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Research and exploration - where do they meet?

4th Biennial SGA Meeting

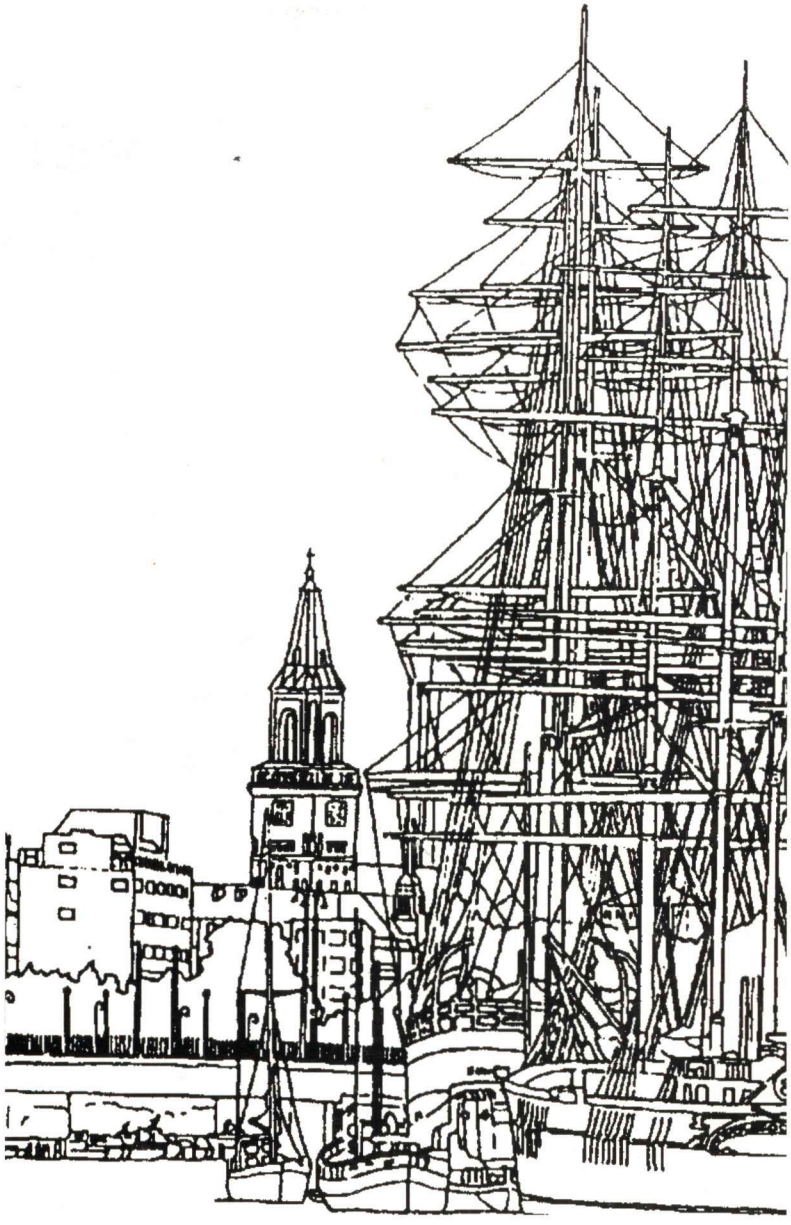
August 11-13, 1997, Turku, Finland

Excursion Guidebook

A4

Ore Deposits in Eastern Finland

edited by Kirsti Loukola-Ruskeeniemi and Peter Sorjonen-Ward



Society for Geology Applied to Mineral Deposits

Geologian tutkimuskeskus, Opas —
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ORE DEPOSITS IN EASTERN FINLAND

edited by Kirsti Loukola-Ruskeeniemi and Peter Sorjonen-Ward

Espoo 1997

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The excursion visits some of the most important metallic and non-metallic ore deposits in the Proterozoic of eastern Finland, as well as providing an introduction to exploration history and respective geological environments. Archean geology and mineralization are also represented by the Pampalo gold deposit within 2.75 Ga sediment-dominated Hattu schist belt (Stop 6) and the major soapstone operations at Nunnanlahti (Stop 4), while a kimberlite pipe near the abandoned Luikonlahti Cu-Zn-Co deposit (Stop 1) provides an opportunity to examine some the youngest events to affect the Fennoscandian shield in Finland.

The main theme of the excursion is the mineralization associated with episodic rifting of the Karelian craton, particularly after 2.1 Ga, when there was a major phase of rifting and predominantly mafic volcanism, followed by more quiescent passive margin deposition; the exhausted sediment-hosted Hammaslahti Cu-Zn deposit and the 300 Mt low grade Ni-Cu-Zn mineralization at Talvivaara (Stop 7) appear to have formed during this time. Renewed rifting culminated in the formation of oceanic crust at 1.97–1.95 Ga, which was subsequently thrust back on to the craton margin, together with the passive margin sequence and overlying monotonous turbidites, during the Svecofennian Orogeny, between 1.92–1.85 Ga. The Jormua ophiolite complex (Stop 8) is the best preserved and exposed example of oceanic crust and mantle lithosphere, while the Outokumpu region is characterized by a distinctive metamorphic assemblage comprising serpentinites, quartz rocks, calcsilicate skarns and black schists, and hosting major Cu-Co-Zn deposits which were mined until recently at Luikonlahti (Stop 1), and at Outokumpu itself (Stop 2). This distinctive assemblage is also well-represented at Horsmanaho (Stop 3), where talc is mined commercially.

A review of exploration, genetic models and metallogeny of the Outokumpu region, and of black schists in eastern Finland is given, including a synopsis of petrophysical properties, supplemented by appended maps of regional geophysical data.

Excursion held on: August 8–10, 1997

Key words (GeoRef Thesaurus, AGI): metal ores, metallogeny, mineral exploration, Precambrian, field trips, guidebook, Eastern Finland

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Itä-Suomen kallioperään ja tärkeimpiin malmiesiintymiin tutustutaan kahdeksan ekskursiokohteen avulla. Lisäksi esitetään uusimpien tutkimustulosten perusteella kallioperän kehityksen eri vaiheet arkeisella ajalla sekä erityisesti 2,5–1,95 miljardia vuotta sitten, jolloin alueella tapahtui mannerreunan repeäminen, joka 1.97 Ga eteni merenkuoren muodostumiseen asti. Myös taloudellisesti merkittävien Outokummun massiivisten Cu-Co-Zn malmiesiintymien synty liittyy näihin prosesseihin, koska malmit esiintyvät poikkeuksetta serpentiniittien välittömässä läheisyydessä.

Outokummun alueella käydään Luikonlahden Cu-Zn-Co malmin entisen kaivoskuilun ja avolouhoksen reunan paljastumilla (Kohde 1), Outokummun vanhalla Cu-Co-Zn kaivoksella (Kohde 2) sekä Horsmanahon talkkilouhoksella (Kohde 3), jossa on myös näkyvissä Outokummun sulfidimalmeihin tyypillisesti liittyvä kivilajiseurue. Luikonlahdessa tutustutaan lisäksi timantinetsintäprojekteihin ja nähdään kimberliittilohkareita. Outokummun malmien löytöhistoriaa, niihin liittyvää kivilajiseuruetta, Kylylahden Cu-Co malminetsintäkohteen tuloksia, mustaliuskeprojektin tuloksia ja malmin eri syntymalleja esitellään eri artikkeleissa.

Nunnanlahdessa (Kohde 4) tutustutaan vuolukiven kaupalliseen hyödyntämiseen ja sen lähellä, Kolin kvartsiittivaaralla (Kohde 5), nähdään proterotsooisen sarjan alaosan muodostumia. Ilomantsin vihreäkivivyöhykkeellä nähdään sedimenttejä ja vulkaniitteja, jotka kuuluvat iältään Euroopan vanhimpiin, sekä niissä esiintyviä kultamalmeja (Kohde 6). Kainuussa tutustutaan Talvivaaran Ni-Cu-Zn mustaliuske-esiintymään (Kohde 7) ja Jormuan ofioliittikompleksin kiviin (Kohde 8). Talvivaaran mustaliuske-esiintymässä on 300 Mt mineralisoitunutta mustaliusketta. Lisäksi esitellään Itä-Suomen proterotsooisten mustaliuskevyöhykkeiden tunnistamista magneettisista ja sähköisistä anomaliakartoista.

Oppaassa on kolme liitekarttaa: geologinen kartta, geofysikaalinen yhdistetty painovoima- ja magneettinen anomaliakartta sekä Jormuan alueen magneettinen ja sähköinen anomaliakartta.

Eksursioaika: 8–10. elokuuta 1997

Avainsanat (Fingeo-sanasto, GTK): metallimalmit, metallogenia, malminetsintä, prekambri, ekskursiot, oppaat, Itä-Suomi

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INTRODUCTION

by Peter Sorjonen-Ward and Kirsti Loukola-Ruskeeniemi

A NW-SE trending line drawn between the head of the Bothnian Bay and Lake Ladoga effectively separates the Baltic, or Fennoscandian Shield in Finland into a late Archean domain in the northeast, known as the Karelian craton, and the Paleoproterozoic Svecofennian domain in the southwest. The route followed in this excursion will traverse the boundary zone between these two domains, illustrating the transition from a stable cratonic environment through rifting and passive margin deposition to the development of oceanic crust, remnants of which will be seen exposed in the Jormua ophiolite. All of these lithostratigraphic units were subsequently thrust back northwards and northeastwards onto the Archean basement foreland during the Svecofennian Orogeny, with the general tectonic style having a geometry and scale reminiscent of the earliest stages of the Alpine collision zone — a comparison first made long ago, by Wegmann (1928).

The plate tectonic paradigm has been widely applied in interpreting crustal growth, deformation and metallogenesis in the Svecofennian domain, beginning with a synthesis by Hietanen (1975). Northeast-vergent emplacement of the Jormua ophiolite (Kontinen, 1987) and Outokumpu assemblage onto the Karelian craton foreland is inferred to record the initial collision with a Svecofennian oceanic island arc (Ward, 1987), generating primitive tonalites from a low-K tholeiitic source (Lahtinen, 1994). Continued volcanism within this arc at 1.92–1.90 Ga led to the formation of VHMS deposits, including the Pyhäsalmi Zn-Cu deposit (Ekdahl, 1993). Reversal of subduction polarity following collision (Gaal, 1990), or a further arc-arc collision (Lahtinen, 1994) is invoked to explain the most extensive phase of volcanism, magmatism and deformation in southern and western Finland, and also Sweden, including the Skellefte district (Allen et al., 1996) between 1.89–1.86 Ga.

Although archeological evidence exists for at least transient human occupation in eastern Finland as far back as 7000 BP, it is only within the last hundred years or so that the region has seen any large scale commercial exploitation of mineral resources. The first extensive operations involved the quarrying of soapstone at Nunnanlahti towards the end of the nineteenth century, although production declined steadily and eventually ceased for a time. The industry has however been revived during the last decade with spectacular success, such that the two companies operating at Nunnanlahti now represent the largest soapstone quarrying enterprises globally; a visit to one of the quarries has therefore been included in the excursion itinerary.

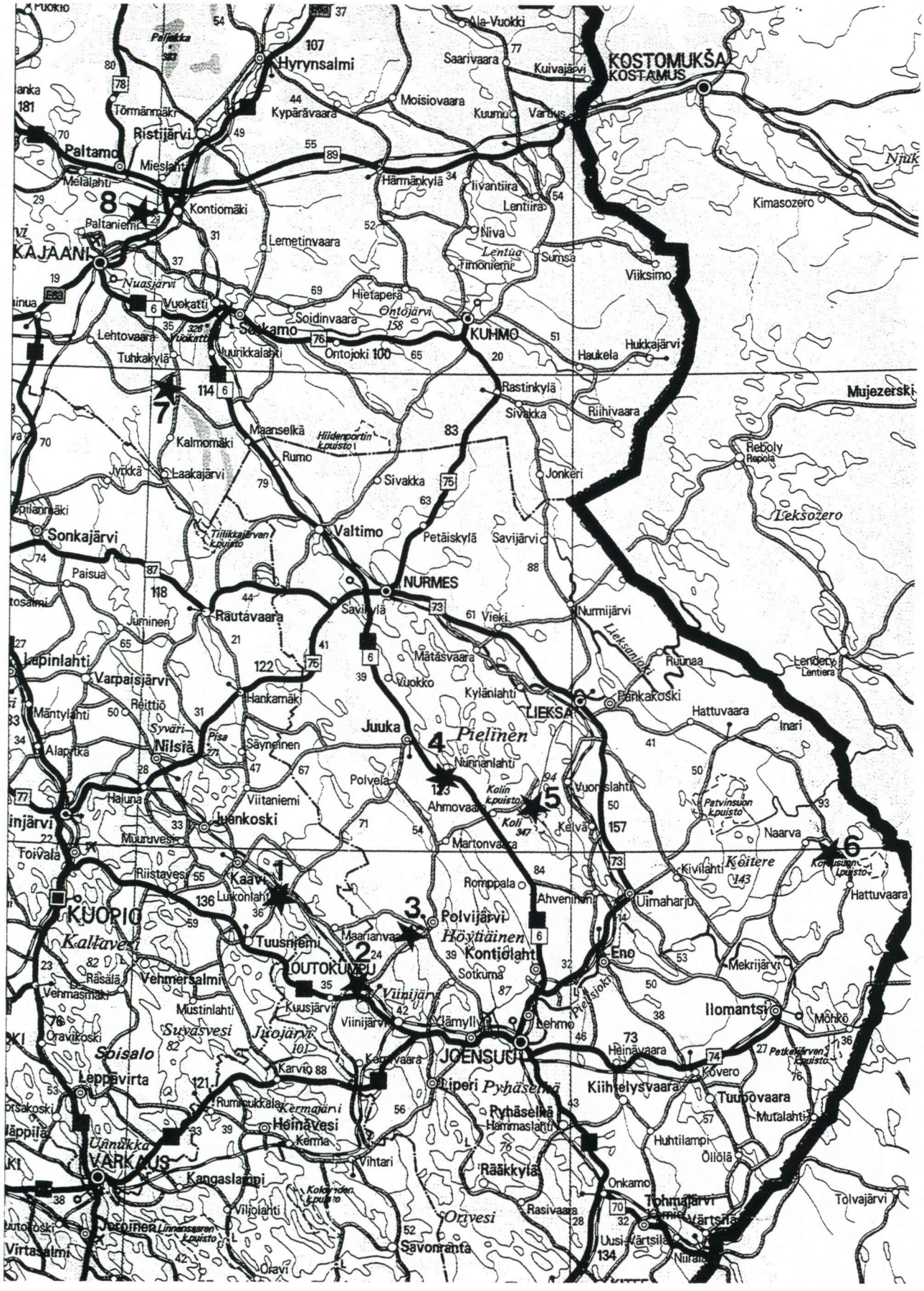
Undoubtedly the most important mineral discovery in eastern Finland was the finding of the distinctive serpentinite-associated Cu-Co-Zn-Au massive sulfide deposits at Outokumpu during the early part of this century. The Outokumpu mine was at one time the largest Cu mine in Europe and together with two other deposits, Keretti and Vuonos, yielded a total of 1.1 Mt copper between 1913 and their closure in 1989. Even though no deposits are currently being mined in the area, the discovery provided a firm basis for the development and expansion of the mining and metals processing industry in Finland, an area which still ranks very highly in terms of export earnings.

Only one other Outokumpu-type massive sulfide deposit has been exploited to date, namely the Luikonlahti mine, which operated from 1968–1983 and was situated some tens of kilometers to the north of Outokumpu. This deposit will be visited during the excursion in conjunction with an examination of a nearby kimberlite pipe. The only one other Proterozoic base metal deposit to have been mined in the region is the Hammaslahti Cu-Zn-Au deposit, which represents a different style of mineralization, having been hosted by rift phase turbiditic greywackes and distally associated with mafic volcanics; time constraints, and the poor quality of exposure since cessation of mining activities in 1987, nevertheless precludes us from visiting this area, which lies some 70 km to the southeast of Outokumpu (Appendix 1). The Talvivaara prospect will however, present an opportunity for examining an extensive and rather unusual sediment-hosted Ni-Cu-Zn deposit.

Mention should also be made of the late Archean Siilinjärvi carbonatite, some 20 kilometers northeast of Kuopio, which in terms of annual tonnage, is currently the largest mining operation in Finland. Extensive reserves of kyanite, resulting from Svecofennian metamorphism of a thick paleoregolith developed across the Archean-Proterozoic unconformity, have also been investigated in recent years (Kohonen and Marmo, 1992). Otherwise, until recently the Archean of eastern Finland has received less attention from an exploration viewpoint. The Otravaara massive pyrite deposit, hosted by a submarine felsic volcanic sequence was worked briefly early this century, but recent years have seen a growing interest in the gold potential of greenstone belts in eastern Finland and a number of prospective areas have been delineated, principally on the basis of till geochemical anomalies. At the risk of making our timetable rather tight, and with the additional motive of showing examples of some of the oldest rocks in Europe, we have decided to include one of the most promising prospects in the Ilomantsi greenstone belt within the exçursion programme.

We hope that you find the excursion interesting and rewarding!

Fig. 1. (on the right) Route map. Day 1: Stop 1 — Luikonlahti Cu-Zn-Co deposit and diamond exploration projects; Stop 2 — Old mining town at Outokumpu (+ presentation of a new Cu-Co-Zn prospect); Stop 3 — Horsmanaho talc deposit; Stop 4 — Soapstone industry at Nunnanlahti (fireplaces by Tulikivi Oy); Stop 5 — Koli quartzite; Day 2: Stop 6 — Pampalo gold deposit and related outcrops in the Archean Ilomantsi greenstone belt; Stop 7 — Talvivaara black schist-hosted Ni-Cu-Zn occurrence; Stop 8 — Jormua ophiolite complex.


Hyrynsalmi
KOSTOMUKŠA
KOSTAMUS
Paltamo
Ristijärvi
Kontiomäki
KAJAANI
Nuasjärvi
Vuokatti
Sotkamo
KUHMO
Ontojoki
Lemetinvaara
Niva
Lentiira
Viiksimo
Kimasozero
Mujezerski
Rebola
Leksozero
Sonkajärvi
Valtimo
NURMES
Rautavaara
Juminen
Lapinlahti
Varpaisjärvi
Nilsiä
Juuka
Pielinen
LIEKSA
Hattuvaara
Inari
Naarva
Kaavi
KUOPIO
Kallavesi
Tuusniemi
Polvijärvi
Höytiäinen
Kontiolahti
JUUKA
Eno
Ilomantsi
Mekrijärvi
Viinijärvi
Suvasvesi
Juojärvi
Soisalo
Leppävirta
JOENSUU
Liperi
Pyhäselkä
Kiihtelysvaara
Tuupovaara
Heinävesi
Ryhäselkä
Hammaslahti
VARKAUS
Kangaslampi
Rääkkylä
Tohmajärvi
Värtsilä
Orivesi
Savonranta
Virtasalmi
Joroinen
Kolovesi
Koitere
Patvinsuo
Petkeljärvi
Möhkö
Mutalahti
Huhtilampi
Öllölä
Tolvajärvi
Onkamo
Uimaharju
Hattuvaara
Kivilahti
Romppala
Ahveninen
Ahmovaara
Kolin kpuisto
Koli
Patvinsuon kpuisto
Petkeljärven kpuisto
Hiidenportin kpuisto
Tiilikkajärven kpuisto
Linnansaaren kpuisto
Kokonniemi kpuisto
Pielisjoki
Lieksanjoki
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AN OVERVIEW OF THE GEOLOGICAL AND TECTONIC EVOLUTION OF EASTERN FINLAND

by
Peter Sorjonen-Ward

Sorjonen-Ward, P. 1997. An overview of the geological and tectonic evolution of eastern Finland. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 42, 11–22, 3 figures.

Key words (GeoRef Thesaurus, AGI): tectonics, sedimentation, igneous activity, metallogeny, Proterozoic, Paleoproterozoic, Archean, Eastern Finland

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A GENERAL GEOLOGICAL OUTLINE OF FINLAND

The Baltic — or Fennoscandian — Shield can be conveniently visualized in terms of three major NW-SE trending crustal domains, namely the Paleoproterozoic Svecofennian Province exposed in southwestern Finland and Sweden, the Kola-Lapland Province occupying the Kola Peninsula and northernmost Norway and Finland, and the intervening Late Archean Karelian Province, covering eastern Finland and the adjoining Republic of Karelia. These crustal domains have shared a common history since about 1.8 Ga and essentially comprise a late Archean cratonic nucleus — the Karelian craton — flanked on both sides by early Proterozoic mobile belts. The Karelian Province contains some material as old as 3.1 Ga but is dominated by 2.9–2.7 Ga granitoids that intruded greenstone belts of broadly similar age (Luukkonen, 1992, Lobach-Zhuchenko et al., 1993, Vaasjoki et al., 1993). The Karelian Province also acted as stable platform throughout much of the Early Proterozoic and its northern part evidently formed the substrate for the 2.5–1.9 Ga Lapland greenstone belt.

The Kola-Lapland Province, to the NE of the Karelian craton, records the amalgamation at around 1.9 Ga of several distinct crustal units of both Proterozoic and Archean age, and is more characteristic of collisional tectonic processes. In contrast, the Svecofennian Province, to the SW of the Karelian craton, and covering more than half a million square kilometers, is entirely early Proterozoic in age, and indicates relatively rapid formation and accretion of new crust between about 1.97–1.86 Ga.

For a general review of the Shield the reader is referred to Gaál and Gorbatschev (1987) and Gaál (1990), while recent reviews of the Russian parts of the Kola and Karelian provinces can be found in Turchenko (1992) and Rundkvist & Mitrofanov (1993). The tectonic evolution of the northernmost part of the Shield has also been summarized by Berthelsen and

Marker (1986) and Gaál et al.,(1989). Recent syntheses of Svecofennian metallogeny and petrogenesis have been published by Ekdahl (1993) and Lahtinen (1994) respectively.

During the Paleoproterozoic Svecofennian Orogeny, the Karelian craton was subjected to several tectonic events directed from both east and west. The transition zone between the Kola and Karelian Provinces, known as the Belomorian domain, is considered to represent late Archean high grade gneiss terrain that was extensively reworked, if not exhumed, during thrusting southwestwards over the eastern margin of the Karelian Province at 1.9–1.8 Ga. Conversely, the southwestern margin of the Karelian Province was strongly deformed and imbricated during NE-directed thrusting associated with the Svecofennian Orogeny and emplacement of the Outokumpu assemblage and associated sedimentary and basement nappes at about 1.9 Ga. As stated above, the Svecofennian Province is isotopically distinctive and represents rapid crustal growth and deformation around 1.9 Ga, with no compelling evidence for the large-scale involvement of pre-existing crust. Evidence is thus accumulating to support interpretations invoking collisional shortening involving an island arc and a passive continental margin at around 1.9 Ga, followed by the development and successive accretion of further arc terranes over the next hundred million years or so (Hietanen, 1975, Kontinen, 1987, Ward, 1987, Gaál, 1990, Lahtinen, 1994).

SOME GENERAL FEATURES OF ARCHEAN GEOLOGY AND METALLOGENY IN EASTERN FINLAND

The Late Archean Karelian craton is characterized by narrow northerly trending greenstone belts surrounded by areally more extensive granitoids and higher grade gneiss domains. Although reliable isotopic ages up to 3.2 Ga exist for tonalitic gneisses and migmatites in various parts of the craton, the earliest well-documented magmatic and metamorphic event seems to have taken place at around 2.84 Ga (Luukkonen, 1985). Several lower grade greenstone sequences formed after this event, and were variably deformed and intruded by granitoids with tonalitic to granitic compositions between 2.75–2.69 Ga (Martin et al., 1984, Luukkonen, 1988). The Kuhmo and Suomussalmi greenstone belts are the most extensive, outcropping over a strike length of nearly 200 km, though seldom exceeding 10 km in width. They both contain well-preserved tholeiitic and komatiitic volcanics, together with related intrusive and subvolcanic cumulates, and some felsic volcanic and volcaniclastic units. Although intercalated sediments and volcanic features attest to a submarine setting for volcanism, there is also evidence to suggest that the greenstone belts were initiated by ensialic rifting of the older migmatitic basement at about 2.8 Ga. Detailed mapping of volcanic lithologies and facies, particularly within the olivine-pyroxene cumulates in the komatiitic sequence is providing a useful and encouraging framework for nickel exploration throughout the greenstone belts.

Recent exploration has also shown that Archean greenstone belts in eastern Finland contain gold mineralization similar to that in other shield areas. The first discoveries were made in the Hattu schist belt, near the southwestern margin of the Karelian craton, where the Geological Survey of Finland has documented and drilled more than ten prospects within a structurally defined gold anomaly zone over 40 km in length. The Hattu schist belt represents a distinctive sediment-dominated supracrustal sequence that records rapid crustal growth and deformation between 2.75–2.72 Ga. Felsic volcaniclastic sediments in this belt, and lithofacies, as well as geochemistry of granitoids and some basalts are consistent with a collisional arc setting. Gold is hosted by extensive structurally controlled alteration systems and in contrast to many classical greenstone terrains, there is evidence for mineralization preceeding or accompanying the peak of regional metamorphism.

Some potential for Zn and Ag mineralization within the felsic supracrustal sequences of eastern Finland has also been recognized, with the Taivaljärvi prospect being the best documented (Kopperoinen & Tuokko, 1988). Soapstone deposits developed in ultramafic rocks represent a volumetrically minor but economically significant resource in several greenstone belts.

SEDIMENTATION, MAGMATISM AND METALLOGENESIS DURING EPISODIC PALEOPROTEROZOIC EXTENSION AND RIFTING IN THE KARELIAN PROVINCE

The Karelian craton, particularly in its northern part, in Finnish Lapland, records a prolonged and episodic history of sedimentation, rifting and magmatism throughout the Early Proterozoic. When considering the origins of magmatic events, the role of mantle plumes seems to be becoming increasingly popular; if such concepts are to be applied to the prolonged and episodic nature of mafic magmatic events affecting the Karelian Province, the time periods involved would clearly require that several successive plumes impinged on the region, and that each event may have progressively modified the composition of the lower crust and mantle lithosphere, potentially affecting the isotopic and geochemical characteristics of subsequent magmas. A challenge for future investigations is to attempt to integrate the sedimentary record of the Karelian craton with magmatic events by modelling amounts and rates of extension, rifting and subsidence (cf. Williamson et al., 1995).

