehto south of the Porkonen-Pahtavaara area, on the southern edge of the Kittilä greenstone area, also have sulphide and oxide facies associated with them. In this case the Mustavaara oxide facies showed Au concentrations of 0.10–0.20 g/t, with a maximum of 1.5 g/t in one 0.9 m drill core intersection, while the Karjalehto oxide facies had 0.15 g/t Au over a core length of 12.5 m.

4.3.4 The Jauratsi area

The Jauratsi area (no. 10 in Fig. 5) is located in a 15 x 20 km basin-like schist area composed of metasedimentary and metavolcanic rocks of the Savukoski group in the eastern part of Central Lapland. According to Saverikko *et al.* (1985), this area, also known as Kummitsoiva, belongs to a NW-SE-oriented metakomatiite zone which also encompasses the ultramafic formations of Sotkaselkä, Pahtavaara and Peltotunturi, and that of Karasjok in Norway. The central part of the Kummitsoiva area is in fact a volcanic crater, the products from the eruption of which have been deposited on top of the metasediments. These metasediments consist of black schists, phyllites, dolomites, tuffites and metatuffs with associated rocks representing the oxide and sulphide facies of the iron formation, and they are overlain by Fe-tholeiites and picritic and komatiitic metavolcanites (Lehtonen *et al.* 1985).

There are a number of iron formations in the Jauratsi area, the main ones being Jauratsi itself, Rahkavaara, Matalavaara and Reposalä (Airas & Korvuo 1975, Lehto 1975). Jauratsi is one of the largest iron formations in Finland and is composed of separate haematite and magnetite deposits, with a surface covering of the lateritic goethite formation overlying pyrite-bearing jaspilite. Associated with the oxide facies of this iron formation is a substantial deposit of iron sulphides, representing estimated potential mineral resources of more than 20 million tonnes. The iron formation itself is a fine-grained, layered, syngenetic pyrite-graphite formation. The deposit has a Cu concentration of 0.03 wt%, with Fe 17.8 wt%, Zn 0.06 wt%, Ni 0.05 wt% and S 17.8 wt%, although there are parts where higher Cu and Zn concentrations have been recorded, i.e. Cu 0.09 wt% and Zn 0.4 wt% (Kerkkonen 1982).

Another major iron formation in the Jauratsi area is that of Reposalä, with an Fe concentration of 16 wt% and S 15 wt%. A 24 m drill core sample from the surface of the pyrite deposit has given a Cu concentration of 0.47 wt%, an abnormally high figure that has been regarded as representing an electrochemical phenomenon (Airas & Korvuo 1975).

No gold deposits are yet known to exist in connection with the Jauratsi iron formations, but there is a copper occurrence with a gold anomaly at Vesilaskujänkkä further south, which will be described below in the section on copper deposits. Only a small number of gold analyses for this area are known to the author, and these are well over twenty years old and give Au concentrations < 0.05 g/t. If there had been refractory gold ore in the area, its concentration could well have remained unnoticed given the analytical techniques used at that time.

4.3.5 Archaean gold deposits

There are two small gold prospects associated with Archaean formations in the eastern part of Central Lapland, those of Auermavaara and Rovaukonselkä (no. 6 in Fig. 5). A rock composed of garnet, quartz and amphibole is found as an interlayer in the mica gneisses of the Auermavaara area which is evidently a metamorphic equivalent of the silicate facies of an iron formation (Juopperi 1994), and the formation is partly a gold

anomaly, although even the highest known Au concentrations are < 1 g/t. According to Inkinen (1988), however, the Auermavaara deposit corresponds to the gold deposits of the Archaean greenstone formation in Zimbabwe in terms of its position on a $\text{SiO}_2 + \text{FeO} / \text{MgO} + \text{CaO} + \text{Al}_2\text{O}_3$ diagram.

According to Inkinen (1990) the Rovaukonselkä area is composed of amphibolites, mica schists and felsic metavolcanic rocks, with some garnet and cordierite-antophyllite rocks present. The prospect was originally found on the basis of gold-bearing goethite boulders which were assumed to be derived from an iron sulphide zone. A 2.05 m diamond drill core from the garnet-cordierite mica schist gave an Au concentration of 2.25 g/t.

4.4 Palaeoplacer gold deposits

Two palaeoplacer gold deposits are known in Central Lapland, those of Kaarestunturi and Outapää (no. 7 in Fig. 5). Both are connected with mainly polymictic conglomerate lenses in quartzites of the Kumpu group deposited at the molasse stage of the orogeny. The metasediments of the Kumpu group were deposited discordantly on metasedimentary and metavolcanic rocks mainly of the Kittilä group at a late stage in the Svecokarelian orogeny, the Kaarestunturi formation representing a deltaic environment, whereas the Outapää area has features of a fluvial fan environment (Härkönen 1984, 1986).

The quartzites of the Kumpu group are connected geographically with a NW-SE-oriented deformation zone. Metasedimentary rocks of this kind are indeed typical of large deformation zones (Colvine *et al.* 1988).

According to Härkönen (1984, 1986), the host rocks of the Kaarestunturi and Outapää deposits are conglomerate lenses occurring in quartzite, their material being derived from various metasedimentary and metavolcanic rocks of the Kittilä greenstone area. The gold occurs in detrital grains of size 0.03–0.40 mm appearing together with magnetite, haematite and numerous accessory heavy minerals in the matrix of the conglomerate. Detrital sulphide grains do not occur in the Outapää deposit at all and are only of accessory status in the Kaarestunturi deposit (*op. cit.*). There are numerous gold deposits associated with the Kittilä greenstone belt from which the palaeoplacer gold belonging to the Kumpu group could in all probability have originated.

4.5 Placer gold deposits

The placer gold deposits of the north-eastern part of Central Lapland are to be found chiefly in the tributaries of the rivers Lemmenjoki, Ivalojoiki and Sotajoki, close to the contact with the granulite complex (no. 8 in Fig. 5). The first gold rush to the River Ivalojoiki took place in 1870, when there were almost 300 gold diggers working in the area at the height of the boom. Another gold rush was experienced on the River Lemmenjoki, where gold was first found in 1945.

A total of some 1000-2000 kg of placer gold has been panned in Central Lapland over this period of 135 years, with an economic value that has been of significance only for the gold panners themselves and the jewellery industry that has made use of these nuggets. The custom has been for the nuggets to be priced separately, and for the price per gramme to be dependent on the size of each nugget and to some extent on its shape. The price has in any case been very much higher than that paid for industrial gold at the time, even ten times that price in the case of good-sized nuggets. The largest one to have been found in Lapland so far weighed 393 g.

The search for the bedrock provenance of the placer gold of Lapland is a task that has enthralled ore prospectors and gold panners for decades. Gold-bearing magnetite-haematite veins have been identified in the bedrock on the north-eastern edge of the Central Lapland Greenstone Belt, close to the granulite contact, and it has been assumed that this is where the placer gold originated, as it is quite possible that magnetite-gold occurrences similar to those at Mäkärärova and Palokiimasselkä described below could also be an origin of the Lapland placer gold. Saarnisto and Tamminen (1987) regarded quartz-carbonate veins as possible sources in addition to the above, and Forsström and Tuisku (1990) considered the placer gold of Lapland to be derived from greenstone belts.

In addition to actual river bed deposits, there are many sites in Lapland where "placer gold" may be found in a bedrock interface or weathered crust, as revealed by regional or local geochemical surveys. The local nature of these gold enrichments points directly to gold anomalies in the adjacent bedrock.

Although it has not been possible to demonstrate with certainty how gold nuggets are formed, it is generally supposed that they are grains of gold that have become detached from the bedrock and rounded and worn by erosion. On the other hand, it would seem that no sufficiently large clusters of bedrock gold have come to light in Central Lapland from which nuggets weighing a few tens or hundreds of grammes could have broken away, with the exception of a gold enrichment in albite fels which contained several tens of grammes of virtually pure gold that was discovered during underground mining of the Saattopora gold ore. A similar enrichment has also been found in a drill core from the Bidjovagge gold-copper mine in Norway (Söderholm K., pers.comm. 2004).

Ideas have been put forward in recent times that gold nuggets may grow by supergene enrichment in weathered bedrock under the influence of bacterial activity in the groundwater. The latest international research has demonstrated unambiguously, however, that nuggets are grains of gold that have originally crystallized out in the bedrock and have been rounded by erosional action (Knight *et al.* 1999a and b). GTK has recently developed a non-destructive method for determining the chemical composition, physical properties and surface structures of a gold nugget (Kinnunen 1996, Kinnunen *et al.* 1997). This represents a major step forward, since destruction of the nugget itself had previously constituted a barrier to such determinations, especially in the case of the larger, more valuable specimens.

5 Iron oxide-copper-gold deposits of Central Lapland

5.1 General

The discovery of the Olympic Dam ore deposit in Australia in 1975 aroused discussion over a new type of copper-gold ore, one essential constituent of which is iron, in the form of magnetite and/or haematite, whereas iron sulphides are relatively low. Within a short space of time a number of major ore deposits that contained iron in addition to copper and gold were assigned to this type, not only in Australia but also elsewhere in the world. These included the Ernest Henry, Eloise, Starra and Osborne deposits in Australia, La Candelaria in Chile, the Sue-Dianne deposit in Canada and the Salobon deposit in Brazil.

Extreme examples of such iron oxide-copper-gold (FeOx-Cu-Au) deposits are taken to be the monometallic Fe-P deposits of the Kiruna type at one end of the scale and polymetallic Fe-Cu-Au-U-Ag-REE deposits at the other end (Hitzman 1992, 2000). Where the monometallic deposits such as the Kiruna magnetite ore usually amount to several billions of tonnes, the polymetallic deposits vary in size from several hundred million tonnes, e.g. 600 million in the Olympic Dam case (Reynolds 2000), to just a few million tonnes, e.g. 7.4 million at Starra (Pollard 2000). Polymetallic deposits usually have a Cu content of 1–2 wt% and an Au content of less than 1 g/t, except for certain smaller ones such as Eloise, with Cu 5.5 wt%, and Starra, with Au 3.8 g/t (Williams 1999). The FeOx-Cu-Au deposits are predominantly Proterozoic in age, although very much younger ones are also known to exist.

FeOx-Cu-Au deposits are associated with a number of tectonic events, the main ones being intracontinental orogenic collapse, intracontinental anorogenic magmatism and extension along a subduction-related continental margin (Hitzman 2000). All these are characterized by extensive acidic magmatism, high heat flux and oxidized rock types. The deposits are bound both temporally and spatially to magmatic events. Intrusions are usually acidic to intermediate and in no way characteristic, but rather their chemical composition tends to vary.

The FeOx-Cu-Au deposits resemble porphyry-copper deposits in their mineralogical principles and geological mode of occurrence, and a whole continuum of mineralogically differing deposits exists between the two, all of which may well be of a similar genetic

origin (Hitzman 2000). There are gold and copper-bearing magnetite skarn deposits of the kind to be found in the Rautuvaara and Ylläs formations that belong to each of these types.

Pollard (2000) mentions as Scandinavian representatives of the FeOx-Cu-Au ore type the Pahtohavare Cu-Au, Aitik Cu-Au and Kiruna FeOx-P ore deposits in Sweden and the Bidjovagge Cu-Au ore deposit in Norway. Weihed (2001) describes a number of FeOx-Cu-Au deposits in Northern Sweden in which the host rock is a Palaeoproterozoic acidic intrusive rock and the ore minerals occur either as breccia or as disseminations. In terms of their host rock and the mode of occurrence of their sulphides these are similar in type to the Olympic Dam ore deposit.

Although these FeOx-Cu-Au-type ore deposits have been major objects of research and exploration throughout the world for practically thirty years, it was only in the 1990s that interest began to be shown in the possibility of their existence in Finland, when Outokumpu began exploration for such ores in Western Lapland in 1993. The initial object of the prospecting was the group of known copper and gold-bearing magnetite deposits belonging to the Rautuvaara formation that lay between the acidic intrusions of Western Lapland and the quartzites (Korkalo 2001). This research gained momentum towards the end of the decade, when GTK, the University of Helsinki and a few foreign companies began investigations and explorations focused on the FeOx-Cu-Au deposits in Northern Finland.

The FeOx(\pm Cu-Au) deposits in the Rautuvaara formation are geologically and mineralogically comparable to the FeOx-Cu-Au ore type (Korkalo 2001), as also are, in the author's opinion, the magnetite-copper-gold deposits of the Ylläs formation located east of the Rautuvaara formation. In addition, a number of more modest magnetite(\pm copper-gold) showings are known in the Sodankylä region that possess FeOx-Cu-Au features, and the Fe-Co-Au-(U) deposits of Kuusamo in Southern Lapland are assigned to this type by Vanhanen (2001), although Pankka (1997) is inclined to liken them to the Archaean mesothermal gold deposits. Vanhanen (op.cit.) also relates the Saattopora and Pahtavaara gold ores to the FeOx-Cu-Au type and names the Porkonen-Pahtavaara and Jauratsi iron formations as potential areas of occurrence for ores of this same type, although, in his own words, the connection is "more disputable".

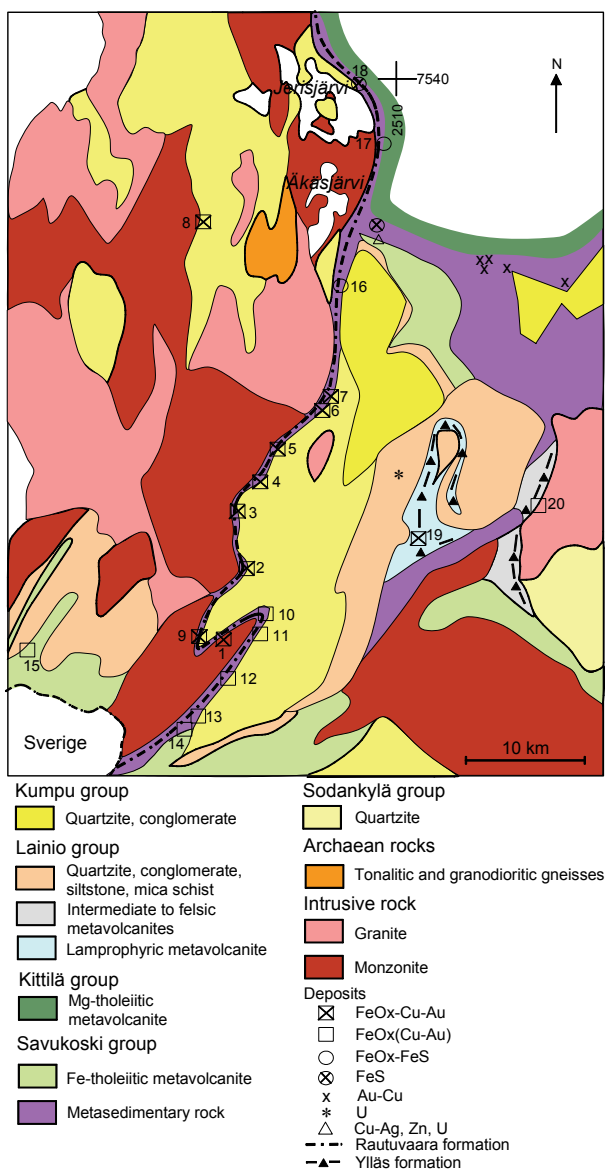


Fig. 16. Geology of the western part of Central Lapland, simplified from Lehtonen *et al.* (1998). Locations of the FeOx-Cu-Au deposits of the Rautuvaara formation after Hiltunen (1982), except for the northern part of the formation. These and other deposits identified by the author. Latvavuoma after Puustinen *et al.* (1980). Deposits: 1) Rautuvaara (NE-Rautuvaara, SW-Rautuvaara, Cu-Rautuvaara), 2) Hannukainen (Laurinoja, Kuervaara, Lauku, Vuopio, Kivivuopio), 3) Kuervitikko, 4) Aavahelukka, 5) Tuohilehto, 6) Äkässaivo, 7) Jassanjärvi, 8) Nivunkijoki, 9) Rautuoja, 10) Rautuhelukka, 11) Rytijänkämä, 12) Sivakkalehto, 13) Sainkangas, 14) Juvakaisenmaa, 15) Mannakorpi, 16) Liiskonjärvi, 17) Vuomanmukka, 18) Jerisjärvi, 19) Ylläs, and 20) Latvavuoma

Table 6. FeOx-Cu-Au deposits in western Lapland, including the FeOx-FeS-(Cu,Au) deposits in the Rautuvaara formation.

