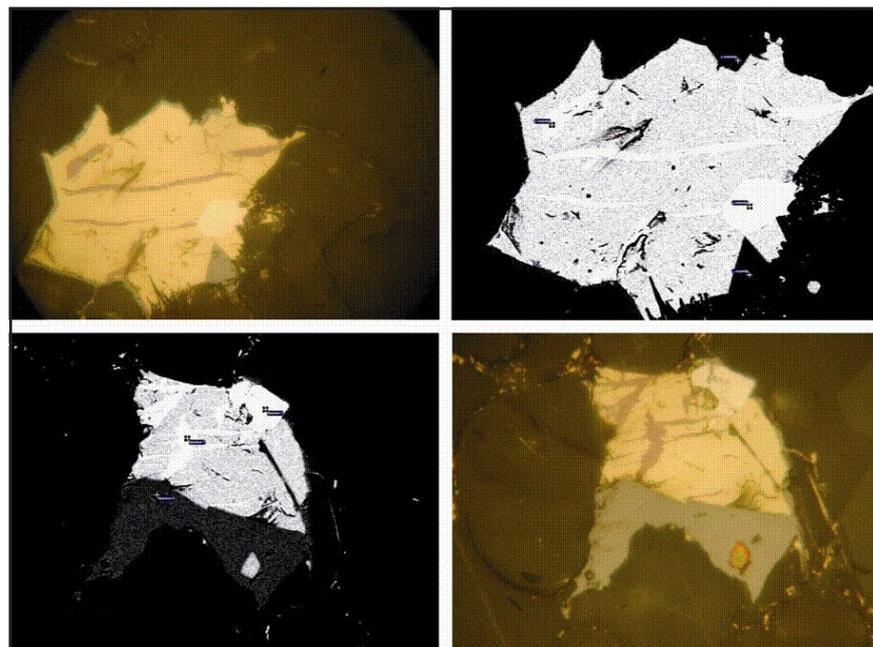


The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study

Christine Andersen

Examensarbete i geologi vid Lunds Universitet -
Berggrundsgeologi, no. 249
(15 hskp/ECTS)



Geologiska institutionen
Centrum för GeoBiosfärsvetenskap
Lunds universitet
2009

**The mineral composition of
the Burkland Cu-sulphide deposit
at Zinkgruvan, Sweden –
a supplementary study**

Bachelor Thesis
Christine Andersen

Department of Geology
Lund University
2009

Contents

1 Introduction & Aim	5
2 Background	5
2.1 The Zinkgruvan Mine	5
2.2 Regional Geology	6
2.3 Local Geology	7
2.4 Geology of the Zinkgruvan deposit	8
3 Methods.....	8
3.1 Sample selection	8
3.2 Reflected light microscopy	9
3.3 Scanning Electron Microscopy	9
4 Results	10
4.1 The mineralization & The drillcore	10
4.2 The opaque phases	10
4.2.1 Major ore phase	11
4.2.2 Common ore phases	12
4.2.3 Minor ore phases	20
4.2.4 Rare minerals	22
4.2.5 Silver & Silver bearing phases	24
4.3 Problematic elements	26
4.4 Mineral distribution	26
4.5 Chemical variation	28
5 Discussion	29
6 Conclusions.....	31
Acknowledgements	31
References.....	32
Appendix.....	34

Cover Picture: Chalcopyrite aggregates with pink bornite, grey magnetite, white breithauptite and gudmundite. Optical microscope and SEM- photographs (93m/7.1 and 7.2).

Abstract

CHRISTINE ANDERSEN

Andersen, C., 2009: The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study. *Examensarbeten i geologi vid Lunds universitet*, Nr. 24x, 41 pp. 15 ECTS credits.

Abstract: The Zinkgruvan Mining AB, situated in south-central Sweden in Örebro County, south-east of Ämmeberg, plans to expand their production on a massive, carbonate hosted copper-sulphide ore deposit, the Burkland Cu-mineralization in the eastern part of Knalla. At present mainly Zn-Pb-Ag are mined.

The deformed Cu-mineralization belongs to the south-western Bergslagen ore province. It is of Paleoproterozoic age, hosted by supracrustal, metavolcanic- and metasedimentary rocks, mainly serpentine- and dolomitic marble as well as skarn. Hydrothermal ore forming processes are suggested for the formation of the Zinkgruvan deposit. It is described as a Volcanic Massive Sulphide (VMS) and a volcanic SEDimentary EXhalative (SEDEX) type.

In order to judge the economic value of the Cu-ore deposit, the mineralogy and possible variation in chemical composition of the opaque minerals as well as the mineral distribution have been investigated. Also the distribution of problematic elements such as Sb, As, Hg and Bi were studied. These can lead to fines during the processing of Cu-ore. Ten thin sections from the most ore rich 18m section of the drillcore DBH2992 have been analysed under a reflected light and in a scanning electron microscope. This study is a complement to the master thesis of Bjärnborg (2009) on the same topic to test and strengthen her findings through extra samples and analysis.

The major ore mineral found in this study is chalcopyrite (CuFeS_2), mostly occurring in aggregates. Other common ore minerals are sphalerite, pentlandite and magnetite both in aggregates and as disseminated grains. Cubanite is often found intimately intergrown as lamellea in chalcopyrite or as almost massive grains. Minor ore minerals found are breithauptite, cobaltite and pyrrhotite/mackinawite. The latter two minerals could not definitely be discriminated. The problematic elements Sb and As are found in nine different minerals. None of the major or common ore phases contain Sb or As. The Sb carrying minor ore phase breithauptite (NiSb) occurs in all but one sample. Most of the Sb or As is contained in rare minerals that are found in samples poor in ore. No Hg or Bi is found during this study. The occurrence of Ag is linked to an extensive red to purple-blue tarnish of chalcopyrite. However, tarnishing is common also when no Ag is present.

No distinct mineral zoning throughout the studied section is observed. With increasing ore grade, the number of different ore minerals is stable or even decreased. The host rock composition influences the ore grade: Skarn seems to contain the highest quantities of ore minerals. No major variation in chemistry is found in most opaque minerals. Exceptions are pentlandite with varying amounts of (Fe,Co,Ni), sphalerite (a low-Fe and a high-Fe type) and safflorite with a Co-rich and a Fe-riche type.

Keywords: Zinkgruvan, Bergslagen, Ämmeberg-deposit, Burkland Cu-mineralisation, chalcopyrite, hydrothermal-copper sulphide, VMS, SEDEX copper sulphide, VMS, SEDEX

Christine Andersen, Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund. andersen.chrisine.s@gmail.com

Sammanfattning

CHRISTINE ANDERSEN

Andersen, C., 2009: Mineralsammansättningen av Burkland- kopparsulfidmalmen i Zinkgruvan, Sverige – en kompletterande studie. *Examensarbeten i geologi vid Lunds universitet*, Nr. 24x, 41 sid. 15 hskp.

Sammanfattning: Zinkgruvan Mining AB som ligger i Närke i syd-mellersta Sverige, sydöst om Åmmeberg, planerar att utöka produktionen med en massiv kopparmineralisering som ligger i en karbonatsten. Den kallas för Burkland-kopparmineraliseringen och ligger i östra Knallagruvan. Idag bryter företaget mest zink, bly och silver.

Den paleoproterozoiska kopparmineraliseringen tillhör sydvästra Bergslagens malmprovins. Malmkroppen är deformerad och finns i suprakrustala, metavulkaniska- och metasedimentära bergarter, huvudsakligen i kalcit/serpentin- och dolomitisk marmor och i skarn. Zinkgruvanförekomsten anses ha bildats genom hydrotermala malmbildande processer: den har beskrivits som Vulkanisk Massiv Sulfid (VMS) och vulkanisk SEDimentär EXhalatitiv (SEDEX) typ.

För att kunna bedöma kopparmalmens ekonomiska värde, har mineralsammansättningen, möjliga kemiska variationer i de opaka mineralen och deras fördelning undersökts. Även uppträdandet av problematiska elementer som Sb, As, Hg och Bi har bestämts. Dessa kan leda till straffavgifter i kopparmalmsmältningen. Tio tunnslip ur den 18m långa malmrikaste delen av borrhölen DBH2992 har analyserats med reflexionsljus och scanningelektronmikroskopi. Studien utgör komplettering till Bjärnberg's (2009) Masteruppsats i samma ämne och ska testa och styrka hennes resultat med extra prov och analyser.

Det dominerande malmmineralet som har hittats i studien är kopparkis (CuFeS_2), vilket oftast uppträder i aggregat. Andra vanliga malmmineral är zinkblände, pentlandit och magnetit, både i aggregat och som enstaka korn i moderbergarten. Kubanit hittas ofta som lameller i kopparkis men även som nästan massiva korn. Mindre ofta förekommande malmmineral är breithauptit, kobaltit och magnetkis/mackinawit. De sista två kunde inte helt säkert särskiljas. De problematiska elementen Sb och As har hittats i nio olika mineral. Inget av de dominerande eller vanliga malmmineralen innehåller Sb eller As. Den Sb-förande mindre malmfasen breithauptit (NiSb) återfinns i alla utom ett prov. Sb eller As finns mest i accessoriska mineral i malmfattiga tunnslip. Inget Hg eller Bi har upptäckts. Förekomsten av silver kan relateras till en intensiv röd till lila-blå oxidation av kopparkisen. Oxidationen förekommer dock även utan silverassociation.

Ingen tydlig mineralzonering har observerats i det undersökta avsnittet. När malmhalten ökar, förblir antalet olika opaka mineral konstant eller t.o.m. minskar. Det finns en korrelation mellan typ av sidoberg och malmhalt: Skarn verkar innehålla den största mängden malmmineral. Ingen stor variation i kemin har hittats i de flesta av de opaka mineralen. Undantag är pentlandit med varierande mängder (Fe,Co,Ni), zinkblände (en järnfattig och en järnrik variant) och safflorit med en koboltrik och en järnrik variant.

Nyckelord: Zinkgruvan, Bergslagen, Åmmeberg-malmförekomst, Burkland kopparmineralisering, kopparkis, hydrotermal kopparsulfid, VMS, SEDEX

Christine Andersen, Geologiska Institutionen, Centrum för GeoBiosfärsvetenskap, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. andersen.christine.s@gamil.com

1 Introduction & Aim

Zinkgruvan is a mining company (*Zinkgruvan Mining AB - ZMAB*) and an associated small township in south-central Sweden. The Zn-Pb-Ag-Cu ore deposit is located in the Province of Närke/Örebro County, south-east of Askersund and Åmmeberg (Fig. 1).

Since 1857, the main stratiform Zn-Pb-(Ag) deposit of *Zinkgruvan* has been exploited continuously. With zinc and lead as the main products, sphalerite and galena are the most important ore minerals. Also minor amounts of economical feasible silver are mined (Malmström et al., 2009). The company aims to expand their production on a massive Cu-sulphide orebody, the *Burkland Cu-mineralization*. This is planned for the coming year 2010 (personal communication with Malmström, L. 2009).

Geologically the Precambrian *Zinkgruvan*-deposit belongs to the south-western Bergslagen ore province. The Cu-mineralization is hosted by supracrustal, metavolcanic and metasedimentary rocks of Paleoproterozoic age, mainly serpentine- and dolomitic marble as well as skarn. Structurally the Bergslagen district is part of an extensional continental rift setting (Hedström et al., 1989).

The aim of this study is to investigate the character of the *Burkland Cu-mineralization* of *Zinkgruvan*. Focus of this study is the mineral and chemical composition of the ore body as well as the distribution of problematic elements. If the end Co-product contains more than certain levels of elements, such as Sb and As (Hg and Bi), that can contaminate the soil and are poisonous to humans) fines apply to the company. In particular the following questions were set up:

- Which are the interesting ore phases and mineral assemblages in the Cu-mineralization and how are they distributed?
- Which phases, containing the problematic elements As, Bi, Sb and Hg, are found and how are they distributed?
- What is the chemical composition and variation of the minerals?

This study complements the master thesis of Bjärnberg (2009) on the same topic. Through extra samples and analysis, her findings shall be tested and strengthened.

2 Background

2.1 The *Zinkgruvan* Mine

The *Zinkgruvan-Åmmeberg* ore deposit has at least been known since the 16th century (Hedström et al., 1989; Henrigues, 1964; Malmström et al., 2009). From a historical mine north of the current industry, the earliest known, small-scale production is reported from around 1700. This mining company made no profit and was shut down in 1845. ZMAB was originally owned and driven by the *Vieille Montagne Company* of Belgium. The company started large-scale mining activity in 1857. Before it was acquired by *RioTinto* in 2000, the mine went into the ownership of an Australian company (*North Limited*) in 1995. Nine years later, in 2004, it went into the possession of ZMAB, a part of *Lundin Mining Co*, Canada (Malmström et al., 2009).

The *Zinkgruvan* deposit is divided by a large fault into a deposit named *Knalla* in the west and *Nygruvan* in the east (Fig. 1 and 2) (Hedström et al., 1989; Malmström et al., 2009). Apart from the Zn-Pb-(Ag) deposit, a stockwork Cu-mineralization was discovered during 1996/97. It is situated in the hanging wall of the Zn-Pb deposit at *Burkland*, in the eastern part of *Knalla* (Fig. 1 and 5) (Malmström et al., 2009).

Between 1976 and 2008 the annual production rates of the mine increased with a factor of 3. From around 300 000t ore per year in the end of 1976, production increased during six years to the double of ~600 000t in 1982. In 2008 an annual production of approximately 900 000t ore was achieved (Malmström et al., 2009). In 2007, *Lundin Mining Co* (2007) stated that ore production at *Zinkgruvan* is planned to increase by 33% to 1.2Mt per year by 2010. In the technical report of *Zinkgruvan* by Malmström et al. (2009) is stated that the known mineral reserves will approximately last for ten more years at present production rates. The mine life might further be extended when the present ore recourses were converted to reserves.

The *Burkland Cu*-deposit contains a probable mineral resource of 2.9Mt. The directly indicated resource is 0.46Mt, the inferred one 0.55Mt. Compare these estimates with the metal production in Sweden and in the EU (table 1). The ore grades of the *Burkland Cu-mineralisation* are: 2.6% - 3.0%, Zn: 0.1% - 0.5% and Ag: 28g/t - 42g/t (Malmström et al., 2009). The global Cu-resource is estimated to approximately 480Mt with Chile being the leading Cu-producing country (SGU, 2003).

t	Year	EU	Sweden
Cu	1999	740 600	71 200
	2008	714 800	57 700
Zn	1999	750 200	174 400
	2008	823 000	172 200
Pb	1999	314 000	116 400
	2008	193 200	63 500
Ag	1999	1 660	342
	2008	1 721	293

Table 1.

Estimates of the total metal production in Sweden and the 27 major ore producing EU-countries in tonnes of the years 1999 and 2008. (SGU, 2009)

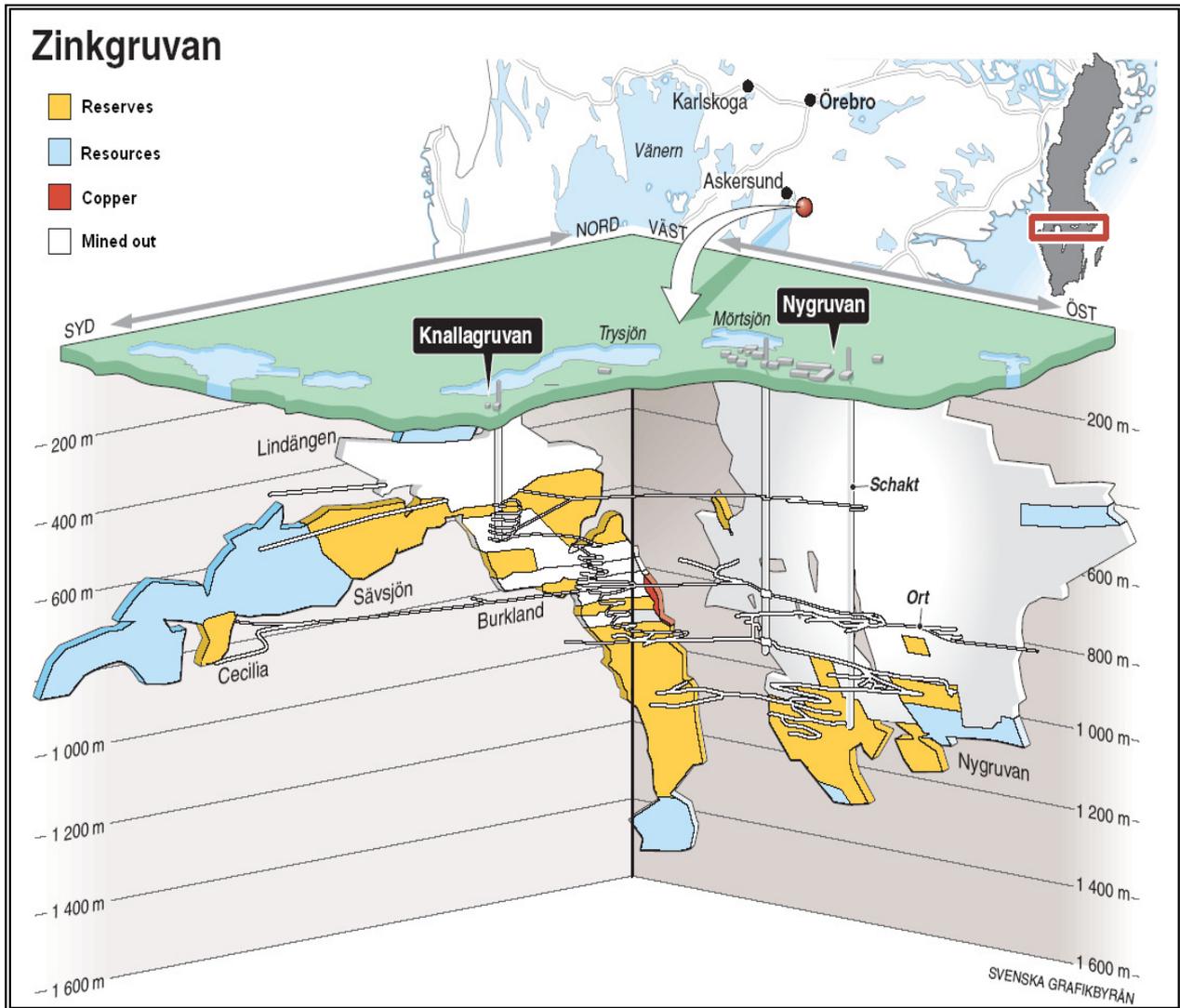


Fig. 1. Location and schematic model of the Zinkgruvan Mine (Malmström, et al. 2009)

2.2 Regional geology

Geologically, the area of Zinkgruvan belongs to the south-western Bergslagen region. The Bergslagen ore province, known for its numerous Precambrian ore deposits, consists of supracrustal and plutonic rocks (Hedström et al., 1989). Bergslagen formed during the Palaeoproterozoic period as part of the Svecofennian domain. The latter is part of the Fennoscandian Shield which includes Sweden, Finland as well as parts of eastern Norway and western Russia (Lehtinen et al., 2005; Weihed et al., 2005). The dynamics of the formation of the Svecofennian Shield are still controversial. A short summary of a model by (Lehtinen et al., 2005) is presented: sediments (limestone) and felsic volcanics (rhyolite and dacite) were deposited at ~1.89Ga on an unknown Archean basement. After that they were depressed to a depth of about 20km. During the following ~200Ma of the Svecofennian Orogeny the rock masses were lifted back to surface until granitoids intruded at a depth of ~5km.

The Svecofennian felsic volcanism took place under extensional rifting conditions in a continental arc basin. The following subsidence and sedimentation lead to a rock sequence of sediments that overlay volcanics on an unknown basement (De Groot and Baker, 1992; Malmström et al., 2009; Weihed et al., 2005). Many supracrustal rocks of southern Bergslagen have experienced low-pressure/high-temperature metamorphism (greenstone-amphibolite facies), they show signs of deformation and hydrothermal alteration. (De Groot and Baker, 1992; Lindström et al., 2000; Malmström et al., 2009). The rocks were transformed into meta-sediments and metavolcanics (Fig. 2), the latter are often referred to as leptite. Today the term leptite describes fine-grained, felsic to intermediate, supracrustal rocks that probably have a volcanic origin.

For more details on the Zinkgruvan district in context of the Svecofennian Orogeny and the ores of Bergslagen, also see Bjärnberg (2009).

2.3 Local geology

The Bergslagen sulphide deposits can be divided into the *Falun* and *Åmmeberg* types. The Åmmeberg type is characteristically stratiform. (Hedström et al., 1989; Lindström et al., 2000; Sundblad, 1993). The Zinkgruvan deposit is an example of the Åmmeberg type (Hedström et al., 1989; Henrigues, 1964; Magnusson, 1973).

Through repeated deformation events, the ore body was forced into a synclinal fold structure (Fig. 1 and 2) that strikes east-west and dips towards the north (Hedström et al., 1989; Malmström et al., 2009). Deformation terminated prior to low-pressure/high-temperature metamorphism, of the greenschist-amphibolite facies. This also involved migmatization and partial melting (Malmström et al., 2009).