The Karelian Province between 2.5–2.4 Ga — predominantly mafic magmatism and localized extension

The Lapland greenstone belt is by far the largest mafic-dominated terrain preserved in Finland and despite its Paleoproterozoic age the overall dimensions, deformation style, metamorphic grade and abundance of ultramafic volcanism are more reminiscent of the Late Archean Abitibi and Norseman-Wiluna greenstone belts than other greenstone units within the Fennoscandian Shield. A sequence of bimodal komatiitic and felsic volcanics dated at around 2.5 Ga unconformably overlie the Archean basement and represent the onset of rifting, followed by widespread emplacement of gabbro-norite layered intrusions between 2.45–2.39 Ga. These intrusions host the important Kemi chromite mine, and also contain widespread PGE-Au enrichment, although to date no economic deposits have been discovered.

A major plume event has been implicated in the genesis of the 2.45 Ga mafic layered intrusions, especially since the recognition that an extensive suite of komatiitic basaltic volcanics in the eastern part of the Karelian Republic is of similar age and may have had similar source characteristics as well (Puchtel et al., 1996). Moreover, Heaman (1997) has attempted to correlate these rocks with the Matachewan and Hearst mafic dykes swarms and Huronian flood basalts of the Superior province of Canada, and suggested that this was a global event, equivalent to younger large igneous provinces.

Terrigenous clastic sediments discordantly overlie these layered intrusions, with field relationships commonly recording angular discordances, suggesting tilting of the layered intrusions during ongoing extensional deformation (Ward et al., 1989).

The Karelian Province between 2.4–2.1 Ga — stable platform terrestrial to shallow marine sediments and mafic igneous activity

A prolonged phase of stable terrestrial to shallow margin sedimentation is recorded in eastern Finland by a well-defined sequence of orthoquartzites and related sediments that has been documented and interpreted in detail by Kohonen and Marmo (1992). Archean basement is locally overlain by some of the earliest known glacial deposits, with a total preserved thickness of some 400 m, followed by a period of intense weathering, resulting in the formation of the Hokkalampi paleosol; this regolith, which is up to 80 m thick, was developed in both the glacial deposits and the underlying basement, implying some topographical or tectonically induced relief. The paleoregolith shows a progressive upwards increase in alumina content, grading through sericite-quartz schists into a rock consisting largely of kyanite, with some andalusite, and accessory fuchsite, chloritoid. The widespread Koli Formation fluvial orthoquartzites were deposited next, with basal conglomerates including clasts derived largely from the underlying paleosol. This is then overlain by an arkosic quartzite sequence, which records a transient episode of basement rejuvenation and rifting

associated with a very distinctive suite of approximately 2.2 Ga differentiated mafic sills found over large parts of eastern Finland; although intruded close to the basement-cover contact, comagmatic extrusive facies have not been recognized. These intrusions are distinctive in that they contain abundant albite (Vuollo et al., 1992), even where other evidence for hydrothermal alteration is difficult to detect, and they are generally strongly magnetic and readily discernible in the regional aeromagnetic data (Appendices 1, 2 and 3).

Another period of fluvial quartzite deposition followed this tectonically unstable phase, until about 2.1 Ga, when there was an abrupt transition to stage of rifting, magmatism and subsidence. This transition has been studied in detail, but due to the structural complexity of the contact zone, it is difficult to determine precise relationships. Kohonen (1995) concluded that the ambiguity with many stratigraphical relationships can be resolved by interpreting some thrusted contacts as reactivated syn-depositional basin margin faults.

The Karelian Province between 2.1–2.0 Ga — rifting and subsidence leading to passive margin formation

Further episodes of mafic magmatism in Karelia are recorded by mafic volcanics, sills and dykes dated at 2.10 Ga, and 2.05 Ga. These broadly coincided with rifting and subsidence of the Karelian craton margin, recorded by coarse clastic turbidites, which hosted the now-exhausted Hammaslahti Cu-Zn deposit, and carbonates, iron formations and finer-grained graphitic schists, the latter hosting the extensive, though low grade Talvivaara Ni-Cu-Zn deposit.

Fe-tholeiite dikes intruded the Archean basement throughout eastern Finland and some of these, which cut the basement unconformity and terminate within the Proterozoic cover sequence, have been interpreted as feeder channels for lava flows (Pekkarinen and Lukkarinen, 1991). The Tohmajärvi mafic volcanic complex has been dated to 2.1 Ga and is believed to correspond to the initial phase of rifting and basin subsidence, being closely associated with coarse-clastic turbidites that record an Archean basement provenance. Nykänen et al. (1994) attributed geochemical differences, particularly with respect to REE patterns, between the dyke swarms and the Tohmajärvi complex to melting at different depths during progressive extension, with the latter being derived from more attenuated continental margin lithosphere.

Coarse clastic lithofacies occuring in association with the Tohmajärvi volcanic complex are interpreted as proximal, partly channelized prograding fan sequences characterized by fining and thinning upward sequences which pass upwards and laterally into quartzose metapsammites assigned to a suprafan — middle fan setting (Ward, 1988). Stratigraphical relationships with associated chemogenic and pelitic lithologies are obscure, due to complex deformation, but the coarser lithologies are considered to represent an influx of coarse detritus associated with basin formation and rapid subsidence after 2.1 Ga (Fig. 2). Sporadic calc-turbidites and pink dolomite clasts in thick-bedded debris flows are of particular interest as they may be the only surviving evidence for the existence of a penecontemporaneous carbonate shelf environment at the basin margin.

Finer grained sequences are then considered to overlie the coarser and volcanic-related sediments, recording a more prolonged phase of starved intracratonic basin or passive margin deposition that was eventually terminated, or rejuvenated by a renewed phase of rifting between 1.97–1.95 Ga, which culminated in the formation of oceanic crust, now best represented by the Jormua ophiolite (Kontinen, 1987).

Fine-grained facies commonly contain fine-grained disseminated pyrrhotite, as well as some lithologies containing abundant carbonate and graphite. Some thin and weakly graded sedimentary couplets consist of impure calcareous and graphitic laminae that could have formed from tractional currents in a shallow marine environment or else from dilute turbidity currents that transported terrigenous or authigenic carbonate shelf detritus into a deeper basin environment. Presumed chemogenic or hydrothermal deposits are also present, lacking textural evidence for the presence of detrital quartz and clay minerals and characterized by a rather distinctive metamorphic paragenesis comprising calcite — microcline — Mg-tremolite — pyrrhotite — graphite — albite — sphene; a satisfactory explanation has not yet been found for the widespread precipitation of authigenic or diagenetic feldspar or a hydrous precursor to feldspar, and

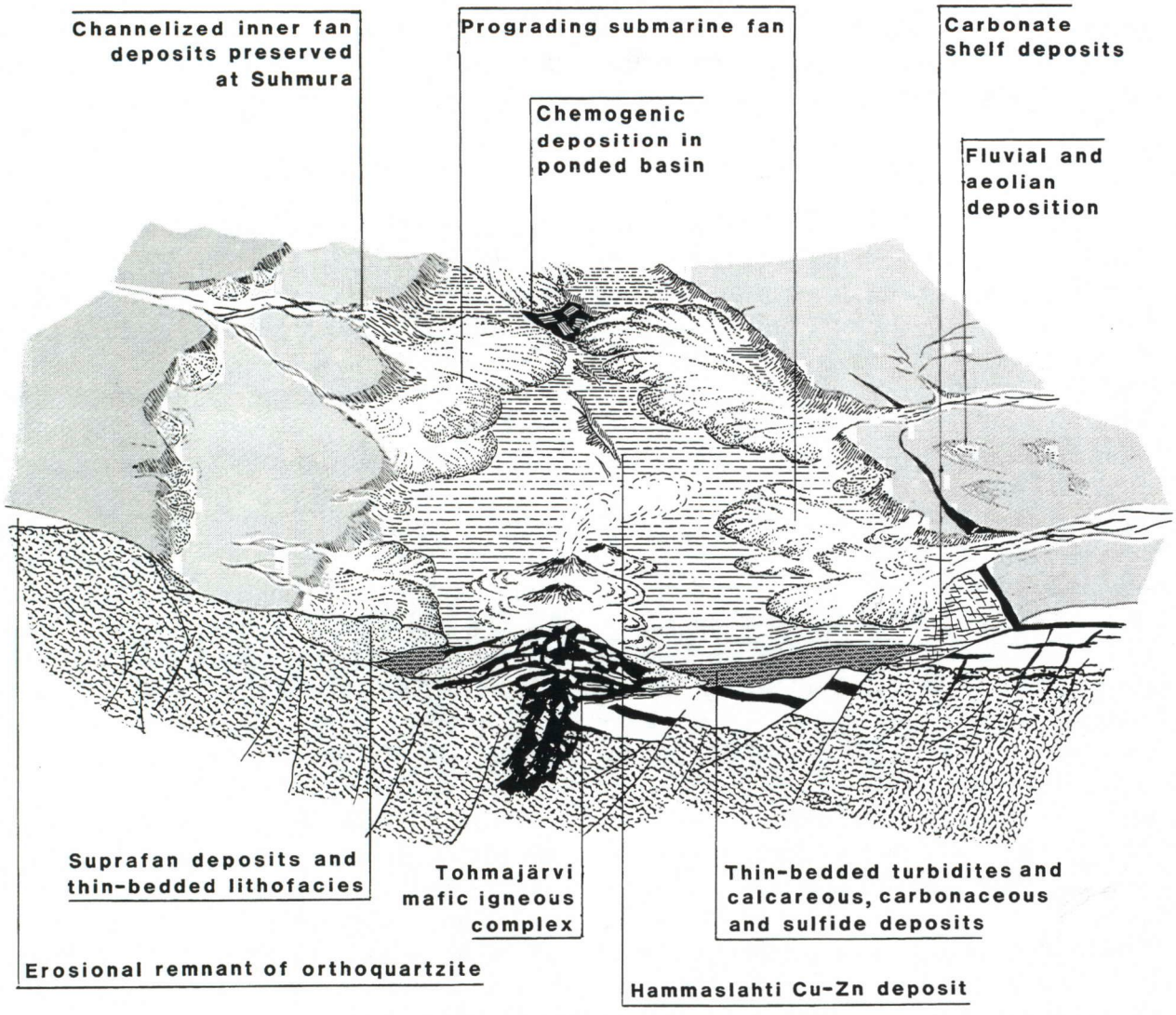


Fig. 2. Schematic depiction of lithofacies relationships during the early stages of 2.1–2.0 Ga rifting and subsidence of the southwestern margin of the Karelian craton (from Ward, 1988).

it is not clear whether the depositional environment was a deep restricted basin or might have been shallow enough to produce evaporites. Nevertheless, the generally high sulfide and graphite contents of these sediments point to the possibility of microbial activity in an anoxic environment — be it shelf or basin floor.

Carbon isotope studies by Karhu (1993) and Melezhik and Fallick (1996) show that the Jatulian carbonates deposited between 2.2 Ga and 2.0 Ga in the Fennoscandian Shield record a signicant isotope excursion, that corroborate less comprehensive results from elsewhere. This change, from more normal $\delta^{13}C$ values of around 0 per mil at 2.4 Ga to +12 per mil by 2.2 Ga, and back to 0 per mil by 2.0 Ga, is the largest such excursion so far documented, and requires the burial of a large amount of carbon, in the form of organic matter, in marine sediments at that time. This is consistent with the presence of extensive black schists within the Kalevian sedimentary sequences of this age in eastern Finland. Since evidence has recently been found for the development of the earliest eukaryotes during this time interval (Han and Runnegar, 1992), it is interesting to speculate whether the isotope excursion reflects this development, or whether changes in the chemistry of the hydrosphere and atmosphere enabled evolutionary advances to take place (cf. Karhu and Holland, 1996).

This time period also broadly overlaps with other events such as the first appearance of redbeds in the Fennoscandian Shield, widespread development of stromatolites in carbonate platforms, and the earliest record of carbonate concretions in pelitic sediments (Melezhik and Fallick, 1996). This in turn may have implications for the age and distri-

bution of stratiform sediment-hosted sulfide deposits, since the relative proportions of carbonates and carbonaceous sediments within intracratonic basins and rifted margin sequences may be of great significance in controlling the redox behaviour of basinal fluids.

Mineralization within the 2.1 Ga rifted margin sequence

A single base metal deposit, at Hammaslahti, has been mined from the rifted margin sequence, following the discovery of a cupriferous gossan in 1968 during 1 : 100 000 scale bedrock mapping by the Geological Survey. The Hammaslahti Cu-Zn deposit is hosted by coarse-clastic quartz greywackes and in spite of complex deformation and substantial remobilization, retains some lithological and stable isotope evidence for a strata-bound, syngenetic origin (Hyvärinen and others, 1977, Loukola-Ruskeeniemi et al., 1993). Pb-Pb isotopic modelling by Vaasjoki (1981) suggests a mixing of ambient Pb with that from an older source, for which greywackes derived from an Archean granitoid terrain and the proposed rifted craton margin setting would be appropriate. However, graded hornblende-bearing greywackes found near the deposit have been interpreted as epiclastic turbidites, if not pyroclastic deposits derived directly from the Tohmajärvi mafic volcanic complex. Tremolitic intercalations are also present amongst coarse-clastic lithofacies within the Cu-Zn deposit itself and could represent altered mafic tuffs or sills.

The intercalation of turbiditic greywackes of predominantly Archean basement provenance with more mafic mass flow deposits therefore led Ward (1988) to propose a model involving either distal hydrothermal acivity related to the Tohmajärvi mafic volcanic complex, or diagenetic leaching of metals from deeper basin sediments after the cessation of volcanism, with more permeable coarse clastic deposits acting as preferred pathways for fluid migration, while finer grained clay-rich and locally graphitic units would have acted as barriers to fluid flow. This model may encounter difficulty in explaining the migration and deposition of copper, which should require higher temperatures, and more recent lithogeochemical evidence for a distinct alteration halo around the deposit (Loukola-Ruskeeniemi et al., 1993) favors a more local and direct rather than distal and diagenetic source for hydrothermal activity. The predominance of Cu and Zn with respect to Pb is in either case consistent with metal leaching from predominantly basaltic rather than felsic volcanics (cf. Large 1992), while the Archean aspect to the Pb model ages (Vaasjoki, 1981) is in accord with the rifted cratonic margin setting and granitic basement provenance of the coarse clastic sediments hosting the deposit.

Structural and lithofacies mapping, in combination with recently acquried geophysical data, are continuing in the area, in order to establish the potential for discovery of further deposits within the sequence.

The Karelian Province at 1.97–1.95 Ga — renewed rifting at a passive margin resulting in the formation of an ocean basin

Rifting culminated in the formation of oceanic crust at 1.97 Ga, fragments of which were subsequently thrust back onto the Karelian craton as the Jormua complex, which is renowned as one of the few examples of Paleoproterozoic ophiolites (Kontinen, 1987) and the Outokumpu assemblage, which is perhaps best known for its Cu-Co-Zn deposits and chromian skarns (Väyrynen, 1939, Koistinen, 1981).

The Outokumpu assemblage was first described as an ophiolite by Wegmann in 1928, an interpretation quite consistent with the concept as understood in Alpine terms at that time. However, whether the assemblage contains all or some of the elements explicit in more recent definitions is still debated (Park, 1988a). Interpretation of primary lithologies and geochemical characteristics has been difficult, partly due to intense deformation but also as a result of extensive hydrothermal processes associated with ore formation. In studying some of the serpentinite bodies of the Outokumpu assemblage near Luikonlahti, Park (1983) also identified a relict high temperature aureole enclosing the serpentinite and interpreted it to represent their emplacement as high level sills. However, more recent studies,

still in progress (Asko Kontinen, personal communication), have shown that relict olivine and enstatite is unlikely to be of primary magmatic or contact metamorphic origin, since primary mineral assemblages were already converted to hydrothermally altered serpentinite and talc-carbonate lithologies prior to the onset of regional metamorphism. Olivine is therefore reinterpreted as belonging to a peak regional metamorphic assemblage that was in turn extensively serpentinized during late stage retrogression. Park (1988a) favoured a back-arc setting for volcanism and exhalative mineralization, deduced from the presence of deformed vesicular pillow lavas, as well as immobile trace element geochemistry.

At the scale of the whole Fennoscandian Shield, the full significance of mafic and ultramafic magmatism and rifting at this time has not been properly appreciated. In addition to the Jormua ophiolite and Outokumpu assemblage, a major province of essentially undeformed picritic flood basalts is present around Lake Onega, in the eastern part of the Karelian craton, while a suite of picrites, hosting major nickel deposits at Pechenga, in the Kola Peninsula, also have an age of 1.97 Ga (Hanski et al., 1990). Hanski (1989, 1992) found that the chemistry and isotopic characteristics of the Pechenga ferropicrites were consistent with a plume-related origin, but advocated caution in advancing this interpretation, since the regional setting and duration of subsequent events need to be well-constrained. Moreover, it is not entirely clear that the Kola picrites formed in their present position with respect to the Karelian Province, due to the presence of several intervening allochthonous terranes (Berthelsen & Marker, 1986).

It is also apparent that the main part of the volcanics within the Lapland greenstone belt structurally, as well as stratigraphically overlie units correlated with the 2.1–2.0 Ga rift phase (Ward et al., 1989), while similar rocks, including komatiites, in the Karasjok greenstone belt in adjacent northern Norway have yielded Sm-Nd isochron ages between 2.0–2.1 Ga (Krill et al., 1985, Bergh & Torske, 1988, Barnes & Often, 1990). The recent recognition of a suite of serpentinites with depleted harzburgitic mantle affinities within the greenstone sequence in central Finnish Lapland (Hanski et al., 1996) indicates that a large part of this sequence must be allochthonous, presumably emplaced onto the Karelian craton at some time prior to 1.89 Ga (Sorjonen-Ward, 1996). It is hence conceivable that the Lapland greenstones, the Jormua ophiolite and the Outokumpu assemblage each represent the deformed remnants of a formerly contiguous segment of oceanic crust being consumed towards the southwest and emplaced across the Karelian province foreland, which would then imply and allochthon of dimensions 50–100 km in width and greater at least 500 km in length, which for example, is an area similar in magnitude to that of the Oman ophiolite.

It is tempting therefore to speculate as to whether a plume was responsible for extensive mafic and ultramafic magmatism at the scale of the Fennoscandian Shield in the period preceding the 1.97–1.95 Ga rifting process. Moreover, is it possible that the impingement of a plume at that time might have influenced the geometry of plate boundaries and motions, leading to sea-floor spreading, in much the same way as plumes have been implicated with initiation of sea-floor spreading, or reorganization of plate-motions in the Phanerozoic?

Transition from divergent to convergent tectonics — passive margin or arc-derived sediments and incipient collision between 1.95–1.90 Ga

In contrast to the 2.1–2.0 Ga rift phase deposits, sediments associated with and overlying the Outokumpu assemblage and Jormua ophiolite are dominated by remarkably monotonous metapsammites preserving few indications of depositional environment. In many exposures the sediments are so homogeneous as to resemble fine-grained granodiorite, but rare examples of primary basal load and flame structures, scours and tractional bedforms, support interpretation as medium- to thick- bedded mass flows deposited in a submarine setting. Near the Suhmura thrust zone, on the inverted limb of the Kompakka nappe (Appendix 1), coarse, chaotic deposits contain intraformational detritus which suggests deposition from debris flows and high-density turbidity currents in a submarine canyon or channelized inner fan environment.

Although most of this monotonous sequence

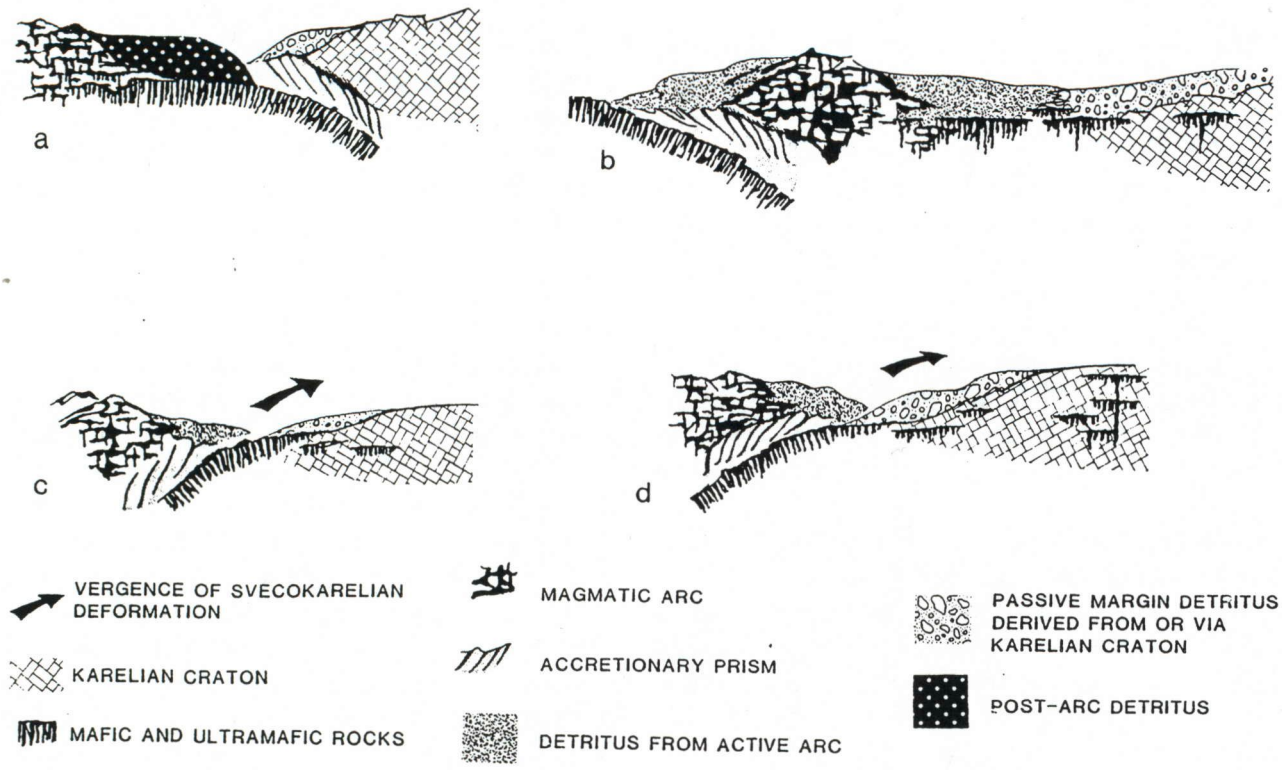


Fig. 3. Alternative scenarios for tectonic and depositional environment of the <1.95 Ga monotonous clastic sequences overlying the Jormua ophiolite and Outokumpu assemblage, from Ward (1987); a: highly implausible situation with sediments representing post-arc flysch incorporated into accretionary prism with putative subduction beneath Karelian craton, for which no coeval continental arc magmatism exists; b: a more reasonable scenario in which the Outokumpu assemblage is interpreted as a back-arc basin, so that sediments could represent a mixture of passive margin and arc-derived detritus. However, this does not provide a simple mechanism to account for the relatively late thermal metamorphic peak following tectonically thickening and nappe emplacement; c: attempted subduction of passive margin towards the southwest, with oceanic island arc supplying most of the detritus, due to restricted sediment supply and low relief on the cratonic foreland; same tectonic setting as in c, but with sediments deposited on the passive margin shelf and slope dominating supply — this is the preferred scenario to satisfy current tectonic and provenance considerations.

is allochthonous, its widely transgressive nature is indicated by local preservation of basal depositional contacts in several places; these include the 2.1–2.0 rift phase deposits, the Jormua ophiolite, the Outokumpu assemblage and, in the southern parts of the region, they locally rest directly on Archean basement retaining paleoregoliths. The absence of the 2.1–2.0 Ga rift phase sediments in the latter areas is not simply a result of lateral facies changes during basin transgression. Instead, it may relate to the incipient stages of attempted subduction of the passive margin, with the development of flexural bulge and consequent erosion of the earlier rift-phase passive margin deposits, prior to general subsidence and deposition of the main part of the monotonous sequence. Systematic changes in clast composition in basal coarse-clastic deposits are also consistent with progressive denudation of firstly cover sediments and then Archean basement in the source area, with intrabasinal detritus dominating at later stages (Ward, 1988). So far, attempts to establish the provenance of these deposits using petrography, chemistry, Sm-Nd model ages and detrital zircon have yielded ambiguous results, neither confirming or precluding derivation from the Svecofennian arc terranes (Ward, 1987). However, the textural immaturity and chemical homogeneity of the sediments led Kontinen and Sorjonen-Ward (1991) to favor an origin as a major submarine fan system prograding over the subsiding passive margin, just prior to collision, with sediments being derived from the craton, or a more distant orogenic source (configurations c and d in Fig. 3).

Such a tectonic setting also appears to be in accord with the geometry of compressive deformation, which is most readily interpreted in terms of the Outokumpu assemblage and overlying sediments having been thrust over the

Karelian foreland during imbrication and attempted subduction of the craton margin. Moreover, there is no evidence for any contemporaneous arc activity within the craton itself, as would be expected if subduction took place beneath it, nor are there any intrusive or volcanic units within the Svecofennian fold belt known to be coeval with the Outokumpu assemblage or the Jormua ophiolite; the oldest dated Svecofennian arc-related lithologies are some 30 Ma younger than the Outokumpu assemblage, (Huhma, 1986; Vaasjoki & Sakko, 1988, Lahtinen, 1994). A minimum age constraint for deposition of the sediments (and hence a maximum age for the onset of deformation) is however given by 1.94–1.92 Ga U-Pb SHRIMP ages for detrital zircons — a result which does indeed approach that of the earliest Svecofennian intrusions and volcanics (Huhma et al., 1991). Although considered less likely than the passive margin scenario, if the Svecofennian arcs were a major source of sediment, the situation could then resemble that depicted in configurations a and b in Figure 3.

Convergence at 1.9 Ga, recorded by nappe emplacement and crustal thickening

There has been some uncertainty concerning the extent of the 1.97–1.95 rifting event, with the prevalent view having been that the Outokumpu assemblage and Jormua ophiolites respectively represented other back arc and incipient, intracratonic ocean basin opening respectively (Koistinen, 1981, Park et al., 1984). The alternative interpretation involves the Outokumpu assemblage being passive margin ocean floor, or even including fore-arc material from an oceanic arc, emplaced onto the Karelian craton during collision (Ward, 1987). A rough minimum estimate of the amount of nappe emplacement involved can be calculated due to the effects of deformation following nappe emplacement, as a result of which several basement windows protrude through the Outokumpu allochthon (Appendix 1). On this basis it is possible to deduce a minimum displacement of 50–60 km parallel to the principal lineation and inferred thrusting direction, with the present trace of the Outokumpu assemblage enclosing an area of nearly 5000 km^2 for the allochthon. The original displacement must be somewhat greater, since nappe geometry is to some extent complicated by subsequent imbrication, which also involved thrusting of basement (Frosterus & Wilkman, 1920, Park & Bowes, 1983, Park & Doody, 1990, Kohonen et al., 1991).