Deposit	Status	Mt	Diamond drill core m	Cu wt%	Au g/t	Fe wt%	S wt%	References
NE Rautuvaara	mine (closed)	11.7		0.21		46.8	2.2	Hiltunen (1982)
SW Rautuvaara	mine (closed)	4.5		0.15		42.7	2.5	Hiltunen (1982)
Cu Rautuvaara	deposit	2.8		0.50	0.30	21.0	1.0	Mattila (1976)
Laurinoja	mine (closed)	3.3		0.45	0.25	43.0	2.6	Rautaruukki (1988), Hiltunen (1982)
Laurinoja	mine (closed)	0.2		0.93	1.01			Korvuo (1995)
Kuervaara	mine (closed)	1.1		0.08		41.6	3.6	Rautaruukki (1988), Hiltunen (1982)
Lauku	deposit	2.5		0.15		42.0	2.8	Lindholm (1976a)
Vuopio	deposit	25.0		0.14		43.7	3.8	Hiltunen (1982)
Kivivuopio	prospect		21.0	0.07		40.8	1.7	Mattila (1978a)
Kuervitikko	deposit	0.7		0.39	0.46	40.2	3.5	Kerkkonen (1987)
Aavahelukka	prospect		6.0	0.07		35.3	2.5	Hiltunen (1982)
Tuohilehto	prospect		10.0	0.05		40.0	2.5	Mattila (1978a)
Äkässaivo	prospect		0.55	0.33	1.48			Keinänen (1996)
Jassanjärvi	showing		2.0	0.12	<0.02	11.2	3.2	Outokumpu (1988), Hugg (1990)
Nivunkijoki	showing		core sample	0.19		53.2	6.0	Hugg (1979)
Rautuoja	deposit	1.9		0.19	0.34	36.7	1.2	Korvuo (1982)
Rautuhelukka	prospect		core sample			52.5	0.3	Hiltunen (1982)
Rytijänkkä	prospect		core sample			40.0	3.0	Hiltunen (1982)
Sivakkalehto	prospect		60.0	0.03		30.6	0.87	Hiltunen (1982), Korvuo (1983)
Sainkangas	prospect		11.6	0.12		53.0	3.0	Hiltunen (1982)
Juvakaisenmaa	prospect	0.1		0.10		43.7	5.1	Hiltunen (1982)
Mannakorpi	prospect		41.4	0.07		33.2	3.8	Hiltunen (1982)
Liiskonjärvi	prospect		?					Outokumpu (1986)
Vuomanmukka	prospect		core sample	0.08	0.25	28.9	18.0	Pääkkönen (1989)
Jerisjärvi	prospect		7.98	0.21		9.2	5.8	Reino (1975)
Ylläs	deposit		73.17	0.21	0.45	16.8	0.72	Korvuo (1984)
Latvavuoma	occurrence		core sample			28.5	1.07	Hugg (1979)

5.2 The Rautuvaara formation

The term Rautuvaara formation is applied to the schist zone composed of amphibolites, quartz-feldspar schists, carbonate rocks, skarns and magnetite deposits associated with the latter that runs along the contact between the acidic plutonic rocks and quartzite in Western Lapland (Hiltunen 1982). According to Lehtonen *et al.* (1998), this zone belongs

to the Matarakoski formation in the Savukoski group. The author believes, however, that the Rautuvaara formation extends a good deal further north than is presupposed in Hiltunen's publication (1982), so that it is at least 60 km long and extends as far as Lake Jerisjärvi and possibly still further north (Fig. 16). Its northern end belongs to the contact between the monzonite and either the quartzites of the Kumpu group or the metavolcanites of the Kittilä group.

The Rautuvaara formation is the best-known area featuring FeOx-Cu-Au deposits in Central Lapland, and indeed in the whole of Finland. Observations regarding the existence of an iron prospect at Juvakaisenmaa, part of this same formation, date from the late 17th century, and a number of magnetite deposits were located in the Rautuvaara area by Suomen Malmi Oy from 1956 to 1960 with the aid of new aerogeophysical maps. Rautaruukki carried out extensive research and exploration in the area in the early 1970s, and this led to the discovery of economically viable magnetite ores and the opening of a mine at Rautuvaara in 1975 (Hiltunen 1982). The Kuervaara open pit mine at Hannukainen, about 6 km north of Rautuvaara, was opened in 1978 and that of Laurinoja in 1982. The ore from this latter site was processed to both magnetite and gold-bearing copper concentrates (Juopperi *et al.* 1982).

At least 20 magnetite deposits associated with skarn and partly also albite-antophyllite rocks are known within the Rautuvaara formation, some of which contain significant quantities of copper and gold (Fig. 16, Table 6). The formation alters in nature from south to north, however, so that the amounts of skarn and magnetite decrease and those of sulphides increase. At the northern end of the formation, close to Lake Jerisjärvi, the magnetite virtually disappears altogether and is replaced by massive copper-bearing sulphide sequences and lenses (Cu 0.1–0.5 wt%) in association with the skarn rocks.

5.2.1 Rautuvaara

The Rautuvaara mine area comprises three separate magnetite deposits: NE Rautuvaara, SW Rautuvaara and Cu Rautuvaara (Fig. 17). According to Hiltunen (1982) all of them are situated within a couple of kilometres of the NE-SW-oriented Rautuvaara formation that occupies the contact between the quartzite and monzonite. The magnetite deposits are normally massive (Fe approx. 45 wt%) or semi-massive in texture (Fe approx. 20 wt%). The Cu Rautuvaara deposit is the main one in which copper and gold are also to be found (*op. cit.*).

The inventory of total ore resources at Rautuvaara prior to the decision to open the mine amounted to 15.2 million tonnes, and a total of 11.7 million tonnes of magnetite ore was extracted from NE and SW Rautuvaara in 1970–1988, 11.2 million tonnes by underground mining and 0.5 million tonnes from two small open pits (Rautaruukki 1988).

The NE Rautuvaara ore deposit consists of three separate ore bodies located in a schist zone composed of quartz-feldspar schist, skarn and amphibolite lying between diorite (an altered marginal monzonite) and the monzonite proper (Fig. 17). The host rock is a skarn with diopside and hornblende as its principal minerals and scapolite, plagioclase, calcite, biotite, andradite and quartz as accessory minerals. The principal ore mineral is magne-

tite, with accessory pyrite, pyrrhotite and chalcopyrite and secondary pyrite (Hiltunen 1982).

The SW Rautuvaara ore deposit is associated with the Rautuvaara formation, the main rock types in which are albite-antophyllite rock, skarn and amphibolite (Fig. 17). The magnetite deposit has a hanging wall of monzonite and diorite and a footwall of quartzite. The principal ore minerals are magnetite, pyrrhotite and chalcopyrite, with pyrite encountered sporadically, similarly löllingite, arsenopyrite, cobalt-pentlandite and molybdenite (Hiltunen 1982).

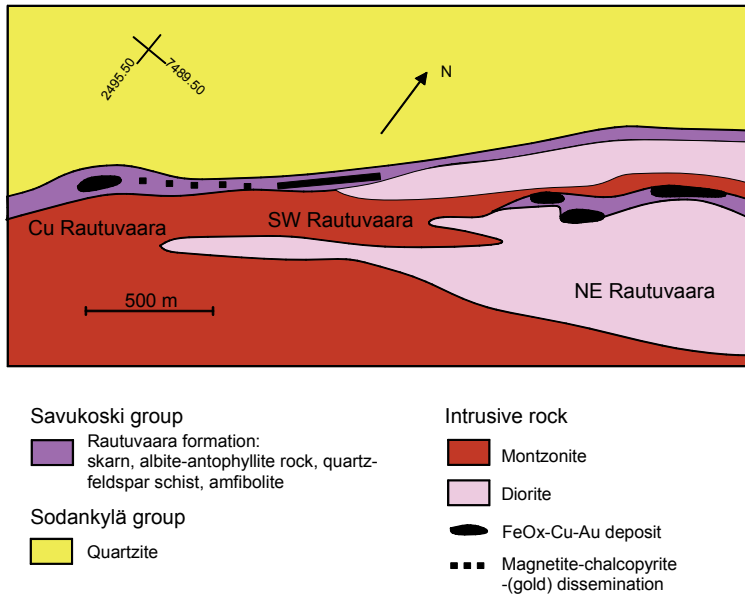


Fig. 17. Geology of the Rautuvaara mine area, simplified from Hiltunen (1982). The magnetite-chalcopyrite-(gold) dissemination is from Mattila (1976).

The magnetite lenses of Cu Rautuvaara are associated with a formation about 150 m wide composed of skarn, albite-antophyllite rocks and amphibolites (Fig. 17) and located between the monzonite and quartzite (Hiltunen 1982). Cu Rautuvaara consists of four types of FeOx-Cu-Au deposit: a narrow skarn-magnetite deposit a few metres wide, a dissemination-like magnetite-chalcopyrite deposit about 25 m wide in its footwall, associated with an albite-amphibole(-biotite) rock, a low grade magnetite-chalcopyrite dissemination associated with an albite-antophyllite-biotite rock that links Cu Rautuvaara with SW Rautuvaara (Fig. 17), and fourthly a disseminated magnetite-chalcopyrite deposit that forms a continuation of Cu Rautuvaara and is associated with an albite-antophyllite rock some 300 m away but is not visible anywhere at the surface (Mattila 1976, Hiltunen 1982).

The mineral resources of Cu Rautuvaara amount to some 2.8 million tonnes, with an Fe content of 21 wt%, only about a half of the concentrations reached in NE and SW Rautuvaara (Mattila 1976). The copper and gold concentrations, on the other hand, are

markedly higher than in the other Rautuvaara deposits, amounting to Cu 0.5 wt% and Au 0.3 g/t (op. cit.).

5.2.2 Hannukainen

The Hannukainen magnetite deposit was discovered by Rautaruukki in 1974 on the basis of an aeromagnetic anomaly. According to Hiltunen (1982) the area comprises five separate deposits: Laurinoja, Kuervaara, Lauku, Vuopio and Kivivuopio (Fig. 18, Table 6). The largest and economically most significant of these is Laurinoja, which contains chalcopyrite and gold as well as magnetite. The total mineral resources of the Hannukainen deposits amount to some 68 million tonnes (op. cit.).

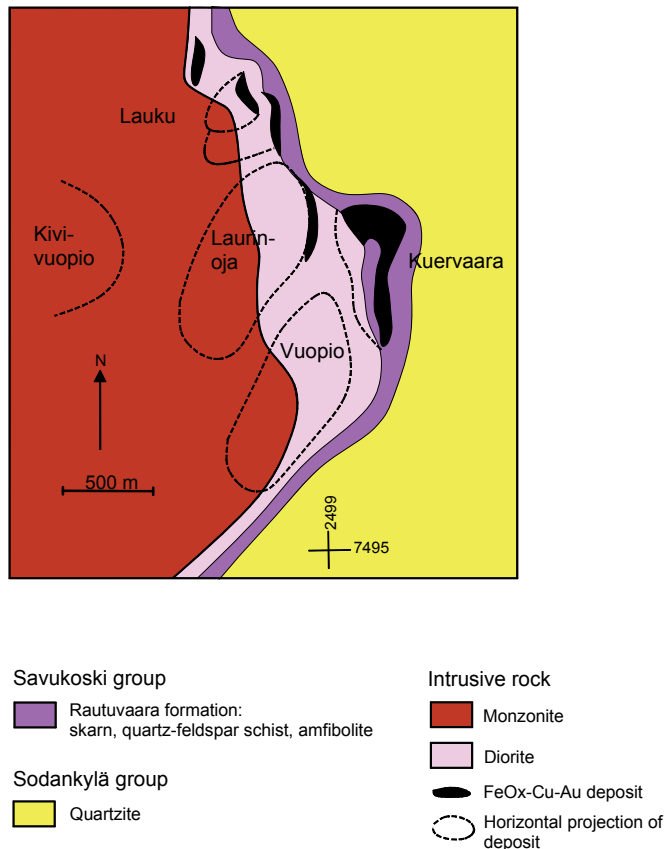


Fig. 18. Geology of the Hannukainen area, simplified from Hiltunen (1982).

According to Hiltunen (1982), the Hannukainen FeOx-Cu-Au deposits are associated with the N-S-oriented Rautuvaara formation located between quartzite and the dioritic marginal zone of the monzonite intrusion (Fig. 18). The formation is composed of skarn, quartz-feldspar schist and amphibolite. At the southern end of the Hannukainen deposits is a NE-SW-oriented fault/shear zone that runs across the whole of Central Lapland. The Kuervaara and Lauku deposits comprise several lenses that are divided one from another by the dioritic marginal zone of the monzonite. All the deposits are exposed at the surface except for that of Kivivuopio, the upper surface of which reaches a depth of 300 m at its highest.

The Hannukainen deposits are N-S-oriented slab-like lenses that have a gentle ($< 20^\circ$) dip towards the west. The dimensions of the best-known of them, Laurinoja, Kuervaara and Vuopio, are length 800–1200 m, breadth 200–700 m and thickness 10–40 m, and they are either massive, disseminated or banded, the banding being caused by alternating magnetite-rich and silicate-rich layers (Hiltunen 1982). The host rock is a skarn composed mainly of diopside, hornblende and in places also scapolite, while the hanging wall and footwall consist of skarn, amphibolite or diorite. The principal ore mineral in all the deposits is magnetite. The main sulphide mineral at Laurinoja is chalcopyrite, with accessory pyrrhotite, pyrite and gold, while at Kuervaara and Vuopio the magnetite is accompanied by pyrrhotite and smaller amounts of pyrite and chalcopyrite. At Lauku and Kivivuopio the principal sulphide mineral is pyrite, with accessory pyrrhotite and chalcopyrite (op. cit.).

Rautaruukki began mining at Hannukainen in 1978, concentrating at first on the Kuervaara open pit, from which 1.1 million tonnes of magnetite ore were extracted. The major part of the mining operation, however, was directed at the Laurinoja deposit, where a total of 3.3 million tonnes of copper and gold-bearing magnetite ore was extracted from the open pit in 1982–1988 (Rautaruukki 1988).

The estimate for the mineral resources at Laurinoja was approx. 33 million tonnes (Hiltunen 1982), while according to Lindholm (1976b) the mineral resources consisted of 26 million tonnes of copper-rich ore with a Cu concentration of 0.46 wt% together with Fe 41.0 wt% and S 2.75 wt% and 6.7 million tonnes of a copper-poor ore with Cu 0.13 wt%, Fe 46.9 wt% and S 2.08 wt%.

Outokumpu extracted 0.21 million tonnes of an ore with 0.92 wt% Cu and 1.01 g/t Au from an open pit at Laurinoja in 1990. This exceptionally copper and gold-rich ore lens was located in the NE wall of the open pit, at a dip of about 70° and extended from the surface down to the base of the open pit. Some 0.20 million tonnes of country rock had to be mined from on top of the ore lens. The ore was transported 8 km by road to the Rautuvaara mine for processing to a gold-bearing copper concentrate with a Cu content of 19.32 wt% and an Au content of 16.4 g/t (Korvuo 1995). The copper recovery rate was 95.8 % and the gold recovery rate 74.8 %. A magnetite concentrate was also produced for experimental purposes, but its quality was marred by too high a sulphur content.

The Laurinoja ore body becomes more or less horizontal at the base of the open pit and its copper and gold concentrations fall. Outokumpu investigated the possibilities for exploiting the underground part of the deposit but had to admit that it was economically unprofitable.

5.2.3 Other FeOx-Cu-Au deposits

Apart from the Rautuvaara and Hannukainen deposits, numerous smaller magnetite occurrences are known within the Rautuvaara formation, some of which contain copper and gold (Fig. 16, Table 6). The most significant of these are Kuervitikko, Aavahelukka, Tuohilehto, Äkässaivo, Jassanjärvi and Nivunkijoki, all north of Hannukainen, Rautuoja, Rautuhelukka and Rytijänkkä between Hannukainen and Rautuvaara, and Sivakkalehto, Sainkangas, Juvakaisenmaa and Mannakorpi south of Rautuvaara.

The Kuervitikko magnetite deposit north of Hannukainen contains significant copper and gold concentrations. The host rock is a skarn or albite-quartz rock overlying the amphibolite of the Rautuvaara formation, and the hanging wall is of monzonite or its marginal alteration product diorite (Hiltunen 1982). The formation dips gently to the west (about 20°). The ore minerals present are magnetite, pyrrhotite, pyrite, chalcopyrite and gold, and the deposit consists of a massive skarn-magnetite body and magnetite dissemination associated with the albite-quartz-antophyllite rock. The estimated mineral resources in the former amount to some 0.5 million tonnes, with a Cu concentration of 0.37 wt% and Au 0.36 g/t and Fe 44.4 wt%, while those in the latter are 0.17 million tonnes, with a Cu concentration of 0.43 wt%, Au 0.74 g/t and Fe 27.7 wt% (Hiltunen 1982, Kerkkonen 1987). The best drill core passed through the deposit for a distance of 8.15 m and had Cu 0.90 wt%, Au 1.14 g/t and Fe 26.18 wt%. The highest copper and gold concentrations were associated with the albite-quartz-antophyllite rock.

The Aavahelukka and Tuohilehto prospects (Fig. 16) also lie within the skarn zone, but the occurrences are small and their copper and gold concentrations low, e.g. Cu <0.1 wt% (Hiltunen 1982).

The Äkässaivo prospect, a typical FeOx-Cu-Au occurrence in the Rautuvaara formation (Fig. 16), was found by GTK in 1990 on the basis of a layman sample. The magnetite-bearing zone is associated with the contact between a limestone and a diopside skarn, with basic metavolcanites and garnet-bearing mica gneisses. The known copper and gold-bearing magnetite-skarn zone is only about 1 m wide and has been shown from drill core samples to have a Cu concentration of about 1 wt% and an Au concentration of nearly 2 g/t (Keinänen 1996).

