Geologian tutkimuskeskus, Opas - Geological Survey of Finland, Guide 41

Research and exploration - where do they meet?

4th Biennial SGA Meeting

August 11-13, 1997, Turku, Finland

Excursion Guidebook

A2
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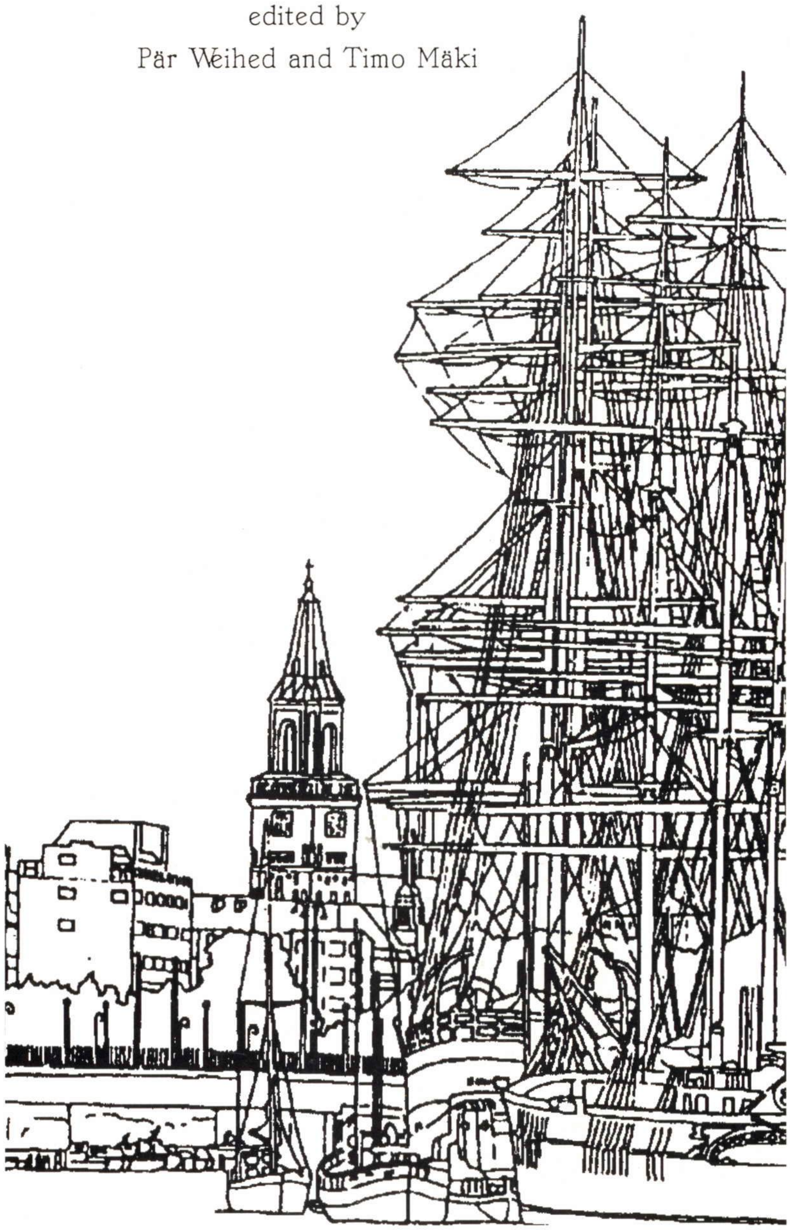
edited by

Pär Weihed and Timo Mäki



Society for Geology Applied to Mineral Deposits

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VOLCANIC HOSTED MASSIVE SULPHIDE AND GOLD DEPOSITS IN THE SKELLEFTE DISTRICT, SWEDEN AND WESTERN FINLAND

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Espoo 1997

Weihed, P. & Mäki, T. (eds.) 1997. Volcanic hosted massive sulphide and gold deposits in the Skellefte district, Sweden and western Finland. Research and exploration — where do they meet? 4th Biennial SGA Meeting, August 11–13, 1997, Turku, Finland, excursion guidebook A2. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 41, 81 pages, 41 figures and 7 tables.

The Skellefte District occurs within an early Proterozoic (mainly 1.90–1.87 Ga) magmatic province of low to medium metamorphic grade in northern Sweden. The district contains over 85 pyritic Zn-Cu-Au-Ag massive sulphide deposits, gold lode deposits and subeconomic porphyry Cu-Au-Mo deposits. An Epithermal high sulphidation origin has recently been proposed for the Boliden deposit. The massive sulphide deposits tend to be located within, and particularly at the top of a regional felsic dominated volcanic sequence attributed to an intense episode of extensional continental or island arc volcanism. The massive sulphides in the Skellefte District span a range in ore deposit style from deep water seafloor ores, to subseafloor replacement ores, to shallow water and possibly subaerial subvolcanic replacement ores.

In the last few years two quartz vein-hosted gold lode deposits have been discovered in the eastern part of the Skellefte District; at Björkdal and Åkerberg. The Björkdal deposit is currently one of the largest gold mines in Europe and is characterised by a quartz vein system at the contact between a granodiorite-tonalite and surrounding supracrustal rocks. Gold at Åkerberg is hosted by a set of narrow parallel quartz veins in a shear zone within a gabbroic intrusion.

Across the Bothnian bay in central Ostrobothnia in Finland the Raahe–Ladoga Zone (RLZ) has been interpreted as a collisional boundary zone between the Archaean continent and Palaeoproterozoic, Svecofennian lithosphere. Several epochs of mineralisation and different metallogenic provinces are associated with of this zone. In the early orogenic stage intracratonic rifting in the east produced the Jormua–Outokumpu ophiolites, 1960 Ma in age, and the associated Cu-Zn-Co-Ni ores. Volcanic complexes and associated Vihanti–Pyhäsalmi type ore deposits, 1890–1920 Ma in age, are related to immature island arc volcanism on the margin of the Archaean craton. Subsequent synorogenic basic and ultrabasic intrusions, 1890–1880 Ma in age, host Ni-Cu deposits. Synorogenic calc-alkaline intrusions host numerous porphyry type occurrences and epigenetic Au-As mineralisation.

Excursion held on: August 5–9, 1997

Key words (GeoRef Thesaurus, AGI): massive sulfide deposits, metavolcanic rocks, copper ores, zinc ores, nickel ores, gold ores, metallogeny, mines, Proterozoic, field trips, guidebook, Skellefte Mining District, Sweden, Oulu Province, Finland

Timo Mäki, Outokumpu Mining Oy, P.O.Box 51,
FIN-86801 Pyhäsalmi, Finland
e-mail: Timo.Maki@outokumpu.fi

Pär Weihed, Geological Survey of Sweden, Box 670
SE-751 28 Uppsala, Sweden
e-mail: per.weihed@sgu.se

ISBN 951-690-657-5
ISSN 0781-643X

Weihed, P. & Mäki, T. (toim.) 1997. Volcanic hosted massive sulphide and gold deposits in the Skellefte district, Sweden and western Finland. Research and exploration — where do they meet? 4th Biennial SGA Meeting, August 11–13, 1997, Turku, Finland, excursion guidebook A2. Geologian tutkimuskeskus, Opas — *Geological Survey of Finland, Guide* 41, 81 sivua, 41 kuvaa ja 7 taulukkoa.

Skellefteån alue sijaitsee varhaisproterotsooisessa (pääasiassa 1,90–1,87 Ga) alhaisesti tai keskiasteisesti metamorfoituneessa magmaattisessa provinssissa Pohjois-Ruotsissa. Alueella on yli 85 rikkikiisuvaltaista, massiivista Zn-Cu-Au-Ag- esiintymää, juonikultaesiintymiä ja subekonomisia porfyyrityyppisiä Cu-Au-Mo- esiintymiä. Nykyisen käsityksen mukaan Bolidenin kultaesiintymän muodostuminen on katsottu syntyneen epitermisen korkea-asteisen sulfidoitumisen kautta. Massiiviset sulfidimalmit sijoittuvat felsiseen vulkaaniseen tapahtumaan, yleensä sen yläosaan, joka tapahtuma liittyy joko mantereen vulkanismiin tai saarikaarivulkanismiin. Skellefteån alueen massiiviset sulfidimalmit edustavat erilaisia syntyolosuhteita. Malmit ovat syvänmerenpohjan malmeja, lähellä merenpohjaa korvautumisen kautta syntyneitä malmeja, matalaan veteen saostuneita malmeja ja mahdollisesti ilmanalaisiin vulkaniitteihin korvautumisen kautta syntyneitä malmeja.

Muutaman viime vuoden aikana on Skellefteån alueen länsiosasta; Björkdalista ja Åmmabergistä, löytynyt kvartsijuoniin liittyviä kultamalmeja. Björkdalin esiintymä on yksi Euroopan suurimmista kultakaivoksista ja sitä luonnehtii kvartsijuonisysteemi granodioriitti-tonaliitti-intruusion ja sitä ympäröivien suprakrustaalisten kivien välissä. Åkerbergin malmissa kulta liittyy yhdensuuntaiseen ohuista kvartsijuonista liittyvän systeemiin gabrointruusiossa.

Raahe–Laatokkavyöhykettä (RLZ) on pidetty arkeeisen mantereen ja svekofennisen litosfäärin törmäysvyöhykkeenä. Tähän vyöhykkeeseen liittyy useita malmiutumistapahtumia ja erilaisia malmiprovinsseja. Jormuan–Outokummun ofioliitit (ikä noin 1960 Ma) ja niihin liittyvät Cu-Zn-Ni-Co-malmit syntyivät varhaisorogeenisessa vaiheessa kratonin sisäisen vajoamis- ja halkeamisprosessin myötä. Vihanti–Pyhäsalmityyppiset malmiesiintymät liittyvät 1,89–1,92 Ga vuotta vanhoihin monimuotoisiin vulkaanisiin keskuksiin, jotka syntyivät arkeeisen kratonin reunalle muodostuneeseen epäkypsään saarikaarisysteemiin. Synorogeenisiin, emäksisiin ja ultraemäksisiin intruusioihin (1,88–1,89 Ga) liittyy useita Ni-Cu- esiintymiä. Myöhäisorogeenisiin kalkkialkaalisiin intruusioihin liittyy useita porfyyrityyppisiä esiintymiä sekä epigeneettisiä Au-As- mineralisaatioita.

Ekskursioaika: 5–9. elokuuta 1997

Avainsanat (Fingeo-sanasto, GTK): massiiviset sulfidiesiintymät, metallivulkaniitit, kuparimalmit, sinkkimalmit, nikkelimalmit, kultamalmit, metallogenia, kerrokset, proterotsooinen, ekskursiot, oppaat, Skelleften alue, Ruotsi, Oulun lääni, Suomi

Timo Mäki, Outokumpu Mining Oy, PL 51,
86801 Pyhäsalmi
sähköposti: Timo.Maki@outokumpu.fi

Pär Weihed, Geological Survey of Sweden, Box 670
SE-751 28 Uppsala, Sweden
sähköposti: per.weihed@sgu.se

AUTHORS:

[1] *Björn Albino, Terra Mining AB, Björkdal mine, SE-934 94 Kåge, Sweden.*

[2] *Jeanette Bergman Weihed, Institute of Earth Sciences, Uppsala University, Norbyvägen 18B, SE-752 36 Uppsala, Sweden.*
e-mail: jeanette.weihed@geo.uu.se.

[3] *Eljas Ekdahl, Geological Survey of Finland, P.O.Box 1237, FIN-70211 Kuopio, Finland.*

[4] *Pertti Hakanen, Outokumpu Mining Finland, Exploration office, Tehtaank. 2, FIN-83500 Outokumpu, Finland.*

[5] *Olli-Pekka Isomäki, Outokumpu Mining Oy, Hitura Mine, FIN-85560 Ainastalo, Finland*

[6] *Benno Kathol, Geological Survey of Sweden, Box 670, SE-751 28 Uppsala, Sweden.*
e-mail: benno.kathol@sgu.se

[7] *William Karvinen, SES Finland LTD, 4356 Unity Rd., Odessa, Ontario, Canada K0H 2H0.*

[8] *Jukka Kousa, Geological Survey of Finland, Regional office for Mid-Finland, P.O.Box 1237, FIN-70211 Kuopio, Finland.*

[9] *Ingmar Lundström, Geological Survey of Sweden, Box 670, SE-751 28 Uppsala, Sweden.*
e-mail: ingmar.lundstrom@sgu.se

[10] *Jouni Luukas, Geological Survey of Finland, Regional office for Mid-Finland, P.O.Box 1237, FIN-70211 Kuopio, Finland*

[11] *Timo Mäki, Outokumpu Mining Oy, P.O.Box 51, FIN-86801 Pyhäsalmi, Finland.*
e-mail: Timo.Maki@outokumpu.fi

[12] *Roger Nordin, Boliden AB, SE-971 87 Boliden, Sweden.*
e-mail: roger.nordin@boliden.se

[13] *Pekka Nurmi, Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland*
e-mail: pekka.nurmi@gsf.fi

[14] *Heikki Papunen, Department of Geology, University of Turku, FIN-20500 Turku, Finland*

[15] *Kalevi Pelkonen, Outokumpu Mining Oy, P.O.Box 51, FIN-86801 Pyhäsalmi, Finland*

[16] *Vesa-Jussi Penttilä, Outokumpu Mining Oy, Hitura Mine, FIN-85560 Ainastalo, Finland*

[17] *Cecilia Rapp, Department of Applied Geology and Centre for Applied Ore Studies (CTMG), Luleå University of Technology, SE-971 87 Luleå.*
e-mail: cera@sb.luth.se

[18] *Sven-Åke Svenson, Boliden AB, SE-971 87 Boliden.*
e-mail: sa.svensson@boliden.se

[19] *Kaj Västi, Geological Survey of Finland, P.O.Box 1237, FIN-70211 Kuopio, Finland*

[20] *Pär Weihed, Geological Survey of Sweden, Box 670, SE-751 28 Uppsala, Sweden.*
e-mail: per.weihed@sgu.se

CONTENTS

INTRODUCTION

This field trip will take the participants to two of the most well known base-metal mining camps in northern Europe; the Skellefte district in Sweden and the Vihanti–Pyhäsalmi area in Finland. Both camps have been, and still are, active producers of a significant tonnage of Cu, Zn, Pb, and Ni. In both areas substantial amounts of Au and Ag have also been produced as byproducts from the base-metal ores. In addition to the base-metal deposits several new discoveries of Au have been made, especially during the last decade. This means that the Skellefte district today is one of the largest Au camps in Europe. The Skellefte District and the Vihanti–Pyhäsalmi area together annually produce 18 000 tonnes of Cu (8 000 in Skellefte + 10 000 in Vihanti–Pyhäsalmi), 94 000 tonnes of Zn (60 000 + 34 000), 7 000 tonnes of Pb (5 000 + 2 000), 3 100 tonnes of Ni (Hitura in Finland), 4.8 tonnes of Au (4.5 + 0.3) and 95 tonnes of Ag (76 + 19).

The field trip will start in the town of Skellefteå which is the main municipality in the northern part of the County of Västerbotten (Fig. 1).

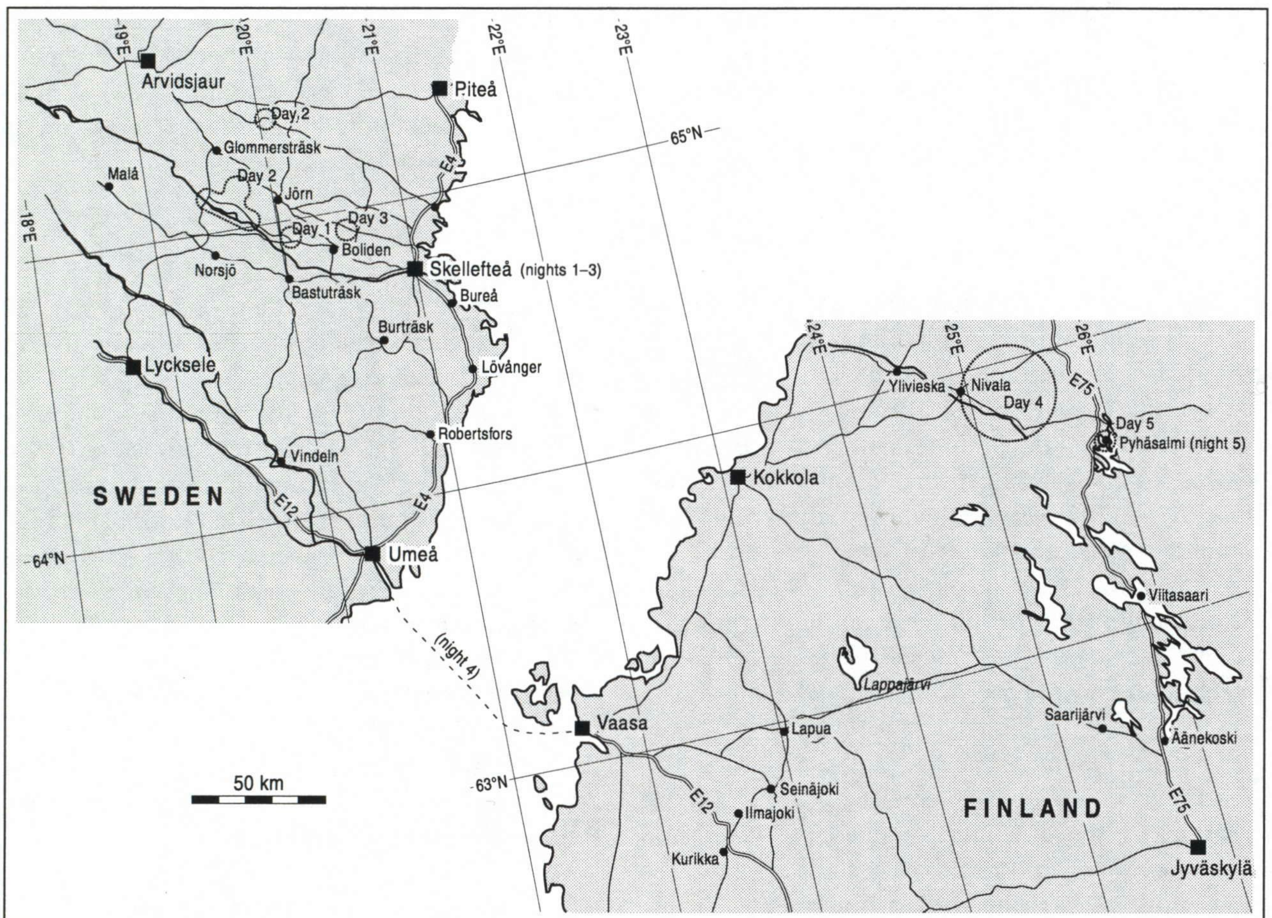

Fig. 1. Route Map. Stops indicated.

Skellefteå is located close to the coast by the Skellefte river and approximately 700 km north of Stockholm. The Rönnskär smelter of Boliden AB, which treats all concentrates from the Skellefte District, is located at the coast east of Skellefteå. From Skellefteå the field trip will make day trips to various parts of the Skellefte district where base-metal deposits, owned by Boliden AB and gold-deposits owned by Terra Mining AB, will be examined. The field trip will continue across the Bothnian bay in Finland from Vaasa to central Ostrobothnia. The first stop will be the Hitura Ni-mine, which is the only active Ni-mine in Finland today. Near the Hitura mine the Kopsa Au-Cu-prospect is located. Investigations in Kopsa were renewed in 1996 by a Canadian junior company Glenmore Highland Ltd. During the trip from Kopsa to Pyhäsalmi some outcrops will be seen. After staying overnight in Pyhäsalmi the field trip continues to the Pyhäsalmi Cu-Zn-S-mine and the Mullikkoräme Zn-Cu-Pb-mine.

GEOLOGY OF THE FENNOSCANDIAN (BALTIC) SHIELD

Introduction

The Fennoscandian or Baltic Shield (both names occur in the literature) occupies the northern part of Europe. Precambrian areas are exposed in Norway, Sweden, Finland and Russia and their continuation beneath the platform cover sequences to the east and south (Fig. 2) is becoming better understood through studies within the European "Europrobe" project. The craton of which the exposed Fennoscandian Shield forms a part is bordered to the west by the Caledonian orogenic belt. Precambrian rocks of the same craton again outcrop in the Ukrainian Shield and the Voronezh Massif (cf. Gee & Zeyen 1996).

The Fennoscandian Shield is composed of Archaean to Neoproterozoic rocks. It is beyond the scope of this guide book to describe all different settings in detail, but adjoining areas that both pre- and post-date the Svecofennian rocks that are of interest in this field trip will be briefly described. The term Svecokarelian is used for the orogeny that occurred between 1900 and 1800 Ma (i.e. emphasising deformation and metamorphism as defining the orogeny), while the term Svecofennian is used for the supracrustal rocks that were emplaced during c. 1.95 Ga to 1.85 Ga. To the unfamiliar reader of literature on the Fennoscandian Shield it is important to remember that these terms are not used consistently in the literature.

Pre-Svecokarelian crustal growth

The pre-Svecokarelian crustal growth can be subdivided into Archaean and Palaeoproterozoic. During the Archaean greenstone belts and TTG-terranes formed, while crustal growth during the Palaeoproterozoic involved rifting of the Archaean basement with the formation of riftfill sequences of sedimentary and igneous rocks, and addition of juvenile Palaeoproterozoic crust by accretionary processes along the margin of the Archaean continent.

Archaean complexes

The oldest known rocks in the Shield are c. 3.2 Ga in age. Rocks of the age 3.2–2.7 Ga are present in the Archaean nuclei of the shield and they are composed of tonalitic gneisses and migmatites. The oldest documented magmatic and metamorphic event took place at c. 2.84 Ga (Nurmi & Sorjonen-Ward 1996). The well preserved greenstone belts seem to have been emplaced after this event and were deformed and intruded by granitoids between 2.75 and 2.69 Ga. These greenstone belts form a prominent part of Finnish and Russian bedrock, but are minor in Sweden. The Hattu schist belt in the south-western part of the Archaean of Finland seems to record a collisional arc setting for the rocks at 2.75–2.72 Ga (Nurmi & Sorjonen-Ward 1996). The Archaean complexes make up parts of a Proterozoic craton sometimes referred to as the Karelian craton.

Palaeoproterozoic complexes

The post Archaean crustal growth of The Karelian craton is manifested in several epi-

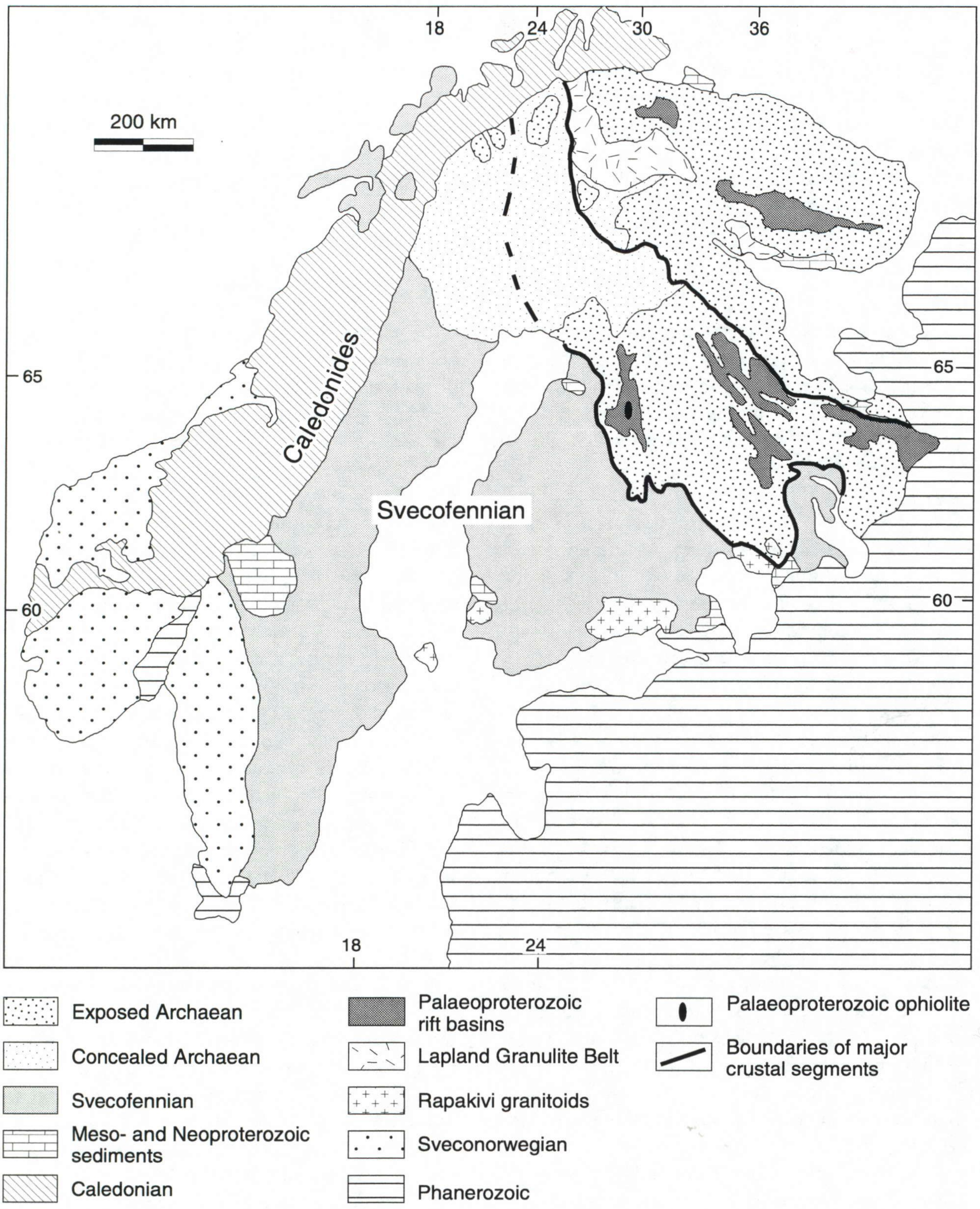

Fig. 2. Geology of the Baltic or Fennoscandian Shield (from Gee & Zeyen 1996).

sodes of sedimentation, rifting and magmatism between 2.5 and 1.9 Ga. The Lapland greenstone belt in Finland and the equivalents in Sweden occupy a large area in northern Finland and Sweden and are composed of mainly mafic volcanic rocks, with a minor felsic component. These are intercalated with sedimentary rocks which all were deposited unconformably on the Archaean basement at c. 2.5 Ga (Nurmi & Sorjonen-Ward 1996). This volcanism may have persisted to c. 2.0 Ga. Layered intrusions with Cr-Ni mineralisations were also emplaced at c. 2.4 Ga. Continued rifting caused subsidence of the Karelian craton and basins formed on the rifted Archaean craton. The sedimentary rocks deposited in the basins include quartzites, turbidites, carbonates, and graphitic schists (cf. Stephens et al. in press). Eventually at c. 1.97 Ga oceanic crust wasformed which later was partly obducted or thrust on top of the Karelian craton forming the Jormua and Outokumpu ophiolites. After this stage juvenile volcanic arcs formed at the margin of the Karelian craton and the rocks formed by this process are referred to as Svecofennian rocks.

Scattered occurrences of granitoid intrusions with an age of 2.0 to 1.9 Ga occur both in Finland and Sweden. Their tectonic significance is not fully understood and they are not described further here.

The Svecokarelian orogeny and Svecofennian crustal growth

As mentioned above Svecofennian rocks are defined as the supracrustal rocks deposited between c. 1.95 and 1.85 Ga and related intrusive rocks. The late orogenic S-type granites emplaced around 1.83–1.80 Ga in Sweden and the late to post-Svecokarelian, c. 1.80 Ga, A- to I-type alkaline Revsund and TIB granitoids in Sweden are also included in the Svecofennian rocks. In Finland there is strong evidence for a peak-metamorphic event at c. 1.88 Ga (Korsman 1988) and this age of metamorphism is also described from northernmost Sweden (cf. Skiöld 1988). However, in the Skellefte district and southwards in Sweden and in southern Finland the age of peak metamorphism is between 1.84 and 1.80 Ga (cf. Billström & Weihed 1996 and refs. therein).

A number of Palaeoproterozoic volcanic provinces such as the Vihanti–Pyhäsalmi area and the Tampere Schist Belt in Finland and the Bergslagen area and Skellefte District in Sweden, are bordering the Karelian craton. These areas are probably remnants of volcanic arc systems that were accreted to the Karelian continent shortly after the emplacement of the rocks. All these areas are extensively mineralised and the different character of the metallogeny in each area reflect variations in the tectonic setting. It is likely that the earliest volcanic arc to be accreted onto the Karelian craton was the Vihanti–Pyhäsalmi area which is 1.93–1.90 Ga in age. The rocks of the coeval Tampere Schist Belt and the Skellefte District have recently been proposed to be part of the same volcanic arc system (Ekdahl 1993). All rocks in the Skellefte district have primitive eNd values which indicate only minor incorporation of older material into the source for these rocks. In contrast the Tampere Schist Belt greywackes contains a marked component of older partly Archaean material (Huhma, 1987). The existence of a felsic basement only slightly older than the volcanic rocks is possible in the Skellefte District and the tectonic environment in which the rocks were emplaced may have resembled the present day Okinawa through. In contrast, Allen et al. (1996b) interpreted the extremely felsic Bergslagen area as part of a continental arc system with shallow marine basins between land areas. The rocks are also more alkaline in character than the Skellefte rocks and the metallogeny is characterised by different types of iron ores which do not exist in the Skellefte district. The so called Leptite belt of south-western Finland which contains several small iron deposits and Zn-Cu-Pb deposits (the Orijärvi–Aijala deposits) has long been considered as an eastern continuation for the Bergslagen region in Sweden.

At the same time as the areas discussed above formed, the magmatism seems to have continued in the rifted craton to the north, but the opened oceans were probably partly closed after 1.95 Ga as indicated by the Jormua and Outokumpu ophiolites. In the Kiruna area the greenstones are unconformably overlain by c. 1.89 to 1.87 Ga old felsic volcanic rocks which may manifest a time of convergent plate movements and closing of the oceans and rift basins.

Post-Svecokarelian crustal growth

All supracrustal rocks were intruded by granitoids at c. 1.89–1.85 Ga, both in Finland and Sweden. For example, the Central Finland Granitoid Complex is dominated by intrusions of this age. These rocks are often granodiorites to tonalites and appear to be comagmatic with at least some of the coeval volcanic rocks. The granitoids have also been the subject for exploration since they are known to contain porphyry type Cu and Au deposits and shear zone hosted

Au deposits both in Finland and Sweden (cf. Weihed 1992b and references therein). One such occurrence, Kopsa, will be shown on the field trip. Subsequent magmatism is closely related to peak metamorphism at 1.84–1.80 in Sweden when the Svecokarelian metamorphism peaked in the Skellefte district and areas to the south. The area between the Skellefte and Bergslagen districts is characterised by high-grade ortho- and para-gneisses. Minimum melt granites and pegmatites are common among these migmatites and in some areas they form homogeneous granitoids like the Skellefte- and Härnö granites.

At c. 1.80–1.78 Ga major calc-alkaline batholiths referred to as the Revsund granitoids and the Trans-Scandinavian Igneous Belt (TIB), were emplaced at the western border of the craton. This magmatism seems to have continued intermittently to c. 1.65 Ga. Scarce supracrustal rocks are associated with these batholiths, e.g. the Duobblon and early Dala volcanic rocks, and the Småland porphyries in Sweden.

Younger anorogenic magmatism in the Fennoscandian shield includes the Mesoproterozoic (1.65–1.55 Ga) Rapakivi granites in both Finland and Sweden as well as mafic dyke swarms which were emplaced at different times after the Rapakivi intrusions. All of these rocks intruded a cratonized crust.

Metallogeny

The Fennoscandian Shield hosts several world class ore deposits. Unlike other shield areas the Proterozoic, and not the Archaean, has so far been the main contributor to metals in the Fennoscandian Shield. In Finland the Outokumpu copper mine was the base for the Outokumpu mining company. Other famous deposits include the Vihanti and Pyhäsalmi massive sulphide deposits and the Kemi chromite deposit. In Sweden, world class deposits include the Kiruna iron ore, the Boliden and Falun massive sulphide ores, and the low-grade copper ore at Aitik. A good recent review on Finnish metallogeny is found in Nurmi and Sorjonen-Ward (1996).

Six base metal and gold mines are currently in operation in Finland (Fig. 3): Kemi, Pyhäsalmi, Mullikkoräme, Hitura, Orivesi, and Pahtavaara. This field trip will examine the Pyhäsalmi and Mullikkoräme massive sulphide deposits (see below). The Hitura mine is the only operating Ni-mine and it is one of several early Proterozoic Ni-deposits found in mafic-ultramafic rocks, most of which are situated in central and eastern Finland. The old term Raahe–Ladoga zone is widely used to describe the NW-SE trending zone where most of the Finnish sulphide deposits are located. The Orivesi gold deposit is situated in south-western Finland in the Tampere schist belt (Fig. 3).

Traditionally Sweden has been divided into three main mining areas, namely the Bergslagen area in the south, the Skellefte district in northern Sweden, and the Norrbotten region in northern-most Sweden (Fig. 4). Today, only two mines are in operation in Bergslagen: the zinc-lead deposit Zinkgruvan near Åmmeberg and the zinc-lead-copper deposit Garpenberg. A good review on metallogeny and volcanology of the Bergslagen district is found in Allen et al. (1996b). In the Norrbotten region the iron mines

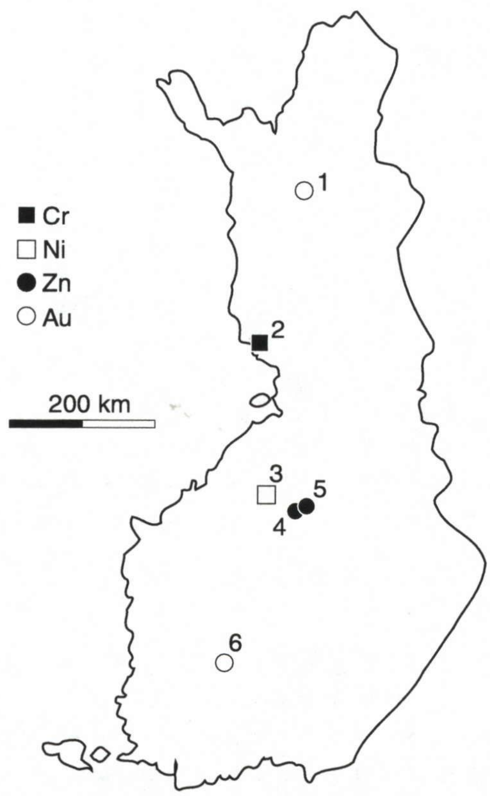

Fig. 3. Active mines in Finland. 1=Pahtavaara, 2=Kemi, 3=Hitura, 4=Pyhäsalmi, 5=Mullikkoräme, and 6=Orivesi.

at Kiruna and Malmberget are still big producers of iron from underground operations, while the Aitik open pit mine is a low-grade disseminated copper-gold deposit. In the Skellefte district massive sulphide ore is extracted from six mines (Långdal, Kankberg, Åkulla Östra, Renström, Petiknäs, and Kristineberg) and gold ore is mined in one open pit operations at Björkdal and underground at Åkerberg. The closed Enåsen gold deposit in Sweden which is situated in the Bothnian basin south of the Skellefte district has been interpreted as a metamorphosed and deformed high-sulphidation epithermal ore body (Hallberg 1994). In the Caledonian orogen the only mine still operating is the Laisvall lead-zinc mine.

The genesis of most of the deposits mentioned above, apart from the deposits in the Skellefte District and the Pyhäsalmi-Mullikkoräme area, will be the themes for other field trips and will not be discussed further here.

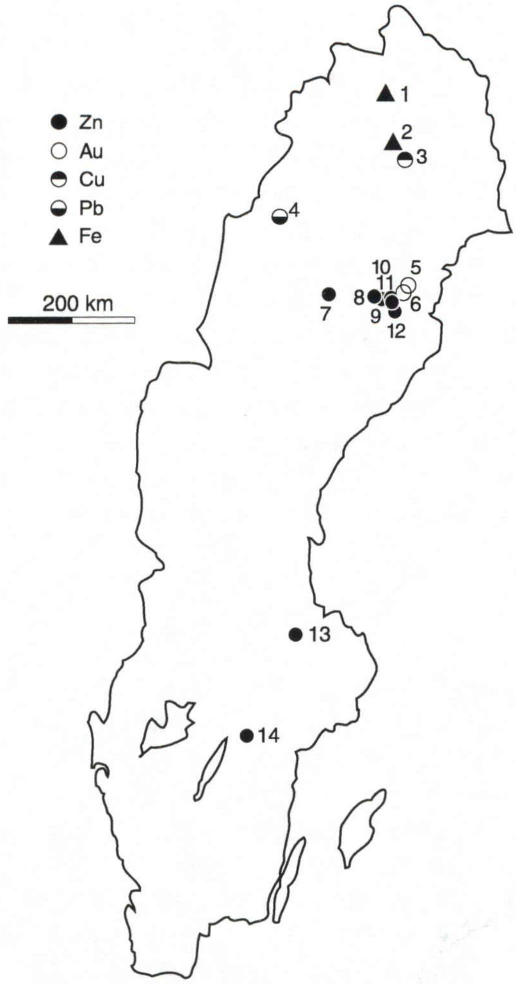

Fig. 4. Active mines in Sweden. 1=Kiruna, 2=Malmberget, 3=Aitik, 4=Laisvall, 5=Åkerberg, 6=Björkdal, 7=Kristineberg, 8=Petiknäs, 9=Renström, 10=Kankberg, 11=Östra Åkulla, 12=Långdal, 13=Garpenberg, 14=Zinkgruvan.

THE SKELLEFTE DISTRICT

The Skellefte district (Fig. 5) is a loosely defined area, approximately 150 x 50 km in size, in northern Västerbotten and southern Norrbotten in the northern part of Sweden. It is extremely rich in mineral occurrences and today 5 underground mines and one open pit are in operation on VHMS-ores, and the Björkdal gold-lode deposit is mined in an open pit operation while the Åkerberg gold-lode deposits is mined underground.

History of mining

The name "Skellefte district" stems from Högbom (1899) who, in a note for the Geological Society, described his trips to the interior of northern Västerbotten and southern Norrbotten. However, the record of mineral exploration dates back to the early eighteenth century. The brief historical outline of premodern mining below is based largely on the summary presented in Tegengren (1924).

The first record of mining is from 1704 when copper ore was mined in the north-eastern part of the Skellefte district at Storkågeträsk (Hermelin

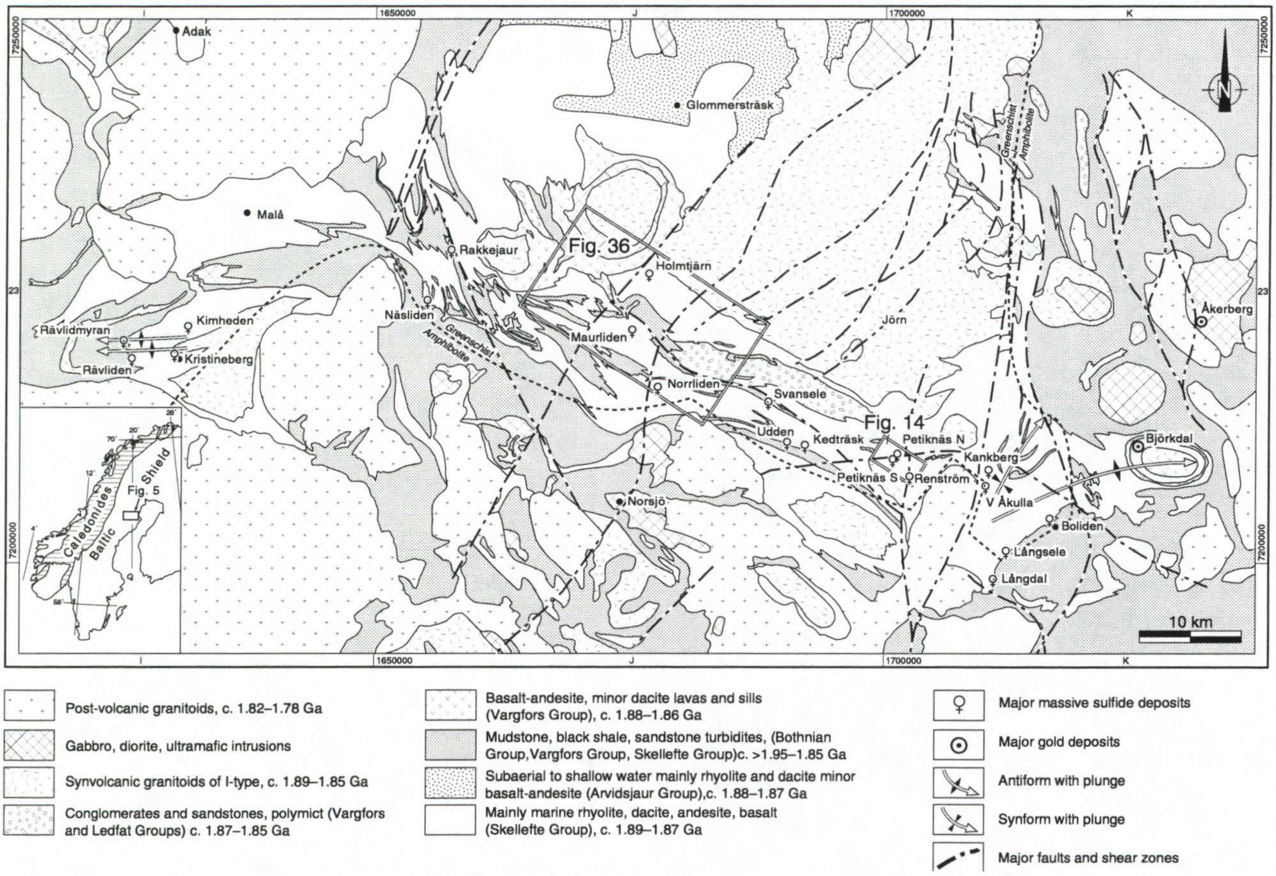

Fig. 5. Geology of the Skellefte district. Modified from Allen et al. (1996).