Likewise, it is reasonable to consider that the Jormua ophiolite was similarly emplaced from the southwest across the Archaean basement and subsequently imbricated and refolded into a tight synform, thus representing an allochthonous klippe (Sorjonen-Ward, 1991, Peltonen et al., 1996). A corollary of this interpretation is that the Jormua and Outokumpu sequences belong to the same large tectonic unit, with a total preserved area of at least 20 000 km^2.

The overall structural and metamorphic evolution of the Outokumpu region has been well documented as a result of several detailed studies (Koistinen 1981, Park et al., 1984). The earliest, D_1, D_2 and D_3 structures relate to the formation of thrust nappes and recumbent folds that are considered to record a combination of progressive deformation, diachronism and changing structural style across the region, with the locus of most intense deformation migrating towards the east and northeast (Ward, 1987, Ward and Kohonen, 1989). Progressive migration of deformation towards the foreland, with thick-skinned imbrication of the Archean craton margin following earlier thin-skinned deformation (including the emplacement of the ophiolite nappes) seems to be broadly consistent with available metamorphic data showing a thermal peak following the main thrusting event (Ward, 1987).

Of the three D_1 nappes shown in Appendix 1, the Outokumpu nappe is the highest structurally and is well defined due to the strongly magnetic character of the Outokumpu assemblage; the boundaries between the Kompakka and Savonranta nappes are not so clear, except for the eastern margin of the Kompakka nappe above the Suhmura Thrust Zone. Downward facing F_3 and F_5 folds are also found in this region and indicate that the Kompakka nappe may be a recumbent fold nappe, rather than a simple thrust nappe. Elsewhere it has been more difficult to recognize inverted D_1 or D_2 fold limbs, although most determinations of younging directions with respect to early foliations seem to indicate that the bulk of the allochthonous sequence is upward facing.

1.90–1.85 Ga responses to crustal thickening in eastern Finland

The deformational sequence in southeastern Finland has been interpreted as a continuum involving an initial phase of thrusting, causing crustal thickening and resulting in thermal and gravitational disequilibrium within the deep crust, leading in turn to the development of extensional structures (Ward, 1987). The geometry and sequence of structures, as well as the timing of the thermal metamorphic peak thus essentially records a loading-unloading response, involving a progressive increase in magnitude of the vertical stress component with respect to horizontal compression (Fig. 4). Such kinematic interpretations also need to consider the possibility of changes in the orientations of the far-field stress system, for example due to changes in directions of convergence at plate boundaries, as well as changes in the mechanical behaviour of deforming rock units with time.

In general however, an interpretation involving sustained NNE-SSW compression from about 1.90 Ga — 1.86 Ga is consistent with the observed structural sequence and its overall geometry, namely the transition from N-NE-directed thrusting to the development of NW-trending dextral transcurrent shear zones, such as the Suvasvesi Shear Zone (Väyrynen, 1939, Halden, 1982), which clearly shows truncation and reorientation of the Outokumpu nappe (Appendices 1 and 2). Reorientation and reactivation of early, thrust-related structures within the NW-dextral shear zones was intimately associated with extensive granite and gabbro emplacement at 1.89–1.86 Ga, which must also made a major contribution overall crustal strength, in turn influencing responses to further compression.

If crust is mechanically and thermally unstable, isostatic equilibrium can be restored in several ways, including rapid erosion, tectonic expulsion or escape, extensional collapse and generation of intracrustal granites, or by convective thinning of the lithosphere involving delamination at the base of the crust and underplating by hotter asthenospheric material, of which the Tibetan plateau is regarded as a type example (Platt & England, 1994). Lahtinen (1994), in a comprehensive synthesis of collisional and post-collisional Svecofennian magmatism in central and southern Finland, invoked post-collisional underplating by mafic magma whose enriched mantle geochemical characteristics differed from the more depleted mantle signatures of the Karelian Province mafic volcanics, as well as from the earliest Svecofennian, pre-collisional arc magmas.

On the other hand, deep seismic surveys have revealed the existence of an unusually thick crust in the region (Korja et al., 1993), which tends to suggest that widespread crustal collapse was inhibited (assuming that the features present in seismic images are truly inherited from Paleoproterozoic time). Understanding the implications of these different lines of evidence are of both academic and economic interest in eastern Finland; in particular, the deep thermal structure and history of the region is highly relevant because of recent diamond exploration activity.

Archean basement between Kuopio and Nunnanlahti — and including the Luikonlahti area — has undergone extensive ductile reworking during the Svecofennian, usually such that feldspar porphyroclasts are recognizable in a highly strained quartz-mica matrix (Kohonen et al., 1991). This suggests plastic behaviour by quartz and semi-plastic behaviour by feldspar, which as the dominant minerals, would control the overall strength of rock at least at this crustal level.

Moreover, some granitoids, post-dating thrusting and crustal thickening, and closely associated with the NW-dextral dextral transcurrent shear zones, have ages of 1.87–1.86 Ga, and clearly show isotopic and chemical evidence for melting of Archean crust at depth (Huhma, 1986, Lahtinen, 1994).

This combined evidence for crustal thickening and widespread rheological weakening of the crust can be linked kinematically to the formation oblique sinistral normal sense shear zones. A scenario involving sustained N-directed compression, for which evidence exists in southern Finland at both 1.88 Ga (Nironen, 1989) and 1.84 Ga (Ehlers et al., 1993), would allow for flow of weakened middle crust outwards, at a high-angle to the direction of convergence, which is an appealing way of explaining the orientation of linear fabrics throughout the region. Such an interpretation would also allow extensional and compressional structures to form simultaneously at dif-

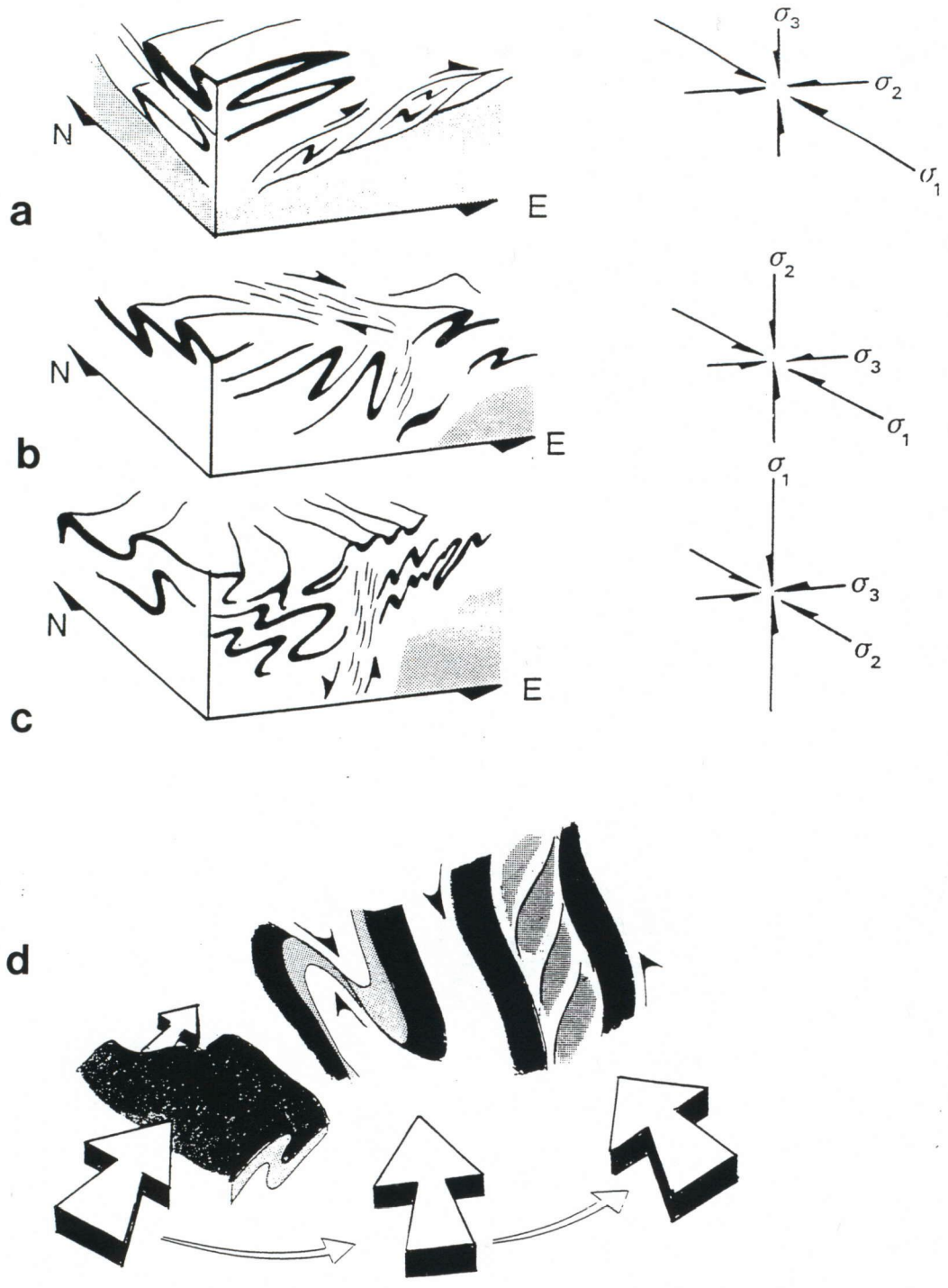


Fig. 4. Progressive deformation continuum reflecting uniform boundary conditions but varying internal responses to explain the geometry and sequence of structures in eastern Finland, after Ward (1987) and Ward & Kohonen (1989). (a) Emplacement of cover nappes towards the N and NE and eventual imbrication of deep levels, involving thrusting of basement. (b) Relative increase in vertical stresses, due to buoyancy of buried crust and abundant partial melting (due to post-collisional magmatic underplating?) and/or relaxation of far-field collisional stresses, resulting in the generation of dextral NW-trending strike-slip shear zones. (c) Continued response to gravitational and thermal instability leads to the development of normal sense shear zones. (d) Alternative possibility in which external boundary conditions change, such as rotation of convergence vector, leading to progressive overprinting and reorientation of structures; in this case, the later structures have a stronger strike-slip rather than normal sense displacement.

ferent crustal levels, explaining such the observed successive overprinting of earlier low-angle structures by sinistral oblique normal shear zones as they propagated towards the foreland, coeval with crustal shortening elsewhere in the fold belt (Kohonen, et al., 1991).

Interaction with strike-slip displacements along the NW-dextral shear zones could be

responsible for the broad regional refolding of the Outokumpu nappe, which has given rise to the current pattern of distribution of the Outokumpu assemblage (Appendix 1). Alternatively, this later folding could relate to a regional reorientation of stresses such that the NW-trending dextral shear zones record deformation essentially parallel to the continental margin, as favoured in the Cordilleran analog applied by Park et al. (1984). It should be noted however, that lithological units can be traced across individual shear zones (Appendices 1 and 2), suggesting that they record displacements of the order of tens of kilometers, rather than representing terrane boundaries between disparate tectonic units.

Perhaps these boundary conditions, namely sustained convergence, with a combination of tectonic uplift and extensional orogen-parallel transfer of middle crustal material, enabled a dynamic equilibrium to exist between crustal thickening and crustal extension and allowing the Svecofennian lithosphere to eventually attain thermal and gravitational equilibrium in spite of the crust remaining nearly 60 km thick.

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OUTOKUMPU DISTRICT

by
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STOP 1 — LUIKONLAHTI

The Luikonlahti area is located some 30 km north of Outokumpu, but is clearly part of the same tectonostratigraphic sequence and shares many of the distinctive characteristics of the Outokumpu-type massive sulfide deposits, including a close spatial association with serpentinites, quartzitic rocks, carbonates and graphitic sediments. The Outokumpu assemblage probably occurred at the same structural level throughout the entire region, even following nappe emplacement, but refolding about NE-SW trending axes has produced an elongate dome and basin geometry, resulting in separate tectonic outliers or klippen of the Outokumpu nappe, with Luikonlahti now being separated from Outokumpu by an antiformal culmination exposing Archean basement and Proterozoic granitoids (Appendix 1). The ore bodies at Luikonlahti appear to lie within a SW-plunging isoclinal fold with a highly curvilinear hinge, interpreted by Park (1988b) as a large scale sheath fold structure formed after emplacement of the Outokumpu nappe. The Luikonlahti ore bodies differ from the Keretti and Vuonos ores at Outokumpu in the relatively greater proportion of calc-silicate rocks, which hosted some 40% of the ore, compared to Keretti for example, where the ore was mainly found within fine-grained quartz rocks.

Cu-Zn-Co ORE DEPOSIT AND KIMBERLITES AT LUIKONLAHTI

by Matti Tyni

The Luikonlahti Cu-Zn-Co mine

The first indications of copper mineralization at Luikonlahti were found the Geological Survey of Finland during regional bedrock mapping surveys in the early 1900's. An outcrop of the main orebody was subsequently discovered by a private prospecting company, Malmikaivos Oy, in 1944. Extensive research and test mining was carried out after World War II, when the main target for exploration were the reasonably high nickel contents of the outer contacts of serpentinite lenses within the Outokumpu assemblage. Nevertheless, insufficient tonnages and the remote location caused all exploration activity in the area to be suspended for the next ten years.

When drilling resumed, this time with better techniques, it was found that the main orebody continued at depth, while two additional smaller ore bodies were also discovered (Figs. 5, 6). Ore reserves were estimated at eight million tons of copper ore containing: Cu 1.1% (in chalcopyrite); Zn 0,6% (in iron sphalerite); Co 0.1% (in Co-pentlandite and in the lattice of pyrite and pyrrhotite) and S 18% (mainly in pyrrhotite). Dimensions of the main ore were: maximum width 80 m, depth 480 m and length 700 m. The dip of the ore body was nearly vertical, allowing the use of low cost mining methods, while the ore mineralogy of the ore was favorable for producing high grade mineral concentrates. Production commenced in 1968 after mine development, construction of railroads, power lines, roads and other infrastructure and continued until 1983. Annual production was of the order of half a million tons of ore and after three years of open pit mining, operations continued underground using a sublevel caving method. About 220 people were employed in various aspects of mining operations and the mine had a major impact on the local economy. Five different mineral concentrates were transported by rail to domestic smelters: copper, cobalt and zinc to several Outokumpu smelters, pyrrhotite to the sulfuric acid plant built by Kemira Oy at Siilinjärvi and roasted iron oxide from Siilinjärvi to the Rautaruukki iron furnaces at Raahe. Mining at Luikonlahti was carried out by the Finnish paper company, Myllykoski Oy, which was at that time the owner of Malmikaivos Oy.

Prospecting continued throughout the duration of mining operations and as the copper ore became progressively depleted, Malmikaivos delineated and evaluated reserves of high quality talc raw material (soapstone) at Luikonlahti. Talc production commenced after modification of the sulfide concentration plant for talc flotation and the application of new jet milling technology for micronizing the products. Talc is an important industrial mineral for the forest products industry. Production of talc started in 1979, at first alternating in shifts with copper ore processing. After closure of the copper mine, mining of a variety of talc products continued at a rate of 80 000 tonnes per year at full capacity.

Kimberlite projects

The first kimberlite pipe in Finland was discovered by Malmikaivos Oy as long ago as 1964 during regional sulfide ore prospecting in the surroundings of the Luikonlahti mine. This strongly magnetic pipe is located about 5 km SW from the mine but the significance of the discovery was not fully appreciated at the time. In the early 1980's two new kimberlite bodies were found during sulfide ore exploration, located some 20 km NE of the mine. The lack of specific diamond expertise in the evaluation of these discoveries led Malmikaivos in 1985 to approach Ashton Mining Limited from Australia for assistance. A technical cooperation and funding agreement was signed between Myllykoski Oy and Ashton Mining in 1986, with Malmikaivos being the company responsible for management of the project. Ashton Mining has had at least two experienced diamond exploration geologists working as members of the Finnish exploration team, with Malmikaivos Oy having provided a well-equipped field laboratory and established a 5 tons per hour bulk testing plant. To date 24

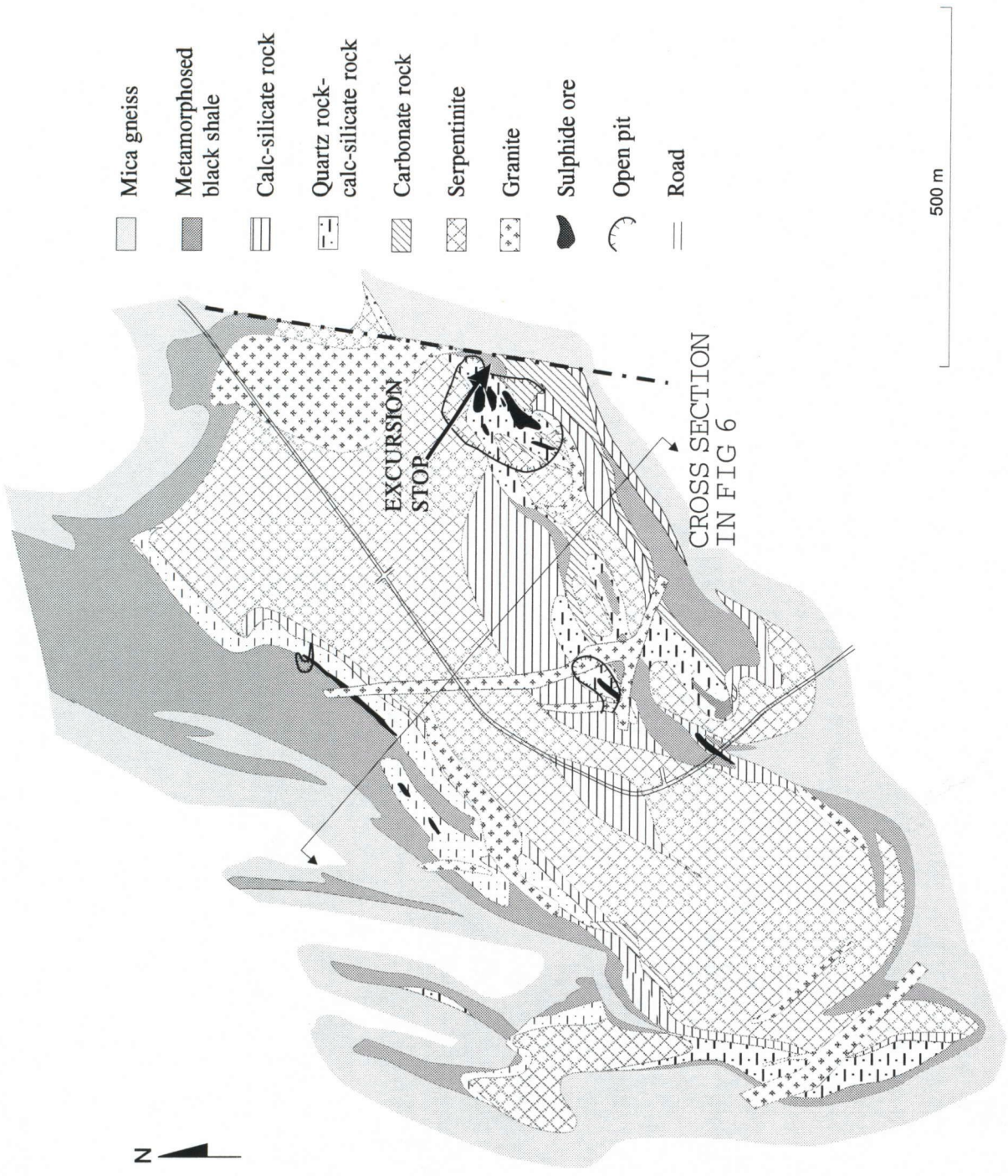


Fig. 5. Geology of the Luikonlahti area.

kimberlite pipes and dikes, mainly from one to four hectares in area have been discovered. All are located beneath some 5–25 m (at one locality 45 m) of recent glacial deposits that mask the underlying structurally complex granitoids and schists of the Baltic Shield. Fifteen of the pipes contain at least micro-diamonds. Preliminary tests on bulk samples from four of the pipes show significant grades, i.e., above 10 carats per hundred tonnes. The quality of stones is comparable with stones from existing diamond mines.

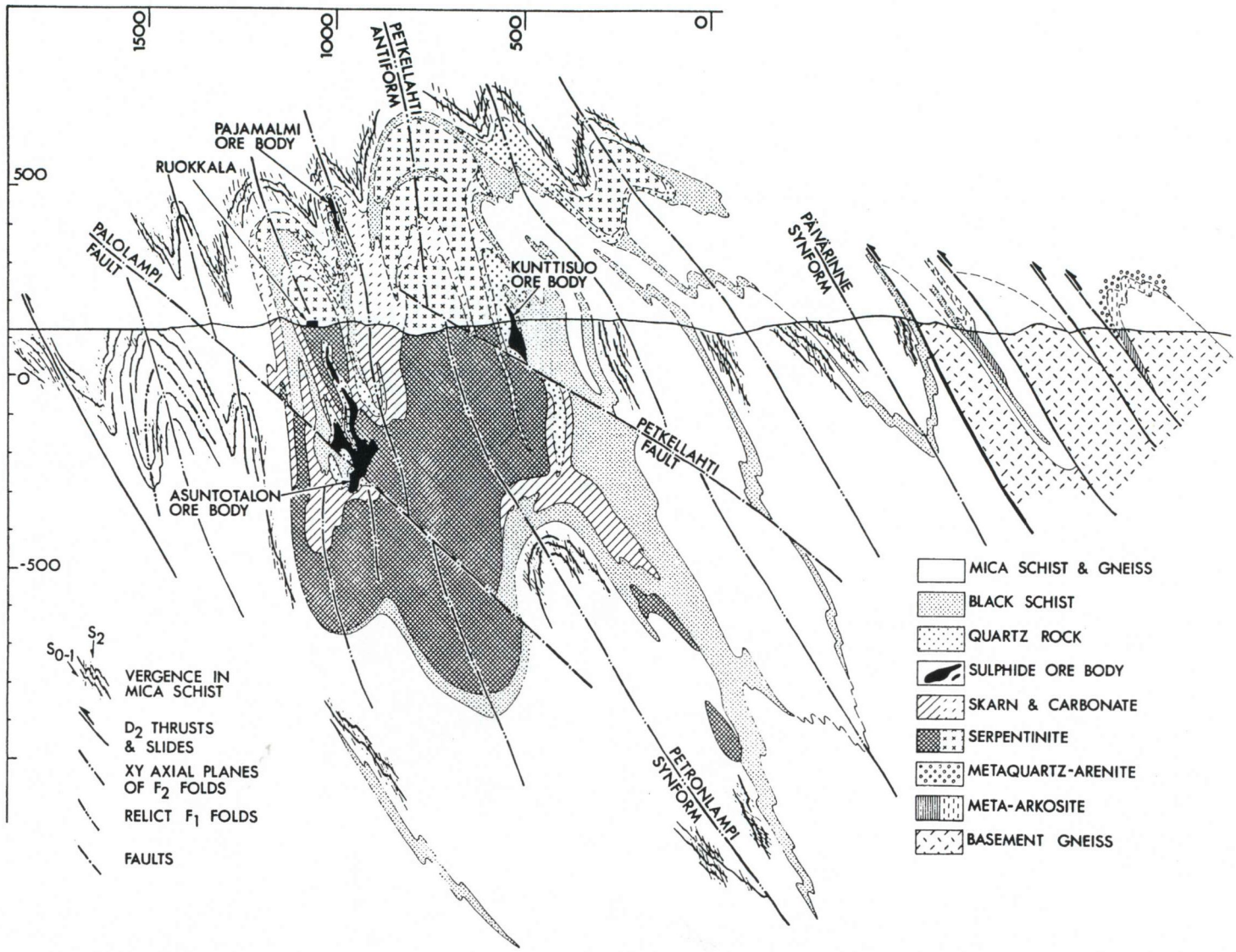


Fig. 6. Cross-section NW-SE looking SW (down plunge). Across the mine site the section is constrained by borehole and stope records to a depth of 500 m below the surface. The rest of the section is constructed by projection of information from the surface and other serial sections along paraboloid trajectories reflecting the x-y profile of the F_2 folds, controlled by the L_2 intersection lineations (from Park, 1988b).

STOP 2 — OUTOKUMPU

AN OUTLINE OF THE HISTORY OF EXPLORATION AND MINING IN THE OUTOKUMPU DISTRICT

by Jyrki Parkkinen

The history of mining and exploration in the Outokumpu district effectively started with the discovery of the main Outokumpu ore body, which is still the largest copper-zinc-cobalt deposit known from the region, in 1910. The mining history of the district spans the period 1913–1988 and of the eleven massive suphide deposits known, three have been mined, producing a combined total of 50 Mt of sulfide ore averaging 2.8 % Cu, 1 % Zn and 0.2 % Co (Table 1). In addition, several low grade nickel-copper-cobalt occurrences have been identified, one of which has been mined for nickel and cobalt and one for nickel.

In 1908 Otto Trustedt, a geologist employed by the Finnish Geological Commission (the precursor to the Geological Survey of Finland), was sent to Kivisalmi, some 60 km SE of Outokumpu, to investigate a large glacial erratic dredged up during widening of a channel between some of the main waterways in Karelia; the boulder proved on analysis to assay 3.74 % copper. Funded by the National Board of Industry Trustedt then commenced tracing the source of the boulder. He had two main clues to follow; although the main trend of the glacial striations at Kivisalmi was to the west, there was another set of striations trending nearly north-south. Since the boulder conisted largely of quartzite, and the only known exposures of quartzite were to the north and northeast of Kivisalmi, Trustedt started examining reported quartzite localities, not realizing that the trail was in principle misleading, since the quartzite in the erratic was quite different in character from the detrital orthoquartzites that he was seeking. During the course of the search, however, another geologist, W. W. Wilkman recognized that he had encountered banded sulfide-bearing quarzite schist, resembling that of boulder, on the northern slope of a peculiar hill named Outokumpu.

At Outokumpu Trustedt started a systematic search for boulders, finding several interesting floats. He was able to delineate a boulder train, he mapped the focus of the train with a magnetometer, and he had exploration pits and trenches dug. He decided that the ore deposit might be located in the quartzite between the Outokumpu hill and the younger mica gneiss 300 m north of it. The first two drill holes failed to verify his hypothesis but the third hole intersected the ore between 28.85 and 38.18 m on 17 March 1910.

Another major deposit, the Vuonos ore body, was located by deep drilling in 1965. As such it is one of the few blind ore bodies lacking surface manifestations to have been found in Finland, its discovery being based on scientific principles. Geologists had been able to recognize the structural and lithological continuation of Outokumpu type features northeastwards from the existing mine. Some of these features, such as the coexistence of graphite bearing quartz rocks and black schists and of serpentinite bodies could be followed by means of geophysics. Some of the diagnostic characteristics of the Outokumpu assemblage, such as pervasive enrichment in nickel, chrome and cobalt, could be identified due to dense drilling in the critical zone. However, the principal clue was to recognize the increase in the Co/Ni ratio of country rock when approaching an ore deposit. This encouraged geologists to drill a few holes a little deeper, the first of which encountered the ore.