About 2 km north of Äkässaivo is the Jassanjärvi FeOx-Cu-(Au) showing (Fig. 16), again related to the Rautuvaara formation and discovered by Outokumpu in 1988. The area is composed geologically of amphibolites, quartz-feldspar schists and skarn rocks, in which magnetite occurs with accessory chalcopyrite. A drill core sample gave a maximum Cu concentration of 0.2 wt%, with Fe 21–25 wt% (Hugg 1990).

The Nivunkijoki occurrence to the west of the Rautuvaara formation lies at the contact between quartzite of the Sodankylä group and the monzonite (Fig. 16). Drilling conducted by Rautaruukki pointed to two magnetite-bearing layers 2 m in width associated with a skarn zone about 40 m wide (Mattila 1978b). Although the Nivunkijoki FeOx-Cu(-Au) showing does not belong to the Rautuvaara formation proper, its skarn-magnetite zone corresponds to those known in Rautuvaara.

The Rautuoja magnetite deposit, lying about two kilometres west of the Rautuvaara mine area (Fig. 16), is associated with a diopside-hornblende-albite skarn that represents the dioritic marginal zone of the monzonite. According to Korvuo (1982), the mineral resources at the site are estimated to be 1.9 million tonnes, with Cu 0.19 wt%, Au 0.34 g/

t, Fe 36.7 wt% and S 1.2 wt%, in addition to which several million tonnes of a magnetite, pyrite and chalcopyrite-bearing occurrence belonging to the marginal zone of the monzonite is to be found in the hanging wall and footwall. The highest copper and gold concentrations at Rautuoja are to be found in the marginal zone or the albite-rich skarn, the best drill core intersection being a 9 m sample with a Cu concentration of 0.65 wt% and Au 1.88 g/t. The Fe concentrations in this marginal zone, on the other hand, are around 18 wt%, only a half of that to be found in the albite-poor skarn-magnetite deposit. The Rautuoja magnetite deposit is comparable to the best FeOx-Cu-Au deposits such as Laurinoja, Cu Rautuvaara and Kuervitikko in terms of its copper and gold concentrations, and in part with respect to its size.

Rautuhelukka and Rytijänkkä (Fig. 16) are small skarn-magnetite prospects with estimated mineral resources of a few thousand tonnes each. Their Fe concentrations vary in the range 35–60 wt% and S in the range 0.1–4.0 wt%. The ore minerals present are pyrrhotite and pyrite as well as magnetite, and also a small amount of chalcopyrite (Hiltunen 1982).

Sivakkalehto is a skarn-magnetite prospect (Fig. 16) with the special characteristic of a high phosphorus content, P_2O_5 2.36 wt%, more than ten times the concentrations to be found in the Hannukainen or Rautuvaara deposits and almost a half of that in the Kiiruna phosphorus-magnetite ore deposit. The host rock is a scapolite-rich skarn similar to those at Kuervaara and Rautuvaara, and the Fe content of the occurrence is high in places, reaching 67 wt% at its maximum. The occurrence also contains a little pyrite and sporadic amounts of chalcopyrite and pyrrhotite in addition to magnetite. The Cu concentration over a core length of 60 m was 0.03 wt%, with Fe 30.6 wt%, S 0.87 wt% and P_2O_5 2.36 wt% (Hiltunen 1982).

Sainkangas and Juvakaisenmaa are located in a skarn sequence at the contact between the diorite and amphibolite of the Rautuvaara formation (Fig. 16). Both are typical magnetite-skarn prospects, containing iron sulphides and a little chalcopyrite as well as magnetite. A 11.6 m core sample from Sainkangas gave a Cu concentration of 0.12 wt%, Fe 53.0 wt% and S 3.0 wt%, while the mineral resources in the best part of the Juvakaisenmaa deposit were estimated at 100 000 tonnes, with Cu 0.10 wt%, Fe 43.7 wt% and S 5.09 wt% (Hiltunen 1982).

The Mannakorpi site close to the Swedish border represents the westernmost prospect in the Rautuvaara formation (Fig. 16), although it differs from all those mentioned above in that it does not belong to the formation proper. It is composed of several separate prospect, the largest of which is estimated to amount to some 20 million tonnes and to have an Fe concentration of 25 wt%. The best drill core to intersect the occurrence (length 41.4 m) gave a Cu concentration of 0.07 wt%, Fe 33.2 wt% and S 3.8 wt% (Hiltunen 1982). According to Lehtonen *et al.* (1998), the Mannakorpi prospect is associated with a sequence of Fe-tholeiitic metavolcanites of the Savukoski group lying close to the quartzite of the Lainio group.

According to Hiltunen (1982), the skarn-magnetite deposits of the Rautuvaara formation were formed metasomatically in the skarn rocks following the monzonite intrusion, under the influence of fluids transporting ore material, and metasomatic alterations have also taken place in the marginal zone of the monzonite intrusion. In the course of the multi-stage metasomatic reaction the skarn minerals usually crystallized out ahead of the ore minerals, with magnetite and pyrite first, followed by pyrrhotite and chalcopyrite. The

silicate rocks have given rise to albite-antophyllite and/or scapolite-bearing rocks in places. Little can be said with certainty about the origins of the ore-conducting fluids or the ore material itself.

5.2.4 FeOx-FeS deposits

In addition to the above magnetite-copper-gold deposits, a number of skarn-associated magnetite-iron sulphide and simply iron sulphide prospects have been discovered in the northern part of the Rautuvaara formation (Fig. 16). The Liiskonjärvi site north of Jassanjärvi, for example, contains large amounts of iron sulphides as well as magnetite. The northernmost prospect connected with the Rautuvaara formation are the Vuomanmukka magnetite-sulphide deposit north-east of Lake Äkäsjärvi (Pääkkönen 1989) and the small massive pyrrhotite occurrences east of Lake Jerisjärvi. The iron sulphide(± magnetite) occurrences in the northern part of the Rautuvaara formation are associated with skarn rocks at the contact between the monzonite and the metavolcanites of the Kittilä group, and deviate from the FeOx-Cu-Au ore type mainly in the abundance of sulphide material contained in them. Their copper concentration is sporadic but clearly anomalous.

The Liiskonjärvi iron sulphide-magnetite prospect (Fig. 16) is located at the southern end of Lake Äkäsjärvi, at a point where the Rautuvaara formation runs between two quartzite formations of differing age. The quartzite to the west of the deposit belongs to the Sodankylä group and that to the east to the Lainio group. The schist zone running between them is composed of metasediments typical of the Rautuvaara formation.

The Vuomanmukka magnetite-iron sulphide prospect (Fig. 16) lies in the Rautuvaara formation, where the main rock types are a markedly deformed hornblende and diopside gneisses and amphibolites containing magnetite-skarn and graphite-phyllite interlayers of width 0.2–5 m. Chalcopyrite is found sporadically (Pääkkönen 1989).

Where the Rautuvaara formation runs along the eastern shore of Lake Jerisjärvi it is composed of albite-sericite schist, amphibolite, phyllite and skarn zones, while to the west is an extensive monzonite area which belongs to the acidic intrusive rocks of Western Lapland. Associated with the skarn-phyllite zone are small occurrences of massive pyrrhotite containing a little chalcopyrite. One example would be a 2.25 m drill core sample with a Cu concentration of 0.4 wt% with Ni 0.03 wt%, Co 0.01 wt%, Fe 14.70 wt%, S 9.16 wt% and Au < 0.05 g/t. Several granite boulders have been found close to the skarn-phyllite zone, some of which contain chalcopyrite in disseminated or brecciated form. As well as occurring in the schist zone, magnetite is also found in disseminations and massive veins within the monzonite.

5.3 The Ylläs formation

About 15 km east of the Rautuvaara formation and associated with the skarn layer of the Lainio metavolcanite area is the Ylläs FeOx-Cu-Au deposit (Figs. 16 and 19), discovered by Outokumpu in 1979 on the basis of a bedrock exposure observed in connection with

investigations into the Kittilä greenstone area. Research in the area was focused initially on two deposits of different types located about 400 m apart, one a small but rich (Cu 30–50%, Au 0.06 g/t) chalcocite occurrence in the lower part of a quartzite of the Lainio group, and the other an FeOx-Cu-Au deposit in lamprophyric metavolcanites of the same group. The chalcocite occurrence proved to be small, evidently representing a secondary enrichment within the quartzite, but the FeOx-Cu-Au deposit is comparable to the skarn-magnetite deposits of the Rautuvaara formation.

Attention had initially been drawn to the Ylläs FeOx-Cu-Au deposit by the magnetite contained in it, until the economic significance of the copper and gold became evident. The author is also of the opinion that the Latvavuoma magnetite-haematite occurrence described by Puustinen *et al.* (1980) may well be associated with the Ylläs formation (Fig. 19).

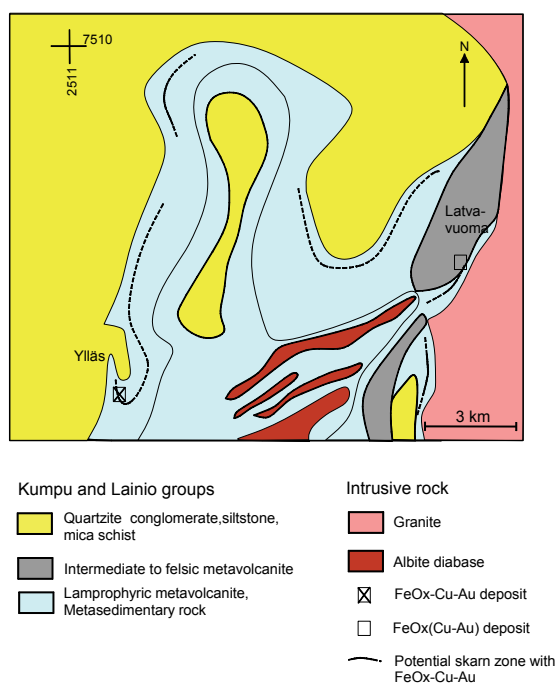


Fig. 19. Geology of the Ylläs area, simplified from Rastas (1984) and Lehtonen *et al.* (1998). The Ylläs skarn zone and Ylläs FeOx-Cu-Au deposit are as defined by the author, and the Latvavuoma deposit is after Puustinen *et al.* (1980).

5.3.1 Ylläs

The Ylläs FeOx-Cu-Au deposit is associated with the lamprophyric metavolcanites of the Lainio group, which are chiefly composed of metatuffs and tuffites and have interlayers of quartz-feldspar schists and carbonate and skarn rocks. The skarn sequence consists mainly of amphibole and varying quantities of scapolite, carbonate and biotite, while apa-

tite and tourmaline are also encountered. The author is inclined to interpret the Kittilä sheet of the geological map of Finland (Rastas 1984) as implying that the skarn sequence forms an interrupted zone in the metavolcanites that runs along the quartzite contact of the Lainio group for a distance of some 50 km (Fig. 19).

The host rock of the Ylläs FeOx-Cu-Au deposit is a skarn (Fig. 20) chiefly composed of coarse-grained tremolite and dolomite, while the ore minerals are magnetite, pyrite, chalcopyrite and in places pyrrhotite. Gold is fairly evenly distributed throughout the sulphide-bearing zone.

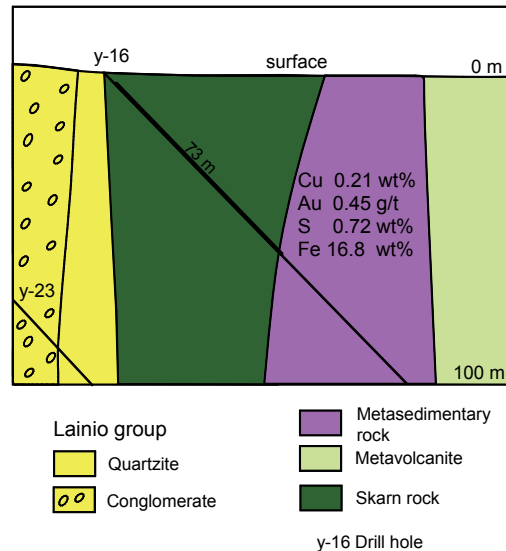


Fig. 20. Diamond drill section through the Ylläs FeOx-Cu-Au deposit, simplified from Korvuo (1984).

The mean metal composition of the FeOx-Cu-Au deposit (means weighted by sample length from two drill cores of total length 149 m) is Cu 0.28 wt%, Au 0.56 g/t, Ni 0.04 wt%, Co 0.01 wt%, Zn 0.01 wt%, Pb < 0.01 wt% and Fe 18.21 wt%, with S 1.00 wt%. The best known sequence as far as Cu and Au concentrations are concerned is a 6.2 m drill core intersection with Cu 0.61 wt%, Au 1.19 g/t, Fe 8.99 wt% and S 2.07 wt%. A radiating layer 0.6 m in width in the dolomite associated with the skarn rock has been discovered that contains U 0.09 wt% and Th < 0.01 wt% (Korvuo 1984).

There are only two small granite outcrops in the area concerned here, but diamond drilling has intersected about 20 m of monzonite in one place. The nearest acidic plutonic massif is the extensive Kallo monzonite intrusion south of the Ylläs area, which belongs to the same Haparanda series as the monzonite intrusions lying west of the Rautuvaara formation (Lehtonen *et al.* 1998).

The Ylläs skarn rock associated with the basic metavolcanites of the Lainio group is of an age of some 1883 million years and the Rautuvaara formation > 2130 million years (Lehtonen *et al.* 1998). Thus the difference in age between these formations is at least 250 million years. Nevertheless, the Rautuvaara and Ylläs FeOx-Cu-Au deposits are closely

comparable in terms of their geological mode of occurrence, mineralogy and metal composition in spite of the age discrepancy between the Rautuvaara and Lainio formations.

The small Ylläs chalcocite occurrence lies in the lower contact of the quartzite of the Lainio group, near the lamprophyric metavolcanites of the same group. The surface exposure suggests that the occurrences may be a secondary vein of width 10–30 cm and length several tens of metres conformable with the stratigraphy and containing almost entirely chalcocite. Diamond drilling failed to reveal any high-grade Cu concentrations, but there was a chalcopyrite zone which gave concentrations of Cu 0.47 wt%, Au < 0.2 g/t, Zn, Pb and Ni < 0.01 wt%, Co 0.02 wt%, Fe 6.26 wt% and S 3.52 wt% over a core length of 2 m. Also connected with the sulphide zone was a tourmaline-bearing quartzite which had a gold concentration of 1.1 g/t in a 1.4 m core sample.

5.3.2 *Latvavuoma*

The Latvavuoma magnetite-haematite occurrence (Fig. 19) was discovered by GTK in connection with bedrock mapping in 1971. The area is composed of intermediate and felsic metavolcanites of the Lainio group, various greywacke-like schists, conglomerates and quartzites. To the east lies the extensive Kittilä granite intrusion (Puustinen *et al.* 1980, Lehtonen *et al.* 1998).

The occurrence of the Latvavuoma area can be divided into three types: a haematite occurrence associated with felsic metavolcanites, a detrital haematite occurrence, and a magnetite-pyrite-dolomite vein of width 10 m and length about 1.5 km connected with the contact between a greywackeous schist and a calcareous conglomerate. This vein has an Fe concentration of about 43 wt%, with Ni 0.04 wt%, Co 0.02 wt% and S 2.02 wt% (Puustinen *et al.* 1980). Also associated with this deposit are skarn layers with an S concentration of 1.9 wt%, and chalcopyrite is to be found occasionally (Hugg 1979).

5.4 The Sodankylä area

5.4.1 *Sodankylä, Outolampi, Kelujoki*

A number of magnetite showings bearing similarities to the FeOx-Cu-Au ore type are known in the Sodankylä area (Fig. 25), namely the Sodankylä, Outolampi and Kelujoki showings. Common to all of them is their magnetite concentration and low-grade sulphur content, in addition to which they frequently contain chalcopyrite and gold and in places also cobalt. The bedrock of the area is chiefly composed of metasedimentary rocks of the Matarakoski formation, quartzites of the Sodankylä group and to a lesser extent tholeiitic and komatiitic metavolcanites of the Onkamo group (Lehtonen *et al.* 1998). The acidic intrusive rocks are represented by the extensive Central Lapland granite area to the south of the Sodankylä area and the post-orogenic Nattanen-type granites of the northern part of the area.

Magnetite-bearing hornblende and albite-hornblende-mica rock exposures and boulders have been observed in the built-up area of Sodankylä itself, and one sample from a boulder has given Cu concentrations of 0.26–2.8 wt%, Au 9 g/t and Fe 27–60 wt% (Rossi 1977). In terms of its mineralogy and metal composition, this sample resembles the albite-antophyllite rocks to be found in connection with FeOx-Cu-Au occurrences in the Rautuvaara formation.

The Outolampi FeOx-Cu-Au showing located about 10 km east of the community of Sodankylä was discovered by Otanmäki Oy (Rautaruukki) in 1956 on the basis of an E-W-trending low-altitude aeromagnetic anomaly and is associated with a mica schist-quartzite-amphibolite zone about 30 m broad. The zone that contains magnetite and sulphides is just a few metres wide and consists of markedly quartzized mica schist. The ore minerals present are magnetite, pyrite, pyrrhotite and chalcopyrite. Cu concentrations in the drill core samples are < 0.5 wt%, but there are occasional Au concentrations of up to 1.3 g/t (Makkonen 1962).