Three major stratigraphic groups are distinguished between the supracrustal rocks in the Zinkgruvan area (Fig. 3): *Metasediments* at the highest level have undergone strong deformation. Veined, partly migmatized gneiss belongs to this group. Felsic, red, fine grained *metavolcanics*, which partly are classified as ignimbrite are found at the lowest level. The *metavolcanic-sedimentary group* is found in between the other two groups. This group consists of layers of calcisilicate rock (marble and quartzite) and sulphide ores, intercalated with layers of metasediment (mixed tuffaceous and chemical precipitated) (Hedström et al., 1989; Malmström et al., 2009).

Which ore forming processes that lead to the formation of the Zinkgruvan deposit is still discussed. It seems to be certain that hydrothermal processes were involved. These are the most common processes that have lead to the deposition of sulphide ores (Wenk

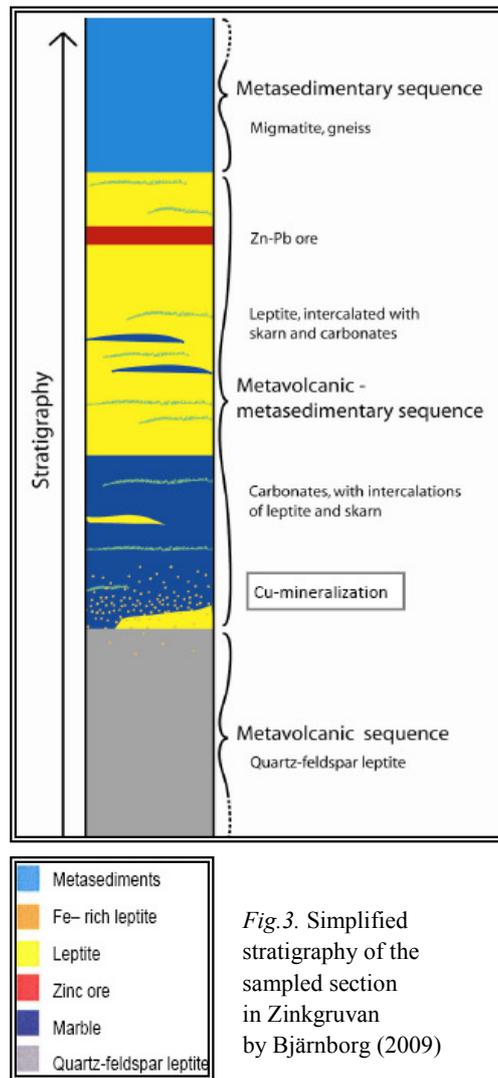


Fig. 3. Simplified stratigraphy of the sampled section in Zinkgruvan by Bjärnberg (2009)

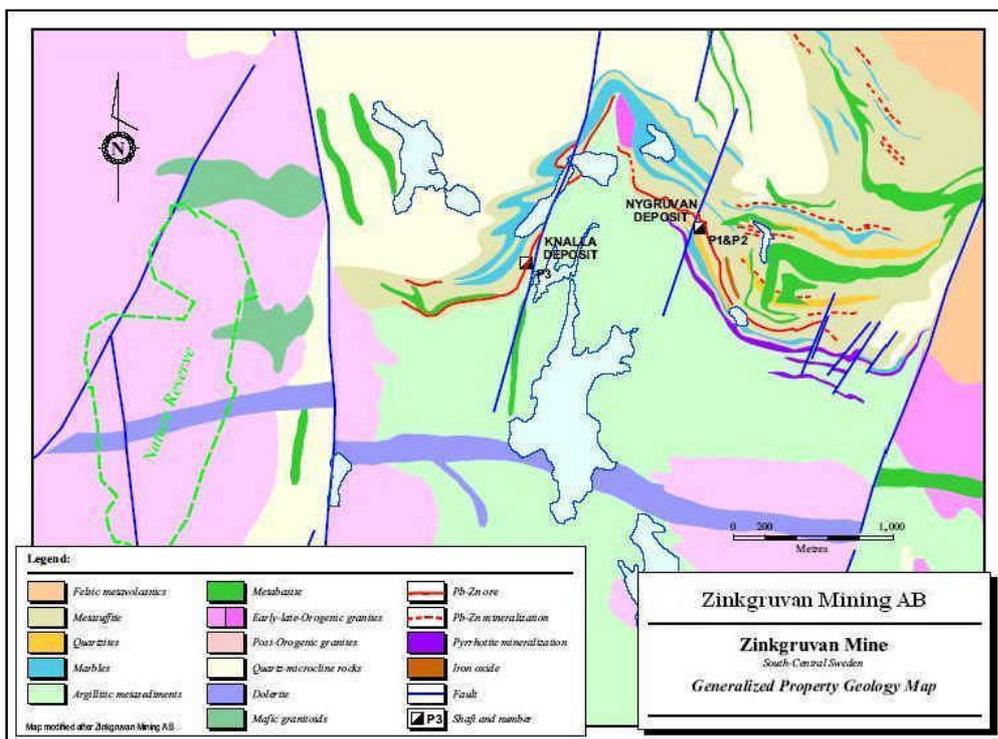


Fig. 2. Map of the regional geology in the Zinkgruvan area (Malmström et al. 2009)

and Bulakh, 2004). Critical for the formation of hydrothermal deposits is the mode of fluid flow (Cathles and Adams, 2005; Evans, 1993). Both a Volcanic Massive Sulphide (VMS) deposit and a volcanic SE-Dimentary EXhalative (SEDEX) deposit type is suggested for the Zinkgruvan deposit (Annels et al., 1994; Malmström et al., 2009). Hedström et al., (1989) classified the Zinkgruvan deposit as a stratiform syngenic ore which formed simultaneously to the host rocks. That is in contrast to epigenetic ores, that form later than the host rock, as described in Evans (1993). A volcanic SEDEX origin is suggested by Hedström et al., (1989) and Billström, (1991). The model describes hydrothermal brine fluids, which circulate through the sedimentary-volcanic unit and precipitate carbonates, sulphides and magnetite distal to the volcanic vent. Walters, (1998) classified the Zinkgruvan mineralization as a Broken Hill type deposit, which is defined as a Proterozoic Zn-Pb-Ag SEDEX with distinct mineral zoning. The massive Burkland Cu-sulphide mineralization might be classified as a distal Volcanic Massive Sulphide (VMS) deposit. There, metal rich hydrothermal fluids ascended through a vent system and sulphides were deposited on the seafloor (Galley, 1993; Malmström et al., 2009).

2.4 Geology of the Zinkgruvan deposit

Brittle fracturing in the Åmmeberg area have produced the NNE striking Knalla fault system that divides the Zinkgruvan deposit into its two main parts: Knalla and Nygruvan. The synclinal fold structure is overturned; the stratigraphic footwall becomes the structural hanging wall (Hedström et al., 1989; Malmström et al., 2009).

The Zn-Pb-(Ag) deposit at Nygruvan has until recently been the most actively exploited section of the mine. It is located to the east of the fracture zone and forms tabular-shaped, 5-25m thick lenses. It is situated in the upper part of the metavolcanic-sedimentary group. The NW-SE striking ore horizon, is about 5km long and dips 60-80° to the NE (Fig. 1). The deposit reaches depths up to at least 1200m; on the surface outcrops of ore are found. (Malmström et al., 2009).

The more heterogeneous Knalla deposit is located in the western section of the mine and strikes NE-SW (Fig. 1). The NW dip varies from near vertical to sub-horizontal. The Knalla mine consists of several Zn-Pb ore bodies of variable, 3-40m, thickness. Extensive, partly isoclinal folding can be observed (Fig. 1 and 5) (Hedström et al., 1989; Malmström et al., 2009).

A Cu- mineralization (Burkland Cu-mineralization) with chalcopyrite as its major ore phase, has been identified in the structural hanging wall of the Sävsjön-Burkland orebody in the eastern part of Knalla (Fig. 1 and 5). It is hosted by serpentine-calcite and dolomitic marble as well as skarn. It is found at a depth between 600 and 1500m. Its thickness varies between 5 and 60m, the length between 100 and 180m. In its upper part, the Cu- zone dips steeply NW with about 80° and flattens out at depth to about 45°. In the NE It is cut off by the Knalla fault (Malmström et al., 2009).

3 Methods

3.1 Sample selection

Ten samples from the drillcore DBH 2992 (Bu 800 sk3Ö) at the 800m level at Burkland (Fig. 4) in the eastern part of Knalla (Fig. 1 and 4) were examined. The diameter of the drillcore is 60mm. Drilling started at a depth of 629m from the structural hanging wall, directed in an approximately westerly direction. As the stratigraphy at Knalla is partly overturned the structural hanging wall is the stratigraphical foot wall at this part of the deposit. With a dip of ~10° the core was almost drilled horizontal. The drillcore cuts the Cu-mineralization between 709 and 713m below ground level (Björnberg, 2009).

The samples originate from a ~18m section between 91.80 and 109.71m of the drillcore. Further all samples

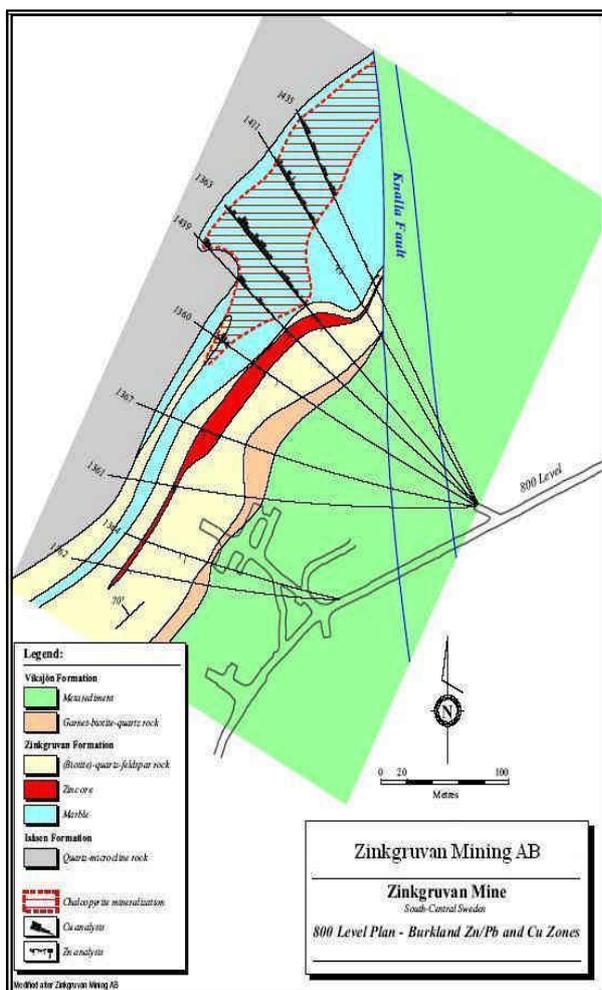


Fig. 4 (to the left). Burkland 800-level plan. Area of red lines in the NW: Cu-ore; Massive red area: Zn-Pb ore; green: metavolcanics; blue: marble. (Malmström, et al. 2009)

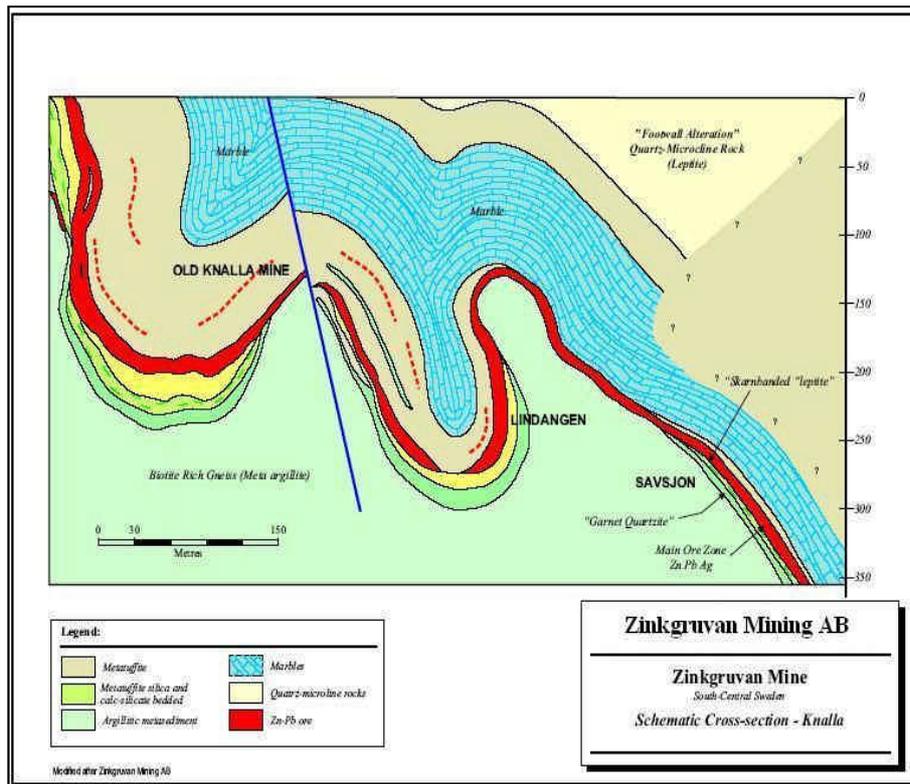


Fig. 5. Schematic cross section Knalla (Malmström, et al. 2009).

will be referenced by their location in the drillcore (e.g. 91m, the exact position can be seen in Fig. 6). This is only a reference to the position in the drillcore and shall not be mistaken for the depth. Spectra obtained during chemical analysis will be specified with a suffix (e.g. 91m/2). The sampled section corresponds to the most ore rich part of the mineralization. Sampling has been performed by Bjärnberg (2009) for her Master thesis. There the number of samples was judged too large and had to be decreased. The ten samples of this study originate from the middle of the interval investigated by Bjärnberg (2009) and shall be a supplement to that study. Sampling was performed with two meters equal distance in between. The ten polished thin sections of about 2 x 3cm (Fig. 6) were prepared by Gerald Berthold at the Institute of Geosciences/University of Halle, Germany.

3.2 Reflected light microscopy

The opaque minerals and mineral assemblages of each thin section were determined using a "Nikon Eclipse E400 POL" optical microscope. The opaque ore phases were analysed in air, under reflected light with objectives of 5, 10 and 50x magnification.

Properties such as colour, reflectivity, bireflectance, anisotropy, texture and hardness were studied in order to determine the different ore minerals. Colour (in air instead of in oil) and colour contrasts were used to distinguish different ore phases. The light reflectivity (here noted as low, medium or high) of the minerals was also studied. Bireflectance, an optical effect of

changing colours which can be observed in opaque minerals under plane polarized light when the sample is rotated, similar to pleochroism and anisotropy, observed under cross polars also help to identify ore minerals. Even properties as texture, internal reflections and hardness are useful to distinguish different ore phases. The relative hardness between adjacent mineral grains can be determined from a pseudo-Beckel-line, called the Kalb-line. Another common tool for the discrimination of different ore phases is to study mineral associations and possible intergrowth as these can be characteristic for certain minerals. (Ineson, 1989). Determination tables for ore microscopy (Ineson, 1989; Schouten, 1962) were used to identify the opaque minerals as well as the online databases webmineral.com and mindat.org.

3.3 Scanning Electron Microscopy

More detailed mineralogical and chemical composition was obtained with a scanning electron microscope (SEM) fitted with an Oxford Instruments (INCA Suit version 4.06) Energy Dispersive System (EDS). The SEM is a HITACHI S-3400N Instrument at the Department of Geology, Lund University. An acceleration voltage of 17,5kV was applied. Images were mainly obtained using a four-element solid-state backscatter detector. Intergrowth structures were analysed through element mapping of larger areas. Analyses were normally performed in point mode. As INCA Quant Optimisation, native cobalt was used. Both natural and synthetic element standards were used dur-

ing spectra acquisition. Prior to SEM- analysis the samples were coated with coal (Cressington Carbon-Coater108,Carbon/A).

The presentation of data with total sums of more than 3% deviation from 100% (weight %) has been avoided. Poor total sums can be the result of the exclusion of traces of elements that should not appear in a respective mineral. Even if the spot size is very small, interactions between the electron beam and the target material involve an area with a diameter of approximately 3µm. This means that neighbouring crystals might influence the analyses of very small grains. In a few cases, where no other data was available, data with poor total sums were kept. For some phases as e.g. molybdenite, magnetite and native silver, no suitable INCA-standard was available. Also amounts of oxygen appear seemingly random in phases they do not belong. In these cases the total sums often exceeded 100%. This is probably due to a software error (non-compensated sulphur escape peak).

4 Results

4.1 The mineralization & The drillcore

The drillcore investigated in this study (DBH 2992, Bu 800 sk3Ö/800m) consists of alternating bands of following rocks of the metasedimentary-volcanic unit: fine to medium grained calcite-serpentine and dolomitic marble along with varying degrees of serpentine-diopside skarn. Towards the lower section leptite bands occur. Occasionally the rock shows gneissic structures and signs of shearing (Fig. 7).

Two end member types of marble are distinguished: a dolomite rich and a calcite rich marble (Fig. 6). All sorts of intermediate grades can of course be found. The dominating carbonate is difficult to determine by the naked eye and in routine microscopy work. The dolomite rich marble consists of a dolomitic ground-mass containing minor amounts of calcite and serpentine. It has a light grey colour with a grain size of around 5mm. The calcite rich marble has smaller-sized grains (1-2mm) and a patchy black and white look. Here the dominating carbonates are serpentine and calcite (Björnberg, 2009).

In the almost 18m long section of the core (91-109m), which was sampled for this study, varying degrees of skarn alternate with dolomite and serpentine marble (Fig. 7). Leptite does not occur in this part. The sampled section (91-109m) begins with calcite marble that soon changes into dolomite rich marble (at 93m). At 97m a transition back to a ~3m wide zone of the calcite rich type can be observed. In the middle a ~2m wide skarn section is found (between ~100m and 102m). Between 102 and 107m, the calcite rich marble dominates. On the last three meters (107- 110m) an ~1m wide skarn horizon (at 109m) is embedded between dolomite at the beginning and calcite-rich marble at the end. Signs of shearing and a gneissic structure is seen in these last three meters.

The samples were chosen in the mineral richest zone of the core. In this section most ore is roughly found the middle (97 – 101m) of the sampled section. Here the ore aggregates appear with ~50% ore minerals, close to massive (Fig. 6). This is confirmed by optical microscopy and SEM analysis. Chalcopyrite aggregates that show a metallic lustre and a characteristic yellow/golden colour can be seen in a matrix of marble or skarn.

4.2 The opaque phases

When thin sections are studied under a reflected light microscope, it is possible to determine mineral phases, which are difficult to identify with drillcore logging. EDS spot analysis of single mineral grains and aggregates in the SEM give even more information: data about the chemical composition allow the identification of minerals with high precision and the possibility to observe possible variations in their chemistry.

In the following sections, all ore phases found in the analysed samples are described in detail. A classification is done, as usual in ore geology, in following four groups: Major, common and minor ore phases as well

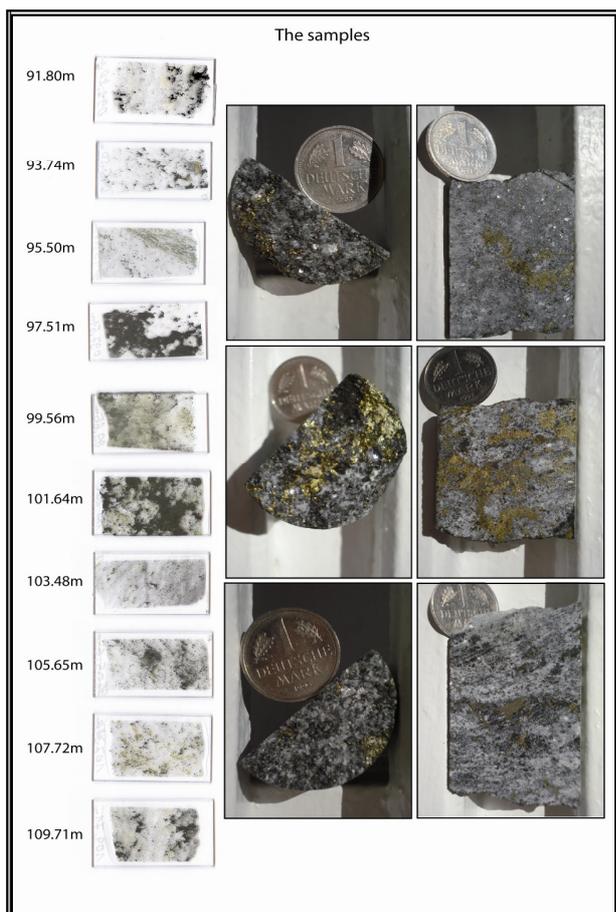


Fig. 6. The ten thin sections (2 x 3 cm) and parts of the drillcore DBH2992. From the top: 91m, dolomite rich marble, 101m, Skarn and 105m calcite rich marble.

as rare minerals. Major ore phases are the most important and main ore minerals, found in all samples in large quantities. Common and minor ore minerals are found in most samples, minor phases often only in small amounts. Ore minerals that are found more irregularly, often only in a few samples, are listed as rare minerals.

Twenty different opaque phases could be identified and confirmed with chemical analyses: one major, four common and four minor ore phases along with eleven rare minerals, five of which only occurred once.

Mean chemical compositions and large variations are presented in the following section for more detailed data, see appendix. All chemical data in the following section are given in atomic %.