The above scientific exploration concepts were further developed within the so-called Outokumpu Project in the early 1980's. The Project was able to identify the structural control of the main mineralized (and then deformed) zone and to locate new ore occurrences within that zone. Unfortunately, none of these new occurrences have proven to be economic so far, but one of them, the Kylylahti deposit, is still under investigation, and will be discussed further below.

Table 1. Major chacteristics of the Outokumpu-type deposits.

Deposit[1]	Metals[2] Zn (%)	Cu (%)	Au (g/t)	Ag (g/t)	Ni (%)	S (%)	Co (%)	Fe (%)	Tonnage (Mt)	Host rocks	Wall rocks	Year of discovery	Years mined
Cu-Zn-Co massive sulphides													
1. Outokumpu (Keretti)	1.07	3.8	0.8	8.9	0.12	25.3	0.24	28.11	28.5	Quartzite	Quartzite, skarn, serpentinite, dolomite	1910	1913-1988
2. Luikonlahti	0.5	0.99			0.1	16.5	0.11	25	7.5	Quartzite (60%), skarn (40%)	Quartzite, dolomite, skarn, black schist	1944	1968-1983
3. Vuonos	1.6	2.45	0.1	11	0.13	17.5	0.15	24.8	5.89	Quartzite (90%), black schist (10%)	Quartzite, mica schist, skarn, black schist	1965	1972-1981
4. Saramäki	(0.63)	0.71			(0.50)	(12.39)	(0.086)	(17.87)	3.4	Skarn	Skarn	1967	
5. Kylylahti (Alamalmi)	0.72	2.9	0.64	10	0.11	23.63	0.43	21.65	1.55	Skarn-bearing quartzite	Serpentinite, dolomite, mica schist, black schist	1983	
6. Perttilahti	1.89	2.15			0.145	18.9	0.16	(25)	1.32	Quartzite	Quartzite, dolomite, serpentinite, skarn	1982	
7. Riihilahti	0.09	0.72			0.03	3.84	0.09	9.05	0.7	Skarn, garnet-cummingtonite rock	Garnet-cummingtonite gneiss, peridotite, skarn	1957	
8. Kettukumpu	0.1	0.44			0.18	13.5	0.07	(15)	0.4	Diopside skarn, quartzite	Mica gneiss	1976	
9. Hietajärvi	1.82	0.78			0.2	18.2	0.17	(34)	0.33	Skarn	Skarn, black schist, mica gneiss, dolomite	1955	
10. Hoikka	<0.1	0.5			0.15	15	0.04	(20)	0.2	Diopside skarn, quartzite	Mica gneiss	1974	
11. Sola	1	2			0.15	17	0.1		0.1	Quartzite (70%), skarn (30%)	Quartzite, skarn, dolomite	1957	
Low-grade Ni-Cu-Co mineralization													
12. Kokka Ni					0.31				1.9	Diopside skarn, quartzite	Skarn, quartzite	1957	
13. Keretti Co-Ni	0.1	0.35	0.15		0.47	3.9	0.16	6.3	1	Skarn, anthophyllite-cordierite rock, quartzite, chlorite schist	Skarn, quartzite, serpentinite	1952	1987
14. Vuonos Ni	0.07	0.07	0.04	0.3	0.33	4	0.05	6.3	1	Quartzite, skarn, chlorite schist, cordierite-mica rock	Skarn, quartzite, serpentinite	1965	1972-1977

[1] For locations, see Figure 1.
[2] Numbers in parentheses are grade estimates.

AN INTRODUCTION TO THE OUTOKUMPU TYPE FORMATIONS

(Translated synopsis of a paper published in Vuoriteollisuus vol. 41, p. 18–22, in 1983)

by Markku Mäkelä

The Outokumpu assemblage, which essentially comprises serpentinites, calc-silicate and quartzitic lithologies, can be traced as a complexly deformed, discontinuous, sinuous ribbon of lenses, sheets and pods for nearly 250 km. Stratiform Outokumpu-type Cu-Co-Zn deposits are exclusively found within this assemblage, and three such deposits — Keretti, Luikonlahti and Vuonos — have been significant past producers; other occurrences include Hoikka, Riihilahti, Saramäki, Sola, Hietajärvi (and Kylylahti, which will be discussed in more detail below). In addition to metallic ore deposits, there are a number of commercially viable talc deposits associated with the Outokumpu assemblage, including those at Horsmanaho, Vasarakangas and Sola. The genesis of both the assemblage and the ore deposits has been the subject of debate for nearly seventy years, with a sea-floor exhalative model being favoured for the last ten years.

From a regional exploration point of view it is important to note that in the Vuonos area, the Outokumpu assemblage and the enclosing metasedimentary sequence form a gently dipping layer overlying Archean basement and the Proterozoic Maarianvaara Granite at relatively shallow depth, whereas the basement-cover contact plunges to greater depths along strike both to the northeast and southwest, as illustrated in Figure 7. The results of magnetic, gravity and AMT surveys all lend support to this interpretation (see Appendix 2). It is therefore concluded that the ore-critical part of the Outokumpu assemblage has been removed by erosion from the area between Vuonos and Keretti, and that the sequence may have been tectonically thinned between the axial culmination at Vuonos and Kokonvaara, becoming thicker again further to the northeast, towards the axial depression between Perttilahti and Kylylahti (Fig. 7).

However, this interpretation implies that the ore-critical horizon would be expected to occur at a depth possibly in excess of 1000 m, and the expense of drilling to such depths required the development of a well-defined structural model, based on careful interpretation of magnetic, gravity and AMT data. The resultant structural model, depicted in Figure 8, was tested by drilling a profile four kilometers to the northeast of the Vuonos ore (Fig. 9).

Drill hole 733 (Fig. 9) intersected a sequence of black schists nearly 100 m thick, and was assumed to envelope Outokumpu assemblage lithologies — this conclusion was then verified when the drill hole 737, structurally below 733, penetrated around 150 m of Outokumpu assemblage lithologies, including a six meter thick mineralized layer that proved on analysis to show the same element enrichment patterns found in the Ni-bearing mineralization above and around the Vuonos ore body. Finally, drill hole 740 successfully penetrated a sizeable Outokumpu-type ore body.

Petrophysical measurements were carried out

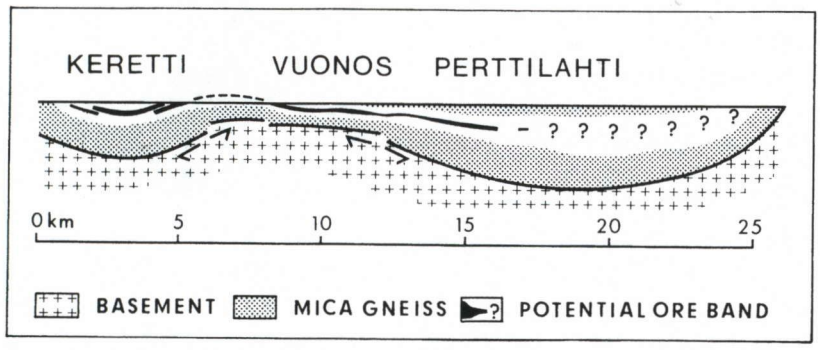


Fig. 7. Vertical profile along NE-SW trend showing location of Keretti and Vuonos ore bodies with respect to culminations and depressions of the basement-cover interface.

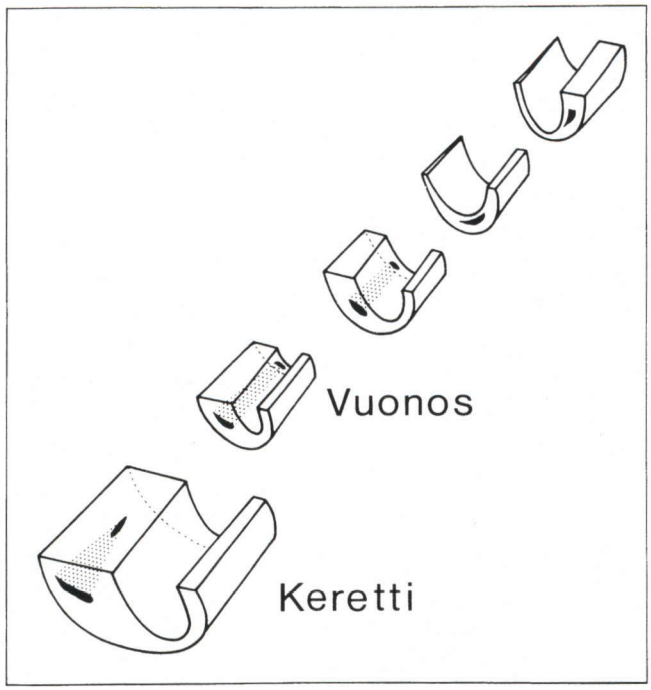


Fig. 8. Structural model used in the dipping prism gravimetric modelling. Inferred position of the ore-critical horizon, trending obliquely across the fold hinge, is also indicated.

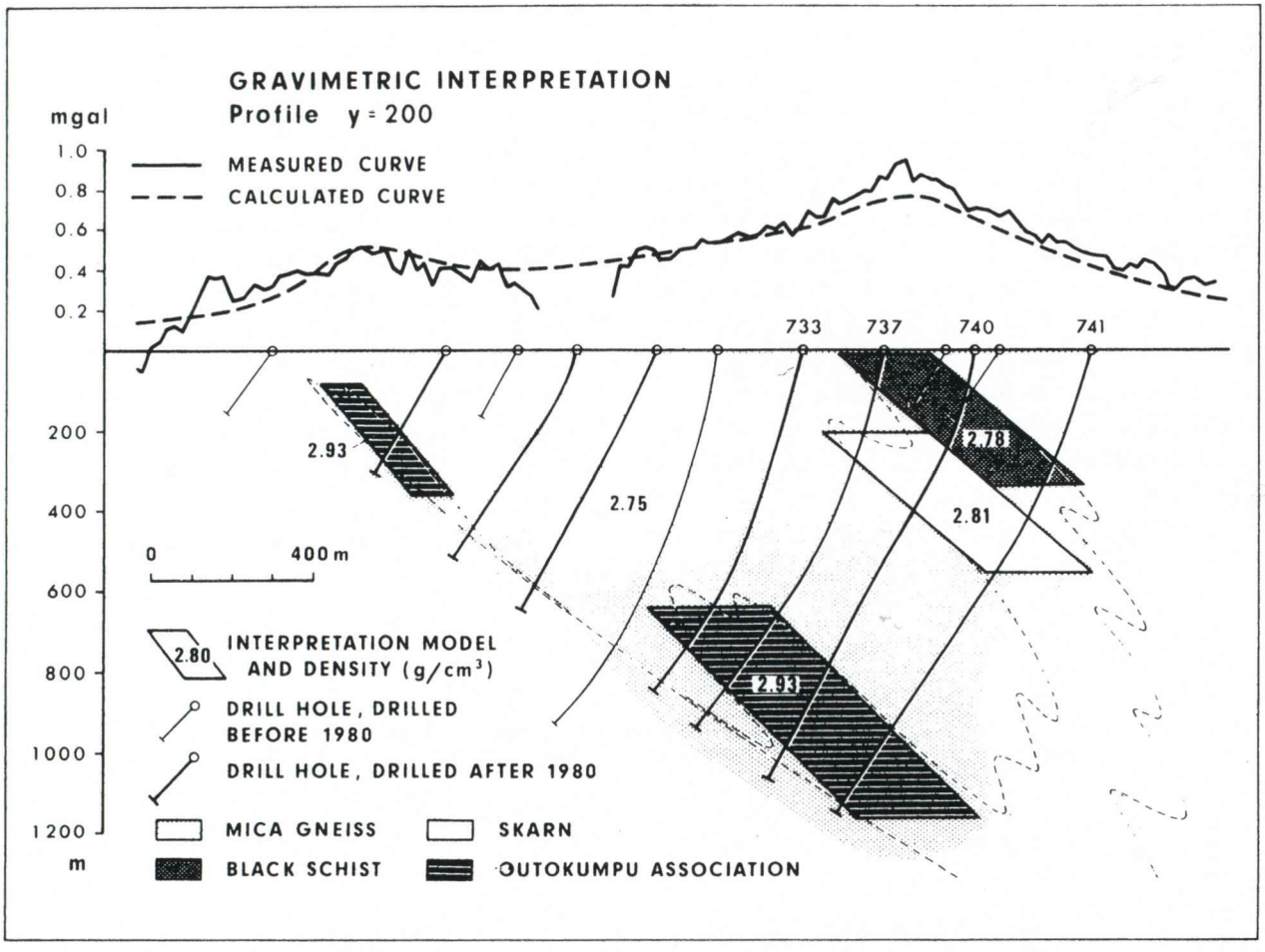


Fig. 9. Gravimetric interpretation of the test profile at the Kylylahti prospect, 4km northeast of Vuonos. Dipping prisms are assigned densities according to inferred distributions of principal lithologies. Broken lines indicate the inferred trace of the reclined synformal structure.

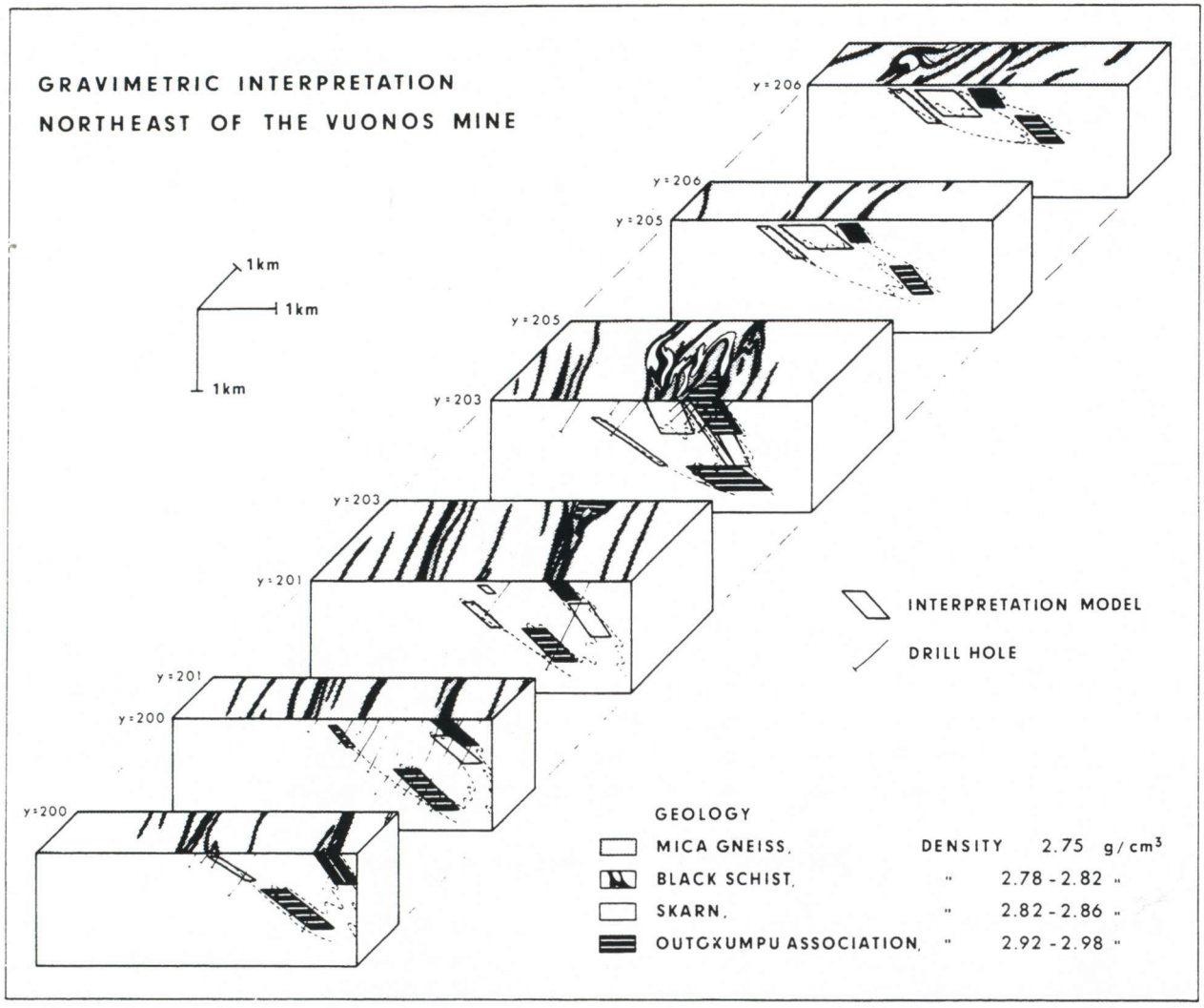


Fig. 10. Block diagram viewed towards northeast, showing a sequence of interpreted gravimetric profiles, including the drilled test profile of Figure 3, at northing co-ordinate y =200.

on recovered drill core and it was found that while the Outokumpu assemblage lithologies present on the inferred lower limb of the fold had a mean density of 2.93 gcm^{-3}, the overlying metasediments had mean densities of 2.75 gcm^{-3} and were moreover of sufficient thickness that the two units could potentially be successfully discriminated using gravimetric modelling. It was found that the modelled prisms and calculated values agreed very well with observed densities, thus providing support for the overall model. On this basis, a further exploratory hole (741 in Fig. 9) was then drilled to a record depth for Finland, of 1297.50 m. Using the results obtained from the drilled profile, a series of gravimetric models were then developed at kilometer intervals between Vuonos and Kylylahti, resulting in the block diagram shown in Figure 10.

Subsequent drilling showed that actual intersection deviated from the modelled horizons by a relatively small amount, effectively of the order of several per cent with respect to each meter drilled. Drilling also intersected an Outokumpu-type ore body at a distance of 3.5 km northeast of Vuonos. The total length of the ore-prospective synformal structure in this area, before it intersects and extrapolates above the present erosion level near Kylylahti, is some 13 km.

When considering the potential for finding more Outokumpu-type ore deposits beyond this particular zone, it is important to precisely define the position of the ore-critical horizon within the overall tectonostratigraphical sequence. The use of aeromagnetic pixel images has greatly enhanced the ability to follow key horizons throughout the area, enabling a more detailed interpretation of stratigraphical relationships than was previously possible (see Appendix 2). The concentric patterns of magnetically

responsive and subdued units evident in aeromagnetic pixel images clearly delineate structural domes and basins and also demonstrate that many lithological units are laterally extensive. This in turn indicates that the Outokumpu assemblage occurs as a coherent package at a consistent stratigraphical level on a regional scale, over an area of some 4500 km^2. This support the hypothesis that the assemblage and associated ores represent products of intense hydrothermal interaction between seawater and submarine — presumably basaltic — volcanics; Br, Cl and S isotope data are also consistent with this model.

THE KYLYLAHTI Cu-Co DEPOSIT

by Lauri Pekkarinen

Introduction

According to current prevailing ideas, the serpentinites, Cr-bearing calc-silicate rocks and quartz rocks of the Outokumpu assemblage represent hydrothermally altered relicts of ophiolite-related submarine volcanics and intrusions. The synformal fold structure at Kylylahti is but one part of the intricately deformed and discontinuous chain of occurrences of Outokumpu asemblage throughout the Outokumpu region.

Background to discovery and exploration

The existence of the Kylylahti Cu-Co deposit (Fig. 11) was established during two spearate phases of exploration. During the first active phase of exploration, between 1983 and 1986, the "deep ore body" was intersected by drilling, together with a disseminated sulfide halo both enclosing the deposit and extending along strike. Geophysical and lithogeochemical studies both played an important role in this stage of investigation, which nevertheless came to a conclusion in 1986 when Outokumpu decided to discontinue cobalt production and processing.

During the second exploration phase, between 1994 and 1995, the surface extension of the deep ore body was identified, as well as further extensions to the disseminated sulfide envelope. This was undertaken on the basis of the results of reconnaissance gas geochemical, geophysical and drilling surveys carried out during the years 1991–1993. The second phase involved the use of avariety of geophysical techniques, notably Gefinex 400S, magnetic, Slingram and gravity surveys and IP measurements, as well as drilling. As a result of these investigations, estimated reserves were increased to some extent.

On the basis of these investigations, the Outokumpu assemblage at Kylylahti is interpreted as defining a synformal structure plunging some 30° towards the southwest. The main lithologies present, from the center outwards, are serpentinite, gabbro lenses, talc-carbonate rocks, Cr-bearing skarns and quartz rocks, with an envelope of black schists separating them from the enclosing micaceous metasediments, just as at Keretti.

The host rock to the Cu-Co mineralization is a mixed Cr-skarn and quartz rock lithology immediately adjacent to black schists at the eastern edge of the fold (Fig. 11). The main Cu-Co bearing horizon has been traced from a depth of 500–700 m almost to the present erosion surface. The mineralization appears to have a step-like geometry approaching the surface, due to disruption by numerous transverse faults. The main ore zone is flanked by a somewhat irregular and less continuous zone of disseminated sulfides, which is also anomalous with respect to Cu, Co and Ni. It is also of interest that podiform chromite has been encountered in the Kylylahti area.

Resource estimates carried out for the Kylylahti Cu-Co deposit to date indicate

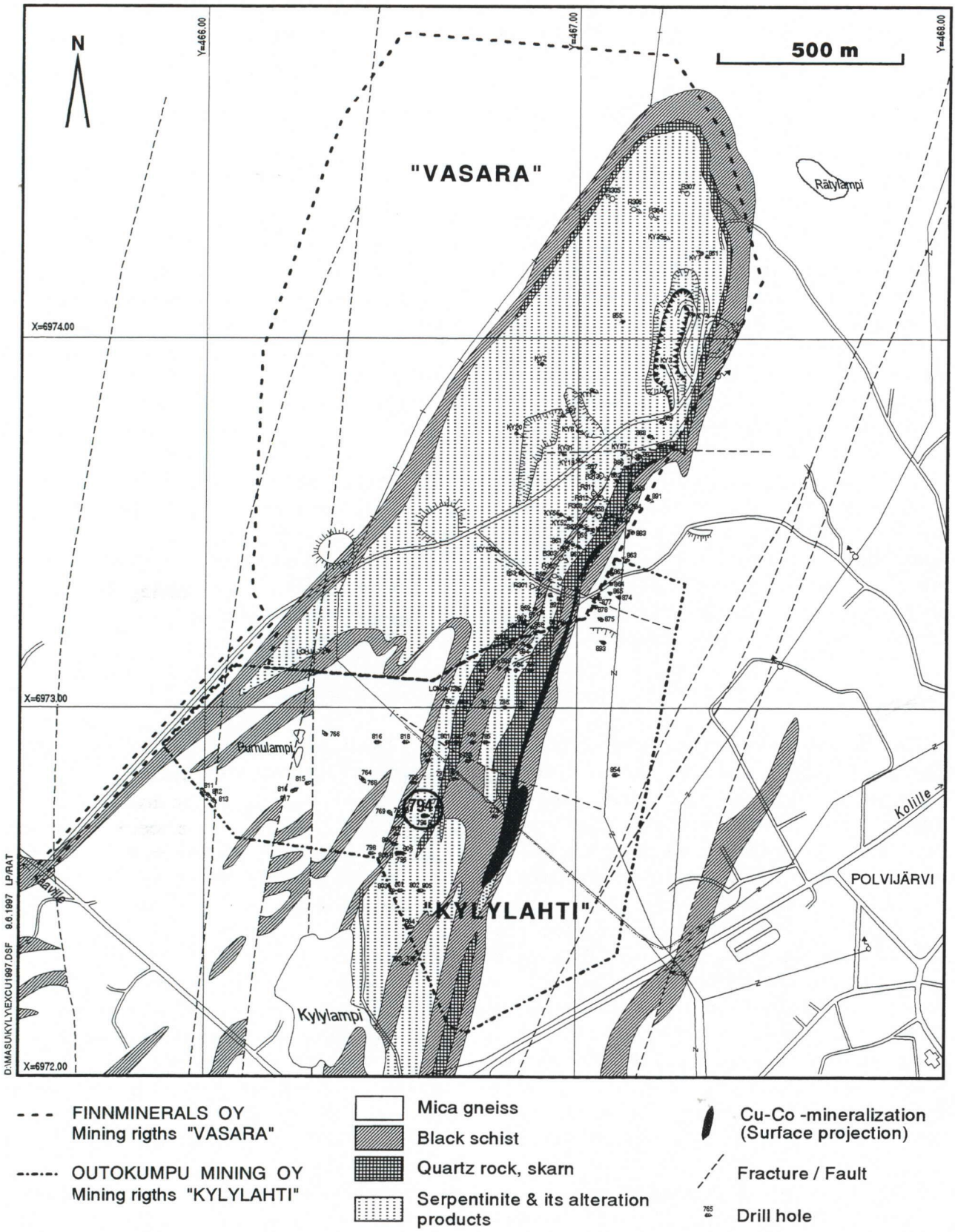


Fig. 11. Simplified geology of the Kylylahti fold structure.

probable reserves of around 2.5 Mt containing 2.5% Cu, 0.4% Co and 0.8 g/t Au, and possible additional reserves of a further 2.5 Mt, averaging 0.6% Cu, 0.2% Co and 1.2 g/t Au (Outokumpu Mining Annual Report, 1995).

RESEARCH AND EXPLORATION — WHERE DO THEY MEET: CAN COMPARATIVE BLACK SCHIST STUDIES BE USED AS AN EXPLORATIONAL TOOL FOR OUTOKUMPU-TYPE MASSIVE SULFIDE DEPOSITS?

by Kirsti Loukola-Ruskeeniemi

Introduction

The Black Schist Project was financed jointly by the Geological Survey of Finland and the Academy of Finland during 1988–1995. One of the goals of the project, in addition to basic scientific research, was to discover whether the black schists (metamorphosed black shales) associated with the Outokumpu deposits possess characteristic, easily recognizable features that might be used as an additional tool in exploration. Black schists are easily distinguished from other rock types by their geophysical properties and therefore, in poorly exposed areas, sampling could focus upon black schists and their chemical and textural characteristics might reveal whether hydrothermal ore-forming processes were active in their vicinity, either, during deposition on the seafloor or later, during diagenesis, metamorphism and tectonic deformation. Black schists have also been used previously with success in exploration in Finland: the Petsamo Ni deposit was discovered as a student of geology followed a geophysical anomaly caused by pyrrhotite-bearing black schists in the 1920's.

During the Black Schist Project more than one thousand samples were selected from unweathered drill cores representing Outokumpu-type ores and prospects from throughout the Outokumpu-Kainuu region (Fig. 12). For comparison, samples were also taken from Early Proterozoic black schists from southern, western and northern Finland.