The Kelujoki magnetite showing located about 5 km NNE of the centre of Sodankylä was known about in the 1930s, leading Saariselkä Oy to register a claim over its pyrite occurrence in 1937. The showing is situated at a contact between sericite-quartzite and amphibolite, the ore minerals being magnetite, pyrite and chalcopyrite.

Diamond drilling through the amphibolite running between the felsic metavolcanite and the biotite schist showed this to contain pyrite disseminations and bands of tremolite and magnetite. The 7 m drill core gave a Cu concentration of 0.14 wt%, Co 0.05 wt% and S 0.97 wt% (Karvinen 1982). Unpublished correspondence from the years 1938–1942 (between Prof. P. Haapala and the engineer L. Holman) suggests that samples taken by hand from the excavation at Kelujoki gave individual high metal concentrations such as Cu 2–3 wt%, Au 1–2 g/t and Co 0.3–0.7 wt%, but one should be cautious when assessing the results of analyses performed over 60 years ago, especially in view of the manner in which samples were taken at that time.

5.4.2 Mäkärärova and Palokiimaselkä

The Mäkärärova and Palokiimaselkä magnetite occurrences are located close to a contact between granulite and the Archaean granite gneiss north of Sodankylä (Ollila 1976, Hugg 1979, Front *et al.* 1989). Both occurrences are associated with the tonalitic and granodioritic garnet-hornblende gneisses of the Eastern Lapland Archaean formation, which are intersected by rhyolite and quartz dykes running parallel to the NW-SE-oriented deformation zone. Palokiimaselkä lies close to the contact with the post-orogenic Natanen-type granite, and the NW-SE-oriented shear system is also visible in this granite.

The host rocks for these FeOx-(Cu)-Au occurrences are narrow haematite-magnetite-quartz veins no more than 2 m in width that run in virtually a N-S direction, thus deviating from the NW-SE orientation of the main deformation zone. The mean Cu, Zn, Pb and Ni concentrations are all < 0.01 wt%, but the mean Fe concentration is high, 65 wt%. The S concentration is low, only 0.03 wt%, and Au varies in the range 0.1–5.2 g/t, with Ag < 1 g/t (Hugg 1979).

6 Copper deposits of Central Lapland

6.1 General

The majority of the world's copper is obtained from porphyry copper deposits associated with acidic intrusive rocks, deposits which are also important sources of molybdenum and gold. Another significant type of copper ore is represented by sediment-hosted deposits, in which the geological environment consists predominantly of sedimentary rocks. These deposits usually contain uranium and cobalt in addition to copper. The third major type consists of volcanogenic massive sulphide deposits associated with acidic or basic volcanites, in connection with which the ores were precipitated out onto the sea bed from erupting salt solutions. Other significant metals to be found in these deposits are zinc and lead together with the precious metals gold and silver. A further copper source is represented by the iron oxide-copper-gold deposits mentioned above, in addition to which nickel deposits in basic or ultrabasic intrusions contain significant amounts of copper.

The main copper deposits in Finland are connected with serpentinite-black schist-skarn-quartz rock assemblages of the Outokumpu type, notably those of Outokumpu, Vuonos and Luikonlahti, which have together accounted for about 70% of the 1.9 million tonnes of copper (in copper concentrates) produced by mines in this country. Other copper ores that have been mined to a significant extent are those of Orijärvi and Aijala in the SW Finland metavolcanite zone, Ylöjärvi in the Tampere schist zone and Hammaslahti and Virtasalmi in SE Finland, in addition to which the zinc ores of Pyhäsalmi, where mining is still going on, and Vihanti have yielded significant amounts of copper as well (a total of 0.5 million tonnes) and the country's principal nickel ores, mined at Vammala, Enonkoski, Kotalahti and Hitura, have contributed some 0.1 million tonnes of copper between them. Of these, the Hitura mine is still in operation.

Although it would seem in the light of current research that no major copper deposits have been found in Central Lapland, there are four significant deposits in which copper is economically the most important metal present, those of Pahtavuoma, Saattopora II, Riikonkoski and Vesilaskujänkkä, of which the Pahtavuoma ore also contains silver and the Saattopora II deposit gold, as also does the Riikonkoski deposit, but only sporadically. These deposits are of size 1–11 million tonnes, but with a low copper content (Cu 0.5–1.0

wt%). The best source of copper in the region has been the Laurinoja iron-copper-gold ore at Hannukainen, in addition to which copper concentrates have been produced from the Pahtavuoma copper ore and the Saattopora I gold ore. The total volume of production to date from all these sources has been 0.02 million tonnes of copper.

Table 7. Copper deposits in Central Lapland.

Deposit	Status	Mt	Diamond drill core m	Cu wt%	Au g/t	Ag g/t	Reference
Pahtavuoma	mine (closed)	4.4		1.04	< 0.01	23	Korkalo (1976)
Riikonkoski	deposit	9.2		0.48			Puustinen (1985)
Vesilaskujänkkä	occurrence		91.0	0.23			Kerkkonen (1982)

Of the deposits mentioned above, those of Pahtavuoma, Riikonkoski and Vesilaskujänkkä (Table 7) will be described in this section, which will also briefly consider other showings in Central Lapland with a copper ore potential. The copper-dominated gold deposit of Saattopora II has been described above, as also have the FeOx-Cu-Au deposits, which are regarded as constituting a separate ore type of their own.

6.1.1 Pahtavuoma

The Pahtavuoma chalcopyrite deposit is located in the western part of the region, close to the contact with the acidic intrusive rocks of Western Lapland (Fig. 21). It was discovered by Outokumpu in 1971 on the basis of an indication arising in the course of an extensive stream sediment survey in Western Lapland and parts of Central Lapland during which a number of local copper anomalies were detected. Pahtavuoma was not identified directly from these anomalies, however, as it lies in between the network of streams. Several chalcopyrite-bearing bedrock exposures were found during bedrock mapping in the same area, however, and these led directly to the discovery of Pahtavuoma.

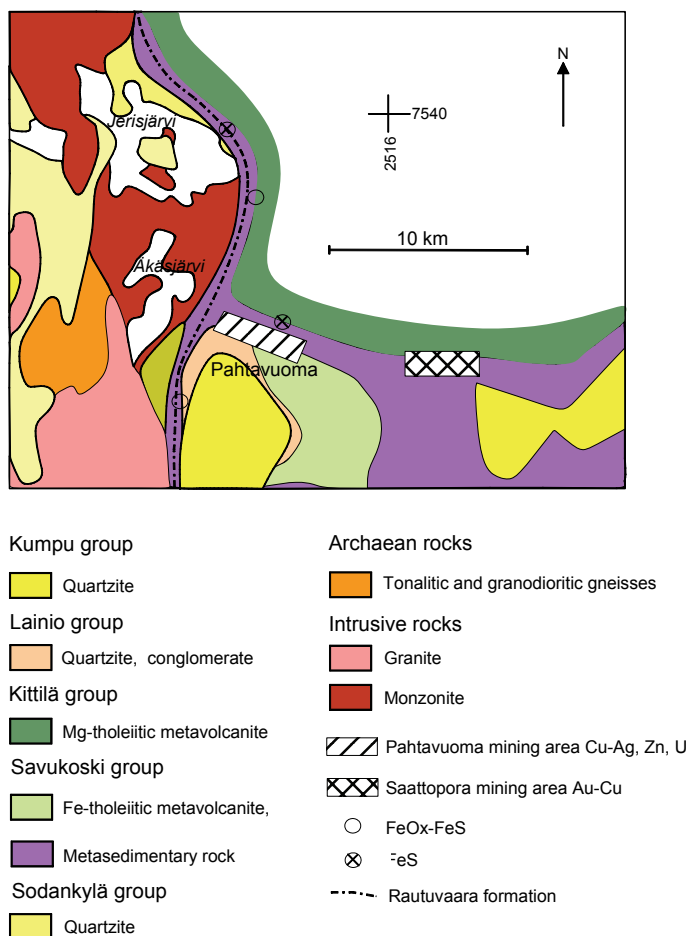


Fig. 21. General geology of the Pahtavuoma area, simplified from Lehtonen *et al.* (1998). Deposits defined by the present author.

The Pahtavuoma area belongs to the Matarakoski formation in the Savukoski group (Fig. 21) and consists of a number of parallel E-W-oriented schist zones composed mainly of phyllites, graphite phyllites, mica schists, greywackes, metatuffs and tuffites, with albite schists and skarn and limestone rocks to be found in smaller quantities. The magmatic rocks are represented by basic metavolcanites and albite diabases encountered between the schist zones. The Pahtavuoma area is bounded in the south partly by quartzites of the Lainio group and partly by an Fe-tholeiitic metavolcanite area belonging to the Savukoski group, while to the north is the extensive Mg-tholeiitic metavolcanite area of the somewhat younger Kittilä group. In the west the Pahtavuoma area borders on the contact of the N-S-oriented zone of acidic intrusive rocks to which the Rautuvaara formation described above and its FeOx-Cu-Au and FeS deposits also belong. About 10 km away from Pahtavuoma to the east are the Saattopora gold and copper deposits, also described earlier.

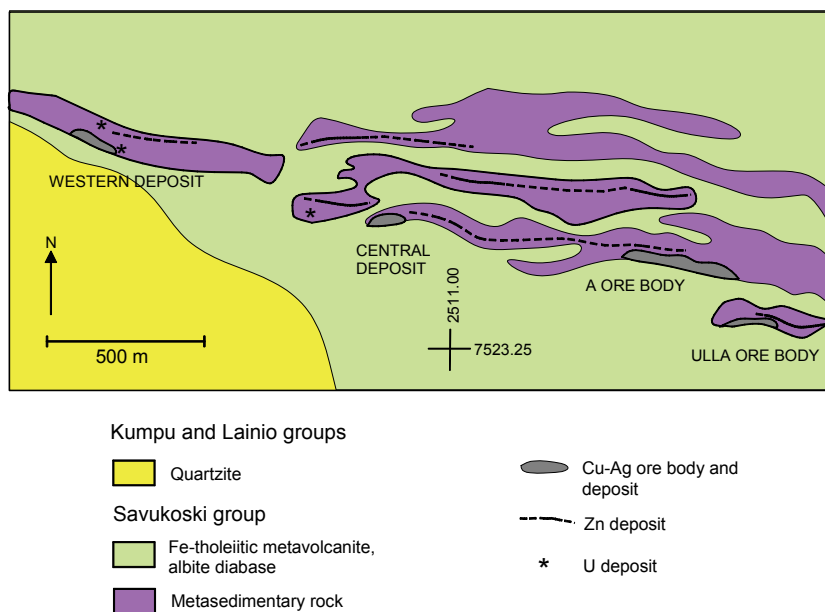


Fig. 22. Geology of the Pahtavuoma area, simplified from Inkinen (1979) and Lehtonen *et al.* (1998).

The four separate copper deposits at Pahtavuoma are all associated with the contact between metasedimentary and basic metavolcanic rocks close to the southern edge of the schist zone (Fig. 22). The host rock is mostly phyllite, and also mica schist or greywacke in places, while the occurrence of large quantities of scapolite, amphibole and garnet porphyroblasts is typical of the sulphide-bearing zone. The scapolite is of a meionite-rich composition (Tuisku 1981), while the garnet is an iron-rich almandine (Latvalahti 1973). Large amounts of garnet occur together with magnetite, especially in the narrow copper-rich skarn zones, although this exceptional abundance of garnet is rare in the context of the copper and gold deposits of Central Lapland.

About 3 km north of the Pahtavuoma deposits, on the northern edge of the schist zone, is the massive Levijärvi iron sulphide occurrence (Fig. 21), which is associated with a phyllite sequence located close to the Mg-tholeiitic metavolcanites of the Kittilä group. This occurrence is at least a hundred metres in length and a few metres wide and contains chalcopyrite in places (Cu 0.1–0.4 wt%). No other comparable massive sulphide zones occur in connection with the copper deposits at Pahtavuoma.

The Pahtavuoma copper deposit consists of four separate lenses, known as the Western and Central deposits and the A and Ulla ore bodies (Figs. 22 and 23). The Ulla ore body consists of two lenses, with a 20 m broad tongue of relatively coarse, massive amphibole rock lying between them. The largest of the deposits is the A ore body, which is 450 m in length, has a mean width of 20 m and is a maximum of 400 m deep, while the smallest is the Central deposit, the corresponding dimensions of which are 150 m, 10 m and 220 m. The longitudinal direction of these deposits follows the E-W orientation of the

host phyllite zone and its dip of 70° to the north. The direction of the lengthwise axis of the ore lenses is the same as the lineation of the area, i.e. 70° to the NE.

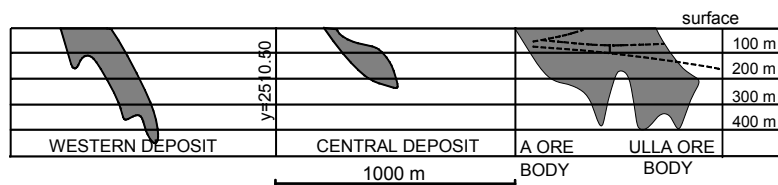


Fig. 23. Longitudinal section through the Pahtavuoma copper deposits, after Korkalo (1976). The incline shaft and ore drifts are marked by dotted lines.

The host rock of the copper deposits is chiefly a graphite-bearing phyllite and in part a mica schist, these being intersected by narrow quartz-carbonate and sulphide-filled fracture veins. The deposits are located at the contact between basic metavolcanic rocks and phyllite but within the latter, so that the hanging wall is composed of phyllite and the footwall of metavolcanites. There is a narrow mica schist zone in the footwall of the Western deposit that borders on the quartzite of the Lainio group. The contact between the schists and the quartzite has been intersected by several drill holes and has been shown to be sharply defined, with no shear zone distinguishable. Large amounts of scapolite and hornblende porphyroblasts are to be found in the contact zone, however.

The copper concentration of the Pahtavuoma deposits rises sharply at the footwall contact and is usually 1–2 wt%, while at the hanging wall it rises gradually and is only 0.1–0.6 wt%. The deposits are relatively poor in sulphides, however, as reflected in the low mean sulphur content of 2.4 wt%. The principal ore minerals are chalcopyrite and pyrrhotite, with numerous accessory sulphide minerals such as pyrite (secondary), sphalerite, galena, arsenopyrite, cubanite, pentlandite, gersdorffite and native silver. Magnetite is to be found especially in the skarnized zones. The iron sulphide-rich schists and massive iron sulphide veins typical of many of the gold deposits of Central Lapland are almost entirely absent, as also are ultramafic rocks. Chalcopyrite occurs as breccia filling along with calcite and quartz, and also in fine-grained impregnations running parallel to the layering, which points to a genesis of the strata-bound type.

Table 8. Mineral resource estimates for the Pahtavuoma copper deposits (Korkalo 1976).

Deposit	Size Mt	Cu wt %	Zn wt %	Pb wt %	Ni wt %	Co wt %	Fe wt %	S wt %	As wt %	Au g/t	Ag g/t
A	1.37	1.03	0.19	0.03	0.03	0.02	7.66	2.16	0.04	<0.01	27
Ulla I	0.61	1.33	0.13	0.01	0.02	0.02	6.97	2.25	0.06	<0.01	24
Ulla II	0.87	1.05	0.12	0.01	0.03	0.03	6.93	1.77	0.07	<0.01	25
Central	0.35	0.78	0.33	0.06	0.03	0.03	8.64	3.28	0.15	<0.01	35
Western	1.20	0.99	0.01	0.01	0.02	0.01	7.81	2.72	0.01	<0.01	14
Total	4.40	1.04	0.12	0.02	0.03	0.02	7.53	2.34	0.05	<0.01	23

Mineral resource estimates for the Pahtavuoma copper deposits, based on cross-sections at intervals of 12.5–25 m with 1–4 diamond drill holes each, are presented in Table 8. The cut-off is Cu 0.6 wt% and the specific gravity of the ore 2.93 g/cm³. If the cut-off were Cu 0.3 wt%, the total volume of the deposit would be 6.53 million tonnes with a mean Cu concentration of 0.84 wt% and Ag 21 g/t. The estimate does not take account of the 0.27 million tonnes of ore that has already been mined from the site. The mean metal concentrations (and also those of sulphur) are very similar from one deposit to another, with the exception of the Central deposit, where the Cu content is lower than elsewhere but the concentrations of the Zn, Pb, Fe, S, As and Ag are higher. Another deviant feature of the Central deposit is the occurrence of a barite layer about ten centimetres in width.

Both the A ore body and the Ulla ore body feature narrow skarn layers about a metre in width containing abnormally high amounts of magnetite, pyrrhotite, chalcopyrite and arsenopyrite. Apart from sulphides and magnetite, the skarn itself is composed of carbonate, amphibole and garnet. The drill hole records suggest that the Cu content of the skarn zones may be a matter of several wt%. Magnetite-rich zones of a similar type are to be found in connection with the Viscaria copper ore at Kiruna in northern Sweden, for example (Martinsson 1995).

