SVERIGES GEOLOGISKA UNDERSÖKNING

SER. Ca AVHANDLINGAR OCH UPPSATSER I A4 NR 61

INGMAR LUNDSTRÖM & HEIKKI PAPUNEN (Eds.)

MINERAL DEPOSITS OF SOUTHWESTERN FINLAND AND THE BERGSLAGEN PROVINCE, SWEDEN

7th IAGOD SYMPOSIUM AND NORDKALOTT PROJECT MEETING

EXCURSION GUIDE NO 3

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With contributions by L. G. Andersson, H. Christofferson, R. Frietsch, P. Hedström, T. A. Häkli, I. Lager, I. Lundström, H. Papunen, W. Vivallo & A. Wikström

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A. Trochlea ad cavernam, Reguminus nomine inſignitam. Suedice Regerings Schaktz wind. B. Aquæ ductus, ubi collecta in ciſternis aqua egeritur. Suedice Kuſt Stugu
C. Trochlea, quæ jumentis circumagitur, ad cavernam à Rege Carolo XII. dictam, altitudine LX. hexapedum ſeu ulnarum. D. Peritrochium, ſeu machina tractoria, ad cavernam nomine Reginæ
Udalricæ Eleonoræ appellatam, et LX. ulnas profundam. E. Fumus ex officinis molliendo metallo exstructis. Suedice Kallroſtar. F. Vetus Curia metallicorum. G. Peritrochium ad cavernam, quæ columna
candida dicitur, vulgo Blankſtoten, XL. ulnarum profunditate. H. Caverna columnæ candidæ 35 ulnarum. I. Trochlea arcularum, Suedice Kiſtenvinden, 51 uln. K. Curia nova conventu metallicorum constituta
L. Trochlea ad cavernam lignariam 70 ulnarum. M. Caverna à Carolo XI dicta, per ſubterraneos meatus 127 ulnas depressa. N. Ligamentum magnum e columna candida delapsum Anno 1687

Falu copper mine has been continuously mined for more than 900 years. Copper plate engraving from 1687 in Dahlberg's *Svecia Antiqua et Hodierna*.

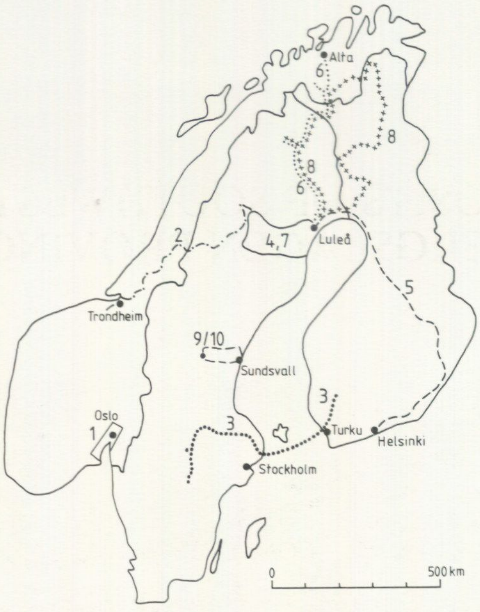
FOREWORD

Mining has ancient traditions in Scandinavia and Finland. In Bergslagen, Sweden, numerous mines produced Cu, Fe and Ag already during the medieval period. Some of them, e.g. Falun and Dannemora, are still active and are thus among the oldest operating mines in the world. Minerals like scheelite, gahnite and långbanite were first recognized in this region and the word skarn (originally having a pejorative connotation in Swedish meaning crap and whore) was used as a name for a certain mineral association for the first time by the old miners in Bergslagen. The most famous mining districts in Norway are Kongsberg, where silver was produced 1623–1957, and Røros, where copper was mined from 1644 until recently. The first mine in Finland was the Ojamo iron ore deposit, which was opened in 1540.

In addition to these ancient workings, ore bodies in several new mining districts have been exploited during the last century. Some of the most important of these occur in northern Sweden such as the Kiruna iron ores, the sulphide ores in the Skellefte district, the Laisvall Pb-mine and the Aitik Cu-Au mine. The sulphide ores in the Outokumpu district and in the Vihanti-Pyhäsalmi area are the most well-known Finnish deposits discovered during this century. In Norway, numerous deposits of pyrite and base metals were discovered round the turn of the century in the Sulitjelma and Grong districts and have been of major importance for the Norwegian mining industry. The discovery of extensive Mo-mineralization in the Oslo area, Norway and Pt-mineralization in the Kemi area, Finland have not led to any significant mining but have revealed new aspects of the metallogeny in the Nordic countries.

As a result of this long tradition in mining, the question of how ores are formed has been debated longer than any other geological problem in Scandinavia and Finland. It is therefore of special interest for the Nordic countries that the International Association on the Genesis of Ore Deposits (IAGOD) this year will arrange its 7th symposium in Scandinavia. The symposium, which is held in Luleå, Sweden, is arranged by the Geological Surveys of Sweden, Finland and Norway and the Luleå University of Technology. As an important part of the symposium programme, nine pre- and post-symposium excursions covering most of the important mining districts in Norway, Sweden and Finland are arranged (see overleaf). For these excursions, guide books have been written and are now available amongst the publications of the Geological Survey of Sweden (SGU Ca 59–67). The Swedish part of excursion no 6 was prepared in 1980 and was published by the Geological Survey of Finland. To all who have been involved in planning and organizing the excursions as well as writing the guide books I would like to express my sincere thanks.

Krister Sundblad, Geological Survey of Sweden
coordinater of the IAGOD-excursions 1986



1. Metallogeny associated with the Oslo Paleorift
Guide book: SGU Ca 59.
Excursion leader: S. Olerud.
Topic: Porphyry molybdenum mineralizations (Nordli, Hurdal and Bordvika, Drammen). Native silver-bearing veins at Kongsberg. Mineralizations associated with the Drammen granite; contact metasomatic Zn-Pb deposits (Konnerudkollen), intramagmatic Mo deposits.

2. Stratabound sulphide mineralizations in the central Scandinavian Caledonides
Guide book: SGU Ca 60.
Excursion leaders: M.B. Stephens and A. Reinsbakken.
Topic: Early Palaeozoic, massive Cu-Zn sulphide mineralizations in both volcanic (Gjersvik, Joma, Løkken and Stekenjokk) and sedimentary (Ankarvattnet) environments. The Laisvall sandstone-hosted, disseminated Pb-Zn deposit.

3. Mineral deposits of southwestern Finland and the Bergslagen province, Sweden
Guide book: SGU Ca 61.
Excursion leaders: H. Papunen and I. Lundström.
Topic: Proterozoic Zn-Cu-Pb deposits in volcanosedimentary environments including the mined-out Orijärvi and Aijala deposits in Finland, and the Garpenberg and Åmmeberg deposits in Sweden; the iron ore deposit of Dannemora in Sweden. Deposits associated with intrusive rocks include the Vammala Ni-Cu mine in Finland and the Wigström W deposit in Sweden.

4. Massive sulphide deposits in the Skellefte district
Guide book: SGU Ca 62.
Excursion leader: D. Rickard.
Topic: Proterozoic Cu-Zn-(Pb-As-Au) mineralizations in volcanosedimentary environments, including the Boliden, Långsele, Näsliden and Kristineberg deposits.

5. Proterozoic mineral deposits in central Finland
Guide book: SGU Ca 63.
Excursion leader: G. Gaál.
Topic: Early Proterozoic mineralizations including the Kemi Cr mine, PGE mineralization in the Penikat layered intrusion, Pyhäsalmi Cu-Zn deposit, Outukumpu Cu-Co-Zn mine and the Enonkoski Ni-Cu deposit.

6. Precambrian mineral deposits in northernmost Scandinavia
Guide books: SGU Ca 64 (Norwegian part)
Geol. Surv. Finland (1980), Guide 078 A+C, part 1 (Swedish part)
Excursion leaders: J.S. Sandstad and H. Lindroos.
Topic: Precambrian copper and iron ore deposits including visits to two of the largest mines in northern Europe: Kiirunavaara underground mine (Fe) and Aitik open pit operation (Cu, Au). In addition, the Raipas, Repparfjord, Bidjovagge and Viscaria Cu deposits and Au prospects in the Gällivare area will be shown.

7. Proterozoic mineralizations associated with granitoids
Guide book: SGU Ca 65.
Excursion leader: B. Öhlander.
Topic: Mineralizations associated with Proterozoic granitoid intrusions including the Pleutajokk, Rävaberget and Björklund U deposits, the Allebouda and Kåtaberget Mo deposits, the Storuman W mineralization and Tallberget Cu-Mo deposit.

8. Archaean and Proterozoic geology in northern Finland, Norway and Sweden
Guide book: SGU Ca 66
Excursion leaders: T. Sjöstrand, M. Often and V. Perttunen.
Topic: Archaean and Proterozoic geological environments in the ore-bearing Nordkalott area, including greenstone belts and granulites.

9/10. Enåsen Au deposit and Alnö alkaline complex
Guide book: SGU Ca 67.
Excursion leaders: T. Lundqvist, S. Sundberg and P. Kresten.
Topic: Geology at and around the Proterozoic Enåsen Au deposit and the Alnö alkaline complex.

IAGOD-excursions 1986

MINERAL DEPOSITS OF SOUTHWESTERN FINLAND AND THE BERGSLAGEN PROVINCE, SWEDEN

CONTENTS

INTRODUCTION

The Precambrian Baltic Shield consists of three major geotectonic units: The Archaean basement complex in the northeast, the Proterozoic Svecokarelian orogenic complex in the central part of the Shield and the Proterozoic, Sveconorwegian complex in southwestern Scandinavia (Fig. 1, inset map). The Baltic Shield is, in the west, covered by flat-lying autochthonous and allochthonous Caledonian units and, in the south, by flat-lying autochthonous Phanerozoic sediments.

Most of the ores that have been mined in Sweden and Finland during the last millenium are hosted in supracrustal rocks belonging to the Svecokarelian orogenic complex. Svecokarelian supracrustal formations include Karelian epicontinental and geosynclinal units in northern and eastern Finland and Svecofennian units in Sweden and southwestern Finland. This excursion will focus attention on the geology and ores of the southern part of the Svecokarelian area, which include the classical ore province of Bergslagen in central Sweden and the geologically related areas in southwestern Finland.

Although the Finnish and Swedish Svecokarelian areas are thought to have formed simultaneously and by similar processes, detailed correlation between them has not been established. Therefore, the stratigraphy of Bergslagen and southwestern Finland will be treated separately in the text.

PROTEROZOIC GEOLOGY OF SOUTHWESTERN FINLAND AND THE BERGSLAGEN PROVINCE, SWEDEN

I. Lundström and H. Papunen

SUMMARY OF GEOLOGICAL EVENTS

Bergslagen

Despite minor differences between various areas, the main features of the geological evolution in Bergslagen can be summarized as follows (see also Fig. 2):

Around 1850–1900 Ma a volcanosedimentary succession was deposited on a basement, which still remains unidentified. Prior to 1850 Ma, i.e. in close connection with the deposition of the supracrustal rocks, this succession was intruded by early Svecokarelian plutonic rocks ranging in composition from gabbros to granites. These are frequently called primorogenic intrusions, "urgraniter" or "gnejsgraniter" in Swedish geological literature (cf. Lundqvist 1979). Shortly afterwards this succession was regionally deformed and metamorphosed to various degrees in different areas. It is thought to have occurred prior to 1841 Ma because late Svecokarelian granites of that age are unaffected by this event. Basic magmatism occurred intermittently all since the deposition of the supracrustal rocks, which contain occasional basic intercalations, and stopped before the intrusion of the late Svecokarelian granites.

The granites which intruded soon after the main phase of deformation have been called "serorogenic" or "late kinematic" in Swedish literature to separate them from the "postorogenic" granites, which generally yield ages between 1650 and 1730 Ma. However, evidence is currently accumulating which indicates that the subdivision into ser- and postorogenic granite groups is not valid (Åberg & Strömberg 1984). In fact, it appears that there is a continuous suite of granite intrusions from ser- to postorogenic times.

Finally, at about 900–1000 Ma, anorogenic dolerites intruded the consolidated Svecofennian crust as a set of steeply inclined dykes, mostly with a strike in NNW–ESE or E-W.

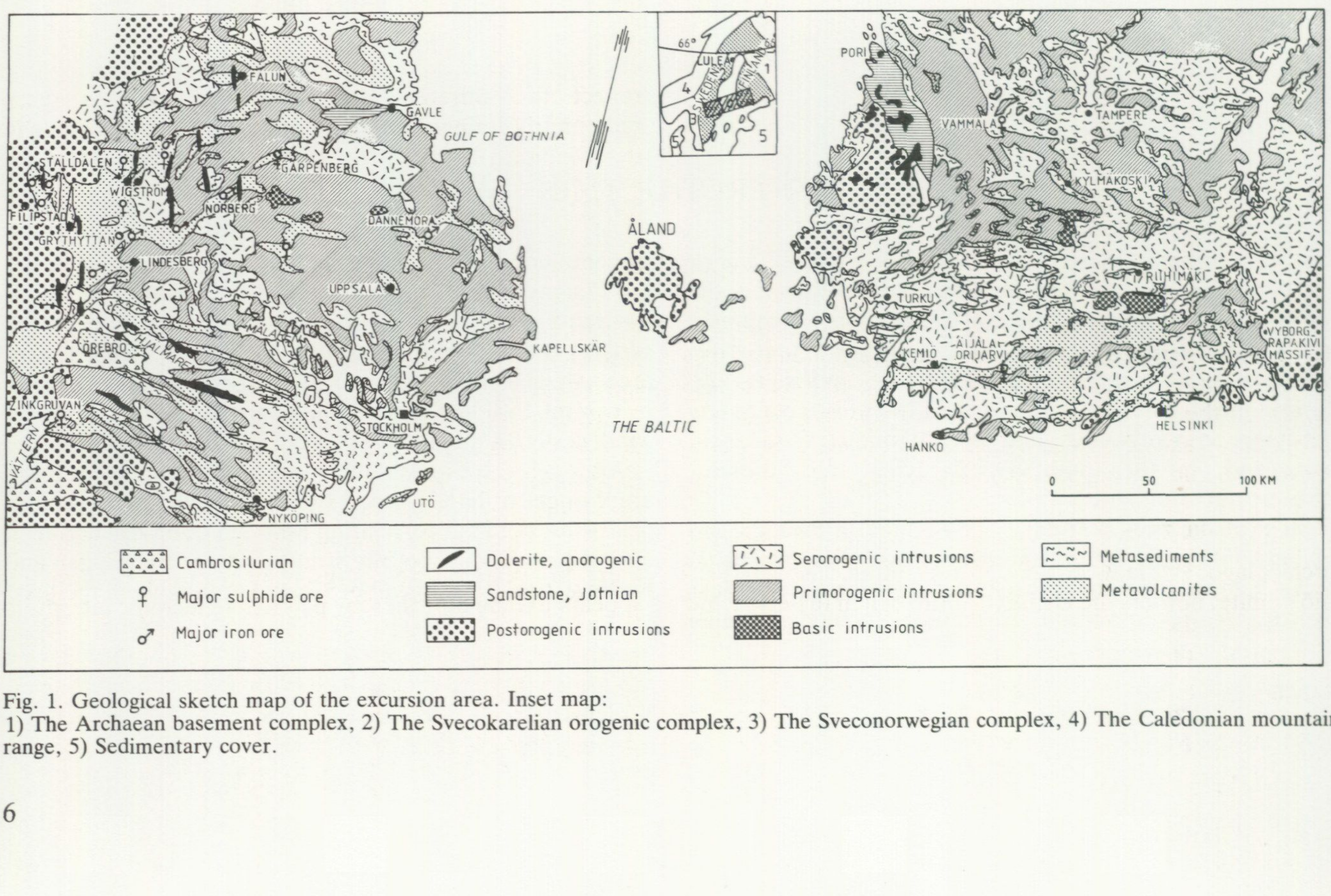


Fig. 1. Geological sketch map of the excursion area. Inset map:
1) The Archaean basement complex, 2) The Svecokarelian orogenic complex, 3) The Sveconorwegian complex, 4) The Caledonian mountain range, 5) Sedimentary cover.

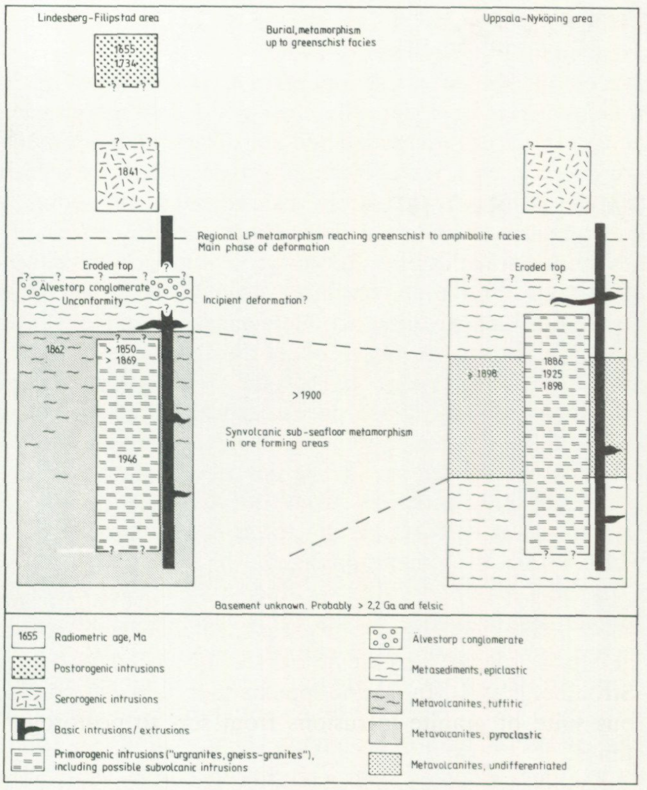


Fig. 2. Main stratigraphic features of the Bergslagen province. Anorogenic dolerites excluded. Cf. text. References for radiometric ages in Ma: 1655 (Welin 1980), 1734 (Åberg & Fredriksson 1984), 1841 (Oen & Wiklander 1982), 1850, 1946 (Åberg, Bollmark, Björk & Wiklander 1983), 1869 (Åberg & Strömberg 1984), 1900 (Åberg, Levi & Fredriksson 1984), 1898, 1886 (Welin, Kähr & Lundegårdh 1980), 1925, 2200 (Welin 1980, after Åberg 1978).

Southwestern Finland

In southwestern Finland similar processes as in Bergslagen created a bedrock which is composed of Svecofennian supracrustal formations and plutonic rocks of mainly felsic composition. The supracrustal belt trending almost east–west from the Åland archipelago through Kemiö island, Orijärvi, Lohja and Hyvinkää and terminating at the Vyborg rapakivi massif in the east is frequently mentioned in the literature as the Orijärvi leptite belt. A schist belt, similar in composition to the Orijärvi belt but separated from it by an intrusion of late-orogenic microcline granite, trends along the southern coastal area from Hanko through Helsinki to the Pellinki archipelago. The late-orogenic granite, often called the Perniö granite, borders the Orijärvi leptite belt in the north and separates the Orijärvi supracrustal rocks from the supracrustal belt of Hyvinkää, Somero, Jokioinen and Forssa, which forms an arc around the granitoid area of Riihimäki.

TECTONICS

In both Finland and Bergslagen several phases of deformation have been descerned.

On the Finnish side, three phases of folding have thus been distinguished in the Orijärvi area (Latvalahti 1979, Mäkelä 1983, Schreurs & Westra 1985). The first (F_1) was isoclinal and produced prominent foliation in supracrustal and infracrustal (the Orijärvi batholith) rocks with subhorizontal fold axes. The rocks were intruded subsequently by microcline granitoids (the Perniö granite). The second phase (F_2) resulted in isoclinal folds with NE–SW trending axial planes and subvertical fold axes. The third fold generation (F_3) is characterized by large open folds with N–S trending axial planes (Schreurs & Westra 1985). Numerous post–metamorphic fault planes are encountered in the Aijala-Orijärvi area, the most prominent being the Jyly fault zone east of Orijärvi and the Kirkkojärvi-Kiskonjoki fault zone. Numerous minor faults have been identified in the mines of the area.

In Bergslagen, the main phase of deformation (cf. Fig. 2) is thought to be dominated by a regional east–west compression, which created N–S trending macroscopic folds with steeply E-dipping axial surfaces and horizontal fold axes (Stålhös 1984). However, due to the presence of large early granitoids, (the primorogenic intrusions) which were more competent than the supracrustal rocks, the stress pattern became very varied over the area. Thus, E–W trending septa or folds of supracrustal rocks are thought to have been squeezed in between these large blocks of more competent infracrustal rocks. As a result secondary N–S compression was created, which formed E-plunging mesoscopic lineations and fold axes on the limbs of the macroscopic folds. These two axial systems were previously considered to reflect two different deformation phases. As recent radiometric datings have reduced the time span available for deformation, a one-stage model has gained favour. The reader is referred to Stålhös (1984) for a detailed discussion of these questions.

Regardless of the model for the deformation, the Bergslagen fold pattern can be described as an interplay of N–S and E–W trending macroscopic folds with subhorizontal fold axes and steep axial planes. This large scale fold structure is corrugated by mesoscopic lineations and fold axes with a steep easterly plunge.

Minor folding and block movements must have occurred prior to the main phase of deformation, i.e. during the deposition of the supracrustal rocks. These structures were mostly obliterated where the regional deformation, which followed, was strong, i.e. over most of Bergslagen. However, in westernmost Bergslagen regional deformation appears to fade out, thereby permitting tectonic interpretations in terms of syndepositional rifting (Oen *et al.* 1982). These questions will be considered when the excursion visits the Grythyttan area (day 6).

STRATIGRAPHY

Many of the supracrustal rocks of southwestern Finland and Bergslagen occur in fairly isolated areas, surrounded by large bodies of infracrustal rocks, and detailed stratigraphic correlation is therefore difficult. However, some well-established but somewhat different stratigraphic type areas can be described from the region.

The Orijärvi area in southwestern Finland is part of the Svecofennian supracrustal belt that runs across southern Finland approximately from east to west. The late-orogenic Perniö granite bordering the schist belt is about 1800 Ma old (Simonen 1980). According to Mäkelä (1983), the supracrustal rocks were deposited on the roof of the Orijärvi batholith, which is a tonalite-gabbro complex surrounded by a quartz phyric marginal facies. Other authors maintain that the basement of the supracrustal rocks is unknown (see e.g. Simonen 1980) and that the Orijärvi batholith, in consequence, should be younger than the supracrustal rocks. Stratigraphically, the supracrustal rocks have been divided into Lower, Middle and Upper Svecofennian Groups (Latvalahti 1979, Simonen 1980). The Lower Svecofennian Group consists mainly of felsic metavolcanites that are either pyroclastic rocks or less foliated quartz-feldspar porphyries. Locally preserved layering indicates that there are also sedimentary interbeds between the volcanoclastic rocks. The occurrence of aluminous silicates, andalusite, sillimanite and abundant biotite also indicates the existence of weathering material in the original sequence. The metavolcanites are rhyolite or dacite in chemical composition. In the upper part of the Lower Svecofennian Group intercalations of calc-silicate rocks (skarn), marbles and cherty quartzites represent the original limestone, chert and iron-bearing horizons. Sill- or dyke-like amphibolites represent the original feeder dykes of the overlying mafic volcanites. The abundant beds of chemical sediments and conglomerates in the upper part of the Group are attributed to a quiet period of volcanism.