As it is difficult to achieve a quantitative estimate of the different ore phases in the samples, the classification into the described groups, merely gives a hint on the quantitative relations of the existing opaque minerals. The order, in which the minerals are listed in the different groups can approximately be taken as quantitative. When extrapolated, this gives an idea of the estimated quantities of the ore phases in the whole Cu-mineralization.

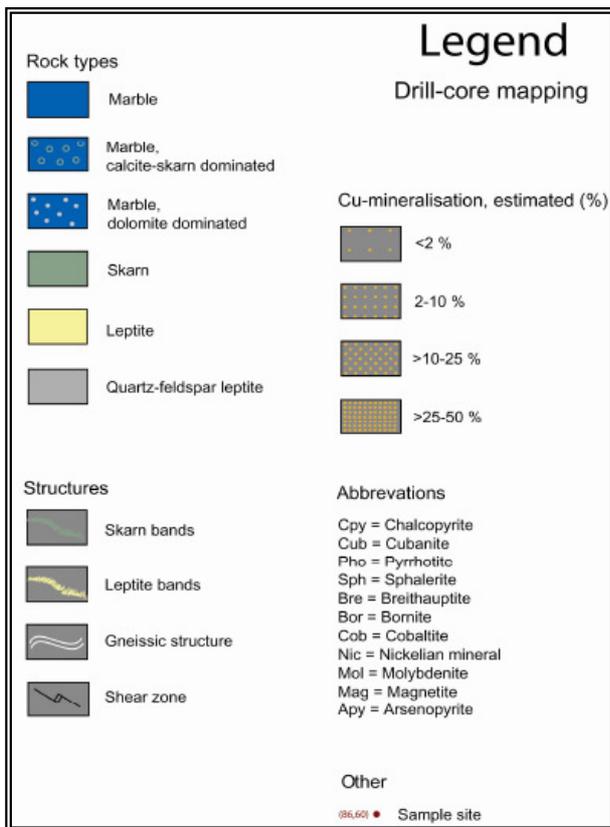


Fig. 7. Part of the mapping log of the drillcore DBH2992 by Bjärnberg, 2009. The samples 91.80 - 109.71m of this study lie between the red marked sites.

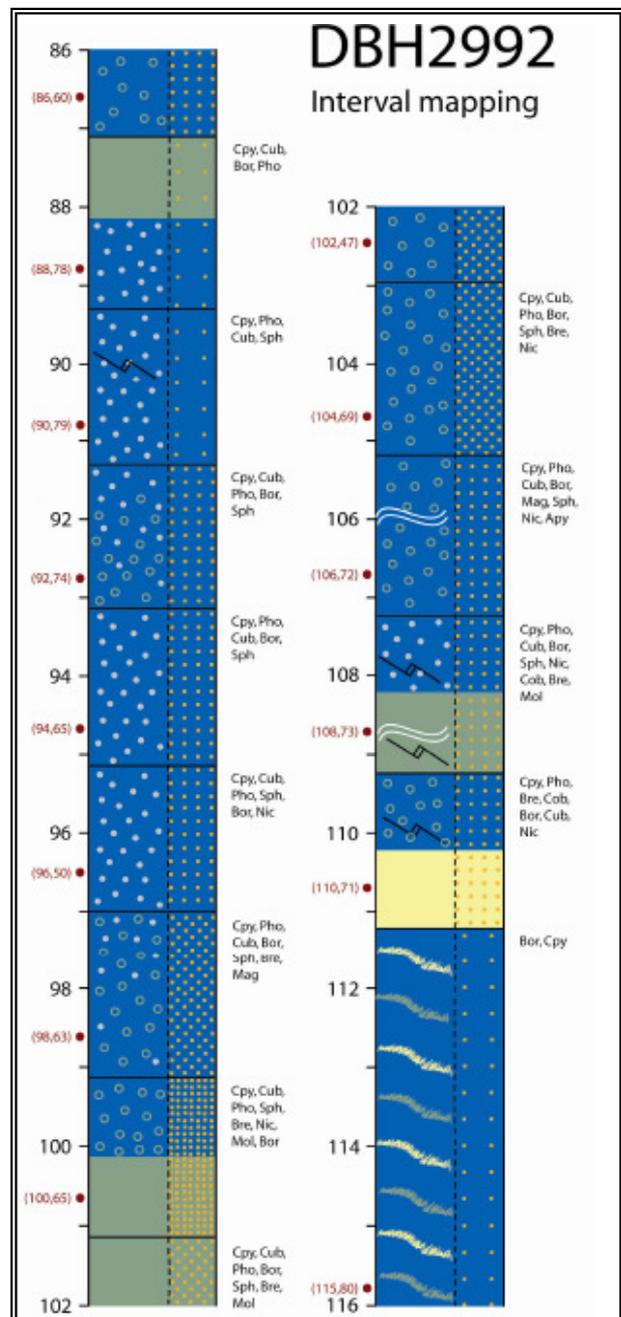
4.2.1 Major ore phase

Chalcopyrite - $CuFeS_2$

The Cu-sulphide, chalcopyrite, is according to quantity and frequency, undoubtedly the major ore mineral in the studied thin sections from the Cu-mineralization at Zinkgruvan. It is found in every sample and one of the few ore phases, which is easily identified by the naked eye in the drillcore as well as in the thin sections. It has a characteristic gold/yellowish colour (Fig. 6, 8 and 10).

Texture & Mineral associations

Chalcopyrite has a great range of grain sizes: grains appear from less than $5\mu m$ as an emulsion in sphalerite (Fig. 10III). A common size of between 100 and $500\mu m$ for single chalcopyrite grains agrees with the study by Bjärnberg (2009). Grains of chalcopyrite mostly appear



in irregular shapes with rounded, smooth edges (e.g. Fig. 8 and 10). In aggregates and intergrowth-structures, grain shapes can be less rounded (Fig. 8I and III). Other phases are often found as single grains in a groundmass of chalcopyrite. Chalcopyrite often occurs in granular, random aggregates as the main mineral among several mineral phases (random aggregates:= aggregates without a specific orientation (Ineson, 1989)). These aggregates can reach a size of ~20mm. Other phases which typically occur in these aggregates are sphalerite, magnetite, pentlandite and bornite (Fig. 8I, II, VII and VIII). However, also minor and rare phases as breithauptite, cobaltite or gudmundite can be present (Fig. 8I - IV). Where chalcopyrite and cubanite occur together, they often are closely intergrown. Cubanite occurs as about 5 to 50µm lamellae in chalcopyrite (Fig. 14d and 15I). Also chalcopyrite can often be found intergrown with host rock minerals of the samples. The latter often fills up fractures that penetrate chalcopyrite (Fig. 10I). Also up to 50µm broad magnetite and pyrrhotite/mackinawite filled fractures are a common feature in chalcopyrite (Fig. 10III and IV). Also chalcopyrite can be found as an emulsion, small rounded, drop-like inclusions in sphalerite (Fig. 10III).

Optical properties

Under the reflected light microscope, chalcopyrite appears yellow with a high to medium reflectivity. Compared to pentlandite it is darker (Fig. 10I-III and V). Cubanite is more beige (Fig. 15I). Chalcopyrite is softer than both sphalerite and pentlandite. In numerous samples, chalcopyrite is very strongly tarnished to e.g. purple, blue, green, red, orange, turquoise (Fig. 8 IV-VIII). Often smaller grains are tarnished (Fig. 10II, 15III and IV). Moreover, when silver is found in chalcopyrite, the latter appears with a bright purple/bluish colour (Fig. 8VI and 10IV). Note that a tarnish often occurs without an association of silver (Fig. 8V). When silver is found, the associated chalcopyrite is always tarnished as also described by Bjärnberg (2009). Only a chemical analysis can confirm the presence of silver. In the studied thin sections, chalcopyrite does not show any birefractance, but a weak anisotropy.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

S 50.5%, Fe 24.4%, Cu 24.4%.

The composition of the analysed chalcopyrite is almost

constant. Silver in amounts between 0.9 and 3.6% are found at a few spots in two samples (97m at three spots and 109m at one spot). An amount of +/- 1% is frequent. Similar findings are done in Bjärnberg (2009). There, a rather low Ag content of ~0.3% is found in a number of samples. A peak value of 7.3% Ag is detected there.

4.2.2 Common ore phases

Sphalerite - (Zn,Fe)S

Sphalerite is found in every sample but in varying quantities. This is the reason why sphalerite is not listed as a major ore mineral. Moreover, the amount is always significantly lower than the amount of chalcopyrite. It is a main ore mineral in other mineralizations of Zinkgruvan.

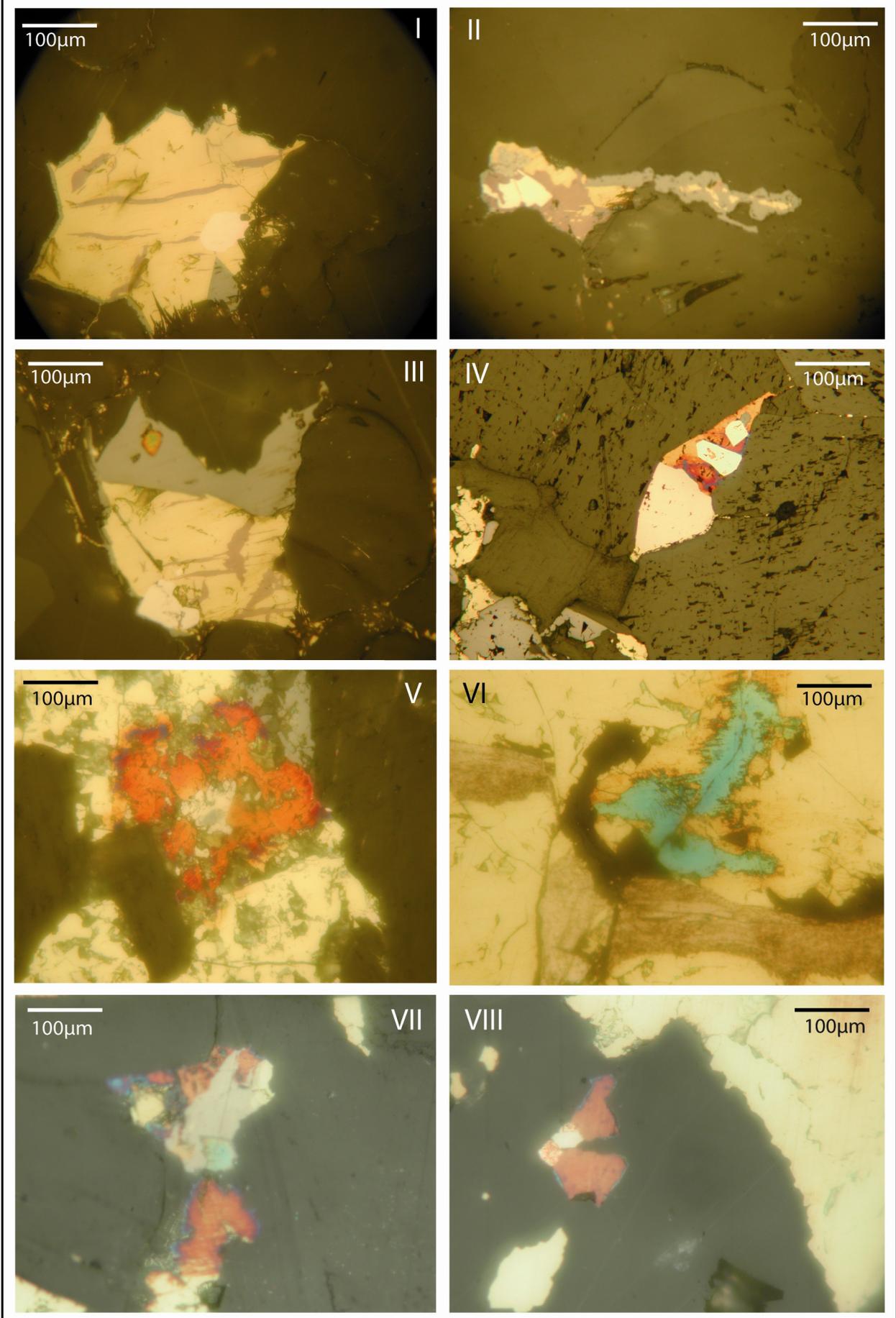
Texture & Mineral associations

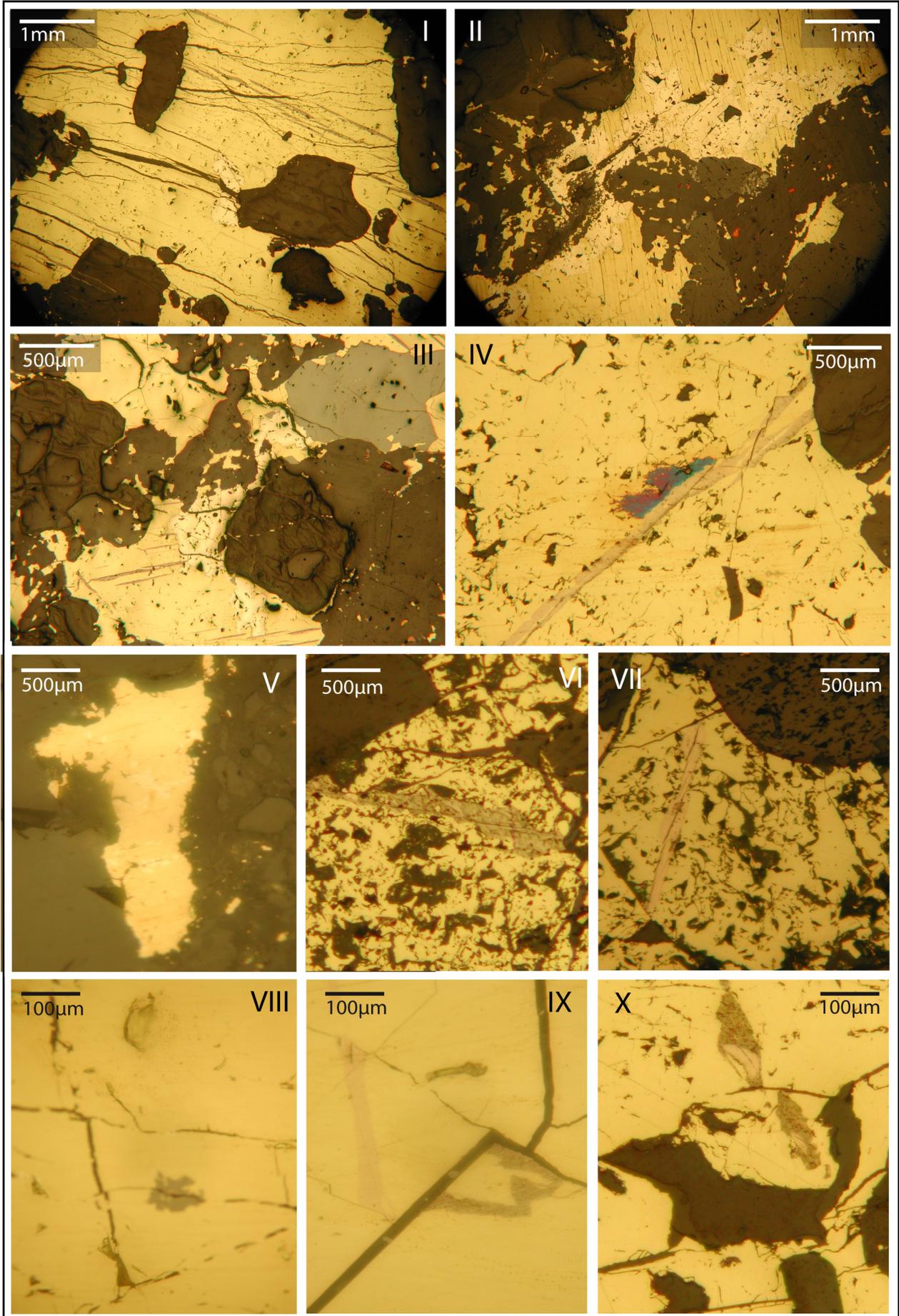
Sphalerite often occurs in association with chalcopyrite (Fig. 10III and 16II). Grain boundaries can be both rounded or irregular. The grain size varies between about 50 and 500µm. At about 50µm, isolated sphalerite star in chalcopyrite was observed once (Fig. 10VIII). An emulsion of small less than 5µm, rounded, drop-like inclusions of chalcopyrite in sphalerite has been observed in a number of cases (Fig. 10III). Larger grains of sphalerite often show cracks filled with host rock minerals (Fig. 16II). In addition, sphalerite is often found together with grains of pentlandite in a chalcopyrite ground mass (Fig. 10III). Sphalerite commonly occurs in random, granular aggregates from between 100µm – 5mm, without specific orientation (sometimes an elongated shape can be observed (Fig. 16II)). These aggregates often consist of sphalerite as the main phase and minor phases as e.g. bornite, breithauptite, cobaltite or gudmundite (Fig. 16II and VII). Also varying amounts of chalcopyrite occur. The aggregates are often found in the host rock matrix (Fig. 16VII).

Optical properties

Sphalerite has a medium grey colour under the reflected light microscope, with a low to medium reflectivity (Fig. 10III, VIII, 16II and VII). It can easily be distinguished from the darker host rock minerals as the carbonates are not opaque and transmit light. Compared to magnetite in the thin sections, sphalerite is more dark grey. The grey variety of pyrrhotite/mackinawite is lighter, occasionally with a silverish tone (Fig. 10IV). Sphalerite is harder than chalcopyrite, isotropic and shows no birefractance; internal

Fig. 8 I - VIII (following page). I- Irregular chalcopyrite aggregate (yellow) with dark pink, elongated grains of bornite, a round, white breithauptite grain, a grey, triangular grain and rim of magnetite (93m/7.1). II - Same opaque minerals as in I, instead of breithauptite, an irregular white grain of gudmundite as well as light grey tetrahedrite (93m/9). III- Same opaque minerals as in I, instead of breithauptite, a white grain of cobaltite (93m/7.2). IV- Aggregate of red tarnished chalcopyrite, pink breithauptite and two white grains of gudmundite (97m/5). V- Pale white pentlandite inside red tarnished chalcopyrite (99m/1). VI- Turquoise tarnished chalcopyrite along a Ag-filled fracture (97m/1). VII- Aggregate of Ag- containing red and turquoise tarnished chalcopyrite, pale grey pyrrhotite/mackinawite above a grain of native Ag, not visible due to the tarnish (97m/2). VIII- Dark red tarnished chalcopyrite and Ag-containing pale grey pentlandite surrounded by a grain of native silver covered with red spots (109m/7).





reflections were observed in a few cases.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Zn 43.4%, Fe 4.9%, S 50.5%.

Björnberg (2009) distinguished a low-Fe and a high-Fe group of sphalerite. In the present study, these two groups were also found with following mean compositions:

Low-Fe group

Zn 44.7%, Fe 3.2%, S 50.6%.

High Fe-group

Zn 42.1%, Fe 6.5%, S 50.4%.

In one sample (107m), a Mn-content of 0.7% is found in a high-Fe crystal. The sulphur content in both groups is constant at ~50%. Zinc and iron in varying amounts sum to the other 50%. It is common for sphalerite that part of the zinc is replaced by iron. This can be visualised with a linear trend between the Zn and the Fe, (Fe+Mn) contents (Fig. 9) as also in Björnberg (2009). In two samples, traces (<1%) of Co are found. This could be an artefact of analysing very small grains in the SEM. A detected Cu-content of 2% at one spot might, as also suggested by Björnberg (2009), originate from the small chalcopyrite inclusions in some sphalerite grains described above.

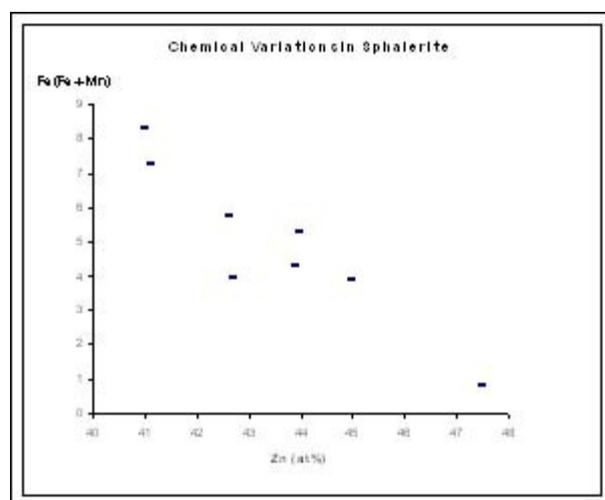


Fig. 9. Linear trend between Fe, (Fe+Mn) (y-axis) and Zn content (x-axis) in Sphalerite

Fig. 10 I-X (previous page). I - Yellow chalcopyrite and white grain of pentlandite penetrated by dark grey/brown host rock and light grey filled fractures of magnetite (101m/7). II- Yellow chalcopyrite and white, irregular grained pentlandite, also small red tarnished chalcopyrite grains (97m/4). III- Chalcopyrite, pentlandite, magnetite filled fractures and grey sphalerite in the top with very small chalcopyrite emulsion (101m/9). IV- Blue/purple tarnished Ag- containing chalcopyrite aside a grey pyrrhotite/mackinawite, partly Ag-filled fracture (97m/3). V- Irregular grain of chalcopyrite with white, fine grained pentlandite (109m/3). VI- Grey pyrrhotite/mackinawite along a fracture in chalcopyrite (99.m/2). VII- Pink pyrrhotite/mackinawite along a fracture in chalcopyrite (99.m/6). VIII- Sphalerite star in chalcopyrite (109m/1). IX and X- Grey and pink pyrrhotite/mackinawite in chalcopyrite (99.m/2).