There are a number of narrow layers of metasedimentary rocks some 1–2 m wide and containing nickel-cobalt arsenides within and adjacent to the chalcopyrite lenses where As concentrations reach 0.1–0.4 wt%. The most substantial of these is in a western continuation of the Ulla ore body, a 2 m drill hole core through which gave a Cu concentration of 0.4 wt%, Ni 0.4 wt%, Co 0.4 wt%, Fe 7.0 wt%, As 0.4 wt% and S 2.0 wt%, i.e. the Ni, Co and As concentrations are about ten times the mean figures for the copper deposits (Table 8).

The highest Cu concentrations, 15–20 wt%, have been encountered in a narrow conformable vein about 0.3 m wide almost exclusively of chalcopyrite and pyrrhotite connected with the A ore body. This evidently represents either a mobilized sulphide precipitation or the proximal part of a volcanic-associated massive sulphide base metal deposit.

Au concentrations in the Pahtavuoma copper deposits are < 0.01 g/t. Although the gold has not been analysed systematically, it is evident that it reaches its highest concentration, 0.16 g/t, in the above-mentioned chalcopyrite-pyrrhotite vein.

An analysis of the A ore points to high absolute concentrations of rare earth elements (REE), especially the light rare earths: La 34.2 ppm, Ce 81.3 ppm, Pr 10.0 ppm and Nd 41.2 ppm. These are comparable to the mean concentrations in the Saattopora I (Au-Cu), Iso-Kuotko (Au-As), Laurinoja (Fe-Cu-Au), Mäkärärova (Fe-Au), Kuusamo (Au-Co) and Bidjovagge (Au-Cu) deposits, which give overall mean values of La 29.1 ppm, Ce 56.8 ppm, Pr 7.0 ppm and Nd 28.3 ppm, whereas the other eight major gold deposits in Central Lapland give mean concentrations for the same REE that are only about a tenth of these: La 3.4 ppm, Ce 7.1 ppm, Pr 1.1 ppm and Nd 5.1 ppm (analyses by Nurmi *et al.* 1991, and by the author for Pahtavuoma, Saattopora and Laurinoja).

Besides the copper deposits there are a number of zinc-bearing zones almost 1000 m in length and with a maximum width of 30 m in the Pahtavuoma area. These are to be found in the hanging wall of the copper deposits (Fig. 22), and also in a set of parallel metasedimentary zones a few hundred metres north of the known copper deposits. No copper deposits appear to be associated with the latter, however.

There are altogether 6 sphalerite deposits at Pahtavuoma, with combined estimated mineral reserves of about 17 million tonnes and mean metal concentrations of Zn 0.81 wt%, Cu 0.11 wt%, Pb 0.09 wt%, Ni 0.02 wt%, Co 0.01 wt%, Fe 7.63 wt%, As 0.03 wt%, Ag 7 g/t and Au < 0.01 g/t, with S 2.44 wt% (Korkalo 1976). One of the best sets of results was obtained from a 17.3 m drill core that gave a Zn concentration of 2.21 wt% with Cu 0.09 wt% and Ag 13 g/t and another drill core with Zn 4.10 wt%, Cu 0.02 wt% and Ag 4 g/t over a length of 6.3 m. In some places the copper and zinc deposits are superimposed, and this is reflected in higher than normal zinc concentrations in the copper deposits.

The cadmium content of the Pahtavuoma copper ore is 50 ppm and that of the zinc deposits 100 ppm, figures that are of quite a different order from those found in the gold(+copper) deposits of Central Lapland, which are < 0.5 ppm (analyses by Nurmi *et al.* 1991 and the author). According to Papunen (1990), Cd concentrations in zinc deposits in Finland average around 300 ppm, with peak values of about 1000 ppm.

In addition to the copper and zinc deposits, there are also three uranium deposits at the western end of the Pahtavuoma area, close to the Western and Central deposits (Fig. 22). No uranium has been observed in or around the A or Ulla ore bodies. The host rock for the deposit is a skarnized phyllite, and the mineral containing it is uraninite, which forms intergrowth structures with pyrrhotite and molybdenite. The combined estimated mineral resources of the two best deposits are 0.14 million tonnes, with a U concentration of 0.39 wt% (Korkalo 1979). The mean concentrations of other metals are Cu 0.24 wt%, Zn 0.08 wt%, Pb 0.09 wt%, Ni 0.02 wt%, Co 0.01 wt%, Fe 9.17 wt%, As 0.02 wt%, Au < 0.01 g/t, Ag 24 g/t and Mo 0.024 wt% with S 2.82 wt%. These results are means weighted by sample lengths (mean 2 m) for a drill core of length 33 m and indicate that the metal and sulphur concentrations of the uranium deposits do not deviate markedly from those of the copper or zinc deposits other than in their higher U and Mo values.

Outokumpu decided in 1973 to commence underground investigations (Fig. 24) into the A and Ulla ore bodies at Pahtavuoma, in order to delimit them more precisely, assess their copper and silver content and conduct a feasibility study with respect to extraction and processing of the ore (Korkalo 1976). An incline shaft and ore drifts with a total length of 1500 m and a ventilation raise of 51 m were constructed in 1973–1976. The underground diamond and percussion drilling failed to alter the estimates of ore volume to any essential degree, as the boundaries of the ore bodies proved to be more irregular than was expected. Concentration tests were carried out at the Pori works of Outokumpu, and a total of 13 000 tonnes of ore with a mean Cu content of 1.01 wt% and Ag 19 g/t was extracted from the ore drifts and stored in the area.

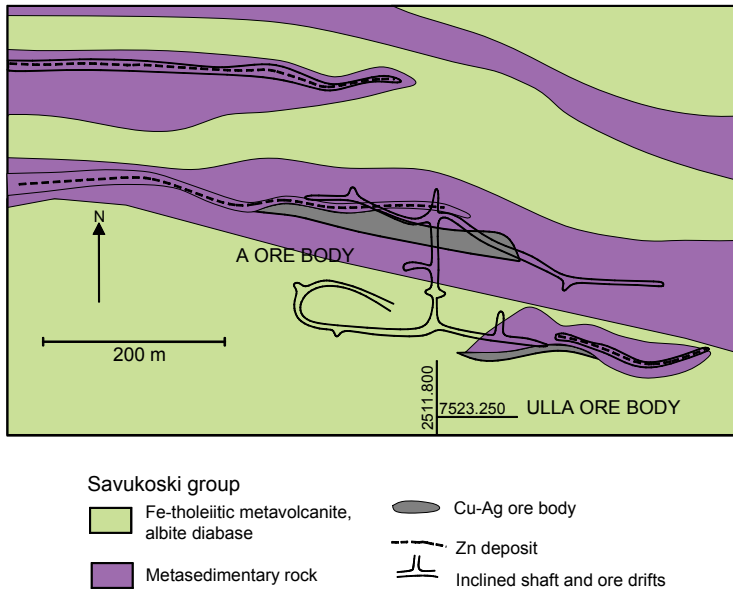


Fig. 24. The incline shaft and ore drifts constructed at the Pahtavuoma test mine (Korkalo 1976).

In 1993 a total of 261 000 tonnes of copper ore were mined from the A and Ulla ore bodies and 13 000 tonnes of the material extracted from the ore drifts in 1974–1976 concentrated at the Rautuvaara mine together with the processing of the Saattopora gold ore. 161 000 tonnes of ore had been obtained from the A ore body by open pit mining, together with 234 000 tonnes of country rock, giving an ore/waste rock ratio of 1/1.45, in addition to which 100 000 tonnes had been obtained by underground mining. The mean Cu content of all this extracted ore was 1.08 wt%, with Ag 27 g/t. Recovery rates were 85.4 % for copper and 65.0 % for silver, the Cu content of the concentrate being 22.64 wt% and the Ag content 410 g/t. Altogether the copper concentrate yielded 2523 tonnes of copper and 4537 kg of silver (Korvuo 1995).

The ore resources obtainable from the A ore body by open pit mining had been estimated in advance to be 173 000 tonnes, with a Cu content of 1.65 wt% and Ag 23 g/t. Owing to the irregular boundaries of the ore body, however, waste rock dilution was greater than predicted, which reduced the mean Cu concentration.

6.1.2 Riikonkoski

The Riikonkoski chalcopyrite deposit, about 10 km north of Kittilä (Fig. 12), was discovered by GTK in 1969 on the basis of a layman sample consisting of a boulder with a high copper concentration (Yletyinen & Nenonen 1972). There are at least 6 separate occurrences in the area, the main ones being the Eastern and Western occurrences, with a com-

bined size of 9.2 million tonnes and a mean Cu concentration of 0.48 wt% (Puustinen 1985).

The Riikonkoski area belongs to the Matarakoski formation, its youngest rocks being quartzites and conglomerates of the Kumpu group, which form an arc on the northern and eastern borders of the area. The metasedimentary rocks that lie inside this arc are composed of a frequently chlorite-bearing mica schist together with phyllite, greywacke, sericite schist, carbonate rocks and albite schists of significance for ore prospecting, in addition to which ultramafic rocks, albite diabases and gabbros intersecting metasedimentary rocks are encountered. The same formation also contains Fe-tholeiitic metavolcanites of the Kittilä group. The oldest rocks in the area are the quartzites of the Sodankylä group to be found in its southern and eastern parts (Papunen *et al.* 1987, Lehtonen *et al.* 1998).

The host rock of the Riikonkoski copper deposits is an albite schist or a phyllite with sericite-bearing interlayers, the principal ore minerals being pyrite, pyrrhotite and chalcopyrite in highly variable proportions, with magnetite, arsenopyrite, pentlandite, cobaltite and gold as accessory minerals, the last-mentioned occurring in conjunction with the arsenopyrite. All the deposits without exception are of the brecciated ore type. The largest sulphide-bearing deposit is almost 150 m in breadth and contains various zones of differing copper content. Cu concentrations rarely exceed 1 wt% in core samples of a few metres in length, however (Puustinen 1985, Lång 1986, Papunen *et al.* 1987).

The mean metal composition of the Riikonkoski copper deposits (arithmetic means of 32 drill core samples) is Cu 1.09 wt%, Zn < 0.01 wt%, Pb < 0.01 wt%, Ni 0.03 wt%, Co 0.01 wt%, Fe 9.70 wt%, As 0.04 wt% and Ag 2 g/t with S 4.62 wt% (Papunen *et al.* 1987). The higher than average copper content may be attributed to exceptionally high concentrations in a few samples. Au concentrations of 1–2 g/t are recorded over a core length of a couple of metres in places, but occurrences of gold are sporadic (Lång 1986). Riikonkoski resembles Pahtavuoma in its metal and sulphur concentrations, the clearest differences being in the precious metals, since Au concentrations at Pahtavuoma are < 0.01 g/t but Ag 25 g/t, whereas Riikonkoski has some accentuated Au concentrations but a mean Ag figure of only 2 g/t.

A total of 110 drill holes have been produced in the Riikonkoski area, with a combined length of 22.2 km (Yletyinen & Nenonen 1972), almost a half of them for investigating the two main deposits. Both of these deposits are exposed at the surface, raising the possibility of open pit mining, although the western deposit lies partly beneath the River Ounasjoki.

Although estimates of the mineral resources in the various deposits are imprecise, primarily on account of the scattered nature of the deposits themselves, they do give a general impression of the ore potential of the area. The eastern deposit is thought to contain about 2.5 million tonnes of copper-bearing rock with a Cu concentration of 0.68 wt%, while the western occurrence consists of a number of separate copper-bearing zones located close together and amounting to estimated mineral resources of 6.7 million tonnes, but with a Cu concentration of only 0.41 wt% (Puustinen 1985).

Puustinen (*op.cit.*) is of the opinion that the Riikonkoski copper deposits, like the other copper occurrences in the nearby area, represent the typical Precambrian distal strata-bound type, while Lång (1986) describes the main deposit as a volcanic-exhalative mas-

sive sulphide ore in which the massive part has been worn away by erosion. There is no concrete evidence that this massive part ever existed, however.

The Riikonkoski copper deposit does not belong to the same NE-SW deformation zone as the majority of the gold deposits in the southern part of the Kittilä greenstone area, but is located some 10 km south of this zone. On the other hand, it has certain features typical of the gold deposits of Central Lapland, such as albitization, low zinc and lead concentrations and naturally enhanced gold concentrations in places.

6.1.3 Vesilaskujänkkä

The Vesilaskujänkkä chalcopyrite occurrence in Eastern Lapland was discovered by Rautaruukki in 1981 in connection with investigations into the Jauratsi magnetite and pyrite deposits. It is situated near the Jauratsi magnetite deposit (Fig. 5), in a broad basin formed by schists and metavolcanic rocks belonging to the Matarakoski formation. There are two metavolcanite formations in the area, the younger of which is composed of ultramafic rocks and the older of basic metavolcanites, with the Jauratsi iron formation lying between them (Kerkkonen 1982, Lehtonen *et al.* 1998).

Vesilaskujänkkä is associated with albitized tuffites and black schists and consists of three distinct types of occurrence: a massive pyrrhotite occurrence, a stringer-type network of sulphide veins and an iron sulphide occurrence of the disseminated type. All three contain small amounts of chalcopyrite. Mean metal concentrations in the deposit as a whole are exemplified by the following results based on five diamond drill cores of total length 91 m weighted by the lengths of core analysed: Cu 0.23 wt%, Zn < 0.01 wt%, Ni 0.02 wt%, Co < 0.01 wt% and Fe 12.24 wt%, with S 8.08 wt% (Kerkkonen 1982).

6.1.4 Other formations with a copper potential

The greatest copper potential in Central Lapland lie in nickel-copper deposits associated with layered intrusions, the best known of which is the Kevitsa Ni-Cu-PGE-Au deposit in Sodankylä. This contains mineable ore reserves of 87 million tonnes, but metal concentrations are low, Ni 0.25 wt%, Cu 0.39 wt% and precious metals in all 0.6 g/t (Outokumpu 1998).

GTK has been studying the valley of the River Jeesiöjoki between Kittilä and Sodankylä since 1979 (Karvinen 1985), and Outokumpu carried out explorations of its own in that area in the early 1990s. The Jeesiöjoki area is located in the south-eastern part of the Kittilä greenstone area, south of the Porkonen-Pahtavaara iron formation, and according to Lehtonen *et al.* (1998) is composed predominantly of graphite phyllites and metavolcanic rocks belonging to the Matarakoski formation and albitized metasedimentary rocks of the Sodankylä group. There are also a number of gold deposits in the area, as described above, and copper showings have been reported in the Jeesiöjoki valley that differ from the other copper and gold deposits of Central Lapland.

A copper-antimony-silver occurrence has been identified in connection with an intermediate tuffite-black schist zone north of the village of Tepsa in the Jeesiöjoki valley. The host rock is a black schist or graphite-bearing tuffite containing carbonate breccia, and a 4 m core has indicated a Cu concentration of 1.00 wt% with Sb 0.06 wt% and Ag 8 g/t, while a separate half-metre core sample gave Cu 0.76 wt%, Sb 0.34 wt%, Ag 33 g/t and As 0.33 wt% (Karvinen 1985).

About 10 km ESE of the village of Tepsa is a copper-zinc-lead occurrence, a rarity for Central Lapland, occurring in connection with a black schist-tuffite zone. Here a 9.1 m drill core gave metal concentrations of Cu 0.15 wt%, Zn 1.26 wt%, Pb 0.80 wt%, As 0.05 wt%, Ni 0.02 wt%, Ag 3 g/t and Au < 0.01 g/t. Gold is encountered sporadically throughout the area, e.g. at a concentration of 4 g/t in a quartz vein 0.2 m in width intersected by one drill hole. One boulder has been discovered in the area with the unusual metal composition of Cu 2.4 wt%, Au 32 g/t, Ag 345 g/t and Sb 1.4 wt%, but it has so far proved impossible to trace its origin (Karvinen 1992).

At the western end of the Jeesiöjoki valley is the Tuonganoja gold deposit described above in connection with the gold deposits of the region. This, too, has considerable Cu concentrations (1–2 wt%) in places and is therefore of significance when assessing the copper potential of the Jeesiöjoki valley as a whole. It should also be mentioned that the catchfly *Viscaria alpina*, which is widely regarded as an indicator of copper in the bedrock, grows in abundance in the Tepsa area, as also in the vicinity of the other copper occurrences in Central Lapland.

The copper occurrences of the Jeesiöjoki valley resemble the Pahtavuoma copper-silver deposits in terms of their Cu, Ag, Zn and Pb concentrations, although the conspicuous presence of gold and antimony sets them apart from the latter.

The postorogenic Tepas granite, about 50 km north of Kittilä, contains a scattered Mo-Cu occurrence with a Cu content of 0.1–0.3 wt% in places and Mo 0.02–0.05 wt%.