1804). Scattered short-lived trial mining seems to have prevailed throughout the eighteenth century. Around 1850 attempts were made to mine silver east of the town of Skellefteå (Moröns silvergruva). I early 1900 gold was discovered at Krångfors and this resulted in intensified exploration in the area. Several minor gold-arsenic mineralisations were discovered as well as Fe-Cu sulphide mineralisations. However, none of the mineralisations were found to be economic and in 1908, only the Krångfors claim was still held.

The modern history of the Skellefte district began after the first world war when the Kristineberg ore (Fig. 5) was found in 1918. At this time, exploration in the area was carried out by Centralgruppens Emmissionsbolag (predecessor to Boliden AB) and the Geological Survey of Sweden. The improvements of electrical and electromagnetic geophysical exploration methods by Lundberg and Nathorst were a big success and led to the discovery of several base metal sulphide ores during 1920–1922. Mensträsk, Näsliden, Rakkejaur, and Bjurfors were the major discoveries. In 1921 Centralgruppens Emmissionsbolag investigated an area where ore boulders had been found and trenches dug near the village of Svanfors. They used the new electrical methods and found some interesting anomalies 2.5 km north of the village of Bjurliden (misnamed Boliden on topographic maps). They decided to drill these anomalies and intersected auriferous arsenic-copper ore on the 10th of December 1924. They had discovered the Boliden ore. Because the name Boliden occurred on the topographic maps the name remained and the Centralgruppens Emmissionsbolag became the Boliden Mining Company now Boliden AB.

Another discovery of auriferous base-metal ore in Holmtjärn was made during the 1920's in the central part of the district, but the Boliden ore was the only to be mined continuously until the Rävliden mine in the west opened in 1936.

Of the mines operating today, the Långdal ore was discovered in the 1930's and put in production 1967, the Renström ore was discovered in the mid 1920's and put in to production in 1952, the Kankberg ore was discovered in the mid 1940's and production started 1991, the Petiknäs ore was discovered in 1986 and production started in 1992, and finally the

Kristineberg mine started production in 1940. The gold deposits Björkdal and Åkerberg were discovered in 1985 and 1988 and put into production in 1988 and 1989, respectively.

Regional geology

The Skellefte district forms part of the Svecofennian c. 1.90–1.85 Ga supracrustal sequence and associated intrusive rocks in the northern part of Sweden. The area is dominated by a thick pile of felsic volcanic units which host over 85 pyritic base metal deposits (cf. Allen et al. 1996). The geology of the district has been the subject of numerous papers since Högbom (1899) first gave the area its present name. In thischapter, an overview of stratigraphy, rock types, volcanic facies, geochemistry, ages and provenance of rocks, and the structural and tectonic evolution is presented.

Stratigraphy, rock types, and volcanic facies

The Skellefte District is a loosely defined area which mainly is defined as the area containing ore-bearing, mainly submarine felsic volcanic units, between Kristineberg in the west and Boliden in the east (Fig. 5). To the north, the district is bordered by the low grade, shallow-water to subaerial, Arvidsjaur volcanic rocks and to the south by the high-grade gneisses and migmatites of the Bothnian basin (Fig. 5).

Many stratigraphic schemes have been proposed for the Skellefte district and the interpretation of the relationship between the supracrustal rocks and different intrusive suites have also changed through time. The main debate has been the relationship between supracrustal rocks and different intrusive suites as well as the relationship between different sedimentary and volcanic rocks. Already early this century, geologists (cf. Eklund 1923, Tegengren 1924, Högbom 1937, Gavelin 1939) recognised a lower, mainly felsic volcanic unit which was called the Skellefte volcanic rocks. These were thought to be overlain by an early sedimentary sequence, often called the "Skellefte sediments" and a later coarse clastic unit called the Vargfors Group. It was generally accepted that the Skellefte volcanic rocks were intruded by an older granitoid suite, the Jörn granitoids. The relationship between the Jörn granitoid and younger supracrustal units as well as the relationship between the Revsund granitoids and these youngest units was a matter of debate. Kautsky (1957) proposed that there were at least two stratigraphically different schist units within the so called Maurliden and Elvaberg series and hence indicated that a more dynamic view on the lateral extent of different rocks units was necessary. The first dynamic approach was made by Helfrich (1971) who also recognised lateral as well as vertical facies changes. In 1980 Lundberg published a paper where the relative ages of rocks for the first time was in agreement with the present view. In all these stratigraphic schemes a major unconformity between the Skellefte Group and Vargfors Group was proposed with the Vargfors Group resting undeformed on top of the steeply dipping strata of the deformed Skellefte Group. This has been challenged in the last years by Weihed et al. (1992) and Allen et al (1995, 1996). In their view both the Skellefte and Vargfors Groups contain the same tectonic fabrics and there is no major time difference between the two units (see below).

The exact stratigraphic position of the Arvidsjaur Group has long been a matter of controversy. The relationship to different generations of granitoids have also been a matter of argument. Högbom (1937) for example placed the Arvidsjaur Group (Arvidsjaur porphyries) below the Vargfors Group which was also considered younger than the Revsund granite. This view was shared by Gavelin (1955), while Kautsky (1957) for the first time considered the Revsund granitoids younger than the Vargfors Group, but still regarded the Arvidsjaur Group as older than the Vargfors Group. Allen et al. (1996) regarded, on new age evidence and facies analysis of clastic rocks, the Arvidsjaur Group as a lateral facies variety to the Vargfors Group in the Skelleftedistrict. They concluded that at least the top of the Arvidsjaur Group is coeval with Vargfors sedimentary rocks in the Skellefte district.

In this guide book we adopt the scheme of Allen et al. (1996) and the different units are described below according to the generalised stratigraphy presented in Figure 6 from Billström & Weihed (1996) after Allen et al. (1996).

The Skellefte Group

The lower-most volcanic units in the Skellefte district are named the Skellefte Group (cf. Allen et al. 1996). The base of this group is not exposed and therefore there is no known basement within the Skellefte District. However, 100 km to the south, within the Bothnian basin, an area with mafic and subordinate felsic volcanic rocks is intruded by granitoids which are c. 1.95 Ga in age (cf. Wasström 1993, 1996). These could constitute a basement to the Skellefte Group. The possible existence of a basement is discussed in more detail below. The total thickness of the volcanic rocks of the Skellefte Group is greater than 3 km in the Petikträsk area (Allen et al. 1996).

The internal stratigraphy of the Skellefte Group is extremely variable (Fig. 6), and the main rock types are volcaniclastic rocks, coherent subvolcanic porphyritic intrusions, and lavas. Allen et al. (1996) also include all intercalated sedimentary rocks which range in composition from mudstone to breccia-conglomerate in the Skellefte Group. Some coarser sedimentary rocks are lime-cemented and only very rare, minor limestones occur within the Skellefte Group.

The composition of the volcanic rocks is mainly felsic in character with rhyolites and rhyodacites dominating. However, the composition of rocks vary considerably between areas as can be seen in Figure 7 where the relative abundance of rock compositions are estimated from different domains (Allen et al. 1996).

The Vargfors Group

Overlying the Skellefte Group is a succession of fine to coarse grained sedimentary rocks with some intercalations of volcanic rocks. This succession is named the Vargfors Group. The stratigraphic position of this group has been accepted for a long time. In some publications the Vargfors Group and some other units are referred to as part of upper Svecofennian (cf. Lundqvist 1991). Previous authors (e.g. Lundberg 1980, Claesson 1985, Rickard 1986) have had the opinion that the Vargfors Group is unconformably overlying the Skellefte Group. Recent mapping, however, shows that the relationship between the Skellefte and Vargfors Groups is complex, gradational and interfingering (cf. Allen et al. 1996). Both conformable and disconformable contacts occur between the Skellefte and Vargfors Groups and also within the Vargfors Group. This indicates that there is no structural break between the two groups. The total thickness of the Vargfors Group in the Nicknoret area exceeds 1 km.

Allen et al. (1996) divide the Vargfors Group into the *Mensträsk conglomerate* which is a volcanic breccia-conglomerate consisting mainly of Skellefte Group clasts (including the Mensträsk breccia of Kautsky 1957), the *Elvaberg Formation* which is composed of argillitic sedimentary rocks with varying abundance of sandstone and breccia interbeds, (corresponding to the Elvaberg slates and Phyllite Series of previous workers), the *Abborrtjärn conglomerate* (Kautsky 1957) which is a polymict conglomerate and sandstone with abundant Jörn GI-type granitoid clasts and Skellefte Group volcanic clasts, the *Dödmanberg conglomerate* which is a conglomerate (and sandstone) with a range of clast types including Arvidsjaur Group volcanic and sedimentary rocks, mafic volcanic rocks, granitoids, vein quartz and jasper, and *the Gallejaur Volcanic rocks* consisting of moderate- to high-Mg basalt lavas, intrusions, and volcaniclastic rocks (the Vargfors Andesite of Kautsky 1957), and other subordinate basalt, andesite, dacite, rhyolite, and interbedded sedimentary rocks.

The Bothnian Group

Rocks of the Vargfors Group grades into high grade para-gneisses and migmatites of the Bothnian basin which have been termed the Bothnian Group by Allen et al. (1996). Stratigraphical interpretations of these high grade rocks are difficult or impossible, but south of the Skellefte District, rocks of the Elvaberg Formation seem to grade into higher-grade equivalents south-wards. The base of the Bothnian Group is, however, unknown and only indirect observations based

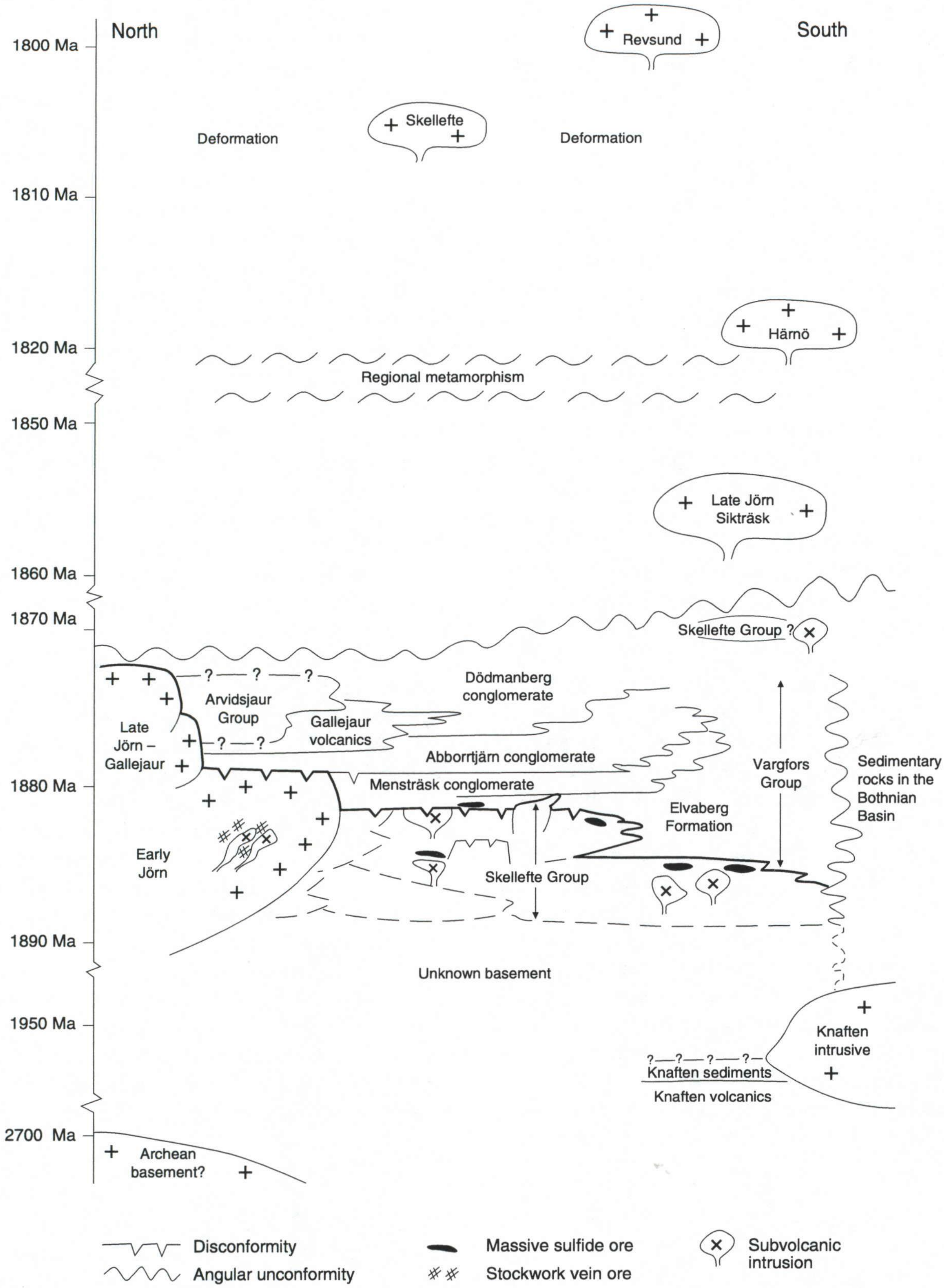

Fig. 6. Stratigraphy of the Skellefte district. Modified from Billström & Weihed (1996) after Allen et al. (1996).

on the age of intruding granitoids can be made. The total thickness of the Bothnian Group is in the order of 10 km in the Västernorrland county (there called the Härnö Formation) about 300–400 km south of the Skellefte District (cf. Lundqvist 1991).

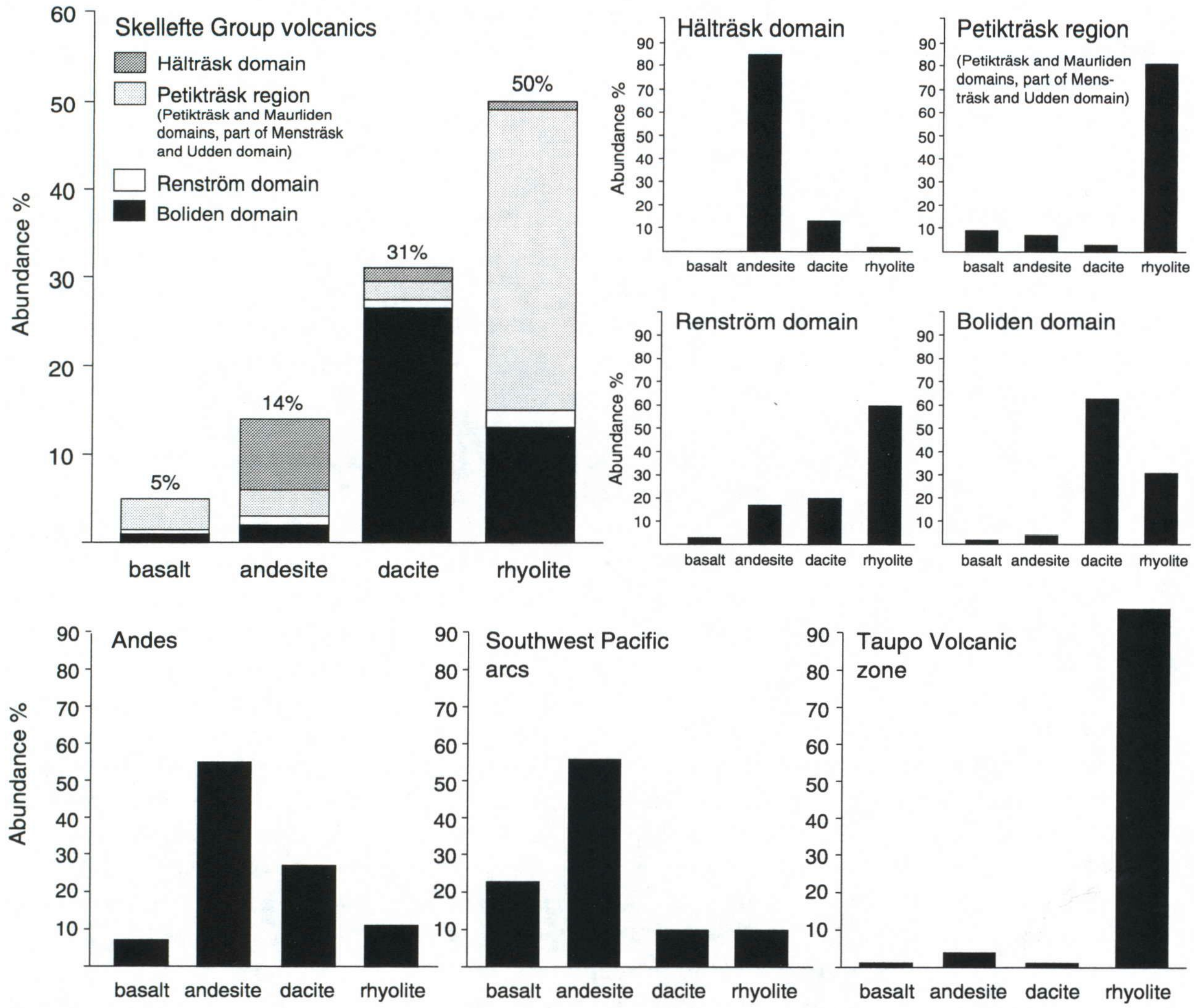

Fig. 7. Abundance of different rock types in different areas of the Skellefte district, compared to abundance in modern areas. From Allen et al. (1996).

The Arvidsjaur Group

The Arvidsjaur Group is a lithologically rather loosely defined term for the supracrustal rocks that outcrop north and north-west of the Skellefte district. The term Arvidsjaur district (i.e. Arvidsjaur *fältet* in Swedish) was used by Grip (1946) for this area of low metamorphic grade. The supracrustal rocks are generally composed of porphyritic volcanic lavas, subvolcanic intrusions, and tuffs. The common occurrence of welded ignimbrites and accretionary lapilli indicates that the depositional environment of many of these volcanic rocks was shallow water or subaerial. Spectacularly well preserved areas are the Rakkur and Hej areas (see below day 2). Subordinate sedimentary rocks are intercalated with the subaerial volcanic rocks of the Arvidsjaur Group. The rocks of the Arvidsjaur Group are often oxidised and red in colour in contrast to the grey colour of the Skellefte Group, indicating deposition in subaerial or shallow water. The chemical composition is also distinct (see below).

Intrusive rocks

The north central part of the Skellefte district is occupied by a zoned batholith of granite to gabbro called the Jörn Granitoid Complex (Wilson et al. 1987). These rocks haveages between 1.89 and 1.87 Ga. The batholith is composed of four distinct intrusive phases GI to GIV with GI being the oldest and outer phase and GIV the central and youngest phase. GI is a heterogeneous, medium-grained tonalite to granodiorite, often with large blue quartz phenocrysts. GII is an even- and medium-grained granodiorite to tonalite, GIII is a reddish medium- to coarse-grained granite, while GIV is a medium-grained grey-red granite. The GI phase contains porphyry type Cu-Au deposits (cf. Weihed et al. 1987, Weihed 1992a, Weihed & Fallick 1994) like the Tallberg deposit (see below).

Deformed bodies of Jörn granitoids occur in several places in the Skellefte district and the Jörn intrusives have long been regarded as comagmatic with the Skellefte Group volcanic rocks. This relationship is, however, not confirmed more than as an overlap in age of the two rock types. Intrusive porphyries within the Jörn batholith texturally resemble the coarser varieties of subvolcanic intrusion within the volcanic pile. The intrusive porphyries have been dated at 1886±15/9 Ma (Weihed & Schöberg 1991) which is within error the same age as the Skellefte Group volcanic rocks.

The Gallejaur intrusion is situated immediately west of the Jörn Granitoid Complex. The rocks range from gabbro to monzonite in composition and are intimately related to the mafic volcanic rocks of the Vargfors Group. It is often difficult to distinguish the intrusive and extrusive phases. Age determinations on both the Gallejaur intrusion and the Vargfors Group are identical within error limits c. 1875 Ma. The Gallejaur intrusion may be related to the so-called perthite-monzonite suite to the north (cf. Skiöld 1988) which to the north post-dates the main deformation.

To the south and east of the Skellefte district the high grade gneissic and migmatitic equivalents to the supracrustal rocks in the Skellefte District are intruded by minimum melt granitoids. The migmatites are often invaded by leucocratic neosome which grades into pegmatites and granitic material. The granites associated in space with these high grade rocks are referred to as Skellefte granites and have ages around 1.80 Ga (e.g. Weihed & Persson in prep, Romer & Smeds 1994). Similar granites to the south are referred to as Härnö granites (e.g. Lundqvist 1991, Claesson & Lundqvist 1995).

The Revsund intrusive rocks form part of a large granitoid batholith belt which borders the Svecokarelian orogeny to the west. If the TIB rocks are included it means that the batholith belt is over 1500 km long and in places over 200 km wide (Fig. 2). The Revsund batholith is composed of many discrete, often rounded plutons. The coarse feldspar porphyritic, granitoids are calc-alkaline and display a monzonitic trend from diorite to granite. Rare occurrences of charnockitic black granites are probably early plutons which have been heated by subsequent magmas. The age of the Revsund granitoids vary between 1.80 and 1.78 Ga and they are considered to have risen from a lower crustal level as hot dry melts (cf. Claesson & Lundqvist 1995).

Geochemistry

Modern geochemical work covering the entire Skellefte District is relatively scarce. Published papers on the volcanic rocks include Claesson (1985), Vivallo (1987), Vivallo & Claesson (1987), and Claesson (1994). Short reviews can be found in Bergström & Weihed (1991), Vivallo & Willdén (1988), Vivallo & Weihed (1989), Allen et al. (1995), and Bergman Weihed et al. (1996). Rocks of the Skellefte Group have previously been considered bimodal in the eastern and western parts of the district whereas the central part was thought to display no such bimodality (cf. Vivallo & Claesson 1987). Claesson (1994) regarded the lower Skellefte Group as bimodal and calc-alkaline. He further stated that the basalts within the Skellefte Group are tholeiitic in the east, mildly tholeiitic in the central part, while in the western part the mafic volcanic rocks are more calc-alkaline in character. Andesites, typical of modern island arcs, are common in the lower part of the Skellefte Group in the west, but absent in the central part and scarce in the east (Claesson 1994). The presence of high-Mg ultramafic rocks in the upper part of the Skellefte Group was regarded by Claesson (1994) as representing a transition to an "inter- or back-arc regime". These rocks were considered to be related to arc extension and rifting which may be in accordance with the ideas of Allen et al. (1996) of an extensional arc as the depositional environment of the massive sulphide deposits in the Skellefte District.

In a small study of the geochemical composition of host rocks to ores made by Allen et al. (1995) no obvious bimodality in the composition of volcanic rocks could be found.

They suggested that almost all sampled rocks in the study were calc-alkaline volcanic arc-type rocks. Allen et al. (1996) presented histograms of the relative abundance of different rock types in different domains illustrating a fundamental difference in evolution between different parts of the Skellefte district from extremely felsic centres in the Petiknäs areas to andesite dominated domains like Hälträsk (Fig. 7). In Figure 8, rocks from different domains are plotted in common classification and discrimination diagrams.

In contrast to the Na-rich submarine volcanic rocks of the Skellefte Group, the Arvidsjaur Group volcanic rocks are subalkaline and have a higher potassium content at similar SiO_2 values (cf. Lundberg 1980).

The early Jörn granitoids which are coeval with the Skellefte Group volcanic rocks are tonalitic to granodioritic in composition and calcic to calc-alkaline in character (cf. Wilson et al. 1987, Weihed 1992a). The relationship between the subvolcanic intrusions in the Skellefte Group and the high-level porphyritic intrusions within the Jörn suite is still an open question. The subvolcanic intrusions are generally more felsic in character and unpublished preliminary results indicate that they are distinctly different in REE-composition from the high-level intrusions of the Jörn suite, and thus are not genetically related.

Age constraints and provenance of rocks

Despite the economic importance of the area, relatively few age determinations have been carried out on rocks in the Skellefte district. Most recently, Billström & Weihed (1996) published new data on the Skellefte district. Table 1 summarises U-Pb age determinations on rocks in the Skellefte district.

The age of volcanic rocks of the Skellefte Group is constrained from only three U-Pb zircon ages. In the eastern part of the district, the Bjurvattnet sample represents a subvolcanic quartz-phyric intrusion emplaced into the lower part of the Skellefte Group volcanic rocks. The intrusion is interpreted to be within error limits the same age as the intruded volcanic rock. The age is 1884±6 Ma (Billström & Weihed 1996). In the central part of the district, two U-Pb zircon dates represent the upper part of the Skellefte Group. The age 1882±8 Ma from Nicknoret (Welin 1987) is poorly described in the literature, but is apparently from the uppermost part of the Skellefte Group north of the Skellefte river in the central part of the district. A new age determination from the south-central part at Melestjärn gave an age of 1889±4 Ma for the upper-most part of the Skellefte Group (Billström & Weihed 1996). There are no age determinations on volcanic rocks of the Skellefte Group from the western part of the district. Although there are no good age determination on the lower part of the stratigraphy of the Skellefte Group, it seems plausible that the entire group span the time interval between 1890 and 1880 Ma.

So far only one age determination has been carried out on the Vargfors Group. The sample was taken from a felsic ignimbrite intercalated with mafic volcanic and sedimentary rocks in the middle part of the Vargfors Group north-west of Nicknoret. The age of this ignimbrite is 1875±4 Ma (Billström & Weihed 1996). This age is c. 5 million years younger than the ages of the Skellefte Group and confirms that the Vargfors Group is only slightly younger.

The oldest intrusive rocks in the district are the Jörn granitoid rocks which have been dated in several localities. Wilson et al. (1987) dated the oldest outermost GI phase of the Jörn batholith at 1888±20/14 Ma, the GII at 1874±48/26 Ma, and the GIII at 1873±18/14 Ma. The ages are poorly constrained but indicate that at least the GI is coeval with the volcanic rocks of the Skellefte Group. The question remains whether the GII-GIV may be related to Vargfors and Arvidsjaur type rocks rather than to Skellefte Group volcanic rocks as indicated by the ages. The age of the Antak granite, 1879±15/12 Ma (Kathol & Persson, in press), which is comagmatic with parts of the Hej volcanic rocks, belonging to the subaerial Arvidsjaur Group, also indicates that the younger Jörn type intrusions may be related to the Arvidsjaur magmatism.

Weihed & Schöberg (1991) dated intrusive porphyries in the Tallberg deposit in the Jörn GI granitoid at 1886±15/9 Ma. Recent age determinations on deformed Jörn type granitoids in the southern part of the district indicate that the calc-alkaline magmatism con-

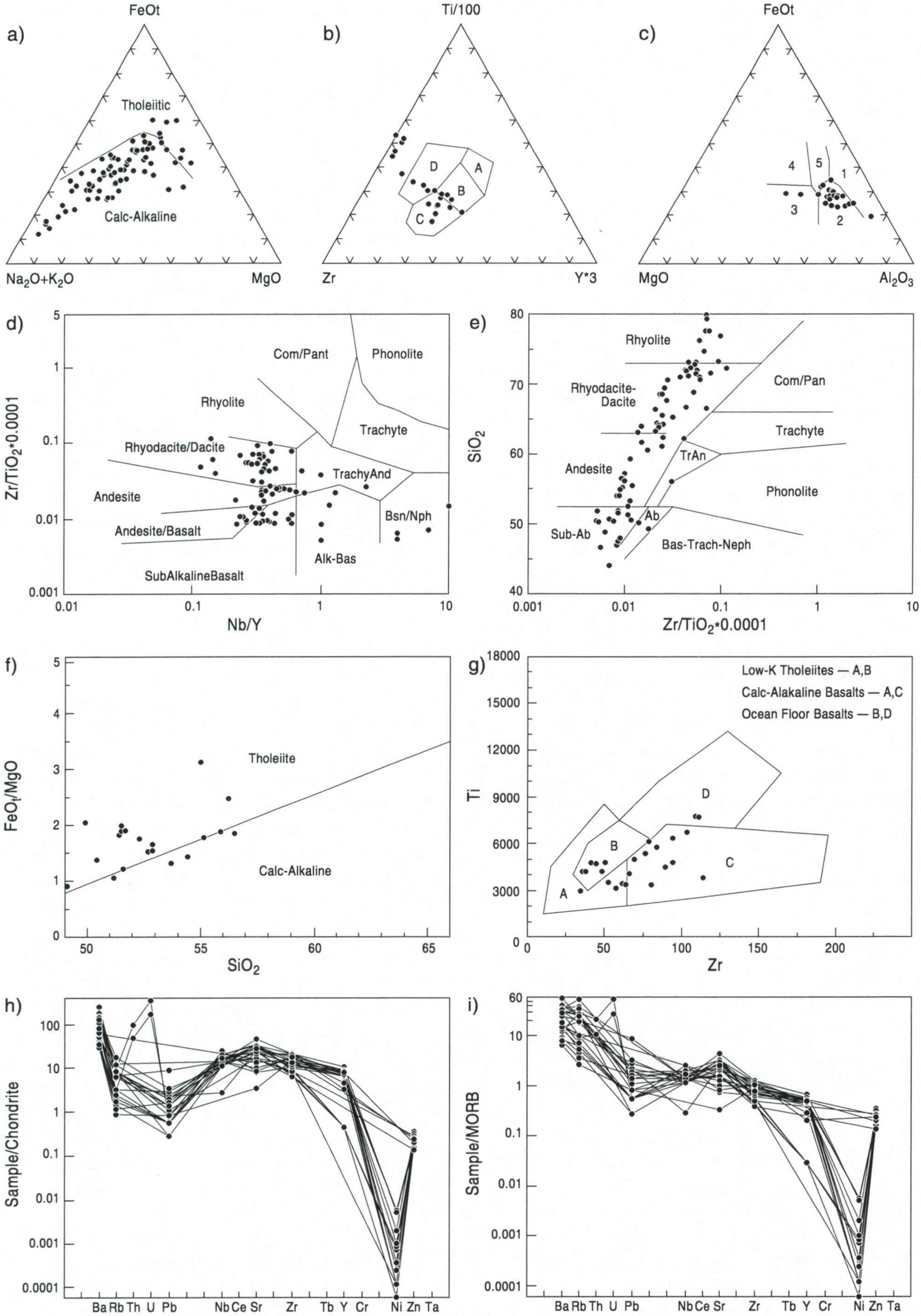

Fig. 8. Geochemical diagrams of rocks in the Skellefte district. In diagrams a), d), and e) 75 analyses from the central and eastern Skellefte district are plotted in conventional classification diagrams. In diagrams b), c) and f–i) basalts only from the same areas are plotted. For discussions see text.

Table 1. Age constraints on different events within and around the Skellefte District.

1.88–1.87 Ga	subaerial volcanism to the north (Arvidsjaur Group), shallow marine to subaerial sedimentary and mafic volcanic rocks in the Skellefte district (Vargfors Group)
1.89–1.88 Ga	submarine volcanism of the Skellefte Group, late stage volcanism and subvolcanic intrusions in Boliden at 1.86 Ga?
c. 2.0–1.85 Ga	I-type intrusions, possibly basement to Skellefte volcanism (Björkdal pluton, c.1.90 Ga)
>1.95 Ga	pre-Svecofennian supracrustals (Knaften) 100 km to the south: turbidites and mafic volcanic rocks, possible basement?
c. 2.7 Ga	exposed Archaean <100 km north of the Skellefte district

tinued to about 1.85 Ga as indicated by the age determinations on the Sikträsk intrusion at 1859±3 Ma (Weihed & Vaasjoki 1993) and 1854±9 Ma (Billström& Weihed 1996). This opens the possibility for volcanism at this age and a single zircon Pb-Pb evaporation age on a coherent feldspar porphyritic dacite from the Boliden area in the eastern part of the district yielded an age of 1869±15 Ma (Bergman Weihed et al. 1996). Bergman Weihed et al. (1996) also report a monazite age of 1852±4 Ma for the alteration system surrounding the Boliden deposit.

The minimum melt granites of the Skellefte and Härnö type have been sparsely dated, partly because of problems with inherited zircons. A monazite age for the Härnö granite at 1822±5 Ma is presented by Claesson & Lundqvist (1995). Unpublished data for the Skellefte granite by Weihed & Persson (in prep.) indicates that titanites in this rocks are 1798±4 Ma. Recently, Romer and Nisca (1995) published a titanite age of a skarn, 1825±4/3 Ma, from the Burträsk area south of the Skellefte district which they regarded as part of a hornfels aureole surrounding a calc-alkaline granitoid of the Jörn type and hence indicating the age of intrusion of the granitoid. However, this area is in middle to upper amphibolite facies, and the skarn related to peak regional metamorphism. In addition an unpublished age of c. 1.89 Ga for the intrusion makes this interpretation questionable. A more likely interpretation is that the published age represents the age of peak-metamorphism in the area which fits well with the ages of minimum melt granites at 1.82 to 1.80 Ga.

The alkaline to calc-alkaline Revsund type granites all have ages that fall within the age interval 1.801.78 Ga (Patchett et al. 1987, Skiöld 1988, Claesson & Lundqvist 1995). This means that they overlap in time with the minimum melt granitoids, but are derived from a deeper source, have risen and crystallised at shallower levels, while the minimum-melt granites like Härnö and Skellefte have been more static in the crust.

Basement to the Skellefte Group?

The question of the nature of the basement to the rocks of the Skellefte Group has always intrigued geologists working in the area. Several gneiss areas have been proposed to be basement to the Skellefte Group. When studied in detail, all such areas have been shown to be similar in age to the Skellefte Group. In recent years, however, several independent results indicate the possibility of basement rocks to the Skellefte Group. Wasström (1993, 1996) described volcanic rocks and associated intrusive rocks from the Knaften area c. 100 km south of the Skellefte district. The age reported by Wasström for rocks that intrude the volcanic units in the area is 1954±6 Ma, i.e. significantly older than the Skellefte Group.

Scattered occurrences of Archaean gneisses have recently been dated (cf. Lundqvist et al. 1996) less than 100 km north of the Skellefte District. These occurrences are situated along what is described by Öhlander et al. (1993) as the Archaean-Proterozoic border which was delineated by a shift from positive eNd values south of a line going from Piteå to Jokkmokk to progressively more negative values towards the north for 1.89 Ga intrusive rocks. This area also seems to correspond to a magnetic low on aeromagnetic maps.

Billström & Weihed (1996) showed that the Skellefte Group rocks have very primitive εNd values and thus do not contain any Archaean crustal material. The possibility of a slightly older basement, c. 2.0 to 1.9 Ga in age, could not be ruled out on the basis of εNd values. Allen et al. (1996) argued on the basis of the overwhelmingly felsic character of the volcanism that the Skellefte Group must have been emplaced on a rifted continental basement during arc extension. The possibility is thus still open that the primitive, early Proterozoic, c. 1.95 Ga old mafic to felsic Knaften rocks may constitute a basement to the Skellefte Group which was totally reworked during the magmatism at 1.90–1.80 Ga. The existence of 2.0 to 2.1 Ga old rocks in the area is also indicated by the presence of detrital zircons of this age in the Bothnian basin metasedimentary rocks (Claesson et al. 1993).

Tectonic and structural evolution

Only a few specifically structural studies exist from the Skellefte district. Edelman (1963) presented the structural evolution in the Kristineberg area, and structures in the central part of the Skellefte district have been presented in Bergman (1989, 1991). Some structural information, however, is also reported in publications dealing with the general geology of the area. Detailed studies of mineralisations and the structures that affect them are presented in Talbot (1988), Assefa (1990), Bergman (1992) and Bergman Weihed et al. (1996).

Two major phases of folding have been proposed for most of the area. The early folds are tight to isoclinal, with upright axial surfaces and variably plunging fold axes (cf. Weihed et al. 1992). Axial surfaces strike north-east in the eastern and western parts of the Skellefte district and west-northwest in the central part of the district. In the strongly altered volcanic rocks and the sedimentary units in the western Skellefte district, fold axes plunge 45° towards SW (Edelman 1963, Du Rietz 1953) and a crenulation cleavage developed along the axial surfaces. In the central Skellefte district, fold axes are variable. Most fold axes plunge 45° SE, but a range of plunges between SE and SW has been observed. An axial planar foliation developed as a penetrative grain shape cleavage in coarser volcanic rocks and as a crenulation cleavage in laminated tuffs and schists. Penecontemporaneous slip along the cleavage is common in this area and shear zones occur in the same general orientation as the axial surfaces. Most of these shear zones have a reverse oblique-slip movement where the southern side has moved upwards over the northern side (Bergman Weihed 1997). In the vicinity of Boliden in the eastern Skellefte district Smith (1986) and Slade (1986) report fold axes and lineations that plunge 75° E and a related axial planar grain shape cleavage. Similar observations were made in the Boliden mine (Bergman Weihed et al. 1996).

The presence of a crenulation cleavage as an axial planar cleavage to the first major observed folds indicates that an earlier foliation is present. Such a foliation is reported by Allen et al. (1996) who interpret it as a bedding parallel foliation. Folds related to this early foliation have been observed in thin sections from the sedimentaryunits west of Kristineberg (Bergman Weihed 1997) and similar observations were also made in mudstones in the central part of the Skellefte district (Bergman Weihed unpublished data). The early foliation may have formed during an early recumbent phase of folding and this has been suggested for the Långdal area by Talbot (1988) and Assefa (1990).

The second major phase of folding produced open folds with steep north- to north-east-striking axial surfaces and fold axes coaxial with the early folds. A spaced axial planar S2 crenulation cleavage developed locally and, in the central part of the Skellefte district, the intensity of the second folding increases towards the south with larger amplitude folds and a more penetrative cleavage. A number of north-striking shear zones are present in the Skellefte district and surroundings. These have a dominating reverse dip-slip movement and they are interpreted to have formed during or after the second major phase of folding (Fig. 9).

The massive sulphide deposits in the Skellefte district were deformed together with the supracrustal rocks, but some differences in structural expression can be observed between the sulphides and the surrounding volcanic pile. In general the massive sulphide ores show stronger deformation than the adjacent volcanic rocks, with shorter wavelength and higher amplitude folds, locally even with the development of mullions. Shearing is also in some instances localised to the massive sulphide ores (Talbot 1988, Bergman Weihed et al. 1996). The structures containing gold probably formed during the later stages of the second deformation. These structures involve e.g. semi-brittle shear zones in Tallberg (Weihed 1992) and en échelon quartz veins in Grundfors (Bergman 1992).