Pentlandite - (Fe,Co,Ni)₉S₈

Pentlandite is an iron-nickel-cobalt sulphide, which is found in all samples. Similarly to sphalerite it is not listed as a major ore mineral because quantities vary considerably between different samples.

Texture & Mineral associations

Björnberg (2009) suggested the presence of two types of pentlandite in the Cu-mineralization: a fine-grained and a coarse-grained type. The fine-grained type has a lower Co-content than the coarse-grained one. These two groups could not be distinguished equally clear in this study. The Co-content varies significantly (see appendix and section "Chemical properties" below), but a clear relation to the grain size cannot be observed in the studied samples. There is only one analysed spot that shows the described fine-grained type with a Co-content of ~7%, (Fig. 10V). In the rest of the samples a weak relation between increasing grain size and Co-content might exist. To test this a significance statistical test should be applied.

Pentlandite occurs in a wide range of grain sizes. Most commonly the size varies from about 100 to 500 µm (Fig. 10I-III). This is a similar size range as sphalerite. Pentlandite is frequently found as compact grains with in a rounded, irregular shape (Fig. 10I and III). Irregular grains occur less often (Fig. 10II). In only one case, the fine-grained type, suggested by Björnberg (2009), is identified clearly (Fig.10V).

Most often pentlandite is found together with chalcopyrite (Fig. 10I -III and V). Also in association with sphalerite, pentlandite can be observed frequently (Fig. 10III). It is rarely found as isolated grains in the host rock matrix.

Optical properties

Pentlandite is white under the reflected light microscope. It has a nuance of yellow but compared to chalcopyrite it looks much whiter (Fig. 10I-II and V). Galena is more grey/silverish compared to pentlandite (Fig. 16VI and IX). The reflectivity of pentlandite is medium to high, slightly higher than for chalcopyrite. It is isotropic and no birefractance can be observed. Pentlandite is harder than chalcopyrite.

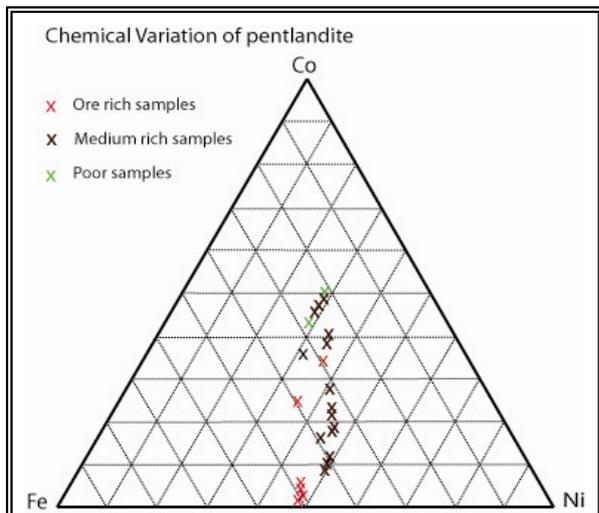
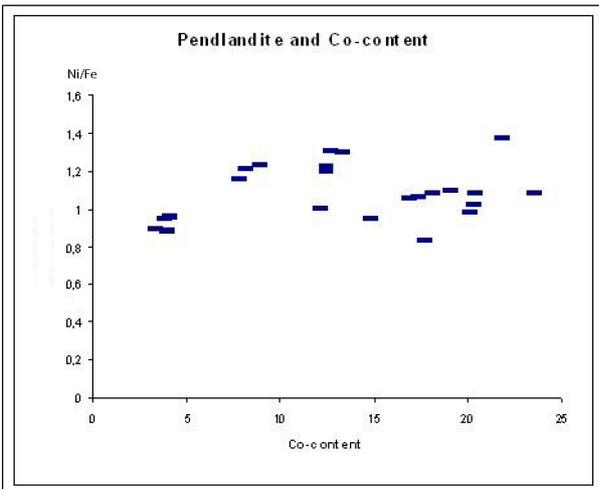
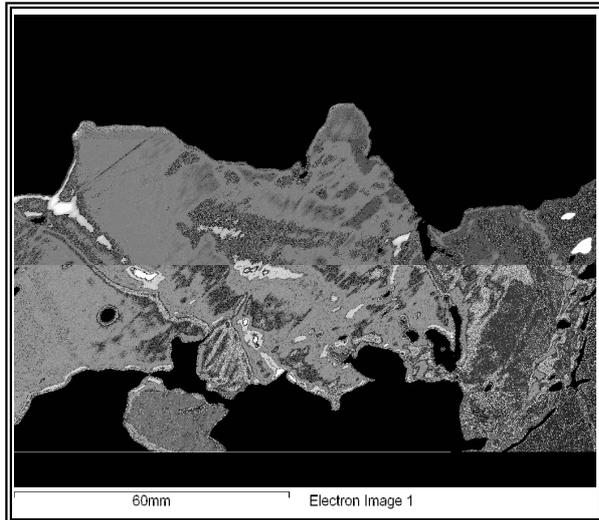
Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Fe 18.5%, Co 13.6%, Ni 19.8%, S 47.8%.

The sulphur-content is almost constant. The Fe- and the Ni- contents vary with about +/- 6% of the mean value. Fe- and Ni-contents are often close (Fe~Ni).

The Co-values have a large range of about 3 - 23%. No significant linear relation between increasing Co-content and increasing grain size nor is there any significant correlation between increasing Co-content and the Ni/Fe- ratio in these samples as suggested by Bjärnberg (2009) (Fig. 12 and 13). A distinct heterogeneity in pentlandite can be observed in the SEM (Fig. 11), only a weak variation in Fe and Co could be detected through element mapping (Fig. 14c).



Cubanite - CuFe_2S_3

Cubanite is after chalcopyrite another important Cu-sulphide in the studied mineralization. Nevertheless, it is not listed as a major ore phase because it is not found in every sample. In one sample (105m) the chemical composition matches the formula for cubanite exactly. In two other samples, cubanite is found in close association with chalcopyrite (95 and 107m), but the chemical data does not agree with the chemical formula (see “Chemical properties” below). A mixed composition of chalcopyrite and cubanite is proposed. In four other thin sections cubanite is identified under the reflected light microscope but no chemical data are available. In some samples (95, 105, 107 and 109m) large quantities of cubanite occur. Cubanite often replaces chalcopyrite. In the lower sections of the core, cubanite is more frequent.

Texture & Mineral associations

Cubanite is in most cases found in close association with chalcopyrite. It might occur that it replaces whole, about 500µm sized grains of chalcopyrite (Fig. 15II and III). Very common is also that cubanite occurs as intergrown, about 5 to 50µm lamellae of in chalcopyrite (Fig. 14d and 15I).

Optical properties

Cubanite is yellow/beige. Compared to chalcopyrite it has more pinkish (Fig. 15I-III). Similar to chalcopyrite, it has a high to medium reflectivity but is harder than the latter. Cubanite shows both a distinct bireflectance and anisotropy. It shifts its colour from light beige/yellow to a darker beige/brown tone. This makes it easy to distinguish it from chalcopyrite.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Cu 16.7%, Fe 33.3%, S 49.9%

In this sample (105m) the chemical composition matches exactly with the mean composition presented in Bjärnberg (2009). Where chalcopyrite and cubanite occur very closely intergrown the following chemical mean composition is obtained:

Cu 22.6%, Fe 30.2%, S 47.1%.

Here the data does not match those reported by Bjärnberg (2009). In the present study, the Cu-content is higher, the Fe and S content slightly lower than in Bjärnberg (2009). A mixed composition of chalcopyrite and cubanite is proposed. The Fe and S values are

Fig. 11 (to the left, upper most). SEM-photograph of a heterogeneous grain of pentlandite. No major chemical variation is seen in mapping pictures (91m/5).

Fig. 12 (to the left, middle). Ni/Fe-ratio (y-axis) to Co-content (x-axis) in pentlandite in the studied samples. No significant trend in Fe/Ni with increasing Co-content.

Fig. 13 (to the left). Triangeldiagram of Co-Ni-Fe in pentlandite of the analysed samples. Sphejarite.jpg

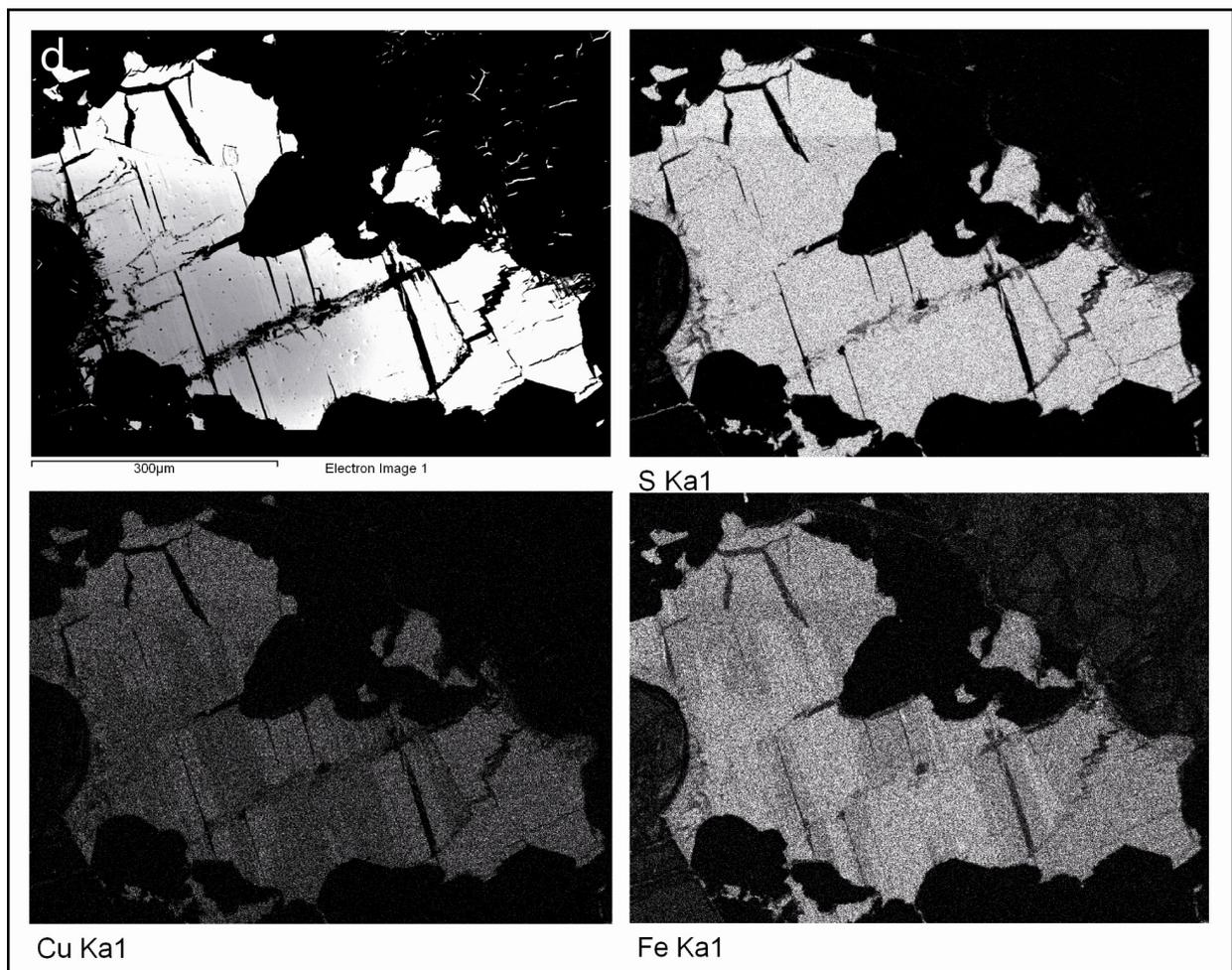
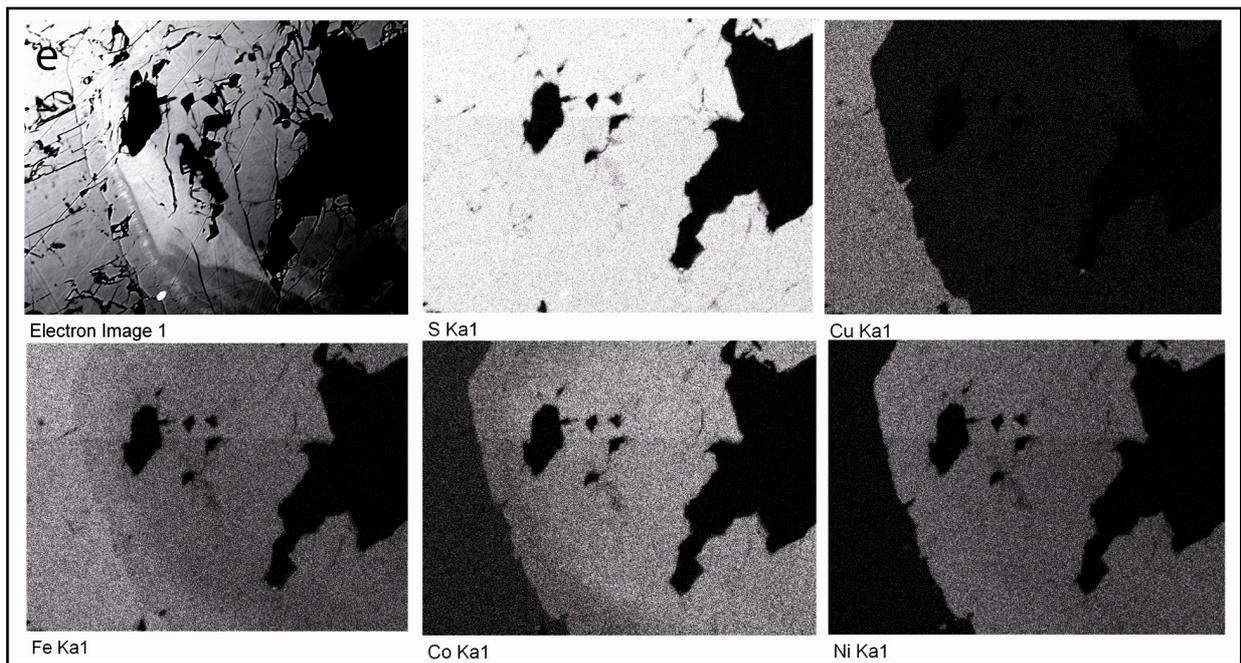
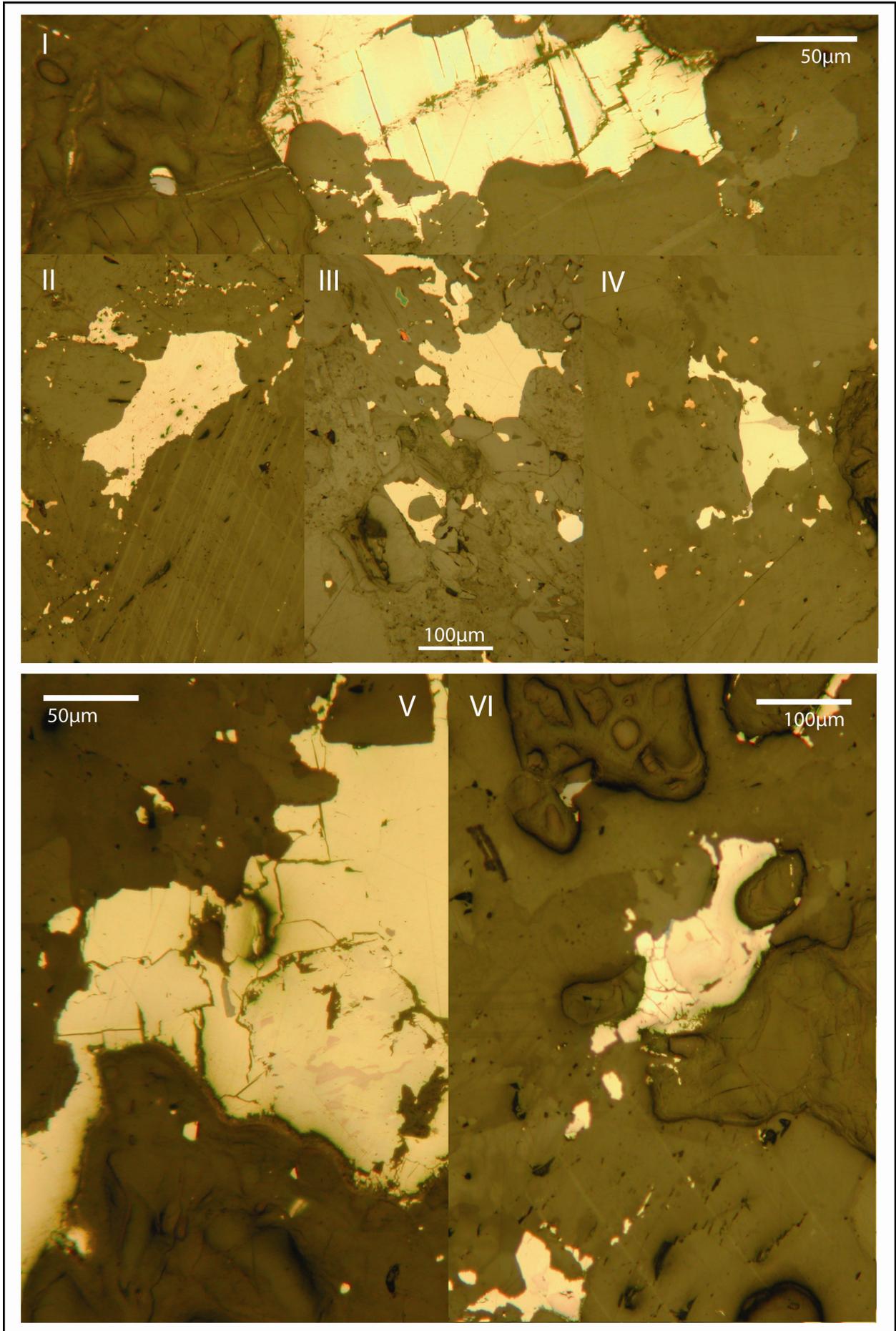
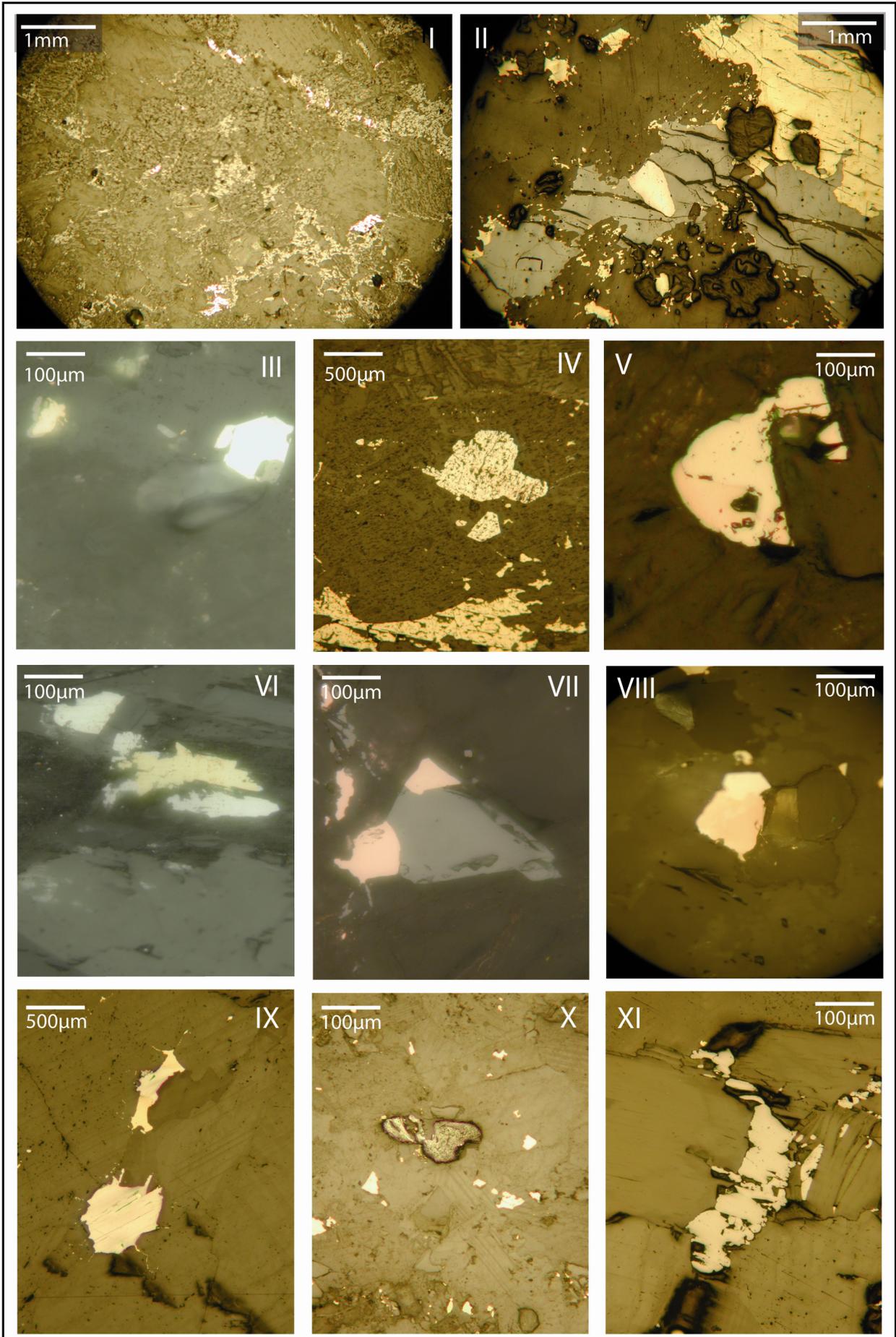


Fig. 14 c and d. SEM-mapping pictures. c – A heterogenous grain of pentlandite (91m/2). A weak variation in Fe and Co can be seen. d - A grain of chalcopyrite with cubanite lamella (107m/5). Variations in Cu and Fe can be seen. S is constant.





slightly too low compared to the standard composition of cubanite, the Cu content to high. Compared to chalcopyrite, the Cu- and the S-content are lower and, the Fe-content higher. Due to the lack of sufficient chemical data the stoichiometric composition suggested by Bjärnberg (2009) cannot be confirmed. The mapping picture shows that only Cu and Fe differ in the composition of cubanite and chalcopyrite, S appears to be fairly constant (Fig. 14d).

