Mineralogical, chemical and textural properties of the Malmberget iron deposit
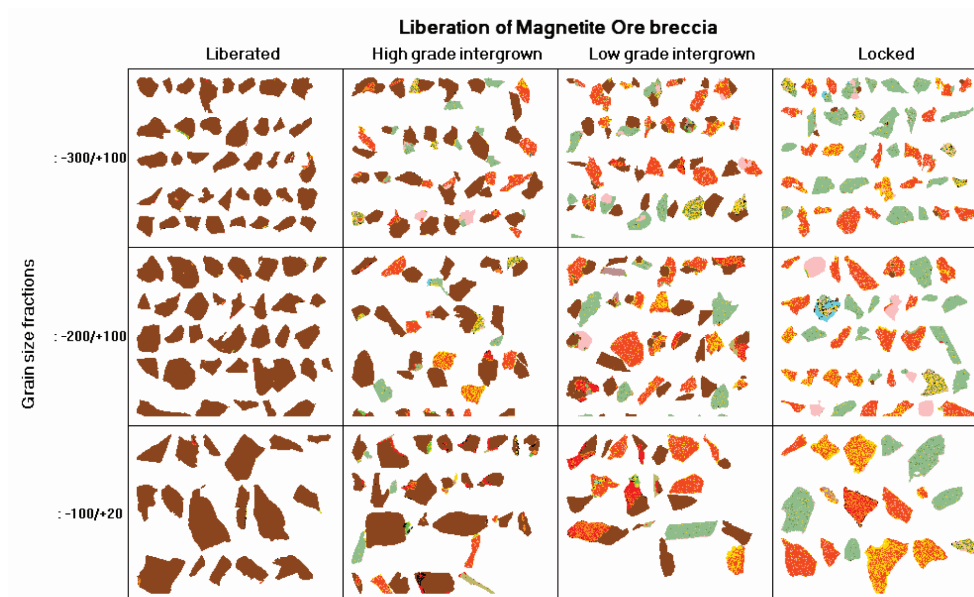
A process mineralogically characterisation

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Cover picture: An image grid report created in iDiscover visualising the particle liberation in ore breccia.

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ABSTRACT

This thesis combine two different but closely connected disciplines in a mining process to each other, ore geology and process mineralogy by studying mineralogical-textural features of the ore and the ore concentrate in an apatite iron ore deposit in Malmberget, Sweden. Apatite iron ore deposits (Kiruna type) exist in a few places around the world and the two most important deposits are mined by LKAB at Kiruna and Malmberget. Their contribution to the global iron ore market is minor but on a local scale these high grade deposits have a large economical importance.

Three different ore bodies from the Malmberget deposit are included in the study; Hens, ViRi and Fabian. Each of these three ore bodies has characteristic mineralogy, chemical and textural properties. The first paper (Paper I) describes the metamorphic influence on the ore, particular the chemical and textural effects on the ore minerals. The ore bodies Fabian and ViRi have a similar mineralogy by the occurrence of Ti-minerals, pyrite and chalcopyrite as common minor components. Hematite is only present in Hens ore body. Magnetite from the different ore bodies and ore types show a chemical variation of the minor elements V_2O_3, TiO_2, Al_2O_3, and MgO. Our data support a model with the massive ore formed from an iron oxide melt while the ore breccia is part of the same ore forming system but of hydrothermal origin.

The second and third paper is about process mineralogy.
Paper two (Paper II) characterise the mineralogical properties of an apatite iron ore body in a quantitative manner by using an automated SEM based system QEMSCAN®. Two major ore types were used; massive ore and ore breccia. Each ore type was crushed and split in the fractions 150 μm, 75 μm and 38 μm. The results show a rather distinct difference between these two ore types, both in the mineralogy but particularly in their textural properties. The particle liberation of magnetite is high for massive ore, being much lower for ore breccia and has a decreasing liberation in finer fractions in each ore type. This has to do with grain size, mineralogy and textures of the magnetite and the gangue minerals. The mineral associations of ore breccia are more diverse than of massive ore by the presence of more binary and complex magnetite bearing particles. Ore breccia is an ore type where some of the magnetite bearing associations will cause an increasing amount of silica in the concentrate or iron content to the tailings.

Paper three (Paper III) shows that is possible to find traceability in a concentration process by identifying significant mineralogical signatures in the ore and in the concentrate. Two possibly useful mineralogical signatures were found. The first is a rather simple association between magnetite and apatite existing as mixed grain and the second is a complex texture with smaller magnetite grains as inclusions in feldspars grains. These signatures can probably be used as a fingerprint for different ore types, particle fractions and grinding circuit which can create traceability in the process.

The results from these two instruments show some differences, QEMSCAN® compared to PTA generate analysis which being more accurate and precise due to the amount of data in each sample.

Keywords: *Process mineralogy, QEMSCAN®, PTA, modal mineralogy, particle liberation, texture, textural association, mineral chemistry, magnetite, hematite, apatite-iron ore, Kiruna type*

SWEDISH ABSTRACT

I den här avhandlingen förenas två olika, men i en gruvprocess närliggande discipliner, malmgeologi och processmineralogi. Det sker genom att studera de mineralogiska-texturella egenskaperna om hur malmen ser ut i fast klyft och hur malmkoncentratet beter sig i en anrikningsprocess. Fyndigheten som studerats är LKAB:s apatitjärnmalm i Malmberget. Apatitjärnmalmer (av Kirunatyp) finns på ett fåtal platser runt om i världen och de två mest betydande fyndigheterna bryts idag av LKAB i Kiruna och Malmberget. Sett till den globala järnmalm marknaden är produktionen liten men i en lokal skala är dessa höghaltiga järnmalmer av största ekonomiska vikt.

Tre olika malmkroppar ingår i denna studie Hens, ViRi och Fabian. Dessa är karaktäriserade i avseende på mineralogi, kemi och texturella egenskaper.

Det första manuskriptet (Paper I) beskriver malmmineralen kemiskt och texturellt med tyngdpunkten på inverkan av den metamorfa överpräglingen. Mineralogiskt är ViRi och Fabian liknande, med avseende på förekomsten av Ti-mineral, pyrit och kopparkis. Hens skiljer sig från dessa två malmkroppar genom förekomsten av hematit. Magnetit från olika malmkroppar och malmtyper visar en kemisk variation mellan elementen TiO_2, V_2O_3, Al_2O_3 och MgO. Magnetit från den massiva delen av Fabian malmkropp har kemiska likheter med andra apatitjärnmalmer och kan ursprungligen ha bildats genom kristallisation från en järnoxidmagma eller genom hydrotermala processer under höga temperaturer. Magnetit från malmbreccia har bildats under lägre temperatur och andra hydrotermala förhållanden.

Det andra och tredje manuskriptet handlar om processmineralogi.

I manuskript två (Paper II) görs en kvantitativ mineralogisk karaktärisering av malmkroppen Fabian mineralogiskt genom att använda ett automatiserat SEM baserat system kallat QEMSCAN®. Två olika malmtyper *massiv malm* och *malmbreccia* har nedkrossats och siktats i tre fraktioner 150µm, 75µm och 38µm. Det är stor skillnad mellan malmtyperna både i avseende på mineralogin men även deras texturella egenskaper. Den modala mineralogin visar att malm breccia innehåller högre andel gångartsmineral. Magnetit från *malm* har en hög frikrossningsgrad medan den är lägre för *malmbreccia*. Båda malmtyperna visar en minskande frikrossningsgrad finare fraktioner. Detta är ett resultat av kornstorlek, mineralogi och textur av både magnetit och gångartsmineral. Mineralassociationerna i *malmbreccia* är fler och mer komplexa än i *malm* och oavsett om mineralassociationer med magnetit hamnar i koncentratet eller avfallet så ökar kiselhalten i koncentratet eller så ökar järnhalten i avfallet.

Manuskript tre (Paper III) beskriver en metod att hitta spårbarhet i anrikningsprocessen i Malmberget genom att påvisa och identifiera signifikanta mineralogiska signaturer både i malmen (fast klyft) och i anrikningskoncentratet. Två möjliga mineralogiska signaturer påvisades. Det är dels en enkel association med halvkorn bestående av magnetit och apatit och dels en mer komplicerad textur där små magnetitkorn sitter som inneslutningar inne i fältspatskorn. Dessa identifierade signaturer kan förmodligen fungera som "fingeravtryck" för olika malmtyper, partikel fraktioner och malningskretsar och kan därigenom användas till spårbarhet genom processen.

Nyckelord: *Processmineralogi, QEMSCAN®, PTA, modalmineralogi, partikelfrikrossning, textur, texturella associationer, mineralkemi, magnetit, hematit, apatitjärn malm, Kirunatyp,*

PREFACE

This licentiate thesis *"Mineralogical, chemical and textural properties of the Malmberget iron deposit – A process mineralogically characterisation"* consists of three manuscripts.

I   **Lund, C.**, Andersen, J. C. Ø., Martinsson, O. Magnetite chemistry, textural and mineralogical aspects of the metamorphosed apatite iron ore, Malmberget, Sweden *(to be submitted)*

II   **Lund, C.**, Rollinson, G. K., Martinsson, O. A quantitative mineralogical characterisation of the Malmberget apatite-iron deposit, Sweden, using QEMSCAN® *(to be submitted)*

III   Oghazi, P., **Lund, C.**, Pålsson, B., Martinsson, O. Applying traceability in a mine-to-mill context by using Particle Texture Analysis *(submitted)*

The following abstracts have been published in conference proceedings, but are not included in the licentiate thesis.