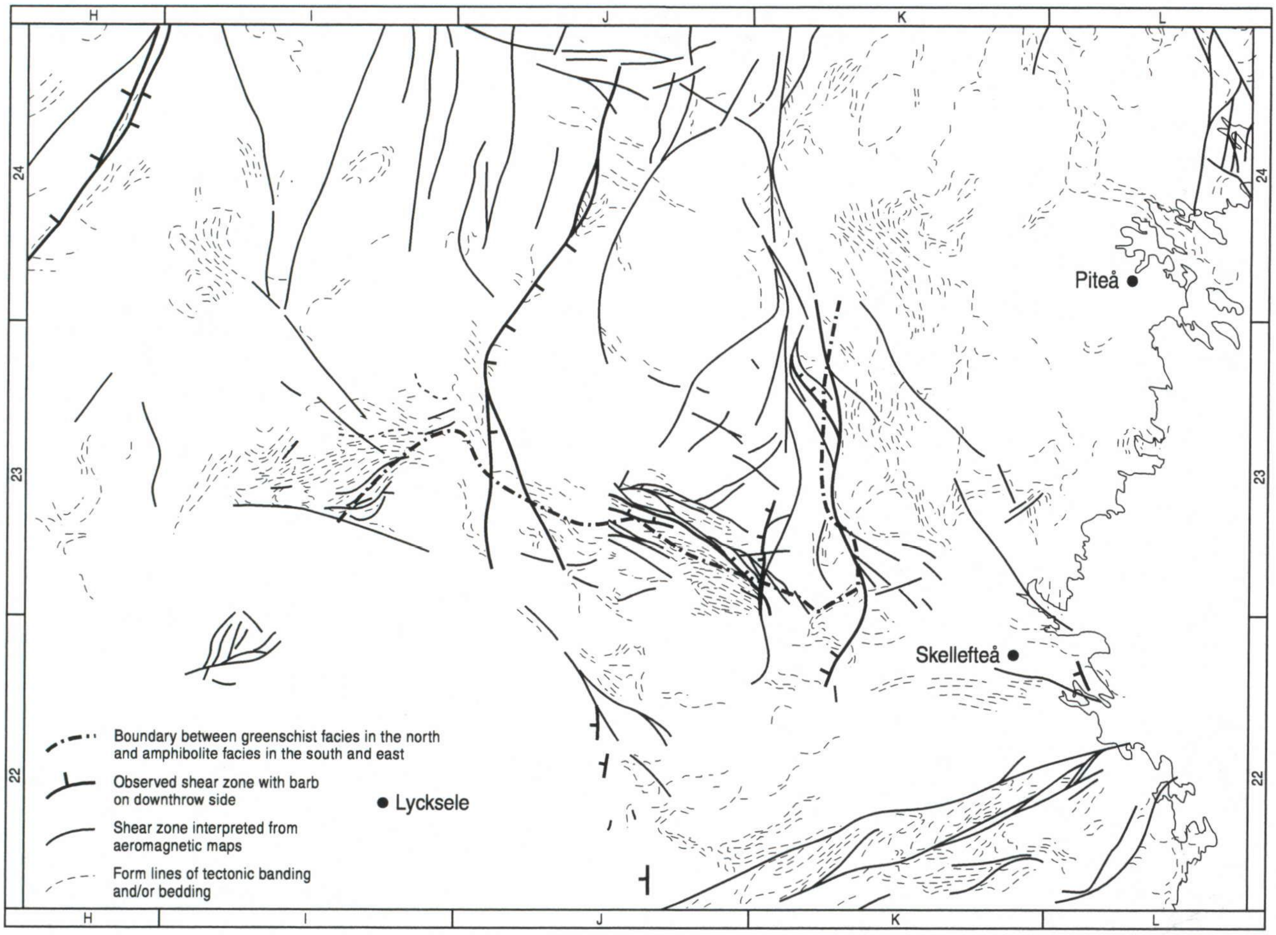

Fig. 9. Major shear zones, thrusts and form lines of foliations from the Skellefte District. From Bergman Weihed (1997).

The timing of deformation is poorly constrained. No differences in structural style can be observed between the deepest exposed level in the volcanic pile and the uppermost Vargfors sedimentary units and andesitic lavas, and many syn-volcanic intrusions (Jörn-type) show the same structures as the supracrustal rocks. This implies that the first major phase of folding was not completed by 1854 Ma, the youngest intrusive age of a syn-volcanic intrusion (Weihed & Vaasjoki 1993). The post-volcanic Revsund granite, however, cuts the first major folds and thus limits this folding event to before 1.78 Ga (Skiöld 1988). The second major phase of folding at least locally affects the Revsund granite and must thus have occurred after 1.78 Ga.

Tectonic interpretations of the area have generally focused on the Skellefte district. Hietanen (1975) proposed a subduction zone dipping north beneath the Skellefte district and after that, many similar models have been proposed (e.g. Rickard & Zweifel 1975, Lundberg 1980, Pharaoh & Pearce 1984, Berthelsen & Marker 1986, Gaál 1986, Weihed et al. 1992). A northward subduction is supported by a magnetotelluric survey (Rasmussen et al. 1987) which found a low-resistivity slab dipping north under the Skellefte district and by a seismic reflection profile in the Bothnian Bay (BABEL group 1990) which reports a north-dipping reflector east of the Skellefte district. The volcanic rocks in the Skellefte district (Skellefte Group) are thusinterpreted to represent some kind of volcanic arc. To the north, subaerial volcanic rocks (Arvidsjaur Group) represent a continental environment coeval with the volcanic arc and, to the south, the large area of metamorphosed greywackes may be interpreted as a fore-arc environment (Weihed et al. 1992). An Archaean component is detected in eNd values and as detrital zircons in the greywackes indicating that Archaean crust was present somewhere in the area. Towards the north-east around Luleå, however, deformed Archaean granitoid intrusions have recently been discovered (Lundqvist et al. 1996a). It is possible that tectonic contacts are most common between Archaean and younger rocks.

Table 2. Grade and tonnage of major VMS deposits in the Skellefte district (from Allen et al. 1996).

Deposit	Size MT	Au g/t	Ag g/t	Cu %	Zn %	Pb %	As %	S %	Host facies
Boliden domain									
Boliden	8.3	15.5	50	1.4	0.9	0.3	6.8	25	?
Kankberg	1.8	2.6	52	1.4	1.8	0.3	1.2	35	?
Långdal	4.4	1.9	149	0.1	5.8	1.7		12	Rhyolitic pumice breccia
Långsele	12.0	0.9	25	0.6	3.9	0.3	0.4	35	Rhyolitic pumice breccia
Renström domain									
Renström	9.0	2.8	155	0.8	6.5	1.5		15	Rhyolitic pumice breccia, siltstone
Petiknäs S.	6.5	2.3	108	1.1	4.8	0.9		37	Rhyolitic tuffaceous siltst, sandstone
Petiknäs N.	1.3	5.6	103	1.3	5.6	0.9	2.7	14	Rhyolitic mass flows
Udden domain									
Kedträsk	2.0	0.5	24	0.4	2.9	0.2	0.3	40	?
Norrliden	2.9	0.4	44	0.8	2.5	0.2		21	?
Svansele	2.9	0.2	4	0.3	0.3	0.1		36	Rhyolitic tuffaceous sandstone
Udden	6.7	0.7	36	0.4	4.3	0.3	0.1	24	?
Petikträsk domain									
Holmtjärn	0.5	7.4	92	0.4	4.0	0.4	0.9	22	Conglomerate, sandst
Maurliden domain									
W. Maurliden	6.9	0.9	49	0.2	3.4	0.4	1.2	39	Rhyolitic tuffaceous sandstone
Näsliden domain									
Näsliden	4.6	1.3	35	1.1	3.0	0.3	1.3	29	Calcite matrix
Rakkejaur	>17	1.0	50	0.3	2.4		1.6	26	?
Kristineberg domain									
Kristineberg	22	1.0	32	1.0	3.2	0.4		26	?
Rävlidmyran	7.5	0.8	51	1.0	3.9	0.6		18	Limestone, skarn
Adak domain									
Rudtjebäcken	4.7	0.3	10	0.9	2.9	0.1		32	?

Metallogeny of the VHMS deposits

The Skellefte district has long been regarded as a massive sulphide district with mining from complex base metal ores. To date about 15 different VHMS deposits (of which some contain several ore bodies) have been, or are presently being mined, all by Boliden AB. During the last decade intense gold exploration in the area has resulted in the mining of two gold lode deposits: Björkdal (Terra Mining AB) and Åkerberg (Boliden AB). Apart from these gold discoveries, other gold occurrences are presently being evaluated by different companies. From the VHMS mining and exploration a total of over 160 million tonnes of pre-mining ore reserves with an average of 1.9 g/t Au, 47 g/t Ag, 0.7% Cu, 3.0% Zn, 0.4% Pb, 0.8% As, and 25.6% S have been outlined (Allen et al. 1996). The Boliden AB concentrator in Boliden today treats 1.4 million tonnes of complex ore producing 8 000 tonnes of Cu, 5 000 tonnes of Pb, 60 000 tonnes of Zn, 76 tonnes Ag and 2 tonnes of Au annually. The Björkdal mine produces c. 3 tonnes of Au per year, which makes the total Skellefte district Au production c. 5 tonnes/year. Including the contribution of Au from Aitik (Norrbotten) and Garpenberg (Bergslagen) the annual production of Au in Sweden is approximately 7 tonnes.

Table 2. (continued)

Deposit	Footwall facies	Proximity to footwall volcanic vent	Hangingwall facies	Type
Boliden domain				
Boliden	? Rhyolitic + dacitic clastics, intrusions	Proximal	? Andesite lava, dacite intrusion	?VHMS + epithermal
Kankberg	Dacite lava/intrusion	Proximal	Mudstone, rhyolitic mass flows, dacite	?Subseafloor
Långdal	Rhyolitic pumice breccia	Proximal	Mudstone, turbidites, andesite, basalt sill	Subseafloor
Långsele	Rhyolitic pumice breccia, intrusion	Proximal	Mudstone, composite mass flow succession	Subseafloor + seafloor
Renström domain				
Renström	Rhyolitic pumice breccia, intrusion	Proximal	Felsic turbidites, mudstone	Subseafloor
Petiknäs S.	Rhyolitic peperitic intrusions	Proximal	Rhyolitic pumice breccia and sandstone	Seafloor/subseafloor
Petiknäs N.	Mudst, rhyolitic pumice breccia, intrusive dome	Proximal	Composite mass flow succession	Subseafloor
Udden domain				
Kedträsk	Felsic and skarny tuffaceous sandst, siltst	?	Felsic tuffaceous sandstone, siltstone	Seafloor/subseafloor
Norrliden	Basalt	?	Rhyolitic sandst and breccia	?
Svansele	Rhyolitic tuffaceous sandstone	?	Rhyolitic tuffaceous sandstone	?
Udden	Felsic and skarny tuffaceous sandst, siltst	?	Felsic tuffaceous sandstone, siltstone	Seafloor/subseafloor
Petikträsk domain				
Holmtjärn	Rhyolitic conglomerate, sandstone, sills	Proximal	Polymict conglomerate, mudstone, rhyolite sills	Subseafloor
Maurliden domain				
W. Maurliden	Rhyolitic/dacitic sills, lava	Proximal	Rhyolitic tuffaceous sandst, siltst, sills	Subseafloor, seafloor
Näsliden domain				
Näsliden	Dacitic clastics, rhyolite intrusion/lava	Proximal	Mudstone, sandstone turbidites	Seafloor
Rakkejaur	Rhyolite intrusion/ lava, breccia	Proximal	Mudstone	Seafloor/subseafloor
Kristineberg domain				
Kristineberg	Rhyolite, rhyolite porphyry ?intrusion	?	Rhyolitic clastics, ?lava	Subseafloor
Rävlidmyran	Rhyolite	Proximal	Felsic sediments	?Seafloor
Adak domain				
Rudtjebäcken	?Felsic volcanics	?	Felsic tuffaceous sandst, siltst, mudst	?

Beside the economic deposits of VHMS and gold lode type, mining has been carried out on a Ni-deposit in the NW-part of the district, Lainejaur, and on a Li-bearing pegmatitic deposit, Varuträsk, in the eastern-most part (cf. Weihed et al. 1992). Occurrences of porphyry type Cu-Au deposits have also been described (Tallberg). All these different ore types are described briefly below.

Volcanic Hosted Massive Sulphide deposits

Over 85 massive sulphide occurrences are known in the Skellefte district of which 6 (Långdal, Kankberg, Åkulla Östra, Renström, Petiknäs and Kristineberg) are currently mined. This makes it the most important mining district in Sweden today. A total tonnage exceeding 160 million tonnes also makes the Skellefte district one of the largest early Proterozoic VHMS districts in the world. In Table 2, the grades and tonnages for the major deposits in the district are listed. The median size of the 51 largest deposits is 1.1 million tonnes (Allen et al. 1996). The largest deposit, Rakkejaur (not mined because of metallurgical problems), probably has a total tonnage exceeding 30 million tonnes.

Detailed description of individual deposits is beyond the scope of this guidebook. Interested readers are referred to the following papers for individual deposit descriptions:

Boliden — Ödman (1941), Grip & Wirstam (1970), and Bergman Weihed et al. (1996); Långdal — Martinsson (1987), Talbot (1988), and Assefa (1990); Renström — Duckworth (1991); Petiknäs — Jonsson et al. (in prep.), Holmtjärn — Nicholson (1993); Mensträsk ores — Grip (1951); Rakkejaur — Trepka-Bloch (1985, 1989); Näsliden — Svenson (1982); Kristineberg — Du Rietz (1953). General information on the massive sulphide deposits can be found in Rickard (1986) and Allen et al. (1996).

Composition

In general the Skellefte district VHMS ores are poor in Pb and rich in Zn, As and Au, but composition vary between individual deposits. High contents of Sb and Hg are common in some deposits. Table 2 lists the grades of main metals for the largest deposits. Some extremely gold rich deposits stand out, for instance the Boliden (average 15.5 g/t Au) and Holmtjärn (average 7.4 g/t Au) deposits. The Boliden deposits was also extremely As-rich. Typically the deposits contain 3–5% Zn, 1–2% Cu, and less than 1% Pb. Well developed Cu-rich stringer zones can be identified in several deposits, e.g. Näsliden (Svenson 1982) and W. Maurliden (Allen et al. 1996). Disseminated pyrite is often found in the stratigraphic footwall of several deposits, e.g. Långsele, Långdal and Holmtjärn (Allen et al. 1996). In several deposits, e.g. Kristineberg, Petiknäs South, Långsele, Rävliden and Rävlidmyran sphalerite is concentrated towards the hangingwall. Chalcopyrite is concentrated to the stratigraphically lower part of the ores in the latter four deposits as well as in Udden. Allen et al. (1996) distinguished four different main types of ores: 1) pyrite with disseminations or streaks of sphalerite±other ore minerals, 2) complex sphalerite-pyrite-galena±chalcopyrite, 3) fine-grained arsenopyrite±pyrite-chalcopyrite, and 4) chlorite with pyrite-chalcopyrite impregnations and veins.

In ternary metal ratio plots (Fig. 10), deposits like Boliden and Holmtjärn (type 3 above) are clearly different to most other deposits. In Boliden and parts of the Holmtjärn massive arsenopyrite ore, quartz and tourmaline veins together with extremely high gold grade make these deposits different from other massive sulphide deposits in the Skellefte district. An epithermal origin for the Boliden deposit has been proposed by Bergman Weihed et al. (1996).

Hydrothermal alteration

Like in most massive sulphide deposits, the Skellefte ores are all associated with sericite and/or chlorite alteration in greenschist facies rocks or equivalent alteration assemblages in rocks of higher grade. Almandine, biotite, cordierite, andalusite, staurolite, and cummingtonite are commonly found in lower amphibolite facies (cf. Rickard 1986). In carbonaceous host rocks actinolite, andradite, diopside, and epidote calc-silicate alteration assemblages are sometimes found (cf. Rickard 1986).

The alteration envelopes are generally asymmetric with most intense alteration in the stratigraphic footwall (Allen et al. 1996). The main alteration type is quartz-sericite-pyrite alteration which may extend from 100 m to 1 km along strike and up to 2 km into the footwall like in Långdal and Långsele (Allen et al. 1996). An inner chloritic zone exists at Långsele and Rävlidmyran, while calc-silicate rocks are present in Rävlidmyran, Rävliden, Rakkejaur, Renström, Långdal, and Näsliden, which according to Allen et al. (1996) are of hydrothermal origin, except the Näsliden occurrence and part

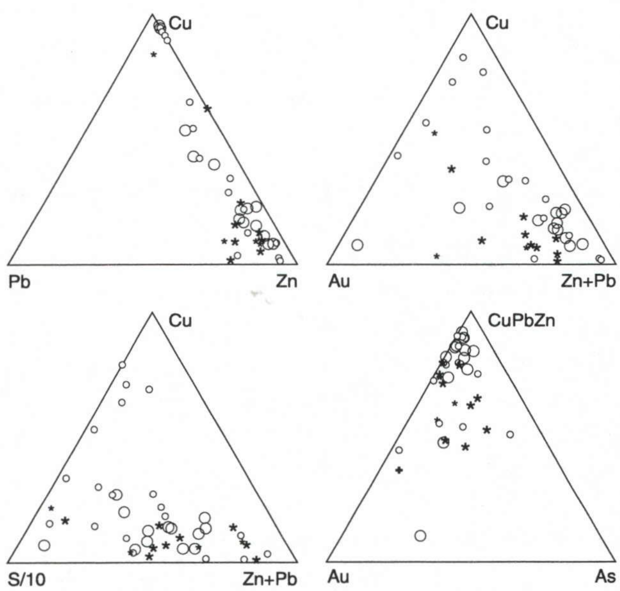

Fig. 10. Ternary diagrams of metal composition of the major VHMS deposits in the Skellefte District. Deposits are listed in Table 2. Larger circles are deposits with a tonnage exceeding 1.1 Mt. Stars refer to tuff cone-cryptodome-hyaloclastite associated deposits. From Allen et al. (1996)

of the Rävlidmyran calc-silicates. Allen et al. (1996) also describe alteration zones which extend into the hangingwall at Holmtjärn.

A special case is the Boliden deposit with a central zone of extremely leached rocks consisting of a silica-alumina residue with sericite-quartz-andalusite and corundum (Bergman Weihed et al. 1996). This zone is enveloped by a sericite-rich zone and an outer chlorite-rich zone. Bergman Weihed et al. (1996) attribute this to strong cation leaching in an environment similar to modern high sulphidation epithermal systems. A similar alteration type is present in the Mångfallberget area immediately north of the Boliden deposit.

Setting of ores

Although most deposits are situated within the uppermost part of the Skellefte Group volcanic rocks, some deposits are situated both deeper in the stratigraphy and at the base of the Vargfors Group rocks (cf. Rickard & Zweifel 1975, Rickard 1986, Allen et al. 1996). The time interval for the deposition of all massive sulphide deposits is probably less than 10 million years, possibly less than 5 million years and according to Allen et al. (1996), corresponds to a period of intense extensional arc volcanism.

The massive sulphide ores have been extensively investigated by lead isotope studies (cf. Rickard 1978, Rickard & Svenson 1984, Vaasjoki & Vivallo 1990, Billström & Vivallo 1994, and Bergman Weihed et al. 1996). Billström & Vivallo (1994) proposed a two stage mixing model for the source of lead in the massive sulphides, where Archaean crustal material was recycled to the mantle and also formed a crystalline felsic basement at 2.0 Ga. The metasomatised mantle and the felsic basement was partially melted at 1.89 Ga and local mixing between mafic and felsic volcanic sources are indicated by short linear trends (see Fig. 11), within individual domains in the district. This model of Billström & Vivallo (1994) fits well with the tectonic setting proposed by Allen et al. (1996) where they suggested that the massive sulphides were related to a continental arc under extension. Possible remnants of an older basement to the Skellefte volcanism may be the rocks of the Knaften area which have an age exceeding 1.95 Ga (Wasström 1993, 1996).

The Renström deposit

Renström is located 15 km west of Boliden and the first discoveries of glacial boulders with sulphide disseminations in the area were made in 1921. Electromagnetic ground-surveys and trenching were performed during 1926. Some anomalies were tested by diamond drilling which intersected what is now called the Renström East ore body. Continued geophysical surveys in the area indicated the Renström ore body in 1928 and subsequent diamond drilling confirmed the find.

Between 1944 and 1948 a shaft was sunk down to the 470 m level and the ore was investigated by drilling on every 50 m level. Full scale production started in 1953. In 1959 the existing shaft was deepened to the 870 m level followed by drifting and diamond drilling in order to investigate the ore at deeper levels. The hoisting system from 1959 is still in use, but ore from lower mining levels is trucked up in a ramp to the lowest raising level.

At present, the deepest mining level is at

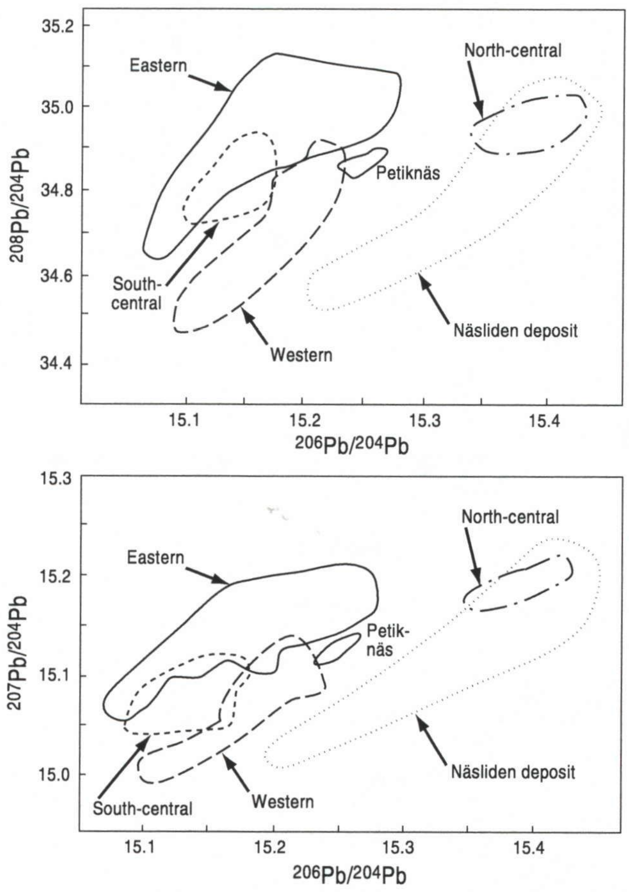

Fig. 11. Lead isotope diagrams of the Skellefte district. Data from Billström & Vivallo (1994) and Billström unpublished.

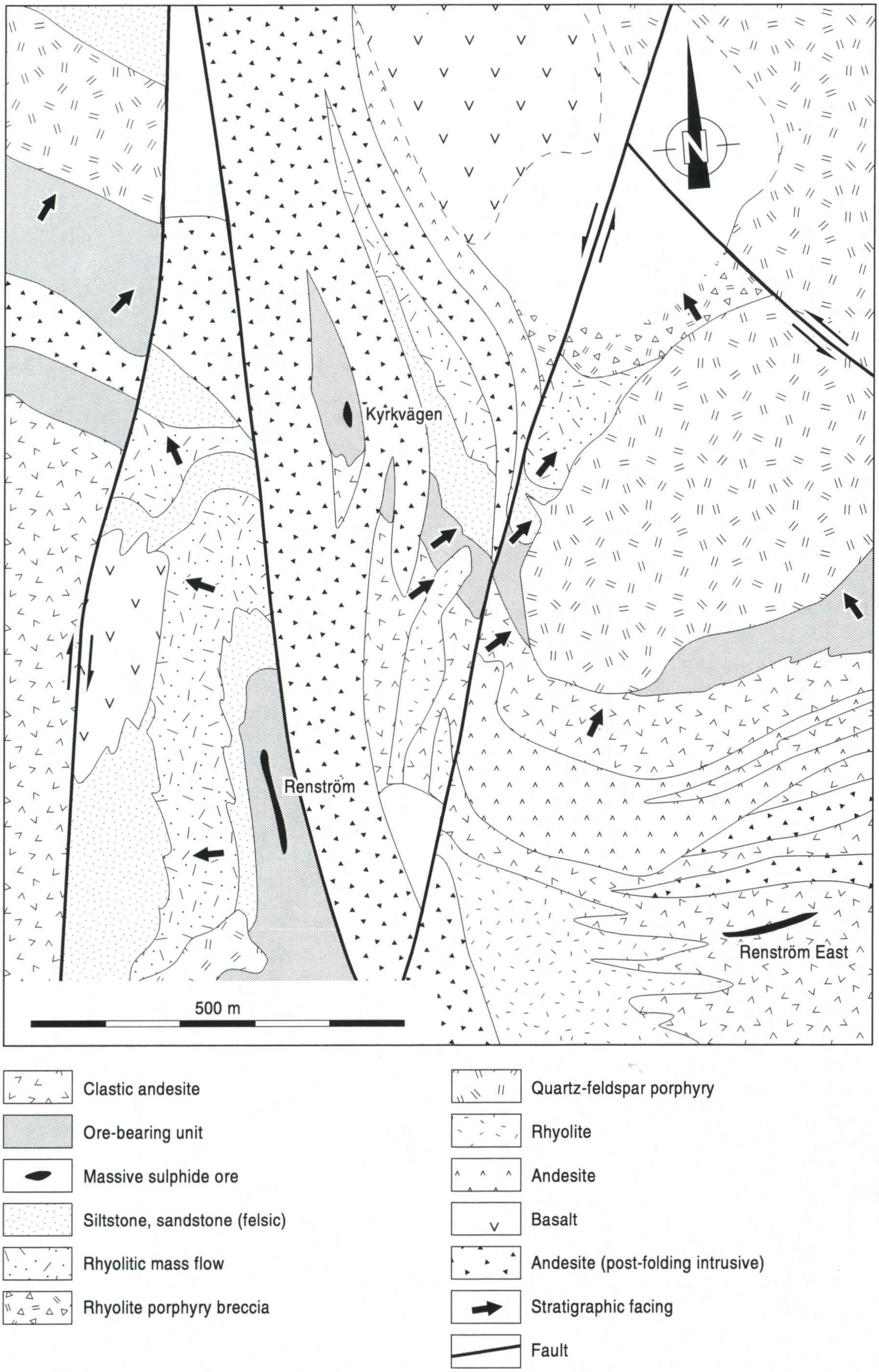

Fig. 12. Geology of the Renström area (published with permission from Boliden AB)

970 m, but preparations to deepen the mine to 1050 m have already begun. A drilling program to test the possible continuation of the ore at greater depths was completed in 1996. Several good ore intersections were obtained between the 1260 and 1550 m levels and further drilling in order to confirm grades and ore continuity will start in 1997.

Pre-production ore reserves down to c. 1000 m were 9 Mt with 2.8 g/t Au, 155 g/t Ag, 0.8% Cu, 6.5% Zn, 1.5% Pb, and 15% S. During 1996 about 140,000 tonnes were mined by the cut-and-fill method. In 1995, construction of a 2.5 km long drift on the 800 m level from Renström to the Petiknäs mine was started. It was completed by the end of 1996 and when it is taken into operation in 1997, ore from the Petiknäs mine will be hauled by train to Renström and hoisted to surface there.

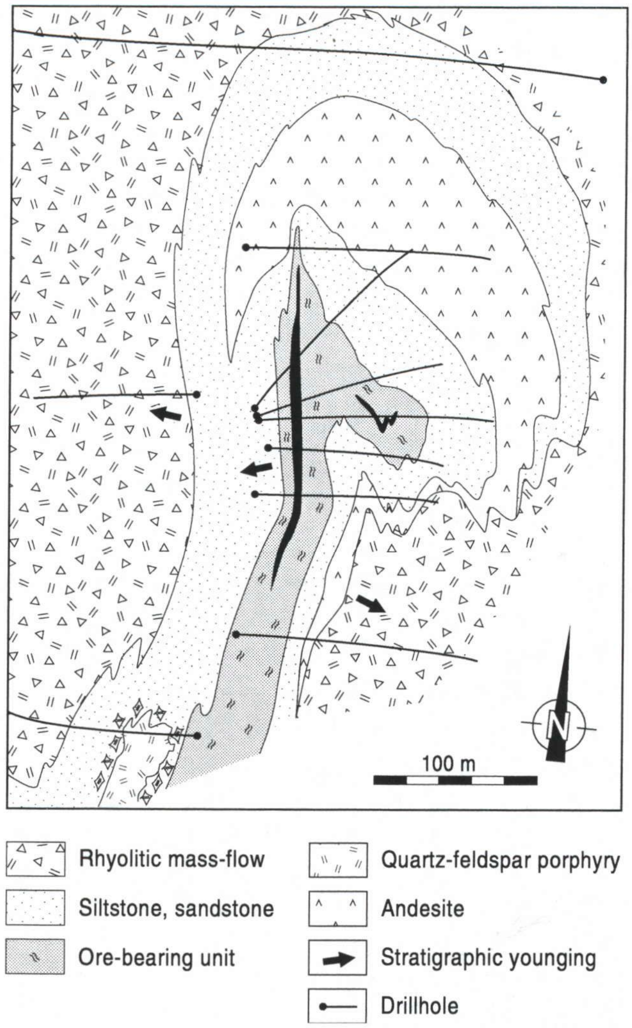

Fig. 13. Geology of the Renström deposit (published with permission from Boliden AB)

Stratigraphy

The footwall stratigraphy to the Renström ore deposit is not exposed in the mine or in drill holes drilled in the mine. However, east of the mine a succession of andesites and basaltic andesites possibly constitute the footwall unit of the ore (Allen 1996). The succession consists mainly of coarse to fine, polymict breccia and sandstone with lithic clasts and yellowish white, flattened pumice clasts. They were largely deposited as normal graded mass-flows but in the upper part of the sequence there are also cross-bedded, channel and traction current deposits indicating a shallow-marine to fluvial deposition (Allen et al. 1996). Pink to brown, oxidised clasts of different types are also common. Shallow-marine to fluvial deposits outcrop less than 50 m stratigraphically below the ore-bearing unit (Allen et al. 1996) and about 350 m south east of the Kyrkvägen massive sulphide deposit (Fig. 12). The succession of clastic andesitic rocks was intruded by syn-volcanic, andesitic sills.

The ore bearing unit, which also contains the Renström ore, consists of rhyolitic, pumice-bearing, siltstone and sandstone. The pumice occurs as diffuse, irregular, strongly chloritic clasts with 1–3 mm large quartz phenocrysts occasionally as big as 7 mm. Due to alteration, feldspar phenocrysts are rarely preserved. Where pumice is abundant, the rock looks very much like a coherent porphyry. The pumice is interpreted as pyroclastic fallout or as blocks that floated off a nearby submarine rhyolite dome and then became waterlogged and sank (Allen et al. 1996). Inconnection with the ore deposition, hydrothermal solutions altered the rocks of the ore-bearing unit. Chloritization, silicification, dolomitization, and sericitization have thus largely altered the original composition and appearance beyond recognition. For example, in strongly chloritized parts, pumice may be recognised only as quartz crystals. In addition to the alterations mentioned, there is also widespread sulphide impregnation.

The ore-bearing pumiceous unit is overlain by laminated siltstone and sandstone with minor intercalations of black phyllite with traces of pyrrhotite and rare graphite. Graded bedding implies that the sediments were partly deposited from turbidity currents. The siltstone-sandstone also contains more or less calcareous parts. A syn-volcanic, often calcareous and calcite brecciated andesitic sill has intruded the silty-sandy unit (Fig. 13).

Rhyolitic mass flows overlie the siltstones-sandstones and consist of several up to 35 m thick graded beds. They are rhyolitic with up to 0.4 m large lithic, mainly rhyolite clasts, and pumice in the form of flattened, chlorite-rich, feldspar porphyritic lenses (fiamme). The tops of the beds are sandy-silty. The matrix of the mass flows is characterised by 1–2 mm large feldspar crystals and about 0.5 mm large quartz crystals. In the southern part of the mine at depths below c. 1 km the rhyolitic mass flows have suffered strong carbonatization.

Quartz-feldspar porphyritic rhyolite domes intrude both the ore-bearing unit (below c. 1100 m level) and the overlying siltstones-sandstones and rhyolitic mass flows in the mine. The porphyries are early intrusions and to judge from diffuse contacts and hyaloclastite breccias (peperite), they intruded while the sediments were still unlithified. Peperitic parts of the porphyries are texturally similar to, and difficult to distinguish from, the pumiceous ore-bearing unit. Phenocrysts in the porphyries are usually 2–3 mm large, but quartz may be up to 7 mm, set in a fine-grained more or less sericitized, chloritized and silicified matrix.

Structure

The geology of the Renström area was re-interpreted by Allen (1996) and Allen et al. (1996) as shown in Figure 12. The clastic andesites are regarded as the footwall unit to both the Renström and Kyrkvägen deposits. Renström East, which is almost identical in composition to Renström, is situated in the clastic andesites (Fig. 12). The Renström and Kyrkvägen ores are separated by a post-folding, feldspar porphyritic, andesite intrusion bound on the western side by a fault. The two deposits are interpreted to be repetitions of the same original deposit (Allen et al. 1996).

A major dextral fault striking about N-S and dipping steeply west occurs about 300 m west of Renström. Stratigraphic correlations across the fault are uncertain. The rocks in the area are represented by strongly sheared mafic intrusions. West of the main fault the rocks strike west-northwest, but between the fault and Renström they strike roughly N-S, possibly as a result of reorientation in connection with the faulting. East of the mine the strike of the stratigraphy is again oriented more E-W.

The structure presented in Figure 13 is the result of detailed core logging where stratigraphic facings and bedding structures have been measured and plotted in order to give a clue as to the spatial orientation and degree of folding. Rhyolitic mass flows west of the ore show normal grading facing west and identical mass flows SE of the ore show younging to the east. The stratigraphically underlying siltstones-sandstones were partly deposited from turbidity currents and show the same younging pattern as the rhyolitic mass flows. Bedding structures are partly sub-parallel to drill cores and varying orientations indicate a fold closure to the north. The pumice bearing sediments that host the ore are thus the oldest, occupying the core of an antiform. The structure on the 700 m level also implies that the ore is in the core of a refolded fold, which is now isoclinal, and partly oriented about ESE-WNW. That part of the structure increases strongly in length with depth and is at least 300 m long on the 1500 m level. The rocks dip steeply and the F_2 fold axes plunge about 75_ to SSE.

The Ore

The Renström ore consists of two bodies above the 600 m level, the A-ore and the B-ore. The B-ore ceases at about 600 m level whereas the A-ore continues downwards. Both ores are massive to semimassive, pyrite-sphalerite dominated ores, but parts of the B-ore also consist of a stringer-type mineralisation with chalcopyrite. Their combined grades are 2.8 g/t Au, 155 g/t Ag, 6.5% Zn, 1.5% Pb, 0.2% As, 300 ppm Sb, 13–20 ppm Hg, and 15% S. The main ore minerals are pyrite, sphalerite, galena, chalcopyrite, pyrrhotite, and arsenopyrite, with minor tetrahedrite-tennantite, other sulphosalts, electrum, and amalgam (Helfrich 1971).

The ore bodies consist of several lenses, which is probably due partly to original deposition and partly to later deformation. The maximum length of the ore is about 400 m and the maximum width about 20 m. Ore reserves are calculated down to the 1050 m level, but mineralisation with good grades is known down to 1550 m. At higher levels the ore strikes approximately N-S and dips about 80 E, but judging from deep drill holes, the strike on the 1500 m level is near E-W. The information below 1050 m is still sparse, but the reorientation of the ore is interpreted to be due to folding around a fold axis plunging c. 75 SSE.

The geology of the Renström mine is structurally complex and a first compressional phase gave rise to folds oriented approximately E-W. A second phase, possibly in connection with shearing, folded the ore around F_2 axes plunging 75 SSE. Younger, steep shear zones, which have partly affected the ore, are common. This shearing produced a variety of textures like lenticular elongate pyrite orientation, pyrite banding, and durchbewegung structures (Duckworth & Rickard 1993).

As mentioned above, ore deposition was accompanied by alteration like chloritization, silicification, dolomitization, and sericitization. Quartz crystals in dolomite matrix are interpreted as relics of pumice, indicating that the dolomite was not deposited as a chemical sediment but is part of the alteration system. Within the alteration there is also widespread sulphide dissemination, which partly forms a chalcopyrite-pyrite-pyrrhotite stringer zone (Jonsson & Larsson 1986).

Shallow-marine to fluvial, andesitic volcaniclastic rocks occur less than 50 m below the Renström-Kyrkvägen ore-bearing unit whereas the ore-bearing unit is overlain by turbiditic siltstone-sandstone with intercalations of black phyllite, which were probably deposited in water depths of 100 m or more (Allen et al. 1996).

Renström is interpreted to be a replacement ore since it occurs within a pumiceous, pyroclastic fallout unit regarded to have been rapidly emplaced (Allen et al. 1996). Besides, there is no consistent metal zoning pattern within and between different ore lenses. The rhyolitic rocks associated with the Renström ore are interpreted as part of a rhyolite cryptodome-tuff cone volcano (Allen et al. 1996).

The Petiknäs deposit

Petiknäs (Fig. 14) is located 18 km west of Boliden. Altered volcanic rocks were mapped and trenched during the 1930's by Boliden geologist. A new exploration program started in 1983, with the aim of locating new mineral resources in prospective area close to the Renström deposit. Geological reconnaissance drilling discovered the Petiknäs North A-lens at the 425 m level in 1986. Geological modelling and downhole-EM measurements indicated the A- and B-lens of Petiknäs North which was quickly followed by the discovery of the Petiknäs South B-lens in August 1988.

Construction of a 2 km long decline to access the Petiknäs South ore-bodies started in March 1989, and the first ore was produced from the 290 m level in Petiknäs South in March 1992. In 1995, construction of a 2.5 km long ore haulage drift on the 800 m level from Renström to the Petiknäs mine was started. It was completed by the end of 1996 and when it is taken into operation in 1997, ore from Petiknäs will be hauled by train to Renström and hoisted to surface there. The decline now extends down to the 600 m level, and will be deepened down to the 750 m level (corresponding to the 800 m level in the Renström system) where it is to be connected to the ore haulage drift to Renström.

At present, cut and fill mining is only taking place in the Petiknäs South ore body, from the 220 m level down to the 600 m level. During 1996 about 393 000 tonnes of ore were mined.

Pre-production ore reserves in Petiknäs South down to c. 750 m level were 6.5 Mt with 2.3 g/t Au, 108 g/t Ag, 1.1% Cu, 4.8% Zn, 0.9% Pb and 37% S. For Petiknäs North the corresponding figures were 1.3 Mt with 5.6 g/t Au, 103 g/t Ag, 1.3% Cu, 5.6% Zn, 0.9% Pb, and 14% S.