Magnetite Fe₃O₄

Magnetite is frequently found in the analysed samples. The term magnetite is used by Bjärnberg (2009). There magnetite could not be clearly discriminated from hematite. In the present study magnetite is suggested, due to the identified optical and chemical properties.

Texture & Mineral associations

Magnetite often occurs in aggregates (Fig. 8I and III) as up to 100µm wide fracture fillings in grains of chalcopyrite (Fig. 10I, III and 16II). In aggregates, it occasionally forms a rim (Fig. 8I). But it can also be found as single, irregular grains of varying size (5 to 500µm) in the host rock matrix (Fig. 16XI).

Optical properties

Magnetite appears grey under the reflected light microscope (Fig. 8I and III). Compared to sphalerite in the analysed samples, it is lighter. It has a low reflectivity, is isotropic and shows no birefractance. Compared to pyrrhotite/mackinawite magnetite is darker.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Fe 42.1%; O 57.7%.

The Fe-content has a range of about 4%. Oxygen has a range of 45-61%. The lowest value for O is higher in the study of Bjärnberg (2009). The other data fit rather well. A standardization error during SEM-analysis might result in high oxygen levels and high total sums of the measured magnetite grains. Another potential

source of error might be that parts of an iron peak possibly were mistaken for oxygen. In cases the electron configurations of both phases leads to overlapping peaks in the measured spectra.

4.2.3 Minor ore phases

Breithauptite – NiSb

Breithauptite is an antimonide that in small quantities occurs in all but one sample.

Texture & Mineral associations

Breithauptite is found together with various phases in the studied samples. It is found as rounded grains in aggregates of chalcopyrite, magnetite (Fig. 8I), sphalerite (Fig. 16VII), and other rare phases as e.g. gudmundite and the minor mineral cobaltite (Fig. 16V). Common are also disseminated, rounded or more irregular grains of breithauptite in the host rock matrix (Fig. 16I). A common grain size for breithauptite is about 100µm.

Optical properties

Breithauptite has a high reflectivity. It is white, most often with a strong pink tone (Fig. 16V and VII). However, also pure white grains are observed (Fig. 8I 16I and IV). Breithauptite is easy to identify not only due to its pinkish tone, but also because it is strongly anisotropic and birefractive. When rotated, colours shift to dark purple and brown nuances. Breithauptite is softer than cobaltite.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Ni 49.4%, Sb 49.5%.

The nickel and antimony contents of breithauptite are almost constant. In ten out of seventeen analysed spots, arsenic with a mean value of 1.7% is found. The amount varies from 0.4 to 4.1%. These numbers are similar to those reported by Bjärnberg (2009). In her study, Fe is found in a few samples.

Fig. 15 I - VI (page 18). I– Chalcopyrite with beige/pink cubanite lamella (107m/5). II - Pale yellow/beige, heterogenous chalcopyrite, possibly with cubanite or pentlandite (103m/9); no chemical data available. III– Pale yellow/beige chalcopyrite, possibly with cubanite. Small red and green tarnished grains of chalcopyrite (91m/8). IV– Irregular grain of chalcopyrite with grey pyrrhotite/mackinawite and small, pale red, disseminated grains of chalcopyrite (101m/6). V– Chalcopyrite with pink flames of (probably) pyrrhotite (107m/3). VI– White pentlandite with light pink grain of (probably) pyrrhotite that shows a high relief (107m/2).

Fig. 16 I - XI (previous page). I– Irregular, disseminated grey sphalerite and white breithauptite (99m/3). II - Pink, rounded grain of breithauptite inside a grey, irregular sphalerite aggregate, penetrated by fractures filled with host rock minerals. In the upper right corner: chalcopyrite with grey magnetite filled fractures (101m/1). III– Hexagonal shaped, bright white Co-safflorite with grey magnetite inside (95m/6). IV– Large grain of white, disseminated breithauptite (99m/10). V– Disseminated grain of intergrown, pink breithauptite and white cobaltite (105m/4). VI– Disseminated, pale grey, irregular galena and yellow chalcopyrite (99m/12). VII– Small aggregate of pink breithauptite and dark grey sphalerite (105m/6). VIII– Disseminated grain of intergrown, pink nickeline and Fe-safflorite (107m/8). IX– Irregular, rounded and elongated grain of pale grey galena and yellow chalcopyrite (103m/1). X– Elongated, rounded grain of molybdenite with high relief and a strong metallic lustre (91m/7). XI– Disseminated, irregular magnetite (93m/1).

Cobaltite – CoAsS

The sulpharsenide cobaltite is found in six out of ten samples; it was recognized with the help of the SEM analyses.

Texture & Mineral associations

Cobaltite is commonly found in chalcopyrite, in aggregates and as single grains in the host rock matrix. Often cobaltite occurs as characteristic, round grains (Fig. 8III), but it can also appear more irregular (Fig. 16V). The grain size is between about 50 and 100µm.

Optical properties

Under reflected light, cobaltite is white (Fig. 8III) with varying nuances of pink. Compared to Breithauptite it is less pinkish (Fig. 16V). Cobaltite is anisotrope and high to very high reflective.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Co 28.9%, As 33.8%, S 33.2%.

Iron is found in all samples; the mean content is 1.9%. Nickel is detected in about half of the samples with a mean of 3.2%. The Co-content has a range of 25- 31%. All other elements have values with a range of +/- 1% of the mean values above, which compares very well with the data presented by Bjärnberg (2009).

Pyrrhotite - Fe₇S₈ and Mackinawite - (Fe,Ni)₉S₈

This study and Bjärnberg's (2009) data indicate difficulties regarding a definite discrimination between the two phases pyrrhotite and mackinawite. Both Pyrrhotite and Mackinawite are iron/iron- nickel sulphides. The phases appear in six different samples, frequently in the most ore rich zone and nearby sections (95-103m).

Due to its varying S-Fe balance, pyrrhotite has a special formula. In the literature, no common formula is found. Notations are found that are similar to the following: Fe₇S₈ (mindat.org), which is also used in Bjärnberg (2009). In (Lennie et al., 1995) and (Ineson, 1989), the notation Fe_(1-x)S is used. On mindat.org and webmineral.com following specification for x in the above notation is done: x:=0-0.2, x:=0-0.17 respectively. For hexagonal pyrrhotite following formulas can be found: Fe₉S₁₀ (Ineson, 1989), mindat.org) and Fe₁₀S₁₁ (mindat.org). For mackinawite different formulas can be found as well: (Fe,Ni)₉S₈ (mindat.org), also used in Bjärnberg (2009), (Fe,Ni)S_{0.9} (webmineral.com) and Fe_(1+x)S in (Lennie et al., 1995).

The notation Fe_(1-x)S for pyrrhotite (found in various references, see above) and Fe_(1+x)S for mackinawite (in (Lennie et al., 1995) are very similar. In pyrrhotite the Fe-content varies between being lower or equal to S (Fe<=S). In mackinawite the amount (Fe+Ni) varies between being higher or equal to S ((Fe,Ni)>=S). In e.g. (Ineson, 1989) is stated that pyrrhotite may contain Ni, Co and Mn. This makes the formulas even more similar.

A connection between the minerals pyrrhotite and

mackinawite might explain the similar optical properties and chemical composition. Both Sarkar et al. (1971) and (Lennie et al., 1995) present hypotheses that mackinawite under heating breaks down to hexagonal pyrrhotite. It then shows both structural and optical properties of the latter. Critical temperatures for the mackinawite break-down, as given in the articles above range from 135°C to maximal 220°C. In (Malmström et al., 2009) a low pressure, high temperature metamorphism of the upper amphibolite facies is mentioned for the Zinkgruvan mineralization. Moreover the occurrence of pyrrhotite in the upper metavolcanic and lower metasedimentary unit is mentioned. The metavolcanic unit underlies the Cu-mineralisation.

Texture & Mineral associations

The phase/phases in question are always found together with chalcopyrite (Fig. 10). Single, about 50µm wide grains are often found along fractures in chalcopyrite (Fig. 10VI and VII). Sometimes pyrrhotite/mackinawite appears very irregular (Fig. 10IX). The phase/phases also appear as about 50µm wide fracture fillings with distinct boundaries (Fig. 10IV and 17c).

Optical properties

In this study, the phase/phases in question appear in two different colours: pink and grey under the reflected light microscope. A pink and a grey-variety of mackinawite are even reported by Sarkar (1971). A low to strong bireflectance and a distinct bluish to reddish/brown anisotropy is observed. The phase/phases are harder than chalcopyrite. Both mackinawite and pyrrhotite (Ineson, 1989) can show a distinct bireflectance. The bireflectance of mackinawite is supposed to be stronger. Bjärnberg (2009) describes the bireflectance of mackinawite as varying from greyish white to dark grey. Further, a distinct anisotropy from white to black is described.

Bjärnberg (2009) has reported mackinawite from all the three drillcores she studied: two samples originate from the section examined in this study. Pyrrhotite is only reported in a few cases by Bjärnberg (2009). Chemical data are available from one sample (in another drill core, DBH2993) analysed at five different spots. Thus the properties for pyrrhotite, described by Bjärnberg (2009), might not be characteristic for the whole Cu-mineralization and should not be generalized.

Chemical properties

Following mean chemical composition is found for what might be **pyrrhotite** in the analysed samples (in atomic %):

Fe 44.4%, S 51.1%.

In addition a mean of Ni 4% and traces (<1%) of Cu and Al are detected. The composition is close to constant. No major difference is observed in the chemical composition of the dark and the pink grains. Bjärnberg (2009) lists the phase with the above composition as

mackinawite. For comparison, she lists pyrrhotite as: Fe 46.6% and S 53.3%. In this study, if the identified mineral is **mackinawite**, (and the data is not based on any error in e.g. software) the chemical data is significantly different to Bjärnberg's data (2009). The following mean chemical composition is found in the analysed samples (in atomic%):

Fe 50.5%, Ni 3.4%, S 44.8%,

as well as traces of Co~1% and Cu ~0.5%.

Two analysed spots show both an increased Fe (~53%) and S (~46%) - content. The total sum there of ~114% is very high. If the values are switched, this matches exactly the above presented composition for pyrrhotite by Bjärnberg (2009). Optically these two grains also fit with the properties for pyrrhotite. Red varieties of both phases in most cases contain Cu. But Cu even occurs in grains of the grey type (see appendix).

4.2.4 Rare minerals

For the rare minerals a distinction is made between the first six phases that are rare but occur more than once and the last six ones, which are found only once in all the studied samples. The former ones lie in a transition zone between minor and rare minerals. They were listed as rare phases because they only occur in a few samples.

Bornite - Cu_5FeS_4

Bornite is found in two thin sections (93 and 105m) at four different spots. In contrast to Bjärnberg's list (2009), in this study bornite is not listed as a major ore phase, but as a rare mineral. The reason is that bornite only is found in two samples in rather small quantities.

Texture & Mineral associations

In 93m, bornite is found in three different aggregates that contain numerous phases (Fig. 8I-III). In one of them, bornite is a major phase found close to rare phases as gudmundite and tetrahedrite (Fig. 8II). In the aggregates, bornite forms elongated, about 100 μm grains with different orientations.

Optical properties

Bornite appears dark pink with a bluish tone in reflected light. It is medium reflective and isotropic without an obvious birefractance. It is softer than chalcopyrite.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

Cu 48.5%; Fe 11.3%; S 40.2%.

The mean values agree well with Bjärnberg's (2009) data. So do the ranges of Cu- and S- contents with about +/- 1% of the mean values above. The maximum iron amount of 14% exceeds the maximum amount in Bjärnberg's data (2009) by 4% units.

Galena - PbS

Galena is found in small quantities in three consecutive samples (99, 101 and 103m).

Texture & Mineral associations

Around 100 μm grains of galena are found together with chalcopyrite in the host rock matrix. One grain is rounded (Fig. 16IX), one is more irregular (Fig. 16VI). In sample 101m a single elongated grain is found in the host rock matrix.

Optical properties

Galena looks white to silvery grey in reflected light. It is isotropic, has a medium to high reflectivity and a high relief (Fig. 16IX). No birefractance is present.

Chemical properties

The mean chemical composition in the analysed samples (in atomic %) is:

Pb 49.6%, S 50.1%.

Deviation from the mean is about 1% for both elements. The chemical data agree well with Bjärnberg's (2009), except that in the present study no iron is found in galena.

Safflorite - $(\text{Co,Fe,Ni})\text{As}_2$

Three single grains of safflorite are found: in samples 95, 99 and 107m.

Texture & Mineral associations

The safflorite grains are all found as disseminated, about 5 μm to 50 μm sized grains in the host rock matrix. Two of the grains are rounded with an almost hexagonal shape (Fig. 16III). One grain of Fe-safflorite is associated with nickeline (Fig. 16VIII). The third, isolated grain is more irregular.

Optical properties

Safflorite is bright white with a very high reflectivity (Fig. 16III). Moreover the grains are anisotropic and shift to a bluish colour when rotated under crossed polars. Safflorite is harder than magnetite.

Chemical properties

Two types of safflorite are suggested by Bjärnberg (2009), which could also be found in this study: a Co-safflorite (two grains in 95 and 99m) with a high amount of Co and a low Fe-content and a Fe-safflorite (one grain in 107m) with lower Co and higher Fe. Mean chemical compositions for the two types (in atomic %) are:

Co-safflorite

Co 17.4%; Fe 9.0%; Ni 6.9%, As 64.0%.

Additional around S 2% in both and Sb 1.5% in one sample, is contained.

Fe-safflorite

Co 10.9%; Fe 18.7%; Ni 5.7%, As 61.3%.

Additional around S 3% is contained, Sb is not detected. The As-content of the Fe-safflorite is rather low, the Co-content rather high.

The chemical data agree quite well with Bjärnberg's data (2009), except in the Fe-safflorite the Co-content is even lower with a mean of around 5% and the Fe-content higher with about 25%. The sum Co+Fe is for all measured samples of both studies between about 25 and 32%. Intermediate types between the two Co and Fe safflorite endmembers described above might of course exist.

Molybdenite - MoS₂

In two samples (91 and 109m), disseminated grains of molybdenite are found.

Texture & Mineral associations

The about 50- 100µm sized grains lie isolated in the host rock matrix. They are rounded, two of them have a conical shape.

Optical properties

Under reflected light, molybdenite has a very distinct silver, metallic lustre (Fig. 16X). It has low to medium reflectivity, a distinct anisotropy and a high relief.

Chemical properties

The mean chemical composition in the analysed samples (in atomic %) is:

Mo 31.1%, S 64.1%.

The Mo-content is almost stoichiometric, so is the sum of (S+O): about 7% oxygen is detected at two spots. High total sums can be the consequence of a lack of an adequate standard for molybdenum during SEM-analysis. The data agree quite well with Bjärnberg's (2009) data. There, both mean values lie about 2% higher and the range of S is only +/- 1% of the mean value..

Gudmundite – SF₂Sb

Three grains of the sulphantimone gudmundite are found in two samples (93 and 97m).

Texture & Mineral associations

All three, 50- 100µm sized grains are found in aggregates. In sample 93m gudmundite is found as an irregular, rounded grain inside a grain of bornite, surrounded by an elongated aggregate of, chalcopyrite, magnetite and tetrahedrite (Fig. 8II). In 97m two grains of gudmundite are found in a rhombic shaped chalcopyrite-breithauptite aggregate (Fig. 8IV).

Optical properties

Gudmundite is white and has a high reflectivity. The grains are slightly birefractive.

Chemical properties

The mean chemical composition of the analysed samples (in atomic %) is:

S 32.6%, Fe 31.2%, Sb 33.1%.

All three elements vary with about +/-3% around the mean. At one spot, about 9% oxygen is detected which, probably is the consequence of a programming error in the Oxford/INCA-software. The chemical composition of gudmundite in this study agrees well

with that obtained by Bjärnberg (2009). However, contrary to her results, no As or Ni were found in this study.

Silver – Ag

Two grains of native silver are found in sample 97 and 109m as well as a silver filled fracture in 97m.

Texture & Mineral associations

The about 50µm silver grain (Fig. 8VIII) is found in strongly red tarnished chalcopyrite and surrounds an hexagonal, pale greyish grain of pentlandite. The other, about 5µm sized grain (Fig. 8VII and 17b) and the less than 5µm wide silver filled fracture (17a and c) is identified through mapping in the SEM, no point analysis of the chemistry has been done. Both, the grain and the fracture are severely tarnished and cannot be seen by the naked eye.

Optical properties

The silver grain is white, covered with small red spots of the same colour as the tarnished chalcopyrite (Fig. 8VIII). Due to the tarnish, other optical properties are difficult to determine.

Chemical properties

The chemical composition of the analysed grain (in atomic %) is:

Ag 100%.

The total sum of 104.5% is somewhat high. This is due to the lack of an adequate EDS-standard for Ag.

Rare minerals that occur only once

Nickeline – NiAs

Nickeline is found once in (107m) as a disseminated grain together with Fe-safflorite in the host rock matrix (Fig. 16VIII).

Texture & Mineral associations

The about 100µm grain is hexagonal shaped, as is the safflorite grain aside. The grain appears heterogeneous, both under reflected light and in the SEM.

Optical properties

Nickeline is light pink to beige, compared to massive cubanite in the same sample it is more pink. Next to breithauptite it appears somewhat darker and has a lower reflectivity.

Chemical properties

The chemical composition of the analysed grain (in atomic %) is:

Ni 47.9%, As 46.2%.

In addition, minor amounts of the following elements are detected: Sb 3.7%; Fe 1%; Co 1.1%. The amounts of Fe and Co might be connected to the heterogeneity seen in the grain. Perhaps the traces originate from the neighbouring Fe-safflorite grain. The total sum is low, only around 94%. The chemical data agree quite well with the data reported by Bjärnberg (2009) even if a

comparison is difficult as in both studies, data from only a single measurement are available and in both cases the total sums deviate with about 6% from 100%.

Costibite – CoSbS

Costibite is found once, in sample 93m.

Texture & Mineral associations

Costibite is found as a very small, less than 10µm, irregular inclusion in an irregular, rounded grain of sphalerite.

Optical properties

Compared to sphalerite, costibite looks pale white with a medium to high reflectivity.

Chemical properties

The chemical composition of the analysed grain (in atomic %) is:

Co 28.6%, Sb 34.1%, S 31.6%.

Also As 0.6% and O 5.1% are detected.

The above three main elements of costibite agree well with the data of Bjärnberg (2009).

Maucherite - Ni₁₁As₈

Maucherite is found in 109m as a single grain in the host rock matrix.

Texture & Mineral associations

The grain is less than 50µm and has an elongated, hexagonal shape.

Optical properties

Maucherite is white and high reflective.

Chemical properties

The chemical composition of the analysed grain (in atomic %) is:

Ni 56.1%, As 37.4%.

Small amounts of Sb 5.7% and Fe 0.8% are detected. The data agree well with Bjärnberg's (2009) data. She also reported maucherite once.

Tetrahedrite (Cu,Fe,Ag,Zn)₁₂Sb₄S₁₃

Tetrahedrite has been found once, in sample 93m.

Texture & Mineral associations

Tetrahedrite occurs in an aggregate of chalcopyrite, bornite, gudmundite and magnetite. It is a small, about 60µm irregular aggregate of small grains itself with adjacent borders to chalcopyrite and bornite (Fig. 8II).

Optical properties

Tetrahedrite is light grey and medium to high reflective. It is lighter than both magnetite and sphalerite.

Chemical properties

The chemical composition of the analysed grain (atomic %) is:

Cu 32.8%, Fe 2.8%, Zn 3.9%, Sb 12.7%, S 41.8%.

Also 5.8% oxygen is found.

Bjärnberg (2009) suggested two varieties of tetra-

hedrite: one Fe-rich type with about 6% Fe and 1% Zn and a Zn-rich type, with about 5% Zn and about 2% Fe. The tetrahedrite in this study lies probably in between these two endmembers. Data of the other elements agree fairly well with Bjärnberg's (2009) data.

Kieftite - CoSb₃

One single grain of kieftite is found in 93m.