      Lund, C., Martinsson, O. A characterising of the ore minerals due to the mineralogy, chemical and textural properties in Malmberget. Conference in Minerals Engineering, Luleå, Sweden, February 2008, pp 71-80 [Extended abstract]

      Lund, C., Martinsson, O. Trace-element chemistry of magnetite from the Malmberget apatite-iron ore. Conference, the 33rd International geological congress Oslo, Norway 2008 [Abstract]

ACKNOWLEDGEMENT

INTRODUCTION

The northern Norrbotten ore province, located in the northern part of Sweden (fig 1), is an important mining area with a several economic deposits. These are epigenetic Cu-Au ores (Pahtohavare, Aitik), stratiform Cu deposit (Viscaria), iron deposits; skarn iron ore (Stora Sahavaara) and apatite iron ores of the Kiruna type (Kiirunavaara, Malmberget) (fig 1). Mine companies, with a long tradition of mining, coexist with minor mining- and exploration companies in order to extract metals and minerals, with iron ore as one of the most important commodity for the demanding global market. The production of crude steel has increased for the last couple of years and the market is tough. It is necessary for the iron ore producers to offer products of good quality and knowledge about the included relevant elements of the product. It is also important to have control over the refinement process and to be able to solve problems of a process mineralogical character, especially in a profitably point of view in times of increasing competition and when the steel market is turning downward.
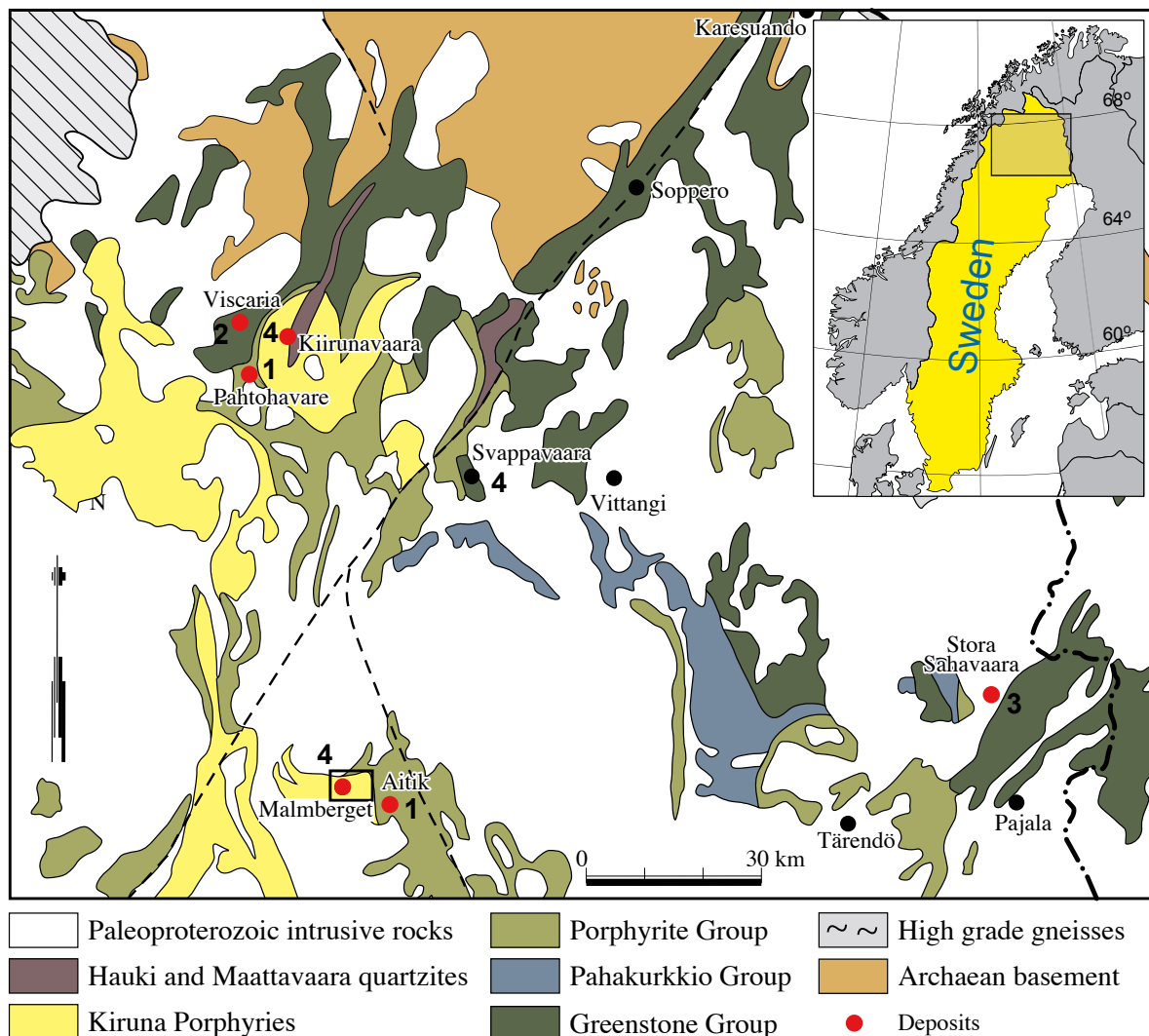

Fig. 1. Simplified geological map of the northern Norrbotten ore province with the economic deposits market in red modified from (Martinsson et al., 2004) 1) Epigenetic Cu-Au 2) Stratiform Cu deposit 3) Skarn iron ore 4) Apatite iron ores

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Mining history

The Malmberget deposit has probably been known since 1735 and there are many mining pioneers during history that have tried to make the deposit profitable. An often returning problem has been the transportation of ore across the Norrbotten wilderness. The invention of the Thomas process to get steel of good quality from high phosphorous ore 1878 made the giant ore reserves in Kiruna and Malmberget very attractive and LKAB (Luossavaara-Kiirunavaara AB) was established at 1890 to exploit these deposits. To get profitability a railway had been discussed for a long time and in 1888, in a period of four years, a railway was completed between Malmberget and Luleå. Initially, the Malmberget ore was pit-mined, but since the mid-1920s, all production has been underground (LKAB, 2006). Today LKAB is contributing to 90 % of Europe's iron ore production from two large underground mines at Kiruna and Malmberget. From the beginning the high phosphorus ore could be sold as lump ore but to be competitive on the market LKAB was forced to start a qualitative work on upgraded products and to specialize on the pellets products. The first pelletizing plant began to operate in Malmberget 1955 (LKAB, 2006). Since then the focus and the demand have been on the concentration properties of the ore and pelletization of the concentrate. Today the company is a minor niche supplier of iron ore pellets and provide the global market by approximately 2-3 % (LKAB, 2006).

The name of the ore bodies in Malmberget

In the Malmberget ore field all the mining-claims (synonymous ore body or mine) from the past until today are named after war ships, special occasions or important persons, often with a royal origin or a connection from the nobility. At 1970 it was approximately 180 mining-claims. Most of them are still existing today but some of them have disappeared (Nilsson, 1999) (fig. 2). This study includes three different ore bodies and the history of the names will be described briefly.

Hens (Hermelin–Nedre Skåne) ore body was from the beginning two different bodies, Hermelin and Skåne (LKAB, pers. comm.). Hermelin is a magnetite ore and was named after baron Samuel Gustaf Hermelin and he was known as a great industrialist in Norrbotten during the 18th century (Nilsson, 1999; LKAB, 2006). Skåne was mainly a hematite ore body with a little part in the north constituting of magnetite. The name is derived from the duke of the county Skåne, prince Karl who later became king Karl XV of Sweden (Nilsson, 1999)

ViRi (Vitåfors – Riddarstolpe) is historically two ore bodies merged into one large body. The Vitåfors ore body is named after the river close to the mine. The mine has in turn given its name to the mine industry area which is placed between the river and the ore body. The Riddarstolpe ore was a small body and has been known for a long time. It was claimed 1798 and named after a president in the national board of mining (Bergskollegium) Fredrik Wilhelm Riddarstolpe who became earl and member of the Swedish royal Supreme Court (Nilsson, 1999).
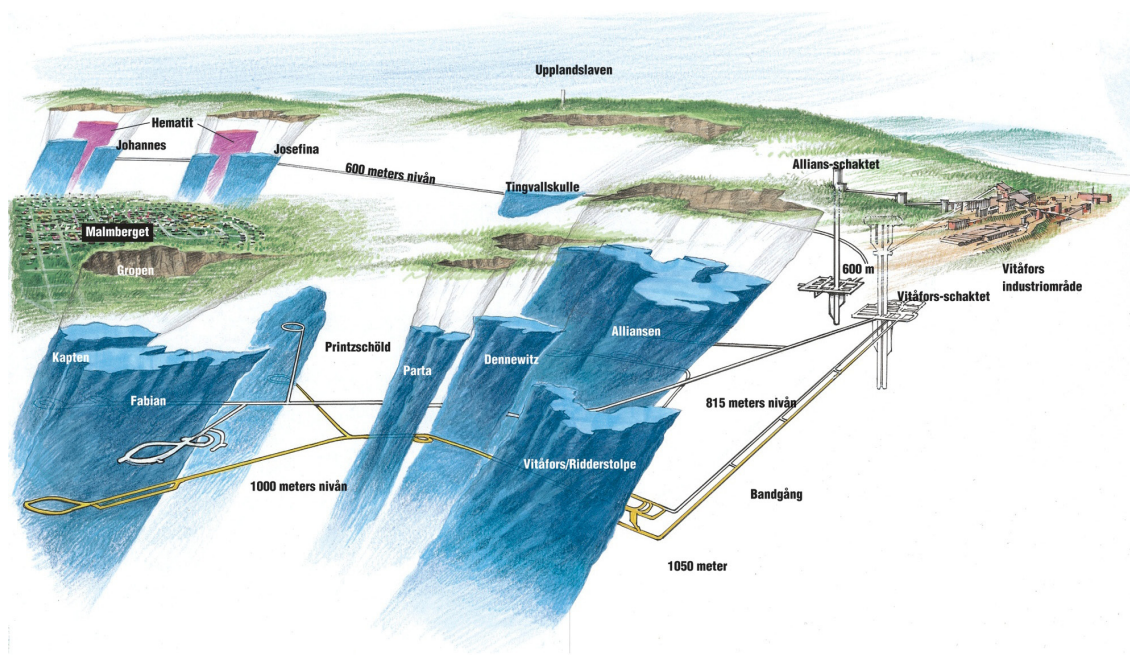
Fig.2. A schematic 3D-picture illustrating the ore bodies at the Malmberget mine. From LKAB photo archive.

Fabian ore is a magnetite ore body located south of the great Kaptenslagret that has only been mined underground. The ore body is named after earl Fabian Wrede but he had nothing to do with the mine himself. Instead it was the king Carl XIV Johan who was concerned about the name-giving of the different mining-claims at Malmberget. He wanted to honour Fabian Wrede who had supported his candidature to become the next king of Sweden (Nilsson, 1999).

AIM

This study connects two different but close disciplines (in the mining industry) to each other by improving the mineralogical-textural knowledge of the ore and the ore concentrate. The first discipline is ore geology; the object is to describe the mineralogy and chemical variations of different ore bodies and ore types but also to characterise the mineral chemistry of the ore minerals. By understanding the metamorphic influence, particular the chemical and textural effect on the ore minerals this study could also contribute to the controversial discussion of the origin of the apatite iron ore (Kiruna type). The second discipline is process mineralogy; the object is to characterise the ore minerals, its ability of liberation, the mineral associations and textures but also to identify specific mineral associations, common for a certain type of ore body and ore type. These mineral associations could act as a signature and create traceability in the process chain during the concentration. By improving the mineralogical understanding of the minerals and their textures, a certain process problem of mineralogical character could be identified and solved.

GEOLOGICAL DESCRIPTION

Apatite iron ore (Kiruna type)

This ore type exists in a few different places around the world (fig. 3) and the characteristic features of this specific type of ore are given in table 1. Geijer described (1910) the ore deposit Kiirunavaara and declared later (Geijer, 1931) that other deposits with similar geological features would be named the *Kiruna type* of ore. The age of the deposits of this kind is ranging between Paleoproterozoic and Pliocene-Pleistocene and they are located/emplaced in intracratonic settings or subduction zones, (Frietsch and Perdahl, 1995). The host rocks are calc-alkaline to alkaline volcanics with an andesitic to rhyolitic composition (Edfelt 2007 and references therein) and the ore mineralogy is dominated by magnetite-hematite with minor gangue minerals like apatite-actinolite-diopside. The alteration comprises albitisation, silicification, seritisation, epidotisation and minor components of actinolite, scapolite, tourmaline, biotite, and carbonates (Edfelt 2007 and references therein).