The Middle Svecofennian Group consists mainly of intermediate and mafic metavolcanites and minor metasediments. The abundance of pyroclastic rocks, tuffs and agglomerates, interbeds of calc-silicate rocks and banded iron-formation (Algoma type) as well as the local pillow lavas of mafic metavolcanites indicate deposition in environments, varying from terrestrial to shallow marine.

The Upper Svecofennian Group consists primarily of sedimentary material mixed with minor volcanogenic units. The rocks are tuffites, metagreywackes and mica schists. The occasional bed of conglomerate is also encountered among the turbiditic metagreywackes. The Upper Svecofennian Group represents a waning stage of volcanism with deposition of weathering sediments in a deep basin. The whole Svecofennian succession indicates a transgressive sequence.

In the coastal areas on the Swedish side of the Baltic, a relatively well established supracrustal stratigraphy is found between *Nyköping and Uppsala* (see Stålhös, e.g. 1975, 1982). These areas will, however, not be visited during the excursion. On Utö island (Gavelin *et al.* 1970), the succession commences with a sedimentary formation (see Fig. 2), which consists of beautifully cross-bedded subgreywackes and greywackes with graded bedding. These metasediments are overlain by a metavolcanic horizon, which frequently contains tuffites with marble, calc-silicates and sediment intercalations. A younger metasedimentary sequence overlies these metavolcanites. Felsic pyroclastic rocks make up a major part of the metavolcanites of the Uppsala-Nyköping area, but metarhyolitic to metadacitic porphyries also appear at various levels, probably both as extrusive and intrusive rocks. Felsic pyroclastic rocks (terminology according to Schmid 1981), particularly of sodium-rich type, appear to be less common in these areas, compared to the Lindesberg-Filipstad area to be described below. Metadacites and meta-andesites from the Uppsala region recrystallized at 1898 Ma (Welin, Kähr & Lundegårdh 1980) which is thus their minimum age.

In the *Lindesberg-Filipstad area*, a somewhat different supracrustal sequence occurs. This succession appears to record an evolution of declining volcanism and will be demonstrated in the Grythyttan area. It commences with felsic pyroclastic rocks, continues with tuffites and generally ends in meta-argillitic sediments (Oen *et al.* 1982, Lundström 1983, 1985, cf. Fig. 2). The lowermost pyroclastic rocks have faint bedding, are poor in sedimentary intercalations such as marbles, and occasionally contain possible pisoliths and welded pumice fragments. Therefore, they may be in part terrestrial. In contrast, the tuffites demonstrate their dominantly subaqueous nature by frequent intercalations of marble, calc-silicate rocks and epiclastic sediments. Both pyroclastic rocks and tuffites may be several kilometres thick and contain sparse intercalations of flows. The metavolcanites mostly have alkali-rhyolitic compositions, which sometimes tend to be sodic in the lower, pyroclastic part and potassic in the upper, tuffitic sections. This is considered to be due to secondary alteration (see below p. 9). These rocks are the well-known "sodium- and potassium-leptites/hälleflintas" of Swedish geological literature (e.g. Lundqvist 1979). Both pyroclastic rocks and tuffites are locally cut by subvolcanic intrusions. Radiometric datings have yielded ages of 1862 Ma (Welin, Wiklander & Kähr 1980) for a subvolcanic intrusion, cutting the uppermost parts of the volcanites in the Grythyttan and Saxån areas.

The ensuing epiclastic sedimentation started with a mere reworking of the pre-existing tuffites into greywacke-like, volcanic arenites, which are frequently slump-folded. These are overlain by siltstones and partly graphitic argillites. The absence of coarser sediments, quartzites, conglomerates etc. is considered to indicate isolated depositional basins, characterized by local provenance.

The impressive polymict Älvestorp conglomerate occurs only in the Grythyttan area, where it is found close to the metasediments. As it also rests discordantly on both metavolcanites and metasediments and contains meta-argillitic fragments, it is thought to be separated from the sediments by an unconformity. This may reflect the onset of the subsequent deformation.

As the volcanites in both of the described Swedish type-areas and in the the intervening terrain yield similar radiometric ages (1900 Ma in Svärdsjö and Yxsjöberg, Åberg *et al.* 1984), they are often regarded as marker beds, correlating the stratigraphies across the Bergslagen region.

Maps (Fig. 1) and sections (Fig. 2) demonstrate, however, that the volcanites of the Nyköping-Uppsala area have a much more restricted vertical as well as lateral extension than those of the Lindesberg-Filipstad area. Evidence in the intervening areas also indicates a continuous lateral shift towards a more sediment-dominated environment in the east. Sedimentary formations underlying the volcanites have been identified as far west as in the Norberg area (Ambros 1983) and also in the Zinkgruvan area (Wikström, pers. comm. 1985). An eastward deepening of the depositional basins in the Örebro area is also indicated (e.g. by Gorbatschev 1969).

The supracrustal belt of southwestern Finland has been considered to correspond to similar rocks of Bergslagen, central Sweden. There are, however, many dissimilarities between these areas:

– The predominance of felsic metavolcanites over intermediate and mafic metavolcanites is much more marked in Bergslagen than in southwestern Finland. In Finland, the felsic metavolcanites are concentrated in certain areas (e.g. Orijärvi-Aijala) and the metasedimentary sequence prevails elsewhere. There are no sodium- and potassium-extreme felsic metavolcanites in southwestern Finland and the stratigraphic division of sodic and potassic metavolcanites recognized in Sweden can not be applied in Finland. Further differences are:

– No apatite or manganiferous iron ores occur in Finland.

– Only several traces of mineralized rocks have been found in Finland, whereas large sulphide and oxide ore deposits exist in Bergslagen.

To date, no basement for the supracrustal successions has been identified on the Swedish side although the following evidence regarding its character may be relevant.

Detrital zircons in the Svecofennian Västervik quartzite (south of Bergslagen proper) yielded U-Pb ages of 2220 Ma (Åberg 1978). This age is interpreted to be inherited from the basement. Likewise, Åberg & Persson (1984) envisaged a 2200–2500 Ma old provenance area for related metasediments and Beunk *et al.* 1985, from Sm-Nd studies, conclude that Proterozoic and Archaean crustal components existed prior to the development of the felsic eruptive rocks in western Bergslagen. From petrogenetic evidence Baker (1985) also concluded that the pre-existing crust was dominantly felsic. A pre-existing continental crust of felsic composition is also envisaged by Rickard (1981), Vivallo & Rickard (1984) and Johansson & Rickard (1985). They base their opinions on the LREE enriched REE distribution patterns, the predominantly acid character of the volcanites and lead isotope relationships, respectively.

VOLCANITE CHEMISTRY AND ALTERATIONS

Volcanite chemistry

In a regional survey, Frietsch (1982b) noted that the metavolcanites of the ore-bearing regions of Bergslagen differ chemically from those of the ore-free regions. Thus, the former frequently are higher in SiO_2, more often have alkali-extreme compositions, are lower in calcium and have fewer basic and intermediate members than the latter. The differences are thought to be due to synvolcanic metasomatism, which was restricted to the ore-bearing regions (see below). Furthermore, bimodal volcanism is not evident in the ore-free regions. In this respect, a comparison of Frietsch's (1982b) Fig. 2 with corresponding diagrams by van der Velden *et al.* (1982) and Vivallo & Rickard (1984) is significant.

These regional differences have obviously resulted in certain recent contradictory interpretations regarding the volcanite chemistry and geological environment in Bergslagen. Thus, the arguments for a pre-existing continental crust listed above (p. 9), as well as the bimodal volcanic associations of the ore-bearing regions (van der Velden *et al.* 1982, Vivallo & Rickard 1984), are thought to indicate an ensialic, continental rift or continental margin environment for these regions. The absence of recognizable, calc-alkaline trends in some areas (Baker 1985) and the presence of continental tholeiitic compositions (Hellingwerf & Oen 1986) in others, seem to corroborate this.

In contrast, workers who have sampled the entire Bergslagen region (e.g. Löfgren 1979, Loberg 1980, Frietsch 1982b) claim that calc-alkaline compositions also occur. These different conclusions probably reflect the different volcanite populations that have been sampled, one group being typical for the ore-bearing regions alone, and another containing all the volcanite varieties of Bergslagen.

The bimodal felsic–mafic volcanites of the Orijärvi area represent a typical calc-alkaline trend of differentiation. The sodium and potassium contents of the felsic metavolcanites are not high, as they are in the "leptites" of central Sweden. The amount of sodium commonly exceeds that of potassium although Na_2O never exceeds 5%. The potassic felsic metavolcanites typical of the Bergslagen province in Sweden have not been detected in the Orijärvi area.

Synvolcanic alterations

Although the pre-metasomatic parent rock of the ore-bearing metavolcanites remains unknown, the metasomatic changes themselves are clearly seen through the variations in chemical compositions. These frequently deviate significantly from the compositions and trends of unaltered eruptive rocks (Frietsch 1982b, Lagerblad & Gorbatschev 1985).

This feature is thought to be due to large scale, hydrothermal, metasomatic synvolcanic alteration. The process was described as sub-seafloor hydrothermal alteration by Oen *et al.* (1982), who also pointed out its significance for the ore formation (see also Frietsch 1982a, b, c and this guidebook p. 14). Seawater thus played an important role as a metasomatic fluid (Baker & de Groot 1983, Lagerblad & Gorbatschev 1985), which convected through the volcanic pile driven by volcanic heat. During this metasomatic exchange sodium, potassium and magnesium were fixed at different places depending on, amongst other factors, prevailing temperatures, fluid compositions and water/rock ratios. Thus, higher temperatures and lower water/rock ratios, which are expected at depth, favoured sodium as opposed to potassium fixation. Consequently, sodic rhyolites are more frequently found at stratigraphically lower levels than the potassic ones and *vice versa.* Magnesium and potassium fixation is believed to have occurred simultaneously in permeable zones, characterized by higher water/rock ratios. They now form large cross-cutting and concordant zones of chlorite/cordierite-bearing mica quartzites. The correlation between these different alteration patterns, stratigraphy and ore geology is treated by many of the authors mentioned above (see also Frietsch, this guidebook). These alterations are best developed in the Filipstad-Lindesberg area, whereas sodic rhyolites and mica quartzites appear to be less frequent in the ore-bearing regions of the Uppsala-Nyköping area. These areas, which are relatively poor in ores, may be transitional to Frietsch's (1982b) ore-free regions. In the Nyköping-Uppsala areas, a faint potassium enrichment is the most frequent manifestation of similar processes.

INTRUSIVE HISTORY

In southwestern Finland "The Orijärvi Batholith" is an intrusive complex varying in composition from tonalite to hornblendite with the felsic phase prevailing. Close to the Orijärvi mine, the tonalite intrusion contains a porphyritic marginal variety with phenocrysts of quartz and microcline in a fine-grained groundmass. The mafic varieties (gabbros and hornblendites) are to be found in the central part of the complex. Locally the mafic rocks form minor layered complexes, similar to those on the western shore of lake Iso-Kiskojärvi, where a small titaniferous iron ore is associated with the layered complex (Sipilä 1981). Mäkelä (1983) is of the opinion that the felsic metavolcanites were deposited on the roof of the Orijärvi batholith, and that, shortly after volcanism, the batholith was mobilized and rose as a dome in the centre of the supracrustal belt.

The microcline granite, known as the Perniö granite, borders the supracrustal belt in the south and north. This granite is very unhomogenous, having pegmatitic varieties, but it is generally only weakly oriented like the other late-orogenic granitoids typical of southwestern Finland. It frequently forms migmatites with the supracrustal rocks.

The Orijärvi batholith is comparable to the "urgranit" intrusions of central Sweden, and the Perniö type of granites to the serorogenic granitoids of Bergslagen.

In Bergslagen, primorogenic intrusions ("urgraniter" or "gnejsgraniter" in Swedish literature), ranging in composition from gabbros to granites are the oldest recognized infracrustal rocks. In most of Bergslagen, penetrative foliation testifies to their pre-deformative age, which from available radiometric datings seems to be around 1900 Ma (cf. Fig. 2). These plutonic rocks may thus well have intruded contemporaneously with the deposition of the supracrustal rocks. A synvolcanic character of a group of such rocks in the Lindesberg-Filipstad area has, in fact, been suggested by Oen *et al.* (1982) and Baker (1985). These rocks showed mixed S- and I-type characteristics according to Baker (1985), whereas similar rocks in the Garpenberg area were found to be of I-type (Vivallo 1984). Their magmas are assumed to have caused much of the volcanite alterations, described above. However, as they are known to have intruded also into sediments overlying the volcanites in the Uppsala-Nyköping area (Fig. 2), they are also postvolcanic in the latter area. In areas where the regional metamorphism is sufficiently low-grade, contact-metamorphic aureoles can often be discerned around the primorogenic intrusions. As in the case of the supracrustal rocks, these pre-deformational intrusions are frequently cut by basic dykes. In the Lindesberg-Filipstad area, some such dykes grade into flows at the lowermost sedimentary levels (Oen *et al.* 1982), indicating that basic magmatism here appears to be late- to postvolcanic. On the other hand, Stålhös & Björk (1984) demonstrated the existense of low-metamorphic, post-deformative basic dykes, therefore mafic magmatism apparently occurred intermittently during both pre- and post-deformational/metamorphic times.

These low-metamorphic dykes provide evidence of a time interval which separated the culmination of regional metamorphism and deformation from the intrusion of the serorogenic granites. Very few radiometric data exist for these granites, which appear to have intruded from about 1840 Ma onwards. They form a fairly undifferentiated suite comprising more or less schlieric, but otherwise unfoliated aplites and pegmatites in addition to normal granites. The granites frequently cross-cut the other rocks, but no minimum age is known for them. Ohlson (1979) suggested that granites of this type were important for the formation of contact metasomatic tungsten occurrences in Bergslagen. However, Hellingwerf & Baker (1985) claim that the tungsten forming granites are in fact primorogenic in age.

The youngest intrusive event of importance created the postorogenic Filipstad-type granites to gabbros in the westernmost part of Bergslagen. The granites are homogeneous, non-foliated and cross-cutting, and contain large megacrysts of potassium feldspar. Some of these granites, which have hitherto been recognized as serorogenic, may in fact also be of this age. The postorogenic granites are often surrounded by hornfelses and various contact-metamorphic phenomena (e.g. Hellingwerf 1985).

METAMORPHISM

Low-pressure amphibolite facies characterizes southwest Finland as exemplified by the rocks of the Aijala-Orijärvi area. Farther to the northeast, however, there is an extensive area, named The West Uusima Complex (WUC) by Parras (1958), of granulite facies metamorphism. The hyperstene-in isograd that defines the boundary of the granulite complex is c. 10 km northeast of Orijärvi. The isograd cross-cuts the major tectonic structures of F_1 and F_2 folding and is probably affected by F_3 folding (Schreurs & Westra 1985). The amphibolite facies metamorphism of the Orijärvi area is associated with the peak of F_2 folding (Latvalahti 1979). The granulite facies metamorphism predates the third fold generation (F_3) and is probably contemporaneous with the later phase of F_2 folding. According to the study of cordierite channel fluids and fluid inclusions by Schreurs (1984) the fluids of the granulite complex are predominantly CO_2-rich whereas H_2O-rich fluids predominate in the amphibolite facies domain, suggesting high-grade rocks with high CO_2 activity. Schreurs (1985) considers the granulite complex to be the result of a low-pressure thermal dome event.

The metamorphic history of Bergslagen is frequently described in terms of three or more phases (Levi *et al.* 1980, Lundström 1983, 1985, Helmers 1984, Vivallo 1985a). The oldest of these is the synvolcanic metasomatism, described above, (p. 9) and the contemporaneous contact-metamorphism, linked to the primorogenic intrusions. The second phase is a regional metamorphism of low-pressure type as is shown by the almost ubiquitous presence of andalusite/sillimanite and cordierite in argillitic metasediments. The metamorphism of this phase reached upper amphibolite facies in the central parts of Bergslagen (the Uppsala-Nyköping area), where migmatites are common. Both east- and westwards, however, a regional metamorphic gradient towards greenschist facies is evident. As the amphibolite facies metamorphism of the central area has affected even the uppermost stratigraphic units, the high-grade metamorphic rocks are clearly not the basement of the lower grade metamorphic rocks. In the regionally low-grade metamorphic areas, vestiges of older contact metamorphic patterns can be found. The regional metamorphic minerals generally show post-deformational textural relationships. Thus, the regional metamorphism outlasted the regional deformation.

In Bergslagen, a pervasive retrogression is often apparent even in intrusive rocks post-dating the regional metamorphism. Since this tends to follow post-metamorphic fracture zones, it evidently reflects a separate, third metamorphic event. It may correspond to the postorogenic late burial metamorphism, as originally suggested by Nyström & Levi (1980).

METALLOGENESIS OF THE BERGSLAGEN PROVINCE AND SOUTHWESTERN FINLAND

BERGSLAGEN

R. Frietsch

HISTORY

The ore province of Bergslagen, which comprises deposits of iron, manganese, zinc-lead-copper and tungsten, has been productive for almost a thousand years. Iron and sulphide ores have been mined ever since the Middle ages and these ancient industries have been of great importance to the country and its economy.

The mining industry developed around the numerous mineralizations of northern Västmanland and surrounding provinces. This area is called Bergslagen (The mining district) and royal charters were given as early as in the 13th and 14th centuries to regulate the activity of the mining and the metallurgical processes. Until about a century ago the region accounted for practically the whole mineral production of Sweden. The sulphide mines of Sala and Falun represented real treasures. By modern standards, however, the production was small. The Sala silver-(lead)-mine was of great importance in the 16th century, the total silver production 1506 to 1600 amounting to 238 metric tons. The Falu mine or Stora Kopparberget (the Great Copper Mine), in production for almost 1000 years, had, during the 17th century, a yearly production of 3 000 metric tons of copper, which at that time represented two thirds of the copper production of the World. Central Sweden has occupied a prominent position as an iron ore producer over a long period. In 1740, the area accounted for 38 % of the World's iron production and 40 % of it's pig iron production. At the end of the 18th century, the production diminished rapidly. At present Central Sweden accounts for only a minor part of the Swedish mining industry. During the last hundred years there has been a decrease in the number of sulphide mines, whereas the production has gone up. In 1873, there were 16 sulphide mines producing 90 000 metric tons of ore and, in 1960, 11 mines producing 933 000 metric tons. In 1984, there were five sulphide mines working and their production was 1.5 million metric tons of ore, equal to 9 % of the total production of Sweden. These mines accounted for about 5 % of the copper, 32 % of the lead, 49 % of the zinc and 39 % of the silver produced in total in Sweden. The reserves of sulphide ore are calculated at 30 million metric tons and thus represent roughly 6 % of the sulphide ore reserves of Sweden. In the case of the iron ores, there has been a still more drastic decrease in the number of mines. In 1873, there were 646 mines producing 823 000 metric tons of ore, in 1960, 68 mines produced 5 510 000 tons and, in 1984, two mines produced 2 380 000 tons representing 13 % of the total in Sweden. A few mines also had a small production of manganese ore which ceased in the 1970s. In addition, there is at present a production of scheelite from Yxsjöberg amounting, in 1984, to 160 000 metric tons of ore.

General reviews of the ores of Central Sweden have been given by Tegengren (1924), Magnusson (1936, 1948, 1960, 1970), Geijer (1952a, 1952b), Geijer & Magnusson (1944), Hübner (1971) and Frietsch (1975, 1977, 1980a, 1980b).

Geological setting

The iron, manganese and sulphide ores of Central Sweden occur in felsic metavolcanites with intercalated horizons of limestone and dolomite. Minor amounts of manganese-bearing iron ores occur in the western part of the ore-bearing area near meta-argillites, metagreywackes and minor mafic volcanites that overlie the felsic volcanites. The main part of the manganese-bearing iron ores and the manganese ores occur in a high stratigraphic position within the felsic volcanites, which here are all potassic.

The ore province of Central Sweden is unique in two respects: 1, the intimate association between sulphide ores and iron ores and 2, the extreme composition of the wall rock, with a richness in sodium or potassium and silica occurring on a regional scale.

The tectonic setting of the volcanites and their ores has been widely discussed. The region has been interpreted as an island arc (Hietanen 1975, Rickard 1979, Löfgren 1979, Loberg 1980) or as an active continental margin (Vivallo & Rickard 1984). The latter point of view is supported by the bimodal basaltic-rhyolitic character of the volcanites reflecting alternating compressional and tensional tectonic regimes (van der Velden *et al.* 1982, Vivallo & Rickard 1984, Vivallo 1985a, 1985b). The importance of a rift zone (tensional) environment for the western part of the region has been emphasized by Oen *et al.* (1982), Helmers (1984) and Baker & Drucker (1985). Frietsch (1982a) pointed out that if the volcanites are the result of subduction-related island arc type volcanism in a subduction zone, the dominantly felsic character of the volcanites is unusual and contrasts with most island arc systems which are built up of mafic–intermediate volcanites. The felsic nature of the volcanites of Central Sweden, if formed in an island-arc environment, would necessitate formation by subduction below a thick continental crust.

Iron and manganese ores in supracrustal rocks

The iron ores form long and narrow bodies which are concordant whithin the enclosing volcanites. Due to later deformation the form of the ores is sometimes rather complicated. The main ore types are: 1, quartz-banded iron ore, 2, skarn iron ore and 3, apatite-bearing iron ore.

The quartz-banded iron ores consist of hematite, magnetite, quartz and small amounts of Ca-Mg and Ca-Fe^{3+} silicates such as andradite, diopside and tremolite. The iron content varies between 30 and 50 %. Phosphorus is in most cases between 0.007 and 0.03 % and manganese usually lower than 0.2 %. The sulphur content is mainly between 0.001 and 0.1 %.

The skarn iron ores, which consist of magnetite and skarn silicates, are divided into a non-manganiferous type (<1 % Mn) and a manganiferous type (1–8 % Mn) with the manganese contained in the silicates. The non-manganiferous type occurs mostly in sodic volcanites whereas the manganiferous variety occurs in potassic volcanites. Both types, in particular the latter one, are more or less intimately associated with limestones-dolomites.

In the non-manganiferous iron ores the skarn (calc) silicates, occurring either irregularly distributed or in a regular stratification, are rich in Ca-Fe and Ca-Mg (andradite, diopside-hedenbergite and actinolite). In a few deposits there is a magnesium-rich skarn with anthophyllite-gedrite, cummingtonite, talc, forsterite, humite minerals and serpentine. The non-manganiferous iron ores are low in phosphorus and sulphur.

The manganiferous iron ores are stratified and built up of magnetite and skarn silicates rich in Fe^{2+} and Mn (spessartine, dannemorite, knebelite, manganiferous fayalite and in some cases rhodonite). The content of iron is between 35 and 50 %. The content of phosphorus is less than 0.1 %; sulphur is relatively high, in several deposits higher than 0.2 %.