Texture & Mineral associations

The grain of kieftite neighbours a sphalerite grain that contains costibite. The grain is tetragonal with rounded corners and with a size of less than 5µm very small.

Optical properties

Kieftite is white with a high reflectivity.

Chemical properties

The chemical composition of the analysed grain (in atomic %) is:

Co 22.0%, Sb 70.2%.

Even in this phase, O 7.8% is found. This might be the result of the small size of the analysed grain. Kieftite was not found in the study by Bjärnberg (2009).

4.2.5 Silver & Silver bearing phases

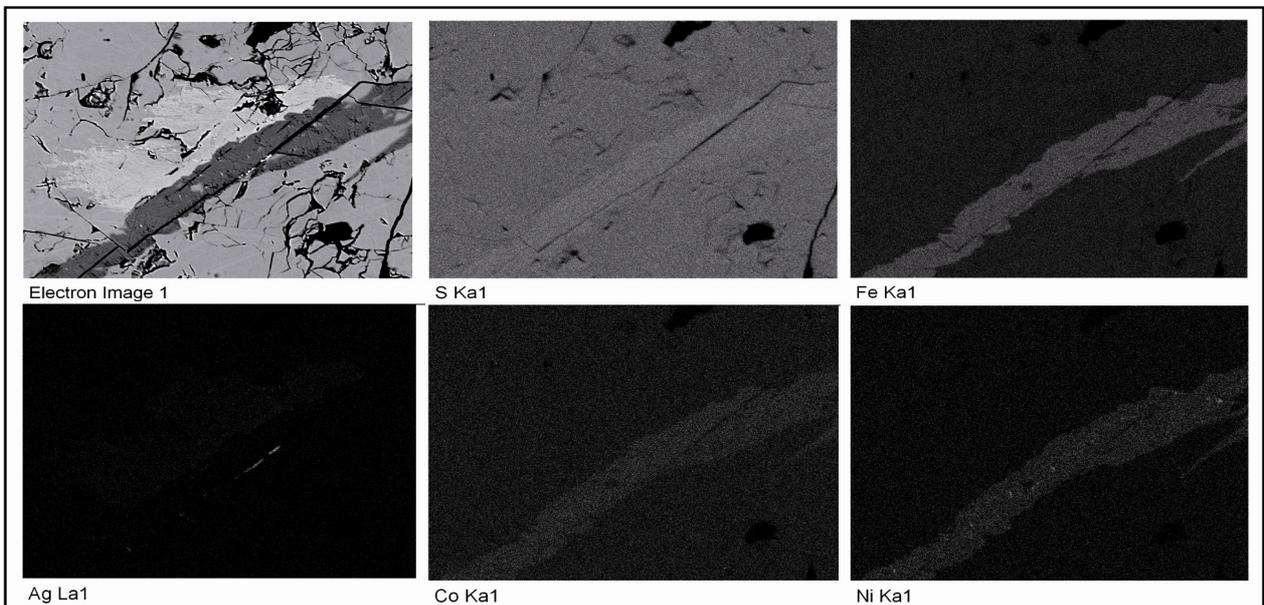
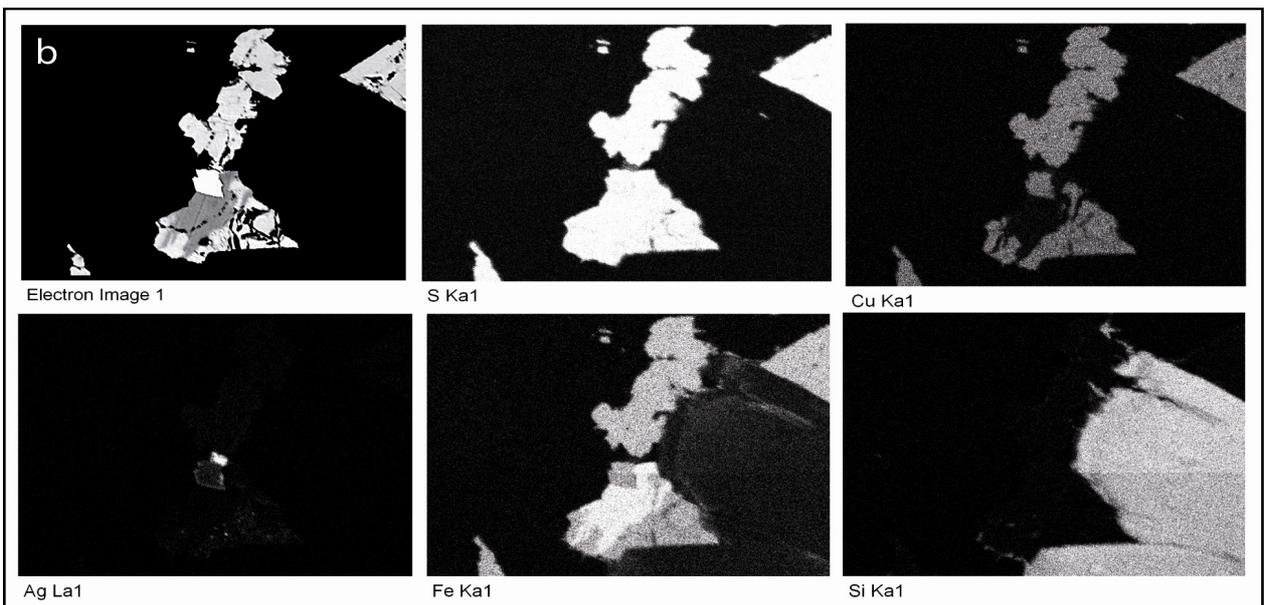
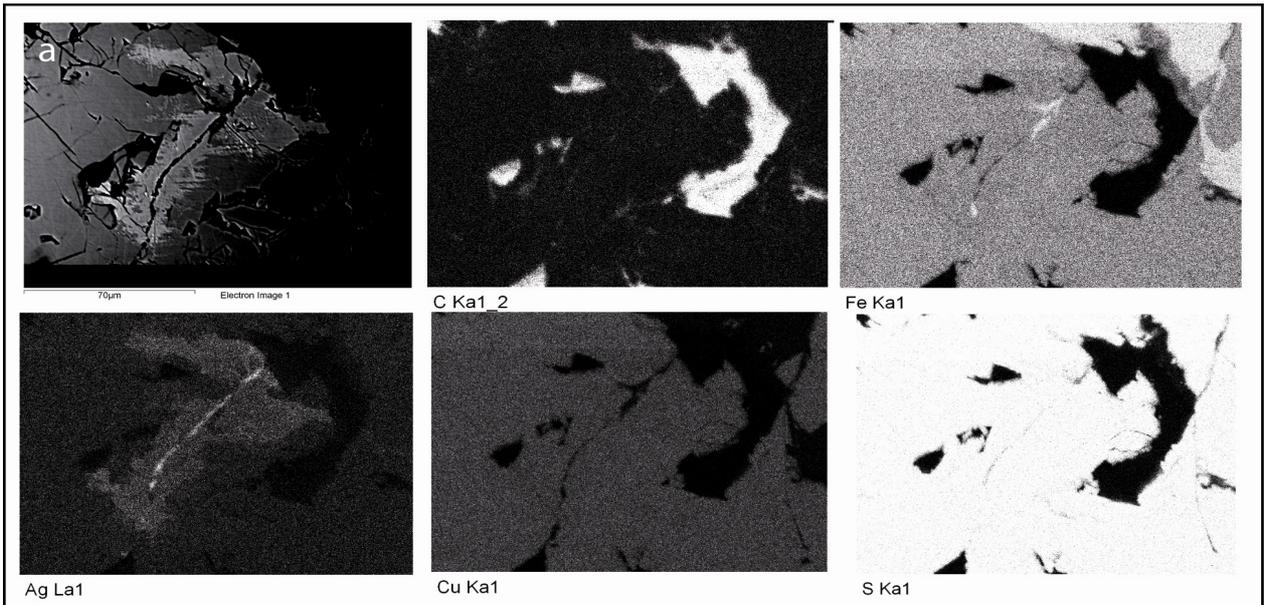
In this study, silver is found in two samples: Two grains of native silver are found in sample 97 and 109m as well as a silver filled fracture in 97m. In addition silver is detected in chalcopyrite at five spots (97 and 109m) and once in pentlandite that is located next a native Ag-grain (109m).

All grains of native Ag are strongly tarnished. The one which can be identified by the naked eye is covered with numerous, small red spots of the same colour as the grains of the Ag-containing chalcopyrite.

In the silver-containing chalcopyrite the Ag-content varies between 0.7 and 3.6%. In 97m, at two spots the chalcopyrite grain is associated with pyrrhotite/mackinawite: one irregular grain of chalcopyrite along a pyrrhotite/mackinawite filled and very small Ag-filled fracture is tarnished in deep blue/purple (Fig. 10IV), the is other more pale turquoise (Fig. 8V). The pale turquoise grain contains 3.6, the irregular grain 1.1% Ag. 1.7% Ag is found in chalcopyrite along a fracture, that is distinctly tarnished in turquoise (Fig. 8VI). In both silver-containing samples, less than 1% traces of Ag are found in red-tarnished grains of chalcopyrite that neighbour native grains of Ag.

In a pale grey grain of pentlandite, which is surrounded by the native grain of silver 0.1% of Ag is found (Fig. 8VIII).

It seems as also expressed by Bjärnberg (2009) that the tarnish in chalcopyrite increases with increasing amounts of Ag. At low Ag-contents of less than 1% the tarnish is reddish. At higher Ag-contents the tarnish becomes turquoise to dark blue/purple. But often chalcopyrite is tarnished without any demonstrable



content of Ag. Whether Ag occurs or not can only be ascertained with a chemical analysis.

It seems that Ag replaces both Fe and Cu, but to a slightly larger extent Cu. The Cu-content is with increasing amounts of silver, in most cases slightly lower than Fe.

In contrast to Bjärnberg (2009), no argentopentlandite is found in this study. Bjärnberg (2009) also has demonstrated small grains and fractures-fillings of allargentum (AgSb) with about 80- 91% silver. She has found allargentum in association with tetrahedrite, in one sample, of the drill-core DBH2992 (110m), which follows the last of the samples analysed in this study, and in a second drillcore. Allargentum is not found in this study, and tetrahedrite as a rare mineral, is only found once.

4.3 Problematic elements

During processing of Cu-ore the removal of low contents of certain problematic elements such as Sb and As (Hg and Bi) leads to increasing costs for the company. When Sb or As occur in low amounts, they are not economically feasible to mine and have to be removed in order to get a pure Cu-product. Fines apply, if the end product contains more than a certain level of these elements. Sb and As can contaminate the soil and are poisonous to humans (SGU, 2005).

In this study antimony or arsenic are found in all samples, in nine different phases (Table 3 and 4a). Five of them contain Sb and four As. No mineral is found that includes both As and Sb. None of the major or common ore phases contain Sb or As. Two of the total three minor ore phases contain Sb (breithauptite, NiSb) and As (cobaltite, CoAsS). In the same way, two of the six rare minerals contain Sb (gudmundite) and As (safflorite). All but one of the six rare phases that only have been found a single time contain Sb or As. Sb is contained in three of them: costibite, tetrahedrite and kiefertite. Arsenic is contained in nickeline and maucherite.

Bjärnberg (2009) reported the occurrence of mercury and bismuth, but it has not been possible to demonstrate these two elements in any of the analysed thin sections in the present study.

Sb- containing minerals

Antimony occurs in five different phases (Table 4a). Most common of these is breithauptite (NiSb) that also contains the highest concentration of Sb (≈ 50 at%). Breithauptite is a minor ore mineral that is found in all but one sample. The other four minerals that contain Sb are the following rare minerals: gudmundite, found

Fig. 17a and c (previous page). SEM-mapping pictures. a – Ag containing grain of chalcopyrite along an Ag-filled fracture(97m/1). b– Grain of native silver surrounded by a chalcopyrite-pyrrhotite/mackinawite aggregate (97m/2). c - Ag-containing chalcopyrite beside a pyrrhotite/mackinawite and small Ag-filled fracture (97m/2).

in two samples (93 and 97m) tetrahedrite, costibite and kiefertite, which are only found once.

As- containing minerals

Arsenic is most common in the minor phase cobaltite (CoAsS), which is found in six out of ten samples (Table 4a). The other three As- containing phases are the following rare minerals: safflorite, which occurs in three samples (95, 99, and 107m), nickeline and maucherite, both of which are found only once.

The distribution of As and Sb in the samples

In most thin sections both Sb- and As- carrying minerals are found (Table 4a). In sample 91m, only one As-containing mineral is found (cobaltite). In two (97 and 101m) of the three quantitatively most ore rich samples (97, 99, 101m) no As-containing but Sb-containing minerals are found. These are breithauptite and gudmundite in sample 97m and only breithauptite in sample 101m. In the ore-richest thin sections none of the rare phases that only have been identified once are present. Most of these are found in the three thin sections with the lowest amounts of ore minerals (93, 103 and 107m) (Table 4a).

4.4 Mineral distribution

The studied 18m long section comes from the ore-rich section of the drillcore. In this section, the most ore-rich zone is located in the middle (97, 99 and 101m), where the most central sample 99m is less rich in ore than the other two. The outer part of the sections are alternating medium to poor in ore minerals (Table 4).

Only an estimate, and no exact numbers, of the quantitative amounts of Cu-ore in the different parts of the core can be achieved. The three thin sections 97, 99 and 101m are richest in ore. These three samples are consecutive, 97 and 101m carry more than 50% Cu-ore and sample 99m between 25 and 50%. The three most poor samples are not consecutive: 93m with less than 2% ore minerals, 103 and 107m with ~ 2 -10% ore. Four medium rich thin sections are found: 91, 95 and 105m with ~ 10 - 25% ore content. 109m also lies in the medium category with approximately 30% (Fig. 6).

The most ore-rich zone begins in a transition zone from calcite- into dolomite-rich marble (97m). The dolomite is then successively transformed to skarn. At sample 101m, which is the thin section richest in ore, almost 100% skarn is reached (Fig. 6). The most ore poor sample (93m) and one of the other poor ones consist of dolomitic marble (Fig. 6). One of the poor samples is found in calcite-rich marble. Two of the four samples, which are medium ore rich are dolomitic marble. The other two, which of one (109m) has quite a high amount of ore, are calcite marble.

As also Bjärnberg (2009) states, no distinct zoning of the minerals can be observed in the studied interval (Table 4). Chalcopyrite, sphalerite, pentlandite and iron-oxide are found in all samples. Breithauptite is

found in small amounts in all but the first sample. Cubanite and pyrrhotite/mackinawite are found in most samples, in varying amounts, cobaltite in rather small amounts. No clear internal relation among the occurrences of different mineral phases can be observed. Cobaltite (CoAsS) and safflorite ((Co,Fe)As₂) only appear together in one single thin section (99m), otherwise only one of the two phases is found. Both pyrrhotite /mackinawite and galena are concentrated in the more ore rich zone.

Chalcopyrite is found in all samples. With increasing contents of ore minerals, the amount of chalcopyrite aggregates increases. Even pentlandite and sphalerite are found in all samples. They occur both as single grains and as part of aggregates. In agreement with Bjärnberg's observations (2009), sphalerite occurs to a less extent in aggregates in the most ore rich zone. The amount of cubanite increases towards the lower part of the sampled section. Bornite is only found twice (samples 93 and 105m), which is outside the most ore rich zone. With the exception of galena, the rare ore minerals often occur as disseminated grains in sections, which are poor in ore. Four of the five Sb- or As-containing rare minerals that only have

been found once appear in these poor samples (93 and 107m). Maucherite (contains As) and native silver occurs in a medium to rich sample (109m).

The number of different opaque minerals does not increase with increasing volume of ore minerals/aggregates towards the richer ore horizon (Table 4). This is consistent with Bjärnberg's results (2009). The number of different ore minerals is rather low in the ore-rich samples and high in the poor samples. The minimum number of seven different minerals is found in the ore rich horizon in sample 97m, the highest number of eleven, in the poorest sample (93m). The mean of the numbers of opaque minerals of all ten samples is 8.8. The mean of the three samples (97-101m) from the most ore rich horizon is 8 different minerals, which is slightly below the total mean. The mean of the three poorest samples is ten, which is higher than the total mean. In a similar way, the three most ore-rich samples contain a mean of two Sb- or As-containing minerals. The total mean of all samples is 2.5. The three most ore-poor thin sections have a mean of 3.6 Sb- or As-containing minerals, which is the highest number. The highest number is six different Sb- or As bearing minerals, found in the poorest

Sulphides, Native Elements, Oxides						
Mineral Group	Cu-Sulph.	(Co,Fe,Ni)-Sulph.	Other Sulph.	Oxides	Native El.	
Major minerals	Chalcopyrite					
Common phases	Cubanite	Pentlandite	Sphalerite	Iron-Oxide		
Minor phases		Pyrrhotite/mackinawite				
Rare phases	Bornite		Galena			
Once			Molybdenite			Silver
No. of phases	10	3	2	3	1	1
Major minerals	1	1	0	0	0	0
Common phases	4	1	1	1	1	0
Minor phases	1	0	1	0	0	0
Rare phases	4	1	0	2	0	0
Once	1	0	0	0	0	1

Table 2. Opaque minerals after chemical composition: Sulphides, Native Elements, Oxides that do not contain problematic elements.

Phases that contain undesired elements: Sb, As					
Mineral Group	Sulphantimonides	Sulpharsenides	Antimonides	Arsenides	
Major minerals					
Common phases					
Minor phases		Cobaltite	Breithauptite		
Rare phases	Gudmundite			Safflorite	
Once	Costibite		Kieffite	Nickeline	
			Tetrahedrite		
No. of phases	10	3	1	3	3
Major minerals	0	0	0	0	0
Common phases	0	0	0	0	0
Minor phases	2	0	1	1	0
Rare phases	2	1	0	0	1
Once	6	2	0	2	2

Table 3. Opaque minerals after chemical composition: Antimonides and arsenides, that contain problematic elements. Red: minor ore phases; most frequent/problematic. Orange and yellow: rare minerals; less problematic

Total	10
Major	0
Common	0
Minor	2
Rare	2
Once	6

sample (93m) (Table 4).

4.5 Chemical variation

A majority of the opaque phases, including the major ore mineral chalcopyrite, has an almost constant chemical composition (appendix). Sphalerite ((Zn,Fe)S) is found in a low-Fe and an high-Fe variety (appendix). Bjärnberg (2009) states that the low-Fe type is more common in the outer parts of the mineralization. Also in this study the low-Fe type is found outside the richest ore zone (93m and 109m). The common ore phase cobaltpentlandite ((Fe,Co,Ni)₉S₈) varies in chemical composition; the amount of sulphur is close to constant, but the Fe-Co-Ni contents vary significantly (see appendix). Bjärnberg (2009) suggests a strong relation between the grain size and Co-content for pentlandite. This relation cannot be verified in this study, even if a relation between increasing grains size and increasing Co-content cannot be disproved. In this study, only small amounts of fine-grained pentlandite is identified, which makes it impossible to get a conclusive answer to that question. An increased Ni/Fe- ratio with increasing Co-content could neither be shown in this study. However the chemical heterogeneity of pentlandite is even seen in

the back-scatter images in the SEM (Fig. 11). However, only Fe and Co show a slight variation in the mapping picture, Ni appears to be constant (Fig. 14a). The last opaque phase that shows a chemical variation is safflorite. As suggested by Bjärnberg (2009), a Co-rich type and a Fe-rich type can be found. In this study three spot-analyses, from three different samples, are available for safflorite. The two different types could be confirmed as in two cases a high Co-content is measured and in one case a high Fe-content.

As it has not been possible to explicitly distinguish pyrrhotite and mackinawite, an evaluation of their chemical variation is difficult. If two phases (as listed in the appendix) are present, pyrrhotite has a constant chemical composition. This is contrary to the findings of Bjärnberg (2009), where a high-S/low-Fe (S 53%, Fe 46%) variety and a low-S/high-Fe type (S 51%, Fe 48%) are presented. Chemical data from another drill core (DBH2993) of only one sample and five different spots are listed by her for pyrrhotite. This might not be representative for the whole Cu-mineralization.

If mackinawite is identified correctly the chemical composition is also close to constant, except of two spots in 107m, where both S and Fe values are somew-

	Sb		As		Sb		As		Sb		As										
	Cha	Sph	Pen	Cub	Mag	Bre	Cob	Pyr/mac	Bor	Gal	Saf	Gud		Mol	Kie	Tet	Nic	Cos	Mau	Ag	
91	x	x	x	Opt	x		x					x								91	
93	x	low-Fe	x		x	x	x		x			x		x	x		x			poorest	93
95	x	high-Fe	x	x	x	x		x			xCo									95	
97	xAg	x	x		x	x		x			x								x	rich	97
99	x	x	x		x	x	x	x		x	xCo									rich	99
101	x	x	x	Opt	x	x		x		x										richest	101
103	x	high-Fe	x	Opt	x	x	x	x		x										poor	103
105	x	high-Fe	x	x	x	x			x											105	
107	x	high-Fe	x	x	x	x		x			xFe					x				poor	107
109	x	low-Fe	xAg	Opt	x	x	x					x						x	x	109	

	Sb or As														
	tot	Maj	Com	Min	Rare	1ce	ok	As	Sb	As	Min	Rare		1ce	
91	7	1	4	1	1	0	6	1	0	1	1	0	0	91	
93	11	1	3	2	2	3	5	6	5	1	2	1	3	poorest	93
95	9	1	4	2	2	0	7	2	1	1	1	1	0	95	
97	8	1	3	2	2	1	6	2	2	0	1	1	0	rich	97
99	9	1	3	3	2	0	6	3	1	2	2	1	0	rich	99
101	8	1	4	2	1	0	7	1	1	0	1	0	0	richest	101
103	9	1	4	3	1	0	7	2	1	1	2	0	0	poor	103
105	8	1	4	2	1	0	6	2	1	1	2	0	0	105	
107	10	1	4	2	2	1	7	3	1	2	1	1	1	poor	107
109	10	1	4	2	1	2	8	3	1	1	2	0	0	109	
Min	7	1	3	1	1	0	5	1							
Max	11	1	4	3	2	3	8	6							
Mean	8,9	1	3,7	2,1	1,5	0,7	6,5	2,5							

Table 4a (above) and b (to the left). 4a- Distribution of the opaque minerals in the analysed samples. Grey: ore rich samples. Purple: poor samples. Not coloured: samples with medium amount of ore. 4b- Statistics.