Outokumpu rock assemblage

The Outokumpu type massive sulfide deposits are characterized by the rock assemblage serpentinite — calc-silicate rock — quartz rock — dolomite — black schist. The type locality is the Outokumpu district in eastern Finland and for a long time these deposits were considered to represent an unique ore deposit type. However, during the past few decades, occurrences having features in common with the Outokumpu deposits have been reported for example from Quebec in Canada (Trottier et al., 1987) and Maryland Piedmont (Candela et al., 1989). The largest of the known Outokumpu type deposits, both in Finland and in the rest of the world, is still however the Outokumpu Keretti deposit (Fig. 13).

Several genetic models have been developed to explain the origin of the Outokumpu rock assemblage, with debate having generally centered around two contrasting hypotheses:

1) that the alteration and metamorphism of the present serpentinites have led to the formation of calc-silicate rocks and dolomites (Haapala, 1936) and black schists (Marttila, 1972); and

2) that black schists, quartz rocks (Väyrynen, 1939; Peltola, 1960), and dolomites (Vähätalo, 1953) formed as the result of seafloor sedimentary processes.

Explanations for the distinctive quartz rocks involved production of excess silica during serpentinization, followed by models based on sea-floor exhalation processes, in which case the quartz-rock is regarded as a chert-like precipitate (Huhma & Huhma, 1970). An alternative viewpoint, based on current studies and analogies with similar deposits in Quebec (Auclair et al., 1993), suggest that the quartz-rock is instead a residual, highly leached rock, representing extreme chemical alteration of an ultramafic precursor (Asko Kontinen, personal communication). This interpretation can potentially explain geochemical similarities in the immobile element abundances of the quartz-rock and serpentinites, including the abundance of chromium, nickel and iridium which are not an element typically associated

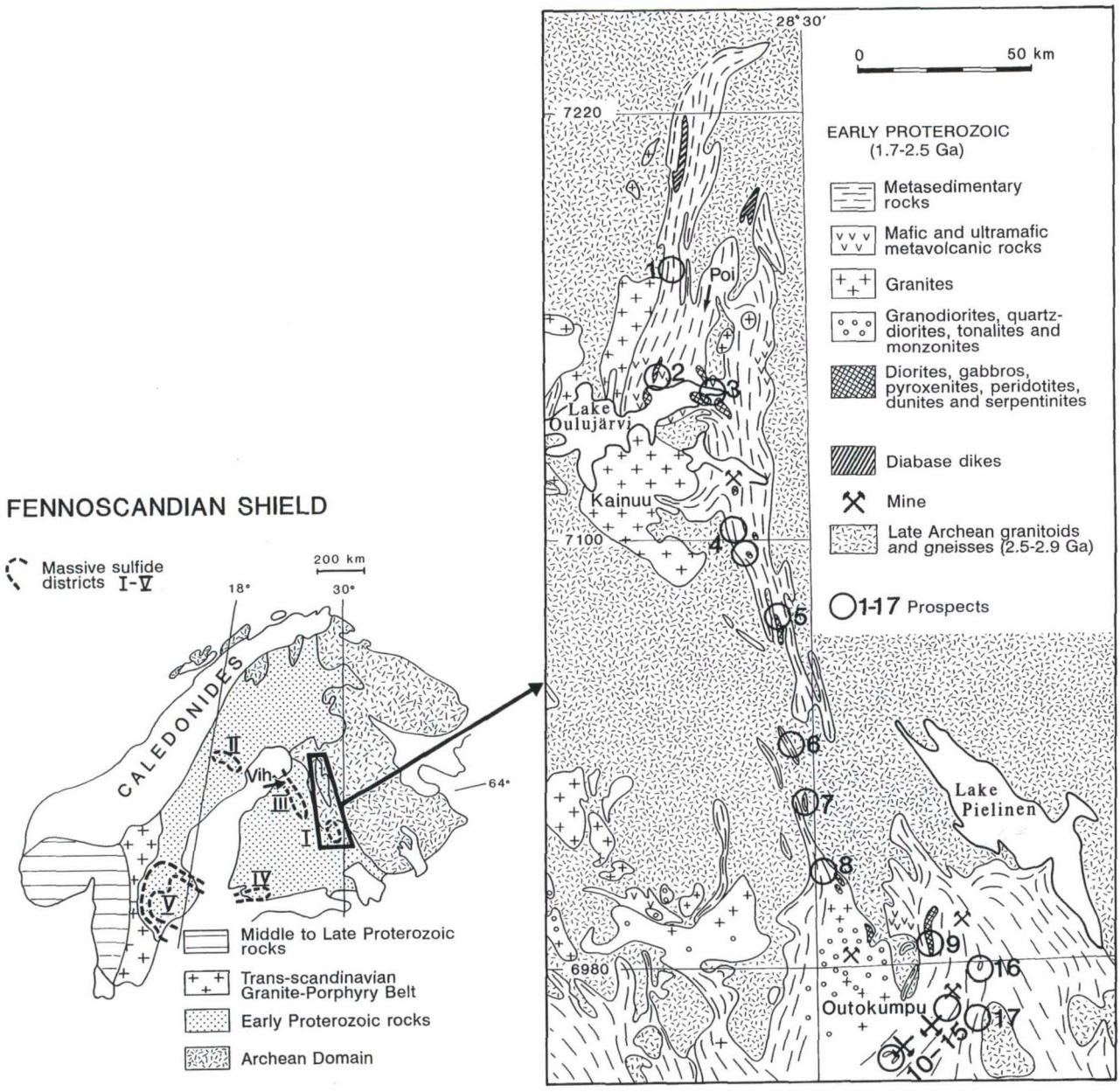


Fig. 12. Geologic setting of the Kainuu and Outokumpu areas within the Fennoscandian Shield. Massive sulfide districts: I = Outokumpu; II = Skellefte; III = Vihanti-Pyhäsalmi (Vih, Vihanti Zn ore deposit); IV = Aijala-Orijärvi; V = Bergslagen. Prospects and closed mines sampled during the Black Schist Project: 1 = Puolanka; 2 = Melalahti; 3 = Jormua; 4 = Talvivaara; 5 = Alanen; 6 = Pappilanmäki and Korpimäki; 7 = Ruukinsalo; 8 = Losomäki; 9 = Miihkali; 10 = Viurusuo; 11 = Keretti mine; 12 = Kaasila; 13 = Kalaton; 14 = Vuonos mine; 15 = Sukkulansalo; 16 = Kylylahti; 17 = Sola. Poi = Poikkijärvi iron formation; Lah = Lahnaslampi talc deposit.

with exhalative processes.

It is probable that both of the contrasting hypotheses contain some valid points: part of the carbonate rocks are of sedimentary origin, while others are derived from alteration and metamorphism of the present serpentinites. Black schist formations from 20 to 120 m thick encountered in the immediate vicinity of the calc-silicate rocks of the Outokumpu rock assemblage certainly are of sedimentary origin, as also evidenced in their geochemical characteristics (Loukola-Ruskeeniemi, 1991, 1992).

The original positions and age relations of the various rock types comprising the Outokumpu assemblage are difficult to establish however, due to the effects of complex, polyphase deformation and amphibolite facies metamorphism (Koistinen, 1981).

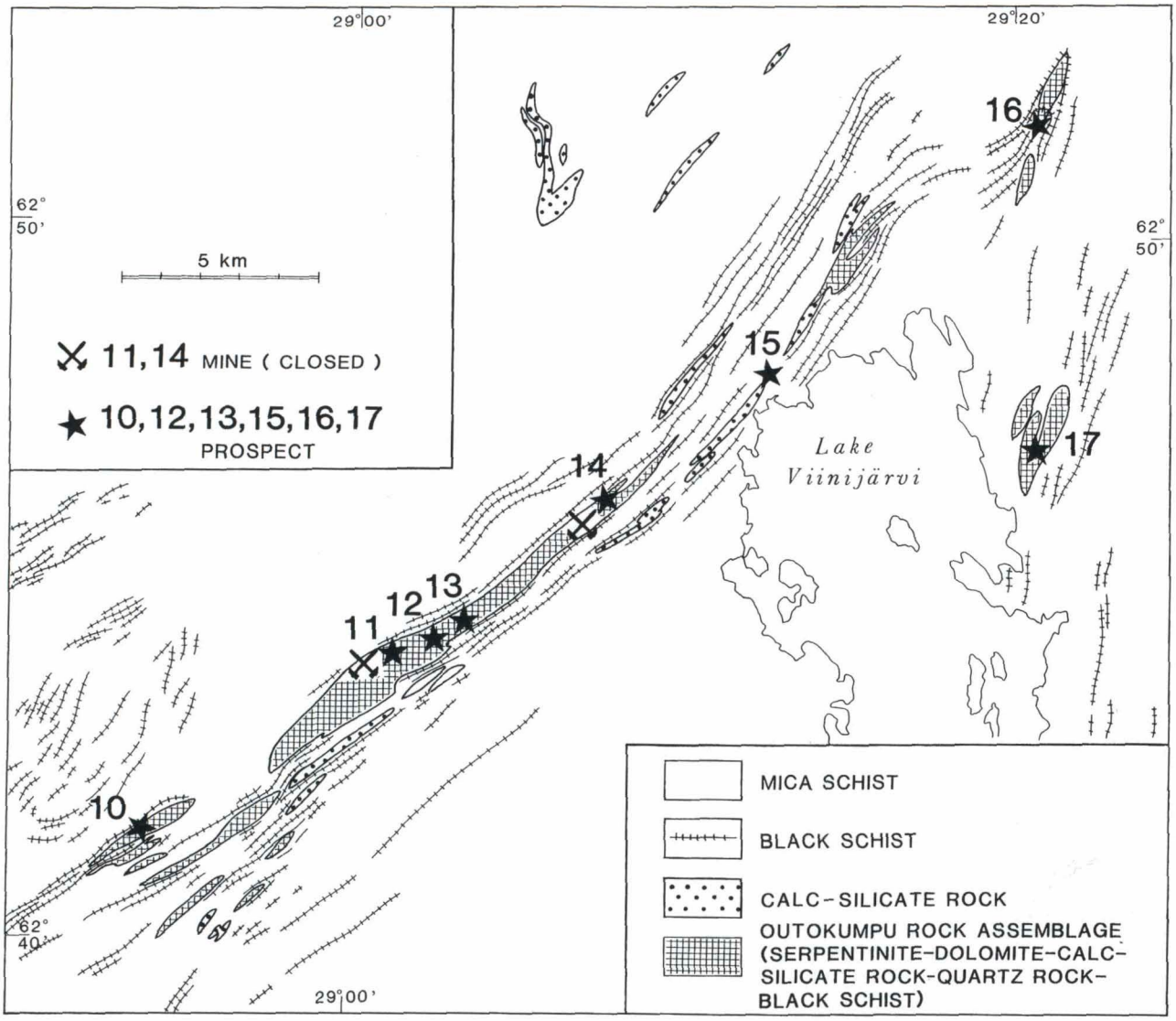


Fig. 13. Geologic setting of the Outokumpu district, modified from Huhma (1975). Prospect numbers refer to the same localities as in Fig. 12.

Black schists in the Outokumpu deposits

Horizons of black schists from 20 to 120 m thick occur in all Outokumpu-type occurrences. In addition, quartz rocks and calc-silicate rocks of the Outokumpu assemblage contain intercalations with > 1% graphitic carbon. For example, at the Outokumpu Keretti deposit, layers containing > 1% graphitic carbon occur in the quartz rock horizon hosting the ore (Fig. 14). At the Vuonos deposit, 10% of the ore was hosted by black schists, and Peltola (pers. comm.) reported that at the footwall contact the ore showed a gradual transition to black schist (Fig. 15). Black schists near ore bodies contain quartz-sulfide veins. At the Kylylahti prospect, thick (> 100 m) black schist formations occur above the other rocks of the Outokumpu rock assemblage, and layers < 3 m thick are present in the ore horizon itself (Fig. 16).

Sulfur isotope $\delta^{34}S$ values for the sulfides of the Outokumpu ores and sulfides within black schists and quartz rocks resemble each other. The average value for 258 sulfide specimens in the Outokumpu deposit is -3.5 per mil. (Mäkelä, 1974) Sulfur isotope results for pyrite in black schists occurring next to the Kylylahti ore (Fig. 16) provide comparable values to those of the pyritic ore (from -5 to -16‰ in ore compared with values from -5 to -10.5‰ in black schist). Furthermore, layered pyritic ore shows a slight compositional layering overprinted by a tectonic layering, foliation (Koistinen, 1981). It is therefore probable that at least part of the Outokumpu ore formed primarily on or close to the seafloor.

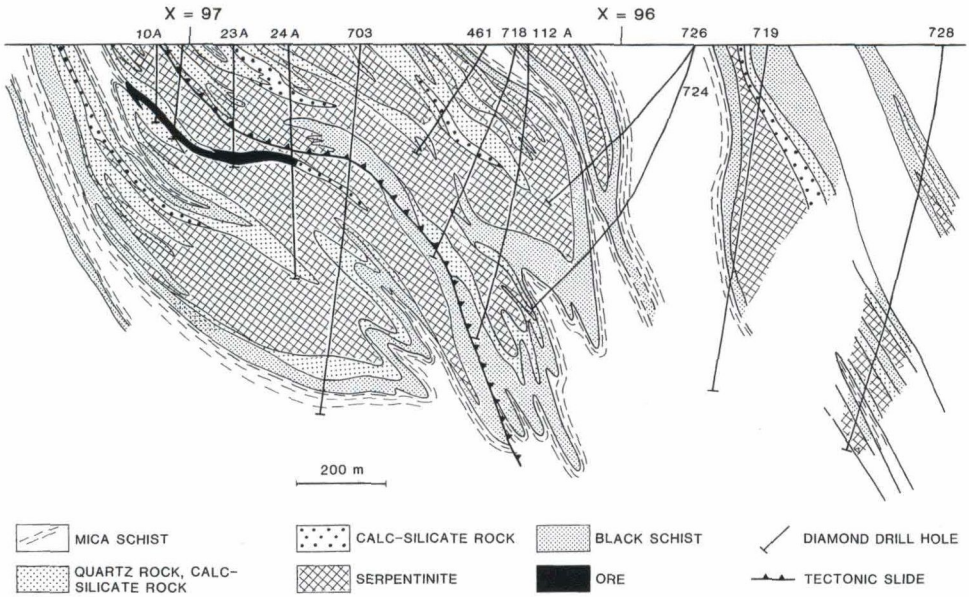


Fig. 14. Outokumpu Keretti Cu-Co mine, cross section Y=186.63 (modified after Koistinen, 1981).

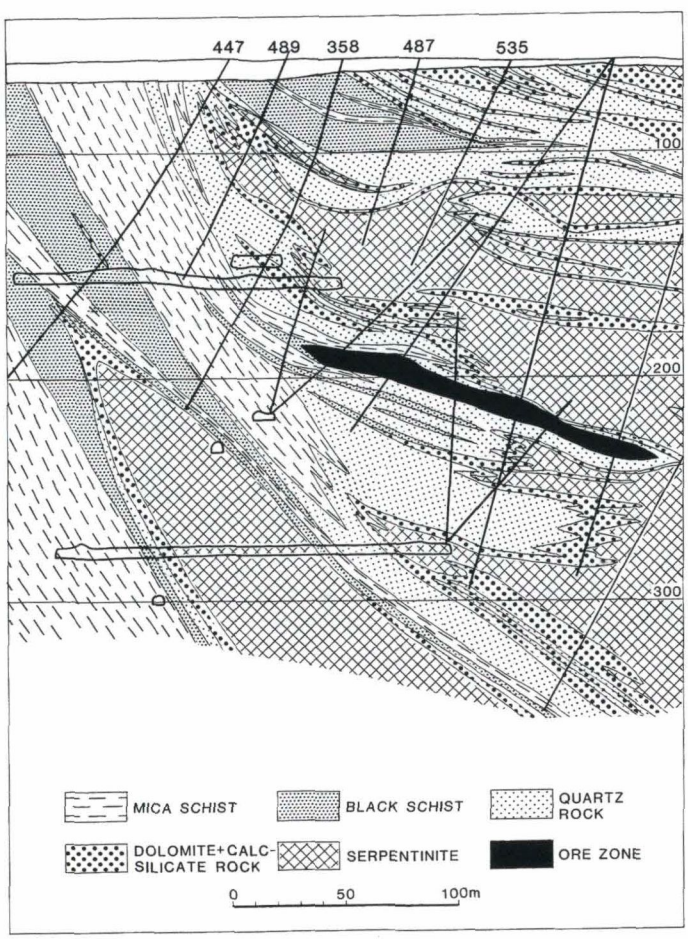


Fig. 15. Vuonos Cu-Co-Zn mine, cross section 194150 (modified from Peltola, 1978).

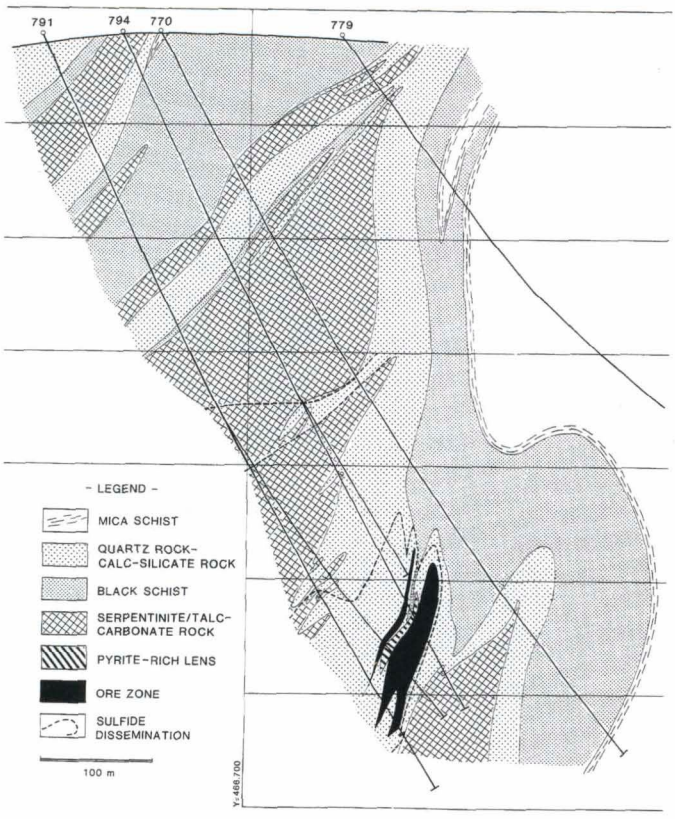


Fig. 16. Kylylahti Cu-Co occurrence, cross section x=72.700±50 m (modified after data from the Outokumpu Mining Oy).

Characteristics of the Outokumpu-Kainuu rift-related black schists

Black schists encountered in the immediate vicinity of serpentinites are characterized by average concentrations of 7% of both graphitic carbon and sulfur. Black schist formation thicknesses of up to 120 m are common in drill cores, and such intersections have also been recorded throughout the entire length of the Outokumpu-Kainuu region (Fig. 12). Within this extensive area, huge amounts of organic matter, sulfur and base metals were deposited some two billion years ago. Life must have been vigorous, even if ecosystems were simple in character. Because the rocks have been metamorphosed and deformed, unequivocal evidence of the past life forms can no longer be seen, and we can only guess that in the absence of more developed predatory organisms, algae and primitive chemotrophic organisms flourished. The surface waters of the sea might also have been rather warm (at least compared to present day Finland!), since the Fennoscandian Shield was at the time located at subtropical latitudes (Mertanen et al., 1989). During Paleoproterozoic times, it is also conceivable that the oceans were more generally anoxic than nowadays, which might also have favoured the preservation of organic carbon in the sediment. Because black schists occur extensively throughout eastern Finland, it is likely that Svecofennian metamorphism has converted to graphite what could otherwise have been quite substantial oil reserves!

Black schist layers can be easily located by geophysical measurements, and on the aeromagnetic anomaly map (Appendix 2), it is possible to trace continuous pyrrhotite-bearing black schist formations for great distances. In addition to the anomalous black schists, which typically are found near serpentinites or altered remnants of the serpentinites, other black schists containing < 3% graphitic carbon and sulfur are also encountered.

Throughout the Kainuu region, the serpentinite-associated black schists contain anomalous concentrations of nickel, copper, zinc and manganese. The largest known Ni-Cu-Zn deposit found so far is at Talvivaara, in the rural municipality of Sotkamo (Fig. 12), although it is of relatively low grade. Ni-Cu-Zn- and Mn-rich black schists are also encountered near the Jormua ophiolite to the north of Talvivaara.

Typical features of black schists associated with the Outokumpu deposits

Black schists characterized by high concentrations (7%) of graphitic carbon and sulfur were apparently deposited in basins associated with rift zones around 2 Ga. Abundances of copper, cobalt, nickel and zinc are also higher than for "average" black schists, described for example by Vine and Tourtelot (1970). Nickel, copper, zinc, cobalt, and manganese concentrations are higher in the Kainuu district than in the Outokumpu district. However, the typical textures of these rift-related black schists are similar in both areas, namely fine-grained sulfide-rich dissemination (Loukola-Ruskeeniemi, 1992). Therefore, rift-related black schists can be distinguished from other black schists. This information could potentially be used in exploration in poorly known and poorly exposed areas, by following geophysical anomalies caused by the anomalous black schists and examining their immediate vicinity for massive sulfide ores.

Proximity to an Outokumpu type ore is seen in the black schists of the Vuonos mine by increasing Cu (>2000 ppm) and Co (>200 ppm) concentrations. At the Outokumpu Keretti mine however, the black schists lack such high Cu and Co concentrations, the difference being due to the fact that at Vuonos, part of the ore was actually hosted by black schists.

In the Outokumpu district, graphite-rich rocks have certain textures that have not been seen in any other Early Proterozoic black schists studied in Finland: black schists with 3-mm-thick greenish grey tremolite-rich layers (see figures in Loukola-Ruskeeniemi, 1992), a textural feature which is common in quartz rocks and calc-silicate rocks. Graphite-rich fine grained quartz rocks are also specific to the Outokumpu rock assemblage.

Evidence of hydrothermal processes is clearly recorded in the chemical composition of the Outokumpu-Kainuu rift-related black schists (Loukola-Ruskeeniemi, 1991), but it is not easy to distinguish black schists associated with ore of economic grade from black schists associated with subeconomic mineralization.

STOP 3 — HORSMANAHO

At the Horsmanaho open pit, we will see a section through the so-called "Outokumpu rock assemblage", which is also representative of the lithologies that hosted the now closed Keretti and Vuonos mines at Outokumpu, including serpentinite, calc-silicate rocks, fine-grained quartz rocks, dolomite and black schist. At Keretti and Vuonos, the ore consisted of massive sulfides, but at Horsmanaho soapstone is being mined for talc production.

HORSMANAHO TALC MINE

by Erkki Kuronen and Ilkka Tuokko

Quarrying operations commenced at Horsmanaho in the 1970's, when the deposit was owned by Oy Lohja Ab. Production by the present owners, Finnminerals Oy, runs at around 400 000 tonnes of soapstone per year, necessitating the quarrying of nearly an equivalent amount of waste rock. The ore is transported by truck to two of Finnminerals' talc processing plants, at Luikonlahti and at Vuonos, the latter receiving the larger proportion.

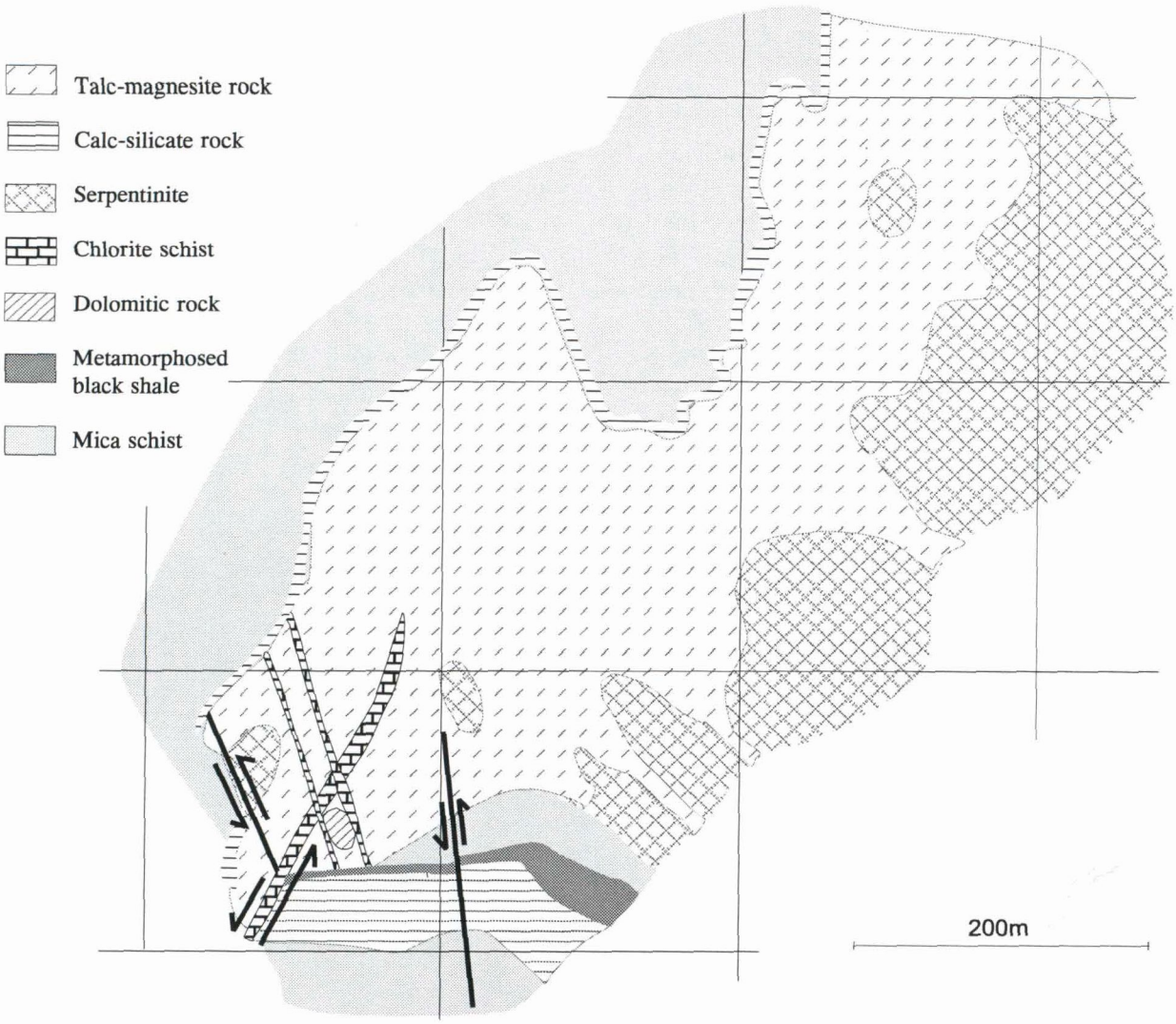


Fig. 17. Geological map of the Horsmanaho talc deposit.