The quartz-banded iron ores are considered as volcano-sedimentary (Geijer & Magnusson 1944, 1952a, 1952b, Frietsch 1973, 1977). The skarn iron ores were previously considered as true pyrometasomatic deposits formed by emanations from the early Svecokarelian intrusive rocks (Geijer & Magnusson 1952a, 1952b) but are now considered to be of exhalative-sedimentary origin (Frietsch 1973, 1977). This is supported by their banded character and by the fact that they are stratabound and form horizons of considerable length, up to 100 km, in which quartz-banded iron ores also occur. The skarn (calc) silicates are formed by internal reactions between iron, carbonate and silica as a result of the regional metamorphism.

Mn-Fe^{2+} skarns without any iron oxides are developed locally in the potassic felsic volcanites, close to the overlying sedimentary suite. These so-called eulysites are composed of knebelite, spessartine-almandine, Mn-rich diopside, dannemorite and iron anthophyllite. The manganese content is between 6 and 12 % and the iron content between 24 and 33 %.

Some bedded manganese oxide-silicate ores associated with jaspilitic hematite and magnetite occur associated with carbonate rocks in the same stratigraphic position. The Långban mine is famous for its mineral wealth, there being a great number of minerals with barium, lead and antimony (Magnusson 1930). Most common among the oxides are braunite and hausmannite. Spessartine, rhodonite and richterite represent the major silicates. The ore type is of volcano-sedimentary origin (Koark 1970). Boström *et al.* (1979) also considered the Långban ores as exhalative-sedimentary but compared them with more recent manganese ores being formed at a spreading centre or at a subduction zone.

From an economic and size point of view, the apatite-bearing iron ores are the most important. Only a few deposits are known, the largest being Grängesberg. The ore minerals are magnetite and hematite which are accompanied by apatite and small amounts of quartz and skarn minerals, predominantly actinolite. The average iron content varies between 45 and 63 % and the average phosphorus content between 0.5 and 1.3 %. The amounts of sulphur and manganese are low. The ores have an intrusive appearance, occurring as lens-shaped bodies and are considered as a late differentiation phase genetically related to the enclosing volcanites (Geijer 1931, Magnusson 1938, 1970, Geijer & Magnusson 1944). Landergren (1948) considered the iron as of sedimentary origin and later remobilized and injected into the wall rock during palingenesis.

Sulphide ores in supracrustal rocks

The sulphide ores occur partly in felsic volcanites and partly in limestones and dolomites. In some cases the sulphides are intermingled with quartz-banded iron ores and skarn iron ores. Iron oxides, mainly magnetite, are relatively common components within the sulphide ores. The sulphide ores contain on average 4.5 % Zn, 2.5 % Pb and 0.5 % Cu and in addition 30–200 ppm Ag and 0.2–2 ppm Au. The main ore minerals are pyrite, pyrrhotite, sphalerite, galena and chalcopyrite. Other ore minerals found locally and mostly in small amounts are magnetite, bornite, chalcocite, cubanite, vallerite, arsenopyrite, molybdenite, gold and selenium-lead-bismuth minerals (Falu mine), cobaltite and glaucodote (Håkansboda), native silver with antimony and mercury minerals (Sala mine), dyscrasite, pyrargyrite, argentite and silver-bearing tennantite-tetrahedrite (Garpenberg mine). The sulphide minerals are present as weak disseminations and massive ore bodies. Occasionally the ore is banded on a centimetre to decimetre scale. In the carbonate rocks the sulphides are mainly sphalerite and galena plus additional arsenopyrite. The carbonates are mostly altered to calc-silicate rocks ("skarns") with tremolite, diopside, garnet, anthophyllite, cummingtonite, humite minerals, forsterite, serpentine and talc. In the felsic volcanites mainly chalcopyrite with subordinate pyrite, sphalerite and galena are encountered. The volcanites are commonly altered to mica schists and "quartzites" with Mg-rich minerals such as chlorite, cordierite, gedrite-anthophyllite, cummingtonite, phlogopite and, in addition, almandine and andalusite. Gahnite is an occasional mineral in Zn-rich associations.

The occurrence of the ores is at least partly related to tectonic structures. The sulphides are often localized along thrust planes, fold axes and zones of schistosity. In part the ore minerals occur in "sköls" of biotite, chlorite and talc together with anthophyllite, gedrite, cummingtonite, hornblende, almandine and cordierite. These "sköls" which are often branching and form a network, are considered as channel-ways for the ore-forming solutions. Long and narrow dyke-like bodies of massive ore occur along shear zones and contain angular or rounded fragments of the wall rock. These "pebble ores" or "ball ores" were formed during the tectonic movements.

The formation of Mg-rich alteration rocks associated with the sulphide ores and with part of the quartz-banded iron ores and the skarn iron ores, imply a gain of Mg and a loss of Ti, Ca, Na and P; Fe and K show indecisive variation. If the potassium is bound to mica, as in the mica schists, the content is high.

During the last decades there has been a radical change in opinion on the origin of the sulphide ores. The sulphide ores and the associated Mg-rich rocks were previously considered to be formed by a Mg-rich metasomatism related to the folding of the volcanites and the intrusion of the early Svecokarelian granitoids (Geijer 1917, 1964, Magnusson 1936, 1948, 1960). A similar point of view was presented by Eskola (1914) for the related sulphide ores in southwestern Finland. The "non-intrusive" hypothesis for the origin of the ores was originally presented by Koark (1962, 1973). The ores were considered to be exhalative-sedimentary and the Mg-rich rocks to have formed metasomatically in connection with deposition of the sulphides. Most of the recent investigations show that the formation of the (non-apatitic) iron ores and sulphide ores, the calc-silicates ("skarns") and Mg-metasomatic alterations are related to a common hydrothermal process during the volcanic activity (Frietsch 1982a, 1982b, Oen *et al.* 1982, Zakrzewski 1982, Hedström 1984, Vivallo 1985b, Lagerblad & Gorbatschev 1985).

In the case of the western part of the ore-bearing region, Oen *et al.* (1982) concluded that the formation of the different ores, skarns and magnesium-rich alterations is related to exhalative-sedimentary and sub-seafloor hydrothermal processes during the various stages of rifting of the volcano-sedimentary sequence. The ores are related to ascending granitic magmas, and partly to a basic volcanism. A sub-seafloor hydrothermal origin for the sulphide ores was also postulated by Hedström (1984) and Vivallo (1985b). Zakrzewski (1982) related some quartz-rich skarn iron ores to greenstones.

Much attention has been paid to the formation of the Mg-rich rocks. Vrána (1957), Schermerhorn (1978) and Berge (1978) considered them to be metamorphic equivalents of the alteration products formed during the volcanism. According to Oen *et al.* (1982) and Baker & de Groot (1983a) the Mg-rich rocks occur in structurally controlled zones. The magnesium was seawater-derived and the hydrothermal fluid causing the alteration was modified seawater; the alteration occurred in the volcanites as a seawater–rock interaction (Baker & de Groot 1983a, Hellingwerf & Baker 1985). In the Hjulsjö area an older Svecokarelian granitoid (1800–1900 Ma) served as a heat source. In the same area, the alteration is considered as a two stage process with alteration of feldspar into clay minerals which in turn are replaced by Mg-chlorite. According to Lagerblad & Gorbatschev (1985) there are two types of Mg-rich rocks: 1, tectonically formed belts along permeability channels and 2, stratiform rocks associated with the ores. A stratabound appearance was indicated by Frietsch (1982a). The Mg-rich minerals have partly a post-tectonic appearance. Mg-rich minerals, and partly the ore-forming sulphides, are found in the older Svecokarelian granitoids and mafic dykes cutting the volcanites (Frietsch 1982b).

The Mg-rich alterations are very restricted in comparison with the large-scale processes that gave rise to the alkali "differentiation" and silica enrichment in the volcanites of the ore-bearing areas (Frietsch 1982b). The extreme sodium and potassium differentiation was formerly considered as a primary magmatic feature (Johansson 1906–07, 1911, Sjögren *et al.* 1914, Sundius 1923, Magnusson 1925, 1930, 1940, Geijer 1936, Geijer & Magnusson 1944). Frietsch (1982b) pointed out that there are important differences between the volcanites in the ore-bearing and ore-free areas; the ore-bearing volcanic rocks differ from the barren ones by 1, the high content of SiO_2, often exceeding 75 % and 2, the extreme division into Na-rich and K-rich members, alkali-intermediate rocks being subordinate. Instead, a secondary internal reconstruction of the chemistry of the volcanites in connection with ore formation was anticipated. The original pre-alteration volcanites were possibly more mafic, andesitic-dacitic in composition. The stability of the sodium and potassium in the feldspar is temperature dependent, higher temperature favouring the stability of Na-feldspar (Frietsch 1982a, Jasiński *et al.* 1985, Lagerblad & Gorbatschev 1985). Only if the concentration of Mg^{2+} is high enough, or pH is low, will albite be altered (Jasiński *et al.* 1985). According to Lagerblad & Gorbatschev (1985) there was an enrichment of Na and Mg, and a leaching of the ore-forming metals in the lower part of the volcanic pile, whereas volcanites in the upper level, which contain the ores, are enriched in potassium. According to Baker & de Groot (1983b) and Jasiński *et al.* (1985), an iron-rich brine, which developed through leaching of the bedrock, created the iron ores in the basins between the volcanic centres.

Our knowledge of the primary structures of the sulphide ores is limited, as most of these features have been changed by later metamorphism and tectonism. At Garpenberg there is a banded stratiform Zn-Pb-Cu ore which is underlain by a Cu-bearing stockwork ore. The latter is a network of chalcopyrite-pyrrhotite-bearing quartz veins with fluorite, mica and garnet (Vivallo 1985b, 1985c). Hedström (1984) showed that the Hällefors Fe, Mn and Zn-Pb-As-Ag ores were deposited distally to the outlet vents of solutions, the distal nature being shown by the absence of wall rock alteration and recognizable conduits of ore solution, and the low copper content of the ore. Frietsch (1982b) pointed out that almost all sulphide ore deposits show an alteration zone, indicating that the ores in that sense are proximal.

According to Frietsch (1982c) and Zakrewski (1982) the iron, manganese and sulphide ores display a zonal arrangement which is dependent on systematic changes in the redox conditions. The Mn-bearing ores (manganiferous skarn iron ore, manganese oxide-silicate ore of the Långban type and the iron-manganese silicate-bearing eulysites) and associated Zn-Pb-As sulphide ores, occurring in the potassic volcanites, were formed in a more reducing environment than the non-manganiferous skarn iron ores in the sodic volcanites (Frietsch 1982c). A paragenetic zoning, with a central part of Cu-W-Mo-bearing skarns and a peripheral part with a Zn-Fe-As-Pb sulphide skarn, partly with Sn, was demonstrated in the case of the Gruvåsen ore by Hellingwerf (1984). This zonation crosscuts the lithologic boundaries and is thus epigenetic.

Lead isotopic determinations from the sulphide deposits show an isotopic homogeneity over large areas indicating that the lead was probably derived from one source (Johansson & Rickard 1985, Billström 1985b, cf. Vaasjoki 1981). The isotopic composition suggests the existence of a pre-Svecokarelian crust and is consistent with exhalative-sedimentary ore formation in an active continental margin environment. Billström (1985b) showed that the sulphur isotopic compositions in two sulphide deposits (Svärdsjö with $\delta^{34}S$ values around 0 ‰ and Åmmeberg with $\delta^{34}S$ values around 2 ‰) exhibits several dissimilarities which means that the sulphur emanated from more than one source. The sulphur emanated from various proportions of leached magmatic sulphides and H_2S derived from reduction of seawater sulphate. There were successive pulses of sulphide-forming solutions. The iron sulphides formed as a result of bacteriogenic sulphate reduction in a system closed to H_2S and SO_4. The sulphides were deposited at 350–250°C, pH 5–6 and a fairly low level of oxygen fugacity.

Somewhat different stratabound sulphide deposits occur in the southern part of the region. They are composed of Zn-Pb-Fe sulphides or Fe sulphides which form long, narrow layered bodies and disseminations in the felsic volcanites and the limestone-dolomite intercalations. The only deposit of importance is Åmmeberg (Zinkgruvan), which contains 10–14 % Zn, 1–3 % Pb, 50 ppm Ag. There are calc-silicate layers ("skarn") in the volcanites with diopside, garnet, hornblende, tremolite, and adjacent to metamorphic gneisses in the south also wollastonite and vesuvianite. The main sulphides are sphalerite and galena. In addition there are small amounts of tetrahedrite, pyrrhotite, pyrite and arsenopyrite. In the same area there are banded ores with only iron sulphides (Dylta and Ervalla), and other with Zn-Pb-Cu sulphides with additional Co-Ni sulphides such as cobaltite, safflorite, smaltite-chloantite and breithauptite (Tunaberg and Vena). These banded ores were previously considered as epigenetic resulting from late Svecokarelian migmatization (Geijer & Magnusson 1944, Magnusson 1948, 1970). However, according to Henriques (1964) the Åmmeberg ore is syngenetic and formed by submarine hydrothermal solutions. Frietsch (1982b) pointed out that the absence of Mg-rich alteration rocks indicates different environment of formation than for the rest of the sulphide deposits of Central Sweden, possibly due to more "distal" deposition.

Tungsten – molybdenum deposits

In the Ludvika area there are several tungsten mineralizations in limestone-dolomites, which are skarn-altered (mostly with garnet and pyroxene) and rich in pegmatitic minerals (Ohlsson 1979). The mineralizations contain some scheelite in association with fluorite, calcite, scapolite, molybdenite, pyrrhotite and chalcopyrite. In addition there are small amounts of magnetite, apatite, sphene, bismuthinite and native bismuth (Lindroth 1922, Hübner 1971, Ohlsson 1979, Hellingwerf & Baker 1985). The Yxsjöberg deposit with 0.3–0.4 % WO_3 and 0.25 % Cu is currently being mined.

According to Magnusson (1970), Hübner (1971) and Ohlsson (1979) these mineralizations are related to late-orogenic Svecokarelian granites and pegmatites. However, Lindroth (1922) considered the tungsten deposits at Yxsjöberg to be related to the older granitoids, a viewpoint shared by Hellingwerf and Baker (1985) for all the tungsten-molybdenum deposits of the area. According to these latter authors the older granitoids served as heat source, circulating hydrothermal fluids by which tungsten and molybdenum were deposited in the skarns. Zakrzewski *et al.* (1980) when describing Co-Ni-Sb sulphides in the Hällefors area, considered these, and some bismuth mineralizations, to be remobilized products derived from older sulphides (of the "normal" type) by hydrothermal solutions during the emplacement of the late-orogenic or postorogenic granites.

Father south, the Baggetorp deposit is a tungsten mineralization in a quartz-aplite intrusion in veined gneisses. The ore minerals are wolframite and subordinate molybdenite, pyrite and chalcopyrite (Magnusson 1953, Grip 1978). According to Gavelin (1985) the mineralization is located to shear zones in the veined gneisses.

SOUTHWESTERN FINLAND

H. Papunen

History

Mining in Finland began in 1540 when the first iron mine was opened at Ojamo in the parish of Lohja about 50 km northwest of Helsinki (Fig. 1). The mining industry was, however, economically unimportant until the beginning of the 19th century although several small iron mines were periodically in production. The separation of Finland from Sweden in 1809 suspended the import of iron ore from Sweden and, as a result, ore prospecting was intensified. Some of the deposits discovered were in production for a short time but, compared with the iron ores of Bergslagen, central Sweden, the ores of southwestern Finland were generally small and of low grade. They also contained sulphides and other elements that impeded the production of iron. Dozens of old pits in the Orijärvi-Aijala area, however, bear witness to the effectiveness of iron ore exploration in the 19th century. The most productive iron mines were Malmberg and Vihiniemi in the parish of Kisko. The last operating iron mine of the area was Jussarö on a small island about 30 km east of Hanko; it was in production in the 1960s.

The copper deposit of Orijärvi was discovered in 1757 and it was in production almost continuously until the 1860s, and again for a short period in the early 20th century; the last productive period was from 1932 to 1954. The vigorous exploration by Suomen Malmi Oy from 1945 to 1952 unearthed the copper deposit of Aijala and the Zn-Pb-Ag-Cu deposit of Metsämonttu. The Aijala mine produced ore from 1949 to 1958 and Metsämonttu from 1952 to 1958 and again from 1964 to 1974. In the 1970s the Orijärvi-Aijala area was the target of intense sulphide ore exploration by Outokumpu Oy and several ore occurrences were discovered and drilled; however, exploitation was not economically feasible.

Sulphide and iron ores in supracrustal rocks

The iron and sulphide ores of the Orijärvi-Aijala area occur in the lower Svecofennian supracrustal rocks which include felsic metavolcanites and metasediments. The metasediments are mainly reworked volcanic material and contain intercalations of limestones and calc-silicate rocks. The iron ores can be classified into massive and banded magnetite accumulations in calc-silicate rocks (skarn ores) and banded iron formations which are frequently associated with the middle Svecofennian mafic volcanites.

Upwards the felsic lower Svecofennian sequence changes into intermediate and mafic metavolcanites. In the Aijala-Metsämonttu area the horizon between felsic and intermediate volcanites is characterized by chemical sediments, limestones, sulphide and oxide facies iron formations and local chert quartzites. The horizon represents a break in volcanism and the associated cordierite-anthophyllite rocks and sericite schists are indicative of hydrothermal alteration and hydrothermal activity during the waning stage of volcanism. The sulphide deposits of Aijala, Metsämonttu, Aurums Aijala and Hopeamonttu are volcanic-exhalative in origin; the deposits of Metsämonttu and Aijala can be explained as of proximal type on the evidence of abundant altered rock types associated with them. The ores are mainly of disseminated and stringer type, massive base metal sulphides are lacking.

Geochemically the ore-bearing horizon is indicated by high copper contents over the entire Aijala-Orijärvi area, but the mineralizations attain the grade of ore only in Aijala and Metsämonttu. The Orijärvi and Iilampi deposits occur in the felsic metavolcanites stratigraphically lower in the strata than Aijala and Metsämonttu. Laterally towards east and west from the Aijala-Orijärvi area the supracrustal belt grades from metavolcanites to more metasedimentary sequences. This indicates that the sulphide deposits are related to the volcanic centres of the supracrustal belt. Iron sulphides and associated altered rocks have been met with also in the Kemiö area, but the contents of base metals are low.

Deformation and metamorphism have affected the ore deposits, but mobilization and redeposition of ore components are on a small scale. Numerous faults have split the deposits into minor blocks, the sizes of the deposits are therefore reduced.

The belt of metavolcanites and metasediments running approximately E–W through the Tampere area includes the Cu-Au deposit of Haveri c. 40 km northwest of Tampere. Haveri was exploited as an iron ore in the 19th century but high contents of sulphides made the iron production difficult. In 1935 Oy Vuoksenniska Ab began to explore it as a copper ore and the high gold contents were encountered.

The Haveri Cu-Au mine was in production from 1942 to 1960; the total hoist was 1.5 Mt ore with 2.8 g/t Au and 0.37 % Cu. Sulphides occurred as disseminated and stringer ore types in basaltic submarine metavolcanites. Near the sulphide ore, the volcanites included also magnetite-banded iron formations and minor dolomite horizons. The sulphides are considered to be of submarine volcanic-exhalative (Cyprus Type) in origin (Mäkelä 1980).

Supracrustal rocks elsewhere in southwestern Finland include minor stratiform sphalerite accumulations, e.g. the Tupala ore body in Somero, about 50 km north of Orijärvi and Leteensuo about 40 km east of the Kylmäkoski deposit (Fig. 1). They associate with hydrothermally altered felsic and intermediate metavolcanites and the ores are stratiform in type.

Lead isotope determinations of galena from supracrustal-hosted sulphide deposits in southwestern Finland have been carried out by Vaasjoki (1981). The isotope ratios for these deposits (and especially the stratabound deposits) are very similar to those reported from stratiform sulphide deposits in Bergslagen (Johansson & Rickard 1985, Billström 1985b). It is, thus, evident that the source for all these deposits was very similar over vast areas in Fennoscandia.

Titanium-vanadium-bearing magnetite ores in gabbro

Synorogenic layered gabbros with low-grade Ti- and V-bearing magnetite ore occur e.g. at Iso-Kiskojärvi (7 km southwest of Orijärvi) and Attu (30 km south of Turku; Sipilä 1981). Similar deposits are also known in the Kramsta-Gruvberget area, central Sweden (Lundegårdh 1957).

Nickel-copper ores in ultramafic rocks

The Ni-Cu ore province of southwestern Finland, the Pori-Kylmäkoski nickel belt, was located in the exploration programme of Outokumpu Oy in the 1960s. Sulphide-bearing Svecokarelian ultramafic rocks exist in a linear belt trending from Pori to Kylmäkoski. The area is characterized by migmatized Svecokarelian mica gneisses with intercalations of graphitic schists and calc-silicate rocks. Some of the ultramafic host rocks of the Ni-Cu sulphides display features – agglomerate structures and surficial alteration – that indicate extrusion of ultramafic magma near to or even on the sea floor. The nickel ore province of southwestern Finland is a part of the major Svecokarelian nickel province that surrounds the central Finland granitoid area.

Copper-tungsten ore associated with granodioritic intrusion

The Ylöjärvi Cu-W mine was about 15 km northwest of Tampere. The ore was discovered in 1937 and the mine produced from 1942 to 1966 about 4 Mt ore containing 0.68 % Cu and 0.04 % WO_3. The wall rocks of the mineralized tourmaline breccia pipe are pyroclastic metavolcanites and the breccia pipe is associated with the Hämeenkyrö granodiorite intrusion (Himmi *et al.* 1979). According to Gaál *et al.* (1981) even the granodiorite intrusion contains anomalously high contents of copper close to its eastern contact zone and the tourmaline breccia pipe. According to Himmi *et al.* (1979) the tourmaline breccia was formed at the periphery of the granodiorite massif in folded metavolcanites that had already attained their current mineral composition through regional metamorphism. The ore type of Ylöjärvi is unique in Fennoscandia and it has certain similarities with the Tertiary tourmaline breccia pipes from the Central Andes. The age of the tourmaline breccia of Ylöjärvi is about 1850 Ma. The main ore minerals were chalcopyrite and arsenopyrite and scheelite was the carrier of tungsten. The ore minerals occurred together with tourmaline in the matrix of the breccia.

Tin mineralizations associated with rapakivi granites

Numerous tin mineralizations are known in southern Finland. They are confined to a belt extending from the archipelago of Åland (Ahvenanmaa) in the west to lake Ladoga (USSR) in the east and are all associated with massifs of rapakivi granites. In the Finnish mineralizations tin is usually found in greisen and quartz veins as well as in pegmatites. In the Pitkäranta area, north of lake Ladoga, USSR, tin mineralization occurs in skarn zones at the southwestern margin of a rapakivi granite massif (Haapala 1977).