The Kesänki uranium occurrence in the sericitic quartzite of the Ylläs formation, belonging to the Lainio group (Sarikkola 1979, Lehtonen et al. 1998), contains uraninite but also regularly sulphides, mostly pyrite and chalcopyrite, and Cu concentrations reach 0.2–0.5 wt% in individual analyses, although they are usually < 0.2 wt%. The other significant uranium occurrence in Central Lapland, that associated with the Pahtavuoma copper deposit, has a Cu concentration of 0.24 wt%. Both uranium occurrences, Kesänki and Pahtavuoma, lie relatively close to the FeOx-Cu-Au deposits of the Rautuvaara and Ylläs formations (5–15 km away). It is the general observation all over the world that significant amounts of uranium, for example, are to be found in conjunction with FeOx-Cu-Au deposits.

Occasional showings of chalcopyrite are to be found in association with massive pyrrhotite and pyrite occurrences in the Kittilä greenstone area, e.g. the massive iron sulphide deposits of Levijoki and Jerisjärvi and many others. No instance is known to the author, however, of such a deposit containing economically significant quantities of copper, but if a massive deposit of this kind were to be composed predominantly of pyrite this could be of importance as a source of sulphur.

7 Metallogeny of Central Lapland

Deposits are known in Central Lapland in which the major coloured metals are nickel, copper and zinc, the major colourless metals are chromium, iron, manganese, vanadium and niobium and the precious metals are gold, silver, platinum and palladium (Table 9). Less significant elements present are sulphur, uranium, arsenic, molybdenum, antimony and tungsten. The deposits that have attracted mining activities to date have been those of iron, iron oxide-copper-gold, gold, gold-copper and copper-silver ores.

The highest nickel, copper, chromium and vanadium potentials in Central Lapland lie in the layered intrusions, which also possess significant amounts of PGE and gold. The deposits associated with the layered intrusions indeed have considerable metal potential on a world scale in terms of their size. In addition to these, the ultramafic rocks of the region, particularly their komatiitic varieties, have a notable nickel potential, the iron oxide-copper-gold deposits copper and gold potential and the Pahtavuoma type deposit a copper and silver potential. The gold occurrences are mainly to be found in the southern and central parts of the Kittilä greenstone area, practically always accompanied by the presence of arsenic, while many of the gold deposits also contain copper, nickel and cobalt.

Iron is an essential element in the deposits of the iron-copper-gold type and in the banded iron formations, while vanadium is associated with the layered intrusions and with the amphibolites in the northern part of the Kittilä greenstone area. The principal uranium occurrences are those of Pahtavuoma and Kesänki, but it is significant that zinc and lead are rare in Central Lapland, being encountered mainly at Pahtavuoma and in some places in the Jeesiöjoki valley. Molybdenum is similarly rare, being found in post-orogenic plutonic rocks and in skarns at contacts with acidic intrusive rocks.

Table 9. Metallogeny of Central Lapland.

Group or intrusion	Age (Ma)	Metallogeny	Host rock	Type area
Placer		Au	Gravel	Ivalojoiki (Subarea 8)
Carbonatite	368–362	Nb, Ta	Carbonatite	Sokli
Kumpu	1930–1850	Au	Conglomerate	Kaarestunturi (Subarea 7)
		Au	Quartzite	Sirkka W (Subarea 2)
Lainio	1930–1850	U, Cu	Quartzite	Kesänki
		Fe, Cu, Au	Skarn	Ylläs
Kittilä	2050–2000	Au, As	BIF, metasediment	Suurikuusikko (Subarea 5)
		Fe, Mn	BIF	Porkonen-Pahtavaara
		Mo	Skarn	Granite contacts
Intrusion	2058	Ni, Cu, PGE, Au	Layered intrusion	Kevitsa
Savukoski	2200–2050	Au, Cu	Metasedimentary rock	Saattopora (Subarea 1)
		Au, Cu, Ni, Co, As	Metavolcanic rock	Soretiavuoma N (Subarea 2)
		Fe, Cu, Au	Skarn	Hannukainen
		Cu, Ag, Zn, U	Phyllite	Pahtavuoma
		S (no metallic)	BIF	Jauratsi
Sodankylä	2400–2200	Au, Cu (Ni, Co)	Albitized metasediment	Kutuvuoma (Subarea 3)
		Au	Komatiite	Pahtavaara (Subarea 4)
		Ni	Komatiite	Pulju zone
Intrusion	2437	Cr, V, PGE, Au	Layered intrusion	Koitelainen, Akanvaara
Archaean	< 3100	Au	BIF	Auermavaara (Subarea 6)

8 Exploration for gold and copper in Central Lapland

Systematic ore exploration in Northern Finland began in the late 1950s. Outokumpu set up an office in Rovaniemi in 1958 for this purpose, focusing its research initially on the ore potential of the Kittilä greenstone area, and Rautaruukki (at that time Otanmäki Oy) established its own prospecting office in Rovaniemi a year later, in 1959, with the aim of looking for iron ores in Northern Finland. The major focus of Rautaruukki's exploration efforts for some decades was nevertheless the Sokli carbonatite massif in Eastern Lapland.

Rautaruukki ceased mining and ore prospecting in 1986, and Outokumpu announced in 2001 that it intended to give up its mining operations and its prospecting and development work with respect to base metals (Outokumpu Oyj 2001), and it has later done the same with respect to precious metals. When Rautaruukki closed its exploration section, some of the staff moved to Suomen Malmi Oy and some to the Outokumpu organization, and the main research and prospecting material accumulated by Rautaruukki was also transferred to Outokumpu. The majority of that and also Outokumpu's own prospecting material was passed on to GTK under an agreement concluded in 2003.

Although GTK founded its regional office in Rovaniemi in 1973 and moved into a building of its own in 1980, it had been working in Northern Finland since the late 1950s under the auspices of its Espoo unit. The establishment of a regional office simply meant that its basic research and ore prospecting work in Central Lapland was greatly expanded and intensified.

The geological research projects carried out by universities which have been intended to be of service to ore prospecting in Central Lapland have not in fact led directly to the discovery of any new deposits, but they have had a significant positive influence on ore prospecting and on the evaluation of the ore potential of certain areas.

In addition to the above organizations and research institutes, a number of international companies began to show an interest in ore prospecting and mining in Central Lapland in the 1990s. Under an amendment to the Finnish mining legislation approved in 1992 (which came into force on 1st January 1994), any person, corporation or foundation resident in the European Economic Area or having its main registered office there is entitled to search for, lay claim to and exploit deposits of certain minerals as designated in that legislation on its own land or that owned by others (amendments to the Mining Law 1925

/ 92). Additional investigations into already known deposits and technical and commercial evaluations of deposits carried out by foreign companies greatly increased in the 1990s, and it became the task of MTI to organize the sale of mineral deposits discovered by GTK to the highest bidder among the interested companies.

The oldest mentions of ore prospecting in Central Lapland date from 1864, when P. W. Aurén discovered an iron formation in the Porkonen-Pahtavaara area. This remained an object of interest for many researchers for several decades, but although Rautaruukki carried out large-scale drilling operations in the area in the 1970s (Paakkola 1971), the research never led to any mining activity.

The first large-scale explorations in the region were those of Atri Oy directed at the Sirkka multimetal deposit and its surroundings in Kittilä over the period 1939–1953. This work included geological and geophysical investigations and the sinking of over 300 diamond drill holes at Sirkka and Loukinen. In 1953 the company Oy Vuoksenniska Ab built an underground test mine at Sirkka, together with a small concentrating plant for technical and economic evaluations of the deposit.

The discovery of the Riikonkoski, Pahtavuoma and Saattopora II copper deposits around 1970 gave a new impetus to prospecting and research into base metals in Central Lapland. The world price of gold was nevertheless so low at that time, around 150 USD per ounce, that inadequate attention was paid to the gold potential of these copper deposits. Later research showed, however, that their gold potential was a factor to be reckoned with, at least in the case of Saattopora II and in part also Riikonkoski. The discovery of the Saattopora I and Pahtavaara gold ores in 1985 then led to a boom in exploration all over Finland, especially in gold ore prospecting. The major deposits in Central Lapland had already been discovered prior to that boom, however, i.e. the Sokli carbonatite massif, the Kevitsa nickel-copper-PGE-gold deposit, the Koitelainen and Akanvaara PGE and vanadium-bearing chromitite deposits, the Suurikuusikko gold deposit (in 1986), the Porkonen-Pahtavaara iron-manganese deposit and the Rautuvaara and Hannukainen iron ore deposits. Although substantial advances have been made in prospecting methods and general geological knowhow and ore modelling over the last twenty years or so, no new ore deposits of any significance have subsequently been discovered in Central Lapland.

One essential factor governing the efficiency and success of ore prospecting is the basic body of geological, geophysical and geochemical data available. About 1/3 of the present area is covered by geological maps to a scale of 1:100,000, and there are numerous other maps produced by GTK and various companies and universities that are useful for exploration purposes. Low altitude aerogeophysical measurements have been carried out over virtually the whole of Central Lapland, and the maps obtained by processing these can be of considerable help in identifying and delimiting the structural features of the bedrock and the zones of rock types with an ore potential. Geochemical surveys provide one of the most important methods for locating metal occurrences as far as ore prospecting in this region is concerned, and have provided a concrete starting point for the discovery of numerous gold and copper deposits.

The principal deformation zones and their associated fault and shear zones occupy a crucial position in prospecting for gold, and to some extent for copper as well, as practically all the gold occurrences in the area are connected with these NW-SE and NE-SW deformation zones and their conjugate shear zone and faults. Although the FeOx-Cu-Au

deposits of the Rautuvaara and Ylläs formations are not directly bound to shear zones, local faults have contributed to their identification.

From the ore prospecting point of view, the most important of the deformation zones, which are composed of numerous practically parallel regional and local fracture and fault zones, is that known as the Sirkka line, running NW-SE along the southern edge of the Kittilä greenstone area (Gáal *et al.* 1989). This represents in effect the same structural feature as the zone of the overthrust surface between the Kittilä and Savukoski groups, which, together with its surroundings, is characterized by ultramafic rocks and graphite-bearing schists. The central and northern parts of the Kittilä greenstone area, on the other hand, feature banded iron formations and associated gold deposits that are connected with a NE-SW deformation zone and its related shear zones, e.g. those of Suurikuusikko, Kuotko and Sukseton.

Almost all the known gold deposits of Central Lapland are connected with altered rocks in deformation zones, so that these rock types can be regarded as indicators for the locating of such deposits. It is often difficult to deduce the origin of the host rock on account of pronounced alteration, but it is most frequently of a sedimentogenic or volcanic nature.

The deformation zones and their conjugate faults and shear zones can be located very accurately by means of magnetic surveys, and the southern edge of the Central Lapland greenstone belt, for instance, which contains numerous gold deposits, can be followed quite successfully on ground or aeromagnetic maps. The majority of the FeOx-Cu-Au deposits in Central Lapland were discovered with the aid of magnetic methods. The amounts of sulphides contained in them are nevertheless so small (S usually < 2 wt%) that it is difficult to distinguish the copper and gold-bearing parts from the magnetite deposit.

Graphite schists can be located by electromagnetic methods, but they have such powerful electrical conductivity that they tend to obscure any gold or copper deposits present, so that the method is not directly applicable for the latter purposes. The copper deposits of Pahtavuoma, for example, cannot be distinguished from their associated graphitic phyllites by electrical conductivity. Induced polarization measurements in diamond drill holes nevertheless revealed two distinct phyllite zones in the Ulla ore body at Pahtavuoma, and later drillings and underground investigations confirmed that the ore body was divided into two parts by a mafic volcanic rock.

Geochemical surveys have been shown to be the most efficient means of exploration for gold and copper deposits in Central Lapland, by contrast with the situation in the Kuusamo schist belt, where till geochemistry has not played a significant role in the localization of such deposits (Vanhanen 2001).

In glaciated terrain, as in Northern Europe, the Quaternary sediments overlying the bedrock are usually allochthonous in origin. The Central Lapland area lies at the centre of various ice flow stages, however, and the till material of interest is frequently autochthonous, so that this till, and still more obviously the products of preglacial bedrock weathering, will usually represent the local bedrock. This means that general geochemical sampling at a density of 1 sample per 4 km² can easily be too sparse to yield any positive results. On the other hand, isolated till anomalies have often provided significant ore prospecting clues under such conditions. It is evident, however, that the character of the

local till means that a denser sampling network than usual is required for a geochemical survey.

At least five till beds of differing age occur in Central Lapland, although the youngest of all and the two oldest are present only in restricted areas and are of minimal significance as far as ore prospecting is concerned (Hirvas 1991). Recognition and differentiation of the various till beds is a matter of some importance for geochemical ore prospecting, however.

The till of Central Lapland thus represents the local bedrock, and it may be said that where a geophysical anomaly provides indirect information on a possible deposit, a geochemical sample can represent such a deposit directly in a qualitative and frequently also quantitative sense, or at least constitute concrete evidence of a rock type that has a certain ore potential. Practically all the gold and copper deposits of Central Lapland were discovered as a consequence of geochemical surveys.

Efficient use has been made of boulder observations in Finland, and these have frequently provided the initial stimulus for exploration. On account of the Quaternary geological situation in Central Lapland, however, boulders containing ore minerals are relatively rare, with the exception of the hundreds or even thousands of haematite and goethite boulders to be found in the eastern part of the area.

The presence of weathered bedrock emerges as a matter of considerable importance for ore prospecting in Central Lapland. The weathering can continue downwards for several tens of metres from the bedrock surface and it is difficult to obtain adequate diamond drilling samples from such material, as core losses are too high. It is therefore common to use the river circle technique in these cases.

The cover of weathered bedrock overlying the Saattopora gold ore was of the order of 1 m in depth and had gold concentrations of 2–5 g/t in places, but the small gold deposit of Kutuvuoma had more than 10 m of weathered material on top of it in places, analyses of which pointed to pronounced enrichment of gold, so that Au concentrations were in excess of 10 g/t in places. By contrast, there is practically no weathered bedrock on the surface of the Pahtavuoma copper deposit, but the sulphide-bearing zone has a dense fracturing pattern that could be regarded as evidence of incipient weathering.

Outokumpu has made successful use of heavy fraction examination of till samples for gold prospecting purposes, employing a method developed by the late Erkki Ilvonen, Lic.Phil., who worked for the company as a Quaternary geologist. No report has ever been published on the method, but the broad outlines of it are as follows. About five litres of till are taken from the area to be studied using a spade or small excavator and processed with a gold hound or a small Knelson concentrator. The processed till material is then panned by hand and the eventual heavy mineral fraction is examined under a microscope. The number of gold nuggets contained in this fraction will then provide information on the gold ore potential of the area and the likelihood of an occurrence. The next step, following the heavy mineral results, is till / bedrock interface / weathered rock geochemistry of the area concerned. The geochemical samples should be of size 250–500 g, depending on the grain size of the gold nuggets: the coarser the gold, the more sample will be needed for analysis.

One of the last stages in ore prospecting is bedrock drilling, the results of which determine whether further investigations are warranted. The drilling density will depend on the geometry and heterogeneity of the deposit. The majority of the gold deposits in Central

Lapland, for instance, are pipe-shaped, with a practically vertical longitudinal axis. Ore outlines are not generally sharp but grade gradually. Also, most of the deposits are composed of individual high-grade ore zones separated by low-grade zones. Narrow, pipe-shaped or heterogeneous deposits require a greater than usual drilling density in order to determine their outlines and form. Good examples of this are the Kutuvuoma deposit, which consists of two vertical ore bodies of elliptical horizontal cross-section, and the Saattopora I A ore body, which has a pipe-shaped internal gold enrichment (Au 5–10 g/t) at its eastern end that is oriented in parallel to the lineation of the area. The Saattopora copper deposit, on the other hand, is a scattered occurrence made up of several copper and gold-bearing zones.

Another factor affecting the required drilling density and the gold concentrations observed is the grain size of the gold. The coarser the gold in the deposit, the larger the number and size of samples that will have to be analysed, which will usually mean a denser network of drill holes. The estimated ore reserves in the A ore body at Saattopora I tripled as a consequence of a denser diamond and percussion drilling network during mining. This was due mainly to the fact that many of the holes drilled from the ground surface gave erroneous information on account of the small sizes of sample obtained.

9 Exploitation of the gold and copper deposits of Central Lapland

The principal factors leading to the opening of a mine have been the following: economically mineable ore reserves and grades, the total mineral resources contained in the deposit, the stoping and processing methods required, rock mechanical conditions, recovery of concentrates, capital costs, operating costs, production capacity, the operating life of the mine, infrastructure, environmental aspects, finance, market prices of the products and the general state of world markets. Such a decision will always be based on profitability calculations, and in general it may be said that the more complex the research and planning is at the various stages in a mining project, the more exacting the economic evaluation, which may take the form of a conceptual, pre-feasibility or feasibility study depending on the degree of detail reached in the investigations. The last-mentioned stage, the feasibility study, may also be extended to meet the requirements of banks or other sources of finance.

Estimates of mineral resources are classified into three levels of probability on the basis of the precision of the research results: measured (proven), indicated (probable) and inferred (possible). The opening of a mine may be contemplated on the basis of the first two categories of estimate. It should be remembered, of course, that the evaluation of an ore body must take account of technical and economic aspects as well as geological data.

As a general rule, the smaller an ore deposit is, the higher the concentrations of its metals or minerals must be to ensure profitable mining, and vice versa. There is not, however, always a systematic relationship between the size and grade of an economic deposit (Mackenzie 1991).