Table 1. General characteristics of apatite-iron deposits (Edfelt 2007 and references therein)

Main features	Apatite iron ore *(Kiruna type)*
Tectonic setting	Regional fault zones of intracratonic settings or subduction zones
Age	Paleoproterozoic to Pliocene-Pleistocene
Host rock	Calc-alkaline to alkaline volcanics rocks (intermediate to felsic)
Mineralogy	Magnetite-hematite and apatite-actinolite-diopside
Alteration	Albitisation, silicification, seritisation, epidotisation and minor carbonate
Ore genesis	Magmatic intrusive-extrusive, and/or hydrothermal replacement
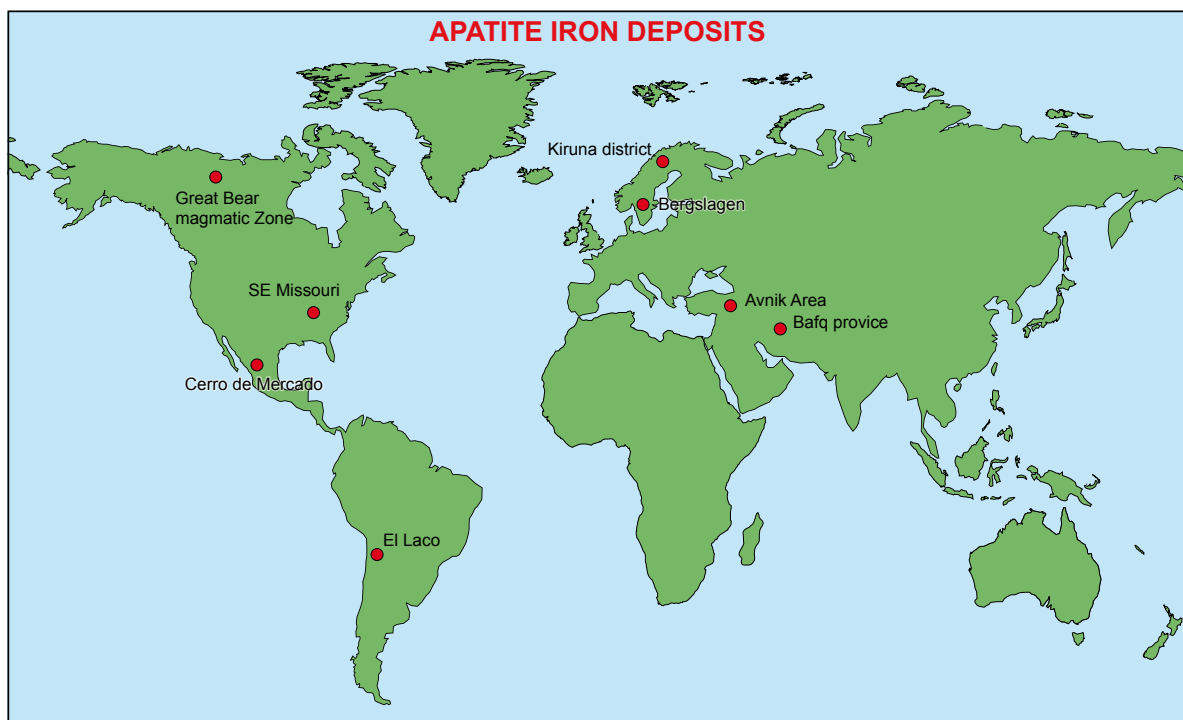
Fig. 3. Apatite-iron ore deposits around the world.

Ore genesis

Ten deposits of apatite iron ore have been mined in northern Sweden and the largest deposits Kiirunavaara and Malmberget are still mined by LKAB and contribute to about 90 % of the iron ore production in Europe. The apatite-iron ores have been in focus for genetic discussions over 100 years. Mainly there is a magmatic model suggested by (Geijer, 1910; Park, 1961; Frietsch, 1984; Nyström and Henríques, 1994; Henríques et al., 2003) and a hydrothermal model which is favoured by inter alia (Hildebrand, 1986; Hitzman et al., 1992; Sillitoe and Burrows, 2002). As not all features of the apatite iron ores are easily explained with a single genetic model a combination of these two models, a magmatic-hydrothermal process (Martinsson, 2004) is suggested to have formed the Kiruna and Malmberget deposits at 1.89-1.88 Ga (Cliff et al., 1990; Romer et al., 1994) However, there are major discrepancies in character between these two deposits, due to later overprinting by metamorphose, deformation and granitic intrusions, which are stronger for the Malmberget ore.

Regional geology

The geology of the northern Norrbotten ore province comprises bedrock sequences with different ages. The oldest rocks belong to an Archaean granitoid-gneiss basement with dated ages of 2.8 Ga. Unconformable overlaying sequences are 2.5-2.0 Ga supracrustal successions followed by c. 1.9 Ga Svecofennian volcanic and sedimentary units. Forty apatite-iron deposits are known from the northern Norrbotten ore province and they are hosted and probably also genetically related to the volcanic rocks in the Svecofennian succession (Martinsson, 2004).
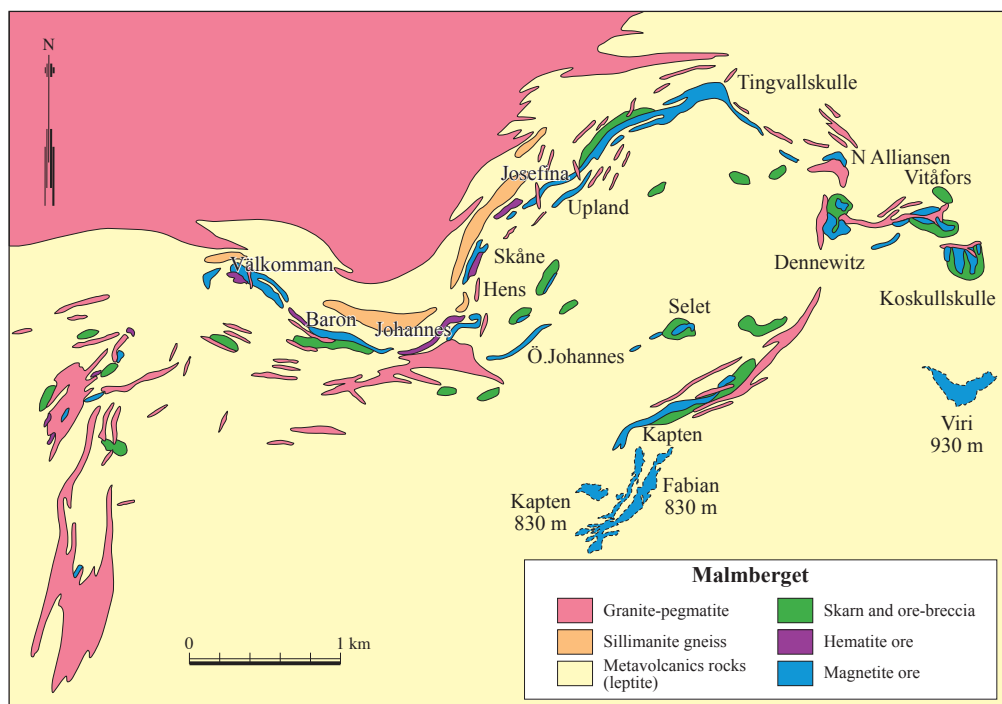
Fig. 4. Simplified geological map over the Malmberget area showing the magnetite and hematite ore bodies, modified from (Bergman et al., 2001).

Deposit geology

More than 20 different tabular to stock shaped ore bodies are known in the Malmberget ore field, occupying an area of 2.5 x 5km (fig 4). The Malmberget deposit was probably from the beginning a more or less continuous ore lens which were exposed for at least two phases of folding and metamorphism. By strong ductile deformation it was torn into several lenses that today occupy a large-scale fold structure were the individual ore bodies stretches parallel to the fold axis, which plunge 40º-50º towards SSW (Bergman et al., 2001). The apatite-iron ore were metamorphosed under high temperature conditions during the emplacement of large Lina granite intrusion to the north at c. 1.8 Ga (Bergman et al., 2001) causing post ore alteration and recrystallization at a temperature of 650-700º C and a pressure of 2-4 kbar (Annersten, 1968). Stilbite-bearing mineral assemblages indicate that the area was not heated above 150º C after 1.62-1.60 Ga (Romer, 1996). The ore bodies are recrystallised, coarse grained, and elongated in the direction of the lineation of the rocks (Martinsson and Virkkunen, 2004). The host rocks to the ore consist of felsic to mafic, metavolcanic rocks that locally contain sillimanite (Geijer, 1930). Mafic rocks are typically rich in biotite and can be found close to the ore as conformable to discordant lenses. Some of them are probably metamorphosed dikes while others seem to have formed as sills or extrusions (Geijer, 1930). These metavolcanic rocks are traditionally called leptites and gneisses (Geijer, 1930; Martinsson and Virkkunen, 2004) and are mainly distinguished by the grade of metamorphose and a coarser feldspar grain size of the latter (Geijer, 1930). Theses rocks may have an origin similar to those of trachyandesitic to rhyodacitic composition that hosts the Kiirunavaara deposit (Martinsson and Hansson, 2004)

TRACEABILITY

Traceability is today used in several industries, such as pharmacy, food, pulp and paper but is also becoming to be used in the mining industry. Traceability can be defined in many ways e.g. the ability to verify the history, location or application of an item by means of documented recorded information. For product quality traceability has become important in any process since it offers the opportunity to tie process data to a certain product or batch. Traceability is much easier to apply in batch processes than in continues processes. A continuous process means that the product gradually and by minimal disturbance is passing different process step (Kvarnström and Oghazi 2008 and references therein). In food and pharmacy industries it is very common to use different traceability tools (Mousavi et al., 2002) but in the mining industry, which is mostly a continuous process traceability is a difficult task. In continuous processes there are different factors that makes the traceability very complicated, there are reflux flows and mixing that makes it problematic to achieve a high level of traceability (Kvarnström and Oghazi, 2008). However, by using different analytical methods and instruments, high levels of traceability can be achieved in a process (Oghazi, 2008).

PROCESS MINERALOGY

To understand the fundamentals of mineral processing it is important to understand and link every single stage in the process chain. It is the mineralogy and the properties of an ore which determines the conditions for further processing (Batterham et al., 1992). By improving the characterisation of ore minerals and textures an efficient process can be designed and the mineral treatment can be optimized (Sutherland et al., 2000). Process mineralogy has combined the two disciplines mineral processing and mineral science (Lotter, 2003). Moen (2006) defines process mineralogy as the mineralogy which is applied to the product in specific mining process such as the concentration, pelletization or in other process stages. It is required to determine the mineralogical and textural properties of the ore as the liberation characteristics are closely related to the mineralogical texture and these parameters sets the crucial design of further beneficiation (Lorenzen and van Deventer, 1994). A large amount of information about the ore fines needs to be obtained, like particle mineralogy, class, porosity, mineral association, texture, hardness, size distribution, mineral liberation, class densities and mineral composition (Donskoi et al., 2007). According to (Sutherland et al., 2000) ore characterisation includes several aspect, such as improved ways of measuring minerals characteristics of ores and ore product, better knowledge of the influence on the measured parameters on the process or better methods for evaluating and present these mineralogical data.