EXCURSION ROUTE

DAY 1. ORE DEPOSITS OF THE ORIJÄRVI AREA, FINLAND

H. Papunen

The excursion will visit the Orijärvi area in the central section of the Svecofennian supracrustal belt of southwestern Finland. The belt has been considered the Finnish counterpart of the supracrustal formations of Bergslagen in central Sweden. In the Orijärvi area it is characterized by numerous ore occurrences and abundant felsic, intermediate and mafic metavolcanites (Fig. 3). Laterally towards east and west the belt grades into the prevailing metasedimentary sequences. This description deals mainly with the central mineralized part of the belt.

Previous descriptions of the area

In the early decades of the 20th century the Orijärvi deposit was owned by "The Finnish-American Mining Company" which, with capital collected from American and Finnish

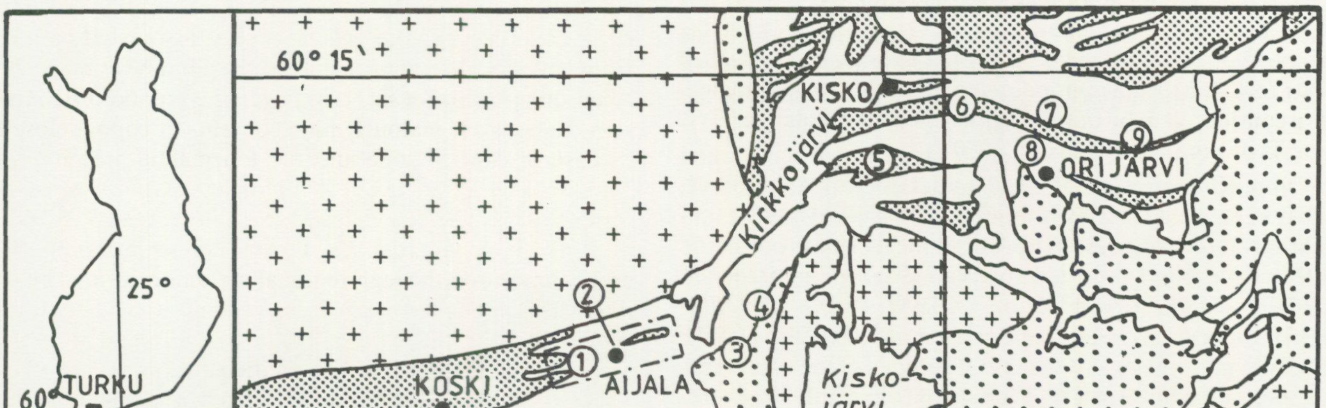


Fig. 3. General geological map of the Aijala-Orijärvi area and excursion stops. Area of Fig. 4 is shown in broken lines.

shareholders, tried to modernize and open the Orijärvi mine. The eminent Finnish prospector and geologist Otto Trüstedt was asked to evaluate the ore reserves and on the basis of previous magnetic surveys, diamond drilling and his own observations he wrote the first geological description of the deposit (Trüstedt 1909). This paper was used by the company as an advertisement in marketing its new shares.

In 1914, Eskola published his dissertation on the geology of the Orijärvi area (Eskola 1914). Based on his meticulous field work, he formulated his ideas on metamorphic facies (Eskola 1915). Eskola (1914) attributed the sulphide deposits and associated cordierite-anthophyllite and other Mg-rich rocks of the Orijärvi area to magnesia metasomatism caused by intrusion of the Orijärvi granitoid. For decades, the idea was adopted also for the "Falu type" of ores in central Sweden (Geijer 1917, Magnusson 1936, 1960). Exploration by Suomen Malmi Oy in the 1940s and 1950s resulted in new concepts of magnesia metasomatism (Tuominen & Mikkola 1950), the origin of the ultrabasic rocks (Mikkola 1955) and of the structure of the whole area (Tuominen 1957). In his paper Tuominen (1957) points out the significance of fault tectonics. "Cubistic" though his geological map was called, nevertheless it woke up Finnish geologists to the importance of faults and lineaments in the deformation of Precambrian areas.

The iron ores of southwestern Finland have been studied by von Knorring (1955), and mineralogical descriptions have been published by Kaitaro and Vaasjoki (1950) and Vorma (1960). The results of geochemical exploration in the 1970s have been reported by Wennervirta and Papunen (1974), and the origin of the Orijärvi, Aijala and Metsämonttu ores has been reinterpreted by Latvalahti (1979). The metamorphism and structural geology of the supracrustal belt of southwestern Finland has recently been reexamined by the geologists of the Free University, Amsterdam (see Schreurs 1984, 1985, Schreurs & Westra 1985). Details of the economic and bedrock geology have been the subject of numerous unpublished master's theses (Lukkarinen 1979, Raikunen 1979, Keinänen 1980, Puustjärvi 1981, Sipilä 1981, Timperi 1983).

Ore occurrences

The Orijärvi area has the following groups of iron ore occurrences: 1) banded iron-formations, either of sulphide, oxide or silicate facies. They are very small in size and occur as intercalations in the upper part of the Lower Svecofennian Group or in the lower section of the mafic and intermediate volcanites of the Middle Svecofennian Group, 2) skarn iron ores as strata-bound lenses in the horizons of calc-silicate rocks (andradite-hedenbergite skarns) and 3) minor titaniferous iron occurrences in the layered gabbros of the Orijärvi intrusive complex. Southwestern Finland has none of the manganiferous and apatite-rich iron ores typical of the Bergslagen province in Sweden.

The sulphide Cu-Zn-Pb occurrences and deposits are related to the hydrothermally altered felsic metavolcanites. Some minor chalcopyrite impregnations also exist in

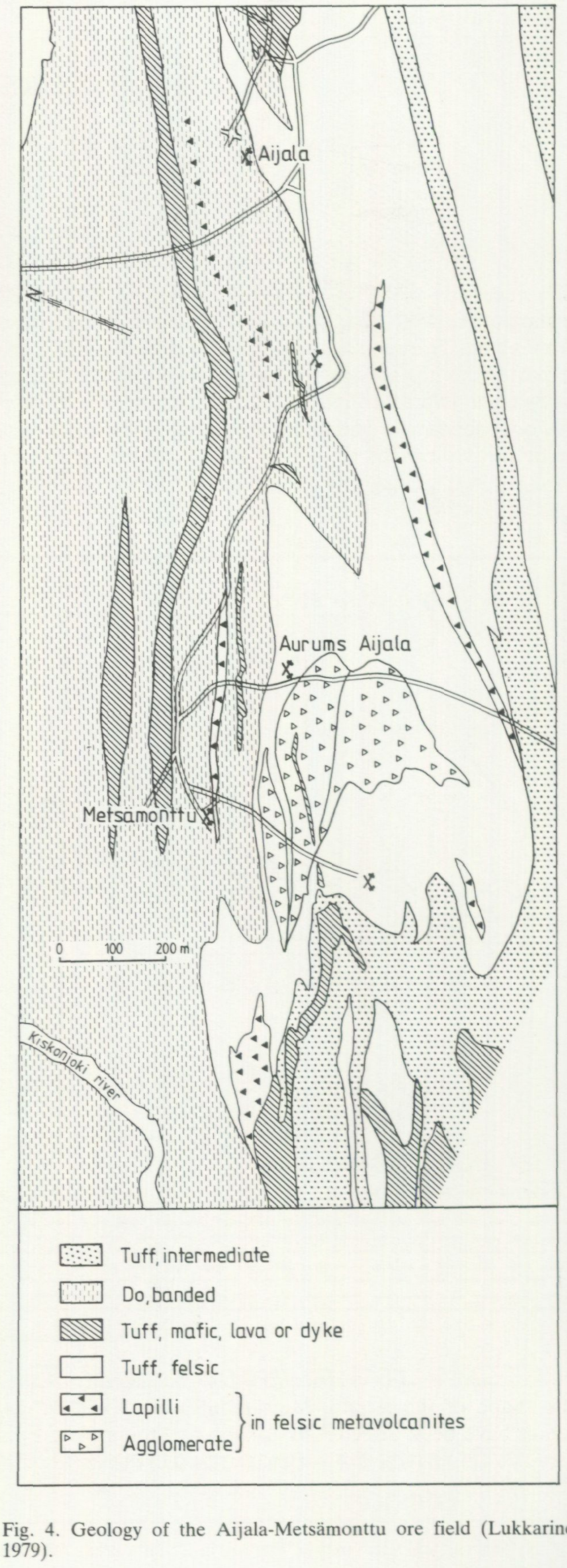


Fig. 4. Geology of the Aijala-Metsämonttu ore field (Lukkarinen 1979).

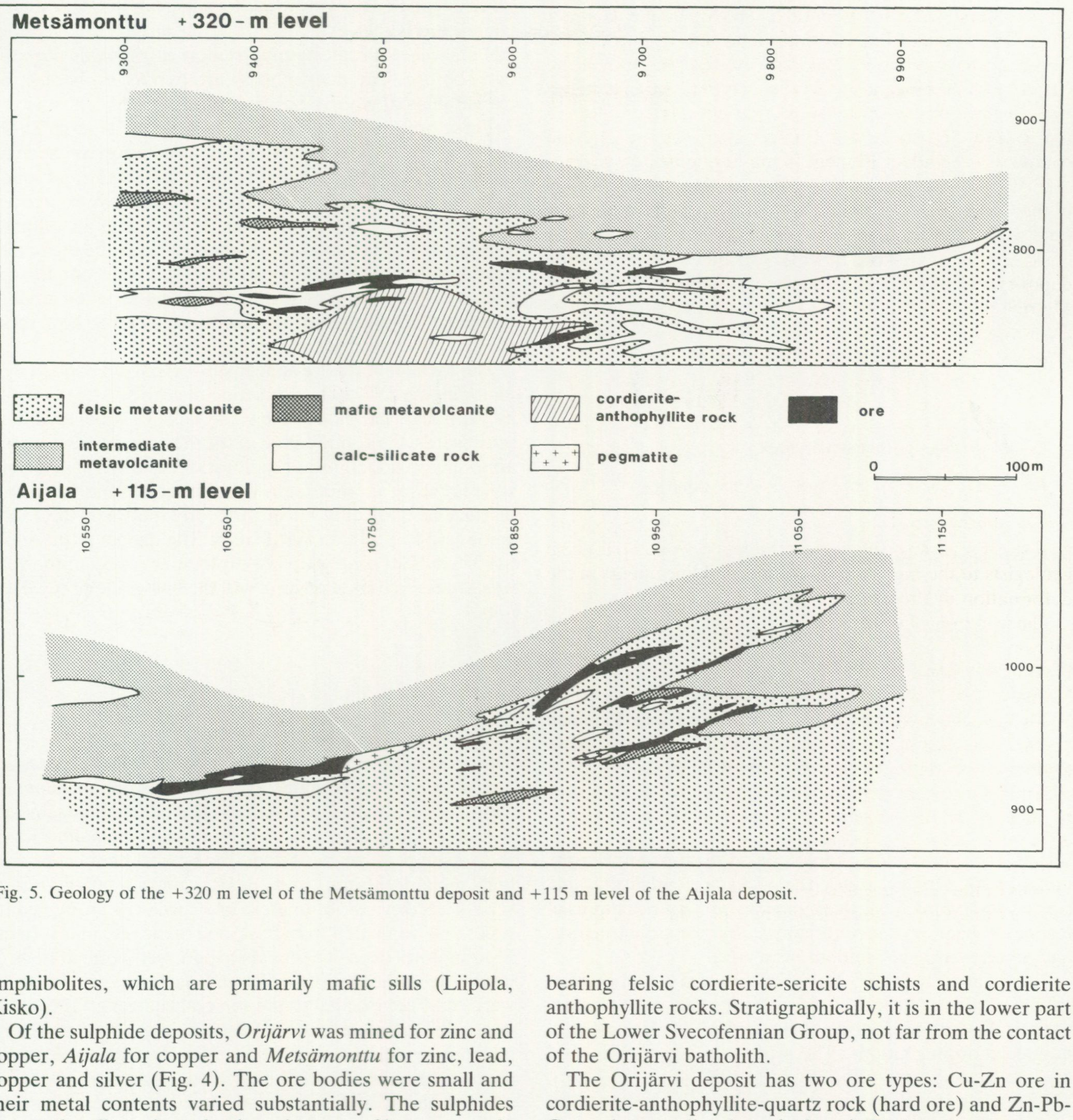


Fig. 5. Geology of the +320 m level of the Metsämonttu deposit and +115 m level of the Aijala deposit.

amphibolites, which are primarily mafic sills (Liipola, Kisko).

Of the sulphide deposits, *Orijärvi* was mined for zinc and copper, *Aijala* for copper and *Metsämonttu* for zinc, lead, copper and silver (Fig. 4). The ore bodies were small and their metal contents varied substantially. The sulphides occurred as disseminated or breccia ores and less commonly as minor massive veins. On a large scale, all the deposits are strata-bound (Figs. 5, 6); in detail, however, they show cross-cutting and breccia structures in relation to the wall rocks. The ore deposits consist of several separate ore bodies, small in size, and narrow and elongated in shape. The shape of the Aijala, Metsämonttu and Orijärvi ore bodies have been affected by folding and the axis of F_2 is parallel to the major axes of the ore bodies. In Aijala and Metsämonttu, the axis is subvertical but at Orijärvi it is less steep, being 45° to 50° northeast.

The Orijärvi deposit is located in a zone of andalusite-bearing felsic cordierite-sericite schists and cordierite anthophyllite rocks. Stratigraphically, it is in the lower part of the Lower Svecofennian Group, not far from the contact of the Orijärvi batholith.

The Orijärvi deposit has two ore types: Cu-Zn ore in cordierite-anthophyllite-quartz rock (hard ore) and Zn-Pb-Cu ore in tremolite skarn (soft ore). Both ore types contain weakly to heavily disseminated sulphides with local massive patches. Laterally, the ore horizon, characterized by calc-silicate rocks and quartz rocks, also contains a massive pyrite ore, mined in the "Nygruva" pit west of the Orijärvi pits. The foot-wall of the ore is non-foliated, coarse-grained cordierite-anthophyllite rock; farther south the fine-grained contact variety of Orijärvi tonalite borders cordierite-anthophyllite rock. The hanging wall of the ore is a felsic cordierite-mica gneiss, but a massive amphibolite, originally a thick mafic sill, intersects the ore horizon and forms the hanging wall of the main sulphide occurrence. The calc-

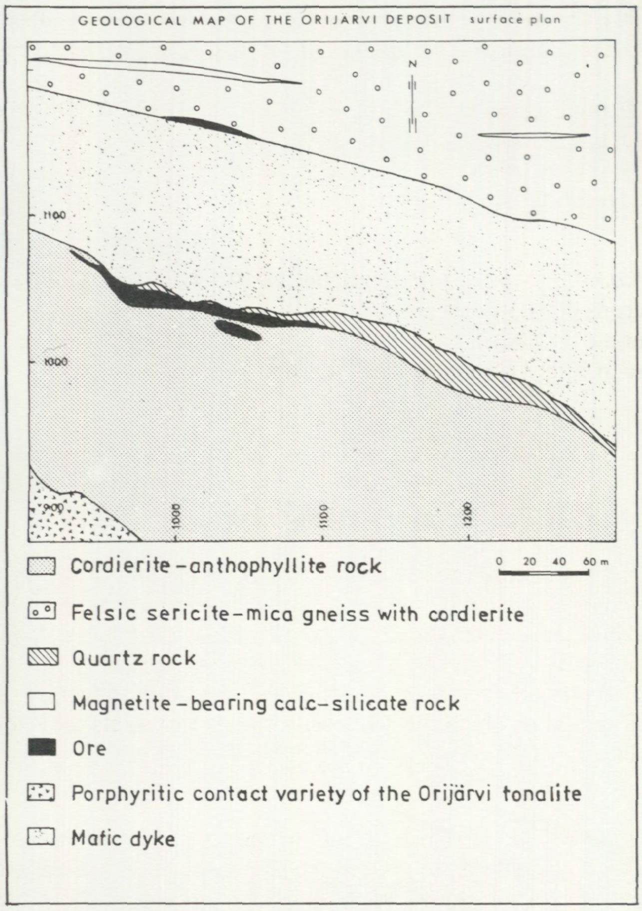


Fig. 6. Geology of the Orijärvi deposit. (From Latvalahti 1979 by permission of Economic Geology Publishing Co.)

silicate rock (tremolite skarn) does not crop out. To the north of the Orijärvi mine, the rocks are andalusite- and cordierite-bearing felsic mica gneisses with intercalations of magnetite-bearing skarn horizons. The primary structures and textures are very seldom preserved.

The Iilampi Zn-Pb-Ag-Au occurrence is in the felsic schist 1.7 km northwest of and stratigraphically above the Orijärvi deposit. The sulphides occur as Ag- and Au-bearing sphalerite-galena impregnations. The wall rocks are silicified and contain a stockwork of biotite-rich veins.

The Aijala and Metsämonttu deposits lie 1.5 km apart in a stratigraphic horizon characterized by cherts, marbles and sulphide-facies iron-formations in the contact between felsic metavolcanites and intermediate to mafic pyroclastic rocks. There are several sulphide occurrences in the mineralized horizon, which extends for about 3 km; a small Ag-bearing occurrence, Aurums Aijala, is located between Aijala and Metsämonttu.

The Aijala deposit contains several separate ore bodies conformable with the axial plane of F_2; their axis is parallel to the subvertical fold axis plunging 80–85° southwest. The main constituent of the ore bodies is either chalcopyrite or pyrite; the exploitable copper ore also comprises minor galena, sphalerite, arsenopyrite and iron sulphides. The copper ore bodies extended from the surface to a depth of 220 m, where a fault dipping steeply northwards abruptly cuts the ore. The deeper parts are pyritic ore bodies; no exploitable copper ore has been discovered.

Three ore types occur in the Metsämonttu deposit: Zn-Pb ores with sphalerite, galena, pyrrhotite and pyrite as main minerals, Zn-Fe sulphides with pyrite, pyrrhotite and sphalerite, and the copper ore bodies with chalcopyrite, pyrrhotite and pyrite. The Zn-Pb ores occur mainly in chlorite-bearing diopside skarns and dolomites; the Zn-Fe ore bodies are in muscovite-cordierite gneisses and the copper ore bodies in cordierite gneisses. The Cu/(Zn+Pb) ratio tends to be higher in the ores of the cordierite-bearing host rocks than in the ores of the skarn host rock.

The Metsämonttu ore zone is subvertical but divided by a fault dipping 25° south and cutting the ore at a depth of 140 m. Although the block below the fault was moved 280 m southwards, the continuation of the ore zone was discovered after intense underground exploration. Below 550 m the ore zone is cut by another fault with the same trend but with a displacement of only 60 m. The ores between the faults amounted to 1 million metric tons. The deeper parts below the 550 m fault zone were not exploited because of the very weak rocks in the shear zone and the low grade of the deep ores.

Altered rocks

The occurrence of hydrothermally altered rock types associated with the ores is characteristic of the sulphide mineralization in the Aijala-Orijärvi area. The altered rocks include dolomitic limestones and chlorite-bearing tremolite skarns that developed from limestones by hydrothermal alteration and metamorphism, and quartz rocks, sericite-quartz schists, cordierite-biotite rocks and cordierite anthophyllite rocks that originated from felsic and mafic volcanites. In the Metsämonttu deposit a funnel-shaped, well-defined stock of cordierite-anthophyllite rocks widens from surface downwards and lies parallel to the mineralized zone. The whole mineralized contact between felsic metavolcanites and intermediate pyroclastic rocks from Metsämonttu to Aijala is characterized by Mg-rich skarn rocks and sericite- and quartz-rich rocks. This zone of altered rocks resembles the blanket-type of alteration noted in many massive sulphide deposits. Stratigraphically below the Orijärvi deposit there is an extensive mass of cordierite-anthophyllite rocks.

It is interesting to note that the supracrustal rocks are also altered outside the actual mineralized zones and especially at the gradual contacts of the felsic intrusive rocks. Large masses of altered rocks, especially cordierite-anthophyllite rocks, exist at Björknäs, about 1.5 km south of Aijala and at Venetkorpi, 2.5 km southwest of Aijala (Mäkelä 1983). "Quartz eyes" indicate silicification of the intrusive rocks.

The change in chemical composition is hard to decipher because one can only very seldom identify the primary rock type. The general trends are: increase in MgO and in some cases also in FeO*; significant increase in the K_2O/Na_2O ratio because of the increase in potassium and decrease in sodium; decrease in CaO and local increase in SiO_2. The primary mineral assemblages of hydrothermally altered rocks were changed during regional metamorphism, as a result, the mafic rocks that were originally montmorillonite- or chlorite-altered are now cordierite-anthophyllite rocks when in the amphibolite facies, and cordierite-hypersthene rocks when in the granulite facies.

STOP DESCRIPTIONS

Stop 1. – Metsämonttu mine. Intermediate-basic metavolcanites crop out in the vicinity of the Metsämonttu mine, displaying skarn-banded tuffite, lapilli tuff and agglomerate intercalations, and acidic quartz-eyed pyroclastic rocks.

A pronounced shear schistosity and associated vertical lineation are seen.

Two exhausted mines, Metsämonttu and Aijala, are located in the area. These were operated by Outokumpu Oy in 1949–1974. Total production was 2.2 million metric tons. The mines are in the same stratigraphic horizon, appr. 1.5 km from each other.

Metsämonttu was a Zn-Pb-Ag-Cu mine grading 3.5 % Zn, 0.8 % Pb, 25 ppm Ag, and 0.3 % Cu. Aijala was a Cu-S mine grading 1.6 % Cu and 14.2 % S.

Stop 2. – Aijala sports field. This micaceous metatuffite is stratigraphically between an acidic and an intermediate-basic metavolcanite bed. Primary bedding and a fold are seen in the outcrop.

Stop 3. – Aikonlahti, Kisko. The contact zone of the Orijärvi batholith.

Two acidic rock types of different ages associated with the Orijärvi batholith are seen in the outcrop. The younger one intersects the surrounding older rock, and is an even-grained plutonic rock. It is of a trondhjemitic composition and contains basic inclusions.

The older rock is a coarse-grained, quartz-eyed hypabyssal dyke. These are common in the border zone of the batholith, extending to the metavolcanites. An even-grained granite also brecciates the quartz-eyed acidic dyke in the outcrop. This is considered younger than the metavolcanites but older than the Orijärvi batholith.

Stop 4. – Marjaniemi, Kisko. This stop shows an iron formation with thin intercalating bands of silicate and oxide facies and chert. The formation is plastically deformed and brecciated by a younger plagioclase porphyrite dyke. The iron formations in the Aijala-Orijärvi area occur stratigraphically in several horizons within the acidic metavolcanites.

Stop 5. – South of Hyypiänmäki, Kisko. 1 km walk. Basic metavolcanites. The objects of interest are a contact between intermediate and basic metavolcanites with agglomerate and pillow lava beds in the latter. Typical of the contact zone is a skarned part in the intermediate metavolcanite. Several agglomerate beds are seen, with bombs and sharp-edged fragments of up to 0.2×0.3 m.

Stop 6. – North of Iilinjärvi, Kisko. 0.5 km walk. The outcrops display mafic metavolcanite and underlying conglomerate. The two folding phases typical of the Orijärvi area are seen in the conglomerate outcrop.