Geological aspects

The Horsmanaho soapstone quarry is closely associated with a lense of massive serpentinite, with the main ore situated towards its western and southwestern margin (Fig. 17). Additional lithologies in immediate proximity to the soapstone include quartz rocks, black schists and tremolitic skarn. The main soapstone occurrence is nearly 500 m in length, while a subsidiary ore body can been traced around the southern margin of the serpentinite body and further to the east as a narrow seam. The deposit consists essentially of magnesite pods and lenses within talc-magnesite rock, as well as talc-rich schistoze soapstone. The immediately adjacent serpentinites are locally rich in carbonate and conversely, the soapstone locally contains small lenses of relict serpentinite.

The contact between the soapstone and serpentinite is typically almost vertical except in the southwestern part of the deposit, where the soapstone dips at a rather low angle beneath the serpentinite body. Contacts are generally gradational over several meters rather than abrupt, corresponding to a progressive decrease in the proportion of talc and magnesite and a concomitant increase in the amount of serpentine minerals. The contact between the soapstone and quartz rock is however much more clearly defined, although here too there is a distinct transition zone usually at least several meters thick.

The general sequence of lithologies, proceeding from serpentinite to regional wall rock is as follows:

serpentinite — soapstone — talc schist — skarn — quartz rock — black schist — micaceous schist. The skarn is usually tremolitic but in some places contains diopside. The quartz rocks closely resemble the typical Outokumpu-type quartzitic sulfide ore and locally may consist almost entirely of silica, although generally they contain small amounts of sulfides, fuchsite, phlogopite, chlorite and tremolite and typically are black in color.

The distribution of the deposit is controlled, apart from its position at the margin of the serpentinite lense, by a lineation plunging towards the southwest at about 30 degrees; both the ore body and the adjacent skarn and quartz rocks are elongated downwards in this direction. A N-S trending fault truncates the ore body just beyond the present southwestern end of the quarry accompanied by numerous chloritic veins that are believed to be related to the faulting or shearing process.

Mineralogy

The deposit locally contains up to 50–70% talc, with the remainder consisting mostly of magnesite and, especially near the margins of the deposit, dolomite. The latter can comprise up to 40% of the rock at the margins, and is commonly from 3–10% elsewhere. Dolomite typically occurs as veins, whereas magnesite is present as discrete grains or grain aggregates.

The abundance of chlorite varies from 5–10% and sulfides from 1–2%. Nickel arsenides are present in variable amounts, but never exceeding 0.3% of the rock; chromite is more abundant than magnetite, but together they comprise less than 1% of the rock.

Talc typically occurs as discrete flaky grains with grain sizes generally from 0.05–0.2 mm. In highly sheared zones however, talc may occur as homogeneous foliated masses in which individual grains are difficult to distinguish.

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NUNNANLAHTI — STOP 4

by
Peter Sorjonen-Ward and Timo Rossi

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GEOLOGICAL SETTING OF THE NUNNANLAHTI SOAPSTONE DEPOSITS

by Peter Sorjonen-Ward

The origin and age of the Nunnanlahti soapstone deposit is still poorly understood. None of the lithologies present in the area have been amenable to isotopic dating and lithological boundaries are generally so highly strained that any evidence for intrusive or truncating relationships has been destroyed. When examining regional scale maps or geophysical data, it would be easy and logical to infer that these altered mafic and ultramafic rocks could correlate with either the 1.95–1.97 Ga Outokumpu assemblage, adopting an imbricate thrust interpretation, or else the 2.1 Ga Tohmajärvi mafic igneous complex, which is associated with the same high strain zone some hundred kilometers to the south. Neither of these interpretations are correct however, since several key exposures reveal that metadolerite dykes, displaying chilled margins and characterisitic albite-rich alteration haloes, truncate foliations within the host metabasalts and metaperidotites. Such relationships are typical throughout the Archean of eastern Finland, where several generations of Paleoproterozoic dyke swarms can be found cutting deformed late Archean granitoids and greenstone sequences. Whether or not the first geologists to map the area at the beginning of this century were aware of these field relation-

ships, it is interesting to note that they clearly regarded these rocks as belonging to the older basement complex, and moreover treated them separately from the talc-carbonate rocks associated with the Outokumpu assemblage (Frosterus & Wilkman, 1920).

So far, none of the Proterozoic dykes have been shown to demonstrably cut the Nunnanlahti greenstones in proximity to the soapstone deposits, so that we are still not sure to what extent the alteration represements a Proterozoic retrogression and fluid influx, as opposed to an entirely Archean phenomenon. Thus, even if an Archean age for the Nunnanlahti greenstones were vindicated by isotopic dating, the question of the timing of the hydrothermal processes that produced the soapstone alteration remains unsolved. Hopefully, evidence will be forthcoming in the form of Proterozoic dykes that either truncate alteration assemblages as well as Archean structures, or else show direct evidence of Svecofennian hydrothermal alteration themselves. Throughout the nearby region, similar metadolerite dykes intruding basement gneisses and Paleoproterozoic quartzites typically display quartz-albite-carbonate-biotite-chlorite-sulfide vein and shear alteration assemblages and stable isotope investigations are currently in progress to assess whether or not different stages of fluid flow can be linked to alteration and deformation events, and hopefully providing some insights into the history of alteration at Nunnanlahti.

The geological history of the Nunnanlahti area is further complicated by the intensity of Proterozoic deformation, during which the Archean basement and Proterozoic cover have been tectonically imbricated, a feature already apparently to the earliest geologists to work in the region (Frosterus & Wilkman, 1920). In effect, the Nunnanlahti soapstones can be said to lie within an allochthonous Archean greenstone belt sandwiched between Paleoproterozoic. The main Nunnanlahti Shear Zone, with the soapstone quarries lying in the hanging wall, has a complex history, being interpreted as an early thrust, or steep frontal ramp within a thrust system (to explain the fact that Archean rocks are structually on top of Proterozoic turbidites), which was reactivated as an oblique sinistral normal sense shear zone (to explain kinematic indicators such as rotated porphyroclasts, cleavage duplexes, minor folds and truncations of lithological units and magnetic anomalies at map scale). In the vicinity of the shear zone regional structural trends in both basement and cover rocks are progressively transposed into a NW-SE orientations with an intense moderately dipping foliation and S-plunging lineation; in the most highly strained domains the foliations in the protomylonitic Archean granitoids, as well as the Nunnanlahti greenstones and soapstones are essentially congruent with those in the Proterozoic sediments (Kohonen et al., 1991). It therefore seems reasonable to assume that in both units, these structures represent the same Svecofennian deformation.

The western margin of the transposed zone at Nunnanlahti also coincides with an abrupt increase in crustal thickness (Luosto et al., 1990). The greater thickness is most readily attributed to thrust stacking although an alternative explanation involves crustal thinning to the east during the early stages of the 2.1 Ga rifting and extensional event; this in turn may have enhanced the potential for fault reactivation in this area during subsequent basin inversion and thrusting (Kohonen et al., 1991, Kohonen, 1995).

SOAPSTONE PRODUCTION AT NUNNANLAHTI

by Timo Rossi

The extent of the soapstone deposits in the Nunnanlahti district was first recognized towards the end of last century by the Chief Government Geologist at the time, Benjamin Frosterus. Frosterus immediately set about promoting the potential of the deposits to leading experts in the mining industry and other prominent people in business and industry, with the result that the first company to work the soapstone, "Finska Täljstens Ab" (in

Swedish, or Suomen Vuolukivi Oy in Finnish), was established in 1893.

By the turn of the century, soapstone from Nunnanlahti was being widely employed in the ornate facades of many of the Art Nouveau period buildings being constructed at the time, the most notable examples in Helsinki being the the Finnish National Museum and the National Theater. The principal market for soapstone products during these early years was Czarist Russia, but after early success, the fall in value of the Russian rouble caused by the Russian-Japanese war led to the company being passed into receivership in 1907. The following year production resumed under the name "Osakeyhtiö Vuolukivi — Aktiebolaget", with steam generation of electricity to supply power to more mechanized processing operations. Profitability was only marginal and ownership changed hands several times throughout the period of the First World War and the turbulence of the Finnish civil war and independence but with the subsequent rapid expansion the paper industry, there was an increasing demand for soapstone as a lining in furnaces and kilns, a purpose for which thermal and chemical properties were ideally suited.

The ownership base was broadened, with a rapid increse in investment and in 1925 the company was again renamed as "Suomen Vuolukivi Osakeyhtiö". The success of the enterprise led to the establishment of additional quarrying operations by three junior companies, although none of these survived for long, due to the combined effects of increasing competition and limited markets, especially during the Depression of the 1930's. Production was then interrupted by the Second World War and operations never fully recovered, eventually ceasing entirely during the 1960's.

In 1980 however, the Suomen Vuolukivi Oy shares were purchased by the chairman of the company now known as Tulikivi Oy ("tulikivi" translating roughly into English as "firestone"), and quarrying operations were revived after more than a decade of inactivity. By the middle of the 1980's, export markets for Tulikivi soapstone fireplaces and ovens and dimension stones were growing rapidly throughout central Europe, and production lines have been modifed and expanded several times, using technology developed at Nunnanlahti, making the operations a market leader in the field. In 1987 a separate company, Mittakivi Oy was established, also with its own production line at Nunnanlahti and specializing in the manufacture of individual ovens and fireplaces according customer wishes and requirements; Mittakivi Oy also became a wholly-owned subsidiary of Tulikivi Oy in 1996.

Tulikivi now exports finished products, principally soapstone ovens and dimension and tiling stones, to more than ten countries and has an annual turnover of nearly 170 million Finnish marks and directly employs about 300 people. Quarrying operations at Nunnanlahti presently include the sawing of some 70 000 m^3 of soapstone annually, of which about 18 000 m^3 is suitable for dressing and oven manufacture. It is also necessary to quarry some 35 000 m^3 of waste rock, and to remove around 60 000 m^3 of overburden prior to quarrying.

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THE KOLI AREA — STOP 5

by
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THE KOLI SUMMIT

by Peter Sorjonen-Ward

The view from Koli across Lake Pielinen was an inspiration to much of the romantic nationalist movement in Finland early this century, and became a symbol of the growing interest in Karelian traditions at the time. Since then the scenery has been captured in music and paintings by numerous artists. The Koli National Park was only declared however in 1991, after the Finnish Government had made a submission to UNESCO for the area to be the first site in Finland nominated for World Heritage Listing; the geological significance of the region was actively promoted and taken into consideration during the nomination process (Jukka Marmo, personal communication).

Koli is the highest point (347 m above sea level and about 250 m above Lake Pielinen) on a series of prominent ridges of quartzite that can be traced through much of North Karelia. In fact, without these early Proterozoic quartzites, which are widespread throughout eastern Finland and Lapland the topography of the country would be very subdued indeed, and winter sports enthusiasts would have trouble in finding suitable locations for downhill skiing. It is therefore somewhat ironic that these highly mature sediments presumably deposited in broad river systems flowing across a very flat and mature Paleoproterozoic landscape, have ultimately proven to be the most resistant to erosion!

The Koli Formation obviously takes its name from this locality (Kohonen & Marmo,

1992) and is well exposed here as a massive orthoquartzite which has been intensely recrystallized, so that primary features, such as cross bedding and layers contiang coarser quartz detritus can only be discerned on close inspection. Asymmetric pressure solution foliations are well developed in some exposures, with orientations reflecting the geometry of Svecofennian thrusting. More impressive are the ice-blue fibrous kyanite and quartz veins with orientations consistent with formation within dilatational fractures associated with thrusting.

Looking towards the northwest from the summit of Koli, it is evident that the line of hills changes trend, forming a broad headland jutting out into Lake Pielinen. This is one of the few areas in Finland where structural features are visibly expressed in the topography, since the break in slope at the foot of the hills effectively coincides with the unconformity at the base of the Proterozoic sequence. Exactly how the basement-cover interface could deform in this way, forming a major syncline, is still unclear. However, rheological contrasts and inhomogeneities, such as between greenstone belts, and granitoid basement may have had an important effect in localization of strain, just as at Nunnanlahti, and particularly where contacts were in favourable orientations (Kohonen et al., 1991). The Kolinniemi syncline appears to be a good example of this, with large-scale ductile deformation of the basement-cover interface being best developed adjacent to the greenstone sequence that can be traced around the base of the syncline. Looking towards the southeast from Koli, and beyond the line of sight to the northwest, where the Proterozoic rocks overlie granitoids instead of greenstones, the basement-cover unconformity reverts to a more typical orientation, with moderate dips to the southwest.

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ILOMANTSI — STOP 6

by
Peter Sorjonen-Ward

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AN OVERVIEW OF THE GEOLOGICAL SETTING AND NATURE OF GOLD MINERALISATION IN THE LATE ARCHEAN HATTU SCHIST BELT, EASTERN FINLAND

by Peter Sorjonen-Ward

The Hattu schist belt represents the first gold province recognized in the Archean of the Baltic (Fennoscandian) shield and is one of the best preserved Archean supracrustal sequences in Finland. Interest in the gold potential of the area was aroused when follow-up investigations into the source of W and Mo anomalies in till also revealed elevated Au abundances in certain vein systems hosted by a tonalite intrusion within the southern part of the schist belt. Drilling has subsequently revealed more than ten prospects with economically interesting intersections, with the largest prospect estimated to contain reserves of at least 0.5 Mt at grades of 5–8 g/t.

In spite of locally intense and complex deformation, detailed structural mapping in areas of good exposure, combined with an abundance of well-preserved depositional younging criteria and high-resolution geophysical data, has enabled local stratigraphical sequences and facies relationships to be established with some confidence. The schist belt is distinctive in consisting principally of felsic volcanogenic and commonly coarse-grained epiclastic deposits, typically of turbiditic aspect. Sporadic thin mafic and ultramafic flows occur throughout the sequence, particularly at higher stratigraphical levels in the northern part of the schist belt. Although the primary goal of

regional mapping and structural studies were to understand controls on gold mineralization, a secondary aim was to provide a basis for assessing the potential of the supracrustal sequence from the point of view of sedimentary or volcanic-hosted massive sulfide deposits. Accordingly, two partially overlapping felsic volcanic complexes have been delineated in the northern part of the schist belt, with the southern part of the schist belt being less diverse lithologically and characterized by presumably more distal finer-grained and thinner-bedded sedimentary facies.

Isotopic data indicate that deposition, deformation and granitoid intrusion were very closely related in time, and almost indistinguishable statistically, the ages of the earliest supracrustal units, at 2754±6 Ma, effectively overlapping with those of syntectonic granitoids. All exposed contacts between the Hattu schist belt and these granitoids are intrusive, or else tectonically modified, and hence the granitoids cannot represent depositional basement to the greenstone belt. No other depositional basement to the Hattu schist belt has been identified, nor have any unconformities been recognized within the mapped sequence. Therefore, there is no direct evidence that the Hattu schist belt developed on an ensialic substrate. The involvement of older continental crust is also evident from some highly evolved granitoids, including tourmaline-muscovite leucogranites, which appear to be analogous to those in Phanerozoic collisional belts (Sorjonen-Ward, 1993, O'Brien et al., 1993). Isotopic data from both detrital and magmatic zircons indicate the presence of older crustal material both in sedimentary detritus and in the source regions of some granitoids, with SHRIMP zircon studies having revealed inheritance from a protolith up to 3.1–3.2 Ga in age. (Sorjonen-Ward & Claoué-Long, 1993). Most of the Hattu schist belt sediments are nevertheless considered to represent reworking of penecontemporaneous volcanogenic deposits, whose age is relatively precisely constrained at 2.76–2.75 Ga (O'Brien et al., 1993).

Since no field evidence exists to suggest that any of the granitoid intrusions were pretectonic, rapid and extensive crustal generation and deformation between 2.76–2.73 Ga is implied. There is accordingly, a close relationship between regional folds and shear zones, and much of the deformation may record accommodation to the emplacement of syntectonic granitoids. For example, a distinctive suite of biotite-tonalites intruded the sequence, initially as tabular semiconcordant sheets during the early stages of fold propagation, and were subsequently deformed along with their host rocks.

The overall structural geometry of the Hattu schist belt is characterized by upward-facing, generally steeply dipping structures; depositional younging determinations are almost invariably upward facing and hence militate against the existence of major recumbent structures. Refold interference patterns observed at outcrop and map scale are therefore more likely to represent progressive deformation of initially upright structures with strain becoming more partitioned within discrete narrow zones. The kinematic histories of these zones suggest the importance of regionally coaxial and vertical constrictional strains, although evidence for more localized local strike-slip deformation is certainly present. Rather than invoking separate deformation episodes, a progressive continuum interpretation is preferred, in which younger structures record the partitioning of deformation into discrete, high-strain zones, with an increasing component of constrictional strain related to continuing granitoid intrusion (Sorjonen-Ward, 1993). It has been possible to establish a close, probably sequential relationship between tightening of folds, attenuation of fold limbs, development of shear zones with strike-slip displacements, and the propagation of new folds due to strain incompatibilities. This resulted in either distinct overprinting fabrics, or transposition and recrystallization of early fabrics. It has thus been possible to delineate distinct D_1 domains based on F_1 fold and S_1 foliation relationships to bedding and S_2 (Fig. 18). Depending on the orientation and F_2 fold wavelength, D_1 structures have been deformed either by coaxial refolding, or by attenuation and extension during oblique D_2 shear. The mechanical behaviour of various lithologies has clearly been significant, with major displacements taking place adjacent to banded iron formations, while shortening of mafic units has in some instances been accommodated by the development of strike-slip duplexes, the most significant of which, the oblique sinistral contractional Juttuhuuhta Duplex, is indicated in Figure 18. The resultant regional geometry suggests a transpressional regime with

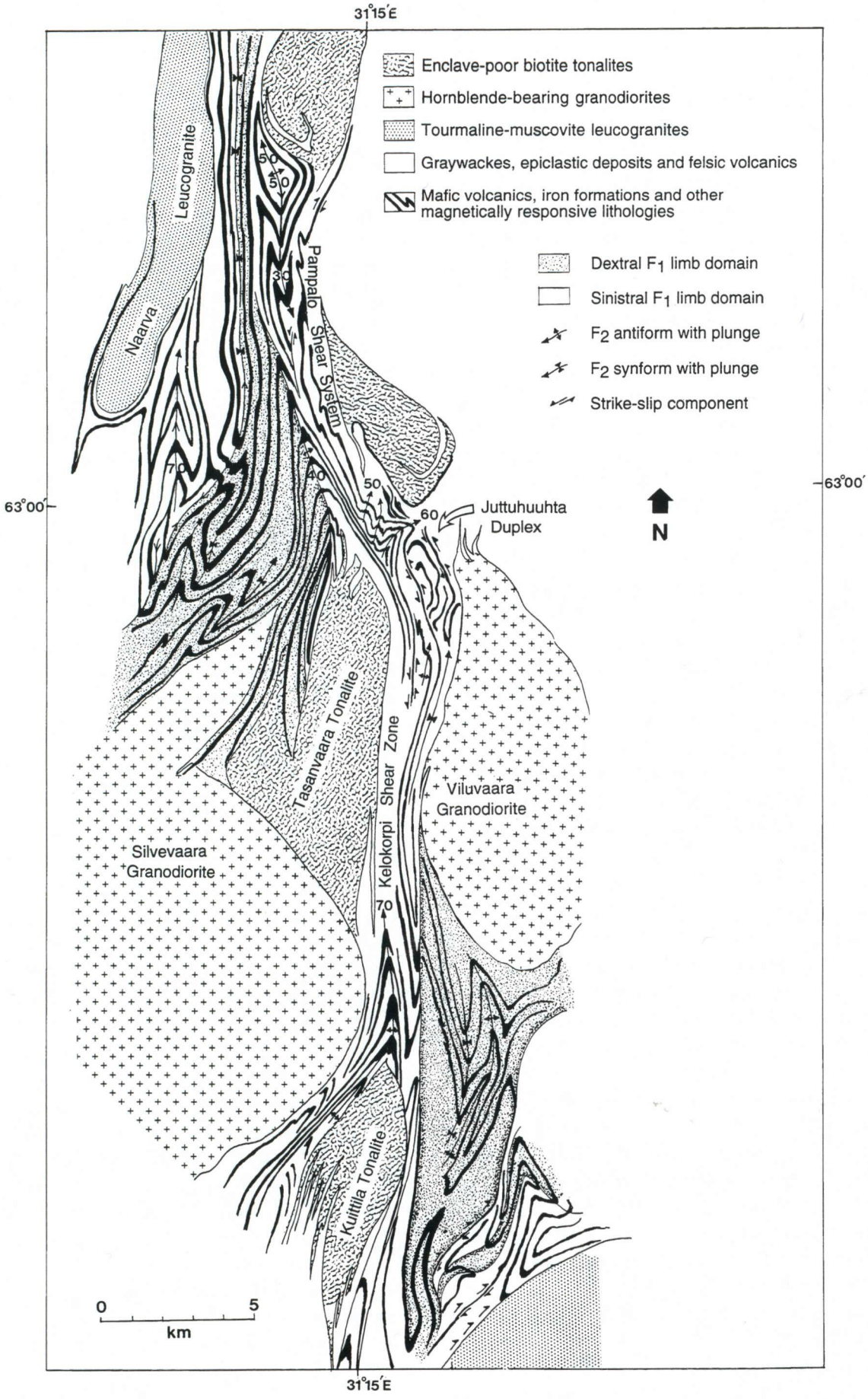


Fig. 18. Simplified geological and structural element diagram of the Hattu schist belt (from Sorjonen-Ward et al., 1997).

plutons being emplaced into dilatant sites within a N-NE trending dextral shear system. Although there is as yet no evidence for the overall duration of deformation and metamorphism, structures are readily interpreted as representing progressive deformation, rather than a sequence of separate tectonic events. Microstructural evidence clearly indicates dynamic recrystallization during deformation under upper-greenschist to lower-amphibolite conditions and that the thermal metamorphic peak was synchronous with, or outlasted deformation (Sorjonen-Ward, 1993). The growth of mica, actinolite, garnet and locally, staurolite and kynaite porphyroblasts, was associated with later stages of deformation, and in some instances outlasted it. This metamorphic mineral growth, and accompanying dynamic recrystallization is also observed to overprint alteration assemblages, particularly in the southern part of the schist belt. Hence, the timing of gold mineralization with respect to the peak of metamorphism differs from that in classic late Archean low-grade greenstone terrains in that metamorphic textures indicate recrystallization after gold deposition. On the other hand, while the presence of mineralization in syntectonic tonalites provide direct evidence for gold introduction during deformation, the progressive nature of deformation and prograde dynamic recrystallization of mineral assemblages does not support the concept of a separate younger metamorphic event being superimposed on lower grade deposits. The U-Pb zircon age obtained from the Kuittila Tonalite (2745±10 Ma) places an upper age limit on the timing of gold mineralization, while concordant monazite and titanite ages around 2700 Ma are considered to constrain the onset of cooling following post-mineralization metamorphic recrystallization.

It has been difficult to characterize the gold deposits or assess the nature, genesis and timing of fluids using stable isotope and fluid inclusion data or thermochronology since the Hattu schist belt was situated within the foreland to the Svecofennian Orogeny and was reheated to greenschist facies by burial beneath a sequence of nappes around 1.9 Ga. Thus for example, muscovite and biotite have K-Ar mineral ages between 1811–1707 Ma, and yield a poorly constrained Rb-Sr isochron of 1655+/-290 Ma. Hornblende K-Ar data tend to retain Archean ages, as does the U-Pb system in titanite and zircon. Although this indicates P-T conditions during the Svecofennian overprint comparable with those at which Archean lode gold deposits characteristically form, there is no compelling reason for advocating a Proterozoic origin for the gold. Several generations of Early Proterozoic mafic dikes contain Svecofennian greenschist assemblages but are essentially unstrained and transect the alteration zones and some gold prospects without being themselves altered or mineralized.

Mineralisation does not appear to occur preferentially in any particular lithology, although lithological transitions may be favoured, due to associated chemical and rheological gradients. Pervasive fluid flow is however also indicated by broad, highly deformed alteration zones and disseminated rather than vein style mineralisation at some prospects. The albite-carbonate alteration mineralogy so characteristic gold deposits in Archean mafic and ultramafic provinces is rare in the Hattu schist belt, although carbonate is locally present in mineralized tonalites. Instead, chlorite, muscovite and tourmaline dominate alteration parageneses in mineralized metasediments. Native gold is fine grained (mostly <15 μm) and occurs largely in free-milling form between silicate grains, associated with pyrite, pyrrhotite and minor arsenopyrite and rutile; it is typically intergrown with Bi, Pb, Ag, Fe and Au tellurides and native bismuth. Gold mineralization at most prospects is geochemically distinctive, with notable enrichments of Te, B, Bi (and locally Mo and W) compared to many other Archean gold provinces, reflected in the abundance of tourmaline, tellurides and locally scheelite, while conversely As, Ag, W and S are rather low, which is manifest in the generally low abundances of sulfides. The syntectonic Kuittila Tonalite contains an early molybdenite-scheelite vein system overprinted by sheared biotite-muscovite-calcite-scheelite-pyrite-gold veins and demonstrates the syntectonic timing of mineralization. Extensive alteration of granites and country rocks in the northern part of the schist belt is typified by microcline-muscovite-pyrite alteration and is perhaps more reminiscent of epithermal systems. Therefore, it is possible that gold mineralization in the Hattu schist belt does record some kind of interaction between magmatic and metamorphic influences during active tectonic processes.

Excursion stops in the Hattu schist belt

Stop 6–1— Poikopää forestry road near Sivakkojoki (Fig. 19)

This is an important locality on the western limb of the regionally significant Pihlajavaara Anticline, which has been a key element in understanding the structure of the region. As well as providing a basis for understanding stratigraphical relationships and structural evolution, these outcrops illustrate typical examples of the main lithologies found in the Hattu schist belt and moreover, retain relatively well-preserved primary depositional features. This is also the lowest stratigraphical horizon exposed in the Hattu schist belt and the plagioclase-phyric andesitic volcaniclastic deposit at the base of the mafic unit here has yielded a relatively precise U-Pb zircon age of 2754 ± 6 Ma. The dominant lithologies include feldspathic coarse clastic deposits that indicate limited reworking of volcaniclastic and volcanic rocks in a shallow marine environment, although it might also be argued that they represent primary pyroclastic deposits with felspar crystals and textures resembling flattened pumiceous fiamme. However, well developed feldspathic arenites alternating with polymicitc, moderately sorted conglomerates in the upper part of this section certainly favour shallow marine to fluviatile deposition. This in itself is of interest when bearing in mind that these are stratigraphically at the base of the preserved hattus schist belt sequence. Evidence for some detrital input from older continental crust is provided by xenocrystic zircons, resulting in highly discordant U-Pb ages, compared to the relatively precise eruptive or depositional age obtained from the andesitic pyroclastic unit. The composite mafic flows and breccias at this outcrop are representative of minor mafic volcanism that punctuates the otherwise felsic-dominated deposits.