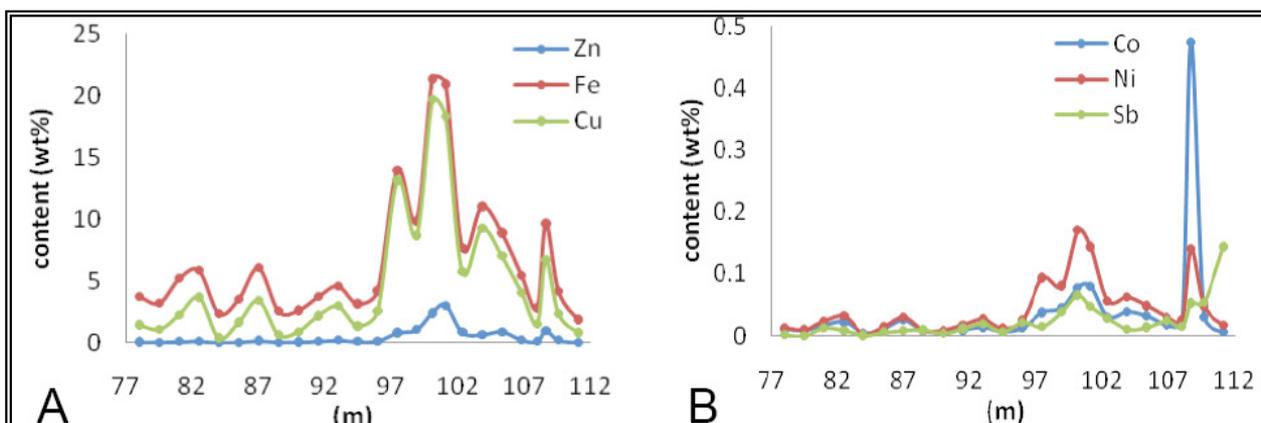


Fig. 18. Bulk chemical analysis of the Burkland Cu-ore, obtained for ZMAB by ACME Analytical Laboratories, Vancouver. Edited from Bjärnberg (2009). All elements show peaks in the ore richest section: 97m-101m.

hat increased (S 46%, Fe 53%). However, at these spots, the total sums are very high, 114%, which might falsify the results. Note that the numbers presented above for S and Fe match, when switched, exactly the values listed as pyrrhotite by Bjärnberg (2009).

5 Discussion

Any study involving analyses of naturally occurring material, has to be restricted to a certain area and amount of samples. This always leads to the question of how representative the results are, and how well they can be extrapolated and translated into not directly studied parts.

In this study, a rather short section of about 18m of one drill core in the most ore rich part was investigated. Thus, this study should not be considered isolated, but in a context of other studies and available data about the mineralization. Especially the paper by Bjärnberg (2009) about the same Cu-mineralization must be taken into account. Bjärnberg (2009) studied three drill cores. The samples of the present study lie with an equal distance of two meters in between Bjärnberg's (2009) samples. They provide a supplement and a test whether her result could be reproduced.

The opaque minerals

In this study, twenty different opaque phases have been identified, nineteen of which are also presented by Bjärnberg (2009). The rare phase Kieffite (CoSb_3) was not found by her. A total of twenty-six different opaque minerals are presented by Bjärnberg (2009). All but six of these were found in the present study: One of them, valleriite is listed as a common mineral by Bjärnberg (2009), all the others as rare phases, including allargentum (AgSb), native bismuth and graphite. Also Ag-containing pentlandite is identified by Bjärnberg (2009), which is not the case in this

study. (To get a better overview over the different opaque phases found in each study see appendix).

Bjärnberg (2009) states that valleriite occurs in symplectites together with iron-oxide. Further is stated, that valleriite is not found in the richest part of the drill core DBH2992, which covers the section examined in the present study. Thus, the lack of valleriite in this study confirms Bjärnberg's results (2009) that valleriite is restricted to the poor parts of the mineralization and does not contradict the possible importance of this phase in other parts of the mineralization.

Chalcopyrite is the only mineral, classified as a major ore phase in this study. Other minerals do not meet the requirements regarding, quantity and frequency. Bjärnberg (2009) also lists cubanite and bornite as major ore phases. Cubanite is identified in many samples, unfortunately only few chemical data are available. The reason is that many sums of the analyses deviated strongly from 100%. Towards the lower part of the studied 18m section, the amounts of cubanite are high. As the studied section is quite short and thus not totally representative for the whole mineralization, cubanite might still count as a major ore-mineral in other parts. The studied section does not involve the poor parts of the mineralization.

Bornite, which Bjärnberg (2009) also lists as a major mineral, is here only found in two samples in limited quantities. It is therefore listed as a rare mineral. Bjärnberg (2009) describes that the occurrence of bornite in the samples is restricted, in a few thin sections, however, it appears in large quantities. Similar to chalcopyrite, bornite might therefore still be a major ore phase in parts of the mineralization.

Sphalerite, pentlandite, magnetite, pyrrhotite/mackinawite and valleriite are listed as common ore phases by Bjärnberg (2009). This can be confirmed in this study, where sphalerite, pentlandite and magnetite are also listed as common phases. Cubanite is here, as motivated above, also included in this category. Pyrrhotite/mackinawite are regarding frequency and quantity listed as minor minerals. So are even breithauptite and cobaltite which both occur in most samples but in small amounts. Bjärnberg (2009) also lists galena and pyrrhotite as minor ore phases. These are here listed as rare minerals, they are, however,

transitional to minor minerals. The rest of the minerals are listed as rare minerals in both studies.

A major difference between this study and the study by Bjärnberg, regards the identification of the opaque phases pyrrhotite and mackinawite. The (Fe,Ni,Co)-sulphide which is identified as mackinawite by Bjärnberg (2009), noted as $(\text{Fe,Ni})_9\text{S}_8$, is here listed as pyrrhotite (Fe_7S_8 also $\text{Fe}_{(1-x)}\text{S}$, $x:= 0-0.17$). The chemical data of the two latter phases are very similar in both studies: Fe 44.4%, S 51.1%, Ni 4%. As the Fe-value is less than 50%, a better fit to the chemical formula of pyrrhotite (Fe_7S_8 also $\text{Fe}_{(1-x)}\text{S}$, $x:= 0-0.17$) is suggested in the present study. The optical properties of both samples are rather similar and can therefore alone not distinguish the two phases. Both phases studied here, show birefractance (if even slightly lower for pyrrhotite) and a distinct anisotropism. Mackinawite might not be present at all in the studied section (in case an error occurred during data collection) or it has a mean chemical composition of: Fe 50.7%, Ni 3.7, S44.6%. Moreover traces of Co 1.5% and Cu 0.5%. Further assessment is needed for a definite answer on that problem.

Problematic elements

The most problematic phase, concerning to frequency and the amount of undesired elements is breithauptite (NiSb) (Table 3). As a minor ore phase it occurs in all but one (91m) thin section (Table 4). Breithauptite often occurs in aggregates together with sphalerite but is also found in chalcopyrite or together with rare minerals. These observations agree with those made by Bjärnberg (2009).

Besides breithauptite, cobaltite (CoAsS) is also problematic (Table 3), as it occurs frequently and contains about 33% Sb. Cobaltite often appears as single grains in chalcopyrite, in aggregates with rare minerals or in the host rock matrix, isolated or together with rare minerals. The results found in this study confirm those found by Bjärnberg (2009).

Gudmundite (SFeSb) is also somewhat problematic, as it is found in aggregates. However, in this study it is only found in two thin sections. One of these cases occurs in the richest ore zone. Safflorite ((Co,Fe,Ni)As₂) is found in three samples, also one of them in the richest ore zone, but always in the host rock matrix. Hence, it may be considered as less problematic, since the ore aggregates are more important than the disseminated phases, when the Cu-ore is exploited. All other Sb- or As- bearing minerals (nickeline, costibite, tetrahedrite, maucherite, kiefertite) are only found once, none of them in the ore richest zone.

Mineral distribution - zoning

No distinct mineral zoning can be observed throughout the analysed section. This is consistent with Bjärnberg's (2009) results. The Cu-ore phases are often found in aggregates, with chalcopyrite as the major mineral. Rare minerals (which often contain As or Sb)

are found both in aggregates and as disseminated grains in the host rock matrix. With increasing volume of ore minerals, the aggregates grow larger which results in a lower number of rare minerals. An important exception to that is breithauptite (NiSb), which is found in all but one sample.

Bjärnberg (2009) states that the mineralogy of the opaque phases is closely related to the composition of the host rock. In this study only two different rock types are present: marble (a calcite rich and a dolomitic one) and skarn. Thus, a conclusive test of the statement is not possible. Nevertheless, it is stated by Bjärnberg (2009) that the skarn sections are rich in ore minerals occurring in aggregates. This study confirms this result. Moreover, in this study, the dolomitic marble appears to be the host rock, which is poorest in ore minerals and the calcite rich marble the host rock with most varying amounts of ore. Bjärnberg (2009) does not mention this. As it is difficult to make general statements from this study it should be tested further.

Chemistry

Diagrams of the bulk chemical composition (obtained for ZMAB by ACME Analytical Laboratories, Vancouver) of the Cu-ore are presented by Bjärnberg (2009). It is stated that the bulk chemical composition correlates well with the results obtained by Bjärnberg (2009) during her microscopic studies. The present study confirms further that the microscopic results link up with the bulk chemical analysis. The elements (Zn,Fe,Cu) and (Co,Ni,Sb) all show a major peak, where the richest ore zone is located. The lowest values are found for poor samples (Fig. 18).

The elements Fe, Co and Ni vary in pentlandite as described also by Bjärnberg (2009). The relation between grain size and Co content found by Bjärnberg (2009), could however, not be confirmed in. In this study only small quantities of fine grained pentlandite, suggested to be low in Co, is found. The heterogeneity that occurs in grains of pentlandite indicates a disequilibrium in the chemical system during crystallisation.

Perhaps, cobaltite (CoAsS) and safflorite ((Co,Fe)As₂) might in some way be related as since they have only been found in a single thin section and then together.

The low and high-Fe types of sphalerite indicate a disequilibrium of the chemical system, as in the case of pentlandite. As the two different types of sphalerite were not found in the same thin sections, they might have crystallised at different times.

Cubanite and chalcopyrite in the studied mineralization seem in some way related: chemical reactions between the two sulphide phases might not have come to an end during the ore forming process. The measured composition of cubanite seems not to be in equilibrium at many spots; the chemistry seems to be half way between the composition of cubanite and chalcopyrite.

Bjärnberg (2009) reported an excess of sulphur of about one atomic percent unit, for most sulphide

phases. A slight sulphur excess of about 0.5% in some sulphide phases can even be observed in this study, the statistical significance of this is not proven.

Additional work

A Cu-sulphide deposit at Tunaberg in south-east Bergslagen (Dobbe, 1991; Krs and Kropacek, 1987) shares many similarities with the Burkland Cu-mineralization of Zinkgruvan. At Tunaberg skarn host rock is common, chalcopyrite, bornite, pentlandite and Co-pentlandite occur as well as other Ni and Co-bearing minerals as e.g. cobaltite (CoAsS) (Krs and Kropacek, 1987). A comparative study between the Tunaberg and the Zinkgruvan Cu-deposit might be able to answer further questions.

In order to allow more representative conclusions, similar, comparative microscopic studies as done by Bjärnberg (2009) and in the present study, of drillcores in other parts of the Cu-mineralization would be interesting. This kind of studies, however, require besides the high drilling costs, quite some time. Alternative or additional to microscopic studies (2009), the use of geostatistics and numerical simulation for e.g. structural reconstruction as in (Annels et al., 1994) and ore resource evaluation combined with the results of the present study might be constructive tools to answer remaining questions.

6 Conclusions

- The major ore mineral of the carbonate hosted, Zinkgruvan Cu-mineralization is chalcopyrite (CuFeS_2), mostly occurring in aggregates.
- Other common ore minerals are: sphalerite, often in aggregates, pentlandite and magnetite both in aggregates and as disseminated grains and cubanite intimately intergrown as lamellae in chalcopyrite or as almost massive grains.
- Minor ore minerals are: breithauptite, cobaltite and pyrrhotite/mackinawite. They are found both in aggregates and as disseminated grains.
- No distinct mineral zoning is observed. With increasing ore grade, the number of different ore minerals is stable or even decreased. The highest number of different opaque minerals is found in the poorest sample
- The host rock composition influences the ore grade. Skarn seems to contain the highest quantities of ore minerals.
- The problematic elements Sb and As are found in nine different minerals. None of the major or common ore phases contain Sb or As. Two minor ore phases contain Sb (breithauptite) and As (cobaltite). No Hg or Bi is found. Most of the Sb or As is contained in rare minerals that are found in poor samples.
- The occurrence of Ag is linked to an extensive red to purple-blue tarnish of chalcopyrite. However, tarnishing is common also when no Ag is present.
- No major variation in chemistry is found in most opaque minerals. Exceptions are: pentlandite with varying amounts of (Fe,Co,Ni), sphalerite (low- and high Fe type) and safflorite with a Co-rich and a Fe-riche type.

Acknowledgements

I experienced the work on this study as very interesting and engaging during most of the time. This project remarkably helped me strengthen my skills of solving scientific problems. I wish to direct special words of grate at my supervisor at the Department of Geology in Lund, Anders Lindh. He sustained me during all stages of the project with instant and constructive feedback as well as very precise and helpful manuscript reviews. I also thank Karolina Bjärnberg who let me complement her study, for part of her samples and logs and all other information. Moreover thanks go to Lars Malmström at Zinkgruvan Mining AB who agreed on this supplementary project. The thin sections were skillfully prepared by Gerald Berthold at the Institute of Geosciences/University of Halle, Germany. In the end I like to thank my grandmother who's constant support in the final phase of this project I would not have been without.

References

- Annels, A.E., Ingram, S., and Malmstrom, L., 1994, Structural reconstruction and mineral resource evaluation at Zinkgruvan Mine, Sweden: Geological Society, London, Special Publications, v. 79, p. 171-189.
- Billström, K., 1991, Sulphur isotope compositions in the Ammeberg Zn-Pb ore deposit, south-central Sweden: genetic implications: *Geologische Rundschau/ Stuttgart*, v. 80, p. 717-727.
- Björnberg, K., 2009, The Copper Sulphide Mineralization of the Zinkgruvan Deposit, Bergslagen, Sweden [Master thesis]: Lund, Sweden, Lund University, pp. 62.
- Cathles, L.M., and Adams, J.J., 2005, Fluid Flow and Petroleum and Mineral Resources in the Upper (<20km) Continental Crust: Economic Geology and the Bulletin of the Society of Economic Geologists, 100th Anniversary-Volume, p. 77-110.
- De Groot, P.A., and Baker, J.H., 1992, High element mobility in 1.9-1.86 Ga hydrothermal alteration zones, Bergslagen, central Sweden: relationships with exhalative Fe-ore mineralizations: *Precambrian Research*, Elsevier Science Publishers B.V., Amsterdam, v. 54, p. 109-130.
- Dobbe, R.T.M., 1991, Tellurides, Selenides and Associated Minerals in the Tunaberg Copper Deposits, SE Bergslagen, Central Sweden: *Mineralogy and Petrology*, v. 44, p. 89-106.
- Evans, A.M., 1993, Ore geology and industrial minerals: an introduction: Oxford, Blackwell Scientific Publications, pp. 389.
- Galley, A.G., 1993, Characteristics of semi-conformable alteration zones associated with volcanogenic massive sulphide districts: *Journal of Geochemical Exploration*, v. 48, p. 175-200.
- Hedström, P., Simeonov, A., Malmstrom L, and Rickard, D., 1989, The Zinkgruvan ore deposit, south-central Sweden; a Proterozoic, proximal Zn-Pb-Ag deposit in distal volcanic facies: *Economic Geology and the Bulletin of the Society of Economic Geologists*, v. 84:5, p. 1235-1261.
- Henrigues, Å., 1964, Geology and ores of the Åmmeberg District (Zinkgruvan), Sweden: *Arkiv för mineralogi och geologi*, v. 4, p. 1-246.
- Ineson, P.R., 1989, Introduction to Practical Ore Microscopy: Essex, England, Longman Scientific & Technical, pp. 181.
- Krs, M., and Kropacek, V., 1987, A contribution to the magnetic properties of natural cobaltite: *Physics of the Earth and Planetary Interiors*, p. 227-232.
- Lehtinen, M., Nurmi, P.A., and Rämö, O.T., 2005, Geology of Finland — key to the evolution of the Fennoscandian Shield in *Condie, K.C., ed., Developments in Precambrian Geology* Elsevier Ltd, Amsterdam, p. 481–532.
- Lennie, A.R., England, K.E.R., and Vaughan, D.J., 1995, Transformation of synthetic mackinawite to hexagonal pyrrhotite: A kinetic study: *American Mineralogist*, v. 80, p. 960-967.
- Lindström, M., Lundqvist, J., and Lundqvist, T., 2000, Sveriges geologi från urtid till nutid: Lund, Studentlitteratur, pp.491.
- Magnusson, N.H., 1973, Malm i Sverige 1 (Mellersta och södra Sverige): Stockholm, Almqvist & Wiksell, pp. 320.
- Malmström, L., Hedström, P., and Syme, D., 2009, Mineral reserves and mineral resources of the Zinkgruvan Mine in South-Central Sweden, December 2008, Technical Report: Zinkgruvan, p. 1-66.
- Schouten, C., 1962, Determination Tables for Ore Microscopy: Amsterdam-New York, Elsevier Publishing Company, pp. 242.
- SGU, 2003, Tema: Koppar, Mineralmarknaden: Uppsala, Sveriges Geologiska Undersökningar, p. 36-69.
- , 2005, Tema: Arsenik, Mineralmarknaden: Uppsala, Sveriges Geologiska Undersökningar, p. 38-80.
- , 2009, Statistics of the Swedish Mining Industry 2008, Bergverksstatistik: Uppsala, Sveriges Geologiska Undersökningar, pp. 53.
- Sundblad, K., 1993, A genetic reinterpretation of the Falun and Ammeberg ore types, Bergslagen, Sweden: *Mineral. Deposita*, v. 29, p. 170-179
- Walters, S.G., 1998, Broken Hill type deposits: *Journal of Australian Geology & Geophysics*, v. 17, p. 229-237.

Weihed, P., Arndt, N., Billstroem, K., Duchesne, J.-C., Eilu, P., Martinsson, O., Papunen, H., and Lahtinen, R., 2005, Precambrian geodynamics and ore formation: The Fennoscandian Shield: Ore Geology Reviews, v. 27, p. 273-322.

Wenk, H.-R., and Bulakh, A., 2004, Minerals: their constitution and origin: Cambridge, Cambridge University Press, pp. 646.