Stop 7. – Cutting in the Salo-Mustio road at Orijärvi. Mica schist. This site is higher in the stratigraphy than any of the previous ones. At these stratigraphic levels the origin is either volcanic or sedimentary. If it is of volcanic origin the rocks are called intermediate or acidic tuffites. When the material is of sedimentary origin, mica schists result. The road cutting displays a mica schist with alternating andalusite and/or cordierite porphyroblast-bearing beds.

The bedding strikes almost E–W. The outcrop features a drag fold in which the schistosity clearly intersects the bedding.

Stop 8. – The Orijärvi mine. On the north side of the open pit a subvolcanic amphibolite dyke cuts across metavolcanites and ore, while on the south side of the open pit there are altered rock types: sericite and cordierite-bearing schists and cordierite-anthophyllite rocks. Geological observations suggest that there are cordierite-anthophyllite rocks of two different origins in the area:

1. Cordierite-anthophyllite rocks genetically associated with the ore deposits, originally acidic volcanites.
2. Cordierite-anthophyllite rocks originating through alteration from sedimentary rocks. Primary bedding is sometimes seen in these.

Only the open pit, 80 m deep, and the head frame remain of the old Orijärvi mine today.

Stop 9. – Cutting on the Salo-Mustio road at Sorastonlampi. Metagreywacke at the same stratigraphic level as stop 7. The outcrop displays a greywacke schist with bedding, graded bedding, load casts and slumps.

DAY 2. THE VAMMALA NICKEL-COPPER DEPOSIT

T.A. Häkli and H. Papunen

The nickel-copper deposits associated with synorogenic mafic to ultramafic intrusions of Svecokarelian age are located in central and southern Finland. Gaál (1972) described a 420 km long and 100–150 km wide belt that trends in a NW–SE direction across central Finland from the Bothnian Bay to lake Ladoga; he called it "the Kotalahti nickel belt". Another belt of nickel-bearing intrusions "the Pori-Kylmäkoski nickel belt" has been delineated in southwestern Finland (Häkli 1971). Häkli (1971) noted that these two belts are connected by an ENE-trending belt, resulting in the U-shaped pattern of the nickel-potential area. If the NE-trending Lappvattnet belt south of Skellefteå in Sweden (Nilsson 1985) is considered part of the Svecokarelian nickel province, the whole area of nickel potential forms a ring pattern around the central Finland granitoid complex. All the nickel mines currently in production – Kotalahti, Vammala, Laukunkangas and Hitura – are located within the structure.

The host rocks of the nickel occurrences are either weakly fractionated ultramafic bodies with rock types varying from peridotites to dunites (Hitura and Vammala) or fractionated intrusions with rock series from peridotites to gabbros (Kotalahti and Laukunkangas). The ages determined for the intrusions are about 1.9 Ga (1.9 Ga–1.86 Ga). For details of the nickel occurrences, the reader is referred to Papunen and Gorbunov (1985).

The first indications of the nickel deposits of the Pori-Kylmäkoski belt were observed in the early 1960s. The ultramafic bodies of Stormi were discovered in 1960 and the small nickel deposit of Kylmäkoski in 1962, but the small occurrences in the Pori area (Harjunpää and Hyvelä) were already targets of exploration back in the 1950s. About 690 000 metric tons of ore with a grade of 0.55 % Ni and 0.48 % Cu (Papunen 1985) were hoisted from the nickel deposit of Kylmäkoski, which was mined in 1971–1974. Mining operations in the Vammala area started in 1975, and about 460 000 metric tons of marginal ore with 0.43 % Ni and 0.32 % Cu were extracted during experimental mining at Kovero-oja in 1975–1977. Exploitation of the ores of the Stormi intrusion started in 1978 at the rate of 300 000 to 350 000 metric tons of ore per year. The mill feed in 1981 was 1.0 % Ni and 0.6 % Cu (Häkli & Vormisto 1985). Several other Ni-Cu occurrences have been discovered in the Pori-Kylmäkoski belt. The most interesting of these are the occurrences of Hyvelä (Stenberg & Häkli 1985) Sahakoski, Korkeakoski and Sääksjärvi.

This report on the Vammala area is based on descriptions by Häkli *et al.* (1979), Heikkilä-Harinen (1975), Mäkinen (1984), and Häkli & Vormisto (1985).

Regional geology

The ultramafic intrusions of the Vammala area are located in a belt of migmatized supracrustal rocks that trends WNW–ESE along the nickel belt of southwestern Finland (Fig. 7). The rocks are mainly sedimentogeneous mica schists and gneisses derived from pelitic and psammitic sediments but minor diopside-bearing calc-silicate rock intercalations have also been noted. The mineral assemblage of the mica gneisses is commonly that of middle-amphibolite facies, but along the nickel belt the gneisses also grade into varieties containing garnet and cordierite and locally sillimanite, indicating metamorphism of high-grade amphibolite facies. In the Vammala area, the mica gneisses contain graphitic varieties that are often associated with the garnet-cordierite gneisses. The abundance of graphite attains 20 % in the gneisses in the north of the area, where graphite was mined in the early years of the 20th century. Tuffaceous amphibolite as well as uralite and plagioclase porphyrites are encountered as interlayers in the mica schists. This rock association also contains intercalations of calc-silicate rocks (skarns) and sulphide-bearing black schists. Synorogenic granodiorite and quartz diorites are the predominant plutonic rocks. Cataclastic garnetiferous quartz diorite around the Stormi ultramafic body forms a westward-opening arc. Porphyritic variants of granodiorite containing large microcline porphyroblasts are encountered in addition to the common equigranular variants. Granitic rocks occur as pegmatitic or aplitic veins.

Ultramafic rocks occur in migmatized mica gneisses as small, isolated bodies. Mafic intrusive rocks are rare and are commonly found in association with quartz diorite. The ultramafic rocks are peridotites, olivine pyroxenites, pyroxenites and cortlandites in composition. In some rare cases the olivine pyroxenites are differentiates in the peridotitic intrusions but more commonly they occur independently as discrete intrusions. Geochemically the peridotites are of either the Al or the Ca-dominant type. In addition to olivine they contain Ca-poor orthopyroxene (Al type) or clinopyroxene (Ca type). Cortlandites, which exist only in the Stormi area, are geochemically related to the peridotite ultramafites. The cortlandites contain primary hornblende and grade locally into hornblendite; they have been regarded as extrusive variants of ultramafic magmatism (Mäkinen 1984, Häkli & Vormisto 1985). About two dozen ultramafic bodies have been discovered in the Vammala area.

Mäkinen (1984) described four deformation phases in the area. The oldest phase of deformation (F_b) transposed the

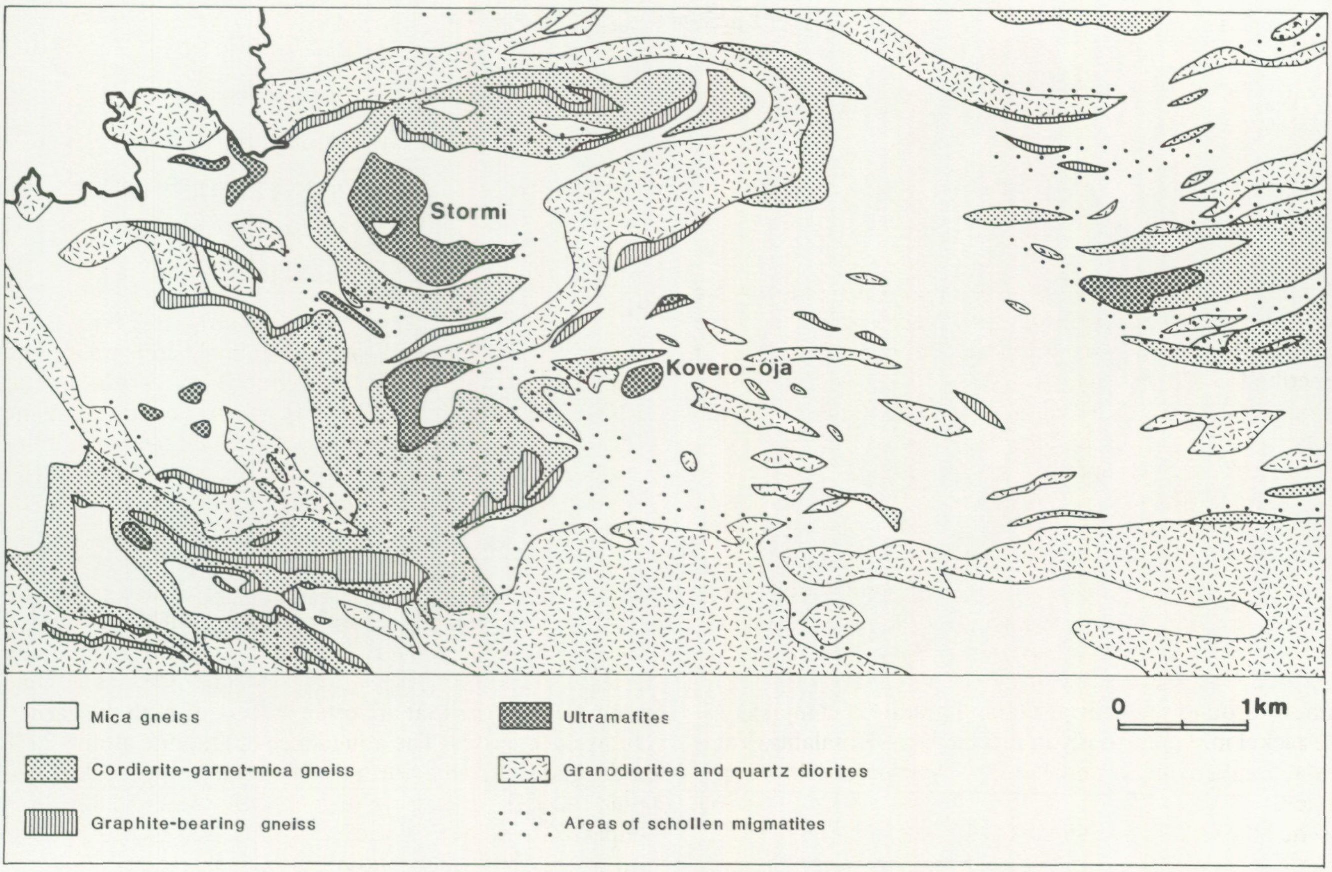


Fig. 7. Geology of the Vammala area (after Häkli *et al.* 1979).

schistosity (S_a) parallel to the primary bedding of the metasediments (S_o). The F_b folds are isoclinal, whereas the next phase of folding (F_c) resulted in open folds and postdates the strong migmatization, indicating that the peak of migmatization and deformation was F_b. The next phase of folding (F_d) was weak and caused culminations and depressions in the area. Marked schistosity is visible in the cortlandites but competent peridotites display foliation only locally. The intrusion of ultramafites pre-dates folding phase F_b.

Schollen migmatites are fairly common in the Stormi area. The groundmass of homogeneous type is palingenetic trondhjemite or quartz diorite, and the fragments are mafic gneisses and plutonic rocks. Silicic gneiss fragments and their ghostlike remnants can be observed in the more heterogeneous varieties. The schollen migmatites represent tectonically complex zones (Häkli & Vormisto 1985).

The ultramafic bodies and nickel-copper ores of the Stormi area

The Vammala nickel deposit occurs in the Stormi ultramafic body, which is about 1.5 km long, up to 600 m wide and reaches a depth of 300 m (Figs. 8, 9). It occurs in migmatized mica gneiss that contains cordierite, garnet and sillimanite, indicating high-grade amphibolite facies metamorphism. The intrusion has subconformable contacts with the wall-rock gneisses; in places, the gneiss occurs as tongues in and between the ultramafic rocks.

The ultramafic body can be divided into three major superimposed layers, one of which is composed of several sublayers. The lowest layer is peridotite and dunite in composition, with olivine, serpentine, orthopyroxene and clinopyroxene as the main minerals, and phlogopite, hornblende and chlorite as accessories. At the basal contact the olivine is well preserved and shows cumulus texture. The lowest layer is rich in sulphides and hosts the nickel ores of the Vammala deposit. Most of the sulphides occur at the base of the layer but significant accumulations are encountered higher up, too.

The intermediate layer is predominantly hornblendite that contains pyroxene, calcite, phlogopite and, occasionally, olivine in addition to pale green amphibole, in which case the rock approaches cortlandite in composition. An agglomerate sublayer exists in the upper portion of the hornblendite layer. Thin layers with orthopyroxene phenocrysts suggest that the major hornblendite layer was actually a succession of ultramafic flows.

The uppermost ultramafic layer has serpentine, amphibole, olivine and pyroxene as major minerals. The primary mafic silicates are commonly altered into serpentine

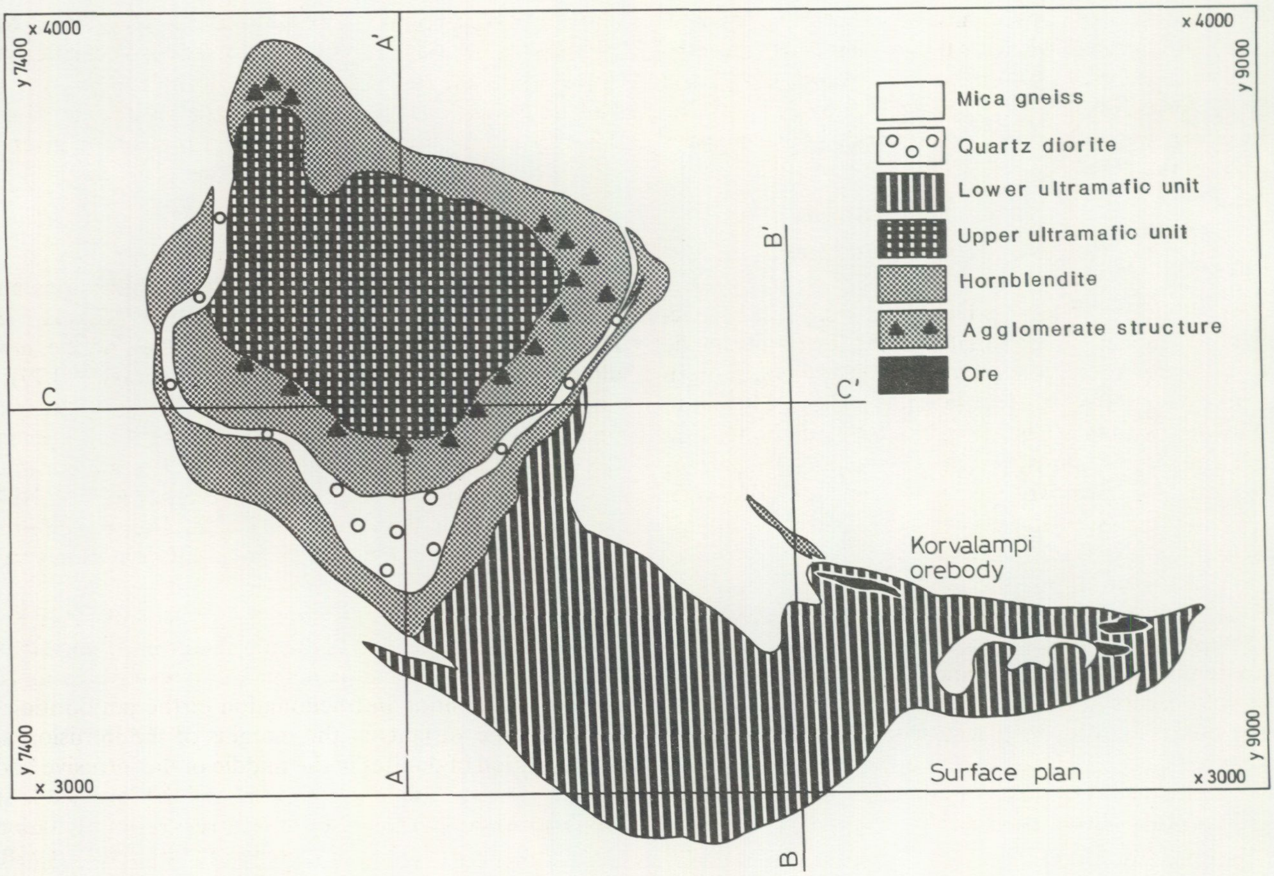


Fig. 8. The Vammala (Stormi) ultramafic body.

but the chemical composition is peridotitic. At the northern end of the ultramafic body a thin layer of hornblendite rests on the upper peridotite layer. Primary sulphides in the upper ultramafic layer have been oxidized into magnetite throughout. The shapes of the sulphide grains are still recognizable although their spaces are now occupied by magnetite and chlorite ("the hymn book texture" by Häkli *et al.* 1979).

A layer of phlogopite rock occurs in the lower contact of the hornblendite layer with the lower peridotite, and a narrow sublayer of diopside and magnesian hercynite-bearing rock exists at the upper contact of the hornblendite with the upper peridotite. These contact rocks are relics of the metasedimentary rocks that define the boundary between the ultramafic units.

The ultramafic rocks are cut by dykes that vary from gabbro to granite in composition. The contacts of the dykes are rimmed by reaction zones 1 to 3 cm wide, composed of chlorite, actinolite and talc.

Ore bodies

The sulphide Ni-Cu ore bodies are associated with the lower ultramafic layer. The ore bodies occur mainly along the eastern and northern margins of the layer but also in the interior and at the basal contacts, the most important ones being Sotka, Iivari and Korvalampi. The Sotka ore body is exposed in the east and plunges towards northwest as a subvertical slab about 700 m long and 70 m wide. The Iivari ore body is a pile of subhorizontal plates 5 to 30 m thick at the base of the western part of the ultramafic rocks at a depth of 250 to 350 m. The Korvalampi ore body is in the eastern part of the ultramafic rocks at the contact zone of the intrusion.

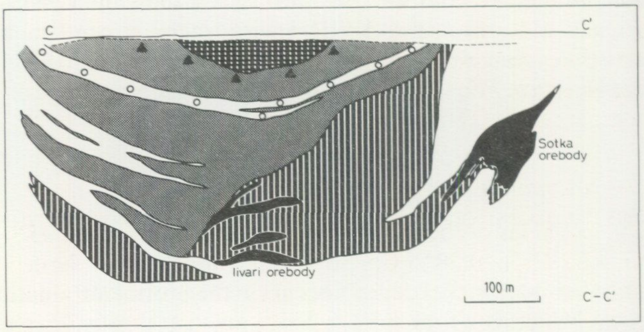


Fig. 9. Cross section of the Vammala (Stormi) ultramafic body; symbols as in Fig. 8.

At the contact zone, the sulphides occur within ultramafic rocks as matrix or massive veins that occasionally extend to the wall-rock gneiss. From the contact inwards the matrix ore grades into a fine-grained sulphide dissemination. At the northwestern end of the Sotka ore body, the sulphides extend into the mica gneiss for a distance of 10 m.

Sulphide minerals

The monoclinic pyrrhotite-pentlandite-chalcopyrite ± mackinawite assemblage predominates in the lower ultramafic layer. The sulphides are partly oxidized and have been replaced by secondary magnetite and violarite. Magnetite also fills the fissures of chalcopyrite and pentlandite. The assemblage monoclinic pyrrhotite, hexagonal pyrrhotite, pentlandite and chalcopyrite occurs at the contact between the lower ultramafic rocks and the mica gneiss. Hexagonal pyrrhotite occurs as inclusions in the monoclinic pyrrhotite. In the Sotka ore body the assemblage also includes mackinawite, cubanite and valleriite. Pentlandite exsolution bodies in pyrrhotite are rare except in the Sotka ore body.

An assemblage of pyrrhotite and arsenopyrite with minor native gold occurs at the basal contact against the garnet-bearing quartz diorite, in places scheelite has also been encountered.

The sulphide-silicate textures allow the ores to be subdivided into the following types:

- massive sulphides as narrow veins and breccia matrix and accumulations along the contacts of the ultramafic rocks;
- matrix ore in the lower ultramafic layer, which grades into disseminated ore as the sulphides decrease in abundance;
- disseminated sulphides in the lower ultramafic rocks, in the mica gneiss and in the contact rocks. The sulphides occur as large blebs, stringers or inclusions in silicate minerals;
- very weak and fine-grained sulphide dissemination in the hornblendite layer.

Oxide minerals

The ultramafic rocks have primary and secondary oxides. The former include chromite, ilmenite and magnetite. Secondary magnetite occurs in serpentinites and as an oxidation product of sulphides. Ilmenite exists as individual grains or as lamellae in magnetite. Chromite is encountered as a low-grade dissemination in the lower ultramafic layer but not as independent chromite layers.

Composition of the ores

The sulphides of the lower ultramafic layer average 6.35 % Ni, 4.35 % Cu, 0.38 % Co, 50.57 % Fe and 38.35 % S calculated to 100 % sulphides. The nickel concentrate produced in 1980 averaged 0.34 ppm Pt, 0.25 ppm Pd and 0.02 ppm Rh. The proportions of the three main components (Ni, Cu and Co) of the sulphide phase vary considerably. At the base of the lower ultramafic unit the Ni/Cu ratio is 4 but it declines upwards. In the lower part of the hornblendite layer the Ni/Cu ratio is 3, but it decreases over a distance of 30 m to 0.3 only to increase to 2 in the upper part of the layer.

Genesis

The isotopic composition of sulphide sulphur varies markedly in the Stormi intrusion (Papunen & Mäkelä 1980, Häkli & Vormisto 1985). The $\delta^{34}S$ values of the lower ultramafic unit fluctuate around zero (average -0.79); in the hornblendite layer the average is $+1.51$ per mil but in the upper ultramafic layer it is still higher, being $+12.51$ per mil; the value in mica gneiss is -1.7 per mil. The sulphur in the lower layer is similar to that in some other Finnish Ni-Cu deposits considered magmatic in origin. The sulphur in the upper layer is heavy and has a source different from that in the lower layer.

According to the genetic model suggested by Häkli *et al.* (1979), the emplacement of the ultramafic body started with the intrusion of ultramafic magma into water-bearing clay sediments, resulting in fractionation of the peridotitic and hornblenditic variants at the margins of the intrusion and consolidation of dunites in the middle of the intrusive body. The magma was sulphide-saturated and the immiscible sulphide liquid sank to the base of the intrusion by gravitational settling. Some of the sulphides separated from the crystallizing magma as the temperature fell and now form higher horizons of low-grade disseminations.

A succession of pyroxenitic flows extruded on top of the lower ultramafic layer and crystallized very close to or on top of the sediments as is suggested by agglomeratic structures and intervening sediments. The pyroxenitic flows were hydrated into hornblendites.

The second set of ultramafic flows erupted on the hornblendite layer. Like the first flow, the magma was rich in sulphides, but during strong hydrothermal alteration the sulphides oxidized and secondary sulphides with an isotope composition corresponding to that of the marine sulphates crystallized at a late stage.

The ultramafic body is cut by numerous dykes. Zircon and monazite fractions separated from a dark pegmatite dyke indicate an age of 1890 Ma. This age is typical of the synorogenic rocks of the Svecokarelides and very close to the age of the Kotalahti intrusion (1883 Ma; Gaál 1980). The age must be considered the minimum age of the Vammala intrusion. A lead/lead age of 1856 Ma has been measured from a Kylmäkoski chalcopyrite fraction (Papunen 1980).