Stratigraphy

The footwall stratigraphy of the Petiknäs South ore body is exposed in the mine and in several drill-holes (Fig. 15). The footwall unit consists of five different types of porphyritic rhyolite-rhyodacite domes, which are distinguished based on variations in quartz and feldspar phenocryst contents, and habit of emplacement (Jonsson et al. in prep.). However, the most common of these rhyolites (comprising c. 90% of the rhyolites) have c. 3% quartz and c. 12% 1–2 mm large feldspar crystals. This rhyoliteintruded into wet, unconsolidated silty sediments with lithic fragments, at a shallow level below the sea-floor. Three other types of rhyolite and one type of rhyodacite occur mainly as dykes intruding into the above mentioned rock

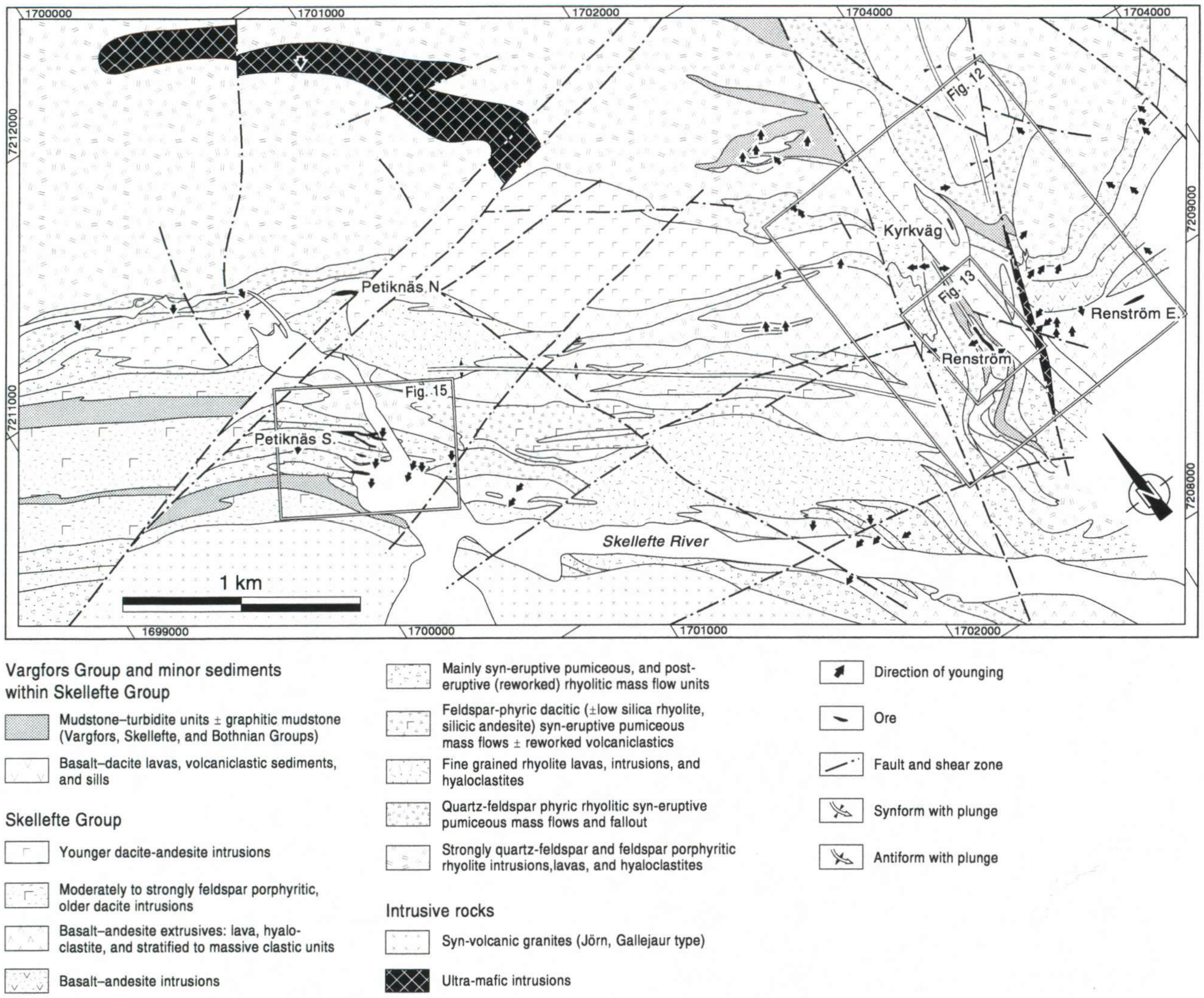

Fig. 14. Geology of the Renström Petiknäs area. Locations of Figures 12, 13, and 15 indicated. Modified from Allen et al. (1996)

units. Zr/Y-ratios indicate that the porphyritic rhyolites are of calc-alkaline to transitional type. The geochemistry of the four different rhyolite porphyries suggest that they have the same magma source and that the difference in phenocryst size and abundance could be due to differences in magma fractionation and crystallisation. The footwall quartz-feldspar porphyritic cryptodome complex has a maximum thickness of approximately 200–250 m.

Eruptive material shed from these domes consists of altered pumiceous siltstones and volcanic sandstones. This unit is dominated by finely laminated grey-black siltstones, with minor quartz-fragment rich, sandstone units. Chloritized pumice clasts ranging from 1 to 7 cm in size, and quartz crystal-rich layers are distributed throughout the siltstone and indicate a pyroclastic origin for this unit. Graded bedding indicates a stratigraphic facing direction towards the south. This unit is the host rock to the massive ores.

A polymict mafic mass flow breccia dominates the hanging wall of the Petiknäs South area. The breccia unit contains 10–20% angular to subrounded clasts in a mafic matrix composed of silt and sand. The three main lithic clast types that occur within this unit are: bluish coloured feldspar porphyry clasts, white rhyolitic quartz-feldspar porphyry, and cream coloured altered basaltic clasts. The source rocks to these clast types are not represented in the rocks immediately adjacent to the mine. Graded bedding observed within the unit indicates a stratigraphic facing direction towards the south. Several faulted contacts are present indicating that this unit was partly tectonically emplaced into its present position. The unit is approximately 100–150 m thick. A pumiceous quartz-feldspar rich rhyolitic tuff with a sandy matrix occurs stratigraphically above the polymict mass

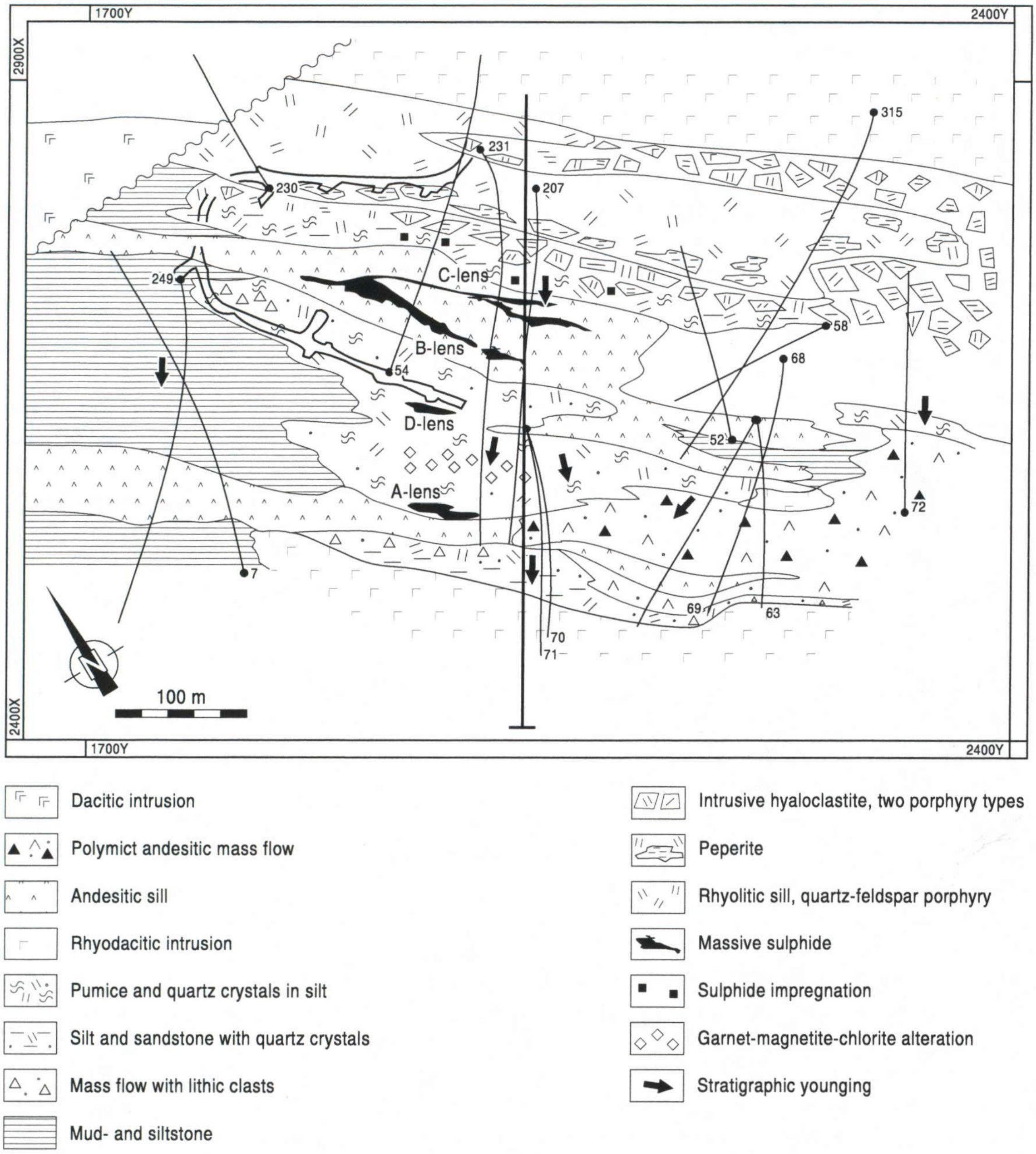

Fig. 15. 300m level of Petiknäs south. Data from Jonsson unpublished.

flow breccias. This 50–100 m thick unit also contains some weak sulphide dissemination. A weakly feldspar-quartz porphyritic intrusion of rhyolitic composition is emplaced into the polymict mass-flow breccia unit and the pumiceous felsic unit. Stratigraphically above these rocks, a weakly feldspar porphyritic dacitic intrusions with a greenish colour occurs. The unaltered, or weakly saussuritized feldspar crystals are 2–7 mm in size and make up 1–5% of the rock. The unit also contains xenoliths of the pumiceous sandy rhyolitic unit mentioned above. An andesite sill-like intrusion has displaced parts of the B-C and A-D lenses. It is a homogeneous, dark green, fine-grained, magnetic unit, composed of plagioclase, amphibole, some biotite and chlorite. The chlorite occurs along contacts and along small shears. In addition to this, euhedral pyrite crystals are common, as well as carbonate veinlets.

A high-level, Jörn-type granitoid occurs to the south of the mine as a large intrusion, with several apophyses intruding into the upper stratigraphic levels of the mine lithology.

Structure

The ores are generally concordant with the stratigraphy which strikes north-west. The ore bodies themselves plunge 60° E. Several faults occur parallel to subparallel (0–15° to S_0) to the main strike of the ore sequence causing repetition of several units. Theapparent fold-like structure of the B and C-lens is the result of such faulting. The andesitic intrusion was emplaced during this faulting (Jonsson et al. in prep). Several brittle north-striking normal faults cross-cut the stratigraphy at higher angles causing displacements of the ore-lenses in the order of 5–15 m. The large Petiknäs Main Fault Zone (PMFZ) cuts the ore stratigraphy, including the massive sulphide lenses, at depth. The whole mineralised system in Petiknäs North is situated in the northern block, i.e. the other fault block compared to the Petiknäs South ore. The Petiknäs South B-C lenses are cut by the PMFZ at roughly 775 m depth (Fig. 16). The PMFZ consists of a zone of several parallel to sub-parallel faults within a c. 100 m wide zone. The PMFZ strikes NE and dips 50–60° SE and the structure of the C-lens indicate that the southern side has moved up relative to the northern side. The PMFZ can be traced for more than 15 km.

The Ore

The Petiknäs South deposit consists of several stacked ore lenses. The spatial relationship of the ore lenses and local geology is shown on the 300 m level in Figure 15 and in the profile at 2030Y (Fig. 16). The average grade of the ores lenses in Petiknäs South are 2.3 g/t Au, 108 g/t Ag, 1.1% Cu, 4.8% Zn, 0.9% Pb, 0.4% As, 200 ppm Sb, and 37% S. The main ore minerals are pyrite, sphalerite, chalcopyrite, galena with minor arsenopyrite, tetrahedrite, bournonite, and gudmundite. Gold is associated with chalcopyrite, arsenopyrite, pyrite, and quartz in the basal B-C lens as amalgam with a gold content of 4–55% (Jonsson et al. in prep.).

The ore system shows a progression from massive pyrite-Zn-Cu-Pb-Au-Ag ores in the basal B- and C-lenses, to Zn-Pb-Ag ores in the stratigraphically higher A- and D-lenses. The maximum length of the B-C lens occurs at the 400 m level where the ore-bodies are roughly 300 m long, and the maximum width is 24 m. The B-C lens also shows a strong metal zonation with sphalerite-pyrite rich margins and a more chalcopyrite-pyrite dominated central part. The B-C lens is underlain by patchy to pervasive silicification often associated with sulphide stringer zones. The ores are situated within strongly silicified, sericite-chlorite altered felsic pumiceous volcanic sandstone/tuff material, which is often strongly pyrite-sphalerite mineralised. The alteration is manifested in breakdown of feldspar to the typical greenish sericite-silica assemblages, which overprint the original textures of the rock.

The A- and D-lenses are situated within strongly garnet-chlorite-magnetite altered volcanic rocks, which probably were pumiceous rhyolitic volcanic sandstones. They are smaller, massive to semi-massive ZnS-PbS-FeS_2 ores, which grade into low-grade disseminated pyrite-sphalerite mineralisation. The average Zn-grade of the A-lens is around 10%. Maximum strike length of the A and D-lenses is 60 m with a maximum width of 8 m at the 350 m level.

A late andesitic sill-like intrusion, occurs within the ore-bearing unit, cross-cutting both the B-C lens and the Zn-Pb-rich A-D-lenses. This andesite exhibits both chilled margins and faulted contacts, and abruptly truncates the individual ore-lenses, creating an apparent fold pattern. It is magnetic and composed of plagioclase, biotite, and amphibole, with chlorite preferably along faulted contacts.

The preferred mode of formation for the whole Petiknäs system is an exhalative seafloor type massive sulphide deposit associated with a cryptodome-hyaloclastite-tuff cone rhyolitic volcano (Allen et al. 1996, Jonsson et al. in prep.). A minor thin subeconomic mineralisation situated stratigraphically below the main B-C lens is interpreted as having formed as a sub-sea floor replacement type of ore. The total thickness of the ore-bearing unit is about 200 m.

Au-deposits

It is only since the last decade that the Skellefte district can be regarded as a gold lode district as well as a massive sulphide mining area. Although the massive sulphide deposits are unusually rich in gold, some even extremely rich (Boliden and Holmtjärn), it was only in 1988, that the first gold lode type deposit (Björkdal) was opened for mining. This was rapidly followed by the discov-

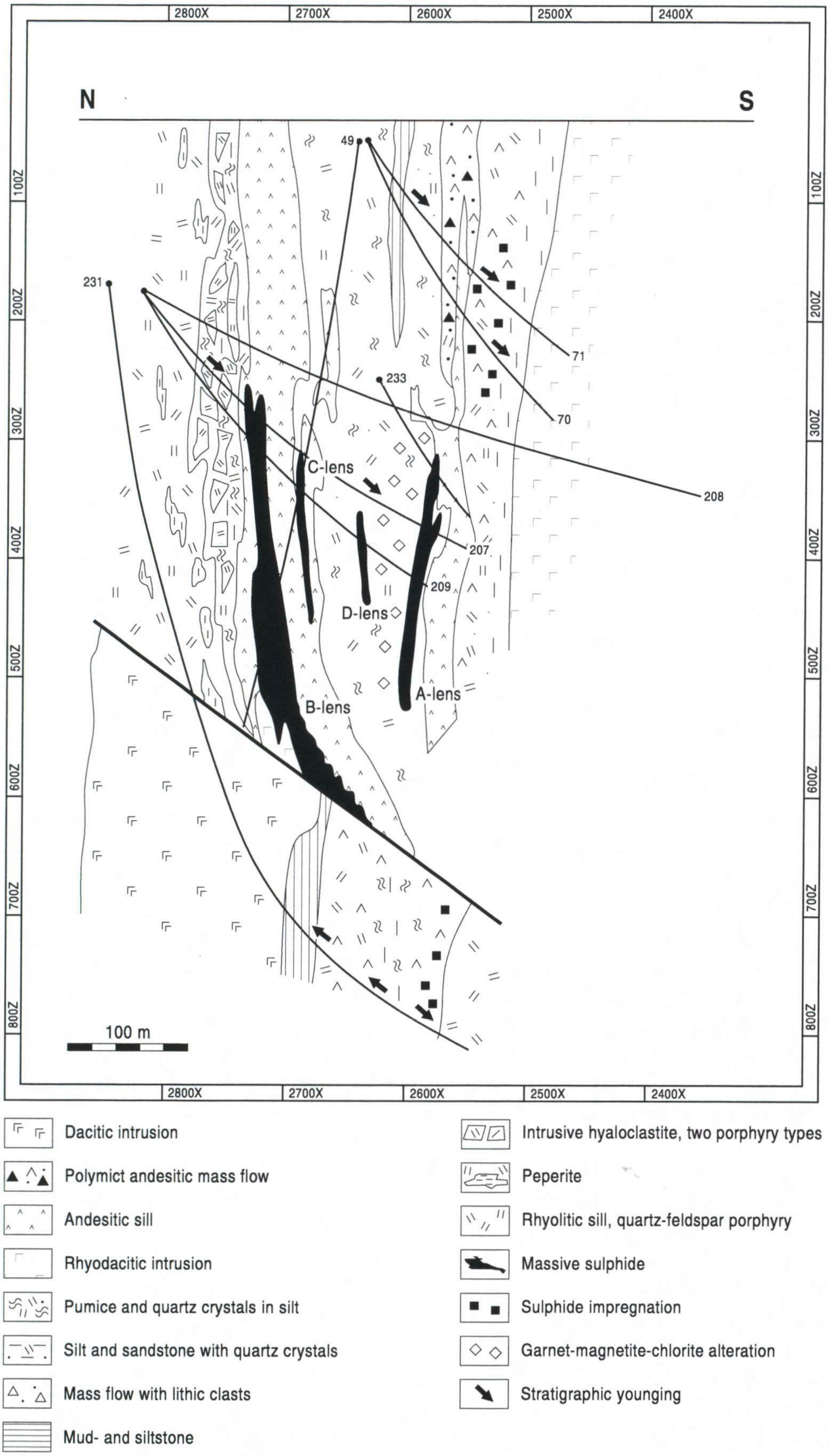

Fig. 16. Profile 2030Y Petiknäs south. Data from Jonsson unpublished.

ery of the Åkerberg deposit which opened in 1989. Today several promising targets are evaluated mainly in the eastern- and westernmost parts of the district, namely Ö. Åkulla by Boliden AB, Barsele by Terra Mining AB and Ersmarksberget by COGEMA. In addition gold rich parts in the Långdal ore which are separate from the massive ore have recently been discovered and mined. The genesis and origin of these gold rich parts are unknown. Short reviews on the setting of gold lode type deposits can be found in Weihed & Bergström (1988), Bergman et al. (1989), Weihed et al. (1992), and Billström (1996).

As mentioned above gold deposits have been known in the district since the last century. Most of the early workings were on quartz-arsenopyrite veins hosted by metasedimentary rocks. One of these is the Grundfors deposit, situated c. 10 km south of Boliden. This subeconomic deposit consists of 1 to 50 cm wide quartz veins locally with abundant arsenopyrite and gold (cf. Bergman 1992). Other subeconomic gold lode deposits described in the literature include Storklinten (Bergström & Lundqvist 1989), Vinliden (Broman et al. 1995, Bergström 1996), and Middagsberget/Fäbodliden (Öhlander & Markkula 1994, Sundblad et al. 1994). Shear zone hosted remobilised gold in the Tallberg porphyry type deposit is also described by Weihed (1992b).

The Boliden deposit, from which 123 tonnes of gold were recovered at an average grade of 15.5 g/t, is also discussed in the massive sulphide section above. This deposit is interpreted by Bergman Weihed et al. (1996) as an equivalent of modern high sulphidation epithermal type of deposits.

No thorough description has been published on the Åkerberg deposit so only a brief summary of the geology of this gold deposit can be given here. The deposit is situated in the north-eastern part of the Skellefte district c. 15 km NNE of the Björkdal deposit (Fig. 5). The gold is confined to a c. 20 m wide zone of cm wide parallel quartz veins within a gabbroic intrusion. The host gabbro probably belongs to the c. 1.89–1.87 Ga old Jörn suite and the ore is cut by late pegmatites related to the 1.80 Ga Skellefte type intrusive rocks. Published figures on grade and tonnage are scarce but, the grade is reported at c. 3 g/t and the proven tonnage is >1 million tonnes (cf. Weihed et al. 1992).

Composition

All gold lode deposits in the Skellefte district are associated with quartz vein arrays. The quartz veins vary in width from mm to 1 m. The gold is always associated with sulphides like pyrite, arsenopyrite, pyrrhotite, and chalcopyrite. The amount of sulphides varies from around 1% only in Åkerberg, c.5% at Björkdal to massive sulphides at deposits like Boliden. The quartz vein hosted gold deposits within metasedimentary rocks (i.e. Grundfors, Fäbodliden, Storklinten, and Vinliden) are commonly associated with arsenopyrite. Arsenopyrite is also common in the Boliden deposit where more than 1 million tonnes of massive arsenopyrite was mined. In the porphyry type deposit Tallberg, gold is associated with pyrite, chalcopyrite, and sphalerite (cf. Weihed 1992b), in Björkdal the main sulphides are pyrrhotite, pyrite, and chalcopyrite with lesser amounts of secondary bornite, covellite, and copper (cf. Broman et al. 1994) while pyrrhotite is the most common sulphide in Åkerberg.

The gold occurs as electrum, amalgam, or tellurides. In Björkdal both electrum and tellurides are found (incl. tsumoite and bismuth-tellurides). The silver content in electrum in Björkdal varies between 5 to 10% (Broman et al. 1994). The gold in Middagsberget occurs as droplets in arsenopyrite or at interfaces between arsenopyrite grains, as inclusions together with pyrrhotite in arsenopyrite, as free grains in silicates, or in fractures in carbonates (Öhlander & Markkula 1994). In Tallberg the gold is most commonly electrum (av. Au_{75}-Ag_{25}) with minor coloradoite, petzite, hessite, and sylvanite. In Boliden the gold is mainly found in strongly brecciated ore as free grains in quartz or at the contact between quartz and arsenopyrite, in fine-grained arsenopyrite as small inclusions together with Bi-Se minerals, in pyrite ore together with sulfosalts and galena in veins cutting the pyrite, and in tourmaline ore in fractures in tourmaline and quartz. All gold in Boliden is present as an Au-Ag-Hg alloy. The gold in Vinliden is associated with tourmaline and Sb-bearing minerals (Bergström 1996).

Hydrothermal alteration

In Björkdal a weak alteration halo (max 30 cm) is developed around the quartz veins

Table 3. A nongenetic classification of gold deposits in the Skellefte district modified from Weihed et al. (1992)

Gold deposits totally or spatially associated with intrusives	1. Cu-Au mineralisation within shearzones in granitoids. Tallberg 2. As-Au mineralizations spatially associated with small porphyries within large sedimentary sequences. Vinliden, Fäbodliden, Storklinten 3. Quartz vein type gold in contacts between granitoids and supracrustals. Björkdal 4. Minor Au mineralisation within mafic intrusives Åkerberg
Gold deposits without any known intrusive relationship, totally within the supracrustals	1. Quartz vein As-Au within metasedimentary rocks. Grundfors 2. Quartz vein As-Au within metavolcanic rocks. Önusberget
Epigentic Au overprinting of massive sulphide deposits	Långdal?
Epithermal high sulphidation deposits	Boliden

with sericite, chlorite, biotite, and sulphides. Tourmaline and scheelite is common in the quartz veins (cf. Broman et al. 1994). Sericitic alteration along faults and albite alteration related to quartz veins is the dominant alteration style in Vinliden (Bergström 1996). The alteration in Middagsberget and Fäbodliden is characterised by shear zones with sericitic and chloritic alteration (Öhlander & Markkula 1994). The alteration assembly associated with quartz veins in the shear zones includes carbonates, sericite, chlorite, albite, and sulphides. In Tallberg strong sericite alteration in shear zones cutting the porphyry mineralisation seems to be related to higher gold grades (cf. Weihed 1992).

Setting

Weihed et al. (1992) proposed a nongenetic classification of gold lode deposits (Table 3). There is a general acceptance that the quartz-arsenopyrite vein-type mineralisations like Grundfors and others are related to syndeformational processes. In Fäbodliden, Storklinten and Vinliden the gold is associated with felsic to intermediate intrusionsemplaced in metagreywackes and the timing of gold mineralisation in these deposits is regarded as syn- to post-peakmetamorphic. The structural control on these deposits seems partly to be related to competency contrasts between intrusions and surrounding metagreywackes. Intrusive hosted gold in shear zones is found in the Tallberg deposit (see also the porphyry type deposit section below).

The structural control on the Björkdal deposits is similar in the sense that tensional quartz veins in the footwall to a major thrust are mainly found in the more competent host intrusive. According to Billström (1996) the early quartz veins were formed in association with the emplacement of the quartz-monzodiorite at c. 1905 Ma. Billström (1996) proposed three subsequent thermal events which all caused remobilization of gold. Fluid inclusion and stable isotope data from Björkdal (Broman et al. 1994, Billström 1996) suggest a complex fluid evolution involving magmatic, marine, and meteoric fluids.

Billström & Weihed (1996) suggested that gold was introduced at. c 1.9 Ga as mesothermal gold in Björkdal. High gold grades are found in VHMS deposits with an age of 1.89–1.88 Ga, epithermal style gold in Boliden was tentatively emplaced as late as 1.85 Ga and finally syn-peak metamorphic gold deposits were formed during crustal thickening during high heat flow in the middle crust in deposits like Grundsfors, Vinliden and Storklinten at c. 1.84–1.80 Ga.

The Björkdal mine

History of the mine

Terra Mining AB, the owner of the Björkdal gold mine was founded in 1980 as an exploration company. Early on the company focused chiefly on gold deposits and all exploration permits as well as most of the approximately 60 claims the company holds today concern gold deposits.

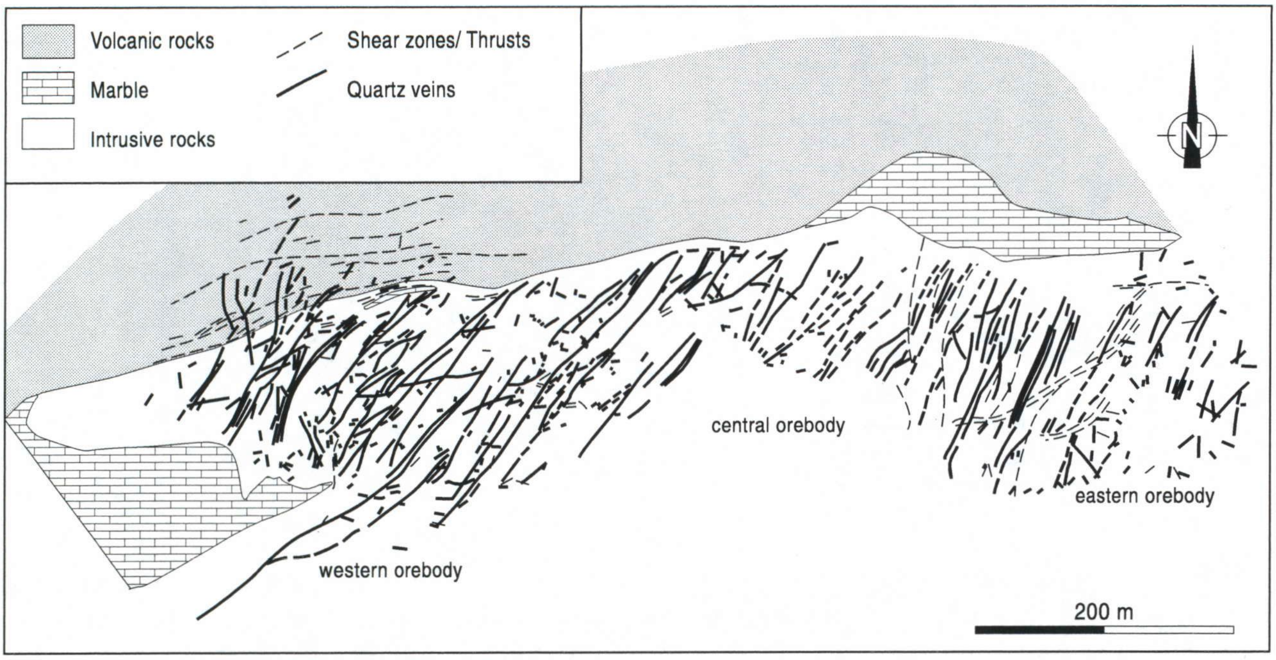

Fig. 17. The Björkdal mine. (published with permission from Terra Mining AB).

The Björkdal ore body (Fig. 17) was first indicated by geochemical sampling in 1983, then in solid rock in 1985. Mining began in 1988, with the development of the Björkdal ore body by open pit mining. The ore reserve 1997 is estimated to 14 million tonnes at 2.2 ppm.

The first ore body, now the central open pit, was followed in 1991 by the eastern open pit. These two pits are now connected. In 1992 larger scale mining with bigger blasts started. In 1996 the new western pit was opened, where mining is presently on a higher level than in the other pit. In 1995 underground mining was commenced with two drifts at the 108 m and 130 m levels. Ore was taken out between the drifts beneath the limestone (Fig. 17). The production was 46 000 tonnes of ore with a grade of 2.8 ppm gold.

The initial annual production capacity of 300 000 tonnes of ore has been expanded in stages to 1 300 000 tonnes of ore through the plant annually, but up to 500 000 tonnes is sorted out after the crushing stage as the coarse fraction after the crushing contains sub-economic grades of gold.

Host rocks

The host rocks are composed of intrusive and volcanic rocks. The host intrusive is a quartz-monzodiorite, and probably belongs to the Jörn intrusive suite. The quartz-monzodiorite is relatively undeformed in its central parts, but is more deformed near the contact and is sometimes recrystallized to a granoblastic texture. The monzodiorite is cross-cut by a system of quartz veins (Fig. 17 and 18). The quartz veins have at least three different trends of which two are mineralised. A marble is situated between the intrusive and the overlying supracrustal rocks in the western and the eastern open pits, but is not present in the central open pit.

Structures

One of the dominant structural trends in the Skellefte district is N60°W, which is also the strike of foliations in the Björkdal mine area. The Kågedals deformation zone to the south of the Björkdal pluton is parallel to the structural trend of the Skellefte district. The Björkdal mine is situated on the northern contact of the Björkdal pluton.

The whole Björkdal area is strongly deformed or tectonized and several shear zones cut the area in different directions. There are examples of both ductile and brittle deformation zones. The area around the mine can be characterised tectonically as an area with internally well preserved megalithons, which are bordered by shear zones. Mapped displacements are in the

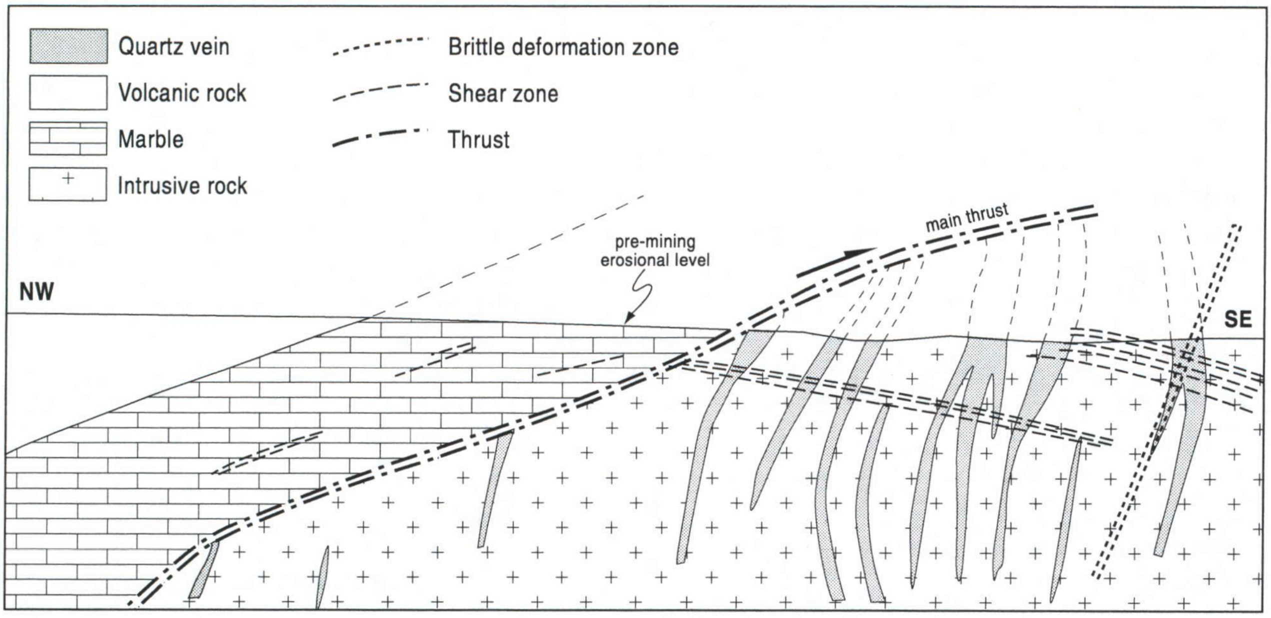

Fig. 18 Generalised cross section Björkdal mine (Albino unpublished).

order of a few meters in the mine area.

The timing of the thrusting is poorly known and late reactivation associated with the intrusions of Revsund granitoids can not be ruled out.

The gold ore

The gold in the mine is associated with the brittle quartz veins which were introduced in tension fractures associated with low angle thrusting towards south. Gold has probably been transported by magmatic fluids as $Au(HS)^{2-}$ complexes. Late hydrothermal fluids, redistributed the gold under high pressure and temperature in the range of 200–300 °C (Broman et al. 1994).

The gold bearing quartz veins are concentrated close to the marble contact and often the veins strike parallel to the contact in the western ore body. The quartz veins are up to meter wide and can be followed for several hundred meters. The ore dips about 25° to the north beneath the limestone. Several brittle deformation zones cut the quartz veins and the gold seems to be concentrated in areas where the brittle zones cross cut the quartz veins, possibly indicating late mobilisation of gold. Shear zones are striking east-west, nearly perpendicular to the wide quartz veins, and have subhorizontal dips. A generalised vertical profile can be seen in Figure 18.

The central ore body is characterised by quartz veins up to one meter wide and up to 200 m long. The mineralised quartz veins can be followed down to 50–70 meterdepth where they get thinner or pinch out. The frequency of quartz veins in the main direction is highest close to the contact to the volcanic rocks, the main thrust and the contact to a folded marble tongue. These quartz veins are rich in gold and bulk mining is done in this part of the mine. Second order shear zones with quartz veins are also present in this ore body and can contain high values of gold. These quartz veins are characterised by the existence of tourmaline and chlorite.

The main thrust in the contact zone strikes E-W and is 30–40 m wide. Tensional quartz veins were preferentially emplaced beneath the thrust within the more competent intrusive, but smaller veins can be seen for instance in boudinaged amphibolites within the deformation zone between the marble and the volcanic rocks. The mineralisation in this deformation zone consists of small amounts of pyrite, pyrrhotite, and chalcopyrite with gold grades of maximum 1–2 ppm.

In the eastern ore body quartz veins with extremely high values of gold have been found. This ore body consists of less deformed rocks between transverse shear zones. The main quartz veins are more or less vertical, and they may deflect close to the deformation zones. A marked albitization can be noticed close to the gold mineralisation. At the intersection between the shear zones and major quartz veins an area of extremely high gold grades exist. The grade in this ore body varies between 3 and 20 ppm gold.

The main quartz veins are very distinct with sharp contacts. The host rock alteration is insignificant only 2–3 dm away from the quartz veins. A weak sericitization is found close to the veins. The gold seems to be concentrated in the rim of the veins, which are rich in pyrite and pyrrhotite. Tsumoite, bismuth-telluride and scheelite are associated with gold. Bornite, covellite, and cuprite exist as secondary copper minerals as well as pure copper.

Other non-economic deposits

Apart from gold lode and massive sulphide ores, the Skellefte District also hosts porphyry type deposits (e.g. Tallberg), minor mafic- to ultramafic-hosted Ni-deposits (Lainejaur, Lappvattnet, Mjödvattnet, Njuggträskliden, and Älgliden), and Li-pegmatites (Varuträsk). Although these deposits will not be studied during the field trip a short description of each type is given below as they are important for understanding the metallogenetic evolution and the tectonic setting of the Skellefte District.

Porphyry type deposits

Porphyry type deposits have now been described rld, and the Tallberg deposit in the Skellefte district is one of the best described (e.g. Weihed et al. 1987, Weihed 1992a, Weihed 1992b, Weihed & Fallick 1994).

The Tallberg porphyry deposit is situated in the outer and oldest GI phase of the Jörn granitoid and it is associated with high-level quartz-feldspar porphyritic dykes and intrusions. The age of these porphyritic intrusions is 1886±15/12 Ma (Weihed & Schöberg 1991) which is, within errors, the same as the GI host rock and the age of the host rocks to most massive sulphide deposits in the district. The deposit is of a lowgrade (0.3% Cu) and high tonnage (>50 Mt), disseminated type. A typical alteration zoning exists with a proximal zone of phyllic alteration with quartz, sericite, and pyrite grading out into a distal propylitic alteration with abundant chlorite. Ore minerals occur both disseminated and in a sulphide-quartz vein stockwork which is most intense in the central part of the deposit. Metals are also zoned with Cu concentrated to the central parts while Zn and Pb are concentrated to the marginal parts. Magnetite appears to be an early phase of the alteration system. Gold grades are low (< 1 g/t), but in strongly sheared sericite alteration zones cutting the deposit the gold grades can reach >10 g/t. Stable isotope data and fluid inclusion studies indicate that the sulphides precipitated when magmatic fluids mixed with sea water at elevated temperatures of 450 to 500° C (Weihed & Fallick 1994, Weihed et al. 1992).

Ni-deposits

Only minor Ni-deposits occur within the central part of the Skellefte District (e.g. Älgliden). In the north-western part of the district, the Lainejaur deposit was mined during the second world war and to the south, several Ni-deposits have been investigated, including the Lappvattnet, and Njuggträskliden prospects. A review of these Ni-deposits can be found in Nilsson (1985).

The Lainejaur deposit has been described by Grip (1961) and Martinsson (1987). The total production was only 100 526 tonnes of ore with a content of 2.20% Ni, 0.93% Cu, and 0.1% Co (Grip 1961). The ore is associated with a gabbroic intrusion composed of a feeder (?) dyke with apophyses and an overlying gabbro laccolith. Three types of ore were identified: disseminated nickel-pyrrhotite, massive nickel-pyrrhotite-chalcopyrite at the contact between the dyke, laccolith and metasedimentary wall rocks, and late stage nickel-arsenic veins.

The Älgliden deposit is associated with a 3.5 km long and up to 100 m wide mafic dyke in the Jörn batholith (Fig. 3). The dyke is a multiple intrusion with c. 90 000 tonnes of copper and 26 000 tonnes of nickel at grades of 0.7% and 0.2% respectively (Nilsson 1985).

The Lappvattnet deposit is one of several Ni-occurrences in the so called Nickel zone or Burträsk Shear Zone which is a prominent NE-striking shear zone c. 30 km south of the Skellefte District (see cover illustration). The ultramafic intrusions with associated Ni-Cu ore are small, <150 m long and <40 m wide (Nilsson 1985). The Lappvattnet deposit was the subject of trial mining and a shaft was sunk to the 120 m level in the period 1978–

1982, but the ore was considered subeconomic. A total of 11 000 tonnes of Ni at 1% and 2 300 tonnes of Cu at 0.2% was outlined.

Li-occurrences

Lithium-bearing pegmatites are found in the Varuträsk area in the eastern-most part of the Skellefte district (cf. Quensel 1960). The pegmatite is of a lithium-cesium-tantalum-type (LCT-type) according to Romer & Smeds (1994) and it is associated with the Skellefte-type granitoids. Romer & Smeds (1994) dated columbite from this deposit which yielded an age of 1775±11 Ma. Other similar pegmatites are known in the eastern-most part of the Skellefte District, but they have not been studied in any detail.

Other deposits

To the west and north of the Skellefte district, Mo, W, and U mineralisations have been identified. None of these have been mined, but a large number of reports on the occurrences exist. The interested reader is referred to Öhlander (1986 and references therein) for information regarding these deposits.

GEOLOGY AND MINERAL DEPOSITS OF THE CENTRAL OSTROBOTHNIA

Regional geology

The bedrock of central Ostrobothnia is a part of the Svecofennian Domain (SD) bordered by the Archaean Basement Complex (ABC) in the east and the Central Finland Granitoid Complex (CFGC) and the Bothnian Belt (BB) in the south and south-west. The eastern part of central Ostrobothnia belongs lithologically to the Savo Belt (SB) and structurally to the Raahe–Ladoga Zone (RLZ) (Fig. 19 and 20). This area is well known for its VHMS deposits.

The idea, first described by Hietanen (1975), that rocks of the Svecofennian Domain are closely related to Palaeoproterozoic island arcs which formed 1.8–2.0 Ga ago (Gaál 1985, Kähkönen 1989, Park 1991, Ekdahl 1993, Lahtinen 1994, Kousa et al. 1994) is now widely accepted. Most of the supracrustal rocks of the SD are turbiditic metasedimentary rocks. Graphite bearing schists, black schists, and carbonate beds are common intercalations in many areas. The minimum age of deposition of the turbidites can roughly be estimated by the age of detrital zircons from the metasedimentary rocks. The zircons show a bimodal age distribution with the majority of tqazhe zircons having ages between 1.91–2.1Ga while some are Archaean in age (Huhma et al. 1991, Claesson et al. 1993). Volcanic rocks exist as narrow discontinuous belts or limited occurrences among both metasedimentary rocks and intrusive complexes. Metavolcanic rocks in central Ostrobothnia represent two different age groups which also have distinct chemical characteristics.