ANALYTICAL METHODS

The mineralogy, chemistry and metallurgical properties of an ore and its products can be obtained by a combination of different analytical instruments (Henley, 1992). Optical microscopy including point counting has traditionally been used for the identification and quantification for both mineralogical and texturally properties, which is a time consuming process (Petruk, 2000) and dependent on the skill of the mineralogist (Henley, 1992). For that reason quantitative estimations, especially during mineral processing has been a limiting factor in the past (Batterham et al., 1992). To solve that problem a number of different techniques using image analyse systems based on SEM techniques have been developed during the three last decades for a more rapid quantitative estimation and description of mineralogy and particle textures (Jones and Gravilovic, 1970; Gottlieb et al., 2000; Petruk, 2000; Gu, 2003).

QEMSCAN® *(Quantitative Evaluation of Minerals by Scanning Electron Microscopy)*

QEMSCAN® was developed by CSIRO in Australia for the global mining industry to analyse ore and mill products in respect to mineral processing to provide rapid, statistically reliable, repeatable mineralogical and quantitative mineral analyses (Sutherland and Gottlieb, 1991; Petruk, 2001). The system can be operated in different measurement modes; field images scan, bulk mineral analysis (BMA), particle mineral analysis (PMA) and trace mineral search (TMS) (Pirrie et al., 2004). The principle of this technology is to use a combination of signals from the backscatter electron detector (BSE) and the energy dispersive X-ray detectors. The backscattered electrons will recognise particles based on density contrast and the compositional differences from the X-ray spectra will create digital mineral images of a sample based on chemical composition (Gottlieb et al., 2000; Sutherland et al., 2000; Goodall et al., 2005). All the analytical data are processed offline by an integrated software application (iDiscover 4.2) to the QEMSCAN system. To be able to identify the minerals and phases in the sample, every analysed pixel and obtained X-ray spectra is compared to a known database of mineral composition *(SIP- Species Identification Protocol)* which is the base to get an accurate and complete mineral identification (Gottlieb et al., 2000)

PTA *(Particle texture analysis)*

The Particle Texture Analysis (PTA) is developed at the Norwegian University of Science and Technology (NTNU), in Trondheim. By using back scattered electrons (BSE) from the scanning electron microscopy, images are analysed by means of grey levels and every grain of interest is also analysed by X-rays. All analysed grain size fractions are imported to the PTA software, Inca Feature, where images analyses and processing are done offline to evaluate if grains occur as liberated or in composite particles. Standard queries can be done on the output results in a new database that contains information on the mineral liberation of any mineral, mineral association of any mineral and miniature images of particles of a certain texture category (Moen, 2006). To reduce the unclassified group of mineral grains an extensive identification of minerals and phases for classification should be done.

Microprobe

An electron microprobe is a common instrument which is used to qualitatively or quantitatively determine the chemical composition of a very small spot (1μm) of a sample surface. The technique is described in (Potts et al., 1995).

MATERIAL AND SAMPLING

Ore bodies

Three different ore bodies were sampled and analysed. Hens ore body is represented by sublevel 495 m and the ViRi ore body is represented by two sublevels 834 m and 858 m by grab samples. At Fabian three drill cores intersecting the ore from the hanging wall to the foot wall were logged and sampled. Polished thin sections were made of all the samples. Approximately 100 samples were examined and 30 of them were selected for analyses of major, minor and trace elements.

Ore types

The iron ore at Malmberget have been divided in morphologically two different types called *ore breccia* and *ore*. The *ore breccia* is consisting of magnetite, occurring as breccia infill in the wall rocks together with different proportion of gangue minerals like quartz, amphibole, pyroxene, apatite and feldspars. The *ore* consists of massive magnetite, forming large ore lenses and it contains gangue minerals like amphiboles and apatite in smaller amounts. The *ore breccia* is bordering the massive ore, but occurs also partly as inclusions in the massive ore.

RESULTS

This thesis consists of three different papers which characterises the Malmberget deposit with respect to its process mineralogical properties. The first paper contributes to the understanding of the mineralogy, texture and chemistry of three different ore bodies and the importance of metamorphic recrystallization on these parameters. Paper two and three are about process mineralogy. In paper two the mineralogy, texture and mineral association of one ore body is characterised. Paper three aims to find traceability in a concentration process by identifying significant mineralogical signatures in the ore and in the ore concentrate and creating a method to connect the signatures from mine to mill.

Summery of paper I

This paper is a study of magnetite and hematite from three different ore bodies (Hens, ViRi, Fabian) in Malmberget. The aim is to understanding the metamorphic influence, particular mineral chemistry and texture of the ore by the use of optical microscopy and microprobe analyses (EPMA). Two types of ore were mineralogically characterised; massive ore and ore breccia. The massive ore which constitutes the major part of each ore body is massive to its appearance, has high iron content and contains apatite and amphibole as main gangue minerals. Ore breccia is characterised by a breccia style mineralization in the wall rocks to massive ore with magnetite and gangue minerals occurring as breccia infill. The iron content is lower compare to massive ore and it includes several different mineral parageneses. The characteristic

mineralogical feature in ore breccia is the presence of pyrite, chalcopyrite and anhydrite which occurs sparsely disseminated or in larger amounts. The ore bodies Fabian and ViRi have a similar mineralogy with the occurrence of Ti minerals, pyrite and chalcopyrite as a common feature. Hens ore body has a different style of mineralisation by the presence of hematite. However, all three ore bodies have different chemical signatures and magnetite from the different ore bodies which show a chemical variation of the minor elements V_2O_3, TiO_2, Al_2O_3, and MgO. Hens ore body has a content of TiO_2 which is high in hematite and low in magnetite which is suppose to be a redistribution of the element during recrystallization at high oxygen fugacity. The oxidation textures in magnetite indicate that the ore bodies are exposed for different stages of oxidation. Magnetite and ilmenite occur as coexistence minerals and show textures both of the lowest oxidations stage (C_1 & R_1) which is homogeneous magnetite or ilmenite and of the highest oxidation stage (C_5 & R_5) which is replacement textures of hematite and ferrianrutile. The two ore types, massive ore and ore breccia have different mineral chemical composition of magnetite. Massive ore has a content of minor elements which correspond to other apatite iron deposits around the world and could either have been formed from an iron oxide melt or from hydrothermal processes fluids at high temperature. For ore breccia the mineral associations and the low content of minor elements in magnetite suggests a generation by hydrothermal processes with fluids of a temperature similar to that of IOCG-style of mineralisation.

Summery of paper II

The aim of this study is to characterise an apatite iron ore body, Malmberget with respect to process mineralogy to improve the mineralogical knowledge in the process during upgrading. This is the first study of characterising the mineralogy and textural properties by the use of QEMSCAN®. It means a complete identification of all mineralogical phases, the modal mineralogy, particle liberation, mineral associations and mineral textures in a quantitative manner. Two different ore types were used from the Fabian ore body; *massive ore* and *ore breccia*. Each ore types were crushed and split in three fractions 150 µm, 75 µm and 38 µm. Magnetite, amphibole, feldspar, apatite and quartz are the dominating minerals for the two ore types. The particle liberation of magnetite is high for massive ore being much lower for ore breccia and decreases in the finer fractions. It is depending on mineralogy, grain size and textures of magnetite and gangue minerals. Magnetite will easily fall apart and create a highly liberated fine. A binary magnetite/FeTi-oxide association is the most common one in both ore types while magnetite/amphiboles and magnetite/apatite are characteristic for ore. *Ore breccia* has more associations of both binary and complex magnetite bearing particles. Typical associations are magnetite/feldspar and magnetite/quartz. A mineral texture frequently found in ore breccia is small magnetite grains occurring as inclusions in feldspar. From a process point of view this ore type has magnetite particles that probably will not be liberated during further crushing and milling. Irrespective if this kind of magnetite particle is being part of the

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concentrate or the tailings the silica content will increase in the concentrate or the iron content increase in the tailings.

Summery of paper III

This paper exemplifies possibilities to have traceability in a mining process, by combining two studies in an iron ore refinement. The first step tries to characterise an iron ore body at Malmberget by identify significant mineralogical and textural signatures. In the second step the focus has been to investigate the raw material that comes from the mine and continues to the concentrator. To identify these signatures, different analytical tools like microprobe and an automatic SEM based system, PTA have been used to examine the liberation, texture and mineral associations of the ore and their concentrate. The main task is to find a method to connect these signatures from mine-to-mill and see if there is any relation between the process stages. To be able to compare results and data all the samples were crushed and sieved at same fractions. Modal mineralogy is the main indicator to find connection in the process by showing the involved minerals. It signifies that magnetite is well liberated and the amount of gangue minerals increases in the finer fractions due to a coarser primary grain size for magnetite. Two possible mineralogical signatures are found in the material from both the mine and the concentrator. It is a rather simple binary associations between magnetite and apatite existing as mixed grains and a more complicated texture there smaller magnetite grains occur as inclusions in feldspars grains. Due to the improved characterisation of the mineralogy of ore and ore breccia it was possible to distinguished these signatures and connects them in the material through the grinding circuit which can create traceability from mine-to-mill.

CONCLUSION

The chemistry of magnetite has partly been changed during these processes as a result of recrystallization and oxidation. Element redistribution between magnetite and silicates has affected the content of MgO and Al_2O_3, while the formation of hematite and Ti-minerals has caused losses of Ti and V in magnetite. The primary chemical signatures for magnetite from massive ore and ore breccia suggest slightly different ore forming conditions which also is supported by the different mineral associations found in these two ore types. Massive ore may have been formed from iron oxide melt magma or from high temperature hydrothermal fluids, while ore breccia have a hydrothermal origin and probably was formed at lower temperature. Thus, the chemistry of magnetite is different for massive ore and ore breccia due to different ore forming processes but it has also changed by later processes. As a result magnetite from Malmberget deposit shows a large variation in the content of minor and trace elements which also should affect the upgraded products.

In paper two and three two different automated SEM based instrument have been used to characterise the mineralogy and textures in a quantitative manner. The material in these studies has been the same types of ore; massive ore and ore breccia. The ore breccia type will be part of the concentrate in varying amounts during upgrading. Both the mineralogy and its textures differs compared to ore which suggests other process mineralogically properties.

By comparison, the results acquired from the instruments are not exactly the same in the aspects of how precise and accurate the data are generated. In the first place these instruments run the analysis in a similar way but the amount of data differs. The PTA instrument uses back scatter electrons (BSE) to identify particles based on the density contrast between particles and each density phase is analysed by one X-ray spectrum to identify the phase. By the use of BSE signals, images are created based on grey levels and three threshold intervals are manually set to divide the greyscale. QEMSCAN® also uses a combination of back scatter electrons and X-ray spectra but each pixel in the particle is analysed by an X-ray spectrum giving the chemical compositional of each pixel. Secondly, the samples preparation is also highly significant for the outcome of the results. The results from the PTA are a little bit blunted compare to QEMSCAN®, giving the data a not so precise appearance.