The extraction method adopted will depend on the depth of the ore body below the surface, its size and geometry, the metal or mineral concentrations of the exploitable ore and the rock mechanics. Ore deposits of large volume that reach the ground surface, e.g. porphyry copper ores, can be extracted at high capacity by open pit mining, leading to low unit costs, which will in turn enable low-grade ore deposits to be exploited. Underground mining will be resorted to only when open pit extraction is impossible or economically less feasible. It is also possible to begin with open pit mining and to move over to underground mining once the ratio of waste rock to ore has become so high that the former approach is no longer feasible.

The ore mineralogy is one of the most significant factors affecting mineral processing. Especially in the case of gold, the mode of occurrence in the ore is crucial to the choice of concentration method. Apart from the exploitable minerals, ores may contain undesirable by-products that may be of importance for the choice of processing method and for the quality of the eventual products.

The gold and copper deposits known to date in Central Lapland are small in terms of volume and of low metal concentrations, the one exception being Suurikuusikko, which is the largest known gold deposit in Europe, containing 94 tonnes of gold (Riddarhyttan Resources AB 2005), and is highly significant worldwide. Investigations at the site are still in progress. The Boliden copper-gold ore deposit in Central Sweden, belonging to the volcanic-associated massive sulphide ore type, nevertheless contains 8.3 million tonnes of ore with an Au content of 15.2 g/t (Poulsen & Hannington 1995), so that it is substantially larger than Suurikuusikko in terms of the amount of gold available, 126 tonnes, and the same is true of the Aitik copper-gold ore deposit in Northern Sweden, with 185 tonnes of gold (Wanhainen 2002). Many of the known gold deposits in Central Lapland have high gold concentrations (Au > 5 g/t) but their small size or dispersed character prevents their exploitation on a large scale. This would not rule out small-scale mining, however, if the ore could in one way or another be worked up into a saleable product.

The majority of the mining of gold and copper ores in Central Lapland has involved open pit methods. Open pit and partly underground mining has taken place at Saattopora and Pahtavuoma. The Pahtavaara and Hannukainen mines operated entirely on an open pit basis, but when Pahtavaara was reopened in 2003 operations were extended underground.

The fact that most of the gold and copper deposits in Central Lapland are positioned vertically makes them somewhat easier to exploit. Waste rock dilution at Saattopora was greater than expected because of graphite-bearing schists and shear zones located close to the contact between the ore and the country rock, while at Pahtavuoma the tests of bed-rock mechanics and experiences with the inclined research shaft led to the conclusion that there was pronounced fracturing in the phyllite-mica schist host rock down to a depth of 100 m from the bedrock surface, so that there was a considerable amount of water-filled space in the sulphide-bearing zone that caused problems in construction of the inclined shaft and pilot drifts. The location of the test mine at Sirkka close to the overthrust contact between the Kumpu group quartzites and the metasedimentary rocks of the Matarakoski formation also caused mining difficulties, and the vertical shaft and ore drifts had to be lined almost entirely with a log framework during mining in order to prevent rock falls on account of the poor quality of the bedrock (Räisänen 2001). As at Pahtavuoma, large amounts of water also entered the underground parts of the test mine at Sirkka.

In most of the gold and copper deposits of Central Lapland the boundary between the ore and country rock is a gradual one, except for a few massive iron sulphide occurrences. In addition, the deposits are scattered ones, often composed of several zones separated by interlayers of waste rock. In order to achieve selective mining and employ the projected cut-off grade, determination of the boundaries of the ore body has to be based on extensive sampling and analysis. This is essential even in the case of narrow ore bodies. Grade control is in fact one of the most important aspects of mining.

One factor that has to be taken into account when calculating gold concentrations is the nugget effect. It means that the highest analysis results have to be cut down if all or

part of the gold in a deposit is relatively coarse-grained (Korkalo *et al.* 1986). Thus, where a mean Au concentration of 4.4 g/t was obtained in the pre-feasibility study at Saattopora before this adjustment, the decision to drop all the measured concentration values in excess of 20 g/t to exactly 20 g/t lowered the estimate to 3.6 g/t, which was taken as the mean for the 670 000 tonnes of ore reserves in the eventual feasibility study. The head grade of the concentrating plant was 3.2 g/t, the difference in this case being attributed to waste rock dilution and the mining of a greater amount of ore than had originally been planned, so that lower-grade parts of the ore body were included.

The method used for mineral processing depends mainly on the ore mineralogy, and to some extent also on the metal or mineral concentrations of the exploitable ore. The methods used for gold ores are leaching, gravity separation and flotation, or some combination of these. The most commonly used gold processing method on a world scale is cyanide leaching technology, which is especially applicable when the gold is too fine-grained for gravimetric concentration, or else the gold concentration of the initial material is too low, usually less than 1 g/t. The feed to the leaching process can be the primary ore, a flotation concentrate, processing waste containing residual gold or some other material with a gold content. One requirement for the flotation process is that the ore should contain enough floatable particles, e.g. sulphides, to achieve a flotation concentrate. One restriction on gravity separation is that the gold should be of an adequate grain size.

A refractory ore is one in which the gold occurs in small inclusions, usually in pyrite or arsenopyrite or their lattices. In this case cyanide leaching technology alone is not sufficient to release the gold but some form of pre-processing is required, e.g. various bioprocesses, in order to disrupt the lattice structure of the sulphide grains and release the gold from them in a cyanide-soluble form.

The main concentration processes for copper ores are flotation in the case of sulphide ores and leaching in the case of oxide ores. There are only sulphidic copper deposits in Central Lapland, as is the case throughout Finland.

The gold deposits of the Central Lapland Greenstone Belt can be divided into three groups with regard to their concentrating properties. The easiest to process technically are those containing free milling gold but no arsenic-bearing minerals, the second are those containing sulpharsenides, and the third those containing refractory ore. All the gold deposits that have been mined to date have been of the first type. Very many of the deposits in the area nevertheless belong to the group containing sulpharsenides, from which it is difficult to obtain commercially saleable products at reasonable cost using conventional concentration techniques (gravity separation, flotation or leaching). Various bioprocesses such as bioleaching (for copper ores) and bio-oxidation (for gold ores) offer relatively inexpensive alternatives for the concentration of ores that are poor in minerals or difficult to process (Viikari & Rättö 2002), e.g. the sulpharsenide-bearing deposits of the Sirkka-Hirvilavanmaa sequence or the gold deposits in the central parts of the Kittilä greenstone area, which almost without exception contain arsenopyrite. In addition, the Suurikuusikko deposit (MTI 1997, Härkönen 1992) at least, and in part also the Loukinen deposit (MTI 2002), are of the refractory ore type, so that the process planned for Suurikuusikko is a multi-stage one involving flotation, bio-oxidation and cyanide leaching (Riddarhyttan Resources AB 2003).

The processing method applied to the Saattopora gold ore was a combination of gravity separation and flotation, while only the gravity separation technique was used at the

Pahtavaara mine when it was opened, flotation being introduced later. In the case of the Laurinoja FeOx-Cu-Au ore the initial method was magnetic separation, for the production of a magnetite concentrate, after which flotation was employed to obtain a gold-bearing copper concentrate. The Pahtavuoma copper ore was processed by flotation. Attempts to produce a concentrate containing silver and related minerals by gravity separation were unsuccessful.

Fouling elements have caused few problems in the case of the gold and copper ore bodies of the Central Lapland Greenstone Belt that have been exploited to date. The most commonly occurring element of this kind in the ores in question is arsenic, although tellurium, bismuth and antimony are also encountered. The A ore body at Saattopora did not contain any appreciable amounts of such elements, as its As concentration was only 200 ppm, with Te < 2.0 ppm and Bi < 1.3 ppm. The B ore body, however, had sufficiently high As concentrations in places (As 1300 ppm) that special measures had to be taken, the main tactic being to mix ores of different types together before processing in order to achieve a suitably low mean As concentration. The As, Te and Se concentrations in the Pahtavaara gold ore are sufficiently low (As 6.3 ppm, Te 110 ppb and Se 11.8 ppm, Nurmi *et al.* 1991) that they do not detract from the quality of the concentrate at all, while the Pahtavuoma copper ore has a mean As concentration of 500 ppm and a Cd concentration of < 10 ppm.

Neither the Laurinoja FeOx-Cu-Au ore nor any of the other magnetite deposits of the Rautuvaara formation can be said to contain any harmful amounts of As or Te-bearing minerals (Hiltunen 1982), although sulphur concentrations in sulphide-bearing magnetite ores can interfere with the quality of the resulting iron concentrates.

The investments entailed in setting up a mine are of three main kinds; investments in the mine itself, the concentrating plant and the infrastructure. The principal factor affecting the magnitude of these investments is the capacity of the mine, although all aspects can have significant local effects in one way or another. The larger the capacity of the mine, the higher the overall capital investment costs, but the lower the costs per unit of ore extracted. The extent of the infrastructure costs as a proportion of the total is dependent on the size of the mine, the location of the area concerned, natural conditions at the site, environmental factors and the general level of development in the country.

The value of production from a mine, and thus the profitability of the endeavour, will be affected by factors such as waste rock dilution and ore loss and the value of the concentrate obtainable from the ore. Smelters and mining companies usually negotiate a price for the concentrates separately in each case, or else make use of existing sales agreements.

A gold or copper mine will normally receive 60–90 % of the in situ value of the metals in its ores, mainly depending on the recovery rates of the metals. It will normally make precise calculations based on alternative volumes of ore production and cut-off values for the gold and copper in order to achieve the optimal net present value of cash flow.

The profitability of metal ore mines is usually highly susceptible to fluctuations in the world prices of the metals, and choice of the right moment for opening the mine may be crucial in the case of those of small or medium size. Sales of the products of a mine may be affected greatly by worldwide economic fluctuations, as stocks will accumulate and prices drop at times of recession, while the opposite will be the case when the economy is more buoyant.

The capital investments entailed in opening a medium-sized copper or gold mine in Finland (extracting 100 000–300 000 tonnes of ore a year) with processing by flotation or gravity separation are of the order of 20–50 million euros, although both the investment costs and running costs can increase greatly if the deposit contains largely refractory gold ore, for example, on account of the more expensive processing technique.

The working gold and copper mines of Central Lapland, i.e. those of Saattopora (Au-Cu), Pahtavaara (Au), Kutuvuoma (Au), Laurinoja (Fe-Cu-Au) and Pahtavuoma (Cu-Ag), have been very successful in terms of both their mining and processing technology. The Pahtavaara mine was closed for some years but was reopened towards the end of 2003, while the Saattopora gold mine and the part of the Laurinoja FeOx-Cu-Au ore body at Hannukainen that was exploited by Outokumpu both proved economically viable. Exploitation of the Pahtavuoma copper ore was less profitable than expected, however, on account of inadequate prior research, which meant that waste rock dilution was higher than had been allowed for. Exploitation of the Saattopora I, Pahtavuoma and Laurinoja ores also allowed full use to be made of the Rautuvaara concentrating plant at Kolari, to which the ore extracted from these mines was transported by road for processing. The Pahtavaara and Kutuvuoma ores have been processed at the Pahtavaara mine, which is still functioning.

There are a number of small-sized, often widely scattered gold deposits in Central Lapland that it is not economically profitable to exploit. If some of these should prove in the future to contain economically viable parts, it would again be reasonable to construct a single central concentrating plant, the geographical location of which would be determined by the distribution of the ore deposits. Since all the known gold and copper deposits in Central Lapland, including the FeOx-Cu-Au deposits, are situated within 100 km of each other, the ideal location for the concentrating plant would be no more than 50 km away from any of them. The Rautuvaara plant, for instance, was ideally situated for processing the Hannukainen, Saattopora I and Pahtavuoma ores as well as those from Rautuvaara itself.

An alternative for exploiting small and medium-sized ore deposits (with an output of 50 000–200 000 tonnes per year) would be a movable concentrating plant, whereupon the investment costs could be distributed between the mines. One disadvantage, of course, would be that each site would have to have its own tailings bond. Thus the question of which alternative would be economically the most successful, a central concentrating plant or a movable one, would depend on the sizes of the deposits to be exploited and the distances between them.

The capital investment required in 1989 for adapting the Rautuvaara processing plant for concentrating the Saattopora I gold ore was 3.1 million euros, whereas the investment required for opening the Pahtavaara mine 5 years later was very nearly 20 million euros. The feasibility calculations that led to the opening of the Saattopora mine set out from an ore volume of 670 000 tonnes with an Au concentration of 3.6 g/t and Cu 0.3 wt%. Given the cost levels prevailing at that time, transportation of the ore over a distance of 55 km to Rautuvaara was more economical than building a separate processing plant at Saattopora. In practice, however, the exploitable ore reserves at Saattopora tripled in size in the course of mining, and if this had been known at the outset, it would undoubtedly have been a more profitable proposition to build a concentrating plant at the site.

10 Summary and Discussion

The gold and copper deposits of Central Lapland are associated with fault or shear zones belonging to the NW-SE and NE-SW-oriented deformation zones in the region, which in turn intersect the major fracture zone that crosses the whole of the Fennoscandian Shield from Northern Norway to Lake Onega in Russia. Preliminary results of seismic reflection measurements for Central Lapland obtained in the course of the Finnish Reflection Experiment 2001–2005 (Kukkonen, pers. comm. 10.9.2004) point to a bedrock discontinuity that in the author's opinion may be attributed to this fracture zone. The discontinuity has a vertical dimension of several tens of kilometres and is also closely connected with the proximity of the contact between the Archaean craton to the east and the Palaeoproterozoic domain to the west (Fig. 25).

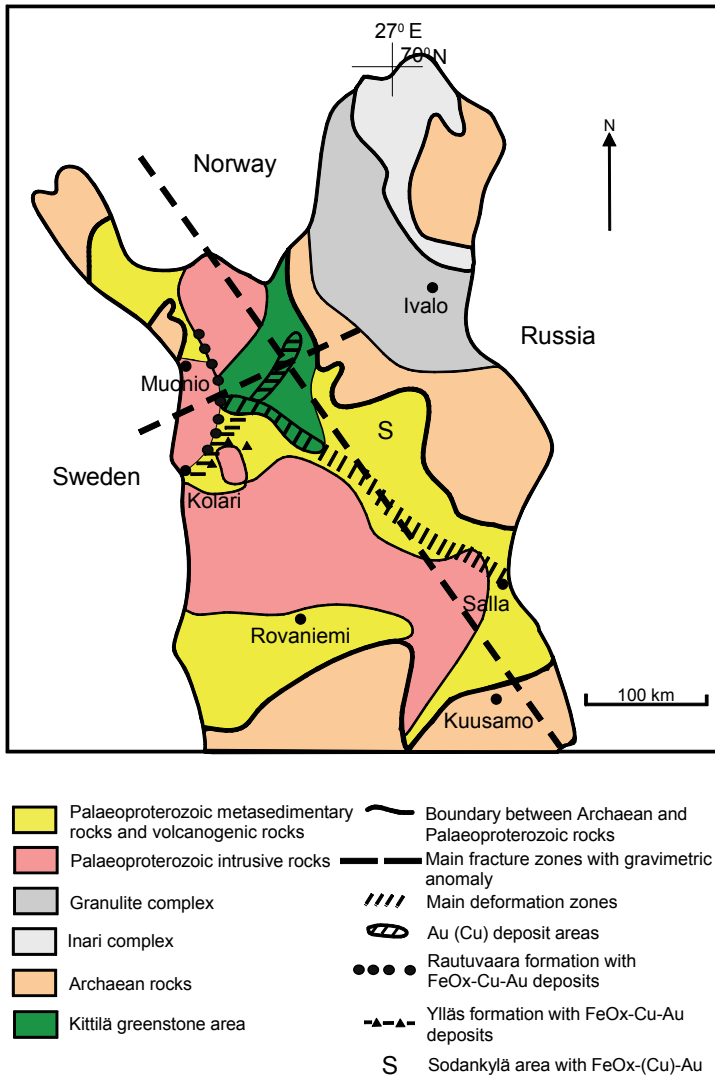


Fig. 25. Simplified geology of Northern Finland, with the main structural setting and main areas in Central Lapland possessing gold, copper and FeOx-Cu-Au deposits.

A considerable proportion of the approximately 30 known gold deposits in Central Lapland are located in the NW-SE-oriented deformation zone that runs along the southern edge of the Kittilä greenstone area (Fig. 25). These can be divided into clusters characterized by similarities in terms of geological environment, mineralogy and metallogeny. The host rock in each case is either metasedimentary or volcanic, and the principal ore mineral is usually pyrrhotite in the deposits connected with metasedimentary rocks and pyrite in those connected with tholeiitic or ultramafic volcanic ones. The deposits frequently contain varying amounts of copper, nickel, cobalt and arsenic-bearing minerals in addition to gold.