Among the plutonic rocks in the SD, quartzdioritic to granodioritic and granitic intrusions dominate over mafic and ultramafic intrusions (Simonen 1980). Granite-pegmatites, probably of S-type, are common n the Bothnian Belt. Intrusive rocks of the central and eastern part of central Ostrobothnia are mantle derived, Palaeoproterozoic rocks with no sign of Archaean components (Huhma 1986, Lahtinen 1994).

Geographically the supracrustal rocks of central Ostrobothnia can be divided into three different areas or blocks, separated from each other by shear zones, thrusts, or intrusions (Fig. 21). The south-western-most part of central Ostrobothnia can be included in the Bothnian Belt, dominated by greywackes and pelites metamorphosed to biotite-plagioclase schists and gneisses. These are intercalated with thin elongated formations of intermediate to mafic metavolcanic rocks of N-type MORB to WPB characteristics (Vaarma & Kähkönen 1994). Well preserved primary sedimentary and volcanicstructures indicate a turbiditic origin for the schists and a subaqueous depositional environment for the metavolcanic rock. The metamorphic grade in this part of the BB increases towards the Bothnian Bay.

The Nivala gneiss complex (Ngc) which is dominated by migmatitic mica gneisses, is situated between a N-trending belt of granitoid

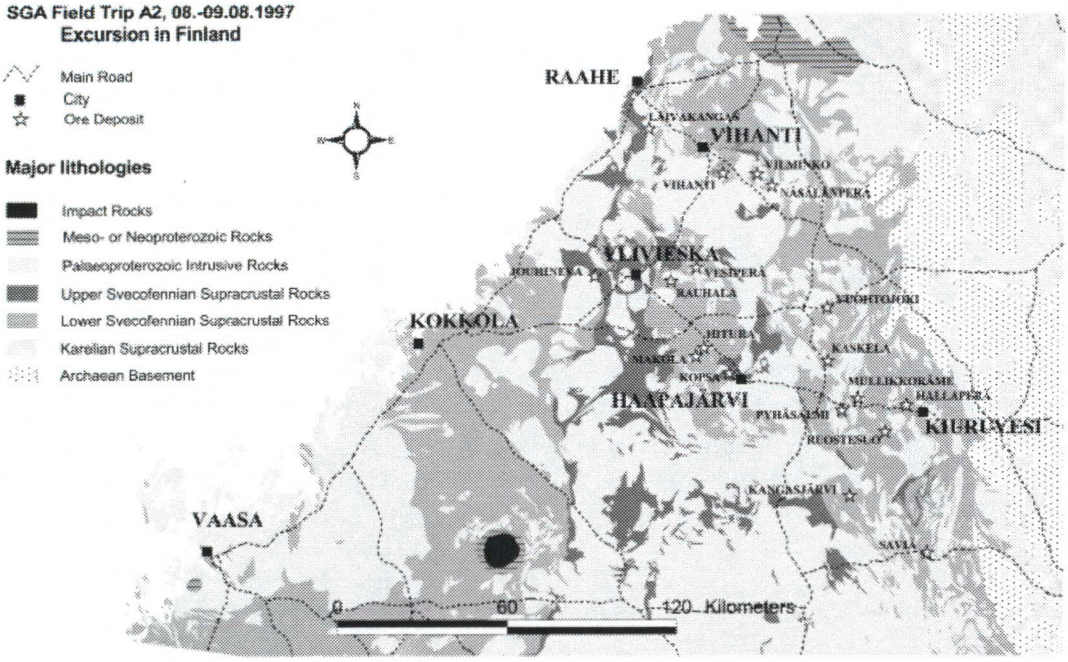

Fig. 19. Generalised lithological map of Ostrobothnia with the ore deposit locations. The maps in the Figs. 19 and 20 are based on the Bedrock Map of Central Fennoscandia (Lundqvist et al. 1996b).

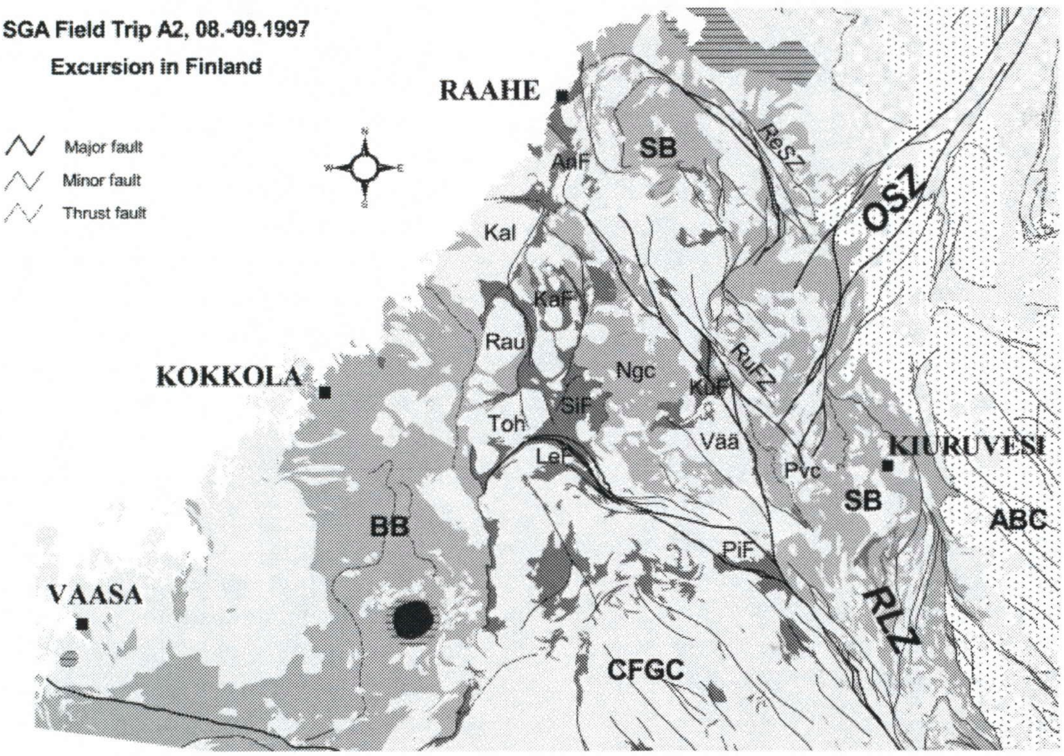

Fig. 20. Major tectonic features and nomenclature of the lithological units. OSZ=Oulujärvi Shear Zone, RLZ=Raahe Ladoga Zone, ReSZ=Revonneva Shear Zone, RuFZ=Ruhaperä Fault Zone, ABC=Archaean basement complex, BB=Bothnian Belt, SB=Savo Belt, CFGC=Central Finland Granitoid Complex, Kal=Kalajoki Batholith, Rau=Rautio Batholith, Toh=Toholampi Batholith, Vää=Vääti granodiorite, Ngc=Nivala gneiss complex, Pvc=Pyhäsalmi volcanic complex, KuF=Kuusaa Formation, SiF=Sievi Formation, AnF=Antinneva Formation, LeF=Lestijärvi Formation.

batholiths (Toholampi-Rautio-Kalajoki) in the west and the SE-trending Ruhaperä Fault Zone. These gneisses locally have amphibolitic, or graphite and sulphide bearing intercalations (Isohanni et al. 1985). Migmatites of the Ngc are host rocks to the Ni-bearing ultramafic in-

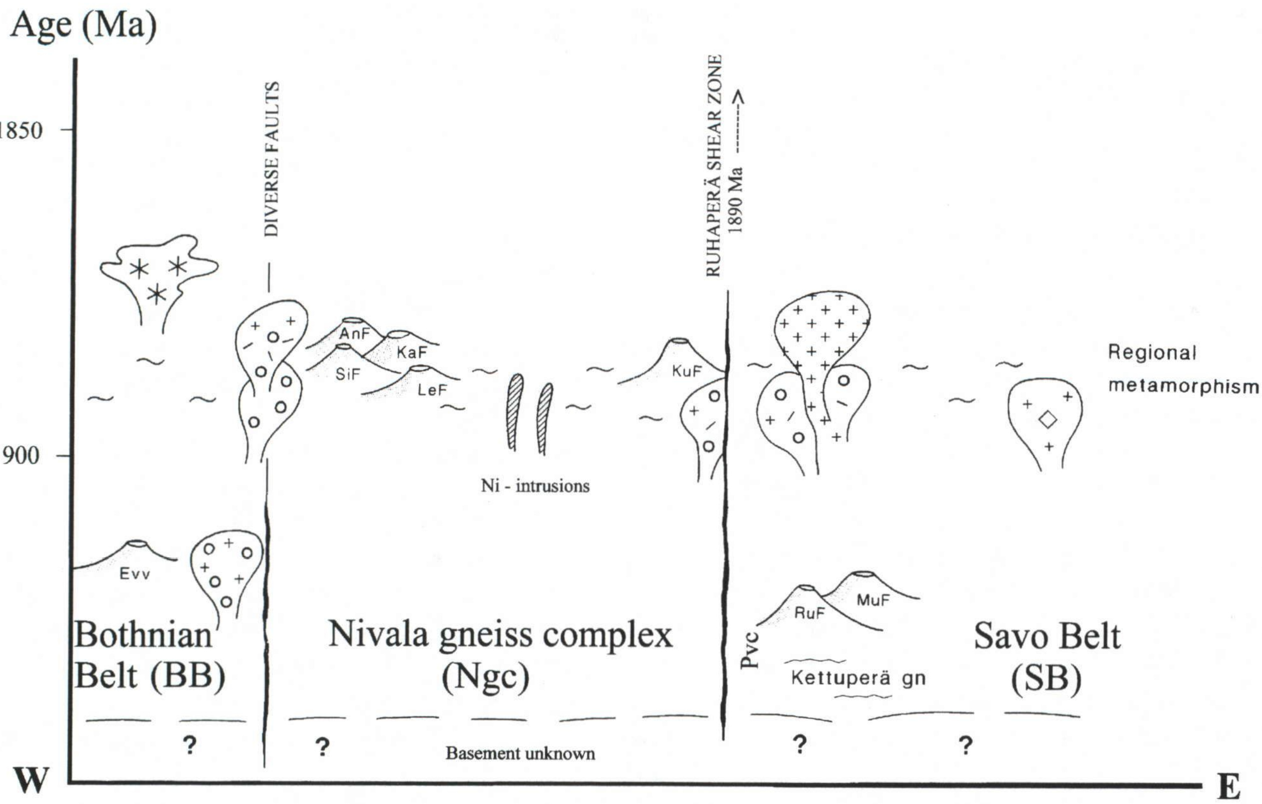

Fig. 21. E-W trending schematic cross section of the bedrock of central Ostrobothnia. Abbreviations as in Fig. 20.

trusions in the Nivala area. Around the Ngc several formations of metavolcanic rocks (Kuusaa Fm, Kangas Fm, Sievi Fm, Antinneva Fm) occur, probably emplaced stratigraphically above the Ngc. The volcanic formations are separated from each other by more ore less continuous volcaniclastic rocks composed of polymict conglomerates and finer-grained silt to sandstones, often crossbedded. Most of the pebbles in the conglomerates are of volcanic origin. Granitoid pebbles are also observed in conglomerates in the Haapajärvi, Ylivieska and Raahe areas. The U-Pb zircon age of one granitoid pebble from the Settijärvi conglomerate (Haapajärvi area) is about 1888 Ma (Vaasjoki & Sakko 1988). Well preserved primary structures indicate subaerial or shallow water depositional environment for the calc-alkaline metavolcanic rocks. The metavolcanic rocks vary from basalts to potassium rhyolites in composition and have a mature island arc affinity. This volcanism in the northern part of the SD is closely related to early, syntectonic magmatism of the CFGC, which is c. 1890–1875 Ma in age. This magmatism is also related to the peak of regional metamorphism in this area. The Ngc area is interpreted as a gently dipping domal structure surrounded by younger, locally flat lying volcanic and sedimentary formations (i.e. Kuusaa, Kangas, Sievi and Lestijärvi Fm).

The third major area in central Ostrobothnia is the Vihanti–Pyhäsalmi ore belt, which constitutes the north-western part of the Savo Belt (SB), bordered by the Ruhaperä Fault Zone and Haapavesi igneous complex in the south-west and the Revonneva Shear Zone and the Archaean Basement Complex in the north and east. The Vihanti–Pyhäsalmi belt is also divided into two major blocks by the SW-trending Oulujärvi shear zone (Kärki et al. 1993), indicating that the Vihanti and Pyhäsalmi belts are at least tectonically separated (Fig. 20). This moderately to highly metamorphosed area is dominated by migmatitic mica gneisses. The turbiditic origin of these metasedimentary rocks can still be recognised in some places. The mica gneisses are intercalated with minor quartz feldspar gneisses, black schists, skarn beds, and some amphibolites of volcanic origin. Massive sulphide deposits of the SB are closely related to these volcanic environments of which the most important are the Pyhäsalmi and Vihanti ore belts. The lithologically similar Pielavesi and Kiuruvesi fields south-east and east of Pyhäsalmi are correlated with the latter (Ekdahl 1993).

The Pyhäsalmi volcanic complex (Pvc) includes two volcanic formations, the Ruotanen Fm and Mullikkoräme Fm, and the Kettuperä gneiss (Kg). These rocks are intruded by numerous syntectonic intrusions. The lowest part of the Pyhäsalmi volcanic complex consists of silicic tuffaceous and pyroclastic rocks with minor mafic intercalations. Towards the top mafic pyroclastic rocks, pillow lavas, and pillow breccias become more abundant. The metavolcanic rocks in the Pyhäsalmi area are locally well preserved, but most of the rocks have been strongly altered by hydrothermal processes and deformed by later tectonic events. The volcanic formations of the Pvc are bimodal (Mäki 1986). Most of the felsic rocks can be classified as calc-alkaline, low-K rhyolites, derived from melting of an unknown Palaeoproterozoic sialic crust. The felsic volcanic rocks are considered cogenetic (Kousa 1990, Lahtinen 1994) with the oldest known rock, the Kettuperä gneiss dated at 1930±15 Ma (Helovuori 1979). A quartz porphyritic variety of these rhyolites from the Riitavuori Mb yields an U-Pb zircon age of 1921±2 Ma. The mafic metavolcanic rocks are sub-alkalic, low-K tholeiitic, basalts to basaltic andesites, with primitive IAT affinity (Kousa et al. 1994).

The stratigraphy of this, in part, poorly exposed area is not well known. General descriptions of some supracrustal formations have been made (Luukkonen & Lukkarinen 1986), and nowhere a basement has been identified. At the moment only very general conclusions can be made, indicating that the BB, Ngc, and SB including the Pyc, may be older than 1910 Ma. Calc-alkaline metavolcanic rocks and related volcaniclastic metasediments in the central part of the area may represent the youngest Palaeoproterozoic supracustal rocks in the north-western end of the Raahe–Ladoga Zone.

Deformation history

The Palaeoproterozoic formations of Ostrobothnia have been variably affected by multiphase deformation which now is manifested in fault bounded blocks, with internally different structural and metamorphic history. The deformation history can be divided into an early phase of thrusting towards the craton in the north, with D_1 and D_2 folds developed, and a younger phase of shearing which produced the major shear zones of the central Fennoscandian Shield (Kärki et al. 1993).

In central Ostrobothnia the earliest compressional structures are isoclinal to tight F_1 folds (Luukas 1991) which have been identified in well preserved mica gneisses near the border of the Archaean craton. It is plausible that this folding thickened the originally thin ore horizons in the Ruotanen Formation making the ores economic. This rarely identified structural stage has been considered to be coeval with the nappe emplacements and recumbent folds described from eastern Finland by Koistinen (1981). During the D_2 stage, the D_1 structures were openly refolded reflecting progressive deformation in the same compressional regime.

The D_1-D_2 tectono-metamorphic stage caused nappe emplacement towards east or north-east with considerable crustal thickening as a result. The abundant intrusions associated with the D_2 stage were emplaced within a very narrow time interval between 1890 and 1880 Ma. Ni-bearing mafic magmas are possibly related to deep faults along the Raahe–Ladoga Zone at this time (Ekdahl et al. in prep.).

The D_3 phase caused intense F_3 folding, which refolded the earlier flat lying structures into an upright position along the Raahe–Ladoga Zone. Contemporaneous magmatism produced a large volume of tonalites and tonalitic migmatites, related to high temperature, low pressure metamorphism at 670–800 °C and 5 kb. (Korja et al. 1994). The emplacement of pyroxene bearing granitoids at 1884 Ma, which are characteristic of the Raahe–Ladoga Zone is related to this stage. In the later stages of D_3 the deformation style changed gradually from folding to ductile shearing causing large scale dextral SE-trending strike slip faults along the Raahe–Ladoga Zone initiating major fragmentation of the crust. At the north-western end of the RLZ the dextral Ruhaperä Fault Zone (RuFZ) and the Revonneva Shear Zone (ReSZ) are examples of these shear zones (Fig. 20). West of the Raahe–Ladoga Zone the effect of the D_3 was not penetrative and more open and flat lying F_3 structures were generated. SE- and N-trending F_3 axial planes are the most conspicuous mesoscopic and macroscopic structures in central Ostrobothnia. The SE-trending structures in the RLZ and in the northern Ostrobothnia Schist Belt, east of Oulu, indicate that the compressional field was directed in SW-NE during D_3 (Kärki et al. 1993).

After the D_3 event, folds and ductile shear zones were formed during the D_4 stage. The E-trending axial planes of F_4 folds can be seen in many places in Ostrobothnia indicating that the compressional field was shifted from SW-NE to N-S at this stage. The Vihanti mine is situated at the south-eastern limb of a large D_4 antiform. The most conspicuous structural feature of the D_4 stage is the crustal scale sinistral SW-trending Oulujärvi Shear Zone (OSZ), which transects the Kainuu Schist Belt and the Archaean craton (Fig. 20). As earlier mentioned the sinistral movement on the OSZ caused a separation of the Vihanti–Pyhäsalmi belt into two separate blocks, the Vihanti and Pyhäsalmi belts, respectively. At this stage the Revonneva and Ruhaperä shear zones formed during the D3 stage were reactivated with significant movements for example around the Vihanti block. This block which is characterised by a high gravity anomaly and a high metamorphic grade is surrounded by major D_4 shear zones and nicely displays the fault controlled nature of metamorphic blocks in the RLZ (Korsman et al. 1988). Other significant D_4 features are the faults and shear zones that surround the large intrusive bodies at the western and southern edge of the Nivala gneiss complex. These faults are important for the localisation of the Au-mineralisations in Ostrobothnia. The south-western-most faults of the OSZ that extend to the Pyhäsalmi area have a strong structural influence on the Pyhäsalmi and Mullikkoräme deposits. Granitic partial melts seen as potassium-rich neosomes and abundant pegmatites along the shear zone were generated during this deformation stage in the Oulujärvi region. Age data presented from the OSZ by Kärki et al. (1995) show that granitic intrusions were emplaced 1860–1800 Ma ago. This magmatism can be related to the 1830–1810 Ma tectonometamorphic event in the south-eastern part of the RLZ (Korsman et al. 1984, Korsman et al. 1988). Kärki & Laajoki (1995) pointed out that the D_4 event is more important than yet realised in the crustal deformation history in Finland.

Metallogeny

History of mining

Introduction

Mining in central Ostrobothnia has been continuous since the second world war. The first mine, the Makola nickel mine in Nivala, was opened in 1941. The Makola mine was in production between 1941–1946 and 1951–1954. The first indications of nickel in the Hitura area were obtained during the investigations in Makola. Both deposits were found by the Geological Expedition (to day the Geological Survey of Finland, GSF). The Kopsa gold-copper mineralisation was also found during this exploration period. Production in Hitura started in 1970. Both the Makola and Hitura mines are operated by the Outokumpu Oy. The location of the mines can be seen in Figure 19.

The Vihanti zinc deposit was discovered in 1947 by the GSF and the mine was opened 1954. After producing 26 Mt in 38 years the famous mine was closed in 1992. The Pyhäsalmi deposit was discovered in 1958 when a local farmer was digging a well in his back yard. Production started in 1962 and with the present reserves mining will continue into the next century. The Pyhäsalmi mine has had three satellite mines, the Kangasjärvi mine which closed in 1985, the Ruostesuo mine which closed in 1989, and the Mullikkoräme mine, which is still in production. Also the Vihanti and Pyhäsalmi mines are owned by the Outokumpu Oy.

The grade and tonnage of the deposits and important mineralisations can be seen in Table 4.

Ni-mines

Makola

The first ore reserve estimation made by the Geological Expedition was 1.5 Mt of Ni-ore with 0.81–1.03% Ni and 0.42% Cu. Outokumpu Oy calculated the reserves to 0.7 Mt. The demand for Ni was high due to the war and the decision to start mining was fast. Makola was the first mine which was wholly planned and built by the Outokumpu Company. The mine was small and annual produc-

Table 4. Cu-Zn mines and main mineralisations in Central Ostrobothnia.

Deposit	Period	Tonnes	Cu %	Zn %	Pb %	S %	Au g/t	Ag g/t
Vihanti*	1951-1992	28 100 000	0.48	5.12	0.36		0.49	25
Kuuhkamo**		150 000		4.0				
Pyhäsalmi*	1962-	30 300 000	0.79	2.47		34.8	0.40	14
Ruostesuo*	1988-1989	240 000	0.4	2.70		30.0	0.3	8
Kalliokylä**		1 200 000	0.41	0.50			25.4	
Kangasjärvi*	1985	86 000	0.09	5.12			41.0	
Mullikkoräme*	1990-	450 000	0.23	5.99	0.62	20.0	1.21	33
Vuohtojoki***		262 000	0.21	2.96				
Säviä***		1 800 000	1.56				20.6	
Hallaperä**		2 000 000	0.57	1.1			14.0	
Rauhala**		1 200 000	1.59	6.66	1.24		0.5	67

* production, ** total mineral resources, *** indicated mineral resources

tion was planned to be 50 000 tonnes (3 000–5 000 tonnes of Ni-Cu-concentrate). In 1941–1942 the Ni-Cu-concentrates were sold to Germany and after 1942 all concentrates went to Outokumpu's smelters, first to Imatra and later to Harjavalta. After the second world war the price of the nickel collapsed and Outo kumpu closed the mine in 1946. The mine was left in care and maintenance and when nickel prices went up again during the Korean crisis, Outokumpu decided to reopen the mine in 1951. The capacity of the mill was increased to 80 000 tonnes per year. In 1954 all reserves were exhausted and the mine was closed. The total production from the Makola mine was 410 000 tonnes of ore with 0.86% Ni, equivalent to 1250 tonnes of nickel metal.

Hitura

The first holes on the Hitura deposit were drilled in 1939, but because of poor results the investigations were concentrated on the Makola deposit. The GSF restarted exploration in Nivala in 1961 and when Outokumpu obtained the mining licences of the deposit in 1964 the company started underground exploration. The results were negative, as the mineralisation, although large, was too low grade and also difficult to concentrate. However, with investment support from the Finnish state the decision to open the mine was made in 1969 and the production started in 1970.

Because of strained economy the annual production was increased from originally 300 000 tonnes, first to 450 000 tonnes and to 500 000 tonnes in 1981. When the Ni- prices collapsed in 1982 the mine was closed but left in care and maintenance. Because of the high price of Ni, the mine was opened during a short period in 1984–1985. A third start up was made in 1988 and since then the mine has been in production.

The total amount of hoisted ore is 9.3 Mt with 0.58% Ni, amounting to 38 000 tonnes of nickel metal.

Massive Sulphide Mines

The Vihanti Mine

The Vihanti mine is located in the small village of Vihanti, close to the geographical centre of Finland. The first indications of ore in the area were pyrite rich boulders discovered by local farmers in 1936. The first boulder containing sphalerite was discovered in 1939 and more pyrite-rich boulders in 1941. After systematic exploration work by the GSF (mainly geophysical measurements) the first zinc ore was discovered in 1947.

Outokumpu acquired the mining licences from the state in 1951. The reserves were estimated to 0.7 Mt of ore with 6% Zn and 0.4 Mt of pyrite mineralisation, but it was understood that the total reserves were higher. At the end of the same year development work started. The reserves were increased to more than 6 Mt with 12.5% Zn, 0.8% Cu, and 0.5% Pb.

Annual production was planned to 400 000 tonnes. In 1968 the capacity was doubled. In the 1970's the plant was rebuilt and the annual capacity was increased to 1 Mt. The mine was closed in 1992 after a total production of 28.1 Mt with 5.12% Zn, 0.48% Cu, 0.36% Pb, 25 g/t Ag, and 0.49 g/t Au.

The Pyhäsalmi and satellite mines

The Pyhäsalmi ore deposit was found in 1958 after a very intense drilling period. The first estimation of reserves indicating 12.2 Mt of ore with 0.81% Cu, 2.93% Zn, and 36.8% S, was done in February 1959. Construction works started in August 1959 and production commenced in March 1962, only three and a half years after the discovery. The mine started as an open pit and the final depth of 125 m of the open pit wasreached in 1967. Underground mining started the same year. The total production from the open pit was 6.8 Mt of ore and 5.6 Mt of waste rock.

In 1967, after extension and automatization of the processing plant, the annual production was increased from 600 000 to 800 000 tonnes. The current annual production from the underground mine is 1.08 Mt.

During the intensive exploration period after the discovery of the Pyhäsalmi deposit, several small massive sulphide deposits were found in the Pyhäsalmi region. None of these were economic by themselves. Using a separate crushing station and increasing the capacity of the processing plant, it has been possibly to mine the best parts of the different smaller deposits in satellite mines. The first satellite mine was the Kangasjärvi mine in Keitele, c. 35 km south of Pyhäsalmi. The Kangasjärvi Zn-pyrite ore was discovered by the GSF in 1964. The second satellite mine to be opened was the Ruostesuo mine in the Kiuruvesi commune c. 30 km east of Pyhäsalmi. The ore deposit was found already in 1959 by airborne geophysical measurements. The Ruostesuo mine was in production in 1988–1989. The third deposit, the Mullikkoräme deposit, was discovered by the Outokumpu Oy in 1987. The Kangasjärvi and Ruostesuo mines were small open pits while the Mullikkoräme mine was the first underground satellite mine. Production started in period in 1989–1990 from levels +50 to +140. A deep ore body called Siperia was found in 1990, and production from the +525 level started 1996.

The total production from the satellite deposits has been c. 800 000 tonnes. Production figures are found in Table 4.

Altogether seven base metal mines have been in operation in central Ostrobothnia of these three are still in production. The total metal production from the area up to the end of 1996 was: 39 000 tonnes of nickel, 1 800 000 tonnes of zinc, 300 000 tonnes of copper and 70 000 tonnes of lead. The Pyhäsalmi mine has produced 16 000 000 tonnes of pyrite concentrate and Pyhäsalmi is today the largest pyrite producer in the world. The Vihanti mine in addition produced 7000 kg of gold and 420 000 kg of silver. The amount of gold and silver produced in Pyhäsalmi is 5400 kg and 246 000 kg, respectively. All of several discovered gold mineralisations are so far subeconomic.

VHMS-deposits

Introduction

The Raahe–Ladoga Zone (RLZ) has been interpreted as a collisional boundary zone between the Archaean continent and Palaeoproterozoic, Svecofennian lithosphere. Several epochs of mineralisation and different metallogenic provinces are associated with of this zone (Ekdahl 1993). In the early orogenic stage intracratonic rifting in the east produced the Jormua-Outokumpu ophiolites, 1960 Ma in age, and the associated Cu-Zn-Co-Ni ores. Volcanic complexes and associated Vihanti–Pyhäsalmi type ore deposits, 1920 Ma in age, are related to immature island arc volcanism on the margin of the Archaean craton. Subsequent synorogenic basic and ultrabasic intrusions, 1890–1880 Ma in age, host Ni-Cu deposits. Synorogenic calc-alkaline intrusions hostnumerous porphyry type occurrences and epigenetic Au-As mineralisation. These represent the last significant metallogenic stage in the RLZ.

The Pyhäsalmi island arc (PIA) zone, which is the volcanic component of the Savo Belt, is about 10–30 km wide and at least 300 km in length. Hydrothermal activity has been confined to areas with volcanic rocks which define a discontinuous, deformed belt. According to Vaasjoki (1981) the Pb-Pb age of the Pyhäsalmi-Vihanti ores is c. 1.9–2.0 Ga and the data suggest that the island arc volcanism was generated from a homogenised crust, influenced by mantle derived magmas.

The PIA zone is known to contain about 55 mineralisations in addition to the economic ore deposits like the Lampinsaari (Vihanti), Ruotanen (Pyhäsalmi), Mullikkoräme, Kalliokylä and Kangasjärvi deposits. The total in situ metal content of the PIA zone is estimated to 2 400 000 tonnes Zn, 500 000 tonnes Cu, 100 000 tonnes Pb, and 15 tonnes Au (Gaál 1990).

According to Ekdahl (1993) the ore depos-

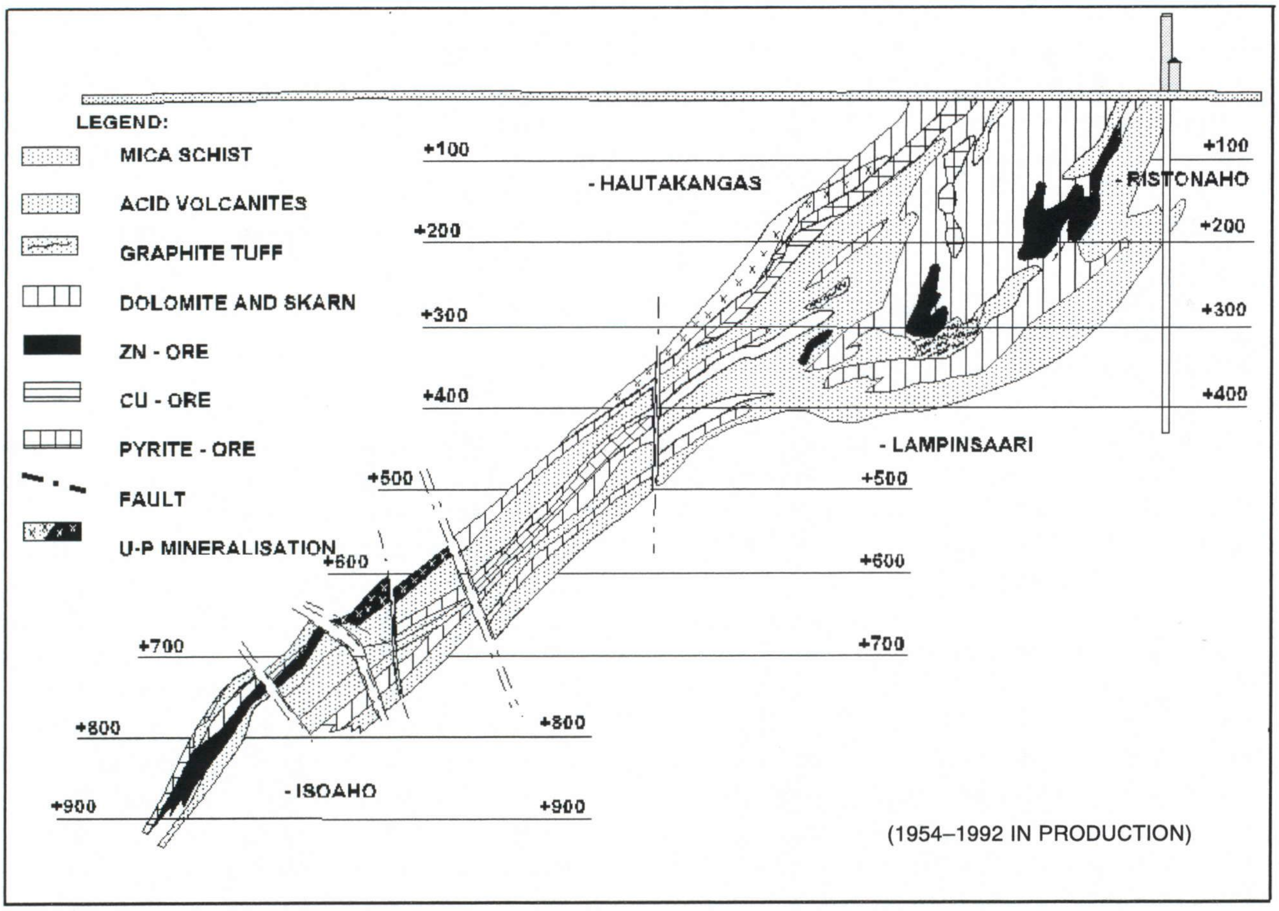

Fig. 22. Cross section 130, Vihanti Mine.

its in the PIA zone have the following characteristics:

* Volcanic complexes and zones are associated with gravimetric highs or gradients and medium- to high-grade metamorphism.
* The volcanism is submarine, tholeiitic and calc-alkaline with island arc affinity.
* Dolomite/carbonate, calc-silicate rocks, felsic volcanic rocks, chert, Uranium-Phosphorous horizons, and black schists are present in the footwall to ores.
* The vertical or lateral hydrothermal alteration is characterised by sericitization, silicification, chloritization, and the presence of garnet-cordierite-anthophyllite rocks.
* Mg, Fe, H_2O and S increase towards the ore (with a corresponding increase in the MgO/CaO ratio in mafic volcanic rocks). Conversely, Si, Ca, Na, and K decrease, as does the Na_2O/K_2O ratio in felsic volcanic rocks.
* The ore deposits are pyrite-dominated, stratabound, massive and stringer ores which display distinct zoning.
* The geometry of the ore deposits is tectonically controlled.

The Vihanti deposit

One of the few large ore deposits in the Raahe–Ladoga Zone is the Vihanti ore deposit (the whole complex including the ores is also known as the Lampinsaari Complex), which is situated near the north-western end of the Raahe–Ladoga Zone.

General geology

The host rock complex is Palaeoproterozoic in age and is composed of different gneissic rocks of volcanic and sedimentary origin. The Lampinsaari complex mainly constitutes felsic volcanic and calcareous rocks (dolomites and skarn). Cordierite bearing metasomatic rocks and black schists are also typical. The host rock to the zinc ores is commonly dolomite or skarn, although the ores are related to felsic volcanism.

The whole complex is strongly deformed in several stages, and the lithology is overturned (Fig. 22). The original volcanic vent(s) has not been detected (the hanging wall contact is tectonic and the direction or magnitude of the displacement is not known.). Different stock like plutonic rocks are common in the region (the Haapajärvi igneouscomplex), but in the Lampinsaari area they occur as dykes and veins, often associated with faults.

Ores

The ore bodies often show a clear zoning of metals. Apart from sulphides, the oldest mineralisation seems to be the uranium-phosphorous horizon (UP), which is situated near the bottom of the formation in felsic volcanic rocks, but also in skarn and dolomites. Uranium is found either in uraninite or in apatite and phosphorous in apatite. The total tonnage is more than 1 million tonnes, but the grade of uranium and phosphorous is too low for exploitation.

Two generations of sulphide mineralisations have been identified, both of which started with pyrite precipitation. The Hautakangas and Hautaräme pyrite bodies have been partially mined out, especially the Cu- and Zn-bearing parts. Some skarn lenses contain enough Cu to form separate chalcopyrite-pyrite ores. Of these some have been mined for Cu, although the Cu-grade was commonly as low as 0.5%. Pyrite and pyrrhotite were treated as gangue in these ores.

By far the most important ore type is the zinc ore. It forms several ore bodies of different size and grade and practically all mineable bodies have been mined out. The most common host rock is dolomite or dolomite skarn. Zn content varies from 3% to over 20%. Besides Zn the ore contains Cu, Pb, Ag, and S. The largest ores have been the Ristonaho, Välisaari, Lampinsaari, Isoaho, and Hautaräme ores. The youngest sulphide mineralisation is a Pb-Ag-Sb mineralisation with diffuse "clouds" of galena. This type of mineralisation contains noticeable amounts of Ag in sulphosalts together with Au. The typical host rock is a coarse diopside skarn.

Remarks

Few attempts have been made to "unfold" the deformed rock sequence. The host rock formation has originally been a single volcanic horizon with two main cycles of sulphide precipitation. No major extensions can be expected in any directions. The Isoaho Zn-ore pinch out under the 1000 m level, and is intruded by granite veins. The Kuuhkamo, Nevasaari, and Vilminko showings, a few kilometres to the south on the other hand are mineralisations where possible ore is still undiscovered.

More detailed descriptions of the Vihanti deposit can be found in Rouhunkoski (1968), Rauhamäki et al. (1978), and Rehtijärvi et al. (1979).

The Pyhäsalmi Zn-Cu-S deposit

Introduction

Production started in 1962. Underground development was coincident with open pit mining until 1976 when the open pit was closed. Underground mining has since continued and the Pyhäsalmi mine celebrated its 35th anniversary in march 1997. The average grade is 0.85% Cu, 2.85% Zn, 37% S, 0.4 g/t Au, and 14 g/t Ag. The ore reserves are c. 4 Mt and the total production has been 30 Mt. The ore from the three satellite deposit hasbeen processed in the Pyhäsalmi mill. The mill has produced a pyrite concentrate from the old tailings together with ore from the satellite mines. The total production in 1997 will be 1.08 Mt from the Pyhäsalmi mine, 0.24 Mt from the Mullikkoräme mine and 0.3 Mt from the D-pond. Altogether 40 000 tonnes of Cu-concentrate (25% Cu), 65 000 tonnes Zn-concentrate (52% Zn), 3 000 tonnes of Pb-concentrate, and 870 000 tonnes pyrite-concentrate will be produced. Some gold and silver is recovered as byproducts with the Cu- and Pb-concentrates.

Mining

The mine layout is shown in Figure 23. The main shaft, 500 m deep, is used for ore hoisting and personnel transport. The auxiliary shaft is mainly used for ventilation. There is also a blind shaft between the +730 and +400 levels for ore hoisting. Crushing stations are situated on levels +400 and +660. The decline starts from surface and continues down to the +1050 level. The deepest production level is planned to +1090. At the present, sub level stoping and bench cut and fill, are the main mining methods. Sub levels are spaced in 30–40 m intervals. The stopes are relative small, 20 000–40 000 tonnes. A high horizontal stress field (up to 120 MPa in pillars) perpendicular to the ore, together with weak wall rocks cause serious rock mechanical problems.