These two studies prove that it is possible to characterise iron ore in a quantitative way. Ore and concentrate have to be categorised during analysis to be able to create a potential tool to improve the mineralogical knowledge to solve future process mineralogical problems.

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Magnetite chemistry, textural and mineralogical aspects of the metamorphosed apatite iron ore, Malmberget, Sweden

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Abstract

Magnetite and hematite from three apatite iron ore deposit (Kiruna type) in the Malmberget deposit, Sweden has been studied by optical microscopy and microprobe analyses (EPMA). The ore bodies (Hens, ViRi and Fabian) have been characterised by mineralogy, oxidation texture and chemistry of the ore minerals to understand the metamorphic influence. Two types of ore were mineralogically characterised; massive ore and ore breccia. Magnetite is the main oxide mineral and apatite, Na-Mg rich amphibole and plagioclase are the main gangue minerals. The ore bodies Fabian and ViRi have similar mineralogical characteristics by the occurrence of Ti minerals, pyrite and chalcopyrite as a common feature. Hematite is only present in the Hens ore body. However, magnetite from the three different ore bodies has different chemical signatures with a chemical variation of the minor elements V_2O_3, TiO_2, Al_2O_3, and MgO. In the Hens ore body the content of TiO_2 is high in hematite and low in magnetite which is suppose to be a redistribution of the element during recrystallization at high oxygen fugacity. The oxidation textures in magnetite indicate that the ore bodies have been exposed for different stages of oxidation. Magnetite and ilmenite occur as coexistence minerals and show both textures at the lowest oxidations stage (C_1 & R_1) which is homogeneous magnetite or ilmenite and at the highest oxidation stage (C_5 & R_5) which is replacement textures of hematite and ferrianrutile. Two types of ore, the main massive ore and ore breccia from the Fabian ore body show distinct different mineral associations and chemical composition of magnetite indicating different origin. Our data support a model with a massive ore formed from an iron oxide melt while the ore breccia is part of the same ore forming system but of hydrothermal origin.

Introduction

Sweden is Europe's most important producer of iron ore with two large underground mines in Kiruna and Malmberget operated by LKAB (total iron ore reserve 1010 Mt @ ~ 46 % Fe), (LKAB, 2007). Both deposits are apatite iron ores, an ore type that is common in northern part of Sweden but quite rare in other parts of the world (fig. 1). The apatite-iron ores have been in focus for genetic discussions over 100 years. Mainly there is a magmatic model (Geijer, 1910; Park, 1961; Frietsch, 1984; Nyström and Henríques, 1994; Henríques et al., 2003) and a hydrothermal model (Hildebrand, 1986; Hitzman et al., 1992; Sillitoe and Burrows, 2002). As not all features of the apatite iron ores are easily explained with a single genetic model a combination of these two models, a magmatic-hydrothermal process (Martinsson, 2004) is suggested to have formed the Kiruna and Malmberget deposits at 1.89-1.88 Ga (Cliff et al., 1990; Romer et al., 1994). The characteristic feature of the Kiruna type deposits is that they occur in intermediate to felsic volcanic rocks, are tabular and concordant with their host rock, include a dominating mineralogy of magnetite, hematite, apatite and actinolite and chemically a high content of phosphorus due to the presence of apatite (Martinsson and Virkkunen, 2004). The typically high vanadium content is similar to magmatic segregation of magnetite in mafic rocks but the titanium content is intermediate to magmatic and sedimentary iron deposits, (Frietsch, 1970; Loberg and Horndahl, 1983). These two world class deposits in Kiruna and Malmberget have a similar origin (Geijer, 1930; Loberg and Horndahl, 1983). However, the Malmberget ore is more strongly affected by later metamorphose, deformation and intrusion of granitic rocks (Bergman et al., 2001).

Two major types of apatite iron ore can be distinguished in the Kiruna area, a breccia type and a stratiform - stratabound type (Bergman et al., 2001). Ore breccia is an irregular network of ore veins which to a varying extent accompany the massive ore (Geijer, 1910; Geijer, 1931; Frietsch, 1982). In the Malmberget deposits, ore bodies situated in the eastern field are more exposed for a stronger brecciation (Geijer, 1930). Mineralogically the ore breccia will be distinguish by the presence of more silicates and a complicated texture with irregular boundaries and inclusions of both magnetite and silicates (Lund and Martinsson, 2008).

Previous research on apatite iron deposits in northern Norrbotten is from the well known deposits around Kiruna (Kiirunavaara, Luossavaara, Per Geijer, Gruvberget etc.) described from (Geijer, 1910; Frietsch, 1970; Parák, 1975; Frietsch, 1982; Nyström and Henríques, 1994). There exist number of different analyses both whole rock chemistry and microprobe data but in the Malmberget area only a few magnetite data exists from unspecified ore bodies and from old works (Frietsch, 1967; Annersten, 1968; Loberg and Horndahl, 1983).

Magnetite (Fe_3O_4) belongs to the spinel group which allow substitution of a small amount of trace elements depending on their physical properties either to the Fe^{2+} and Fe^{3+} position in
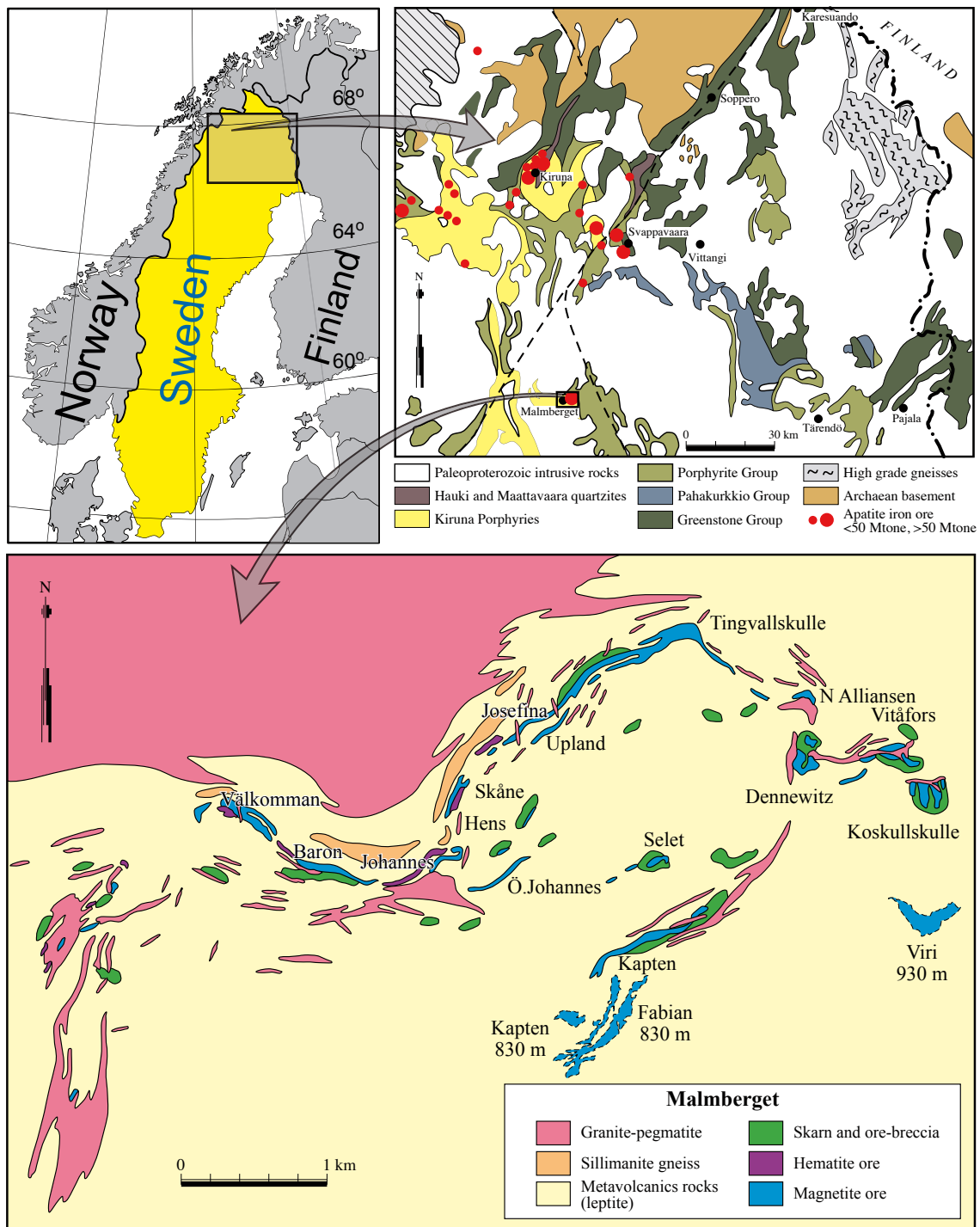
Fig. 1. The geology of the northern Norrbotten ore province, apatite iron deposits marked in red. Lower figure a simplified geological map over the ore bodies at the Malmberget area, modified after Bergman et al., 2001.

the crystal lattice (Frietsch, 1970; Deer et al., 1992). Many different parameters control the substitution of trace elements in magnetite, including pressure, temperature, fluid composition, cooling rate, recrystallization, oxygen fugacity etc. (Buddington and Lindsley, 1964). However, the various combination of minor and trace element content may be distinct for magnetite formed in particular rock types and ore system (McQueen and Cross, 1998).

In this study we have carried out microprobe analysis of magnetite and hematite from three different ore bodies in the Malmberget apatite iron deposit. The aim is to understanding the influence of metamorphic recrystallization on the chemistry of the ore minerals. These data will also be compared to other apatite iron ore deposits around the world for genetic interpretations.

Geological setting and metallogeny

Regional geology:

The geology of the ore province northern Norrbotten is characterised by bedrock sequences with different ages. The oldest unit is an Archaean granitoid-gneiss basement with dated ages of 2.8 Ga. Unconformable overlaying sequences are supracrustal successions of Palaeoproterozoic age 2.5-2.0 Ga, followed by Svecofennian volcanic and sedimentary units dated c. 1.9 Ga. Forty apatite-iron deposits are known from the northern Norrbotten ore province and they are hosted and probably also genetically related to the volcanic rocks in the Svecofennian succession (Martinsson, 2004)

Deposit geology

More than 20 different tabular to stock shaped ore bodies are known in the Malmberget ore field, occupying an area of 2.5 x 5 km (fig. 1). The Malmberget deposit was probably from the beginning a more or less continuous ore lens which were exposed for at least two phases of folding and metamorphism. By strong ductile deformation it was torn into several lenses that today occupy a large-scale fold structure were the individual ore bodies stretches parallel to the fold axis, which plunge 40º-50º towards SSW (Bergman et al., 2001). The apatite-iron ore were metamorphosed under high temperature conditions during the emplacement of large Lina granite intrusion to the north at c. 1.8 Ga (Bergman et al., 2001) causing post ore alteration and recrystallization at a temperature of 650-700º C and a pressure of 2-4 kbar (Annersten, 1968). Stilbite-bearing mineral assemblages indicate that the area was not heated above 150º C after 1.62-1.60 Ga (Romer, 1996). The ore bodies are recrystallised, coarse grained, and elongated in the direction of the lineation of the rocks (Martinsson and Virkkunen, 2004). The host rocks to the ore consist of felsic to mafic, metavolcanic rocks that locally contain sillimanite (Geijer, 1930). Mafic rocks are typically rich in biotite and can be found close to the ore as conformable to discordant lenses. Some of them are probably metamorphosed dikes while others seem to have formed as sills or extrusions (Geijer, 1930). These metavolcanic rocks are traditionally called leptites and gneisses (Geijer, 1930; Martinsson and Virkkunen, 2004) and are mainly distinguished by the grade of metamorphose and a coarser feldspar grain size of the latter (Geijer, 1930). Theses rocks may have an origin similar to those of trachyandesite to rhyodacite composition that hosts the Kiirunavaara deposit (Martinsson and Hansson, 2004).