Stop 6–2 — Conglomerate within Tiittalanvaara Formation, on eastern limb of Pihlajavaara Anticline

Polymictic conglomerates within the upper part of the Tiittalanvaara Formation form a distinctive facies that can be traced for many kilometers along strike, overlying a thin-bedded pelitic sequence and passing upwards into turbiditic sediments and banded iron formations, which mark the transition to the predominantly mafic Pampalo Formation. Some of the clasts here are nearly a meter in diameter (even when measured perpendicular to the tectonic lineation direction!) and unlike conglomerates at lower stratigraphical levels, appear to contain abundant plutonic clasts. Isotopic data are not yet available, but it is quite possible that synvolcanic plutons might have been unroofed in the vicinity, rather than these representing older basement. It should be noted that the nearby Tasanvaara and Korpivaara Tonalites were intruded early during deformation, and were therefore not accessible to erosion at the time these rocks were deposited.

Stop 6–3 — Pyroclastic deposit with komatiitic composition within the highest stratigraphical unit (Pampalo Formation), overlying the previous locality

Geochemical studies are in progress to attempt to establish whether the high magnesium content of the rock is truly representative of a primary magmatic komatiite, since this is the ultramafic unit found within the Hattu schist belt and it accordingly forms a very useful marker horizon. A distinctive feature of these rocks is the presence of rounded to angular clasts, some containing small phenocrysts, suggestive of an eruptive breccia or hyaloclastite. In some places, depositional lamination and grading can also be recognized, but none of the characteristic textures of ultramafic lava flows have been found. This unit is believed to represent the protolith to the highly deformed talc-chlorite-biotite schists lying along the eastern boundary of the main lode system at the Pampalo prospect.

Stop 6–4 — Gold mineralization on the Pampalo mining lease held by Outokumpu Mining Oy

During the course of the Geological Survey exploration and research in the Hattu schist belt (Nurmi & Sorjonen-Ward, 1993), the Pampalo area attracted particular attention, in part because of the presence of mafic and ultramafic lithologies and porphyritic dykes, which are perhaps generally thought of as a typically rock associations hosting Archean lode gold deposits. More significantly however, was a gradual appreciation of the structural geometry and evolution of the area, with the recognition of the Juttuhuuhta strike-slip duplex, which was found to show a fortuitous resemblance to the Golden Mile at Kalgoorlie, in terms of structural geometry and kinematics and magnetic signature — albeit, it should be emphasized — at a considerably smaller scale! Detailed examination of outcrops finally resulted in the discovery of visible gold in association with pyrite in narrow biotite-rich mylonitic seams in a foliated quartz-plagioclase porphyritic tonalite dyke. The first analyses from outcrop samples assayed between 14–35 ppm Au but excavation and subsequent sampling revealed that the dyke, which was found to be some 15 m wide and exhibiting potassic and carbonate alteration, within a sequence of highly deformed talc-chlorite-actinolite schists, was only sporadically mineralized. Because the highest gold grades were found at the western edge of the outcrop, and a till geochemical profile several hundred meters further west had revealed a weak gold anomaly, a reconnaissance drilling profile was undertaken by the Geological Survey late in 1990. The first and third holes were not significantly mineralized, but the middle hole of the profile intersected two ore horizons grading 17 ppm over 7 m and 3.3 ppm over 12.6 m (Nurmi et al., 1993). Subsequent drilling by the Survey delineated a resource containing estimated to contain 0.5 to 0.9 Mt grading 5–8 g/t down to 100-m level with promising intersections at 150-m depth.

Outokumpu Mining Oy purchased the exploration rights to Pampalo prospect, which is the largest deposit in the area, in 1994 and is currently carrying out feasibility studies; During 1995, some 26 000 tonnes of ore were quarried and processed during trial mining, yielding about 330 kg of gold (Outokumpu Quarterly and Annual Reports, 1997), while further drilling intersected mineralization to a depth of 280 m. A further exploration phase is currently planned, involving a decline with 900 m of tunnel, to a depth of 100 m, from which more detailed drilling will take place. (Outokumpu Mining press release, 23/06/1997).

The mineralogy of the deposit was studied in detail by Kojonen et al., (1993) who found that gold typically occurs in free milling form, as inclusions along fractures and alteration zones in silicate grains, or at dynaically recrystallized grain boundaries. Gold is also common as inclusions within pyrite, intergrown with tellurides of Pb, Bi, Ag, Au and Fe, while the Ag content of native gold varies from 1.0–24.8%. Associated sulfides include, in addition to pyrite, which can occur as large porphyroblasts, chalcopyrite (with inclusions of mackinawite and cubanite), pyrrhotite, galena and spahalerite. Magnetite, ilmenite (after rutile) and goethite have also been found in the gold-bearing mylonitic seams in the discovery outcrop.

Gold and associated sulfide minerals are principally disseminated rather than vein-hosted, occurring within several moderately plunging lodes within a steeply dipping highly sheared and heterogenous lithology whose origin has been difficult to infer. By analogy with the lithic units identified outside the mineralized zone, the lithology probably correlates with the coarse-grained, conglomeratic felsic to inter-

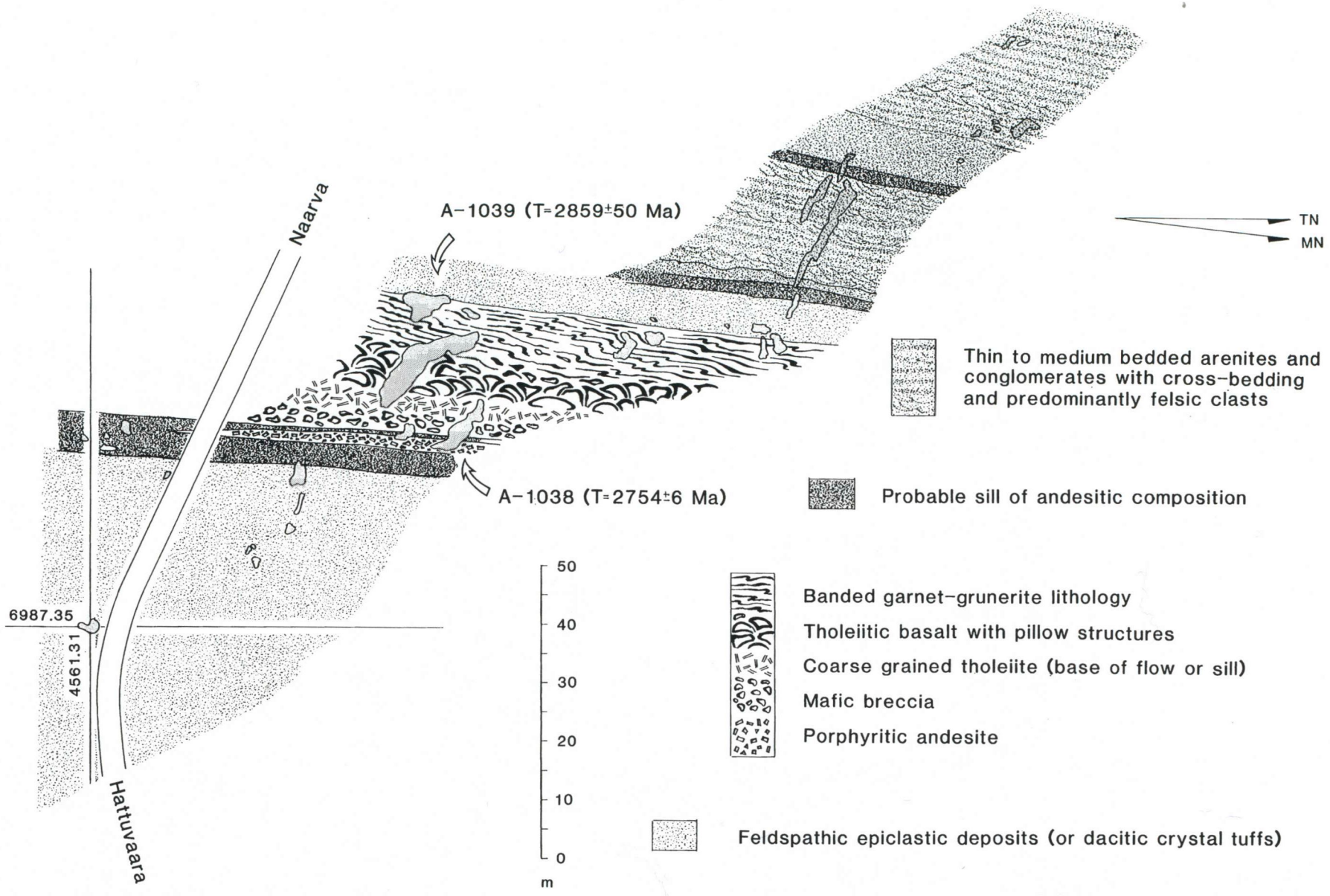


Fig. 19. Outcrop diagram showing lithologies in the Poikopää section (Excursion Stop 6.1), representing the stratigraphically lowermost exposures outcropping in the northern part of the Hattu schist belt (from Sorjonen-Ward, 1993).

mediate volcaniclastic unit overlying the basal mafic volcanic unit of the Pampalo Formation. This is consistent with fact that the main ore zone is bounded to the west by a mafic volcanic unit, which is reasonably interpreted as the basal member of the Pampalo Formation, since it is immediately underlain by a banded iron fomration and in turn by the conglomerates and greywackes of the Tiittalanvaara Formation. The eastern boundary of the main ore zone is structurally more complex, being in the refolded toe of the Juttuhuuhta duplex, so that stratigraphical contacts are no longer easy to determine. However, it but locally coincides with a highly sheared talc-chlorite-biotite schist which represents the hydrothermally altered equivalent of an ultramafic volcaniclastic unit that may originally have been an eruptive breccia. The diversity of lithologies in the Pampalo area is regarded as having had important influence on the localization of mineralization, in providing chemical and mechanical contrasts during deformation. It should be noted that the ultramafic unit itself is seldom mineralized, except in proximity to intrusive porphyry dykes, some of which contain misoriented but foliated enclaves of tonalite, which again strongly supports a syntectonic timing for the mineralization.

The Juttuhuuhta contractional fault duplex is thought to have formed due to incompatabilities related to tightening of a major synform to the south of Pampalo, resulting in imbrication of the mafic units of the Pampalo Formation and their translation with a sinistral sense out of the core of the synform (Fig. 18). The western, or basal bounding shear (analogous to a floor thrust in low-angle duplexes) is taken to coincide with the thin banded iron formations associated with the transition from the turbiditic greywackes of the Tiittalanvaara Formation to the more massive basaltic units at the base of the Pampalo Formation (Sorjonen-Ward, 1993). The introduction of gold at Pampalo is believed to post-date the formation and main stage of deformation within the Juttuhuuhta Duplex. Instead, it is likely to be associated with deformation of the toe of the duplex, attributed to rotational back-folding as relatively greater amounts of sinistral shear strain were transferred from the Pampalo Shear System to the Kelokorpi Shear Zone somewhat further west (Fig. 18).

Ore deposits in eastern Finland
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KAINUU DISTRICT

by
Kirsti Loukola-Ruskeeniemi, Asko Kontinen and Meri-Liisa Airo

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STOP 7 — TALVIVAARA

THE TALVIVAARA BLACK SCHIST -HOSTED Ni-Cu-Zn OCCURRENCE: GEOCHEMISTRY, GENESIS AND ENVIRONMENTAL CONSIDERATIONS

by Kirsti Loukola-Ruskeeniemi

The Talvivaara Ni-Cu-Zn occurrence is situated in the rural municipality of Sotkamo in the province of Kainuu, between the lakes Kolmisoppi and Kuusilampi, and close to the small village of Pirttimäki. Talvivaara can be translated from Finnish into English as "winter hill" and in fact refers to a prominent quartzite hill somewhat southwest of the black schist occurrence (black schist = metamorphosed black shale). The Talvivaara prospect is in terms of total tonnage one of the largest black schist -hosted deposits in the world, containing 300 Mt of mineralized black schist, and it could in principle be exploited as an open cut mining operation, due to its relatively shallow attitude and its location in topographically elevated terrain; this in itself is rather unusual since black schists of this type are in general easily weath-

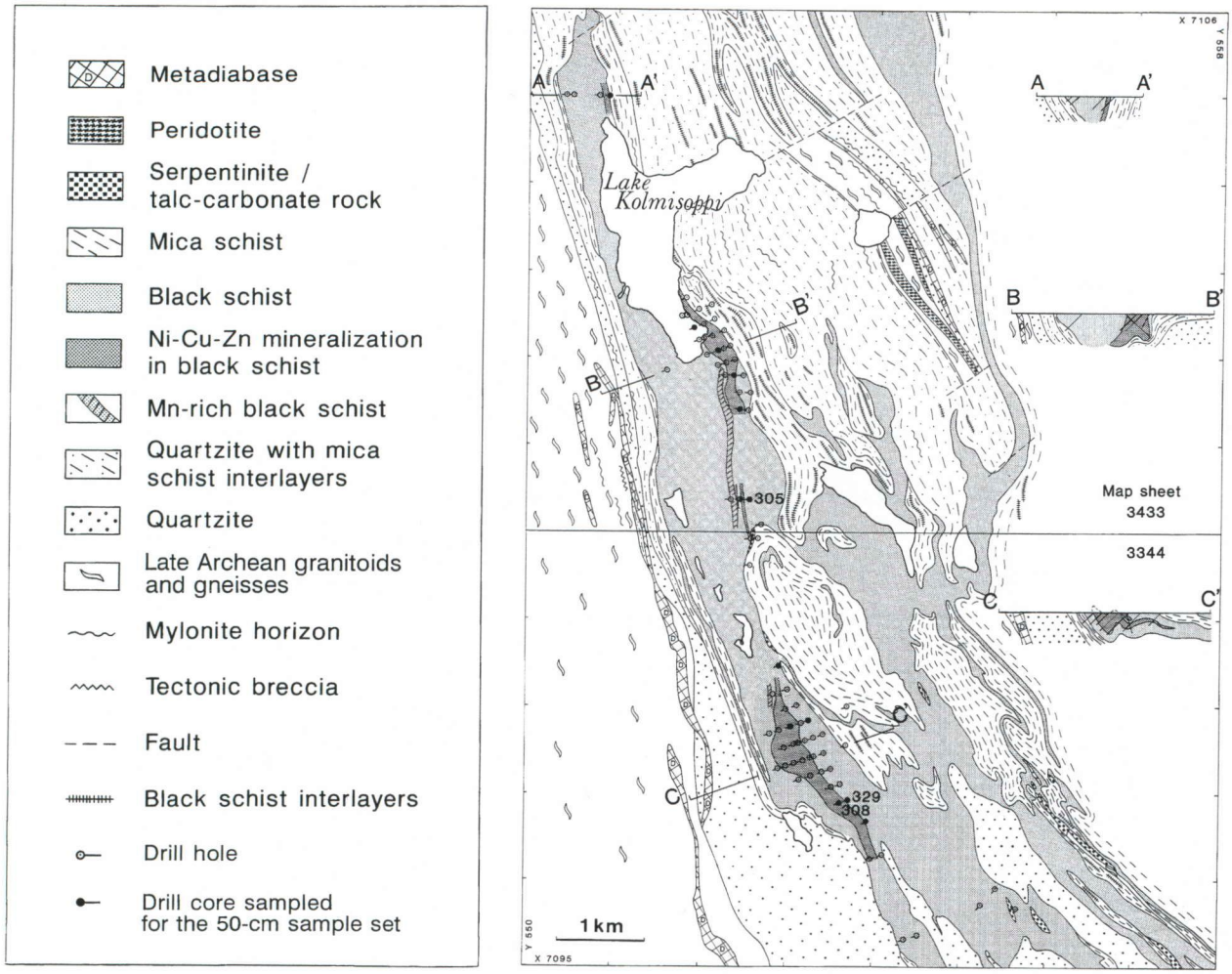


Fig. 20. Generalized geological map of the Talvivaara area. Numbers 305, 308, and 329 refer to drill hole numbers.

ered. Elsewhere in Finland black schists containing comparable amounts of graphite and sulfides typically occupy topographic depressions and are commonly covered by thick swamps, or are situated under lakes. At Talvivaara however, it seems that the original formation was so thick that even intense glacial erosion related to the most recent ice age (which concluded some 10 000 years ago) was unable to level the landscape (though till in the area is full of material derived from the black schists). The base of the black schist sequence has not been penetrated by drilling, although it is likely that the demonstrated present thickness of at least 400 m is the result of isoclinal folding of a black schist sequence originally of the order of 50–100 m thick (Fig. 20). Although the volume of the occurrence alone is sufficient to attract potential interest, and Outokumpu Mining, who have the rights to the area, have been investigating enrichment possibilities with some success, the deposit is unfortunately of rather low grade: the average nickel concentration is 0.26%, copper concentration 0.14%, and zinc concentration 0.53%.

Pyrite and pyrrhotite are the dominant sulfide minerals in the Talvivaara deposit. Pyrite, pyrrhotite, chalcopyrite, sphalerite, alabandite, and pentlandite occur both as fine-grained disseminations (<0.01 mm) and as coarser grains in quartz-sulfide veins. During recrystallization and remobilization processes, part of the nickel that was bound in the fine-grained pyrite, became incorporated into pyrrhotite and pentlandite (Loukola-Ruskeeniemi, 1995).

Geochemistry

The geochemistry of the Talvivaara black schists has been studied comprehensively by Loukola-Ruskeeniemi and Heino (1996). The precursors of the Talvivaara black schists were

organic-rich muds deposited on the seafloor in anoxic conditions. Median concentrations of graphitic carbon and sulphur are 7–8%. Carbon isotope $\delta^{13}C$ values (from -24 to -27‰ PDB) indicate an organic origin. Cerium depletion in rare earth element patterns is consistent with a marine depositional environment, while degree of pyritization values (0.85–0.99) suggest anoxic conditions.

The occurrence is in part syngenetic in origin because nickel is uniformly distributed throughout the extensive nickel-rich horizon (recall that the size of the deposit is 300 Mt). The sulfur isotope $\delta^{34}S$ compositions are also comparatively uniform and the occurrence of pentlandite, chalcopyrite, and sphalerite in the fine-grained (<0.01 mm) sulfide material also leads to the same conclusion.

The elevated concentrations of nickel, copper, and zinc in the occurrence have their origin in hydrothermal processes, since the rare earth element patterns of the Talvivaara black schists exhibit positive europium anomalies. Sulfur isotope compositions are also comparable to those of sulfides in polymetallic sulfide deposits in recent Red Sea deeps and the Guaymas basin. Furthermore, the median S/Se ratio (4100–6400) in the Talvivaara black schists is comparable with that of average Outokumpu ore (5400).

Black calc-silicate rocks with calcium concentrations exceeding 3.5% are encountered as intercalations ranging from 10 cm to 3 m thick within the black schists. They probably represent hydrothermal precipitates, because they have elevated Ca, Mg, F, P, and Ag concentrations, similar to solutions found in the recent Galapagos mounds hydrothermal field. They also exhibit rare earth element values typical of manganese-rich seawater near recent hydrothermal sites, and heavy sulfur isotope values (from -3.8 to +20.8‰ for pyrrhotite and from -7.1 to +20.8‰ for pyrite).

Genetic model

The black schist horizons containing 0.8 or more percent Ni+Cu+Zn probably contained primarily syngenetic concentrations of Ni, Cu, and Zn (Ni<0.1%), which were deposited from seawater contaminated with hydrothermal fluids, and were introduced by upwelling hydrothermal solutions resulting in increased Ni, Cu, and Zn concentrations and precipitation of the black calc-silicate intercalations. This model is also supported by the presence of sodium depletion in the Talvivaara Ni-rich horizon, which is a characteristic feature of hydrothermal alteration in massive sulfide deposits.

Environmental studies

Because the black schist formation, with its anomalous concentrations of sulfur, nickel, copper and zinc, outcrops in part on a hillside, these lithologies are particularly susceptible to weathering and erosion in the absence of an effective vegetation cover. Immediately after the last retreat of the continental ice sheet, some 9000 years ago, before colonization by vegetation had become sufficient to prevent intense weathering, the pH within the small isolated lake called Härkälampi fell to 3.8 and Ni, Cu, Zn, and Al concentrations in the lake sediments increased dramatically (Loukola-Ruskeeniemi et al., 1996, Uutela et al., 1995). Even today, the natural baseline values of Ni, Cu, and Zn in stream waters, organic stream sediments and organic lake sediments are anomalously high in the Talvivaara area. Therefore, it is apparent that in some cases pristine areas, remote from industrial and other anthropogenic influences, can exhibit wide natural variations in trace metal abundances, in some cases exceeding recommended standards. At Talvivaara, spring waters are suitable for human consumption, even in areas underlain by the Ni-Cu-Zn-rich black schists, but wells in which water is in direct contact with the bedrock have in several instances yielded values with excessive amounts of nickel.

STOP 8 — JORMUA

JORMUA OPHIOLITE COMPLEX

by Asko Kontinen

The 1.95 Ga Jormua Ophiolite Complex (Kontinen, 1987, Peltonen, et al., 1996) is one of only three well documented Paleoproterozoic ophiolites that more or less comply with the accepted Penrose Conference ophiolite definition (Anonymous, 1972). In contrast to the 1.992 Ga Purtuniq Ophiolite in northern Quebec, which is considered to represent a relatively mature open ocean or back arc basin (Scott et al., 1992), and the 1.73 Ga Payson Ophiolite in Arizona which is thought to be of intra-arc origin (Dann, 1997), the structural and geochemical characteristics of the Jormua Ophiolite suggest that it formed in an incipient ocean setting. Moreover, the Jormua Ophiolite Complex is currently unique in containing tectonically intercalated peridotites, representing Paleoproterozoic mantle material.

The tectonic setting of the Jormua Ophiolite Complex

The Jormua Ophiolite Complex occupies the central part of the predominantly metasedimentary Kainuu Schist Belt (Fig. 12, Appendices 2 and 3), which in this area comprises three major tectonostratigraphic units: (1) the autochthonous, cratonic to epicratonic Jatuli (2.3–2.1 Ga) sequence, consisting predominantly of quartzites derived from fluvial to shallow marine quartz sands; (2) the 2.1–1.95 Ga rift-phase related "lower Kaleva" assemblage, characterized by turbiditic conglomerates, quartz wackes, greywackes and pelites, as well as distinct turbidite-hosted P-Mn-C-rich silicate facies iron formations and abundant black schists; and (3) the allochthonous "upper Kaleva" sequences, dominated by monotonous massive turbiditic deposits whose depositional age is bracketed by that of the Jormua Ophiolite and the youngest detrital zircon SHRIMP ages, around 1.92 ± 0.02 Ga (Claesson et al., 1993).

The Jormua Ophiolite was emplaced across the foreland, probably as a relatively thin thurst sheet, and has been preserved by subsequent thick-skinned deformation which imbricated and folded the basement-cover contact, including the cratonic pre-rift and rifted and passive margin sedimentary sequences, resulting in the present synformal, klippe-like geometry. The early stages of deformation must also have involved tectonic disruption of the pseudostratigraphy within the ophiolite assemblage itself, so that the Jormua Ophiolite Complex now comprises several fault-bounded "blocks" representing different sections through Paleoproterozoic oceanic crust and mantle lithosphere (Peltonen et al., 1996).

Principal features of the Jormua Ophiolite Complex

The eastern, Antinmäki Block comprises fault-bounded slices of mantle lherzolites-harzburgites and minor dunites, some of which contain small podiform chromitite bodies, all of which have been variably intruded by gabbros and basaltic sheeted dyke complexes and pillow lavas.

The middle, or Lehmivaara Block resemble the Antinmäki Block in many respects, with the mantle lherzolites and harzburgites at Lehmivaara having been intruded by mafic dykes whose abundance progressively increases to the extent that they form a spectacular sheeted dyke complex with only rarely preserved septa of mantle rocks and gabbro. Gabbros have never been observed to truncate sheeted dykes, although the gabbros, sheeted dykes and basalts of the Antinmäki

and Lehmivaara Blocks, all share an E-MORB type chemical affinity and have ε_{Nd} values at 1.95 Ga of around +2 (Peltonen et al., 1996). The basalt and gabbros alike are relatively primitive, with Mg-numbers of 73–59, while REE distributions are generally flat or show slight LREE enrichments; the negative Nb anomalies commonly associated with arc/backarc basalts are nowhere apparent. The gabbros range in composition from high-Mg gabbros to ilmenite-rich ferrogabbros and locally show dioritic to leucotonalitic segregations. The gabbros have also yielded the most precise U-Pb zircon age data obtained so far from the Jormua Ophiolite Complex, namely 1953 ± 2 Ma (Peltonen et al., submitted).

The mantle peridotites of the Lehmivaara Block contain an additional generation of ultramafic-mafic dykes not present in the Antinmäki Block; these are older than the E-MORB sheeted dykes and have OIB basaltic characteristics, having ε_{Nd} values of around 0 at 1.95 Ga and exhibiting considerable LREE enrichments with respect to chondritic values and high (1.5–6.0%) TiO_2 abundances (Peltonen et al., 1996).

The westernmost, Hannusranta Block differs significantly from the Antinmäki and Lehmivaara Blocks in that the E-MORB type gabbros, basaltic dykes and pillow lavas are entirely absent. Instead, serpentinized lherzolitic-harzburgitic mantle peridotites are extensively intruded by dykes consisting of clinopyroxenite, garnet (pseudomorphs) — amphibole — clinopyroxenite and hornblendite. The clinopyroxenite-hornblendite dykes are without doubt igneous cumulates that crystallized in melt channels and pathways in the upper mantle. The chemistry of the preserved primary pyroxenes and amphiboles indicates that the melts percolating through these pathways and precipitating the cumulates were of alkali basalt composition. Isotopic data suggest that these were broadly coeval and closely related to the OIB dykes in the Lehtivaara Block, with a combined whole rock — clinopyroxene Sm-Nd isochron yielding an age that overlaps with the U-Pb zircon data obtained from the Hannusranta dykes. The stability field of the inferred primary mineral parageneses suggest that the dykes crystallized at depths of 25–50 km and at temperatures of 900–1000° C (Peltonen et al., submitted).