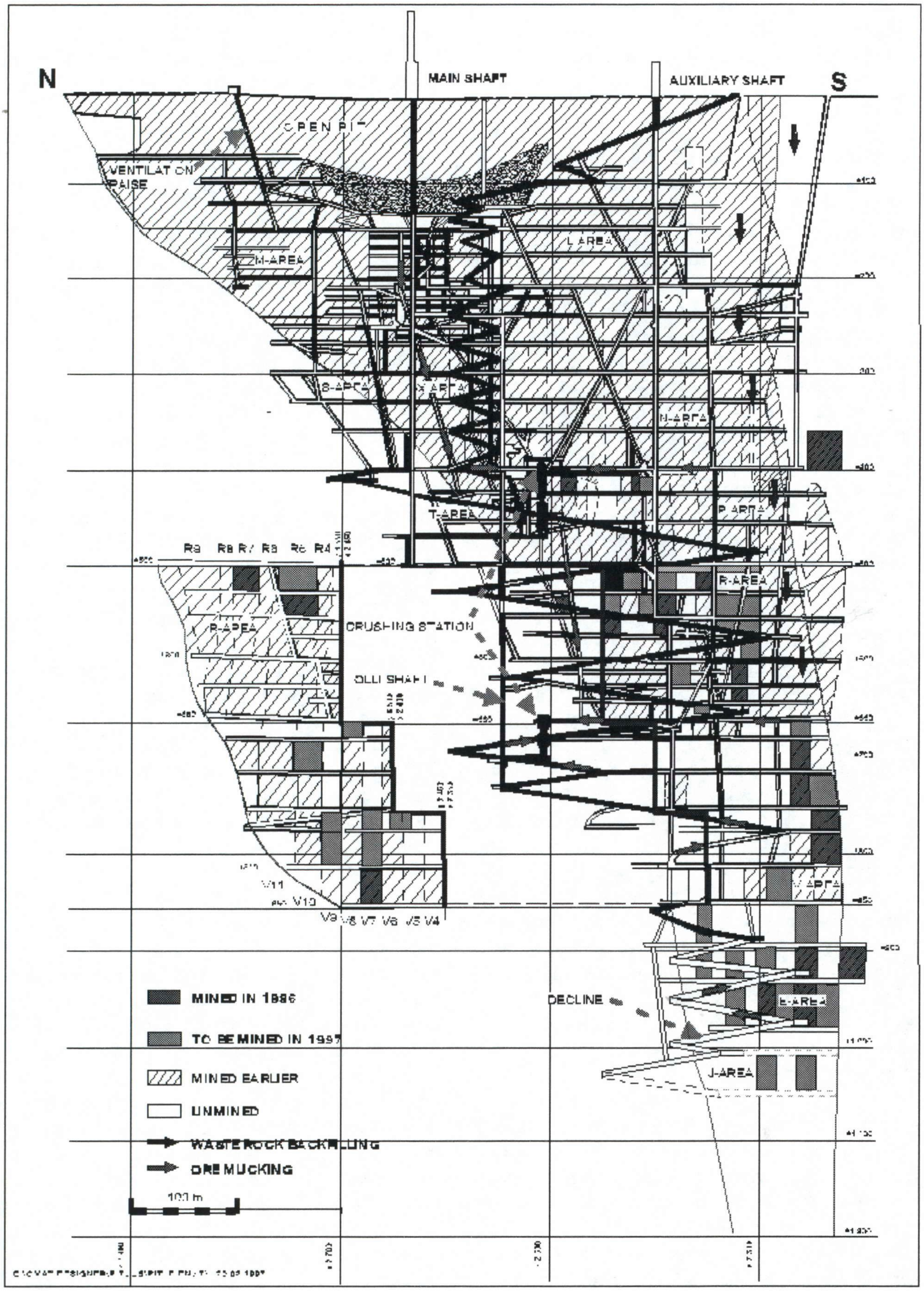

Figure 23. Lay out of the Pyhäsalmi Mine.

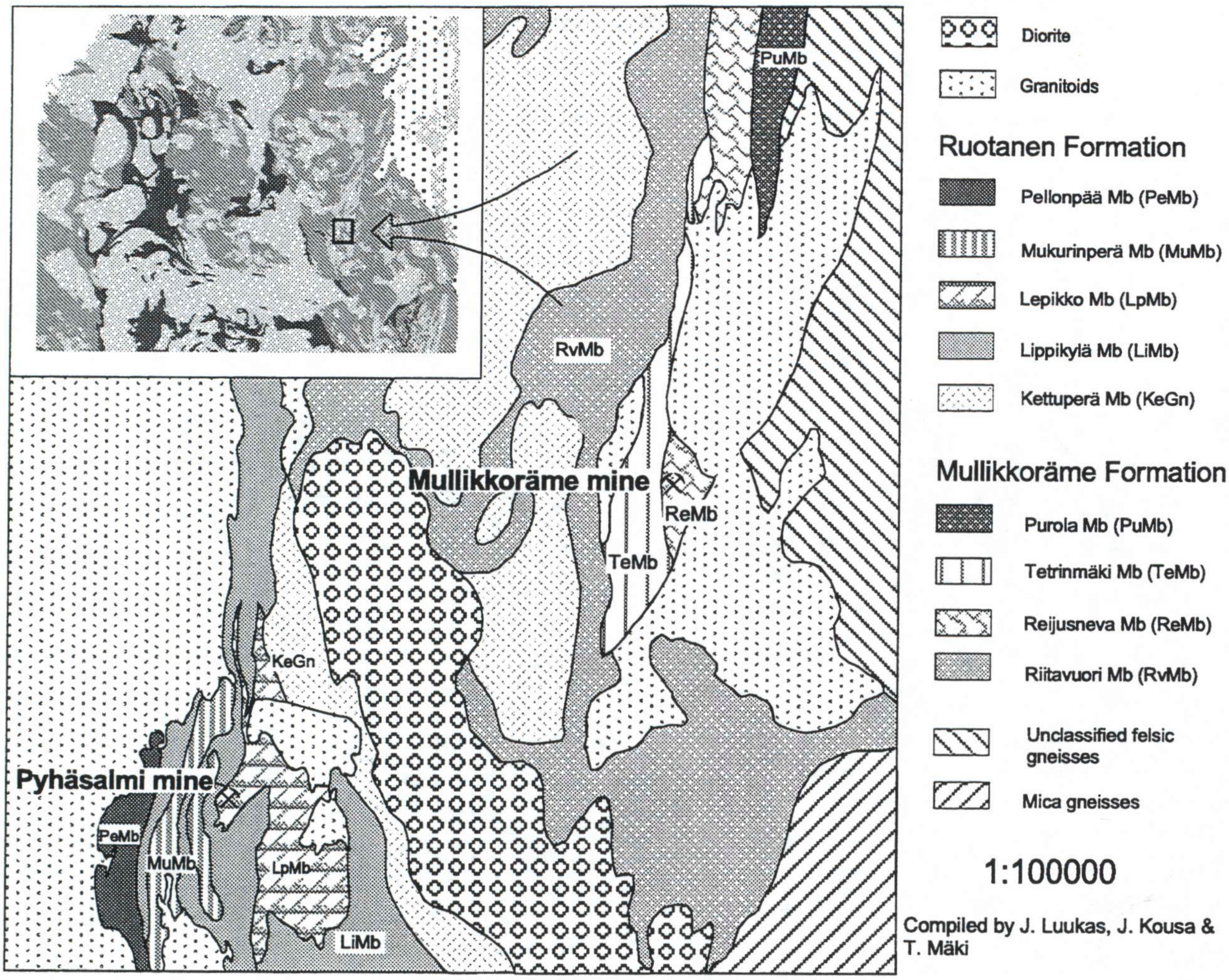

Fig. 24. Lithostratigraphic map of the Pyhäsalmi volcanic complex.

Geology

The supracrustal rocks in Pyhäjärvi are a part of a Palaeoproterozoic, Svecofennian schist belt. The NW-trending schist belt is situated between the Archaean craton in the east and the Central Finland Granitoid Complex in the west.

The metavolcanic rocks in Pyhäjärvi can be divided into two groups on the basis of field observations and chemical composition (Kousa et al. 1994). The western part of the Pyhäjärvi area belongs to the Nivala gneiss complex (Ngc) and the metavolcanic rocks there can be compared to the Kuusaa formation (KuF) (see above). The Pyhäsalmi and Mullikkoräme ores are situated in the eastern part of the volcanic belt (the Pyhäsalmi volcanic complex). The Pyhäsalmi volcanic complex (Ruotanen schist belt in Helovuori, 1979) can be divided into the Ruotanen Formation (RuF) and the Mullikkoräme Formation (MuF) (Fig. 24). A large gneiss area (the Kettuperä gneiss), which is intruded by syntectonic plutons is situated between the Ruotanen and Mullikkoräme formations. Both formations contain large areas of mafic volcanic rocks with pillow lavas (the Mukurinperä Mb and Tetrinmäki Mb), sodium-rich rhyolitic volcanic rocks (the Lippikylä Mb and Riitavuori Mb), and volcaniclastic rocks (the Pellonpää Mb and Purola Mb). The stratigraphy of the area is still unsolved. According to Lahtinen (1994) the Kettuperä gneiss and the rhyolites in the Riitavuori and Lippikylä Mb:s are chemically similar and they may be genetically related. The age of the Kettuperä gneiss and the rhyolites, 1.93 and 1.92 Ga respectively, also suggests a common history (Kousa 1990). Age determinations for the plagioclase porphyrites which have been found as inclusions in the massive ore indicate distinctly younger ages at 1875 Ma (Helovuori 1979). These plagioclase porphyritic inclusions as well as the quartz-porphyry and amphibolite inclusions, are unaltered and represent younger intrusive dykes. Similar dykes have been found in outcrops and drill cores outside the massive ore.

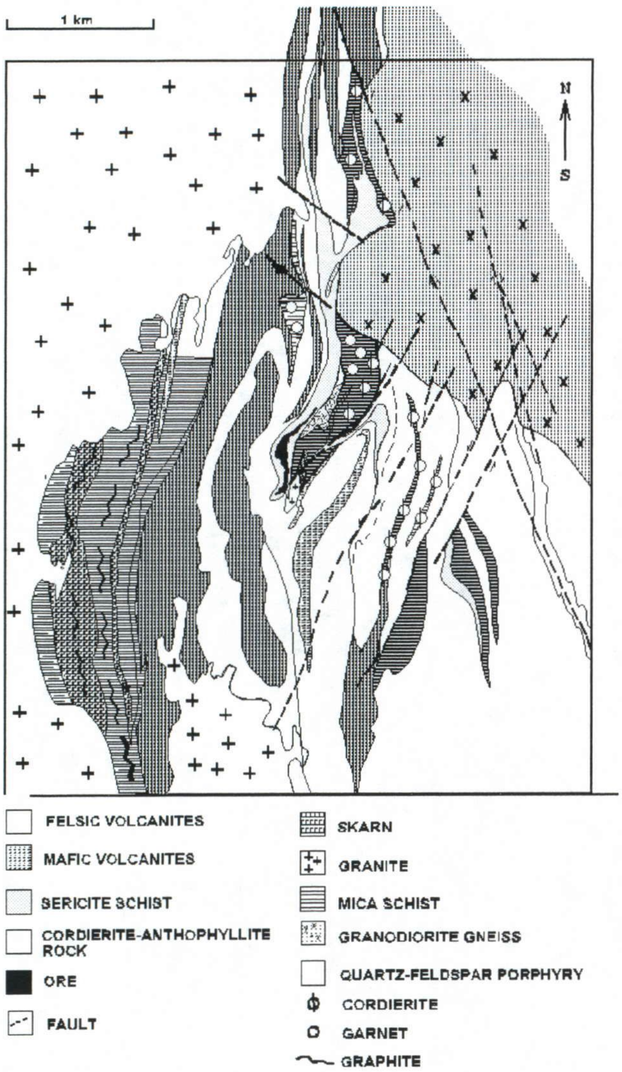

Fig. 25. Geological map of the Ruotanen formation.

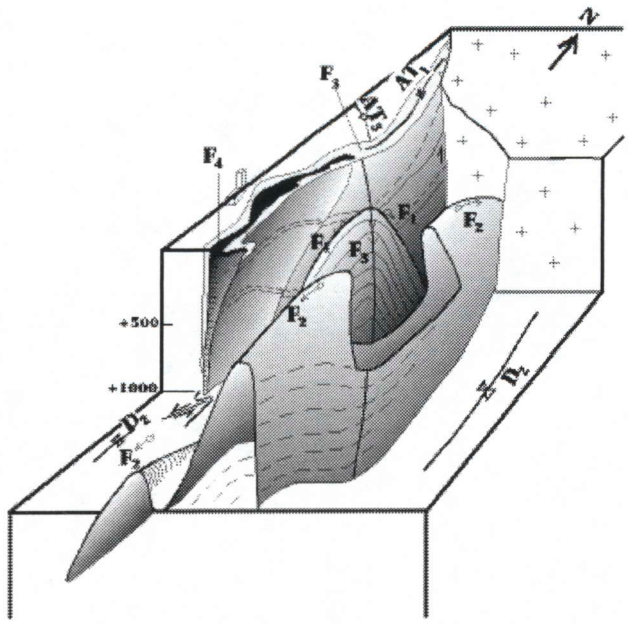

Fig. 26. Structural model of the Pyhäsalmi ore deposit.

Field observations indicate that most of the mafic volcanic rocks seem to be younger than the main part of the felsic volcanic rocks. The volcanism started with felsicvolcanism in an extensional continental margin, followed by mafic volcanism in a rifted marine environment. Large scale hydrothermal alteration is associated with this stage causing strong sodium enrichment in the rhyolites. Ore formation near the centres of mafic volcanism seems to be related to this period. Without longer hiatus, the volcanism continued with more calc-alkaline volcanism south and west of the Pyhäsalmi volcanic complex.

Geology of the ore deposit

The Pyhäsalmi ore deposit is a typical volcanic hosted massive sulphide deposit. The volcanic rocks are mainly felsic pyroclastic rocks and coherent quartz-porphyries. Mafic volcanic rocks are coarse-grained tuff breccias and lavas, including pillow lavas. Mafic and felsic dykes are common.

The stratigraphy is unclear. Polyphase deformation together with amphibolite facies metamorphism make the interpretation difficult. Both felsic and mafic volcanic rocks are strongly altered near the ore. Geology of the mine area is shown in Figure 25 and the structural model of the ore indicating different deformation phases, is explained in Figure 26.

The ore body has a complex shape due to the polyphase deformation and is surrounded by a large alteration zone. The contact between unaltered and altered volcanic rocks can be sharp or gradational. The thickness of the altered rock sequence at the surface is about 100 m in the west and 300 m in the east (Fig. 27). At the deeper levels the alteration zone is only a few meters thick. Sericite-quartzites with a high pyrite content are present adjacent to the ore. Pennitised cordierite porphyroblasts are common. Two zones of cordierite-anthophyllite rocks occur in the footwall, partly within the sericite quartzites. A zone of cordierite mica gneisses that contain portions of a cordierite-anthophyllite rock occurs outside the hanging wall sericite quartzites. The folded alteration zone is over 5 km long at the surface, i.e. the Lepikko Mb in Figure 25. A 3–15 m thick talc-schist occurs near the footwall contact, partly inside the ore (Fig. 27). This schist is 100–200 m long and 200–300 m deep and pinch out with depth. This talc-schist often contains high grade Zn-mineralisation.

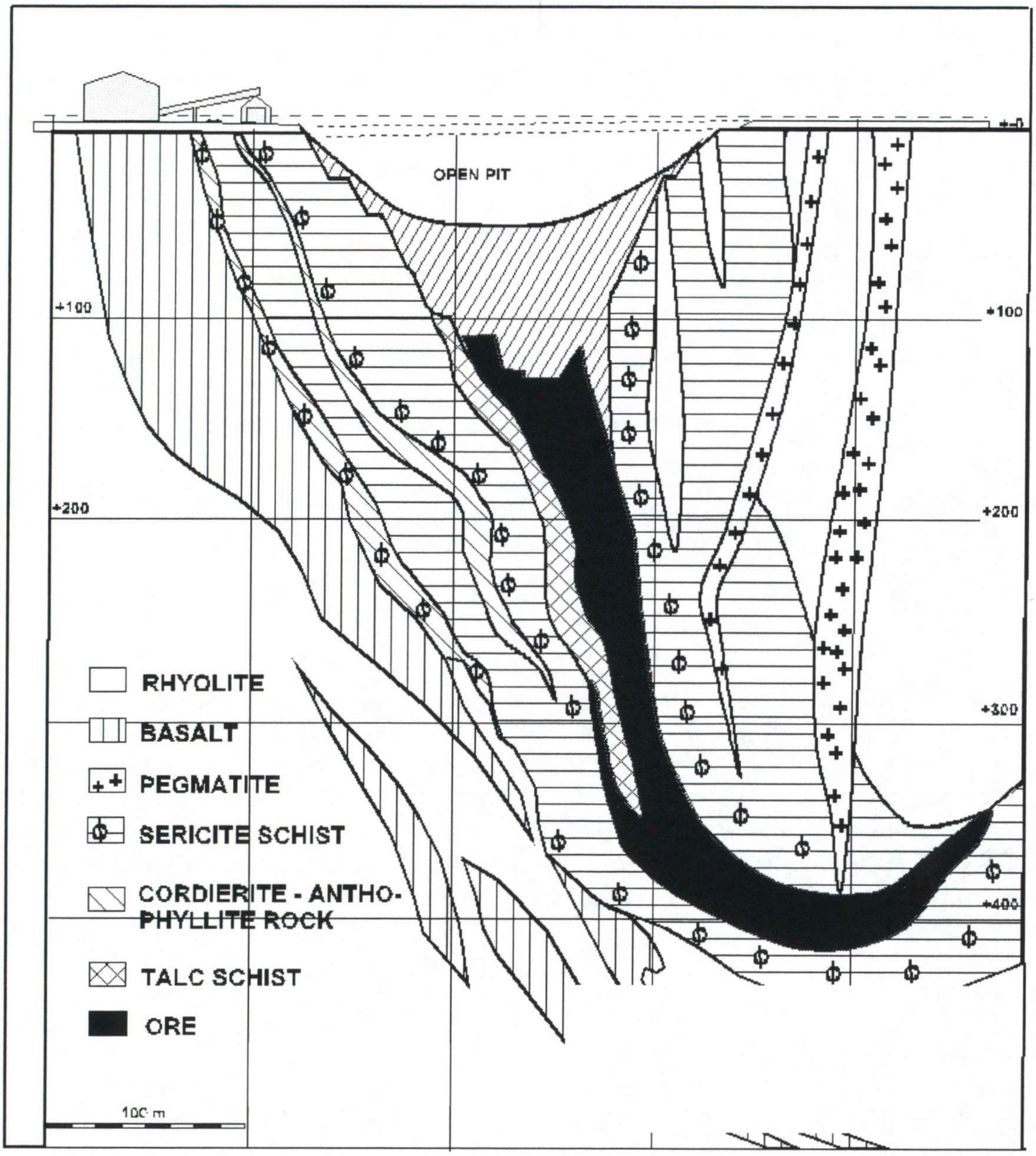

Fig. 27. Profile x=2600, Pyhäsalmi Mine.

Rock chemistry

The chemical composition of the different rock types in the Pyhäsalmi area is presented in Table 5. The felsic volcanic rocks are sodium-rich rhyolites with high a SiO_2 content and the mafic volcanic rocks are basaltic low K-tholeiites of primitive island arc type. The volcanism was thus bimodal in character. Sericite-quartzites and cordierite gneisses were originally felsic volcanic rocks which can be deduced from the TiO_2/Zr ratio while the cordierite-anthophyllite rocks were originally mafic volcanic rocks.

Alteration

The rhyolites in the Ruotanen formation are enriched in sodium. Near the ore the rhyolites are altered to sericite-rich schists with disseminated pyrite (sodium depletion and enrichment of potassium). Cordierite bearing

Table 5. Chemical composition of the rocks in Pyhäsalmi mine. From Zr to Ba in ppm, except in sample 6.

	1	2	3	4	5	6
SiO_2	48.9	75.3	72.6	54.9	54.3	46.5
TiO_2	0.48	0.09	0.17	0.52	0.14	0.53
Al_2O_3	14.1	11.7	12.1	15.2	9.44	16.6
FeO	10.5	1.79	5.76	8.82	2.8	12.2
MnO	0.2	0.03	0.01	0.11	0.10	0.28
MgO	5.18	0.07	0.57	5.37	25	8.57
CaO	8.94	0.65	0.18	0.70	0.52	1.69
Na_2O	3.95	6.03	0.49	2.44	0.78	0.45
K_2O	0.25	0.49	2.64	1.68	1.95	0.41
S	25	7	575	192	667	338
Zr	36	178	105	76	35	280
Cu	200	14	288	134	882	301
Zn	28	28	1018	68	579	9.9 %
Pb	6	9	78	20	43	512
Ba	437	319	2961	788	1142	2.9 %

1. Basalt, railway cut, 200 m east of ore
2. Quartz porphyry, 300 m southeast of ore
3. Sericite quarzite, east side
4. Cordierite gneiss, east side
5. Talc-chlorite rock, footwall contact
6. Cordierite-anthophyllite rock, footwall, +210- level

sericite schists and quartzites, with high MgO content exist in the hanging wall. The basalts are altered to cordierite-anthophyllite rocks that have clearly higher MgO content and lower CaO content than the originalbasalts (Table 5). The talc schists are strongly deformed and altered and are originally probably dolomitic limestones.

Ore types and structures

The ore body is 650 m long and 80 m wide in the centre. The shape of the ore body resembles an open "S" which tails cut off at both ends. Four different deformation events have affected the ore (Luukas 1992) and have also caused mobilisation. The ore is intruded by pegmatites. The ore continues down to at least 1300 m below the surface and is in the deepest part only 5–15m thick. The contacts of the massive ore are sharp and conformable, but remobilised sulphide veins cut the country rocks at high angles. Fragmented felsic dykes and possibly hydrothermal limestone inclusions are common in the ore.

The composition of the Pyhäsalmi ore varies both horizontally and vertically. As a rule sphalerite is concentrated in the central part of the ore and chalcopyrite near the contact. The highest barite contents are generally encountered in the sphalerite-rich areas. The Pyhäsalmi ore is a massive pyrite ore with 70% sulphides. The sphalerite-rich ore is in some places finely banded and thin porphyritic bands are common. Round pyrite phenocrysts occur in the fine-grained sphalerite matrix of the porphyry ore. A pyrite dissemination which in some places has a breccia structure exists around the massive ore. Pyrrhotite has replaced pyrite in the southern end of the ore. Pyrrhotite replacement seems to be related to the intrusion of pegmatites and is common in strongly deformed (D4) areas.

Mining technique

Ore delineation and assessment is based on diamond drilling, percussion drilling, bore hole geophysics and geological mapping. Diamond drilling is carried out by two drilling rigs. Underground diamond drilling is scheduled at a yearly rate of 10 000–11 000 m. Drilling is done in two shifts with one man per shift. 50% of the drilling is for ore delineation and 50% for exploration. Investigation drillings are normally performed in a two stage procedure. Initial exploration holes are made by diamond drilling from the decline. The length of the holes varies from 100 m to 300 m. The holes are drilled in fixed profiles with 25 m intervals. Secondary diamond drilling is done after development drifts are ready in the footwall. The profiles are drilled after the initial stope plans. Drilling profiles are situated in the middle of the stope if it is 10–15 m wide, but if the stope is over 15 m wide two or more profiles are drilled about 10 m from each other. Drilling profiles are always perpendicular to the ore.

Underground percussion sample drilling is done by a Tamrock Solo 505 electro-hydraulic percussion drilling machine. The percussion holes are 20–50 m long. The sludge is collected with a Thompson sludge cutter at 0.9 m intervals (half of a rod). Sludge samples are logged and assayed. Sampling is done in horizontal holes and holes drilled upwards. Down hole geophysical measurements are done with a OMS-log system. Gamma-gamma (density) measurements is used for determinations of the massive ore contacts and inductive conductivity measurements for estimations of the contact between pyrite- and pyrrhotite ore. Percussion sample drilling is scheduled at a yearly rate of 8 000 m. Bore hole logging with the OMS-logg is also made in production holes, when it is necessary to identify large wall rock inclusion in the ore or pyrrhotite- from pyrite ore. Increased information (sample grid from each 20 m to 10 m) with accurate surveying and better positioning of diamond drill and percussion holes has helped the mine to decrease waste rock dilution from 30% in 1980 to 8% today.

The Mullikkoräme mine

The Mullikkoräme ore deposit was first transected by drilling in 1987, drilling geophysical anomalies. An underground mineralisation close to the surface was discovered. Exploration geophysics and intense core drilling continued and in 1989 Outokumpu Finnmines Oy took the decision to exploit the A-mineralisation, which consisted of three different ore bodies with a total tonnage of 247 000 tonnes with the grade of 7,75% Zn (in situ). Mining of those ores took place in two periods between 1990–1993, and the total amount of ore mined was 310 000 tonnes.

During the mining period geophysical investigations (especially TEM-37) and core drilling continued at deeper levels. The deep ore zone was discovered by drilling in 1991. Drifting of the decline to the +540 level was ready in 1995 and inventory drilling of the Siperia ore (the southern part of the "Deep Ore") was made in 1994–1995. The total ore reserves of the Siperia ore was initially 715 000 tonnes with the grade 8,28% Zn, 0,43% Cu, 1,2 g/t Au and 81 g/t Ag. Production began in May 1996. The ore is transported to the Pyhäsalmi mill for treating.

General geology

The Mullikkoräme Formation (Fig. 28) is about 5 times 2 km and is situated adjacent to a large north trending tectonic zone. Although the volcanic complex has much in common with the Ruotanen Formation in the Southwest, it is a separate formation with different ores types. The Pb-isotope composition of Mullikkoräme is comparable to other deposits in the Pyhäsalmi-Vihanti area (Mati Vaasjoki pers. comm.). Also here the volcanism has been bimodal and the mafic rocks typically consist of pillow lavas while the felsic rocks are rhyolitic lavas and pyroclastic rocks. Mafic volcanic rocks predominate in the west while felsic rocks are more common in the east. Outside the ore zone a mylonitized contact of a gneissic granite appears abruptly. Folds are seldom seen, probably because of the faulting and shearing which controls both the mineralisation and alteration zones in the volcanic rocks. The dip of the strongest schistosity (S_2) is subvertical and the plunge of the fold axis is towards south-southwest. The metamorphic grade is much more lower than at the Pyhäsalmi, mostly in greenschist facies. Alteration minerals include: chlorite, sericite, phlogopite, talc, quartz, cordierite, and pyrite. Some alteration types are hydrothermal, and some are related to regional metamorphism (talc schist derived from dolomite).

Ore formations

The Mullikkoräme deposit is a typical small size polymetallic massive sulphide deposit. The largest ore body is the Siperia ore body which contains 700 000 tonnes of ore with zinc as the economically most important metal. The Siperia ore body has an average Zn content of over 8%, but the margins of the ore bodies, which commonly are vein-like, may contain over 30% Zn. The copper content averages 0.4% but the western wall often has a higher content. The average lead content is about 1.2% and the sulphur content is about 18%. In addition, the ore contains approximately 1 ppm Au. Pyrite is the most abundantsulphide followed by sphalerite, chalcopyrite, galena (commonly accompanied by Ag), and pyrrhotite. Magnetite, and barite also occur. The immediate host rock is often dolomite. In the southern part of the Siperia ore body the host rock is dominated by a

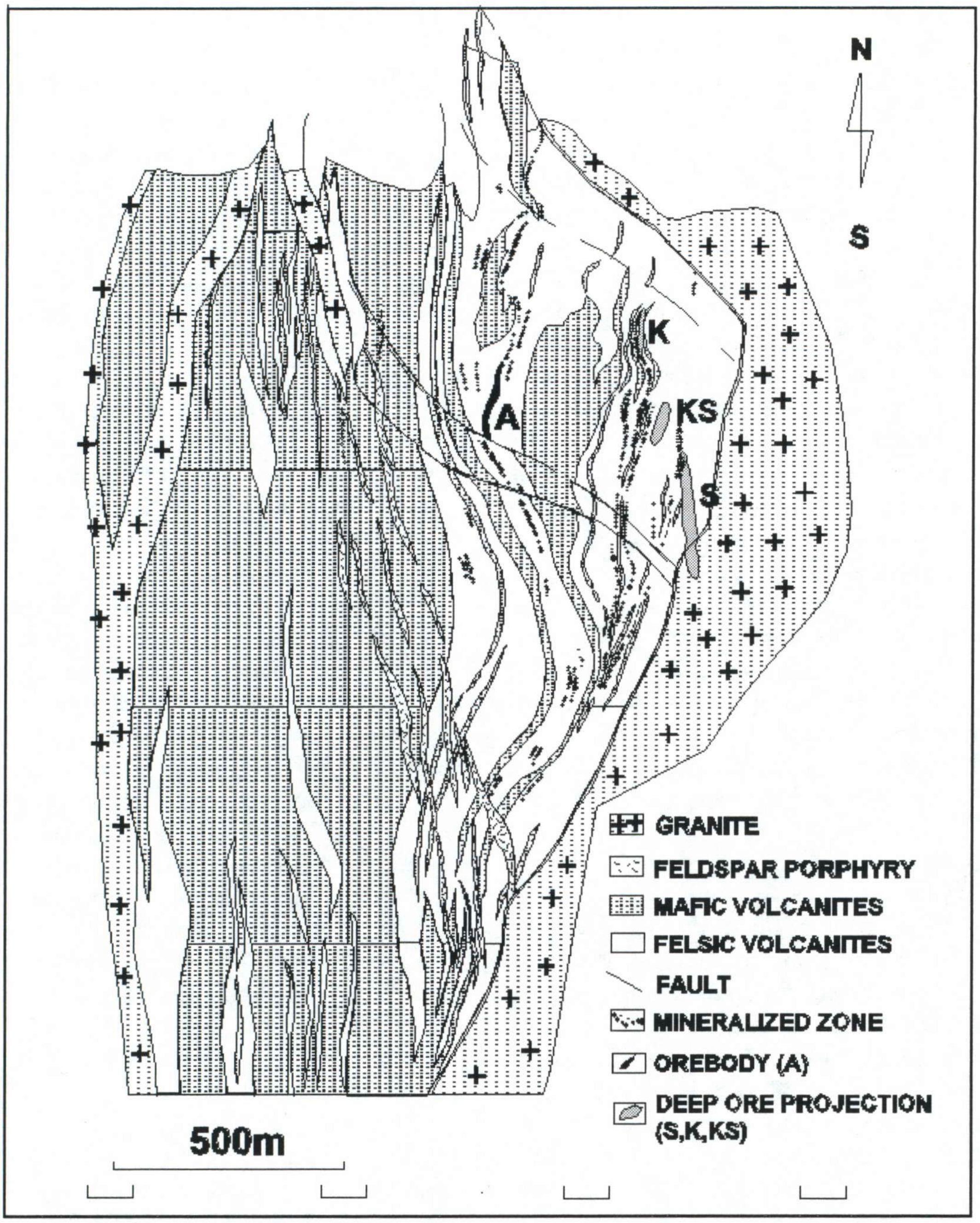

Fig. 28. Geological map of the Mullikkoräme formation.

felsic volcanic rock with talc-chlorite schist intercalations.

The other ore bodies in the Mullikoräme deposit are smaller and have lower metal contents. A typical zoning of metals inside individual ore bodies and also between different ore bodies is recognisable.

Other VHMS-type mineralisations in central Ostrobothnia

Apart from the Vihanti and Pyhäsalmi deposits several smaller mineralisations have been found in this region. The Säviä, Kalliokylä, Kaskela and Kangasjärvi mineralisations are hosted by volcanic rocks, and the Hallaperä and Vuohtojoki mineralisations by tuffaceous metasedimentary rocks. High metamorphic grade and strong deformation make the interpretation of the genesis for these mineralisations difficult.

The Säviä Cu-Zn deposit

The Pielavesi-Pyhäsalmi ore zone is oval shaped and c. 40 km wide and 100 km in length. It is characterised by bimodal volcanism, hydrother-

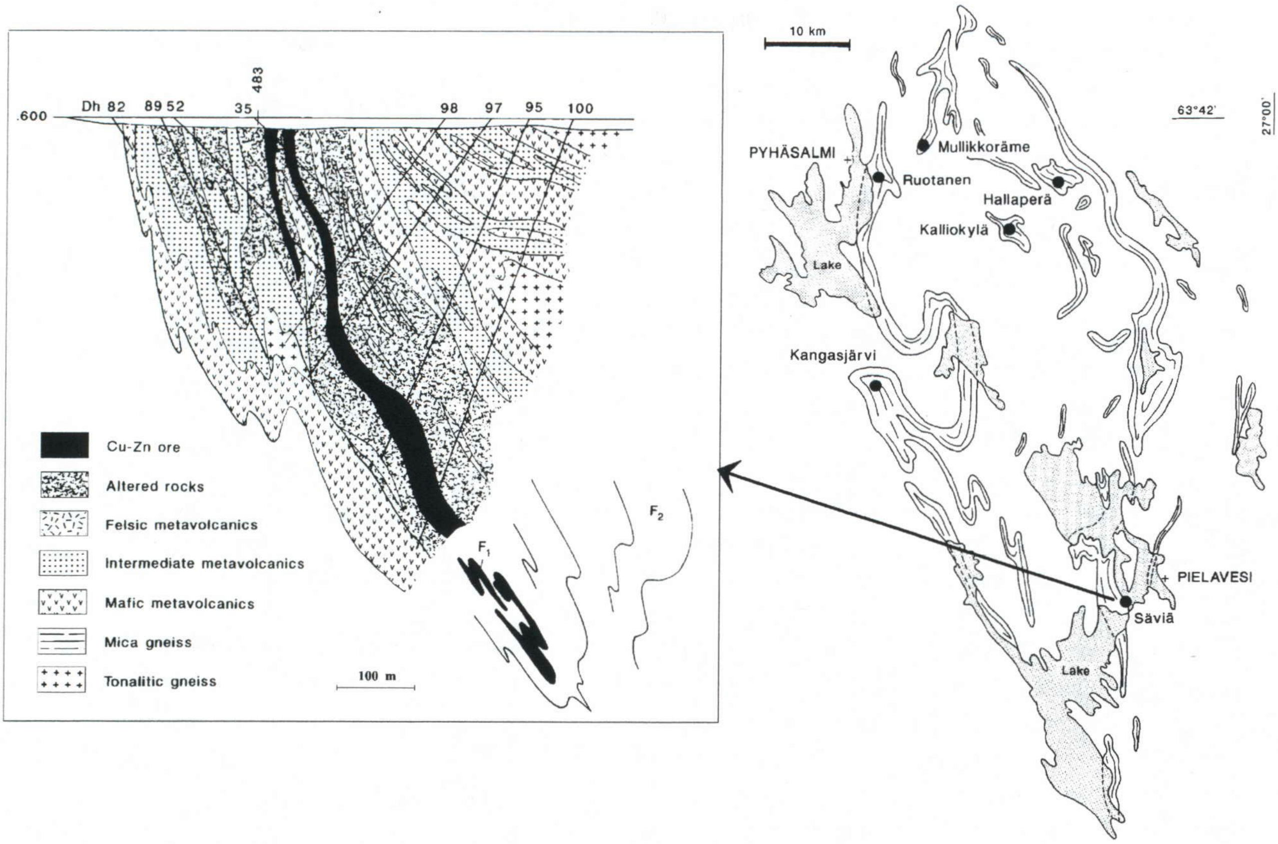

Fig. 29. The Pyhäsalmi-Pielavesi ore zone with a typical section over the Säviä deposit.

mal alteration and stratabound Zn-Cu mineralisation (Fig. 29). Smaller mineralisations tend to occur in close proximity to known major ores, such as the Ruotanen, Kangasjärvi and Säviä deposits.

The Säviä Cu-Zn deposit occurs within hydrothermally altered, felsic, pyroclastic rocks in the upper parts of the lowermost volcanic sequence. Hydrothermal alteration resulted in the transformation of primary minerals into an assemblage consisting of chlorite and montmorillonite, which was further recrystallized during metamorphism to a garnet-cordierite-anthophyllite assemblage. Ore deposition took place during the same hydrothermal processes, during which metals were liberated from silicates and precipitated as sulphides in proximity to volcanic vents (Makkonen 1981).

The Säviä ore body was originally a stratiform massive sulphide sheet, 3–5 m thick, with underlying disseminated and veined stinger ores which were folded and tectonically thickened during the isoclinal F_1 phase and also affected by tight F_2 folding, so that it is now c. 20–30 m thick. Underlying garnet-cordierite-anthophyllite rocks are located on either side of the tightly folded ore body (Fig. 29). During the D_3 deformation the Säviä deposit was split into separate lenses and overthrust towards the north-west.

The ore consists of pyrite, chalcopyrite and pyrrhotite, with occasional sphalerite. Angular fragments of wall rock suggest remobilization of ore while the country rocks were deformed in a brittle manner. Chalcopyrite increases in abundance downwards, and the highest grades are found in the massive ore. Chalcopyrite is also distinctly enriched where the ore has been brecciated. Moderately elevated Au and Ag contents have been recorded in the main ore body and small amounts of barite, carbonate and anhydrite occur in association with copper ore.

The Säviä deposit is estimated to contain around 4.0 Mt of ore, with 1.1% Cu and 28% S and a separate sulphur-zinc ore body contains an additional 1 Mt, with 2.0% Znand 33.0% S (Laitakari 1968) (total mineral resources). The Au and Ag grade of the Säviä deposit is in average 0.2 ppm and 5–10 ppm respectively.

The Kangasjärvi Zn-Cu-S deposit

The Kangasjärvi deposit occurs within the southern extension of the volcanic schist belt in which the Pyhäsalmi deposits is situated in the northern end (Fig. 20). The deposit is hosted by a succession of mafic, intermediate, and felsic volcanogenic rocks and their altered derivatives. Rasilainen (1991) interpreted the sequence as formed in a convergent plate margin setting. Country rocks include altered cordierite-sillimanite-garnet-anthophyllite gneisses, cummingtonite-bearing gneisses and calc-silicate rocks. The volcanic sequence is characterised by magnesium enrichment and by the absence of carbonate minerals, indicating a proximal Kuroko-type environment of deposition (Rehtijärvi 1984).

The Kangasjärvi deposit has also been overthrust towards the north-west and has a highly elongate, flattened profile, plunging towards the south-east at about 45°. The ore is clearly stratabound and pyrite and sphalerite are present as layered bands and massive aggregates, with rare chalcopyrite and pyrrhotite. Gangue minerals include quartz, barite, muscovite, chlorite and diopside. Galena, gold and silver has been found at the margins of the ore body, while the abundance of zinc and the Zn/Cu ratio decreases in the lower part of the deposit (Rehtijärvi 1984). Hydrothermal alteration increases in intensity towards the footwall of the deposit and is characterised by increases in Fe, Mn, Mg, P, Ba, Au, S, Zn and Co and decreases in Ca, K and Sr (Rasilainen 1991). The Kangasjärvi deposit is analogous to the Pyhäsalmi ore body both in terms of its metal abundance and its structural position. The deposit was mined in 1986 by Outokumpu, who extracted c. 86 000 tonnes of ore averaging 5.4% Zn, 0.06% Cu and 38% S, which was concentrated at their Pyhäsalmi plant.

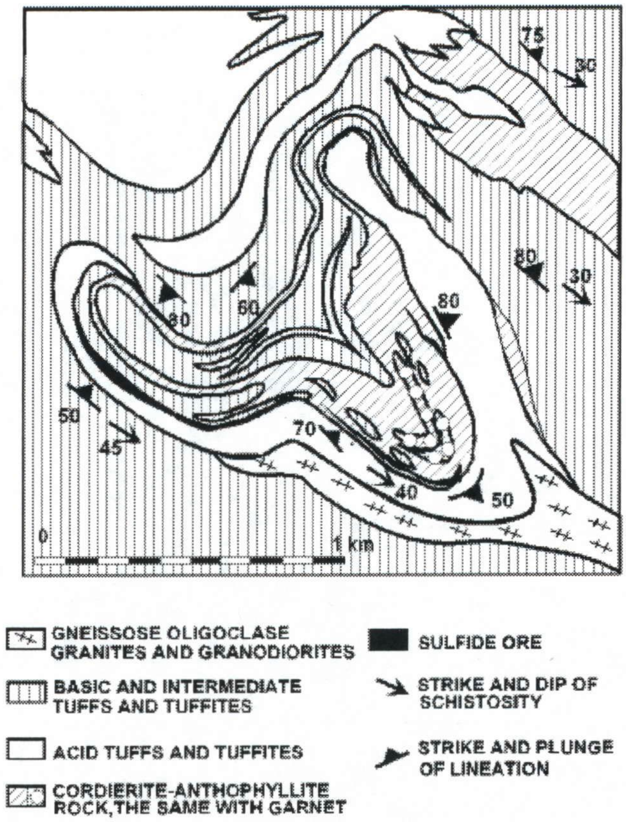

Fig. 30. Geology of the Kalliokylä deposit (after Huhtala 1979).

The Ruostesuo Zn-Cu deposit

The Ruostesuo Zn-Cu deposit, which was mined in 1988–1989, is part of a large mineralisation system in the Kalliokylä volcanic complex c. 30 km east of Pyhäsalmi. The mineralisations were found in 1959 by airborne geophysical measurements by the Outokumpu Company.

The ores occur in the altered portions of a rock suite that contains felsic, intermediate, and mafic volcanic rocks. The host formation forms part of a schist area surrounded by gneissose, migmatitic oligoclase-dominated granites and granodiorites rich in inclusions (Huhtala 1979). The strongly folded formation is metamorphosed in granulite facies (Fig. 30). Mining and ore reserve estimation of the Ruostesuo deposit was problematic because of the strong mobilisation of the ore.

The ore is situated in the transition zone between the felsic volcanic rocks and the overlying mafic volcanic rocks. The rocks around the ore are chemically altered, resulting in almost total depletion of calcium and sodium. Felsic rocks are now cordierite- and sillimanite-bearing schists, which contain biotite and garnet. Coarse grained, massive or foliated cordierite-anthophyllite rocks, cordierite-anthophyllite-garnet rocks, anthophyllite amphibolite, and cummingtonite gneisses occur as alteration products of mafic tuffs and tuffites. The formation contains separate ore bodies located in a ribbon-like folded zone.