Hens ore body

The Hens ore body is located in the western part of the deposit and is also part of an almost continuous ore horizon almost 5 km in length (Bergman et al., 2001). Hens is a tabular shaped ore body approximately 250 x 20 m, composed of individual magnetite and hematite ore bodies. The average content of the ore is 53.5 % Fe and 0.80 % P (fig. 2). A typical feature is coarse grained apatite occurring as a flattened forming regular banding network (Geijer, 1930). The massive ores are surrounded by veins of magnetite and hematite forming an ore breccia which gradually decreases in intensity outwards into the wall rock

Fig. 2. Simplified 3D illustration of Hens ore body, 495 m level is outlined with magnetite ore as blue and hematite ore as purple colour.

Vitåfors-Riddarstolpe ore body (ViRi)

The ViRi ore body and the Fabian ore body are part of the eastern field of the Malmberget deposit that include a number of more or less individual magnetite ore bodies which also are generally poorer in apatite (Martinsson and Virkkunen, 2004). The ViRi magnetite ore forms a tabular shaped ore body approximately 300 x (100-160) m containing 61.5 % Fe and 0.15 % P (fig. 3). The typical feature is a varying extensive brecciation of a strongly altered zone which

encloses the ore body. According to Geijer and Ödman (1974) the hanging wall in ViRi shows an ore breccia with ore veins containing apatite and amphibole. The footwall conditions are similar but with a more sharp contact between the massive ore and the ore breccia, containing less magnetite and more amphibole.
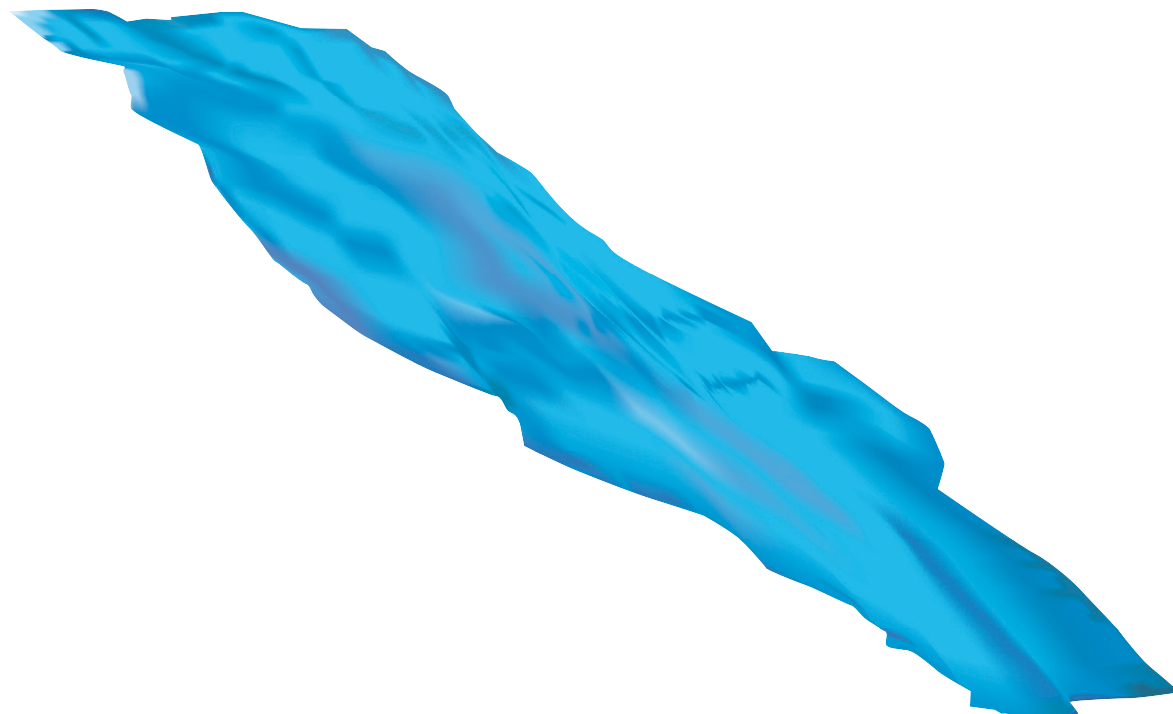
Fig. 3. Simplified 3D illustration of ViRi ore body.

Fabian ore body

This large ore body is mainly lens shaped, but it becomes irregular in the upper part while the deeper parts of the ore body are more compact and regular. The average content of the ore is 55.6 % Fe and 0.35 % P (fig. 4). The characteristic feature for Fabian ore is both a massive ore of magnetite and a mineralization of breccia style. The ore breccia occurs as an irregular infill in the massive ore and at the margin to the wall rock. The ore breccia consists mainly of a feldspar-quartz matrix and anhydrite-amphibole matrix.

Sampling

Three different ore bodies were sampled and analysed. Grab samples were taken from the Hens ore body at sublevel 495 m (fig. 2) and from the ViRi ore body at the sublevels 834 m and 858 m, respectively (fig. 3). At Fabian three drill cores intersecting the ore from the hanging wall to the foot wall were logged and sampled (fig. 4). Polished thin sections were made of all the samples. Approximately 100 samples were examined and 30 of them were selected for analyses of major, minor and trace elements.
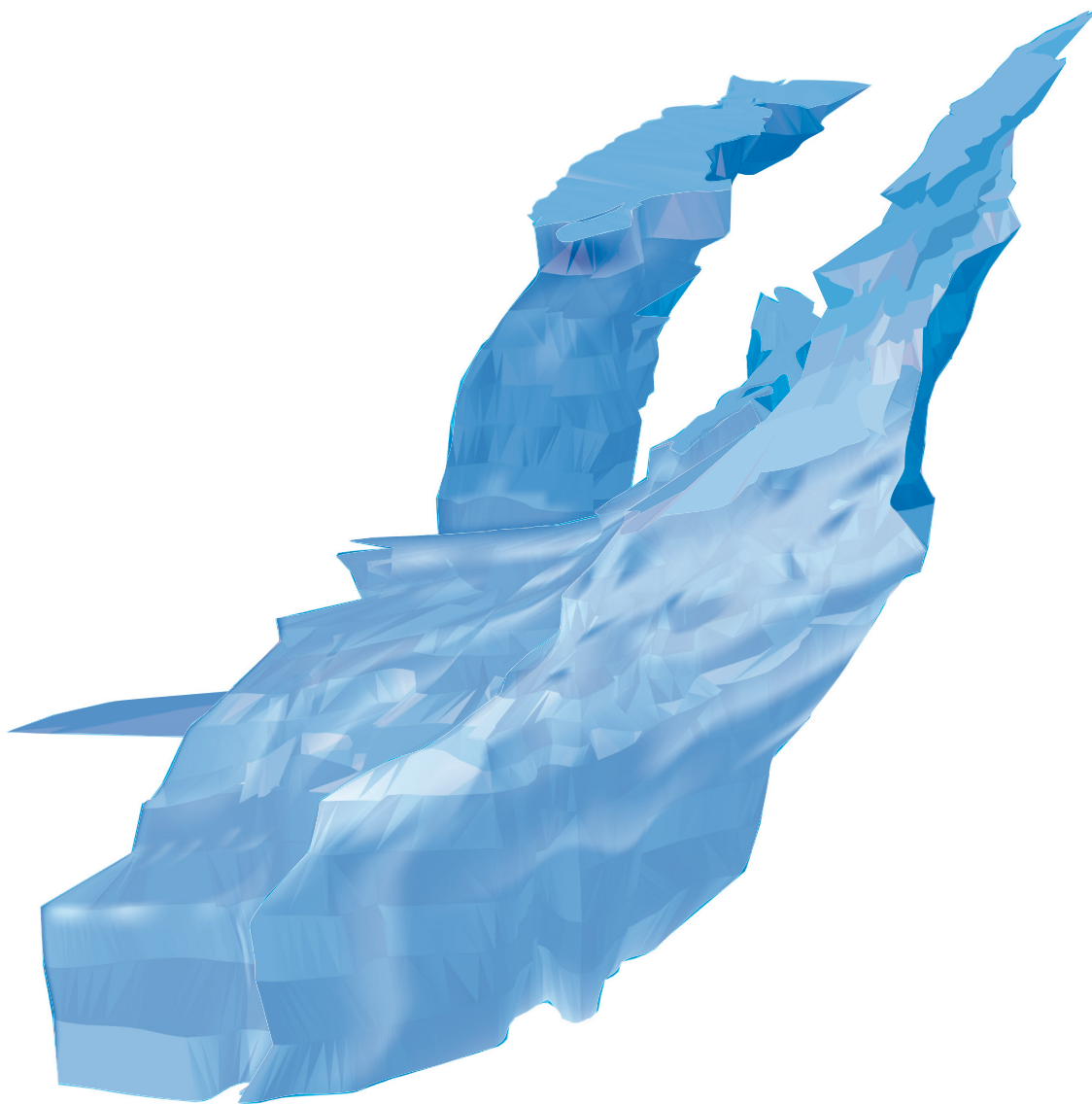
Fig. 4. Simplified 3D illustration of Fabian ore body.

Analytical work

All the analyses of major, minor and trace elements were performed at the Camborne School of Mines, university of Exeter, Cornwall Campus, UK on a JEOL JXA-8200 superprobe with a technique described by (Potts et al., 1995). An accelerating voltage of 15 kV and a beam current of 30 nA were carried out for the oxides. The probe beam diameters was set to 1 μm for the oxides and the phosphates and for the silicate the diameter was set to 5 μm. Standards for the different elements were used of natural silicates and oxides. Petrographical studies were carried out at the Luleå University of Technology, Sweden.

Method

The FeO content of magnetite was calculated from the microprobe analysis and based upon the total content of Fe. To get a correct distribution of the Fe^{2+} and Fe^{3+} cations all the divalent and trivalent cations in the analysis were summarised and then redrawn from the total sum of Fe. For the magnetite the 4 valent cations were added to the sum of the divalent cations based on their octahedral position in the spinel structure. This recalculation of the magnetite and hematite data was prepared by method of Jens C. Ø. Andersen (pers. comm.).