Websites

Lundin Mining Co (2007):

http://www.lundinmining.com/s/NewsReleases.asp?ReportID=264901&_Type=News-Releases&_Title=Lundin-Mining-Plans-to-Quadruple-its-Zinc-Production-at-Neves-Corvo-and-Com...//
[News](#) Release: October 05,2007.

mindat.org: <http://www.mindat.org>

Webmineral.com:
<http://www.webmineral.com>

Appendix

Lists of the opaque phases in this study after chemical composition

Cu-Sulphides

- Chalcopyrite - CuFeS_2
- Cubanite - CuFe_2S_3
- Bornite - Cu_5FeS_4

(Fe, Co, Ni)- Sulphides

- Pentlandite - $(\text{Fe,Co,Ni})_9\text{S}_8$
- Pyrrhotite - Fe_7S_8 or $\text{Fe}_{(x-1)}\text{S}$
- Mackinawite - $(\text{Fe,Ni})_9\text{S}_8$ or $\text{Fe}_{(x+1)}\text{S}$

Other Sulphides

- Sphalerite - $(\text{Zn,Fe})\text{S}$
- Galena - PbS
- Molybdenite - MoS_2

Sulphantimonides

- Costibite - CoSbS
- Gudmundite - SFeSb
- Tetrahedrite - $(\text{Cu,Fe,Ag,Zn})_{12}\text{Sb}_4\text{S}_{13}$

Sulpharsenides

- Cobaltite - CoAsS

Antimonides

- Kieftite - CoSb_3
- Breithauptite - NiSb

Arsenides

- Safflorite - $(\text{Co,Fe,Ni})\text{As}_2$
- Maucherite - $\text{Ni}_{11}\text{As}_8$
- Nickeline - NiAs

Native element

- Silver - Ag

Oxide

- Magnetite - Fe_3O_4

This study**Bjärnborg (2009)****Major ore phases**

Chalcopyrite	- CuFeS ₂ -	Chalcopyrite	Cha
	- CuFe ₂ S ₃ -	Cubanite	Cub
	- Cu ₅ FeS ₄ -	Bornite	Bor

Common ore phases

Cubanite			
Sphalerite	- (Zn,Fe)S -	Sphalerite	Sph
Pentlandite	- (Fe,Co,Ni) ₉ S ₈ -	Pentlandite	Pen
Magnetite	- Fe ₃ O ₄ -	Magnetite	Mag
	- 4(Fe,Cu)S ₃ (Mg,Al)		
	(OH) ₂ -	Valleriite	
	- (Fe,Ni) ₉ S ₈ -	Mackinawite	Mac

Minor ore phases

Mackinawite/pyrrhotite	- Fe _(1+x) S/Fe _(1-x) S-	Pyrrhotite	Pyr
Breithauptite	- NiSb -	Breithauptite	Brei
Cobaltite	- CoAsS -	Cobaltite	Cob
		Galena	Gal

Rare minerals

Galena	- PbS -		
Bornite			
Gudmundite	- SFeSb -	Gudmundite	Gud
Safflorite	- (Co,Fe,Ni)As ₂ -	Safflorite	Saf
Molybdenite	- MoS -	Molybdenite	Mol
Tetrahedrite	- (Cu,Fe,Ag,Zn) ₁₂ Sb ₄ S ₁₃ -	Tetrahedrite	Tet
Nickeline	- NiAs -	Nickeline	Nic
Costibite	- CoSbS -	Costibite	Cos
Maucherite	- Ni ₁₁ As ₈ -	Maucherite	Mau
Silver	- Ag -	Silver	Ag

Not found in Bjärnborg (2009)

Kieftite	- CoSb ₃ -	Kie
----------	-----------------------	-----

Not found in this study

Chalcocite
Allargentum
Bismuth
Parkerite
Graphite
Arsenopyrite

Chemical composition by EDS-analysis of Zinkgruvan Burkland Cu-mineralization drillcore DBH2992
Sample 91.80m—109.71m (all elements in atomic percentage)

Major ore phase

Chalcopyrite - CuFeS₂					
	S	Fe	Cu	Ag	Sum(weight%)
91m/6	50,84	24,29	24,59		99,68
91m/6	51,13	24,35	24,24		98,26
93m/3.1	50,7	24,91	24,39		102,51
95m/7	49,42	24,78	25,8		99,27
95m/7	48,99	24,5	26,51		99,93
97m/1	50,86	23,79	23,59	1,76	98,97
97m/2	51,25	23,94	24,05	0,77	100,38
97m/2	51,23	24,68	24,09		99,93
97m/2	50,31	23,55	22,49	3,65	98,09
97m/3	50,61	24,06	24,21	1,12	99,87
97m/7	50,79	25,02	24,19		98,95
103m/6	50,69	24,51	24,8		99,75
105m/8	49,89	25,36	24,75		97,46
109m/7	51,14	24,16	23,8	0,9	99,04
Min	48,99	23,55	22,49		
Max	51,25	25,36	26,51		
Mean	50,56	24,42	24,39		

Common ore phases

Cubanite - CuFe₂S₃				
	Cu	Fe	S	Sum (weight%)
105m/8	16,68	33,4	49,91	98,06
105m/9	16,85	33,18	49,98	98,96
Intermediate composition: chalcopyrite/cubanite				
95m/2	22,71	29,94	47,22	106,53
95m/4.1	22,64	30	47,35	97,64
107m/5.2	22,25	30,37	47,38	106,79
107m/8.1	22,77	30,48	46,49	101,55
Min	22,25	29,94	46,49	
Max	22,77	30,48	47,38	
Mean	22,59	30,19	47,11	

Sphalerite - (Zn,Fe)S

Low Fe-group	Zn	Fe	S	Sum(weight%)
93m/6	47,41	0,79	49,55	104,76
93m/3.1	42,64	3,9	49,64	101,93
109m/8	44,9	3,86	51,24	99,83
109m/12	43,82	4,35	51,84	97,36
High Fe-group				
95m/3	41,04	7,28	49,74	99,88
103m/2	42,55	5,76	50,84	99,38
105m/7	43,9	5,31	50,79	99,77
107m/5.1	40,94	7,6	50,02	100,19
All				
Min	40,94	0,79	49,55	
Max	47,41	7,6	51,84	
Mean	43,4	4,856	50,45	
Low- Fe				
Min	42,64	0,79	49,55	
Max	47,41	4,35	51,84	
Mean	44,69	3,22	50,56	
High- Fe				
Min	40,94	5,31	49,74	
Max	43,9	7,6	50,84	
Mean	42,10	6,48	50,34	

Iron Oxide - Fe₃O₄

	Fe	O	Sum(weight%)
93m/3.2	45,33	54,24	106,46
93m/7.1	44,62	55,38	108,76
93m/7.1	44,26	55,08	106,55
93m/7.2	38,53	61,47	107,52
95m/4.2	40,9	58,9	95,18
95m/4.2	39,98	59,8	100,94
95m/6	41,04	58,96	96,95
Min	38,53	54,24	
Max	45,33	61,47	
Mean	42,09	57,69	

Pentlandite - (Fe,Co,Ni)₉S₈

	S	Fe	Co	Ni	Ag	Total (weight%)
91m/1	47,75	19,97	8,17	24,11		99,42
91m/5.1	47,66	17,07	12,67	22,33		98,09
97m/4	47,12	16,68	18,1	18,1		102,33
99m/1	48,12	24,71	3,9	23,27		99,58
99m/8	48,59	18,85	14,85	17,71		97,48
99m/9	48,56	19,7	12,09	19,65		98,64
99m/13.1	48,12	24,43	4,04	23,42		100,21
99m/13.2	47,75	25,67	3,93	22,65		100,8
99m/13.2	48,32	25,62	3,33	22,73		98,88
101m/4	47,16	15,97	19,11	17,37		100,49
101m/5.2	47,17	17,23	17,38	18,22		99,43
101m/7	47,32	17,49	16,88	18,3		102,94
101m/8	47,79	16,25	20,08	15,88		101,42
103m/2	47,89	15,12	20,29	15,33		100,8
103m/7	47,68	13,84	23,45	15,03		100,99
109m/1	47,68	19,5	8,86	23,96		101,58
109m/3	48,19	20,35	7,87	23,59		98,36
105m/7	47,25	17,27	17,73	14,24		98,85
105m/9	47,07	15,64	20,34	16,95		98,59
109m/6	48,07	17,93	12,49	21,51		100,73
109m/7	48,43	17,54	12,46	21,43	0,13	99,8
109m/8	47,72	12,88	21,76	17,64		100,7
109m/15	47,71	17,04	13,28	21,97		101,05
Min	47,07	12,88	3,33	14,24		
Max	48,59	25,67	23,45	24,11		
Mean	47,79	18,55	13,61	19,78		

Minor ore phases
Cobaltite - CoAsS

	Co	As	S	Fe	Ni	Sum(weight%)
91m/8.2	26,96	33,81	33,95	2,81		100,14
99m/11	25,72	35,44	31,96	2	4,89	103,32
103m/6	31,05	33,71	34,28	0,96		100,31
103m/A1	29,1	34,72	34,25	1,93		96,89
105m/4	27,2	34,83	31,39	2,32	4,26	100,58
107m/16	28,36	33,45	32,99	2,99		101,31
109m/14	25,35	34,89	31,99	2,51	5,25	104,51
109m/2	25,27	33,81	33,07	1,65	6,2	104,39
109m/4	30,71	33,3	33,22	0,52	2,24	102,22
109m/5	25,65	33,71	33,61	2,07	4,96	104,12
Min	25,27	33,3	31,39	0,52	2,24	
Max	31,05	35,44	34,28	2,99	6,2	
Mean	27,54	34,17	33,07	1,98	4,63	

Pyrrhotite Fe7S8 also $\text{Fe}(1-x)\text{S}$, $x=0-0.17$ ($\text{Fe} \leq \text{S}$)

	Fe	Ni	S	Cu	Al	Sum(weight%)
Grey						
97m/2	44,69	3,62	51,69			99,41
97m/3	44,81	3,64	51,55			99,11
99m/2.1	44,05	4,59	51,36			99,94
99m/2.2	44,5	4,16	51,34			100,03
101m/2	44,35	4,15	50,43	0,75	0,33	99,65
101m/3.2	45,11	3,71	50,48	0,33	0,37	97,97
101m/10	44,56	4,24	51,19			100,52
101m/6	44,42	4,53	51,04			100,84
101m/7	44,95	3,26	51,8			98,65
Pink						
99m/6.1	44,69	4,39	50,92			100,47
101m/2	44,38	3,98	50,69	0,6	0,35	99,23
101m/3.1	44,07	4,15	50,7	0,2	0,47	98,86
103m/3.2	43,14	4,27	51,67	0,92		97,1
Min	43,14	3,26	50,43	0,2	0,33	
Max	45,11	4,59	51,8	0,92	0,47	
Mean	44,44	4,053	51,143	0,56	0,38	

Mackinawite (Fe,Ni)9S8 also $(\text{Fe,Ni})(1+x)\text{S}$ ($(\text{Fe,Ni}) \geq \text{S}$)

	Fe	Ni	S	Co	Cu	Sum(weight%)
Grey						
95m/1	50,62	3,15	44,8	1,43		98,5
95m/1	49,86	3,11	45,07	1,96		99,16
Pink						
95m/4.1	50,83	3,81	44,4	0,3	0,54	99,09
95m/4.1	50,57	3,69	44,78	0,54	0,42	97,81
Min	50,57	3,69	44,4	0,3	0,42	
Max	50,83	3,81	44,78	0,54	0,54	
Mean	50,7	3,75	44,59	0,42	0,48	
107m/2	53,76		46,24			113,97
107m/3	53,31		46,69			113,81

Breithauptite - NiSb

	Ni	Sb	As	Sum(weight%)
95m/1	49,9	50,1		99,28
95m/5	49,58	49,67	0,75	99,29
97m/5	48,8	51,2		99,85
99m/6.2	50,2	49,8		100,8
99m/10	49,81	50,19		100,48
99m/14	49,45	50,55		101,9
101m/1	49,74	50,26		102,36
103m/3.1	49,41	49,53	1,06	103,05
103m/3.1	49,59	49,49	0,92	102,63
105m/4	49,59	46,67	3,74	99,42
105m/5	49,54	46,38	4,08	99,55
105m/6	49,86	50,14		98,82
107m/4	49,03	49,9	1,06	97,74
107m/5.2	48,93	50,28	0,44	97,17
107m/7	48,57	50,16	1,27	96,82
109m/5	48,77	49,41	1,82	102,01
109m/13	49,09	48,58	2,33	100,39
Min	48,57	46,38	0,44	
Max	50,2	51,2	4,08	
Mean	49,41	49,55	1,75	

Rare minerals

Bornite - Cu₅FeS₄

	Cu	Fe	S	Sum(weight%)
93m/7.1	46,8	14,04	39,16	103,53
93m/7.2	48,59	10,8	40,61	103,09
93m/9	48,77	10,19	41,03	102,62
105m/1	50,06	10,07	39,87	99,17
Min	46,8	10,07	39,16	
Max	50,06	14,04	41,03	
Mean	48,55	11,27	40,17	

Galena - PbS

	Pb	S	Sum(weight%)
99m/12	49,56	50,44	96,01
101m/5.	50,05	48,89	94,14
103m/1	49,14	50,86	95,13
Min	49,14	48,89	
Max	50,05	50,86	
Mean	49,58	50,06	

Safflorite (Co,Fe,Ni)As₂

Co-type	Co	Fe	Ni	As	S	Sb	Sum(weight%)
95m/6	17,78	9,31	6,72	64,13	2,05		99,81
99m/11	16,93	8,77	7,11	63,92	1,74	1,53	105,5
Min	16,93	8,77	6,72	63,92	1,74		99,81
Max	17,78	9,31	7,11	64,13	2,05		105,5
Mean	17,35	9,04	6,92	64,03	1,9		
Fe-type							
107m/8.2	10,93	18,75	5,67	61,31	3,34		100,45

Molybdenite - MoS₂			
	Mo	S	Sum(weight%)
91m/7	31,04	62,23	105,48
91m/7	30,76	61,55	112,64
109m/10	31,48	68,52	103,35
Min	30,76	61,55	
Max	31,48	68,52	
Mean	31,093	64,1	

Gudmundite - SFeSb				
	S	Fe	Sb	Sum(weight%)
93m/9	30,32	29,48	30,85	104,42
97m/5	33,65	32,06	34,29	99,84
97m/5	34,01	31,95	34,03	98,81
Min	30,32	29,48	30,85	
Max	34,01	32,06	34,29	
Mean	32,66	31,163	33,06	

Rare minerals that occur only once

Nickeline - NiAs						
	Ni	As	Sb	Fe	Co	Sum(weight%)
107m/8.2	47,94	46,19	3,73	1,01	1,13	94,48

Costibite - CoSbS						
	Co	Sb	S	As	O	Sum(weight%)
93m/6	28,63	34,08	31,66	0,56	5,07	100,65

Tetrahedrite - (Cu,Fe,Ag,Zn)₁₂Sb₄S₁₃							
	Cu	Fe	Zn	Sb	S	O	Sum (weight%)
93m/9	32,86	2,85	3,89	12,67	41,88	5,85	99,34

Silver - Ag		
	Ag	Sum(weight%)
109m/7	100	104,53

Maucherite - Ni₁₁As₈					
	Ni	As	Sb	Fe	Sum (weight%)
109m/9	56,12	37,39	5,69	0,8	102,97

Kieftite - CoSb₃				
	Co	Sb	O	Sum(weight%)
93m/6	22,03	70,17	7,8	102,92

**Tidigare skrifter i serien
”Examensarbeten i Geologi vid Lunds
Universitet”:**

200. Vollert, Victoria, 2006: Petrografisk och geokemisk karaktärisering av metabasiter i Herrestadsområdet, Småland.
201. Rasmussen, Karin, 2006: En provenansstudie av Kågerödformationen i NV Skåne – tungmineral och petrografi.
202. Karlsson, Jonnina, P., 2006: An investigation of the Felsic Ramiane Pluton, in the Monapo Structure, Northern Moçambique.
203. Jansson, Ida-Maria, 2006: An Early Jurassic conifer-dominated assemblage of the Clarence-Moreton Basin, eastern Australia.
204. Striberger, Johan, 2006: En lito- och biostratigrafisk studie av senglaciala sediment från Skuremåla, Blekinge.
205. Bergelin, Ingemar, 2006: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of basalts in Scania, S Sweden: evidence for two pulses at 191-178 Ma and 110 Ma, and their relation to the break-up of Pangea.
206. Edvarsson, Johannes, 2006: Dendrokronologisk undersökning av tallbestånds etablering, tillväxtdynamik och degenerering orsakat av klimatrelaterade hydrologiska variationer på Viss mosse och Åbuamossen, Skåne, södra Sverige, 7300-3200 cal. BP.
207. Stenfeldt, Fredrik, 2006: Litostratigrafiska studier av en platåformad sand- och grusavlagring i Skuremåla, Blekinge.
208. Dahlenborg, Lars, 2007: A Rock Magnetic Study of the Åkerberg Gold Deposit, Northern Sweden.
209. Olsson, Johan, 2007: Två svekofenniska graniter i Bottniska bassängen; utbredning, U-Pb zirkondatering och test av olika abrasionstekniker.
210. Erlandsson, Maria, 2007: Den geologiska utvecklingen av västra Hamrängesyklinalens suprakrustalbergarter, centrala Sverige.
211. Nilsson, Pernilla, 2007: Kvidingedeltat – bildningsprocesser och arkitektonisk uppbyggnadsmodell av ett glacifluvialt Gilbertdelta.
212. Ellingsgaard, Óluva, 2007: Evaluation of wireline well logs from the borehole Kyrkheddinge-4 by comparison to measured core data.
213. Åkerman, Jonas, 2007. Borrkärnekartering av en Zn-Ag-Pb-mineralisering vid Stenbrånet, Västerbotten.
214. Kurlovich, Dzmitry, 2007: The Polotsk-Kurzeme and the Småland-Blekinge Deformation Zones of the East European Craton: geomorphology, architecture of the sedimentary cover and the crystalline basement.
215. Mikkelsen, Angelica, 2007: Relationer mellan grundvattenmagasin och geologiska strukturer i samband med tunnelborrning genom Hallandsås, Skåne.
216. Trondman, Anna-Kari, 2007: Stratigraphic studies of a Holocene sequence from Taniente Palet bog, Isla de los Estados, South America.
217. Månsson, Carl-Henrik & Siikanen, Jonas, 2007: Measuring techniques of Induced Polarization regarding data quality with an application on a test-site in Aarhus, Denmark and the tunnel construction at the Hallandsås Horst, Sweden.
218. Ohlsson, Erika, 2007: Classification of stony meteorites from north-west Africa and the Dhofar desert region in Oman.
219. Åkesson, Maria, 2008: Mud volcanoes - a review. (15 hskp)
220. Randsalu, Linda, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins. (30 hskp)
221. Fredh, Daniel, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta4 basin. (30 hskp)
222. Anjar, Johanna, 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-central Sweden. (30 hskp)
223. Stefanowicz, Sissa, 2008: Palynostratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland. (15 hskp)
224. Holm, Sanna, 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga. (15 hskp)
225. Bjärnberg, Karolina, 2008: Internal structures in detrital zircons from Hamråde: a study of cathodolumine-

- science and back-scattered electron images. (15 hskp)
226. Noresten, Barbro, 2008: A reconstruction of subglacial processes based on a classification of erosional forms at Ramsviklandet, SW Sweden. (30 hskp)
227. Mehlqvist, Kristina, 2008: En mellanjurassisk flora från Bagå-formationen, Bornholm. (15 hskp)
228. Lindvall, Hanna, 2008: Kortvariga effekter av tefranedfall i lakustrin och terrestrisk miljö. (15 hskp)
229. Löfroth, Elin, 2008: Are solar activity and cosmic rays important factors behind climate change? (15 hskp)
230. Damberg, Lisa, 2008: Pyrit som källa för spårämnen – kalkstenar från övre och mellersta Danien, Skåne. (15 hskp)
331. Cegrell, Miriam & Mårtensson, Jimmy, 2008: Resistivity and IP measurements at the Bolmen Tunnel and Ådalsbanan, Sweden. (30 hskp)
232. Vang, Ina, 2008: Skarn minerals and geological structures at Kalkheia, Kristiansand, southern Norway. (15 hskp)
233. Arvidsson, Kristina, 2008: Vegetationen i Skandinavien under Eem och Weichsel samt fallstudie i submoräna organiska avlagringar från Nybygget, Småland. (15 hskp)
234. Persson, Jonas, 2008: An environmental magnetic study of a marine sediment core from Disko Bugt, West Greenland: implications for ocean current variability. (30 hskp)
235. Holm, Sanna, 2008: Titanium- and chromium-rich opaque minerals in condensed sediments: chondritic, lunar and terrestrial origins. (30 hskp)
236. Bohlin, Erik & Landen, Ludvig, 2008: Geofysiska mätmetoder för prospektering till ballastmaterial. (30 hskp)
237. Brodén, Olof, 2008: Primär och sekundär migration av hydrokarboner. (15 hskp)
238. Bergman, Bo, 2009: Geofysiska analyser (stångslingram, CVES och IP) av lagerföljd och lakvattenrörelser vid Albäcksdeponin, Trelleborg. (30 hskp)
239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)
239. Mehlqvist, Kristina, 2009: The spore record of early land plants from upper Silurian strata in Klinta 1 well, Skåne, Sweden. (45 hskp)
240. Bjärnberg, Karolina, 2009: The copper sulphide mineralization of the Zinkgruvan deposit, Bergslagen, Sweden. (45 hskp)
241. Stenberg, Li, 2009: Historiska kartor som hjälp vid jordartsgeologisk kartering – en pilotstudie från Vångs by i Blekinge. (15 hskp)
242. Nilsson, Mimmi, 2009: Robust U-Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland: constraints on the coherency of crustal blocks of the North Atlantic Craton. (30 hskp)
243. Hult, Elin, 2009: Oligocene to middle Miocene sediments from ODP leg 159, site 959 offshore Ivory Coast, equatorial West Africa. (15 hskp)
244. Olsson, Håkan, 2009: Climate archives and the Late Ordovician Boda Event. (15 hskp)
245. Wolle Waldetoft, Kristofer, 2009: Svekofennisk granit från olika metamorfa miljöer. (15 hskp)
246. Månsby, Urban, 2009: Late Cretaceous coprolites from the Kristianstad Basin, southern Sweden. (15 hskp)
247. MacGimpsey, I., 2008: Petroleum Geology of the Barents Sea. (15 hskp)
248. Jäkel, O., 2009: Comparison between two sediment X-ray Fluorescence records of the Late Holocene from Disko Bugt, West Greenland; Paleoclimatic and methodological implications. (45 hskp)
249. Andersen, Christine, 2009: The mineral composition of the Burkland Cu-sulphide deposit at Zinkgruvan, Sweden – a supplementary study. (15 hskp)



LUNDS UNIVERSITET