The ores are brecciated or massive pyrite-pyrrhotite occurrences with some chalcopyrite and sphalerite. The ores in Kalliokylä differ from each other geochemically, particularly in their zinc content. In the south-east, ores in cordierite-anthophyllite rocks are poor in zinc, assaying 0.2 to 0.4% Zn and 0.4 to 0.6% Cu. In the north-east (the Ruostesuo deposit) the ores are hosted by felsic tuffites, amphibolites and cummingtonite gneisses. These ores assay 2.4% Zn and 0.4% Cu. In Table 4 the Kalliokylä figures represent all mineralisations except Ruostesuo.

The total production from the Ruostesuo deposit was 238 000 tonnes with 0.3% Cu, 2.63% Zn and 31.1% S.

The Hallaperä Zn-Cu mineralisation

The Hallaperä Zn-Cu mineralisation was found in 1967 by Outokumpu Oy. This pyrite-pyrrhotite mineralisation was detected by airborne geophysical methods (Huhtala 1979). The country rocks are dominated by mica gneisses of sedimentary origin that often contain garnet, sillimanite and muscovite. The mica gneiss contains hornblende- and cummingtonite-bearing bands and quartz-oligoclase schists, which indicate a tuffaceous origin (Huhtala 1979).

The sulphide ore form a flat body, about 2 km long, which is situated in altered gneisses close to the contact with the oligoclase granite. The alteration zone around the ore is composed of fine-grained cordierite gneisses and coarse-grained garnet-cordierite and cordierite-anthophyllite gneisses (Huhtala 1979). The ore is either disseminated or massive. Pyrrhotite, pyrite, sphalerite, and chalcopyrite are the main minerals. Magnetite is abundant and is locally intergrown with pyrite. The best parts contain c. 1% Cu and 0.5% Zn (Huhtala 1979). The total tonnage of the mineralisation is c. 2 Mt. According to Pajunen (1987) there is a clear Mg increase in rocks near the deposit and at least part of the alteration halo is of metamorphic origin. Due to the high grade metamorphism the genesis of the mineralisation is an open question. The deposit is controlled by prominent NE-trending deformation structures (Pajunen 1987).

The Vuohtojoki Zn-Cu mineralisation

The investigation in the Vuohtojoki area started in 1958 when a local farmer found a zinc rich boulder. Ground geophysical measurements and subsequent diamond drillings led to the discovery of the mineralisation in 1959 by the GSF. The area is completely devoid of outcrops and all geological interpretations are made from drill cores. The predominant rock types are a biotite-plagioclase gneiss with hornblende bearing portions and a quartz-feldspar schists consisting of a variety of volcanic rocks and intercalated sediments. Thin volcanogenic amphibolites, some of which contain cummingtonite are also present in the area (Huhtala 1979).

Pyrite-pyrrhotite mineralisations occur in alteration zones containing quartz, cordierite, biotite, anthophyllite, sillimanite, garnet, andalusite, and muscovite. The mineralisation is composed of several small lenses in a 2 km long zone. Total reserves are estimated at 0.7 Mt of 3.2% Zn and 0.3% Cu.

The Rauhala Zn-Cu-Pb deposit

A stratiform Zn-Cu-Pb deposit, the Rauhala deposit, is situated in central Pohjanmaa c. 10 km east of the town of Ylivieska. A thin and folded ore sheet is hosted by metasedimentary rocks which are intruded by quartz-diorites (Västi 1989). The major ore minerals are pyrrhotite, sphalerite, chalcopyrite, galena, and pyrite. The deposit is geochemically zoned, resembling other volcanic- or sediment-hosted massive sulphide deposit with a vertical zoning of Cu+As+Au-Zn-Pb+Ag+Sb+Ba from bottom to top and a lateral zoning of As+Au-Cu-Zn-Pb+Ag+Sb from distal to proximal (Rasilainen & Västi 1989).

The characteristics of the Rauhala deposit are very similar to other Precambrian massive sulphide deposits formed on the seafloor by hydrothermal exhalative processes. The galena lead of the Rauhala deposit differs from the lead in the Vihanti–Pyhäsalmi deposits and belong, according to Vaasjoki (1989), to the younger lead group of the Central Finland Granitoid Complex.

The Rauhala deposit has later been investigated by the Outokumpu company and new ore reserve estimates have lowered the earlier figures markedly. Original figures were 1.2 Mt of ore with an average grade of 6.66% Zn, 1.59% Cu, 1.24% Pb, 67 ppm Ag, and 0.5 ppm Au. The deposit has not been mined because of the shallow dip (30°), thin ore horizons, and problematic mineralogy.

The Hitura Ni-Cu deposit

Introduction

After the third start up of the Hitura mine in 1988 the mine has been in operation first as an open pit and after 1990 production gradually went underground. This was feasible due to a

Table 6. Nickel ore hoist in Finland 1939-1996

Mine	Period	Orehoist tonnes	Grade %Ni	%Cu	Nickel tonnes	Notes
Makola I	1941-1946					
Makola II	1951-1954	410271	0.86	0.43	1250	Makola I & II
Kotalahti	1959-1987	12300000	0.72	0.27	76634	
Telkkälä I	1969-1970	211331	1.06	0.30	1700	
Telkkälä II	1989-1991	390000	1.41	0.35		included in Enonkoski
Puumala	1970	24000	0.67	0.24	114	
Hitura	1970-	9285524	0.58	0.21	37683	
Kylmäkoski	1971-1974	689586	0.50	0.27	1129	
Petolahti	1972-1973	7000	0.65	0.70	323	
Vuonos Ni	1972-1977	5500000	0.20	0.04	8584	
Vammala	1973-1994	7400000	0.69	0.43	39000	
Enonkoski	1985-1994	6700000	0.76	0.22	40000	+Hälvälä and Telkkälä
Hälvälä	1988-1992	200000	1.41	0.35		included in Enonkoski
Tainiovaara	1989	19984	1.40	0.12	319	

sales contract for concentrate concluded with Kokkola Chemicals Oy for the period 1991–1996. At the Kokkola Chemical Plant, the Hitura concentrate was dissolved in an autoclave to produce nickel salts including sulphate, carbonate, chloride, acetate, and nickel powder.

In the future the Hitura concentrate will be smelted at Harjavalta. The ore hoist is 600 000 tonnes per year and the mine annually produces about 3000 tonnes of nickel in concentrate. In June 1996 the total hoist of ore had reached 9 million tonnes and the ore reserves are estimated to warrant production for at least five more years. Production of Finnish Ni-mines can be seen in Table 6.

Regional geology

The Svecofennian nickel province in southern Finland (Fig. 31) is characterised by a number of mafic-ultramafic intrusive bodies in a roughly circular area of supracrustal rocks around the Central Finland Granitoid Complex (Papunen & Vorma 1986). The Hitura ultramafic body lies in the northern segment of the supracrustal ring-structure around the Central Finland Granitoid Complex. The stratigraphy of the supracrustal rocks in the surroundings of the Hitura ore (Fig. 32), as reported by Isohanni et al. (1985), is from oldest to youngest: 1) gneissose granitoid; probably a remobilised basement, 2) migmatitic mica gneisses with intercalations of graphite and sulphide-bearing gneisses and minor amphibolites, 3) metagreywacke with intercalations of intermediate and felsic tuffites, mafic, intermediate, and felsic metavolcanic rocks, and 4) intermediate and felsic metavolcanic rocks. The ultramafic and mafic intrusions are located in the second stratigraphic unit. The Hitura area includes a number of ultramafic bodies, and the Makola deposit lies only about 3.5 km from Hitura. In addition to migmatitic gneisses, the immediate surroundings are characterised by a belt of sulphide and graphite-

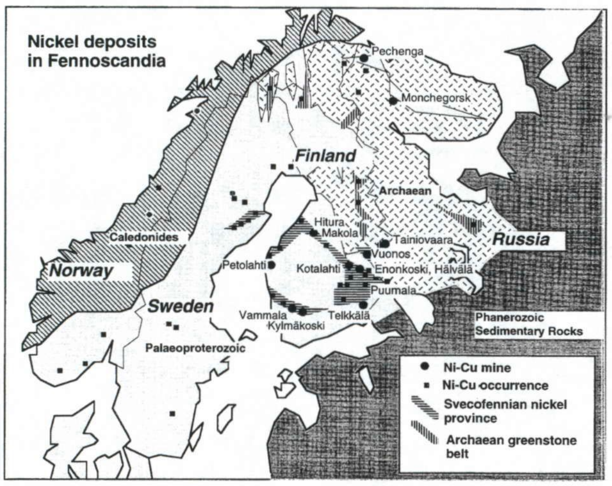

Fig. 31. Location of the Svecofennian nickel province in Fennoscandia.

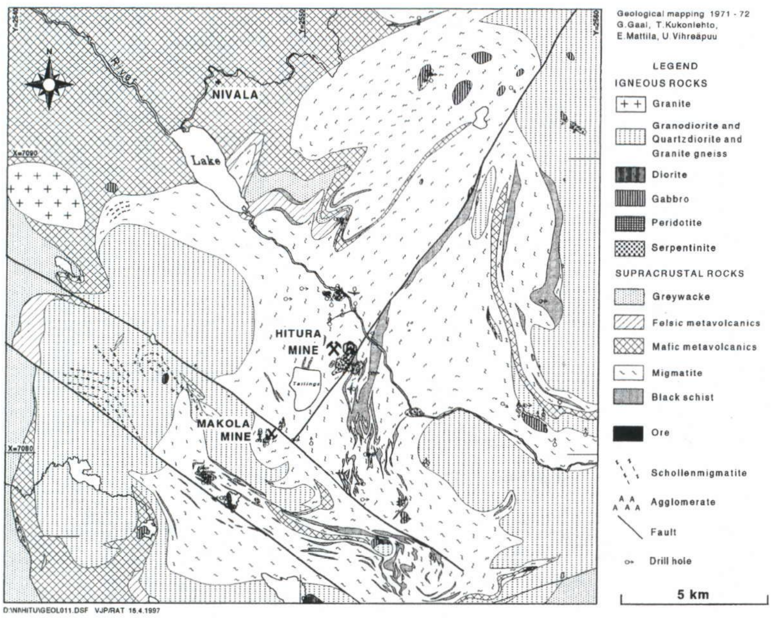

Fig. 32. General geology of the Hitura area.

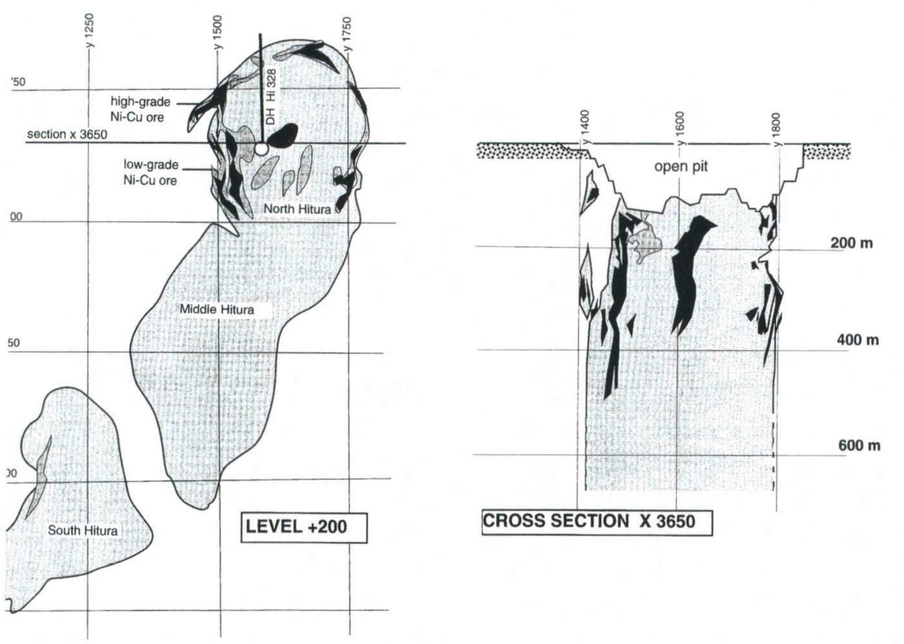

Fig. 33. Geological map of the +200 m level and vertical section x 3650 of the Hitura ultramafic complex.

bearing schists not far from the Hitura body. The area is one of poor outcrop, and geophysics, geochemical sampling, and diamond drilling have all contributed to the geological understanding of the area. The U-Pb zircon age of a felsic dyke intersecting the Hitura body, 1877±2 Ma, is the minimum age of the complex (Isohanni et al. 1985).

The Hitura ultramafic complex

The Hitura ultramafic complex, composed of three closely spaced serpentinite bodies (Fig. 33), has horizontal dimensions of 0.3 x 1.5 km. The vertical extension has not been established although the deepest drill section is at the 550 m level and geophysical surveys indicate a continuation to at least 1000 m. As the bodies roughly conform with the wall rocks and are structurally continuous in a vertical dimension they can be described as vertical plugs. Due to its mineralisation, the northernmost body is the best studied. It displays compositional zoning with a homogene-

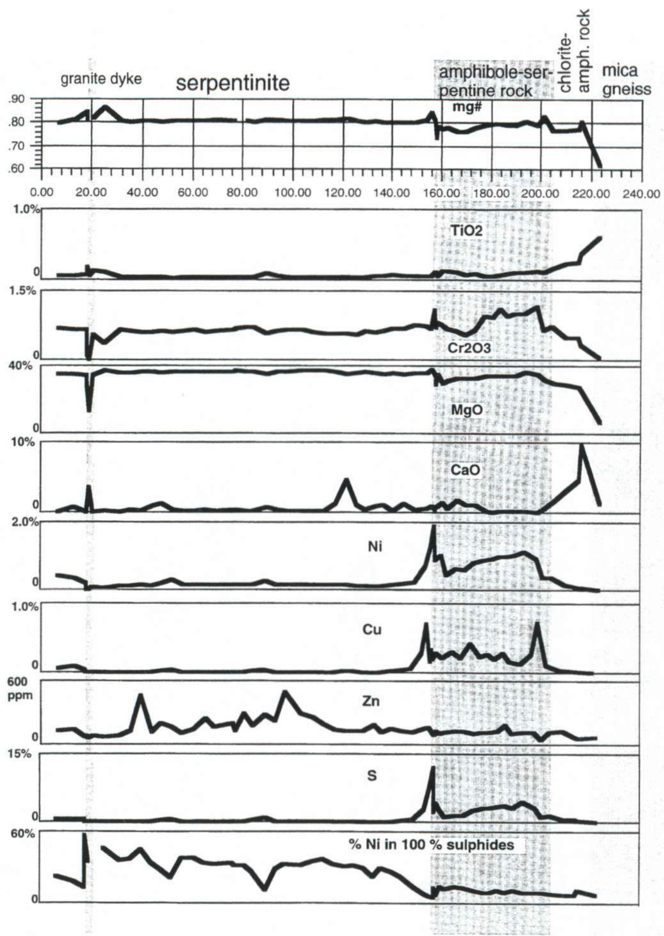

Fig. 34. Variation of major and ore-forming elements in the drill core Hi-328. Location of this horizontal drill hole is indicated in Fig. 33.

ous serpentinite (metadunite) core grading to a zone of amphibole-bearing serpentinite (meta-peridotite) and further to a discontinuous chlorite serpentinite and amphibole rock at the margin of the body (Fig. 33). The contact against gneissic wall-rocks is tectonic, sharp, undulating and filled with talcose joint mortar. The contact zone is characterised by dislocated mafic blocks, erratic wall-rock inclusions and massive sulphide lumps in soft talcose matrix, indicating late-tectonic movements. The western contact zone contains large tongues of partly mineralised ultramafic rocks in the gneiss. Locally, the contact amphibole rock is absent and the serpentinite is in direct contact with the wall-rock. The serpentinite core is fine-grained, porous and of low-density (2.4–2.6 g/cm^3). The main minerals are antigorite (80–90%), chlorite, calcite, and magnetite (7–9%), with local talc, amphiboles, graphite, and phlogopite, and also chromite and arsenides. The proportion of sulphides varies. Talc is abundant close to the contacts, but small specks of talc are common throughout. The rock was originally an olivine adcumulate, but the primary igneous texture is visible only in the small intercumulus specks of talc, chlorite and altered sulphides. The texture is strikingly similar to that of the serpentinized olivine adcumulate of the Mt. Keith Ultramafic Complex, Western Australia (Hill et al. 1990). The primary igneous mineralogy has been totally obliterated and antigorite is a fine-grained felt-like mass with stringers of magnetite and small blebs of altered sulphides. Amphibole-bearing serpentinite is an alteration product of olivine orthocumulate and olivine-orthopyroxene cumulate, and the primary ol-opx cumulus textures are locally preserved as serpentine and amphibole pseudomorphs. The marginal variety of lithology is an amphibole rock that is either a metapyroxenite or a metasomatically derived rock in contact with the felsic gneiss. The TiO_2 values, which are higher here than in the other varieties of the ultramafic rocks, reflect a pyroxenitic origin. The Cr_2O_3 values (Fig. 34) of the core are lower (0.65% Cr_2O_3) than those in the margin (1% Cr_2O_3), indicating that chromite was an abundant liquidus phase in the crystallisation of olivine orthocumulates and Ol-Opx cumulates. Zn dis-

Table 7. Average chemical compositions of the disseminated ore types in the Hitura mine in wt.% (Hautala and Sotka 1976).

Ore type	N (g/cm3)	D wt.%	mt wt.%	Ni wt.%	Cu wt.%	Co wt.%	Fe wt.%	S wt.%	NiS
wall rock mica geiss	28	2.84	0.34	0.06	0.03	0.005	4.74	2.96	0.63
ore in amphibole rock	13	2.92	0.62	0.49	0.09	0.02	7.02	4.59	6.27
ore in amphibole-bearing serpentinite	27	2.71	4.89	0.65	0.17	0.03	5.01	3.38	7.97
serpentinite core	186	2.51	6.83	0.29	0.10	0.02	1.25	0.93	12.23

N = number of samples, D = density, mt = abundance of magnetite, NiS = concentration of nickel in 100% sulphides

plays an interesting enrichment in the core of the body, with peak values of up to 500 ppm, whereas the marginal rocks contain only 150 ppm Zn (Fig. 34). The peaks do not coincide with those of S, indicating that Zn was incorporated in spinel phases during early crystallisation of the magma ormetamorphically derived magnetite. Papunen & Penttilä (1996) indicated on the basis of the Pearce (1968) molecular proportion diagrams that the average Mg# (molar FeO/(FeO+MgO)) of the core is 0.79 and that olivine and orthopyroxene were the fractionating phases (Si/FM=1.86). The calculated average Mg# of the core is 0.81. It decrease gradually towards the marginal rock varieties, and in the contact amphibole rock it is about 0.76. As olivine is totally altered in the core of the body, the composition can only be determined indirectly from the TiO_2 vs. MgO (anhydrous) variation diagram, which indicates a maximum value of 44% MgO for olivine, corresponding to Fo83. According to Roeder & Emslie (1974), Fo83 olivine has been in equilibrium with a basaltic magma with about 11% MgO, which refers to a high-Mg basaltic composition of the primary magma. The fractionated basaltic magma type is in accordance with the relatively high average Cu/(Ni+Cu) ratio of sulphides. The Ni vs. MgO variation diagram of barren ol-adcumulate samples gives an approximation of 2200 ppm Ni for primary olivine. Since the fractionation trend is from olivine to orthopyroxene, the magma type can be referred to as the "Kotalahti type" (Mäkinen 1987), although the fractionation did not reach the liquidus of plagioclase. The body is intensely sheared, with shear zones containing chlorite and local graphite, and random intersecting pegmatite veins ranging in width from a few cm to 10 m. Zonal reaction rims comprising almost monomineralic layers in the succession chlorite, anthophyllite, actinolite, and talc, surround pegmatite zones within serpentinite (Papunen 1971). K, Al, Fe, and Si occur in greater abundances in the alteration zones than in serpentinite. The reaction zones correspond to those described by Marshall & Mancini (1994) from the Vammala deposit. Pervasive random shearing and intersecting felsic pegmatitic veins were accompanied by thorough alteration, chloritization, and an increase in Al content throughout the serpentinite body, thus changing the primary Al/Ti ratios, which are anomalously high in the samples analysed.

Ore types

Sulphides occur throughout the northern part of the Hitura complex. The ore has been divided into three textural types: 1) scattered fine-grained sulphides disseminated in the serpentinite core, 2) medium- to coarse-grained moderate dissemination in the marginal serpentine-amphibole rock, and 3) high-grade interstitial disseminated sulphides and massive accumulations in the amphibole rock of the contact zone, locally extending to the gneissic wallrock. The average compositions of different ore types are presented in Table 7.

Description of ore types:

1) Disseminated sulphides form a cloud-like mass in the core of the northernmost serpentinite body. The opaque mineral assemblage consists of magnetite, pentlandite, mackinawite, valleriite, chromite, and graphite. The sulphides exhibit interstitial forms with regard to the former olivine, but the primary pyrrhotite-pentlandite-chalcopyrite assemblage has been disrupted by intersecting flakes of chlorite and associated magnetite. Hence, the textures now resemble a book with pages of different minerals. Pentlandite has been preserved as small fractured grains, commonly encapsulated in magnetite, but primary pyrrhotite and chalcopyrite have been totally obliterated. Mackinawite exists as an alteration product in pentlandite or together with individual small grains of pentlandite as irregular nebulous dust in ser-

pentine. It contains about 7 wt% Ni. The prevailing copper mineral is valleriite, which locally forms spherical masses up to 10 cm in diameter and is intensely intergrown with chlorite and serpentine. Magnetite iscommon in this ore type and averages 7–10 vol%. Several attempts have been made to exploit this ore type, but the fine grain size of the fractured pentlandite and the associated layer lattice sulphides (valleriite and mackinawite) and silicates make concentration impossible. Only the innermost and highest grade core is the target of exploitation.

2) The ore in the marginal amphibole-bearing serpentinite is the main target of mining. It occupies a subvertical semi-cylindrical zone close to the northern contact of the northernmost serpentinite body. In the east and west it grades into the East and West Contact Ore bodies (ore type 3) hosted by chlorite- and amphibole-rock, but at the northern contact 5–20 m thick barren amphibole rock separates it from the wall rock. The ore is composed of pyrrhotite, pentlandite, and chalcopyrite±cubanite as a heavy interstitial dissemination or matrix ore, with local massive stringers and patches. The secondary opaque mineral assemblage in serpentine-rich rocks consists of magnetite in cleavage cracks of pyrrhotite and pentlandite, mackinawite mainly as an alteration product of pentlandite, valleriite, cubanite which is of the second generation in relation to the early cubanite I, and graphite. The abundance of secondary minerals varies according to the host rock type, and the sulphides of amphibole-rich host rocks are fresher than those in serpentinite. Pyrrhotite is mainly of the hexagonal variety, and exsolved troilite flames are common. Monoclinic pyrrhotite is associated with the alteration process and typically occurs along the cleavage and margins of the hexagonal pyrrhotite grains. Pentlandite is present as euhedral grains and the small exsolution flakes occur mainly in troilite flames with a very low tenor of nickel in solid solution (Papunen 1971). Beneficiation of this ore type is complicated by the secondary sulphides and magnetite encapsulating the valuable sulphides.

3) The contact ore is very heterogeneous, and is composed of disseminated and massive sulphides. The host rock is locally talcose, very soft, heterogeneous and intensely fractured. The textures of sulphides are about the same as those in the marginal ore, but as the amount of serpentinite is less here than in the marginal ore, the secondary ore minerals are not so common. Abundances of layer lattice silicates, chlorite, and talc, hamper beneficiation.

The sulphide mineralogy reflects the polyphase evolution of the complex. The primary magmatic immiscibility and crystallisation of sulphide melt, control the abundances of sulphides in the body. The silicate magma was already sulphide saturated during the crystallisation of olivine adcumulates in the core of the body and gave rise to the sulphide dissemination existing in small interstices of olivine crystals. Residual silicate magma and associated sulphide melt was more abundant in olivine±pyroxene orthocumulates in the marginal part of the body, which now hosts most of the sulphides. The shape of the complex implies that the melt was fractionated in a tube, probably in a feeder channel of overlying volcanic rocks. The early crystallised olivines accumulated and were pressed in the centre, and the residual melt was enriched along walls of the tube, forming the ol-px orthocumulates and pyroxenites. Secondary hydration and carbonation brought about serpentinization and talc-carbonate alteration combined with the deposition of secondary sulphides, minor graphite, and magnetite. Deformation in the eastern and western contact zones fragmented the ore deposits and the alteration was intensive but heterogeneous. The abundance of sulphides was controlled by primary igneous processes but the mineralogy, texture, and beneficiation properties of the ore types are due to secondary processes.

Au-deposits

Gold mineralisation in central Ostrobothnia

The existence of a number of gold prospects in western Finland demonstrates the gold potential of the area although so far no mineable deposits have been located. However, the Björkdal and Åkerberg gold mines in the Skellefte District in Sweden share common characteristics with gold prospects in western Finland and may represent the same gold province. Gold was first discovered in the Ostrobothnia area in an outcrop at Kopsa in 1939, but prospecting did not lead to any economically interesting discoveries at that time. It was not until the late 1970's and early 1980's that modern gold exploration commenced in the area, mainly by Outokumpu Oy and the Geological Survey of Finland. Impetus for gold exploration in most targets arouse by identification of mineralised glacial boulders and outcrops or by geochemical anomalies in till (Nurmi 1991).

Outokumpu Oy delineated a low grade Cu-Au deposit with considerable tonnage at Kopsa, which was regarded as a porphyry type ore hosted by a tonalitic stock (Gaál & Isohanni 1979). Recent drilling by Glenmore Highlands Inc. has revealed encouraging gold grades in several drill cores and trenches. The Laivakangas deposit was studied by Outokumpu in the mid-1980's after the discovery of a mineralised boulder. Mineralisation occurs as discrete quartz vein systems at the contact of a tonalite stock and metabasalt. Mineral resource estimates indicate c. 400 000 tonnes of ore grading 4 g/t (Sandberg 1985, Mäkela et al. 1988). The Geological Survey of Finland discovered the Kiimala deposit after drilling till geochemical anomalies (Kojonen et al. 1991). Disseminated mineralisation is hosted by a sheared and altered gabbroic intrusion, and is estimated to contain about 1.2 Mt of ore grading 1.5 g/t.

The main common features of the gold showings in the area appear to be an association with shear zones and a close spatial relationship with synorogenic (1.89–1.87 Ga) tonalitic stocks or subvolcanic intermediate intrusions. Most deposits are either hosted by the intrusions or occur adjacent to intrusive contacts. However, there is no convincing evidence of a genetic relationship between granitic fluids and gold mineralisation, rather the competent intrusive rocks may have provided structural control of the mineralising fluids.

Gold typically occurs in discrete quartz vein systems with limited alteration halos and less commonly as disseminations in shear zones. Alteration minerals include quartz, sericite, biotite, K-feldspar, and epidote, but carbonates are notably lacking. Sulphides are fairly abundant usually consisting of Fe-sulphides, chalcopyrite, arsenopyrite, and loellingite. Gold typically occurs as free gold which is commonly associated with tellurides and Bi minerals. Geochemically, the occurrences are enriched in As, Te, Bi, Se, Ag, Sb and W (Nurmi et al. 1991).

STOP DESCRIPTIONS

Day 1 — The Petiknäs and Renström mines

The Stops at the Petiknäs and Renström mines will be at available underground exposures. Separate handouts will be distributed at the mine explaining the different underground stops and drill hole PEK207 which cross-cuts the mine stratigraphy.

Outcrops of the mine stratigraphy

Stop 1:1

Sandstone and conglomerate

a) Diffusely stratified, andesitic, coarse-grained sandstone and conglomerate with light grey and reddish andesite(?) clasts in a green chlorite-rich matrix. These are overlain by finer-grained sandstone, partly with cross bedding.

b) Traction current bedding in pebbly, andesitic sandstone. Pink to brown, oxidised, angular clasts of different composition. The outcrops are part of the shallow-marine to fluvial succession of andesites and basaltic andesites constituting the footwall of the ore-bearing unit at Renström.

Stop 1:2

Drill core 1239 from Renström showing the ore-bearing unit including the ore, the stratigraphically overlying sandstones-siltstones, and rhyolitic mass flows.

Day 2

Granbergsliden

Stop 2:1

The Granbergsliden mafic volcanic centre constitutes one of the rare possibilities to examine basaltic volcanic rocks of the Skellefte Group. The Granbergsliden mafic volcano was at least 400 m thick and 3 km wide. In this stop the participants will be able to study: basaltic pillow lavas (Fig. 35a), related pillow breccias, in situ and resedimented hyaloclastites (Fig. 35b), and quench fragmented spalled bomb rind deposits (Fig. 35c).

The basaltic pillow lavas are well preserved with individual pillows up to one meter in size. Well developed radial gas escapement trains can be seen in the pillow interior. The lavas are overlain by pillow breccias consisting of broken pillows and fluidal bombs which are interlayered with deposits of quench fragmented spalled bomb rinds. The whole sequence is interpreted as a subaqueous, basaltic fire-fountain deposit which is a

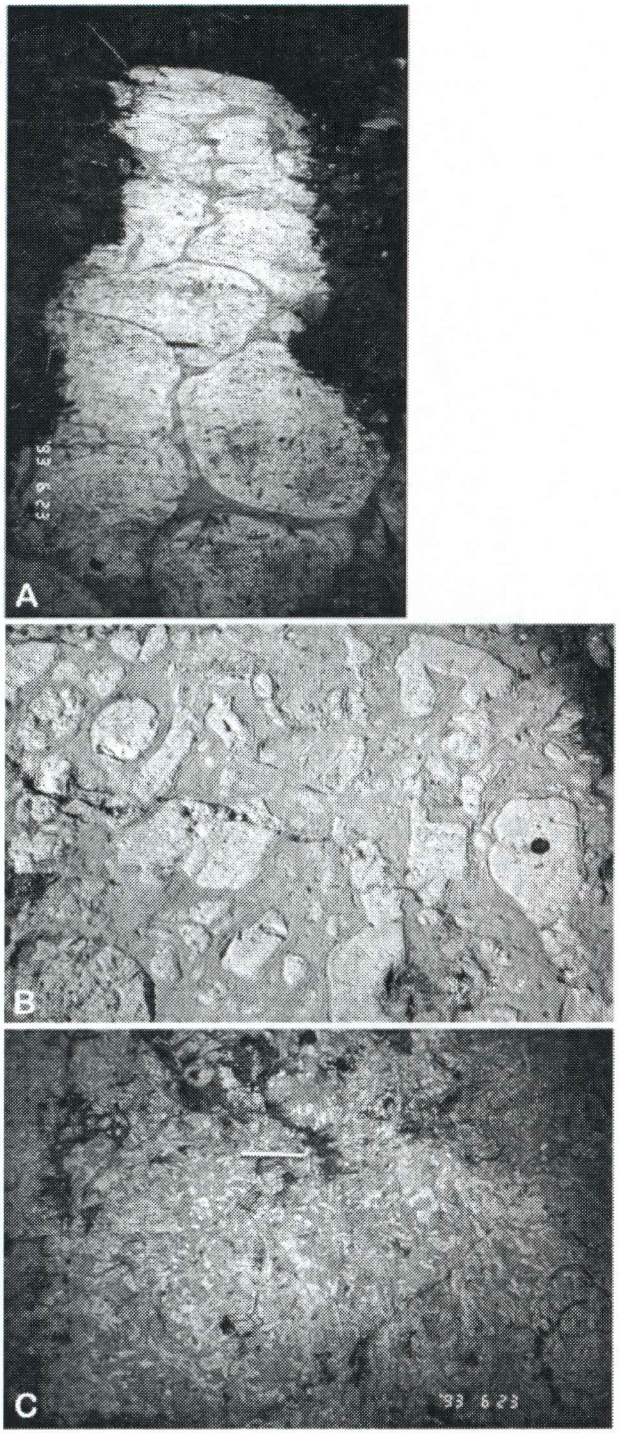

Fig. 35. Photographs of the main lithological units in the Granbergsliden area. a) Pillow lava, b) pillow breccia, and c) spalled bomb rinds of the fire fountaining unit.

subaqueous equivalent to Hawaiian-style fire fountaining. The environment is interpreted by Allen et al. (1996) as a high discharge fissure eruption which jetted rapidly quenched bombs above the sea-floor which then were deposited as quench breccias (Fig. 35c). Similar deposits have also been found in the Renström area.

Stop 2:2

Along the road to the Granbergsliden mafic volcanic centre, outcrops of coherent quartz-feldspar porphyries associated with the Holmtjärn massive sulphide deposit can be found. The Holmtjärn area is characterised by subvolcanic quartz-feldspar intrusions and lavas which also form the main part of the subaqueous rhyolite cryptodome-tuff volcanoes which seem to be intimately associated with several massive sulphide ores in the Skellefte district (cf. Allen et al. 1996).

Nicknoret

Stop 2:3

The uppermost Skellefte Group and the overlying Vargfors Group can be studied in some exposures near the Skellefte river at Nicknoret (Fig. 36). In an approximately 200 m long section we will see volcanogenic conglomerates of the uppermost Skellefte Group grading into Vargfors Group polymict conglomerates with clasts from both Jörn type granitoids and the subaerial Arvidsjaur volcanic rocks. Erratic clasts of mafic volcanic rocks of the Vargfors Group as well as intercalated mafic lava flows of the same composition confirm that all rock units at this locality formed close in time. Approximately 1 km upstream from this stop, a welded ignimbrite yielded an age of 1875±4 Ma (Billström & Weihed 1996) which is considered to represent the middle part of the Vargfors Group. Outcrops c. 3 km downstream was dated by Welin (1987) at 1882±8 Ma which is considered to represent the age of the top of the Skellefte Group in this area (cf. Billström and Weihed 1996).

The traverse starts in a probably slightly reworked, monomict, clast-rich felsic volcanogenic mass flow deposit/conglomerate. It continues into successively more reworked and polymict conglomerates which, at the base, are dominated by volcanic clasts. The traverse ends in a polymict conglomerates dominated by volcanic, microgranite and granitoid clasts intercalated with sand- and siltstones.

Maurliden

In the Maurliden area situated c. 5 km ESE of the previous stop (Fig. 36), the complex transition from the Skellefte Group to the Vargfors Group can be studied. Several subeconomic massive sulphide deposits exist in the area (e.g. the Maurliden deposits). These deposits were interpreted by Allen et al. (1996) to be related to subaqueous rhyolite cryptodome-tuff volcanoes of which some may have been emergent above sea level. The complexity of the transition from Skellefte- to Vargfors Group rocks in the Maurliden area is illustrated by subvolcanic quartz-feldspar porphyries (Skellefte Group) which are intrusive into lime-cemented clastic rocks of the Vargfors Group (Stop 2:6). Sandstone and mudstone turbidites (Stop 2:5), which are part of the Vargfors group, show evidence of very active tectonism during deposition. Frequent rip up clasts, ruptured beds, internal sliding of beds, soft sediment deformation and small scale growth faults are common, as well as dewatering structures like load casts. Complex contact relationships between volcanic rocks and turbidites are indicated by the fact that younging directions in the turbidites often indicates younging towards the older volcanic rocks, which is probably explained by both syn- and post-sedimentation faulting. The presence of pebble conglomerates with well rounded clast in a carbonate dominated matrix(Stop 2:4) indicates that the environment may have been shallow marine, probably with a pronounced relief.

Stop 2:4

Lime-cemented conglomerates are best exposed at the shore of the Skellefte River. The clast material in the conglomerate is polymict with clasts from Skellefte volcanic rocks and Arvidsjaur volcanic rocks. All clasts are

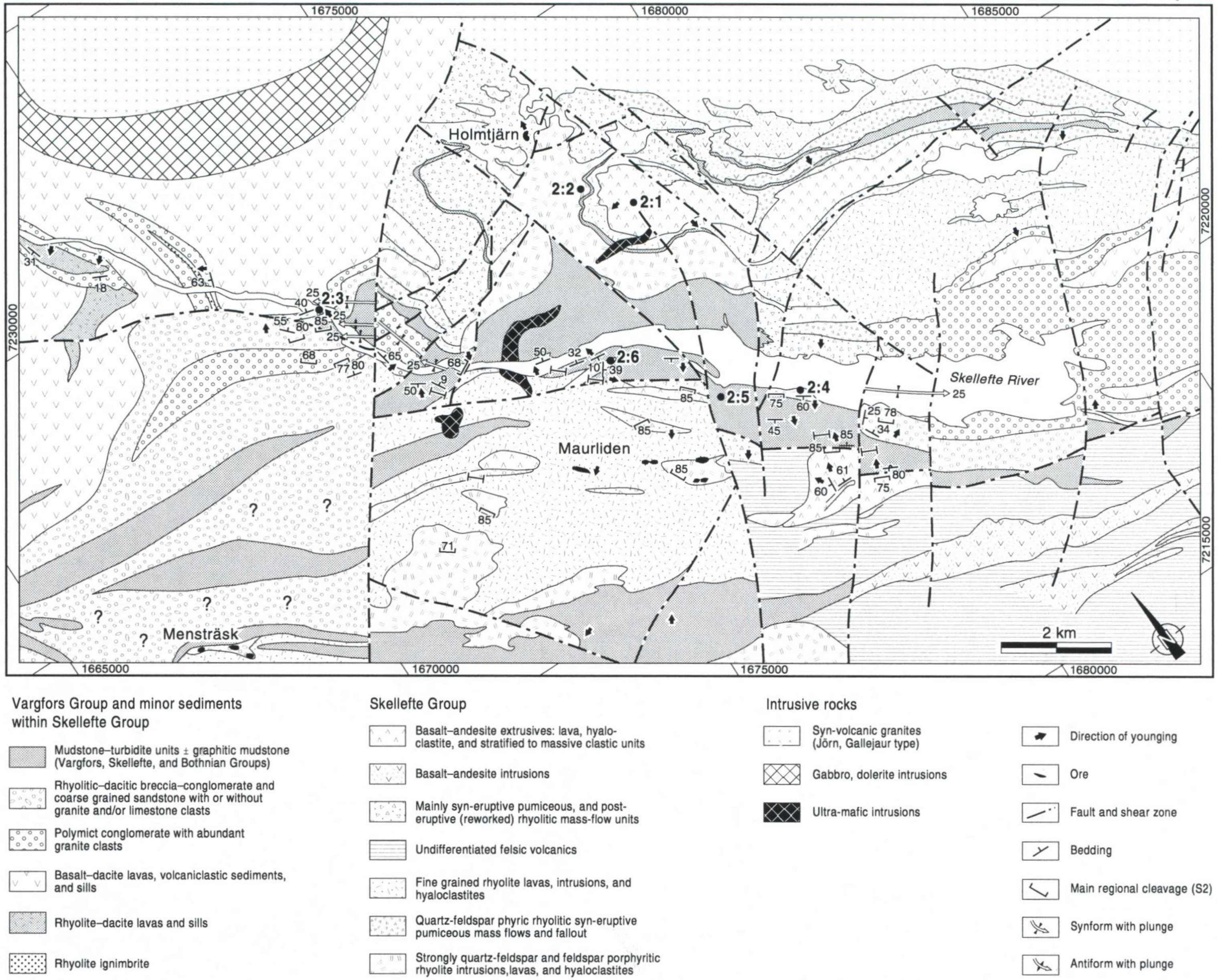

Fig. 36 Map of central Skellefte District (from Allen et al. (1996) with the different stops in Granbergsliden, Nicknoret and Maurliden indicated.

well rounded and the pebbles are flattened in the main cleavage and elongated parallel to the fold axis of the main deformation.

Stop 2:5

A few hundred meters from the lime-cemented conglomerates, good exposures of the turbiditic metagreywackes will be examined. These rocks show abundant evidence of intense syn-depositional deformation indicating active tectonism at the time of deposition.

Stop 2:6

A quartz-feldspar porphyry which intruded the lime-cemented conglomerates will be shown at a final stop in the Maurliden area. Contact relationships are not entirely clear, but the existence of typical Skellefte Group volcanic rocks within the conglomerates illustrates the complex relationship between the Skellefte- and Vargfors Groups.