Results

Ore characterisation - mineralogy and textural relationship

The apatite magnetite ore from Fabian ore body is divided in two ore types; massive ore and ore breccia. Magnetite from the massive ore is subdivided and described in the view of different kind of textures (fig 5). The ore breccia are characterised by different mineral paragenesis.
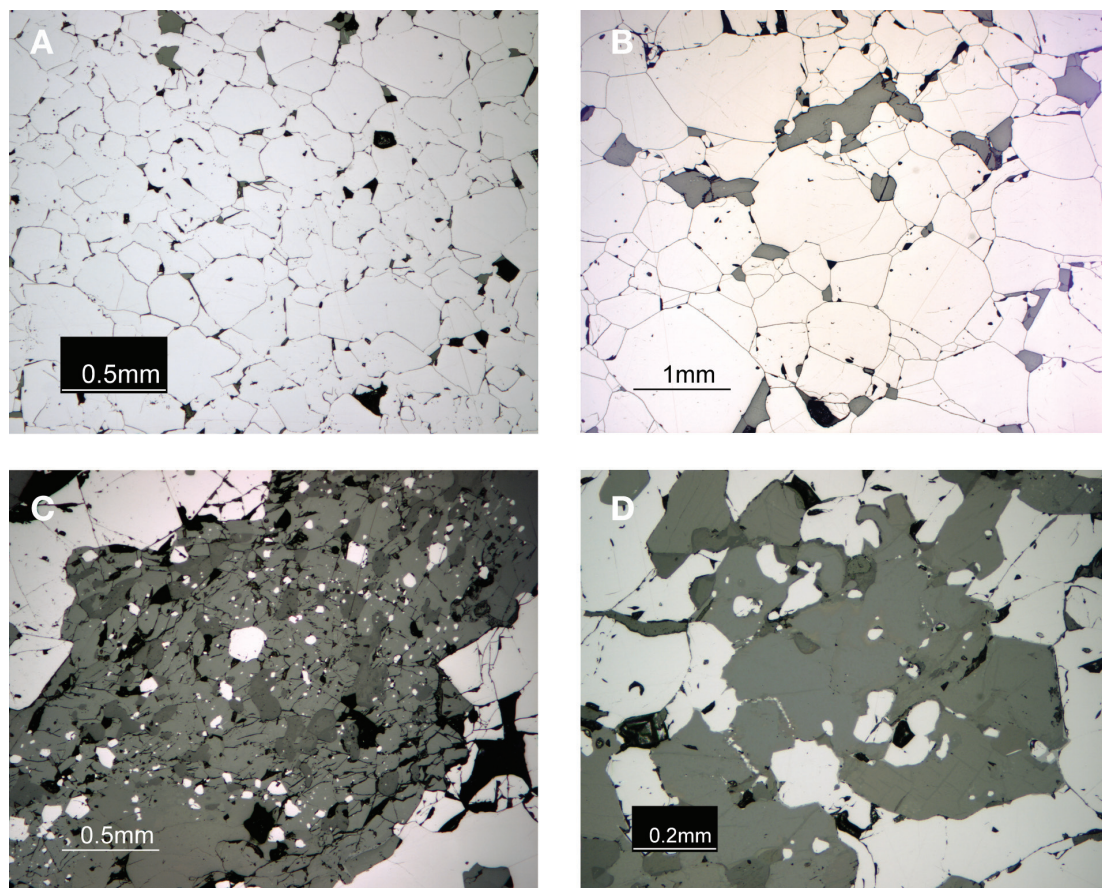
Fig. 5. Photomicrographs showing textures of magnetite at the Malmberget deposit (reflected light). **A**. Massive ore with magnetite grains occurring as an equigranular matrix with triple junction configuration. **B**. Larger grains of magnetite occurring as porphyroblasts. **C**. Small magnetite grains existing as inclusions in the silicate matrix. **D**. Small magnetite grains occurring as inclusions in silicates and along grain boundaries in the granular silicate matrix.

Massive ore

The main oxide mineral is magnetite; accessory opaque minerals are ilmenite, hematite, chalcopyrite and pyrite. Apatite, Na-Mg rich amphibole, pyroxene and plagioclase are the main gangue minerals and quartz, biotite and zircon exist in smaller amounts. The mineral composition of the Hens ore body is slightly different. Hematite occurs frequently but still as accessories, as single anhedral grains 0.04-1.4 mm in a quartz-plagioclase matrix. Grains of apatite and quartz occurring interstitial into the massive magnetite matrix and these grains are often aligned in a linear direction. Fabian ore body contains only minor of plagioclase and quartz and the ViRi ore body lack plagioclase in the massive ore.

Massive magnetite ore

Characteristic for massive magnetite ore is the absence of almost all gangue minerals. A classification is made due to grain size; fine grain magnetite (0.01-0.4 mm), medium (0.4-0.8 mm) and coarse grain (0.8-1.4 mm). Coarser grains exist often as porphyroblasts (>4.6 mm). The magnetite is euhedral to subhedral often with smaller single anhedral (0.01-0.2 mm) large grains occurring at grain boundaries and as inclusions in the silicate matrix. The magnetite grains can have an elongated shape. The grain boundaries are simple and straight occurring with a compact texture but become more crumbly when the grain boundaries become gently curved due to an increasing grain size. Some samples show foam textured magnetite. Typical for the samples of fine grained magnetite is coarser magnetite grains occurring as vein like structures. Ilmenite occur in some samples as single grains (>1 mm) or as large grain interstitial (0.1-0.2 mm) to magnetite in grain boundaries. Exsolution lamellae of hematite are common. Hematite and rutile are present as oxidation surfaces along the grain boundaries. Euhedral grains of both pyrite and chalcopyrite (0.04-0.4 mm) large occur commonly but also some larger grains (>3.2 mm) exist. Pyrite is more common than chalcopyrite, occurring interstitial to magnetite, as inclusions in the matrix and disseminated in veins. Titanite as (0.1-0.2 mm) large grains often occurs interstitial to magnetite and diopside in samples of coarser grains size. More common silicates are Na-Mg- rich amphiboles (actinolite, tremolite) and diopside of a slightly varying composition ($Wo_{37-41}En_{46-48}Fs_{13-17}$). The silicates are euhedral to anhedral and occur as single grains interstitial to magnetite or as aggregates. These aggregates are sometimes outlined in a linear direction. The grain size is (0.04-1.2 mm) but also larger grains exist (> 5.4 mm). Albite, plagioclase (1-4 % An) as (0.04-0.4 mm) large grains and quartz (0.2-0.8 mm) in grain size have a subhedral to anhedral shaped and form an inequigranular matrix with complicated grain boundaries. The plagioclase is subhedral and often twinned and the quartz grains occur as subhedral grains with undulose extinction or as smaller rounded single grains and as inclusions. Both a Fe-rich and Mg-rich biotite are present (annite, phlogopite). Yellow-green to brownish tabular biotite occur as (0.1-0.4 mm) large grains (locally up to <2 mm) which are also is partly altered or replaced by chlorite. Apatite exists as single euhedral grains, (0.1-0.8 mm) large,

interstitial to magnetite or as elongated (0.8-4.6 mm) large grains aligned in a linear direction. The apatite grain size is correlating to the grain size of coexisting magnetite. Element analyses are given in (tab. 1, 3 & 4).

Table 1) Representative electron microprobe analyses of amphiboles and pyroxene

Mineral	Fabian ore			Fabian Ore breccia		Hens	ViRi	
	actinolite	tremolite	diopside	actinolite	diopside	tremolite	actinolite	diopside
Sample No.	V35-2 272	V13-1 623	V20-3 311	V17-3 515	V38-2 12	11-4 73	4-3 102	3-2 677
SiO_2	55,44	57,71	54,69	55,70	54,59	53,84	56,27	54,56
Al_2O_3	1,88	0,94	0,23	1,70	0,58	3,31	1,59	0,41
TiO_2	0,03	0,02	0,02	0,08	0,07	0,02	0,08	0,00
FeO (tot)	10,31	4,00	9,61	9,53	9,03	7,60	8,50	10,17
MnO	0,05	0,03	0,14	0,12	0,08	0,04	0,07	0,06
MgO	17,59	22,06	13,02	17,66	13,27	19,39	18,79	12,87
CaO	11,55	12,64	21,75	11,85	21,84	10,49	11,39	21,40
Na_2O	1,06	0,97	1,51	0,99	1,69	2,48	1,83	1,68
K_2O	0,13	0,01	0,00	0,22	0,01	0,70	0,42	0,01
F	0,18	0,00	0,00	0,23	0,00	1,71	1,09	0,00
Total	98,21	98,38	100,97	98,07	101,16	99,60	100,03	101,16
Wo			38,16		38,95			37,86
En			45,81		46,06			45,24
Fs			15,79		14,86			16,79
No. of oxygens	23	23	6	23	6	23	23	6
Structural formulae								
Si	7,79	7,89	2,02	7,86	2,01	7,52	7,83	2,02
Al			0,01		0,03			0,02
Al iv	0,21	0,11		0,14		0,48	0,17	
Al vi	0,10	0,04		0,14		0,07	0,09	
Ti	0,00	0,00	0,00	0,01	0,00	0,00	0,01	0,00
Fe (tot)			0,30		0,28			0,31
Fe^{3+}	0,32	0,10		0,09		0,47	0,09	
Fe^{2+}	0,89	0,36		1,03		0,42	0,90	
Mn	0,01	0,00	0,00	0,01	0,00	0,01	0,01	0,00
Mg	3,68	4,50	0,72	3,71	0,73	4,04	3,90	0,71
Ca	1,74	1,85	0,86	1,79	0,86	1,57	1,70	0,85
Na	0,29	0,26	0,11	0,27	0,12	0,67	0,49	0,12
K	0,02	0,00	0,00	0,04	0,00	0,13	0,07	0,00
F	0,08	0,00	0,00	0,10	0,00	0,75	0,48	0,00

Amphiboles recalculations from (Leake et al., 1997).