STOP DESCRIPTIONS

Stop 1. – The Vammala mine. Different types of Ni-Cu ore will be seen.

Stop 2. – Close to the Kovero-oja open pit. Migmatite. The contact of the ultramafic rock is only some dozen metres from the outcrop.

Stop 3. – A roadcut at the crossing of the Lauttakylä-Tampere highway and the road to the Vammala mine. Upper metaperidotite of the Stormi ultramafic complex.

Stop 4. – 500 m southwest of the crossroad mentioned above. Migmatite, wall rock of the Stormi ultramafic complex; the outcrop is c. 50 m west of the contact of the ultramafics. Different phases of deformation can be seen in the outcrop.

DAY 3. THE DANNEMORA IRON ORE DEPOSIT

I. Lager

The Dannemora ore deposit is situated in the northeastern part of the province of Uppland, about 100 km north of Stockholm and 45 km north-northeast of Uppala (Fig. 10, 11). It is comprised of numerous bodies of manganese-rich and manganese-poor lime and skarn iron ore. In ancient times small lead-bearing zinc mineralizations also attracted interest in Dannemora. Nowadays only iron ore is mined there.

The Dannemora deposit has been known for at least 500 years. In 1937 all mining there was co-ordinated under one company and, at the same time, the mines had the common name "Dannemora gruvor". Since 1978, they have been owned by SSAB, Swedish Steel Corp.

In 1984, the haulage was 1.1 million metric tons from which lump ore and sinter fines were produced, with an average iron content of 53% and manganese content of 1.46%. The total proved and probable ore reserves in Dannemora were 33 million tons in 1985.

Regional geology

The geology of the Dannemora district and ore deposit has been described by Erdmann (1851), Törnebohm (1878), Nyström (1922), Tegengren (1924) and Geijer & Mag-

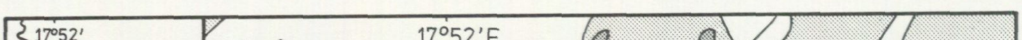


Fig. 10. Simplified aeromagnetic total-intensity survey of the Dannemora district.

nusson (1944) amongst others. These authors have discussed very limited, shallow parts of the Dannemora deposit. Since 1944 many new areas have been exposed and many new facts have appeared, details of which have not yet been published.

The bedrock of the Dannemora district and ore deposit consists mainly of weakly metamorphosed, sedimentary and acid volcanic rocks, belonging to the Svecokarelian "leptite formation". In the Dannemora district, the leptite formation constitutes steeply dipping units between primorogenic granitoids (Fig. 11). The formation thickens parallel to the Dannemora ore deposit as a result of isoclinal folding. There it occurs in two synclines separated by an intermediate anticline. The ore deposit occurs in the southeast syncline – "The Dannemora syncline". It stands out markedly on the aeromagnetic survey map (Fig. 10) as an extensive anomaly with high gamma values. This map also shows other magnetic anomalies, but these have only slight extensions and low gamma values. They are caused by small iron ore bodies, of which several have been prospected and mined in ancient times (Fig. 11).

THE DANNEMORA SYNCLINE

Shape and extension. The shape and continuation of the Dannemora syncline at the 300–350 m level is shown in Fig. 12. The carbonate-bearing part is approximately 3 km in length and 400 to 800 m in width. The syncline strikes approximately N 30 E and dips between 80° and 90° to the northwest at the surface and between 55° and 70° at the 350 m level.

The Dannemora syncline is cut by numerous faults. It is developed with two steeply dipping limbs, one of which is slightly overturned. The stratigraphy in these limbs is similar. The younging directions have been determinated on the evidence of graded bedding, cross-bedding, erosion surfaces and stromatolites. The bottom of the syncline has, to date, been observed only in the southern part (Fig. 12). To the north, the bottom has not yet been penetrated by drilling. In these parts the leptite formation has been proved down to the 1150 m level (ore to the 1000 m level) by diamond drilling. There, the formation continues deeper; its ultimate depth and the occurrence of ore within it have yet to be determined.

Composition. The exposed part of the leptite formation in the Dannemora syncline is composed of supracrustal rocks such as "hälleflinta", marble, calc-silicate rocks ("skarn" in Swedish), iron ore and sulphide ore together with intrusive felsite porphyry, greenstone porphyry and diorite – rock names used on the mining chart (Fig. 12). The supracrustal rocks often occur as thinly bedded or laminated heterolithes. In Fig. 12 the heterolithes have been designated with the name and colour of the predominant rock. Calc-silicate beds, sulphide ore and many of the intrusive

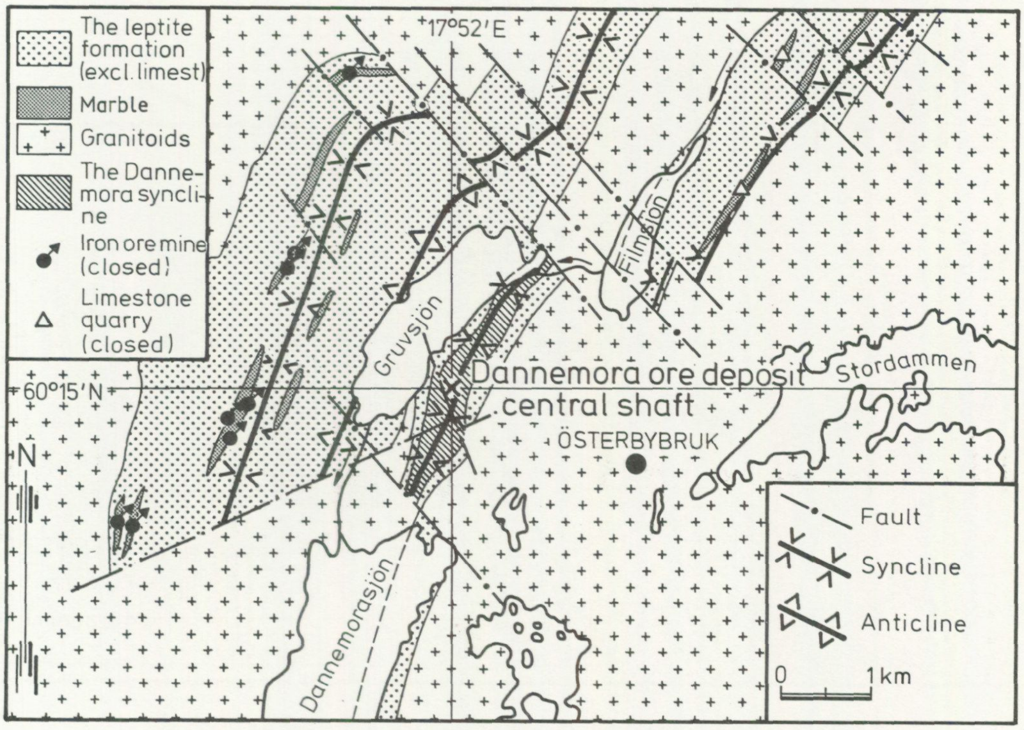


Fig. 11. Simplified geologic map of the Dannemora district.

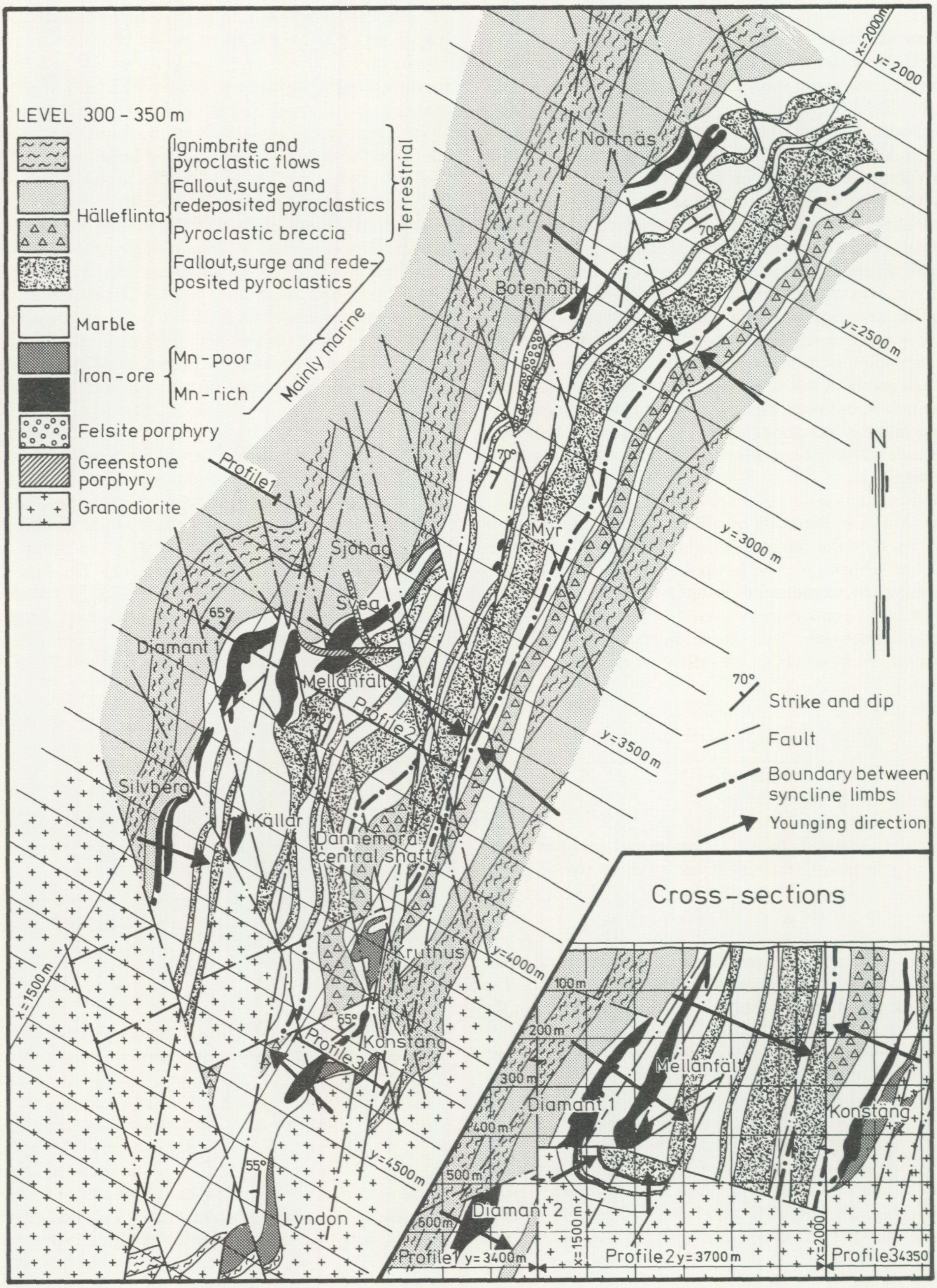


Fig. 12. Geologic map of the Dannemora syncline at the 300–350 m level.

rocks have not been marked in Fig. 12 owing to their insignificant extension.

The "hälleflinta" in Dannemora is a quartz-microcline-albite-sericite rock of acid composition, in most cases rhyolitic with a high K-content. Facies analysis indicates that the "hälleflintas" were originally ignimbrites, pyroclastic flows, subaerial and submarine fallout tephra, sediments of hydroclastic eruptions together with pyroclastic sediments redeposited by fluvial and tidal processes.

The marble is mostly dolomitic with a Fe-content between 5 and 30 % and Mn-content between 0.5 and 1.5 %. Facies analysis suggests that the marble represents a primary shallowing-upward sequence of tidal, partly stromatolitic sediments intermixed with lagoonal and tidal channel sediments.

The calc-silicate rock is partly Mn-rich (up to 25 %) consisting of the minerals knebelite, dannemorite, and sometimes spessartine and varying amounts of magnetite. In some places it is Mn-poor (below 1 % Mn) and is composed of diopside, actinolite, sometimes andradite and some magnetite.

The iron ore is either a Mn-rich or a Mn-poor skarn iron ore or a Mn-poor lime iron ore. The Mn-rich skarn iron ore is composed of the minerals magnetite, knebelite, dannemorite and serpentine. The Mn-poor skarn iron ore consists of the minerals magnetite, diopside and actinolite; the Mn-poor lime iron ore is composed of magnetite, calcite, dolomite and sometimes Fe-bearing carbonate minerals. The Fe-content in the iron ore is generally between 30 and 50 %; only rarely does it reach 65 %. Usually the Mn-content varies between 0.2 and 1 % in the Mn-poor ore and between 1 and 6 % in the Mn-rich ore. The ore occurs mainly as more or less stratiform layers in marble. In a few cases, it cuts other layers as cave fillings in paleokarst zones. The iron ore in Dannemora consists of about 25 ore bodies – some shallow, others deep-seated.

The sulphide mineralization is composed either of sphalerite and galena with traces of silver, or chalcopyrite, pyrite and pyrrhotite with traces of gold. These mineralizations occur as disseminations and fracture fillings in paleokarst zones.

The felsite porphyry is rhyolitic and the greenstone porphyry is andesitic; both are intruded by the diorite. The greenstone porphyry cuts only the felsite porphyry, not the diorite.

In the southwestern, shallow parts of the Dannemora syncline, the supracrustal formation partially borders on a granodiorite belonging to the primorogenic granitoids. To the north, this rock becomes more widespread with depth.

Stratigraphy and supracrustal evolution. A lithostratigraphic section of the WNW limb of the Dannemora syncline is shown in Fig. 13. The ESE limb has a similar stratigraphy, but differs in its lack of iron ore in its northern part.

The supracrustal evolution of the exposed parts of the Dannemora syncline commenced with (sub-) horizontal, terrestrial deposition of ignimbrites, pyroclastic flows, subaerial fallout tephra and pyroclastic sediments redeposited

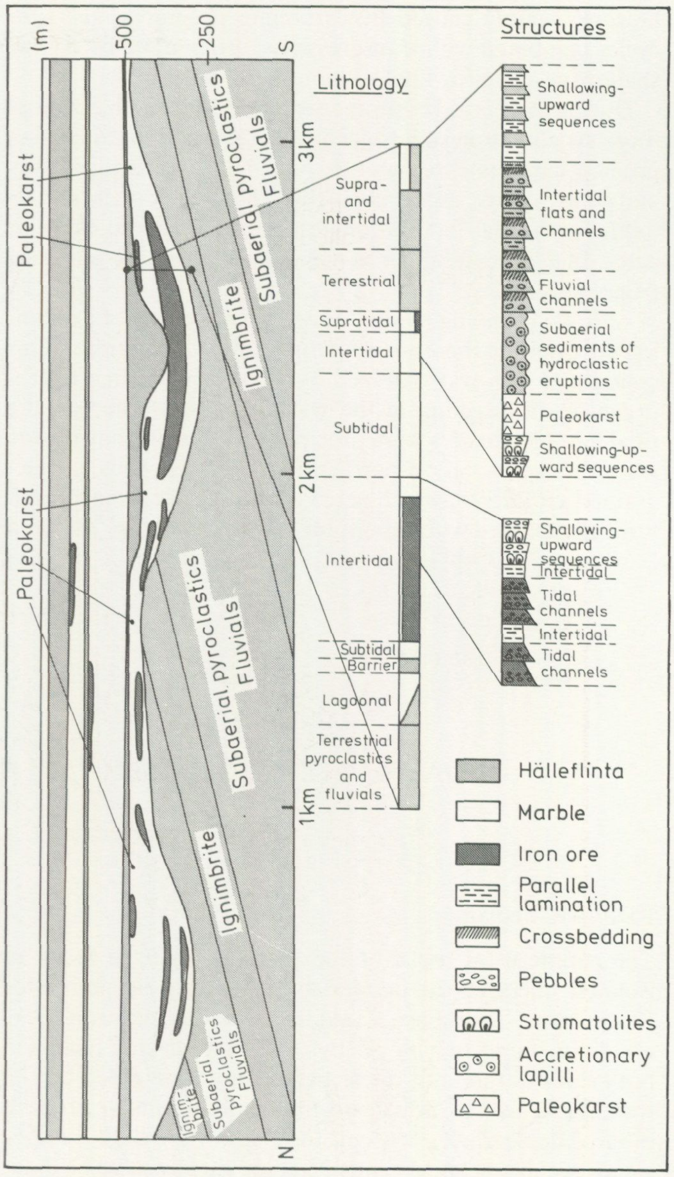


Fig. 13. Lithostratigraphic section of the WNW limb of the Dannemora syncline at the 300–350 m level.

by fluvial processes. At a break in the volcanic activity, the terrestrial layers were subjected to weathering and erosion. An uneven landscape was created with two sub-basins and one intermediate height. A subsequent transgression ushered in a new period of mainly marine sedimentation of carbonates, siliciclastic sediments and ores. The carbonates are tidal and lagoonal. The siliciclastic sediments are composed of submarine fallout tephra sediments of hydroclastic eruptions and pyroclastic sediments redeposited by tidal flat and channel processes. This period of supracrustal evolution of the Dannemora syncline was characterized by cyclic sedimentation. Main cycles, caused by transgressions and long periods of regression, are marked with karst weathering and cave fillings at the top and fluvial sediments at the bottom. Mainly caused by carbonate progradations, subcycles combined with transgressions, are marked by typical shallowing-upward, tidal sequences of carbonates.

During this period of supracrustal evolution in the Dannemora syncline iron was concentrated in medium- to coarse-grained carbonate sediments, with high primary porosity and permeability, especially in tidal channel sediments alternating with tidal flat carbonates, with or without calc-silicates. In a few cases the iron was deposited as cave fillings in paleokarst zones.

A "tidal pumping model" is one possible way of explaining the origin of the iron ore. During high tide marine water containing iron was oxidized by oxygen producing microorganisms fluorishing in the warm, shallow water on the tidal flat. Iron oxides were precipitated. During the low tide stage the water ran off partly through very porous, coarse-grained sediments, which acted as filters. The iron concentration increased with repetition of this "pumping" effect to the tide. If a marine transgression followed terrestrial paleokarst weathering, the iron content in the paleokarst zones can be explained in a similar way.

Tectonics. Apart from the formation of the syncline the main tectonic feature in the Dannemora area is faulting with limited folding. Secondary foliation exists only locally and lineation is missing almost totally.

Among the most important fault zones in Dannemora are parallel, horizontal or gently dipping zones at different levels. A block above such a fault zone is always displaced to the south compared with a block below. The largest measured throw along a horizontal fault zone in Dannemora is 400 m. Two systems of parallel, steeply dipping fault zones, striking N 15° W and N 10 E and dipping 60°W and 85°W, respectively, cut the horizontal zones. These faults always downthrow to the east.

DAY 4. THE GARPENBERG AREA AND ZINC-LEAD-COPPER DEPOSIT

H. Christofferson, I. Lundström and W. Vivallo

Regional geology

The supracrustal rocks of the Garpenberg area form an isolated enclave, surrounded by primorogenic granitoids ("urgraniter", see Figs. 2 and 14). The supracrustal rocks are divided into two blocks by a NE–SW striking fault. On both sides of the fault the structures are dominated by NE trending synclines, which diverge slightly relative to each other. The northwestern syncline is known to have a rather steep axial plane and a gently NE dipping fold axis. To date, the stratigraphic relationships between the rocks of the two blocks are unknown.

In the southeastern block, massive, monotonous porphyritic volcanites predominate. Cordierite-rich horizons are, however, common and tuffitic intercalations occur. Outside the area of the map in Fig. 14 a quartzite layer has been found, revealing the synclinal structure of this block. (Ambros, pers. comm. 1985). According to Geijer & Magnusson (1944), the porphyritic rocks are dacitic.

In the northwestern block, a volcano-sedimentary sequence occurs, which is dominated by rhyolitic tuffites with occasional intercalations of dacitic porphyries (Fig. 15). In the lower part of the sequence, marble beds and skarn iron ores and sulphide ores are present. Above this level lies a 100–200 m thick marker bed of amphibolite, which clearly demonstrates the fold structure of the area.

The economic massive sulphide deposits lie stratigraphically above the amphibolite horizon, close to a marble. The marble is overlain by massive quartz porphyries which indicate a change in the volcanic milieu from submarine, rapidly changing volcano-sedimentary conditions to a voluminous outpouring of ashes and lavas from neighbouring volcanoes. (Ambros, pers. comm.). Dacitic dykes are also known. The magmatic rocks are calc-alkaline and most of the volcanic activity occurred as explosive submarine volcanism according to Vivallo (1984).

The supracrustal rocks have been deformed and metamorphosed under amphibolite facies conditions. A second, retrograde metamorphism in the greenschist facies has also been recognized. The structure of these rocks is defined by NE trending vertical to subvertical isoclinal folds.

The submarine, tuffitic character of the ore-bearing metavolcanites seems to indicate a stratigraphic position within the upper parts of the volcanic part of the stratigraphic column of Fig. 2. Due to the isolated position of the Garpenberg enclave, its stratigraphic position is, however, uncertain. Likewise the position of the dacites remains unclear.

The ore deposit

The *Garpenberg Zn-Pb-Cu-Ag sulphide deposit* is located on the northern limb of the Garpenberg syncline, and consists of 32 lens-shaped ore bodies with various compositions parallel to the bedding and schistosity (Fig. 16). The ore bodies display a zonal arrangement with disseminated Cu

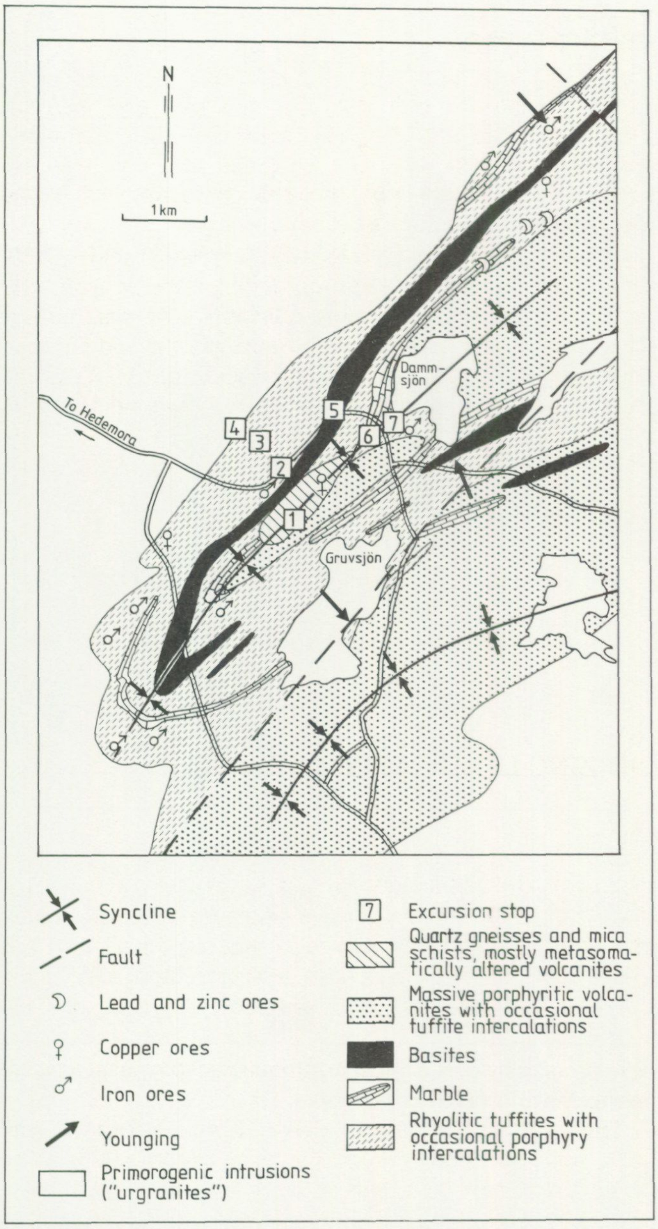


Fig. 14. Geological map of the Garpenberg area. Compiled from Geijer & Magnusson (1944), du Rietz (1968), Vivallo (1985c), and Ambros (in preparation).