In general, the mantle peridotites of the Jormua Complex have been thorougly serpentinized and extensively recrystallized during lower amphibolite facies regional metamorphism following their emplacement. The only primary mineral phase encountered is chromite, though even this commonly shows the effects of zonal alteration and recrystallization. Otherwise, the most widely expressed equlibrium metamorphic mineral paragenesis consists of antigorite + Cr-magnetite + tremolite (with sporadic olivine in the Hannusranta Block). Most of the serpentinized peridotites represent variably depleted lherzolites and harzburgites, though dunites are also present. The peridotites show a preferred alignment defined by strained chromite grains and bands of pseudomorphed pyroxene; the fact that sheeted dykes and gabbros truncate this foliation attest to it being of mantle origin and hence indicate that the peridotites are in fact mantle tectonites. Some of the dunites must nevertheless represent magmatic cumulates, particularly in view of their association with podiform chromitite bodies.

The Cr/Al ratios of accessory chromite within the serpentinites varies from 42–68 and Mg/Fe^{2+} values vary considerably, reflecting various episodes of metasomatic and metamorphic re-equilibration, a phenomenon which is also evident from their unusually high (0.5–4.0%) Zn concentrations.

The Hannusranta Block, with its evidence for deep-level crystallization of pyroxene cumulates from an alkali basaltic melt, is considered to represent a remnant of subcontinental mantle lithosphere, comparable to that present below modern rifted continental margins. The similar ages of these rocks and the Jormua E-MORB gabbros suggests a relatively rapid transition from the early alkaline stage of magmatism, which is again characteristic of the evolution of incipient ocean basins, such as the present Red Sea (Coleman and McGuire, 1988). The absence of a thick layered mafic and ultramafic cumulate sequence, such as those found in many other ophiolites, suggests that the closest analogues for the Jormua Ophiolite Complex are to be found in slow-spreading small ocean basins formed during the early stages of continental break-up and separation (Peltonen et al., 1996). A true oceanic, rather than intracratonic rift setting is also implied by the absence of terrigenous deposits intercalated amongst the pillow basalt sequence.

Excursion localities within the Jormua Ophiolite Complex

Stop 8–1 — Serpentinites at the Shell-Mineraali service station, Kontiomäki

Lherzolitic/harzburgitic serpentinites representative of the dominant lithology within the Jormua Ophiolite Complex. Pale pseudomorphs after pyroxene — probably orthopyroxene occur within a groundmass of serpentinite that has replaced olivine. Oxide minerals, which are predominantly Cr-magnetite after chromite, define a foliation which is of mantle origin. The serpentinites are cut by coarse-grained, rodingitized pegmatitic gabbro.

The initial serpentinization process, under relatively low-T conditions caused alteration of olivine and pyroxene to pseudomorphic mesh textured serpentine (chrysotile + lizardite + magnetite) and bastite (lizardite); during subsequent regional metamorphism, these were replaced by a static growth of antigorite. In other words, the Jormua serpentinites are effectively metaserpentinites.

Stop 8–2 — Podiform chromitite at Pitkänperä

Folded, boudinaged and dismembered lense of massive chromitite occurs with serpentinite that has undergone extensive carbonate alteration. The central parts of the lense shows a massive texture but towards the margins, the Al-content of the chromite decreases and has been altered to a mixture of Al-poor Cr-Fe-chromite and chlorite. The unaltered chromite has a mean composition of 24% Al_2O_3, 17% MgO, 12% $FeO_{(total)}$ and 45% Cr_2O_3.

Stop 8–3 — Basaltic pillow lavas at Pitkänperä

Pillow lavas within the Jormua Complex occur as tectonic lenses of the order of a hundred meters or so in thickness, ususally in faulted contact with adjacent lithologies. At Pitkänperä lavas are juxtaposed against serpentinites and talc-carbonate rocks to the east, and presumably against sheared sheeted dykes to the west. Pillow breccias and hyaloclastites, massive flows and dykes also occur within the basaltic sequence; interstitial and intercalated terrigenous sedimentary material is however absent. Post-extrusive chemical alteration has affected the basalts to varying degrees, locally disturbing Sm-Nd systematics. Infiltration by CO_2-rich metamorphic fluids is attributed to the same process that caused talc-carbonation of the nearby mantle peridotites.

Stop 8–4 — Sheeted dyke complex at Särkijärvi

A typical example of Jormua Complex sheeted dykes, with abundant truncated and chilled margin contacts and locally showing magmatic flow fabrics, defined by phenocryst concentrations. The occasional presence of, widely separated relict septa of gabbro and mantle peridotite attest in a striking way to the magnitude of extension during formation of the Jormua Ophiolite Complex. Because the sheeted dykes tend to be more chemically fractionated than the average Jormua lavas, it is nevertheless considered unlikely that these dykes were conduits for the bulk of currently exposed pillow basalts.

GEOPHYSICAL CHARACTERISTICS OF METAMORPHOSED BLACK SHALES IN EASTERN FINLAND

by Meri-Liisa Airo

The metamorphosed black shales in eastern Finland are associated with locally intense aeromagnetic anomalies, sometimes occurring as banded dyke-like anomalies, or sometimes showing an irregular pattern, composed of chains of magnetic highs and lows. The banded anomalies often follow sedimentary layering, while the irregular patterns are associated with tectonic features, such as folds or fault zones. The nature of the anomaly patterns is influenced by variations in the content, texture and fabric of monoclinic pyrrhotite, which is responsible for the magnetization. Owing to their high conductivity, black schist zones are also readily revealed by EM methods. This is mainly due to their high graphite content, since graphite has a greater effect than sulfides on conductivity. The combination of magnetic and electrical anomalies is thus characteristic of pyrrhotite- and graphite-bearing black schists.

Pyrrhotite-bearing lithologies can be separated from magnetite-bearing units geophysically by virtue of their having high conductivities and high remanent magnetization. The dominance of the remanence component over induced magnetization becomes obvious from petrophysical analysis of a large number of samples; magnetite- and pyrrhotite-bearing lithologies from eastern Finland plot in totally different fields with respect to their relative induced and remanent magnetizations (Fig. 21). Lithologies that generate significant magnetic anomalies have susceptibilities above 2000 10-6 SI, which is here regarded as the upper limit of paramagnetic behaviour. In that field the dominance of remanence in pyrrhotite-bearing sediments

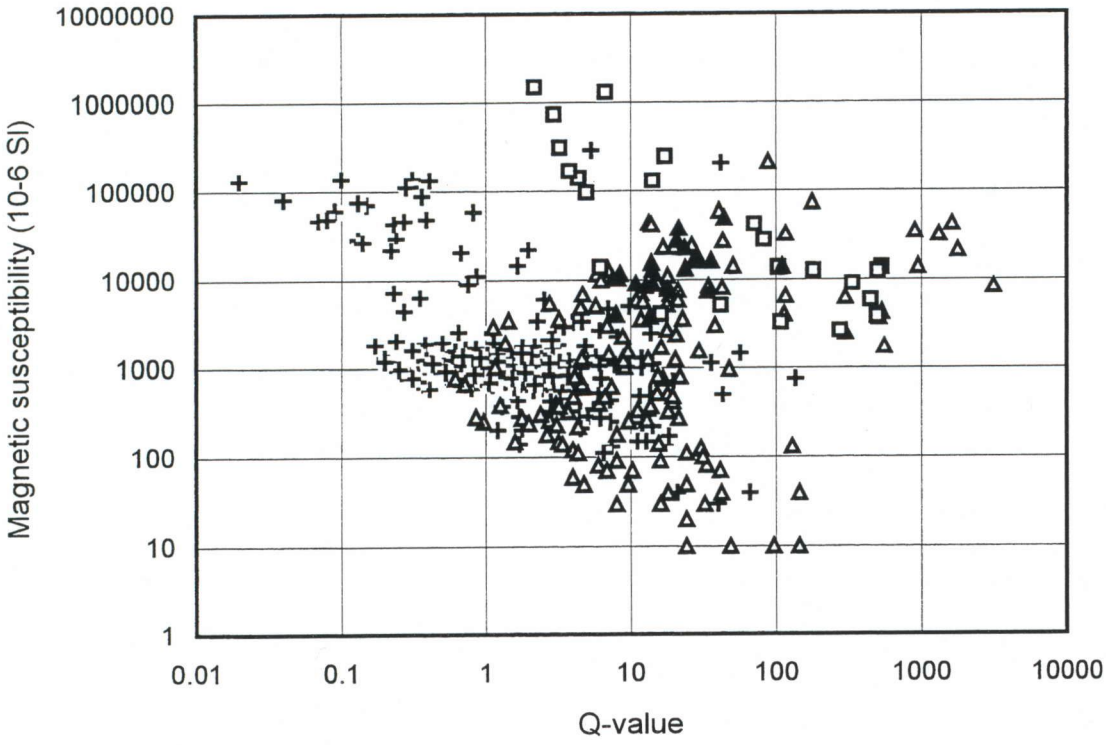


Fig. 21. Magnetic properties of magnetite- and pyrrhotite-bearing lithologies in eastern Finland. Magnetite-bearing rocks are represented by metadiabases (crosses) and banded iron ores (squares). Pyrrhotite-bearing rocks are black schists (open triangles) and sulfide-ores (black triangles). Magnetic volume susceptibilities and Q-values (Königsberger-ratios) from 536 samples, are taken from the GSF petrophysical database.

is indicated by high Q-values (Königsberger ratios), which cluster between 10–100. In contrast, metadiabases, which have magnetite as their main magnetic mineral, are dominated by induced magnetization and typically have Q-values below 1–2. When petrophysical analysis based on a large number of measurements is combined with aeromagnetic interpretations, general conclusions can be made concerning the distinctive magnetic anomaly patterns due to magnetite- or pyrrhotite-bearing lithologies. These results can also be applied to other Precambrian shield areas.

The dominance of remanence is responsible for the irregularity in magnetic anomaly patterns since the remanence vector often lies in the plane of the structure that contains the pyrrhotite. In a fold, for example, this direction is changed with respect to the geomagnetic field vector. In pyrrhotite-bearing rocks the direction of remanence has been strongly influenced by the form and nature of the magnetic bodies and the orientation of pyrrhotite grains relative to the present and ancient geomagnetic fields. This contrasts with the situation in magnetite-bearing rocks, where the magnetization vector is aligned within the present Earth's magnetic field, particularly in cases where the magnetization is carried by coarse grained magnetite but commonly also when it is fine grained. However, very fine grained magnetite of pseudo single domain or single domain size also retains a strong remanence. In banded iron ores the fine magnetite grains are oriented parallel to the layering, resulting in anomalies similar to those produced by black schists, with Q-values >100, and with much higher amplitudes.

Many of the most prominent aeromagnetic anomalies in the Kainuu schist belt are caused by mafic to ultramafic igneous rocks having magnetite as their main magnetic mineral, and pyrrhotite-bearing metamorphosed black shales. In the vicinity of the Jormua ophiolite complex the black schists are associated with strong anomalies beacause of the enrichment of pyrrhotite due to tectonic and metamorphic processes (Appendix 3, upper map). The combination of the apparent resistivity and magnetic maps illustrates the discrimination of magnetite- and pyrrhotite-related anomalies (Appendix 3, lower map). The magnetite-bearing serpentinites and differentiated mafic intrusions are resistive units between the highly conductive black schist

formations. The weakly magnetic black schists representing a lower stratigraphic level can also be separated from the overlying mica schists as better conductors.

The variable appearances of black schist anomalies depend on the geological environment. According to a thermomagnetic and mineralogic study (Airo & Loukola-Ruskeeniemi 1991) on black schists from Kainuu Schist Belt, their magnetization was due to the ferrimagnetic monoclinic pyrrhotite. Black schists from different geological settings, characterized by variation in their sulfide- and graphite-contents, were distinguished on the basis of their typical magnetic properties. The geophysical properties correlated closely with the geochemistry and petrography of black schists. Quiet deposition of pelitic laminae resulted initially in a weak magnetic banding within the graphite-bearing schists. Where a small amount of pyrrhotite is present the induced magnetization is dominated by the paramagnetic matrix which does not contribute to the remanence. Combined sedimentary and tectonic fabrics produced more complex patterns with higher amplitudes due to the increased amount and larger grain size of pyrrhotite, particularly in small fractures and on cleavage planes coincident with high strain. In reduced environments in the Precambrian basement, crustal scale fracture or shear zones are often associated with a magnetic lineaments related to increased pyrrhotite content. In contrast, in magnetite-bearing lithologies the fracture and shear zones are weakly magnetic, as magnetite is commonly destroyed during retrograde metamorphic processes.

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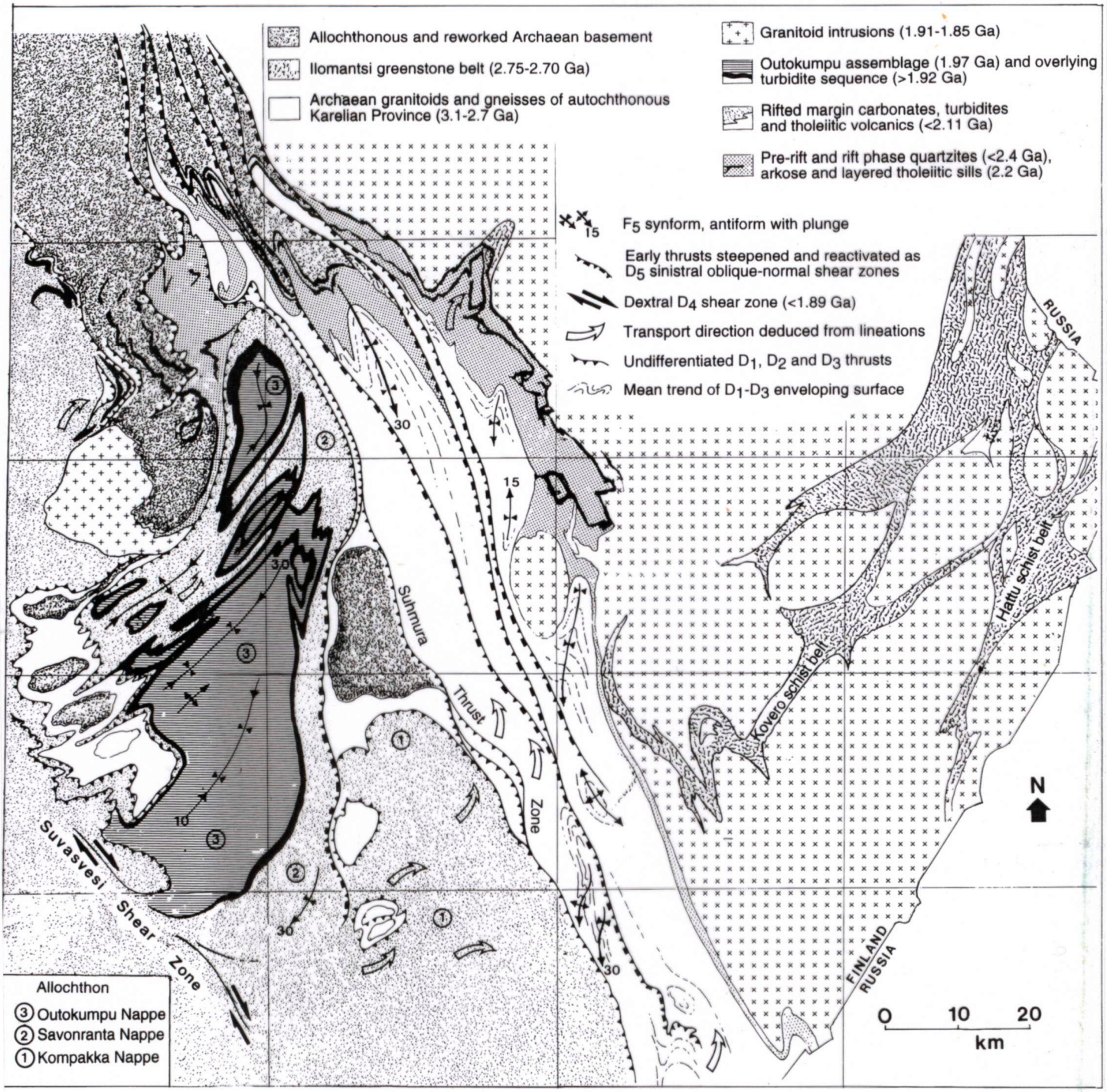
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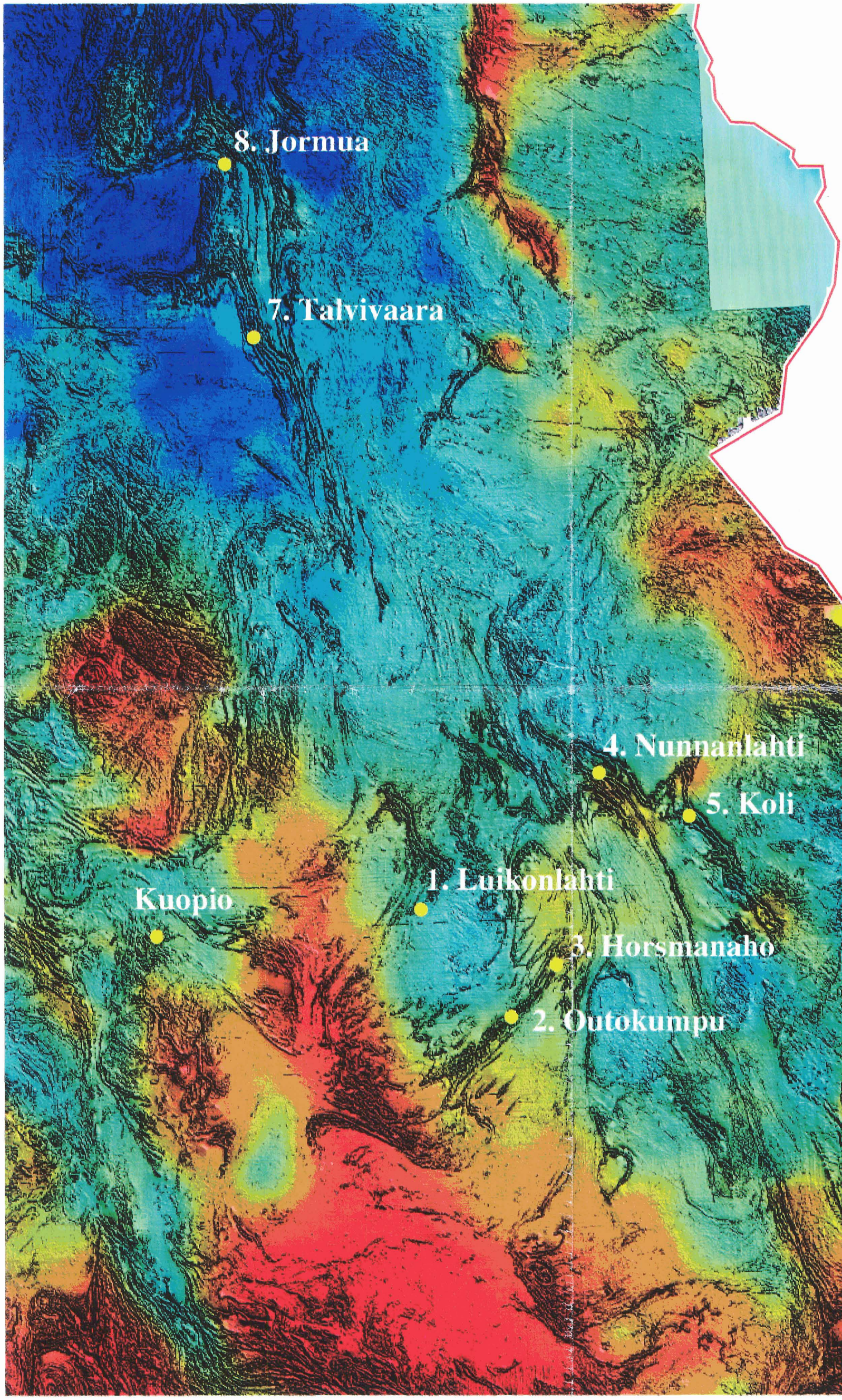
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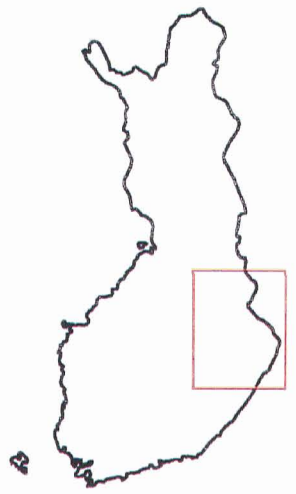
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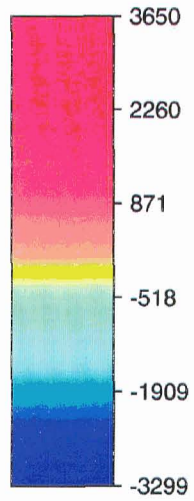
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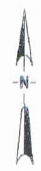

Allochthonous and reworked Archaean basement
Ilomantsi greenstone belt (2.75-2.70 Ga)
Archaean granitoids and gneisses of autochthonous Karelian Province (3.1-2.7 Ga)
Granitoid intrusions (1.91-1.85 Ga)
Outokumpu assemblage (1.97 Ga) and overlying turbidite sequence (>1.92 Ga)
Rifted margin carbonates, turbidites and tholeiitic volcanics (<2.11 Ga)
Pre-rift and rift phase quartzites (<2.4 Ga), arkose and layered tholeiitic sills (2.2 Ga)
F5 synform, antiform with plunge
Early thrusts steepened and reactivated as D5 sinistral oblique-normal shear zones
Dextral D4 shear zone (<1.89 Ga)
Transport direction deduced from lineations
Undifferentiated D1, D2 and D3 thrusts
Mean trend of D1-D3 enveloping surface
RUSSIA
Hattu schist belt
Kovero schist belt
Suhmura
Thrust
Zone
Suvasvesi
Shear
Zone
FINLAND
RUSSIA
N
0 10 20
km
Allochthon
3 Outokumpu Nappe
2 Savonranta Nappe
1 Kompakka Nappe

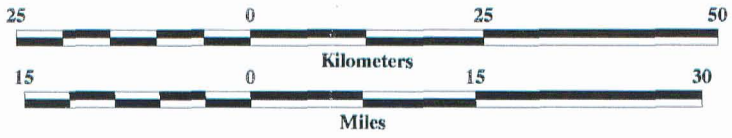
Bouguer anomaly and magnetic composite map of Eastern-Finland







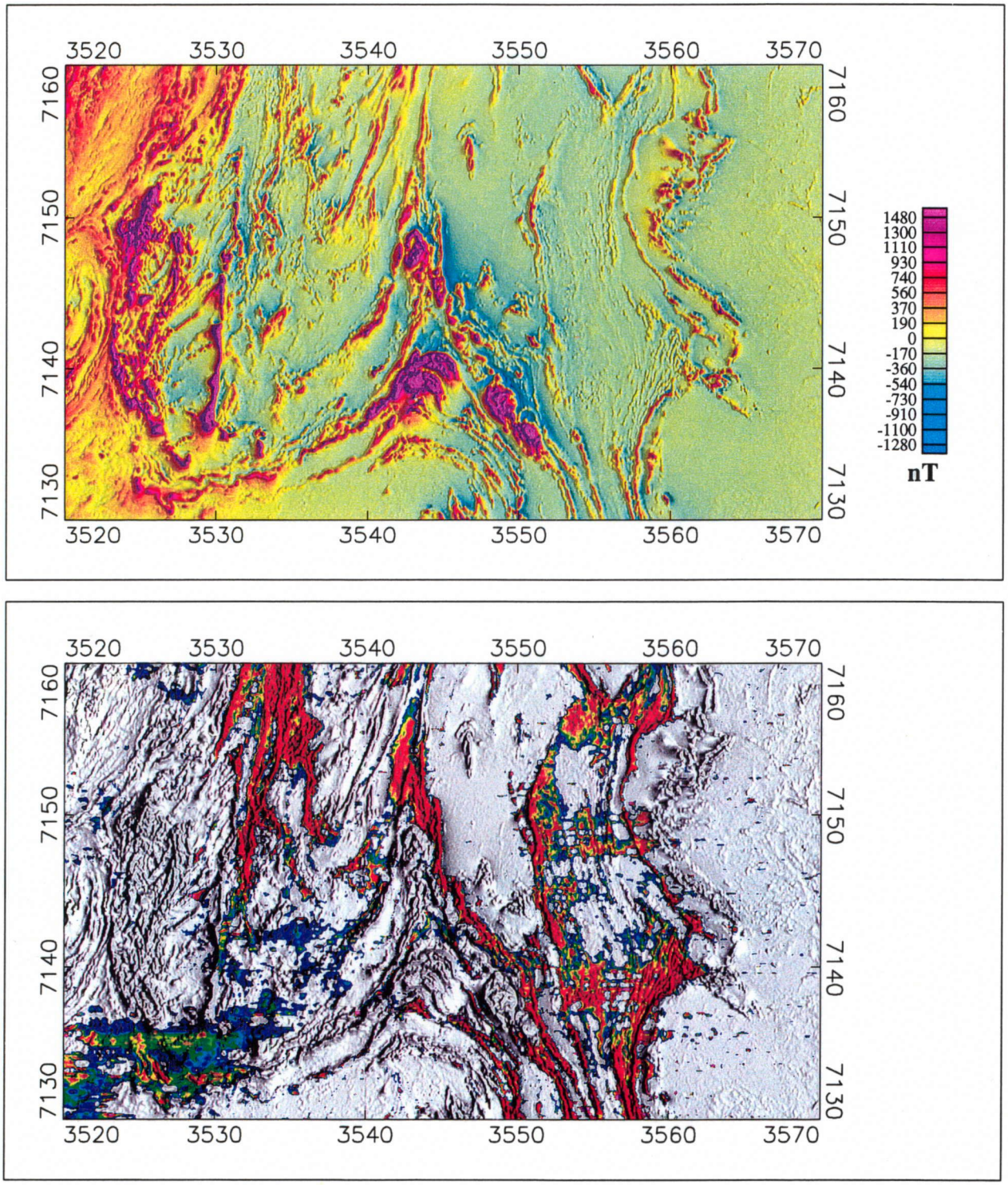






Geological Survey of Finland, Kuopio

Geophysical characteristics of metamorphosed black shales in eastern Finland, by Meri-Liisa Airo:
Aerogeophysical maps showing the Jormua ophiolite complex, at a scale of 1:400 000. Upper map: magnetic field, illuminated from the east. Lower map: shaded magnetic relief combined with apparent resistivity, illustrating only the best conductors (calculated from airborne EM measurements). Aerogeophysical surveys by GSF, compilation of maps by Maija Kurimo.



GEOLOGICAL SURVEY OF FINLAND, GUIDE 42, Kirsti Loukola-Ruskeeniemi and Peter Sorjonen-Ward (eds.)

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