The second significant area of gold deposits is the NE-SW-oriented deformation zone in the central part of the Kittilä greenstone area (Fig. 25). This area has large numbers of quartz-banded iron formations in which both a sulphide facies and an oxide facies are usually represented, and also a silicate and a carbonate facies in some cases, the gold deposits mainly being linked to the sulphide facies. The central part of the Kittilä greenstone area does not possess any of the altered ultramafic rocks typical of the Savukoski group, and copper, nickel and cobalt-bearing sulphides and sulpharsenides are absent or occur only as accessory minerals. One exception to this is arsenopyrite, which is one of the principal ore minerals in the gold deposits along with pyrite, pyrrhotite and to some extent chalcopyrite. The gold is usually present in free milling form, but the Suurikuusikko deposit, for example, is a refractory ore in which the gold is lying within the arsenopyrite and pyrite.

The most extensive iron formation in Central Lapland is the Porkonen-Pahtavaara formation in the south-eastern part of the Kittilä greenstone area. This contains oxide, sulphide, carbonate and silicate facies, but no gold deposit has been found to date, although anomalous gold concentrations have been observed in rocks representing the sulphide facies. More significant gold concentrations have in fact been found in the rocks of the oxide facies in the Karjalehto and Mustavaara iron formations further south. The Suurikuusikko gold deposit is evidently connected with a northward continuation of the sulphide facies of the Porkonen-Pahtavaara iron formation. Similarly, the Jauratsi magnetite-goethite and sulphide occurrences in the eastern part of the Central Lapland region have failed to yield any evidence of gold deposits other than the gold anomaly in the Vesilaskujänkkä copper occurrence.

Other gold occurrences in Central Lapland include two palaeoplacer deposits connected with the quartzites of the Kumpu group and two deposits associated with Archaean iron formations in Eastern Lapland. As a curiosity, mention should also be made of the placer gold to be found in the north of the region.

The FeOx-Cu-Au deposits of Western Lapland are associated either with skarn at contacts with monzonite intrusions or else with skarn zones in metavolcanic rocks close to acidic intrusions (Fig. 25). The FeOx-Cu-Au deposits are not controlled by the regional NW-SE and NE-SW-oriented deformation zones, although local faults appear to be implicated in their location. Those of the Rautuvaara and Ylläs formations are metallogenically comparable one with another, even though they occur in geological formations that differ in both character and age. The FeOx-Cu-Au showings of the Sodankylä area (Fig. 25) are modest in extent but contain varying amounts of gold, copper and cobalt in addition to magnetite. There are no exposed acidic intrusive rocks in the Sodankylä area of the kind to be found in Western Lapland, although the extensive Central Lapland granite area lies to the south of the FeOx-Cu-Au showings and post-orogenic granites of the Nattanen type to the north.

Hiltunen (1982) regards the magnetite(\pm Cu-Au) deposits of the Rautuvaara formation as metasomatic deposits connected with skarn. Such skarn deposits are frequently associated with ores of the FeOx-Cu-Au type, and also with porphyry copper deposits. Vanhanen (2001) takes the Fe-Co-Au-(U) deposits of Kuusamo as representative of this type in Finland, although Pankka (1997) likens them to the Archaean mesothermal gold deposits. Vanhanen also includes the Saattopora gold ore and the Riikonkoski copper deposit in this same type, which, if this is really the case, would imply the classification

of practically all the other gold and copper deposits of Central Lapland as FeOx-Cu-Au ores as well. Vanhanen similarly regards the Porkonen and Jauratsi iron formations as potential locations for FeOx-Cu-Au deposits, although he admits that this is a "more disputable" question. Both of these are chemical, quartz-banded iron formations, however, so that they cannot have anything to do with the magmatic, high-temperature FeOx-Cu-Au ore type. On the other hand, they may well be potential locations for gold deposits.

An albite-antophyllite rock type would appear from a prospecting point of view to be a significant host rock for FeOx-Cu-Au deposits at Cu Rautuvaara and Kuervitikko at least, and to some extent at Hannukainen. Copper and gold concentrations tend to be higher in deposits hosted by albite-antophyllite rocks than in those associated with skarn, although iron concentrations are usually only about a half of those in magnetite skarns.

In spite of the intensive research and exploration that has taken place in recent times, we still lack any clear model for the FeOx-Cu-Au ore type. A highly heterogeneous group of deposits have been assigned to it, deposits that have some features in common but differ in other respects, and it is impossible to say with any certainty which really belong to it and which do not. The author would maintain that it is still unclear whether this ore type really exists at all as an unambiguous entity. The features that deposits assigned to this category appear to have in common include a high degree of oxidation, a high iron content and a low sulphide content, in addition to the presence of copper and gold in practically every case alongside magnetite and/or haematite. The deposits also contain varying quantities of uranium, cobalt, molybdenum, REE etc.

There is in effect only one typical copper deposit in Central Lapland, that of Pahtavuoma, while the others among the best-known such deposits, Saattopora II, Riikonkoski and Vesilaskujänkkä, belong strictly speaking to the class of copper-dominated gold deposits. Pahtavuoma is a syngenetic copper-silver deposit that comes into the category of volcanogenic massive sulphide deposits. It has no clearly defined massive part of the sulphide or stringer type, and its typical breccia structure was created at a later deformation stage. Massive sulphide ores frequently have a distal occurrence associated with them, and this is what the Pahtavuoma copper deposit itself actually represents. On the other hand, the deposit also has features of the FeOx-Cu-Au ore type, since the skarn layers connected with the copper deposit contain large amounts of magnetite, albite-antophyllite boulders of the Rautuvaara type containing magnetite and chalcopyrite disseminations have been found in the area, and the Western Lapland monzonite intrusion and the Rautuvaara formation that lies at its contact are only a couple of kilometres away. On the other hand, zinc is to be found in connection with it, whereas this does not typically occur together with ores of the FeOx-Cu-Au type. According to Papunen *et al.* (1987), this zinc is derived from the volcanites of the area, which have higher zinc concentrations (Zn 175–206 ppm) than occur generally in the greenstone belt (Zn 22–104 ppm).

On account of their epigenetic nature, the gold-bearing deposits of Central Lapland occur in Palaeoproterozoic formations of differing ages. The youngest is the quartzite of the Kumpu group, in which gold-bearing pyrrhotite veins have been detected at Muusalammet and Sirkka, for instance, while the somewhat older Lainio group quartzite contains a small, massive, evidently secondary chalcocite occurrence and drill core evidence of gold and tourmaline-bearing quartzite. The chalcopyrite-bearing Kesänki uranium deposit is also associated with the Lainio group, while the Ylläs FeOx-Cu-Au deposit

belongs to the skarn rocks of this group and the Latvavuoma FeOx-(Cu) deposits to its metavolcanites.

Banded iron formations belonging to the Kittilä group metavolcanites host arsenopyrite-bearing gold deposits such as those of Suurikuusikko, while the Pahtavaara gold ore is located in the komatiitic ultramafic rocks of the Sattasvaara formation in the older Savukoski group. The largest proportion of the gold deposits of Central Lapland belong to the Savukoski group, being connected with the Matarakoski formation. The oldest Palaeoproterozoic units that contain gold deposits are the albitized metasedimentary and the metavolcanic rocks of the Sodankylä group. Thus the formations with gold deposits possess an age range of over 300 million years. In fact, the oldest rock containing gold deposits is the Archaean iron formation in eastern Lapland.

The age of the Saattopora gold ore is 1870–1900 Ma and that of the deposit in the Soretiauvuoma-Kuotko-Suurikuusikko area 1852–1890 Ma, while the Pahtavaara pyrite and magnetite is of age 1811 ± 87 Ma, thus partly coinciding with the pronounced hydrothermal activity between the synorogenic and postorogenic granite intrusions in the late orogenic stage, around 1810–1850 Ma ago (Mänttari 1995). Eilu (1994) dates the metamorphic events in the Central Lapland area to the time of the Svecokarelian orogeny, 1800–1900 Ma ago, maintaining that the synorogenic plutonism provided the stimulus for the hydrothermal system. It is thus evident that the gold deposits are derived from a late stage in the orogeny, so that the concept of "orogenic gold ores" proposed by Groves *et al.* (1998) could well be replaced in this case by "late orogenic or late tectonic gold ores".

About 90% of the gold and copper deposits of Central Lapland have been discovered as a consequence of geochemical surveys, while some have been the result of bedrock mapping or the observation of gold or chalcopyrite in bedrock exposures, e.g. the Pahtavaara gold ore deposit and the Pahtavuoma copper ore deposit. On the other hand, the Saattopora I gold-copper ore is an example of a deposit identified partly on intuition. The FeOx-Cu-Au deposits of the Rautuvaara formation were virtually all identified by magnetic methods, but the first observation of such a deposit at Ylläs arose in connection with bedrock mapping. Aeromagnetic and airborne electromagnetic methods have proved to be important tools for interpreting the lithology and structure of the bedrock for exploration purposes, especially in areas with a thick overburden.

According to the author's experience, the major pathfinder metals of significance for geochemical gold exploration in Central Lapland are Au, Cu, As, Ni, Co, Cr, Mg and Fe together with non-metallic S, while the regular absence of Zn and Pb can also be exploited for prospecting purposes. Gold itself is obviously the most important indicator of all, especially in the case of deposits that are poor or deficient in sulphides. Ultramafic rocks, which often contain gold deposits, can be identified from elevated Cr and Mg concentrations in till, and as many gold deposits in such an environment also contain arsenic, nickel and cobalt-bearing minerals, concentrations of these metals tend to be above the background levels. Gold deposits in iron formations are usually associated with the sulphide facies, so that significant factors are the iron present in oxide form and the sulphur contained in the sulphides, the indicators that enable the oxide and sulphide facies to be distinguished from one another. The main pathfinder elements for these gold deposits are nevertheless gold and arsenic.

Practically all the known gold, iron oxide-copper-gold and copper deposits in Central Lapland have outcrops, but although the region as a whole is still somewhat under-

explored, it is evident that the majority of the main deposits having surface outcrops have now been discovered. This is reflected in the decline in the numbers of new finds over the last fifteen years, for instance. In consequence, geological modelling of rocks and ores for the location of blind deposits is likely to occupy a key position in our ore exploration philosophy in the coming years. Modern computer databases and software applications offer excellent tools for this, but it is still too early to speak of mineral deposit modelling that could be of any positive value for revealing new blind gold or copper deposits in Central Lapland.

There are two other factors as well as size and metal content that affect the profitability of gold deposits in Central Lapland, namely arsenic content and the occurrence of refractory gold ore. The presence of arsenopyrite, gersdorffite or cobaltite in gold deposits is one of the greatest feasibility problems affecting the deposits in this region, as it is virtually impossible to obtain a commercially saleable product from such ores using conventional concentrating techniques. In addition, if the waste rock generated by open pit mining includes minerals that contain arsenic or heavy metals, this will create environmental problems that could affect the viability of mining.

Another factor impinging on profitability is the occurrence of refractory gold ore in which the gold is lying in the lattice of sulphides, principally arsenopyrite and pyrite, as in some cases in the central part of the Kittilä greenstone area. Mining of gold deposits of this type entails considerably higher capital investments and operating costs than for free milling gold ore, chiefly on account of processing difficulties, especially the need to include a pre-processing stage. This means that occurrences of refractory gold ore have to be very much larger than those of free milling ore in order to be feasible commercial prospects.

The global gold rush of the 1980s was brought about by a continuous demand for gold and the value placed on it as a secure, low-risk object of investment, especially at times of economic recession. Many mining companies devoted their main ore prospecting and research efforts to the discovery of sources of gold, and it was even feared that so many new gold mines would enter production that the price would plummet (Mackenzie 1991). This did not happen, however, but rather gold has retained its value well.

It was really only in the early years of that decade that gold prospecting in Central Lapland began in earnest. This was indeed a consequence of the rise in the world price, which reached a new record of US\$ 850 per ounce in 1981, as compared with the 1975 price of US\$ 150 (Fig. 26). The price dropped again rapidly after that, however, to a mean of around US\$ 300 per ounce by 1985, only to recover to almost US\$ 500 by 1988. Since then the situation has remained relatively stable, although with a general decline extending over a period of more than ten years. Thus the price had fallen to below US\$ 300 per ounce by the end of the millennium and did not begin a new rise until 2002. By January 2005 the figure was once more in excess of US\$ 400 and the price at the end of the year was over US\$ 500 an ounce.

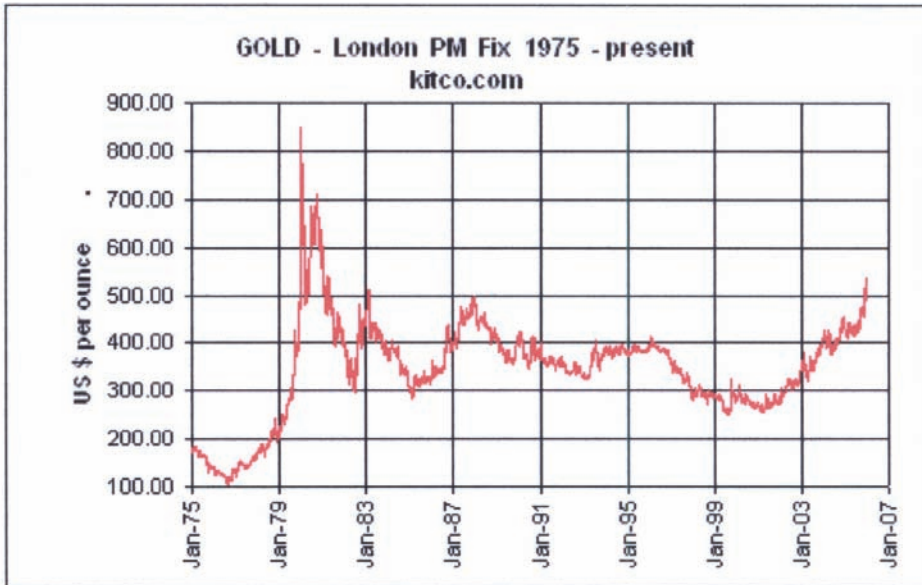


Fig. 26. Trends in the price of gold, 1975–2005 (Kitco 2005).

The mean price of gold during the time when the Saattopora mine was in operation, in 1989–1995, was US\$ 373 per ounce, the lowest level, an annual mean of 326 US\$, being reached in 1993 and the highest, 424 US\$, in 1990. All in all, the Saattopora mine proved to have been economically viable.

The world price of copper has remained relatively stable over the years, although some marked fluctuations have taken place. An abrupt fall of around 40% in the mid-1970s led to the abandonment of underground explorations at Pahtavuoma, for instance, as feasibility calculations showed that the copper and silver concentrations concerned (Cu 1 wt%, Ag 25 g/t) were too low relative to cost levels at the time to warrant the continuation of investigations with the aim of opening a mine.

The accent in exploration for base and precious metals in Central Lapland over the last 20 years has been on potential sources of gold, PGE, nickel, copper and chromium, but in spite of increasing investments and the entry of foreign companies into this field, only two gold deposits among the various sites discovered had actually become the object of commercial mining by December 2005. In view of the resources devoted to ore prospecting in the region over this period, the investments made in the mines that have functioned at various times and the cash flows achieved by them, it is evident that the overall economic balance has been negative.

Considerable deposits of metal ores of size 100 million tonnes (chiefly mineral resources) or even larger have been discovered in Finland over the last 20 years, but low metal concentrations or associated mining or processing problems have prevented the commencement of mining for the time being, or at least hindered it. Cases in point include the nickel-copper-zinc-bearing black schist of Talvivaara in Sotkamo, the Kevitsa nickel-copper-PGE-gold deposit in Sodankylä, the Koitelainen and Akanvaara PGE-bear-

ing chromite zones, the PGE occurrences of Southern Lapland and the Suurikuusikko gold deposit in Kittilä, with estimated ore reserves of about 17.7 million tonnes. Mention should also be made, of course, of the niobium and tantalum associated with the Sokli carbonatite massif in Eastern Lapland. Apart from Talvivaara, all these deposits are located in the province of Lapland. The Suurikuusikko gold deposit was discovered in 1986, so that geological investigations, evaluations of mining potential and feasibility studies have been going on now for 20 years. Another example of the long-term nature of exploration work concerns the PGE occurrences of Southern Lapland, the first discovery hole for which was identified by Outokumpu in 1982 on the basis of re-analyses of earlier drill hole samples.

Research into the geology of metallic ores in Finland over the last 20 years has been largely concentrated on precious metals, with less effort devoted to copper, zinc, nickel or iron deposits, for instance, and this is partly the reason why no new, exploitable occurrences of base metal ores have been discovered here for several decades. Research publications over the interval 1995–2005, for example, were concerned with gold deposits in Finland in 139 cases and copper, nickel or zinc ores in only 169 cases altogether (GTK 2005). It would be of crucial importance for mining and the supply of domestic raw materials for the country's smelting works to discover and be able to exploit new, economically viable deposits of base metals. One of the best examples of the importance of successful ore prospecting for the nation's economy is the Kemi chrome ore in Southern Lapland. If this had not been discovered, the flagship of the metals industry in Finland, the Tornio stainless steel plant, might never have been built.

Although Saattopora in Kittilä and Pahtavaara in Sodankylä are the only gold deposits discovered in Lapland to date that have led to the commencement of mining, precious metal deposits of the kind represented by Suurikuusikko and Suhanko in Southern Lapland demonstrate that large-scale, profitable mining of such metals would be quite possible in Lapland.

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