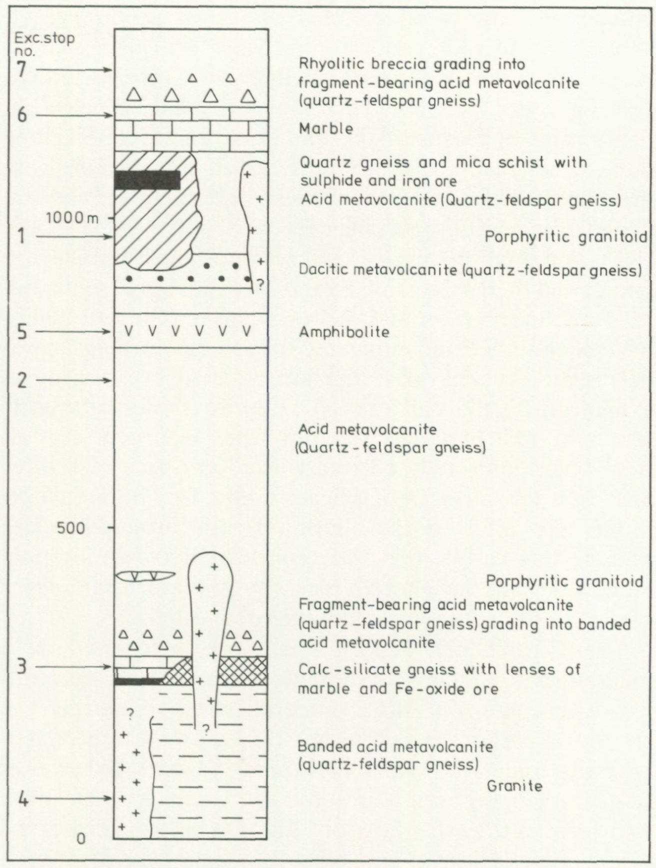


Fig. 15. Stratigraphic sequence at Garpenberg.

ore on the foot-wall side and more massive Zn-Pb-Cu ore on the hanging wall side. The ore mineralogy is simple and consists mainly of varying proportions of pyrite, sphalerite, galena, chalcopyrite and pyrrhotite. Tetrahedrite and argentite are the most common accessories.

The *Cu ores* consist of a network of chalcopyrite-pyrite-pyrrhotite-bearing quartz and quartz-fluorite veins in quartz gneisses and mica schists. Dissemination of chalcopyrite and pyrrhotite with minor pyrite and sphalerite are also present. The *Zn-Pb-Cu ores* occur as massive lenses, 1–2 m thick, or as thinner bands (cm thick) parallel to the bedding and schistosity. They consist of sphalerite, galena, pyrite, pyrrhotite and silver minerals, and are hosted by calc-silicate gneisses (tremolite-skarn) and mica schists. The Zn-Pb-Cu ore bodies show a diffuse to distinct metal and mineralogical zoning not observed in the Cu ores.

Other ore types present in the Garpenberg deposit include *ball ores* and *earthy ores (mullmalm* in Swedish). The first are dyke-like ore bodies, very long in proportion to their width, which is normally only a few decimetres. The contacts with the wall rocks are sharp and normally faulted. The ball ores consist of quartz, calc-silicate gneiss, quartz-gneiss, and rounded mica schist fragments, 2 to 3 cm in diameter, in a matrix of sulphides made up principally of sphalerite, galena, pyrite, pyrrhotite and chalcopyrite. The earthy ores occur on the hanging wall side of the massive Zn-Pb-Cu lenses and have a sub-parallel to obliquely cross-cutting relationship to these lenses. The earthy ore consists of soft and poorly consolidated material, rich in clay minerals, lead, zinc and silver. The ore minerals include sulphides, sulphates and carbonates. The origin of the earthy ores is poorly understood; however, they appear to be a fault-controlled product of either deep-weathering or possibly low-temperature hydrothermal alteration.

An extensive area consisting of quartz gneisses and mica schists makes up the foot-wall and part of the hanging wall of the Garpenberg deposit, they are composed of quartz and phlogopite with variable amounts of cordierite, garnet, andalusite, staurolite, and gahnite. Most of the quartz gneisses and mica schists were originally hydrothermally altered volcanic rocks, probably rhyolitic to rhyodacitic tuffs, but pelitic and epiclastic rocks are also represented among them. Chemically, they are enriched in magnesium, iron, ore metals, potassium, manganese and volatiles, and are depleted in sodium and calcium.

The original shape and geometry of the sulphide ore bodies and their associated alteration zones have been modified by deformation and metamorphism. The ore bodies have been folded and elongated toward the northeast parallel to the syncline axis, and are affected by shearing as evidenced by the ball ores. The pyrite shows cataclastic textures and is partly altered to pyrrhotite. Galena crystals have been deformed and remobilized into small fractures and cleavage surfaces of silicate minerals. The metamorphism also affected the alteration zone around the ore bodies; this resulted in the replacement of the original mineralogy of the altered rocks by mineral assemblages typical of the subsequent metamorphic events.

The Garpenberg deposit has been interpreted as a metamorphosed, massive sulphide deposit of volcanic affinity, where the Zn-Pb-Cu mineralization represents the stratiform part of the deposit and the Cu ores are correlated with the underlying stockwork ores. Several similar ores (e.g. the Garpenberg Norra and the Dammsjön ores) are known from the same horizon. The ore-bearing part of the Garpenberg enclave has recently been described in a number of publications by Vivallo (1984, 1985a, 1985b, 1985c) and by Vivallo & Rickard (1984).

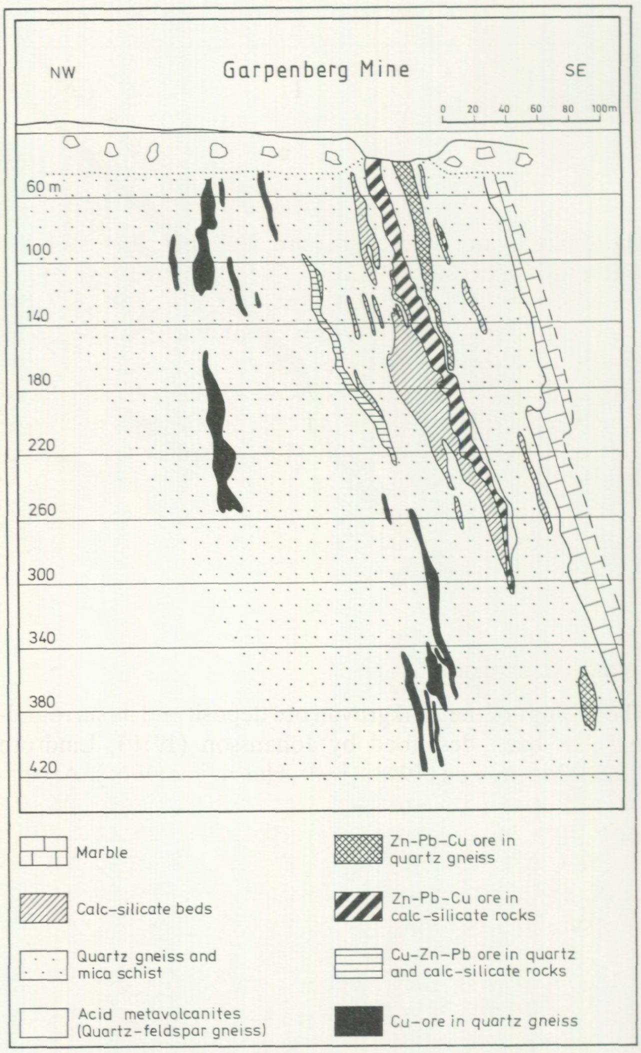


Fig. 16. Vertical section through the Garpenberg mine showing the stratigraphic zoning of the ore bodies.

STOP DESCRIPTIONS

A – Excursion around the Garpenberg mine

Stop 1. – Area, stripped of overburden, 850 m south–southwest of the Garpenberg headframe. Wall rock: altered acid metavolcanic rocks, actually quartz-phlogopite-sericite rocks (quartz gneiss) with minor andalusite, staurolite, cordierite and chlorite.

Stop 2. – Road cut 400 m southwest of headframe. Felsic metavolcanites of rhyolitic composition (leptite).

Stop 3. – Outcrops 400 m south of lake Kuppdammen. Diopside-garnet-epidote calc-silicate rock ("skarn"), commonly associated with iron oxide ores and including lenses of dolomite marble.

Stop 4. – Outcrops 300 m southwest of lake Kuppdammen. Calc-silicate banded metavolcanic rocks.

Stop 5. – Road outcrop 500 m north–northeast of headframe. Basic metavolcanic rock.

Stop 6. – Road cutting 50 m southwest of the church at Garpenberg. Marble on the hanging wall side of the Garpenberg deposit.

Stop 7. – Outcrop by the bathing-place 200 m northeast of the church at Garpenberg. Rhyolitic agglomerate on the hanging wall side of the Garpenberg deposit showing marble lenses and normal grading in the fragment distribution.

B – Underground excursion

A profile normal to the strike of the ore bodies showing (from the foot wall side to the ore) unaltered porphyritic dacitic rocks grading into altered metavolcanites (quartz gneisses and mica schists) will be demonstrated.

Visit to different places to demonstrate the ore types.

DAY 5. THE ZINKGRUVAN (ÅMMEBERG) ZINC-LEAD DEPOSIT

P. Hedström and A. Wikström

The Zinkgruvan (Åmmeberg) ore deposit is situated in the southern part of the province of Närke, about 14 km southeast of the small town of Askersund and about 50 km south of Örebro. The ore deposit has been known from at least the 16th century. From about 1700 onwards the mine was intermittently in production. In 1857 the company of Vielle Montagne purchased the deposit. Mining on a larger scale began and has continued since then. The present annual production (1985) is about 700 000 tons of crude ore, with a grade of 9.5 % Zn, 1.5 % Pb and 45 ppm Ag. The mining method used is mainly horizontal cut and fill stoping.

Regional geology

The geology of the Zinkgruvan ore deposit and its surroundings has been described by Johansson (1910), Lindroth (1925), Magnusson (1948, 1960), Henriques (1964), Arvidsson (1982) and Billström (1985). Of these papers, Henriques' is the most comprehensive one. In addition, bedrock mapping in the scale 1:50 000 is currently being carried out by the Geological Survey of Sweden on the map sheet (9F Finspång SV) covering the Zinkgruvan area. Fig. 17 is a sketch-map based on this mapping.

The region is characterized by amphibolite facies gneisses (ages 1800–2000 Ma) of various kinds including both infra- and supracrustal rocks.

Volcanic rocks (including the "red leptite group" described below) seem to occupy the lower part of the stratigraphy. They are mainly of a rhyolitic composition. About 10 km to the northeast of Zinkgruvan, quartz- and feldspar-phyric textures can be seen. In that area, current bedded quartzites and conglomerates are found within the porphyries and the only stratigraphic way-up determinations in the region have been made there. Several of these volcanites are interpreted as ignimbrites mainly because of their considerable areal extension. Further south, including the Zinkgruvan area, the rock association indicates deposition in a deeper water environment. A marble horizon overlying the acid volcanites can be followed over a large distance and is often connected with volcano-sedimentary rocks of the same kind as described from the Zinkgruvan deposit as the "grey leptite group". Sulphide mineralizations are common in this environment.

Mica schists and gneisses, often highly migmatized with sillimanite, andalusite and cordierite as typical index minerals, seem to occur in the highest stratigraphic position, in which also the "grey gneiss group" of the mine area is found.

The plutonic rocks are divided into an older and a younger suite dominated by granitoid rocks. The older suite is generally conformable with the supracrustal rocks and deformed together with them while the younger suite is usually discordant. However, marginal parts of the younger suite have also been found to be conformably deformed and several structural problems remain to be solved in this respect.

In the close vicinity of the Zinkgruvan ore deposit, three well delimited lithostratigraphic groups can be distinguished (Figs. 18 and 19). They correspond to the major groups described above. In the terminology of Henriques (1964) they are called:

"Grey gneiss group" (Youngest, occurring in the south)
"Grey leptite group"
"Red leptite group" (Oldest, occurring in the north)

The "red leptite group" is totally dominated by a massive rhyolitic, red, fine-grained quartz-microcline rock, strongly enriched in K and depleted in Na by synvolcanic metasomatism. The rock is interpreted as a lava.

The "grey leptite group" consists mainly of tuffaceous sediments. Massive beds, with a higher epiclastic content alternate with well stratified more volcanogenic rocks. Together with the sedimentation of epiclastic and pyroclastic material there has also been a chemical precipitation of carbonates, sulphides and chert. These appear now as marbles, calc-silicate rocks ("skarn" in Swedish), calc-silicate-quartz rocks, quartzitic tuffaceous sediments, sulphide ores and tuffaceous sediments with disseminated sulphides, sometimes with some calc-silicates in their matrix.

The chemical precipitates, at least carbonates and sulphides, are more frequent in tuffaceous strata dominated by pyroclastic material. In detail, carbonates and sulphides are generally separated from each other. The sulphides are dominated by sphalerite and galena and, in certain beds, pyrrhotite. All economic ores are in this "grey leptite group".

The "grey gneiss group" consists of veined gneisses, migmatites and granitoid rocks. They are rich in biotite and sometimes also andalusite and sillimanite. Their protoliths were probably epiclastic sediments with a high clay content. In the veined gneisses there are some concordant beds with disseminated pyrrhotite.

In the Zinkgruvan district there are also older intrusive metabasites. They are found only in the "red" and "grey leptite groups", and occur particularly in the eastern part of the area (Fig. 18).

The supracrustal rocks, including the sulphide mineralizations and the intrusive metabasites, have been subjected to high-grade metamorphism. As a result, especially the clay-rich epiclastic sediments ("grey gneiss group") have been converted into veined gneisses, migmatites and also anatexites.

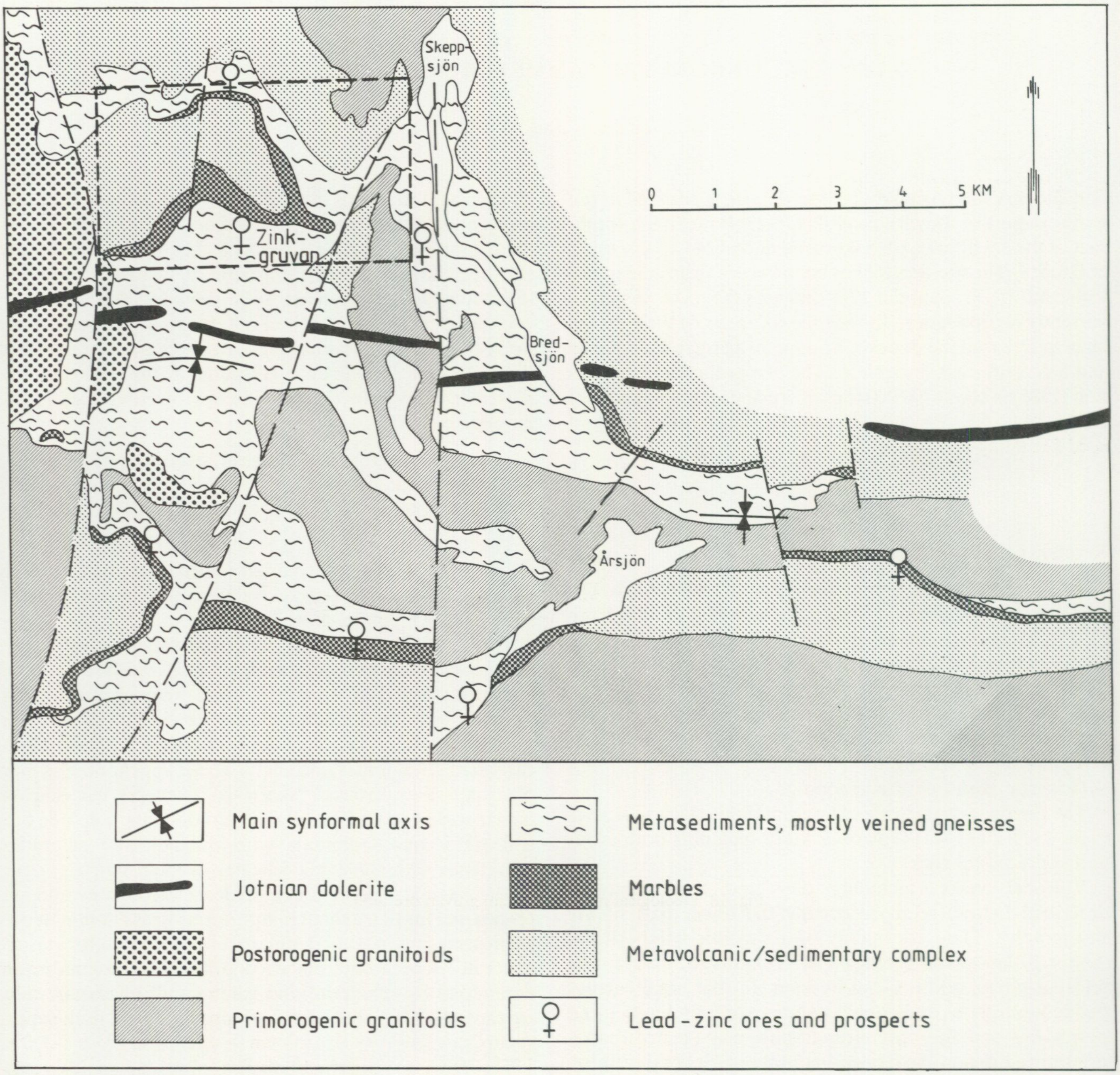


Fig. 17. Geological sketch map of the Zinkgruvan area. After Wikström (in preparation). The area of the map in Fig. 18 is shown in broken lines.

The tuffaceous sediments in the "grey leptite group", which are mainly of a volcanogenic origin, have a metamorphic granoblastic texture while those with a more epiclastic character are gneissic.

This metamorphic terrain is cut by a porphyritic postorogenic granite, which delimits the ore field in the west (Figs. 17, 18). There are also dykes of a still younger diabase in the area and in the mines.

The ore-bearing supracrustal rocks strike mainly E–W and dip steeply (60–80°) towards the north. Four different sets of fold axes have been observed in the mines. Their mutual relationships are not fully known. Two sets have axes with very steep dips, while the axes of the other two sets mainly follow the strike of the rocks, one dipping gently towards the east and the other 10–30° towards the west. These folds are cut by vertical N–S striking faults. Some of the faults have displaced the ore zone hundreds of metres.

Ore and mineralizations

Two types of sulphide mineralization have been recognized in the Zinkgruvan district, namely pyrrhotite, and sphalerite-galena.

The pyrrhotite mineralizations are most frequent in a

Fig. 18. Geological map of the Zinkgruvan ore field.

transition zone between the "grey leptite group" and the "grey gneiss group". The pyrrhotite occur as well-stratified disseminations in concordant beds, which are sometimes enriched in quartz. When this mineralization type is hosted in gneissic rocks, it is often totally remobilized into small veins.

Sphalerite-galena-mineralizations are found only in the "grey leptite group" and especially in beds dominated by volcanogenic materials. The grade of sulphides varies from compact ore to zero. The disseminated type always occurs in well-stratified beds and is itself stratified. These beds, although as thin as 0.5 m, can often be traced for one to two km. The Zn/Pb ratio varies from 0.2 to 40 but is in general between 3 and 8. In a single stratum the ratio is fairly constant.

The productive zinc-lead ores of the Zinkgruvan deposit occur in a 5–20 m thick stratiform ore zone (Figs. 19 and 20). In the Nygruvan mine (the eastern part of the deposit) there are two ore beds (Fig. 20). The richer main ore bed is mainly a compact ore, but towards its structural hanging wall (towards north) thin layers of disseminated ore occur together with sterile layers of marble, tuffaceous and calc-silicate rocks (Fig. 20). In the structural foot wall, there is a calc-silicate bed (locally known as the "skarn") 0.5–1.0 m thick with some pyrrhotite, sphalerite and galena. This calc-silicate rock can be traced along the whole deposit (5 km).

The "parallel ore", in the hanging wall of the main ore, is a 0.5–4 m thick bed with sphalerite- and galena-dissemination in a tuffaceous rock with some calc-silicates in its matrix.

The sterile bed between the main and parallel ore is 3–15 m thick and consists of a gneissic tuffaceous rock, partly quartzitic. The hanging wall of the parallel ore is somewhat gneissic and has some thin beds of calc-silicate hornfels.

This partition of the ore zone into a main and a parallel ore bed is not so distinct in the western part of the deposit (Knalla mine) as it is in the eastern part (Nygruvan mine). In the Knalla mine, the ore beds, in general, seem to be thinner and not entirely continuous along the strike.

The sulphide deposit of Zinkgruvan is interpreted as a

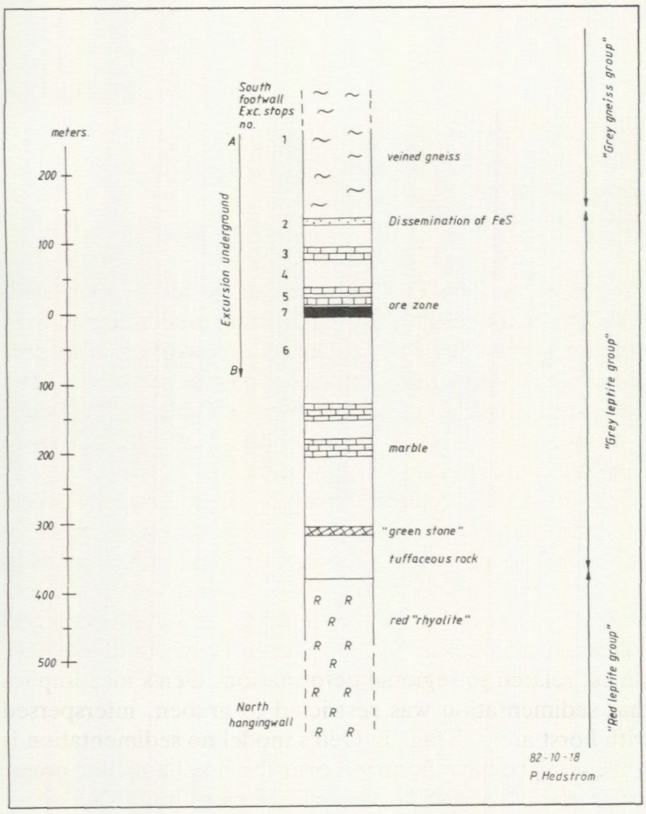


Fig. 19. The stratigraphy of the Zinkgruvan ore deposit at the Nygruvan mine. Younging is towards the south.