Terrestrial volcanic rocks with epiclastic intercalations in the Hej area, northern Västerbotten County

The bedrock west of the village Hej in northern Västerbotten County mainly consists of felsic and subordinate intermediate to mafic volcanic rocks, here called the Hej volcanic rocks (Fig. 37). Together with some epiclastic intercalations the entire succession is called the Hej subgroup (Ehrenborg 1987). This subgroup belongs to the Arvidsjaur Group and occurs in a north-northeast trending synform which is situated close to the transition zone between the subaqueous and the subaerial volcanic successions of the Skellefte and the Arvidsjaur Groups, respectively.

The Hej volcanic rocks comprise rhyolitic to dacitic, quartz- and/or feldspar-porphyritic lavas and volcaniclastic rocks, including a rhyolitic crystal tuff, intermediate plagioclase porphyries and volcanic breccias (Stop 2:7), rhyolitic ash-fall tuffs, non-welded and welded, typically purple ignimbrites (Stops 2:9 and 2:10). The ash-fall tuffs and the ignimbrites are considered to form a 400–500 m thick compound cooling unit, emplaced in an intra-caldera setting (Rapp 1996).

Intercalations of epiclastic sedimentary rocks, mainly polymict conglomerates and subordinate impure sandstones, occur at several stratigraphic levels within the volcanic succession. The most extensive of these conglomerate lenses, here referred to as the Urikberg conglomerate (Stop 2:8), has a north-south extension of more than 4 km and a thickness exceeding 100 m. The clasts range from 1 to 50 cm in size and consist of lavas, volcaniclastic rocks, and granodiorites of the Jörn GI type (Ehrenborg 1987, Kathol 1995, Rapp 1996), all these rocks being derived from the east. Due to the lack of argillaceous material in the matrix and the occurrence of thick massive beds, this conglomerate is considered to represent theresult of mass flows initiated by slope wasting in areas with relatively high relief and unweathered volcanic rocks.

Emplacement of the Hej subgroup in a terrestrial environment is indicated by the occurrence of eutaxitic textures, lithophysae, fiamme, and welding within the rhyolitic ignimbrites, as well as by the red colours of most of the felsic rocks. Further evidence for the terrestrial nature of the Hej subgroup is given by the occurrence of drying cracks within an intercalated sandstone lens in the Urikberg conglomerate (Ildikó Antal, Ingmar Lundström, pers. comm. 1996).

The metamorphic grade within the Hej subgroup does not exceed lower greenschist facies and therefore primary textures are well preserved, apart from epidote alteration of feldspar phenocrysts and epidote growth within lithophysae.

In the eastern part of the field trip area, the rocks dip at moderate angles to the west and north-west, and minor overturned limbs indicate a deformation style with tight to isoclinal folds with vergence to the east and south-east. However, no foliation related to these folds has been observed. The western part of the Hej volcanic rocks dips steeply to the east and south-east. In general, the rocks of the Hej subgroup lie right way up with the purple, welded ignimbrite at the top of the succession, occupying the core of the major synform.

The Hej subgroup is intruded by the even grained, fine to medium grained, light red or reddish Antak granite in the south-central parts (Fig. 38). Through geophysical modelling, the thickness of the elliptic Antak intrusion (c. 5 x 8 km) is estimated to be between 200 and 500 metres at the present erosional level. The intrusive contact relationship between the Antak granite and the volcanic rocks has only been observed in one locality, but at a map scale, the granite contact cuts the bedding within the Hej subgroup confirming the intrusive relationship. A comagmatic origin of the Antak granite, and the ignimbrites and rhyolites of the Hej subgroup is indicated by REE and trace element patterns of these rocks (Kathol & Rapp 1996). A coeval origin of these rocks is also indicated by a zircon U-Pb dating of the Antak granite which yielded an age of 1879 +15/-12 Ma (Kathol & Persson in press) which is comparable to the 1878±2 Ma age of the rhyolitic ignimbrites at Skyberget (Skiöld et al. 1993). The Antak granite is thus considered to have crystallised at a shallow level within comagmatic extrusive phases. The granite itself probably represents the position of the eruptive centre of the rhyolitic parts of the Hej volcanic rocks.

Stop 2:7 — Volcanic breccia south-west of Urikberget

A volcanic breccia is exposed in two north-striking and west-dipping strips in the eastern and western part of Urikberget. East of the breccia a grey dacitic feldspar porphyry lava occurs, which forms the matrix to the volcanic breccias. No distinct contact is exposed between the volcanic breccia and the lava and in the transition zone, irregular flow-banded fragments occur in the lava. The volcanic breccia is both clast- and matrix-supported and the margins between fragments and the feldspar porphyritic matrix vary from diffuse to sharp. The fragments are angular to subrounded and mainly consist of elongated flow-banded fragments, vesicular mafic fragments, and vesicular grey-greenishdacite fragments with or without feldspar phenocrysts. Jig-saw fit texture occurs in parts where the red feldspar porphyritic matrix dominates.

The origin of the breccia is a subject for discussion. Rapp (1996) suggested deposition and emplacement from syn-volcanic, gravity-driven volcaniclastic mass flows which were contemporaneous with the emplacement of the grey dacitic feldspar porphyritic lava flow. Jig-saw fit texture is suggested to have formed by quench fragmentation of the hot lava fragments after deposition.

Stop 2:8 — Urikberg conglomerate west of Urikberget

The Urikberg conglomerate has a north-south extension of more than 4 km and a thickness exceeding 100 m. The conglomerate is poorly sorted and matrix supported. It is characterised by granitic and volcanic clasts with sharp contacts towards the gritty matrix. The granitic clasts are derived from the GI granodiorite phase of the Jörn batholith. The tectonic contact between the Urikberg conglomerate and the volcanic breccia is exposed in a 4 m wide NW-striking shear zone.

Stop 2:9 — Rhyolitic ash-fall tuffs south of Boljerberget

Ash-fall tuffs are exposed south and east of the Boljerberget hill. These tuffs are characterised by very fine-grained, gently west dipping layers alternating with a coarser-grained,

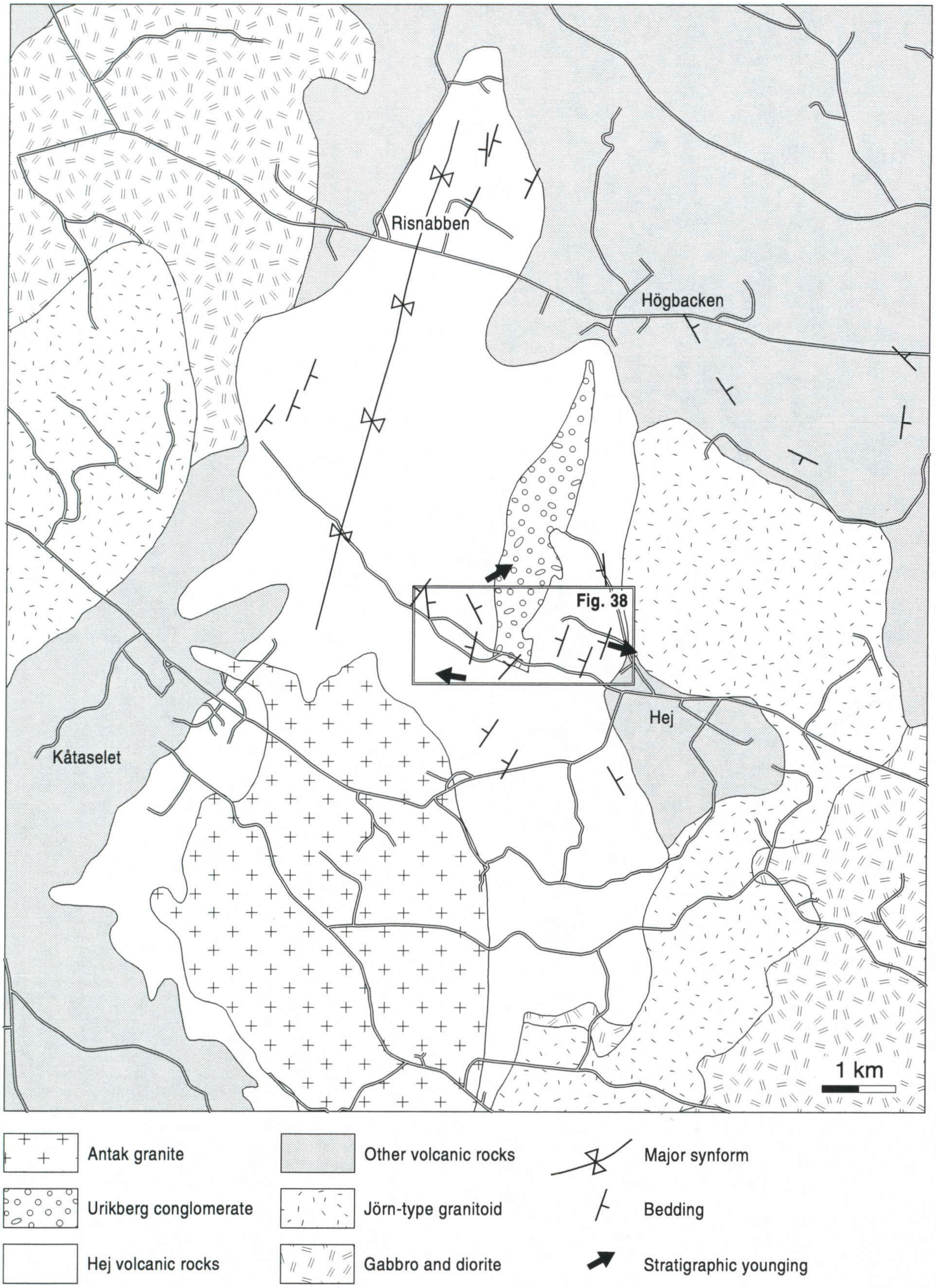

Fig. 37. Simplified geological map of the Hej area, modified from Kathol & Rapp (1996).

vesicular, quartz-feldspar porphyry. Stratigraphic younging is indicated by impact-sags in fine-grained layers and the truncation of underlying layers. The air fall emplacement is indicated by good sorting, lamination, stratification, truncation of underlying layers, impact sags of ballistic clasts, and the lack of traction structures such as cross-stratification.

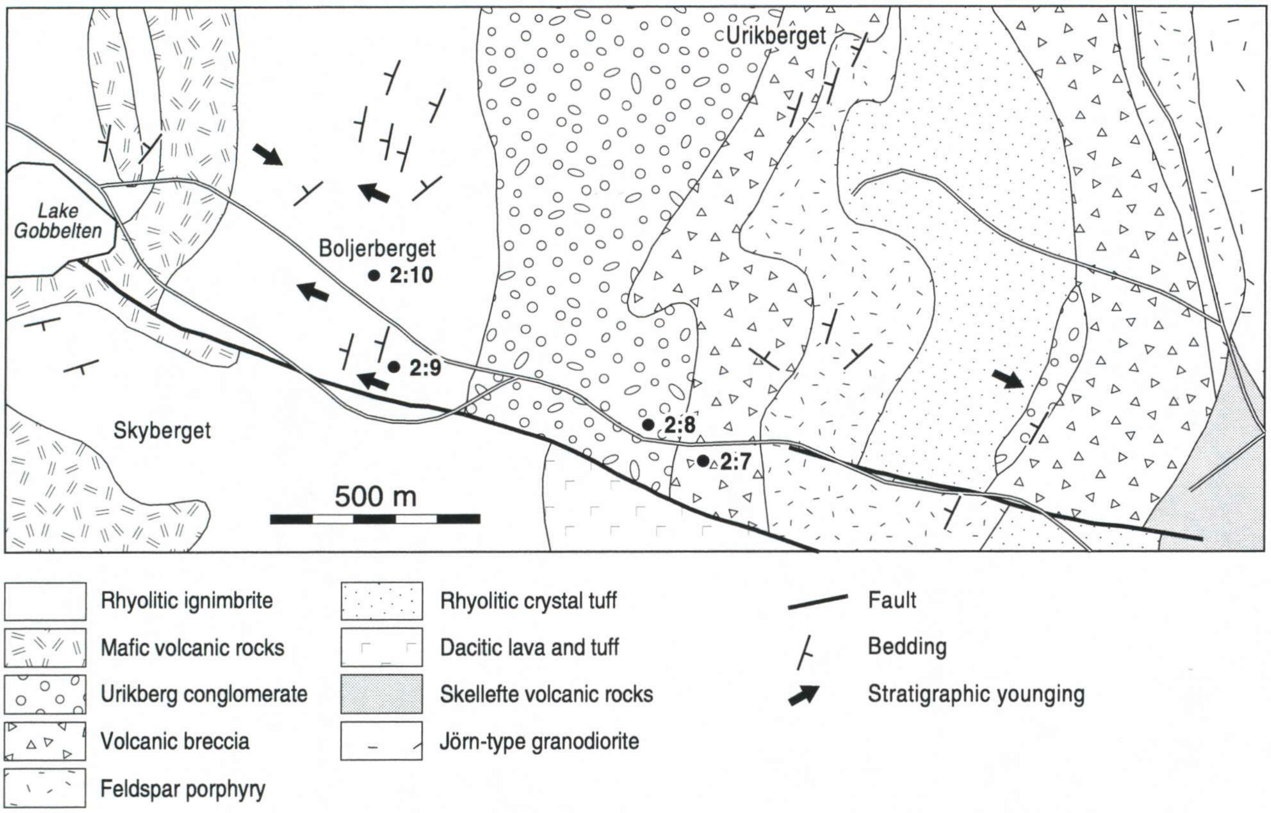

Fig. 38. Geological map of the field trip area west of the village Hej. The map is based on Rapp (1996) and ongoing mapping by the Geological Survey of Sweden (SGU).

Stop 2:10 — Welded ignimbrite at Boljerberget

Welded ignimbrites are exposed at and around the Boljerberget hill. These are lithophysae-bearing, quartz-feldspar porphyritic rhyolites with fiamme and eutaxitic textures. The matrix varies in colour from blue-grey to violet which is due to different oxidation states of iron. A steeply dipping bedding parallel foliation is defined by fiamme and the eutaxitic textures. In thin-section the rock contains broken crystals, eutaxitic, and granophyric textures. The degree of welding is moderate to dense. The poor stratification, variable degree of welding, and the absence of reworked horizons of the welded ignimbrites are consistent with rapid emplacement. either from sustained flows or from a rapid succession of flows.

Day 3

The Björkdal area

Regional geology

The Björkdal area is situated on the hinge-line of a major anticlinal structure, the core of which, outside the Björkdal area, is occupied by metavolcanic rocks belonging to the Skellefte Group of Allen et al. (1996), cf. Figure 5. For the Boliden area, Allen et al. (1996) state that the metavolcanic rocks are overlain by metasedimentary rocks via adisconformity. In the Björkdal area, metasedimentary rocks overlie metavolcanic rocks, but the contact relations are obscured by deformation (Fig. 39 and 40). Furthermore, the core of the anticline is here occupied by a tonalitic-trondhjemitic pluton, which appears to be older than any of the metavolcanic rocks dated so far. Billström & Weihed (1996) presented a preliminary age for this rock of c. 1905 Ma. A tectonic contact between this pluton and the overlying metavolcanic rocks will be seen in the Björkdal mine.

The core of the Skellefte Group anticline is mostly altered to low grade, but the regional metamorphic alteration increases to high grade in the north-east (Fig. 5). Björkdal is situated in an area characterised by lower middle grade rocks.

Mapping by the geological survey of Sweden in the Björkdal area has revealed an unexpected number of complications. This presentation is therefore highly provisional, because many significant features of the geology of the Björkdal area are still poorly known. However, the main structural feature of the Björkdal mine area is a set of ENE to E-W striking, gently north-dipping shear zones. They both obscure the contact relationships between the pluton, the metavolcanic and metasedimentary rocks and destroy almost every primary structure and texture. Kinematic indicators are few, but indicate thrusting towards the south. Movement was probably oblique, because sinistral movements occur on top surfaces. The shear zones are subhorizontal in the central part of the pluton and gently south-dipping in its southern part. The meta-supracrustal rocks therefore seem to have been thrust towards the south above the pluton (Fig. 40). The gold bearing quartz veins of the mine seem to have formed simultaneously with this thrusting, because they both cross-cut shear zones and are deformed thereof. Occasionally, garnet is found in the shear zones, which also seem to be related to a peculiar actinolite blastesis, particularly in the metavolcanic rocks.

Rock types

The Björkdal pluton consists of a greyish, fine- to medium-grained, sometimes trondhjemitic tonalite-granodiorite to quartz-monzodiorite. The trondhjemitic to tonalitic vari-

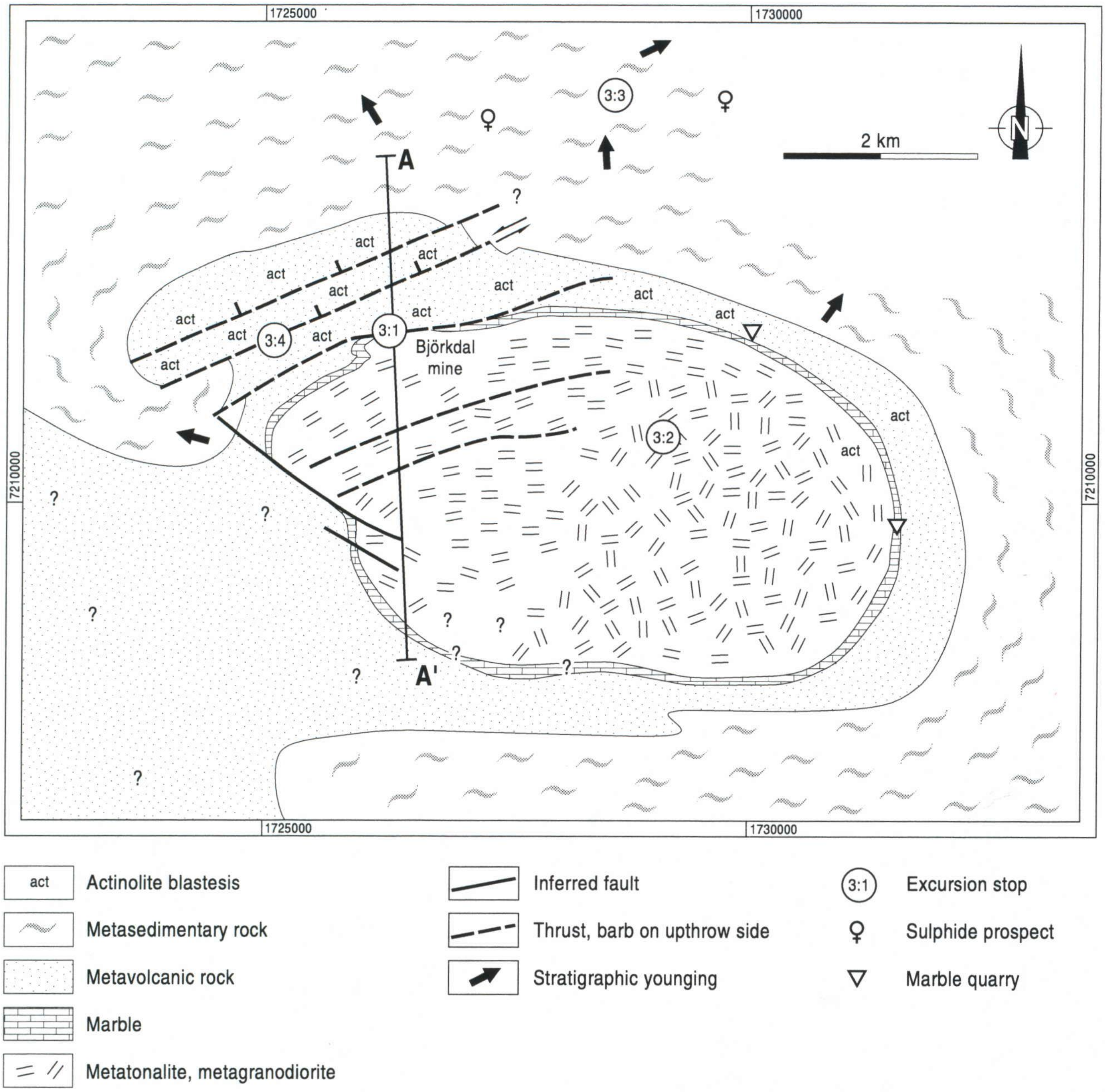

Fig. 39. Geology of the Björkdal area. Based on mapping by I Lundström, Geol. Surv. Sweden, unpublished.

eties dominate the northern parts, the granodiorites the southern areas. The rock is mostly foliated to a somewhat gneissic structure, particularly in the strongly sheared area around and south of the mine, whereas the south-eastern part of the pluton is almost isotropic. In these better preserved rocks, characteristically glomerophyric plagioclases occur. Relics of these are diagnostic for the recognition of the tonalite as the precursor of the strongly deformed and altered gneisses in and to the south of the mine, where the tonalite at places is altered to very feldspar-poor quartz-mica gneisses and mylonites with a microscopic banding. Post-deformative tourmaline indicates late alteration in this area.

The contact relations between the pluton and the overlying supracrustal rocks are obscured by deformation. The pluton is covered by a thin marble layer, which seems to follow the base of the overlying metavolcanic rocks rather closely. As the pluton has been found to be older than any known rocks of the Skellefte Group, it is tempting to consider the marble as deposited on the plutonite rather than as intruded by it.

A fine-grained, quartz-mica mylonite or gneiss with occasional relics of quartz phenocrysts, set in a very fine-grained matrix, has been found directly above the marble. Its composition and structure is very similar to that of the tonalite and is thus very difficultto map out in a consistent way. However, its position above the marble layer as well as minor textural differences make a distinction from the tonalite gneisses justified.

North of the Björkdal mine, a peculiar, poorly understood rock forms an almost km-wide unit. It is affected by numerous, gently north-dipping shear zones, probably related to the zones in the mine. The rock has a planar fabric and the characteristic feature is a penetrative to porphyroblastic, post-deformative actinolite blastesis which gives the rock a rather mafic appearance. As it frequently displays reasonably recognisable, lath-formed plagioclase phenocrysts and probable quartz-calcite amygdules, the rock has previously been interpreted as some kind of a mafic, coherent volcanic rock. However, the rock cannot have been originally mafic because it has a fairly quartz-rich matrix. Furthermore, the actinolite blastesis forms a jig-saw fit pattern and actinolite porphyroblasts very frequently straddle the boundaries of clast-like, more felsic parts, which may in fact be alteration relics. As the same actinolite blastesis also occurs in other rock types, it is most probably due to some kind of poorly understood alteration, here possi-

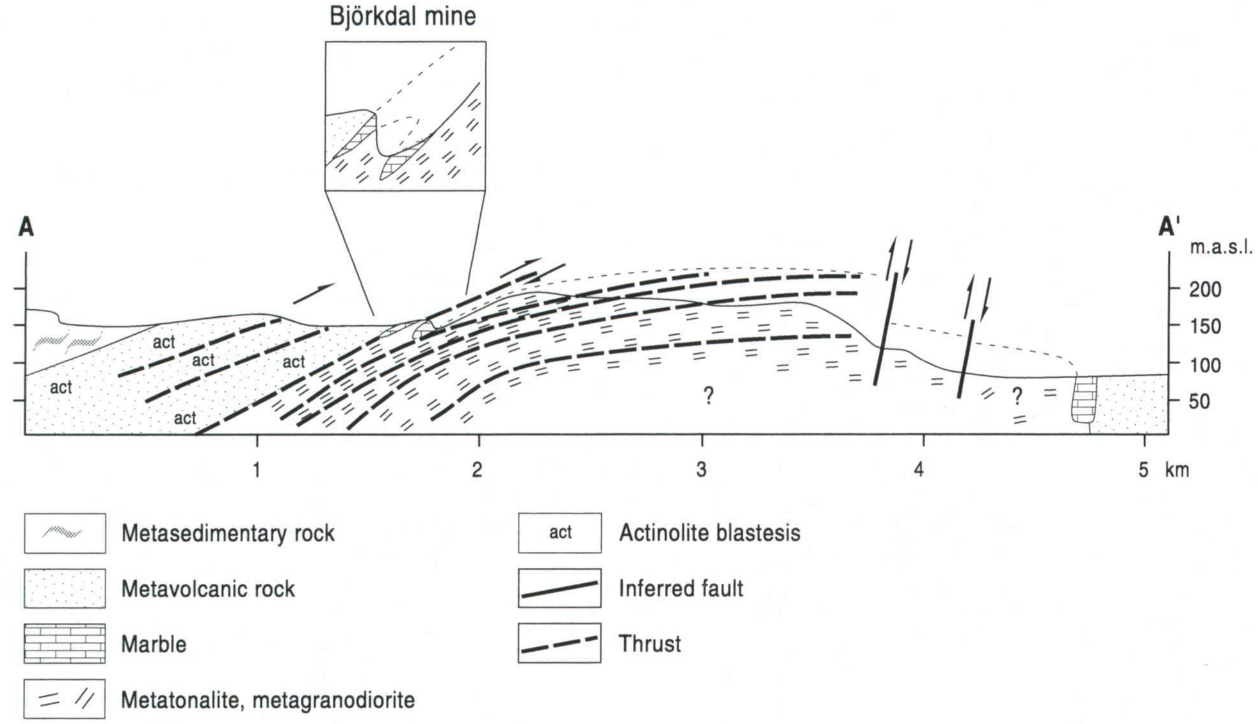

Fig. 40. Profile through the Björkdal pluton.

bly related to the shear zones.

Metasedimentary rocks form the structurally and stratigraphically highest unit in the Björkdal area (Fig. 39 and 40). The contact with the underlying metavolcanic rocks is not exposed, but seem to be situated slightly below a thin layer of a polymict conglomerate. At higher stratigraphic levels, rusty black schists with some sulphide prospects occur as well as turbiditic arenites, indicating rapidly changing depositional environments. Despite medium grade alteration, these rocks frequently display beautifully preserved sedimentary structures and clastic textures.

Stop 3:1 — The Björkdal open pit

The stop will be devoted to available exposures in the Björkdal open pit.

Stop 3:2 — Small outcrop N of the road 1 km ESE of Björkdal village

A greyish, medium-grained, even-grained, isotropic, recrystallized and metamorphic tonalite in the centre of the Björkdal pluton. This outcrop was sampled for radiometric age determination and Billström & Weihed (1996) report a preliminary U-Pb zircon age of 1905 Ma.

Stop 3:3 — Outcrops in the forest, 3 km NNE of Björkdal village

Turbiditic metasediment with various sedimentary structures and post-deformative cordierite porphyroblasts.

Stop 3:4 — Outcrops around the road W of L Mörttjärn

Actinolite altered metavolcanic rocks. Reddish, felsic, plagioclase-phyric, amygdaloidal metavolcanic rocks occur as clasts or alteration relics in a greenish, actinolite-rich matrix. Jig-saw fit relations and diffuse borders towards the matrix suggest that the felsic parts are in fact alteration relics rather than clasts. Furthermore, relics of the plagioclase-phyric and amygdaloidal structure can occasionally be seen in the matrix and indicate that the matrix formed by alteration of the material in the felsic parts.

Metavolcanic rocks of the Skellefte Group in the Boliden area

The significant features of the Skellefte Group metavolcanic rocks are described in the introductory text and by Allen et. al. (1996). The stops described below aim to demonstrate a few of the most significant facies types of the group.

Stop 3:5 — Outcrop N of the road, 2 km NE of Svanström

Thick-bedded, matrix supported, polymict volcanic breccia to sandstone, rich in volcanic clasts. Current bedding and traction deposition structures indicate shallow water deposition. Debris shed off from nearby volcanic centre?

Stop 3:6 — Outcrops on Mångfallberget ski slope

Quartz-feldspar porphyritic, coherent, rhyolitic, metavolcanic rock with relics of a polygonal fracture pattern suggesting polygonal cooling joints. Lava or subvolcanic intrusion.

Stop 3:7 — Outcrop N of small road, 3 km SE of Kankberg

Volcanic siltstones with fine planar bedding with syn-sedimentary deformation structures. The stop demonstrates the subaqeous nature of much of the Skellefte Group metavolcanic sequence.

Stop 3:8 — Torrberget hill, 8,5 km SE of Öster-Jörn

Thick-bedded to massive, matrix-supported, poorly sorted, somewhat polymict volcanic breccia with numerous pumice and other volcanic fragments set in a felsic matrix. Rotated pumice clasts and wavy, planar structure indicate synvolcanic/depositional deformations (welding or compaction) leading to fiamme structures. The rock is interpreted as a juvenile, pyroclastic flow deposit.

Day 4

Stop 4:1 — The Hitura Mine

The Hitura mine is located c. 80 km east from the coast of the Bothnian bay along the river Kalajoki. During the visit different types of ultramafic rocks and surrounding mica gneisses will be seen in the open pit and in the underground mine. Also drill cores through the ultramafic body with different ore types can be examined.

Stop 4:2 — The Kopsa Gold-Copper Prospect

The Au-Cu-Ag mineralisation at Kopsa occurs within and close by a late-orogenic, granodiorite/tonalite stock which intrudes Palaeoproterozoic metasedimentary and metavolcanic rocks near the southern edge of the Main Sulphide Belt in western Finland (Fig. 41). The Kopsa stock, which is about 1200 m long and 600 m wide, is one of at least two mineralised intrusions in a 10 km long, ENE-trending structure. Information on other intrusions and this regional structure is limited because of extensive glacial overburden and little previous exploration.

The following is based on exploration and research carried out since the discovery at Kopsan Kallio (the only outcrop on the property) in 1939 and on the ongoing exploration program. The main mineralisation at Kopsa is within a stockwork of quartz veins, fracture fillings, and disseminations in the granodiorite intrusion. However, some mineralisation has also been found in the contact zone (e.g. Sorola). The predominant sulphide minerals are chalcopyrite, arsenopyrite, and pyrrhotite, with lesser amounts of pyrite. Gold occurs in native form, in tellurides, and closely associated with arsenopyrite, while silver is mainly contained in chalcopyrite. Copper is predominantly contained in chalcopyrite and in rare cases, in cubanite (Ervamaa 1952).

The sulphides occur as massive vein filling fractures, generally a few mm wide, as semi-massive segregations within quartz veins and silicified zones, and in disseminated form. The entire Kopsa intrusion is mineralised. The main alterations accompanying mineralisation in the granodiorite are feldspathization (potassium enrichment, sodium and calcium depletion) and silicification (Gaál & Isohanni 1979). Other elements enriched in the mineralisation are Bi, Te, Sb, W, and Mo.

Mineralisation in the contact zone metasedimentary rocks, as

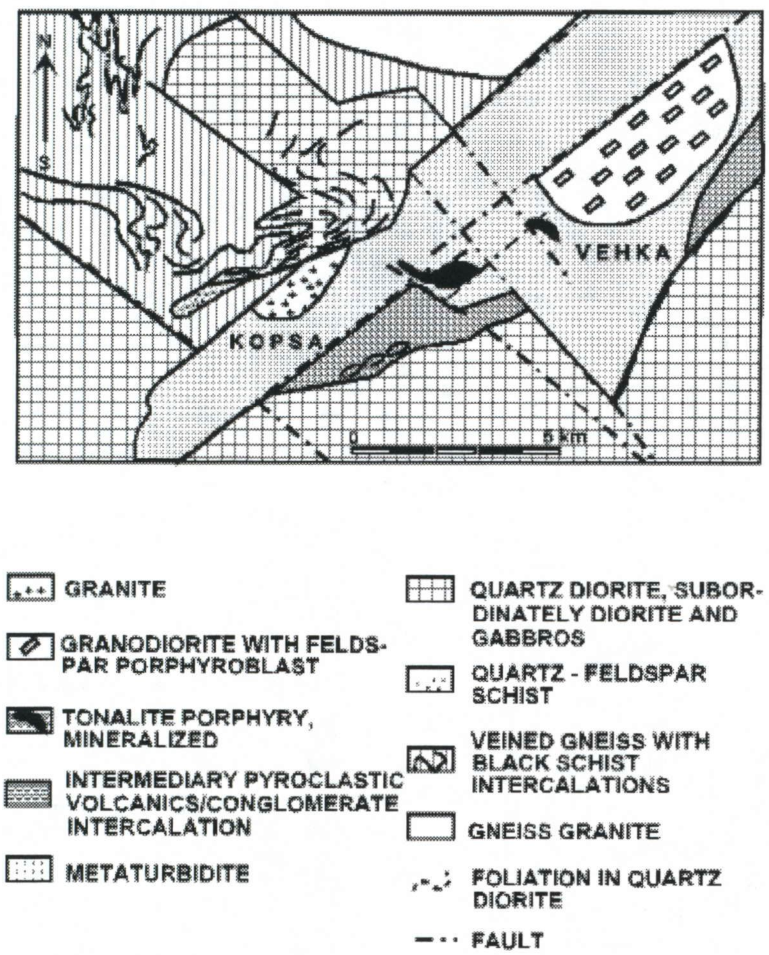

Fig. 41. Geological map of the vicinity of the Kopsa Cu-Au deposit (after Gaál & Isohanni 1979).

exemplified by the Sorola prospect, is similar to that described above. However, quartz veins are generally absent, the main potassic alteration is biotite and sericite, and the silver to gold ratios are much higher. Chalcopyrite, pyrrhotite, and arsenopyrite occur as massive to semi-massive lenses, fracture fillings, and in disseminated form in irregular zones, up to tens of meters wide.

Glenmore Highlands´ current exploration program has involved shallow percussion drilling, geophysical investigations, trenching, and reverse-circulation and diamond drilling, mainly in the granodiorite. Results to date indicate that gold and copper mineralisation mostly is enriched in steeply-dipping, quartz-rich zones (a few meters to over 10 m wide), concentrated over a large portion of the intrusion, and consistent to depths > 175 m.

During the visit different types of mineralisations will be seen in trenches.

Stop 4:3 — The Vesiperä gold mineralisation in Haapavesi

The Vesiperä gold mineralisation is located about 20 km east of the town of Ylivieska. The mineralisation was found in an outcrop in 1984. An arsenopyrite-rich sample contained 75 ppm Au and 15% As. In the course of the next two years the GSF carriedout regional bedrock mapping, geophysical ground surveys (magnetic, electromagnetic, and IP) and geochemical till samplings with the percussion drill. Altogether 17,5 km^2 were covered by geophysical measurements, and in all about 900 till samples were collected with a hydraulic percussion drill. Diamond drilling, totally 2 079 m, was carried out during 1986–1988. The ore reserves, which are based on 9 drill hole intersections, indicate about 0,3 Mt of ore with a grade of 2,5 ppm Au and 0,8% As.

There is no doubt that the mineralisation is related to the NW-striking shear zone, which crosscuts metasedimentary rocks, gabbros, and granitoids. The deposit consists of several ore bearing lenses, most of which strike in the direction of the main shear zone. A few lenses, however, are oblique. Within the shear zone the hydrothermal solutions associated with the gold mineralisations have caused silicification, sericitization and chloritization. In places the amount of potassium feldspar increases considerably.

The Vesiperä gold mineralisation is hosted by a coarse-grained hypabyssal gabbro, which shows ophitic texture in the fine-grained matrix. There are two types of mineralisation: 1) narrow quartz and sulphide rich veins and 2) disseminated ore with only a weak sulphide content. In the quartz veins the main ore minerals are arsenopyrite, pyrite, marcasite, chalcopyrite, pyrrhotite, ilmenite, rutile, and graphite. Arsenopyrite often has a core of loellingite. Native gold, bismuth, and electrum occur as small inclusions in arsenopyrite and loellingite. In the disseminated ore type the most common ore minerals are pyrrhotite, pyrite, arsenopyrite, and chalcopyrite, with minor ilmenite, rutile, and graphite. In addition to the inclusions in arsenopyrite native gold occurs as inclusions in silicates (Sipilä 1988).

Stop 4:4:1 — The Kuusaa formation

The Kuusaa formation, 35 km NW of Pyhäjärvi, mainly consists of highly porphyritic, felsic to mafic metavolcanic rocks with plagioclase and/or uralite phenocrysts. In the southern parts of the Kuusaa formation primary volcanic structures are extremely well preserved giving some information on the physical conditions at the time of eruption. In some metamorphosed basic lava flows, amygdaloidal and flow-top breccia structures can be recognised as well as pyroclastic breccias and ash-flow tuffs in intermediate metavolcanic rocks. Most of the silicic members are composed of tuff and lapilli tuff beds with some pyroclastic breccia and volcanic conglomerate intercalations. Locally there are also ash-flow tuffs with possible ignimbritic textures. Chemically the metavolcanic rocks of the Kuusa formation form a continuous calc-alkaline trend from basaltic andesites to rhyolites with high-K affinity. The U-Pb zircon age of a quartz-feldspar porphyritic rhyolite of the Kuusaa metavolcanic formation is 1887±2 Ma (Kousa unpublished) which is roughly the same age as the 1880 Ma Pihtipudas metavolcanic rocks (Aho 1979).

Stop 4:4:2 — The Settijärvi conglomerate

At the stop situated in the south-western margin of the Kuusaa formation a polymict, volcaniclastic conglomerate with volcanic pebbles derived from the Kuusaa formation and plutonic pebbles of quartz-dioritic composition in mainly intermediate tuffaceous matrix can be seen. The U-Pb zircon age of these plutonic pebbles is 1888±7 Ma (Vaasjoki & Sakko 1988). The quartz-dioritic pebbles in the Settijärvi conglomerate may be derived from the Vääti intrusion described below. This conglomerate and the volcanic rocks of the Kuusaa formation are intersected by a roughly E-W trending diabase dyke swarm.

Stop 4:4:3 — The Vääti granodiorite

The main constituents of the bedrock between the Kuusaa formation and the Pyhäsalmi volcanic complex are large syn- or late-tectonic granitic and granodioritic to dioritic intrusions. The so called Vääti granodiorite south of the Kuusaa formation is one example. The Vääti granodiorite also includes more mafic varieties and is usually slightly foliated indicating a syntectonic origin. The Kuusaa volcanic rocks are probably genetically related to this intrusion. The youngest intrusive phase is represented by coarse-grained potassium feldspar porphyritic granites, about 1880–1865 Ma in age (Kousa et al. 1994).

Day 5

The Pyhäsalmi Mine

Stop 5:1:1–3 — Bimodal volcanism in the Ruotanen formation (Lippikylä Mb.)

This stop consists of different outcrops west and south of the mine with felsic porphyries, pyroclastic rocks with sedimentary interbeds, mafic tuffs and tuff breccias with felsic fragments, and possibly also pillow lavas of the Mukurinperä member. The rather weak deformation in most of the outcrops of unaltered volcanic rocks is typical of the more distal parts of the stratigraphy compared to altered rocks near the ore.

Stop 5:1:4 Altered rocks east of the mine behind old open pit (Lepikko Mb.)

In this stop several outcrops representing different type of alteration will be seen. Sericitic alteration with cordierite and sillimanite, cordierite-quartz rock fragments in pyrite rich matrix, massive pyrite ore, younger pegmatite dykes, and unaltered mafic dykes with zeolites cutting the altered rocks can be studied, as well as cordierite biotite gneisses with lapilli-like texture, massive cordierite-anthophyllite rocks, gneisses representing very strong Mg-alteration, felsic looking, light grey cummingtonite-quartz-magnetite-anthophyllite rocks with clear mafic composition, and younger unaltered quartz-feldspar porphyries.

Stop 5:1:5 — Drill core exhibition

Representative drill cores from different ore types, volcanic rocks and altered rocks will be shown.

Mullikkoräme mine

Stop 5:2:1 — Drill core exhibition

Different ore types, volcanic rocks, and their altered equivalents will be exhibited on this stop.

Stop 5:2:2 — The Tetrinmäki pillow lavas

This stop consists of a large outcrop area with well preserved pillow lava and other volcanic rocks. Mafic dykes (Tetrinmäki Mb) can also be seen.

Stop 5: 2:3 — The Riitavuori felsic volcanic rocks

A typical outcrop of felsic volcanic rocks of the Riitavuori Mb. Among other rocks quartz porphyries (1.92 Ga) can be seen. In some places the rocks are more coarse-grained and intrusive like.

Stop 5:2:4 — Outcrops near the decline

Pillow lavas and lava breccias with strong epidotization and local strong chloritization are exposed near the decline. In the mine it will also be possible to study the ore and waste rock stock piles.

ACKNOWLEDGEMENTS

The editors would like to express their sincere thanks to all the contributing authors and to all involved in preparing and running the field trip. We would also like to thank Boliden AB, Outokumpu Mining OY, Terra Mining AB, and the Geological Surveys of Finland and Sweden for their support of this guidebook and the field trip.

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ISBN 951-690-657-5
ISSN 0781-643X

9 789516 906570

OY EDITA AB
HELSINKI 1997