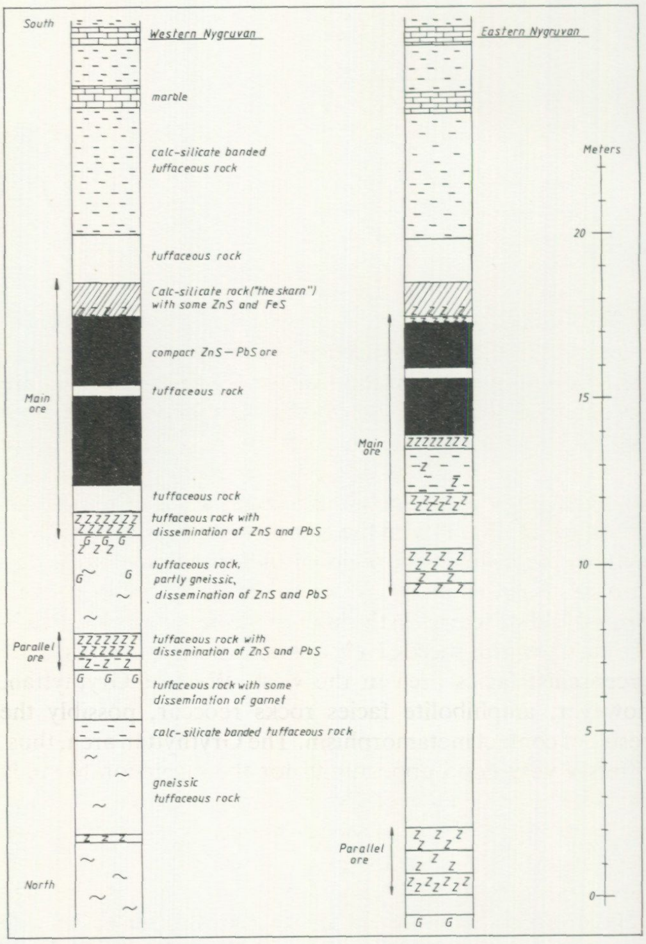


Fig. 20. Stratigraphy of the ore zone at the 650 m level in the Nygruvan mine. Younging is towards the south.

chemical precipitate which was deposited on an ancient seafloor together with carbonates, volcanic ashes and some epiclastic sediments. Shallow depressions on the seafloor were more favourable for the sedimentation and hence the deposition of sulphides. In these depressions, we today find the best ore. This ore-producing event took place at the end of a volcanic epoch, when hydrothermal solutions circulated in the volcanic and tuffaceous sediments and deposited their metal contents on the seafloor. These solutions changed the chemistry of the rocks in the stratigraphic foot wall of the ores. Mainly the alkali metals have been affected, consequently the K/Na ratio in the "red leptite group" and in the "grey leptite group" is very high, while it is closer to unity in the "grey gneiss group". The high potassium content of the metavolcanites of the "red leptite group" causes a spectacular anomaly on the gamma radiation map.

STOP DESCRIPTIONS

Underground

A profile normal to the strike of the ore zone on the 650 m level in the Nygruvan mine, Figs. 18 and 19.

Stop 1. – Veined gneiss, migmatite, granite ("grey gneiss group").

Stop 2. – Transition zone, "grey gneiss group" – "grey leptite group", with pyrrhotite mineralization.

Stop 3. – Well stratified marble, bearing calc-silicates ("grey leptite group").

Stop 4. – Different types of tuffaceous sediments ("grey leptite group").

Stop 5. – Well stratified tuffaceous sediments – marble bearing calc-silicates ("grey leptite group").

Stop 6. – Tuffaceous sediments, mainly somewhat gneissic, with thin light grey beds of more volcanogenic composition bearing some sphalerite ("grey leptite group").

Stop 7. – Sphalerite-galena ore, Fig. 20. Various, currently accessible, stops at the 650 m level ("grey leptite group").

Surface

Stop 8. – Road cut 600 m northeast of Nygruvan mine. K-rich metalvolcanic rock, Fig. 18 ("red leptite group").

Stop 9. – Outcrops along small road along outlet tube, 1 km south of Nygruvan mine. Veined gneiss, migmatites, granite, Fig. 18 ("grey gneiss group").

DAY 6. THE GRYTHYTTAN AREA

I. Lundström

Regional geology

Supracrustal successions such as the one to the left in Fig. 2 (cf. also text p. 8) from the Lindesberg-Filipstad area, are documented from e.g. the Saxån, Grythyttan, Ställdalen and Guldsmedshyttan areas (see Fig. 21). These areas are situated along an east–west regional metamorphic gradient, connecting the high amphibolite facies areas of the Mälaren valley (cf. Fig. 1) with the greenschist facies area of Grythyttan. A change of regional deformational style can also be discerned along this gradient, from isoclinal, overturned fold structures in the high-grade metamorphic area in the east, towards successively less deformed structures in the greenschist facies area in the west. West of Grythyttan, however, amphibolite facies rocks reoccur, possibly the result of contact metamorphism. The Grythyttan area, thus, offers a very good opportunity for the excursion to study extremely well preserved Svecofennian lithologies.

Being of possible economic interest, these areas have been in the focus of geological interest for a considerable time. The Grythyttan area, in particular, due to the high degree of preservation of the supracrustal rocks, has also served as a model for the "Leptite Formation" for most Swedish geologists. The first detailed description was given in 1923 in an excellent monograph by Sundius. The similar lithologies of the adjacent Saxån and Ställdalen areas, which are of a metamorphically higher grade, were described later by Magnusson (1925, 1930, 1940). Subsequently, little work was carried out in these areas until, in 1982, Oen *et al.* suggested an interpretation in terms of incipient rifting for the Grythyttan-Saxån area.

As seen from Fig. 2, the supracrustal succession can be roughly subdivided into a lower volcanogenic, pyroclastic to tuffitic felsic, and an upper metasedimentary sequence. Flows appear to be scarce, but occur just beneath the sediments (stop 1). This succession is supported by numerous way-up structures in the area. Intercalations of subaqueous marble and calc-silicate ("skarn" in Swedish) beds, occur within the entire volcanogenic part of the column. According to Oen *et al.* (1982, for the Saxån-Grythyttan areas) and Lundström (1983, 1985, for the Guldsmedshyttan and Ställdalen areas) such intercalations become more frequent toward the top of the volcanogenic part of the sequence. Likewise, beds of epiclastic sediments, similar to those overlying the volcanites, become successively more common upwards. This is the main reason for the rough subdivision of the volcanogenic pile into a lower, largely pyroclastic and an upper, mostly tuffitic part (Fig. 2, left). Apparently this stratigraphy records a change from volcanic to sedimentary environments. This evolution was suggested by Oen *et al.* (1982) to be the result of rifting, leading to sedimentation in isolated graben structures. Oen and coworkers also proposed a detailed stratigraphic subdivision, illustrating this evolution, which is reproduced here as Table 1. The reader is recommended to consult Oen's paper (op. cit.) for a more detailed elucidation of these aspects.

Although the interpretation of Oen and coworkers depends on the same basic observations that were made by Sundius, Magnusson and Lundström (op. cit.), it leads to one fundamental difference. While Swedish geologists generally tend to understand the interplay of sedimentary and volcanogenic areas in Fig. 21 in terms of synclines and anticlines, related to regional deformation, Oen's idea implies that sedimentation was restricted to graben, interspersed with horst areas. Thus, in Oen's model no sedimentation is considered to have occurred over the horst/anticline areas, while the "Swedish" opinion presumes that the upper stratigraphic units have been eroded from the anticlines in those areas.

The iron ores of the area are thought to have been debouched on to a seafloor as a result of hydrothermal processes, (cf. Frietsch, above). At the same time, subseafloor, hydrothermal leaching processes are thought to have operated at lower stratigraphic levels, creating Mg-enriched mica quartzite zones, some of which will also be visited (stops 6 and 7). Oen *et al.* (op. cit). consider that these alterations are related to basic and acid magmatism, now evidenced by metabasite and granite/granophyre intrusions.

STOP DESCRIPTIONS

The itinerary includes seven stops, which emphasize the different supracrustal lithologies, while infracrustal rocks have to be omitted. The stops do not follow each other in stratigraphic order. The reader is therefore referred to the stratigraphic column of Table 1, where the stratigraphic positions of the different stops are indicated.

Stop 1. – 1 km south-southwest of Kullberget, 2 km southeast of Hällefors. Porphyritic rhyolite with flow breccia and quartz-filled lithophysae. This is one of the few instances where a flow origin for a Bergslagen metavolcanite can be ascertained. It belongs to Sundius' (1923) "Upper hälleflinta division" in which potassic compositions are common. Nevertheless, this rock belongs to a sodic horizon within a

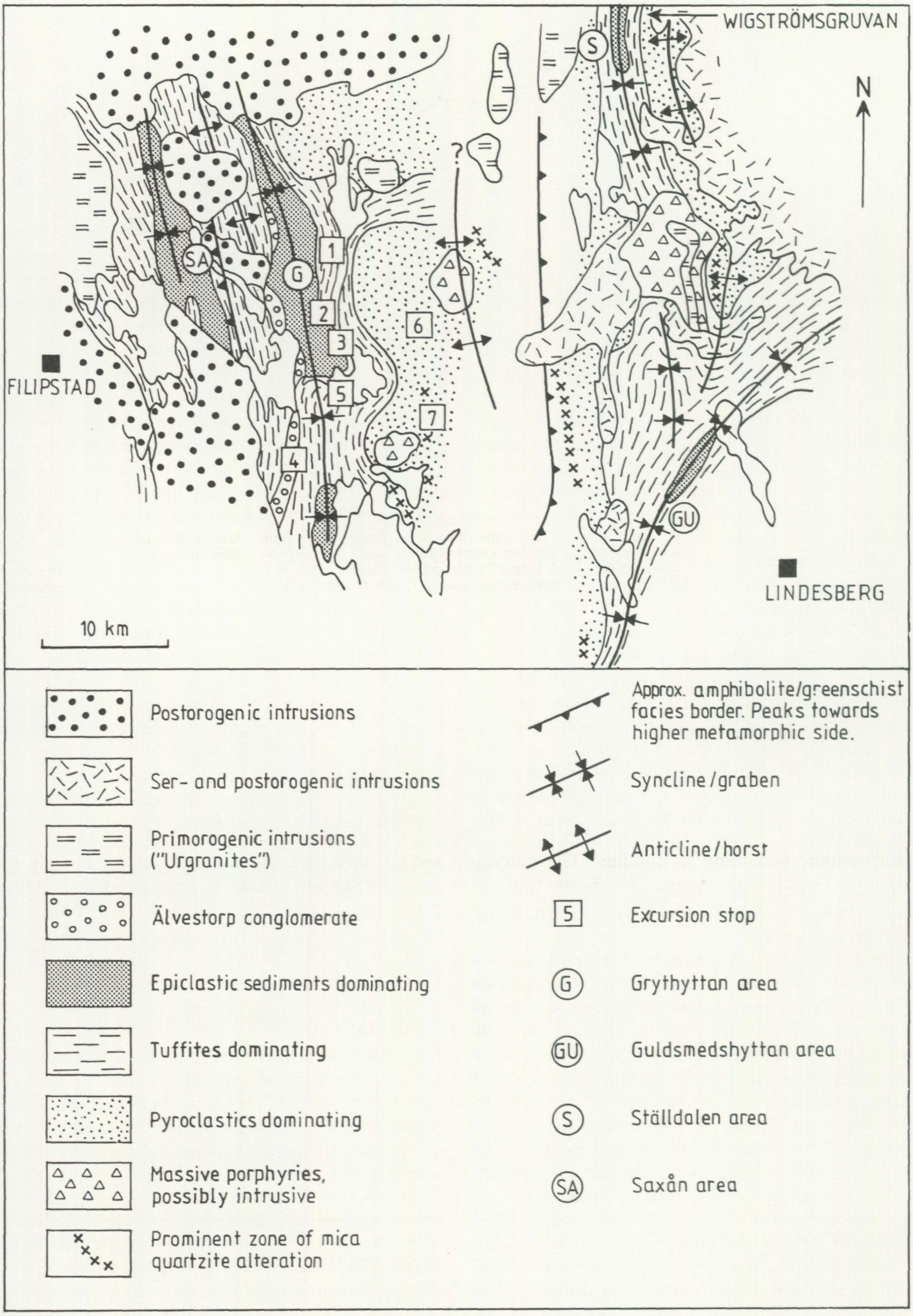


Fig. 21. Geological sketch map of the Filipstad-Lindesberg area. Numbers indicate excursion stops.

TABLE 1

Stratigraphic tables for the Filipstad-Grythyttan-Hjulsjö regions according to Oen *et al.* (1982) and Sundius (1923). Excursion stops on day 6 indicated.

Oen *et al.* (1982)											Sundius (1923)		Excursion stop nr
GEO-CHRONOLOGY		CHRONO-STRATIGRAPHY				LITHOSTRATIGRAPHY							
S V E C O K A R E L I A N P E R I O D	EPOCH OF LATE UPLIFT												
	EPOCH OF YOUNGER GRANITE INTRUSION		Younger Granite Series			Younger Svecokarelian Granite Suite	e.g. Filipstad Granite						
	EPOCH OF EPEIROGENIC SUBSIDENCE REGIONAL METAMORPHISM AND GRANITE INTRUSION	S V E C O K A R E L I A N S Y S T E M	Middle Granite Series			Middle Svecokarelian Granite Suite	e.g. Fellingsbro Granite						
	EPOCH OF SUPRA-CRUSTAL DEVELOP-MENT			Bergslagen Supracrustal Series	Post-rift Stage	Main phase of tectonic compression and regional metamorphism		Hyttsjö Gabbro – Tonalite Suite					
						Metavolcano-sedimentary sequence: Conglomerates					Conglomerate		4
					Rift Stage	Upper Leptite-hälleflinta and Slate Group	Grey Slate Formation	Basic dikes sheets & flows	Granite Grano-phyre Suite		Grey, upper slate Dark, lower slate	The slate division	2
							Black Slate-Tuffite-Siltstone-Greywacke & Upper Leptite-hälle-flinta Formations				Greywacke and slate-hälleflinta rocks		3
												The upper hällefl. div.	1
					Initial Rift Stage	Middle Leptite Group	Acid volcanics, lime-stones, banded pelitic calcareous, siliceous iron formations					The lower hällefl. div.	5
					Early Volcanic Stage	Lower Leptite Group	Predominantly acid volcanics						6, 7

potassic surrounding according to Sundius. The outcrop belongs to the "Upper Leptite-hälleflinta Formation" of Oen *et al.* (1982). This formation is thought to have erupted along fractures related to the rifting.

Stop 2. – Miljongruvan, an abandoned slate quarry 2 km northeast of Grythyttan. The uppermost part of the stratigraphy in all synclines/graben in the Lindesberg-Filipstad area (cf. p. 8) consists of a grey slate or schist. It is dominated by a meta-argillitic composition, but siltstone-like beds also occur. In the Grythyttan area, these rocks mostly have a pronounced slaty cleavage, which earlier made them popular as tiles and paving stones.

Stop 3. – 500–750 m southwest of Brevik, 2 km northeast of Grythyttan. This stop illustrates the transition between the sedimentary and volcanic parts of the stratigraphy. It is situated in the "Black Slate-Tuffite-Siltstone-Greywacke Formation" of Oen *et al.* (1982).

a. *Small outcrops on both sides of the road, 750 m south-southwest of Brevik.* Here, the lowermost unit of the purely sedimentary part of the stratigraphy, namely the "dark slate" of Sundius (1923), is demonstrated. It is finely interbedded with greyish, beautifully current-bedded (and delicately slump-folded?) siltstones.

b. *Outcrops in the forest, southeast of the road 400 m southwest of Brevik.* This stratigraphic level is situated 300 m below that of stop 3a, within Sundius' (1923) "greywacke and slate-hälleflinta rocks", which is characterized by sedimentary reworking of volcanogenic rocks. The same "dark slate" as at 3a can still be seen, but it is here interbedded with more arenitic, greywacke-like and even conglomeratic beds, containing volcanogenic debris, such as hälleflinta fragments. Numerous beautiful sedimentary structures including current bedding, load casts, cut- and fill-structures and clay-galls all indicate younging toward the southwest, i.e. toward the dark slate of stop 3a. According to Sundius (1923), some hälleflinta-like layers on this level show delicate ash textures indicating their tuffitic nature. Although these hälleflinta-like tuffites are difficult to recognize in the field, their existence is important as they form the stratigraphically highest volcanogenic units.

Stop 4. – Outcrops 500 m southwest of Hasselhöjden, west of Älvestorp. The Älvestorp conglomerate, containing pebbles of metavolcanites as well as metasediments. As the metasediment pebbles clearly originate from the sedimentary units of the Grythyttan area, this conglomerate is thought to be essentially younger than the Grey Slate of Grythyttan. As it also tends to cover the folded structures of the underlying formations, it is inferred to be of syn- or post-deformative age.

Stop 5. – Exposures 500 m north of small lake Trolltjärnen, 3 km southeast of Grythyttan. Finely calc-silicate-, carbonate- and iron-chert-laminated red hälleflinta with possible slump folds. Current bedding can also be seen (in loose boulders). This locality is situated immediately underneath the upper boundary of Sundius' "Lower hälleflinta division" and is used to demonstrate the subaqueous nature of the volcanism of the upper part of the stratigraphic column.

Stop 6. – Outcrops and boulders around small cross-roads at Aborrtjärnen, 1 km east of St. Hällsjön. Beautifully preserved, crystal tuffs and volcanic breccias with exotic blocks. Situated approximately on the axis of the anticline/horst separating the Grythyttan and Ställdalen synclines/graben, this locality should represent the deepest levels of the stratigraphy. It is thus situated within the lower parts of Sundius' "Lower hälleflinta division" and most probably belongs to the "Lower Leptite Group" of Oen *et al.* (1982).

A bedding-like structure, simulating cross-bedding, occurs in a small outcrop near the road. However, its origin is obscure, as similar structures appear to develop through metasomatism (cf. next stop).

Stop 7. – Outcrops and boulders 0–500 m east of the road, east of lake Sundsjön. This locality demonstrates a range of Mg-metasomatic alteration patterns from recognizable crystal tuffs, similar to those at stop 6, to feldspar-free, mica quartzites. In its incipient stages, the alteration merely consists of albitization of the plagioclase, while the more advanced stages are characterized by the successive substitution of plagioclase by chlorite, Mg-rich mica and cordierite. Baker & de Groot (1983) have described the development of a similar, nearby zone (cf. p. 14, this volume). Bedding-like structures resembling those at stop 6 are seen as well as "pseudoconglomeratic" structures that are frequently found associated with this type of alteration. The locality is situated within a partly discordant alteration zone which can be traced over an area of approximately 15×4 km.

DAY 7. THE WIGSTRÖM TUNGSTEN DEPOSIT

L.G. Andersson

Geology

The Wigström tungsten deposit is situated in the upper, largely tuffitic part of the leptite formation, close to the overlying epiclastic sediments (Fig. 22). According to Ohlsson (pers. comm.), tungsten deposits are most frequent in this part of the stratigraphic sequence. The host rock is a banded calc-silicate rock. It can be seen unaltered in the thickest part but usually has been almost completely altered to contact-metasomatic skarn. The skarn is a garnet-diopside-scapolite-rock with about 10 % fluorite and 35 % W as scheelite. Minor wollastonite and vesuvianite occurs. A serorogenic Svecokarelian granite some 50 m to the east seems to have formed the deposit by enriching the tungsten that was present in or close to the present strata. According to Ohlsson (1979), this is a common type of genesis for tungsten deposits in Bergslagen.

Hellingwerf and Baker (1985), on the other hand, claim that tungsten deposits are related to the older, primorogenic group of intrusions (cf. Frietsch, this volume p. 15).

Mo-bearing (yellow fluorescence) scheelite as well as Mo-free (bluish white fluorescence) occurs. Also minor molybdenite probably formed when Mo-bearing scheelite was redistributed.

In places, small dykes with scapolite, quartz and minor scheelite cross-cut the deposit.

The ore was found in 1976 by boulder-tracing after regional heavy-mineral geochemistry had drawn attention to the area. Mining started in 1978 and ceased in 1981 after striking a weathered zone in which scheelite-benefication was poor. The ore extracted was some 200 000 metric tons of about 0.35 % W.

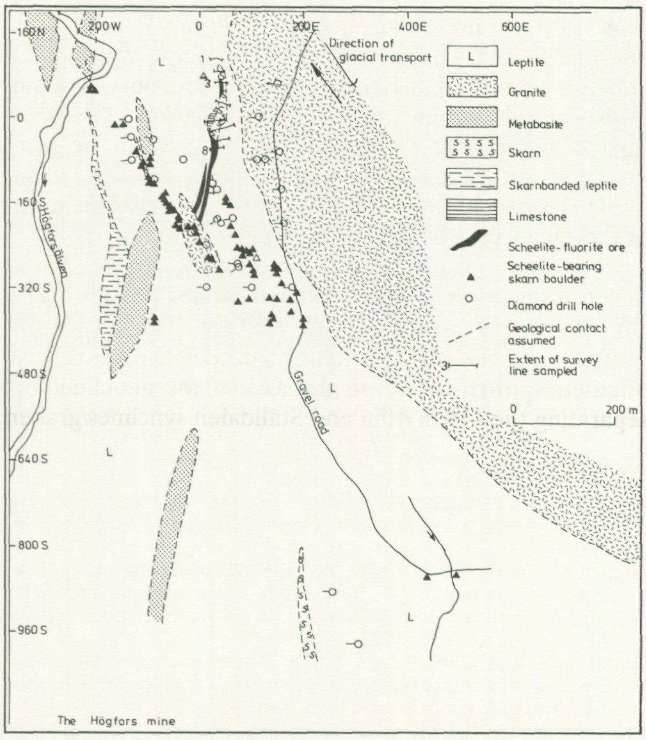


Fig. 22. Geological sketch map of the area surrounding the Wigström tungsten deposit.

STOP DESCRIPTIONS

Stop 1. – Unaltered banded carbonate showing the detailed stratigraphy of the original calc-silicates.

Stop 2. – Skarn in prolongation of ore-zone with minor scheelite-mineralization. Contact is irregular due to reaction between carbonate and sediments.

Stop 3. – Metasediments in the hanging wall of the deposit showing the mixed composition of the countryrock (clastites and pyroclastites).

Stop 4. – "Malingsbo" granite (serorogenic granite), most likely the source of the mineralization.

Stop 5. – Scapolite bearing pegmatitic dyke with scheelite, fluorite and sulphides. The dyke is an offshoot from the "Malingsbo granite". It cross-cuts the deposit.

Stop 6. – Hydrothermally kaolinite-weathered skarn, still with original tungsten content.

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