Mineral paragenesis in ore breccia

The ore breccia is characterised by magnetite with xenolites of plagioclase as the most important silicate mineral which constitute the silicate matrix together with quartz and K-feldspar. Magnetite, Na-Mg rich amphibole together with pyroxene, biotite, anhydrite and a small amount of pyrite, chalcopyrite, anhydrite, ilmenite, titanite and occasionally also zircon occur as breccia infill (fig. 6).
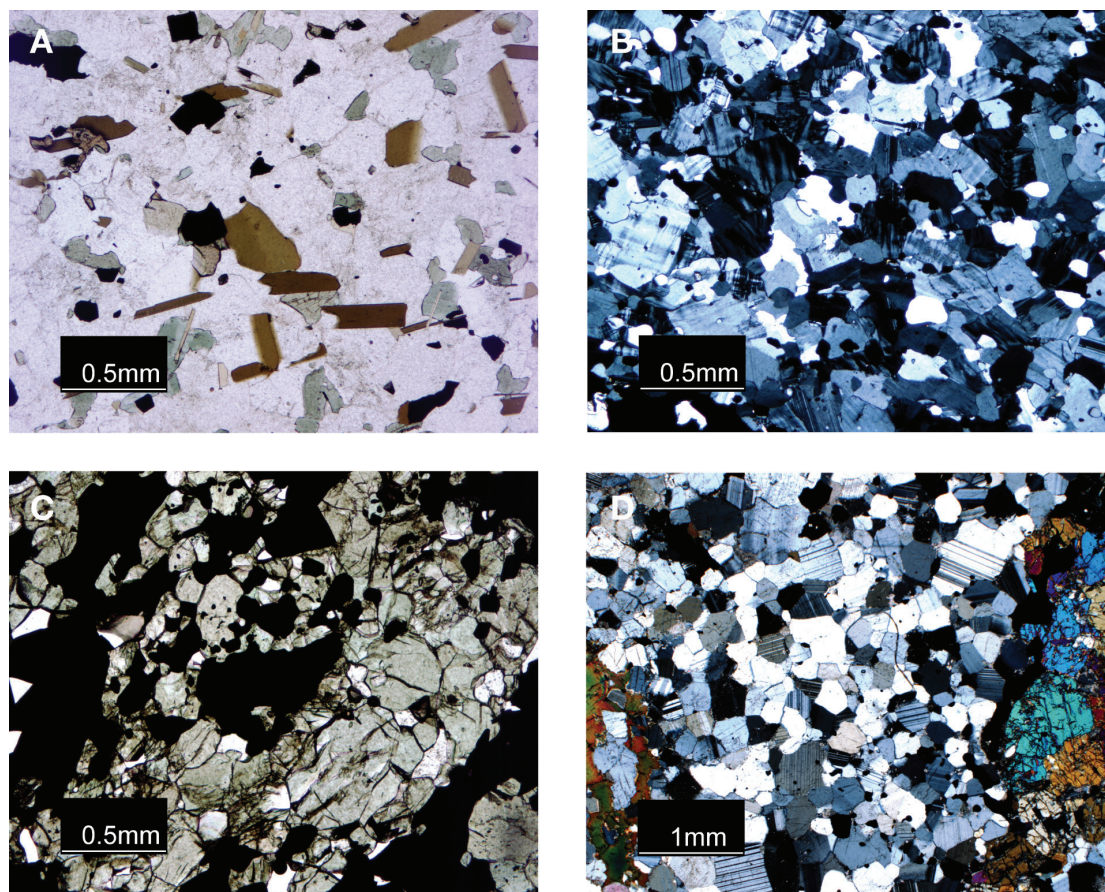
Fig. 6. Photomicrographs showing different mineral paragenesis in ore breccia at the Malmberget deposit (transmitted light). **A**. Biotite aligned in two directions and amphibole outlined in a matrix of feldspar and quartz, plane polarised light. **B**. Microcline, albite and quartz with a subgranular, complicated texture, cross polarised light. **C**. Amphibole and pyroxene occurring as cluster together with aggregates of magnetite, plane polarised light. **D**. Matrix of plagioclase, quartz and amphibole showing seritization of feldspar and also a chloritization of biotite, cross polarised light.

Five different main mineral paragenesis of ore breccia were identified, based on differences in the main mineral composition (tab. 2). These paragenesis occur locally within the massive ore, as veins and as margin to the wall rock.

Table 2) The included mineral paragenesis in ore breccia.

No.	Mineral paragenesis in Ore breccia
1)	Magnetite (massive) + plagioclase + quartz + amphibole ± chalcopyrite ± ilmenite ± titanite ± pyrite.
2a)	Magnetite (inclusion) + plagioclase + quartz + amphibole + chalcopyrite + pyrite ± biotit (red leptite)
2b)	Magnetite (inclusion)+ plagioclase+ amphibole+ biotit + quartz± chalcopyrite± pyrite± titanite (grey leptite)
3)	Magnetite + feldspar r+ amphibole + pyroxene + biotite + chalcopyrite + pyrite ± ilmenite
4)	Magnetite + feldspar + chlorite ± amphibole ± pyroxene ± biotite
5)	Magnetite + amphibole + anhydrite + chalcopyrite + pyrite ± calcite ± plagioclase

Texturally magnetite is occurring both as aggregates of larger grains (0.16-2 mm) and as smaller single grains (0.01-0.20 mm) interstitial in grain boundaries and as inclusions in the

silicate matrix. The grain shape varies from euhedral to anhedral and angular, elongated and somewhat rounded grains occur. The grain boundaries vary from simple and straight to a more complex shape. Plagioclase is present in the ore breccia and together with quartz and K-feldspar it constitutes the silicate matrix. Plagioclase is euhedral to anhedral and often twinned. The composition varies between albite and oligoclase (1-11 % An) and orthoclase (97% Or). Microcline exists in some parageneses. The quartz grains (0.01-0.12 mm) in size are anhedral to rounded. They show no undulose extinction and occur as inclusion in plagioclase or amphibole. The texture of the silicate varies from an equigranular matrix of euhedral grains of plagioclase and K-feldspar to subgranular matrix of inequigranular anhedral grains of both plagioclase quartz and sometimes amphiboles. Especially in parageneses 5) are anhydrite, pyrite and chalcopyrite of importance. Pyrite and chalcopyrite occur as dissemination in veins, at grain boundaries and as (0.005-0.2 mm) large single euhedral grains. Occasional some larger grains (>4.8 mm) occur. Otherwise these sulphides only exist as minor minerals together with (0.4-0.8 mm) large euhedral grains of anhydrite or in larger cluster (> 4mm). The Na-Mg rich amphibole is an *actinolite* and pyroxene has a *diopsidic* composition ($Wo_{38-39}En_{45-48}Fs_{14-16}$) and occurs as cluster (0.8-3.2 mm) in size but also as single grains (0.2-1 mm) interstitial to magnetite. This silicate clusters sometimes forms elongated laths commonly with a preferred orientation. Green to brownish tabular biotite grains exist as (0.04-1.2 mm) large single grains but also as larger grains (>1.2 mm) often interstitial or aligned in lineation. The biotite may be partly altered to or replaced by chlorite. Element analyses are given in (tab. 1, 3 & 4).

Table 3) Representative electron microprobe analyses of apatite and biotite.

Mineral	**Hens**		**Fabian Ore breccia**	
	Apatite	Apatite	Biotite	Biotite
Sample No.	12-2 864	8-2 536	9-3 616	V38-3 28
SiO_2	0	0	44,313	40,898
Al_2O_3	0	0,015	12,933	13,61
FeO (tot)	0,206	0,058	3,886	17,086
MgO	0,121	0,021	24,96	14,192
K_2O	0	0	7,399	8,734
Na_2O	0	0	0,143	0,049
CaO	56,472	57,201	0,005	0
TiO_2	0	0,004	0,899	4,503
MnO	0,005	0,028	0,025	0,037
P_2O_5	36,759	42,028	0,005	0
Cr_2O_3	0	0	0	0
F	6,579	3,571	0	0
Cl	0,278	0	0	0
Total	101,422	102,926	94,568	99,109
No. of oxygens	26	26	22	22
Structural formulae				
Si	0,00	0,00	6,16	5,85
Al	0,00	0,00	2,12	2,30
Fe++	0,03	0,01	0,45	2,04
Mg	0,03	0,01	5,17	3,03
K	0,00	0,00	1,31	1,59
Na	0,00	0,00	0,04	0,01
Ca	11,34	10,60	0,00	0,00
Ti	0,00	0,00	0,09	0,48
Mn	0,00	0,00	0,00	0,00
P	5,84	6,15	0,00	0,00
Cr	0,00	0,00	0,00	0,00
F	1,04	0,52	0,00	0,00
Cl	0,18	0,00	0,00	0,00

All Fe as Fe^{2+}

The alteration of the minerals in massive ore and ore breccia is mainly seen as chloritization and seritization. The biotite is replaced by chlorite occurring as single grains or as veins and quartz, plagioclase and amphibole have rims of seritization.

Table 4) Representative electron microprobe analyses of feldspars.

Mineral	**Hens**			**Fabian Ore breccia**		
	Albite	Albite	Albite	Albite	Albite	Microcline
Sample No.	9-2 592	9-3 610	9-2 589	AP1-8 734	AP3-14 222	H20-1 694
SiO_2	69,27	69,31	68,68	69,77	70,23	69,99
Al_2O_3	19,59	19,58	19,88	20,39	20,61	19,15
FeO (tot)	0,04	0,07	0,04	0,02	0,01	0,18
MgO	0,11	0,03	0,00	0,00	0,00	0,01
K_2O	0,00	0,00	0,00	0,00	0,01	14,83
Na_2O	11,73	11,49	11,27	10,24	10,14	0,21
CaO	0,02	0,02	0,04	0,01	0,09	0,01
TiO_2	0,00	0,00	0,00	0,00	0,02	0,00
MnO	0,02	0,00	0,00	0,01	0,00	0,00
Cr_2O_3	0,01	0,00	0,01	0,00	0,00	0,00
Total	100,79	100,50	99,91	100,44	101,11	104,38
Ab	99,92	99,90	99,80	99,92	99,45	2,10
Or	0,00	0,00	0,00	0,00	0,06	97,84
An	0,08	0,10	0,20	0,08	0,49	0,06
No. of oxygens	32	32	32	32	32	32
Structural formulae						
Si	12,00	12,02	11,98	12,03	12,03	12,19
Al	4,00	4,00	4,09	4,14	4,16	3,93
Fe++	0,01	0,01	0,01	0,00	0,00	0,03
Mg	0,03	0,01	0,00	0,00	0,00	0,00
K	0,00	0,00	0,00	0,00	0,00	3,30
Na	3,94	3,86	3,81	3,43	3,37	0,07
Ca	0,00	0,00	0,01	0,00	0,02	0,00
Ti	0,00	0,00	0,00	0,00	0,00	0,00
Mn	0,00	0,00	0,00	0,00	0,00	0,00
Cr	0,00	0,00	0,00	0,00	0,00	0,00

All Fe as Fe^{2+}

Oxide mineral textures

Ilmenit lamellae in magnetite (ViRi-Fabian)

The magnetite shows oxidation textures of different kind. Homogeneous magnetite shows lamellas of ilmenite and oxidation assemblage of hematite and rutile (fig. 7). The magnetite show signs of oriented lamella (trellis and sandwich) of ilmenit with a thickness of approx. 0.002 mm. An assemblage of hematite and lamellas of rutile occur especially at grain boundaries or in contact to silicates. Martite is found in same samples often along grain boundaries.

Hematite lamellae in ilmenite (ViRi-Fabian)

Another feature is ilmenite grains that occur interstial to magnetite and contain exsolved hematite lenses, ranging between 0.0045-0.027 mm. These lenses occur in centre of the grain (fig. 7).

Martitization (Hens)

In the Hens ore body hematite occur as single grains but also as oxidations surfaces along grain boundaries, fractures and crystal faces (fig. 7). This feature is equally distributed from the footwall to the hanging wall.
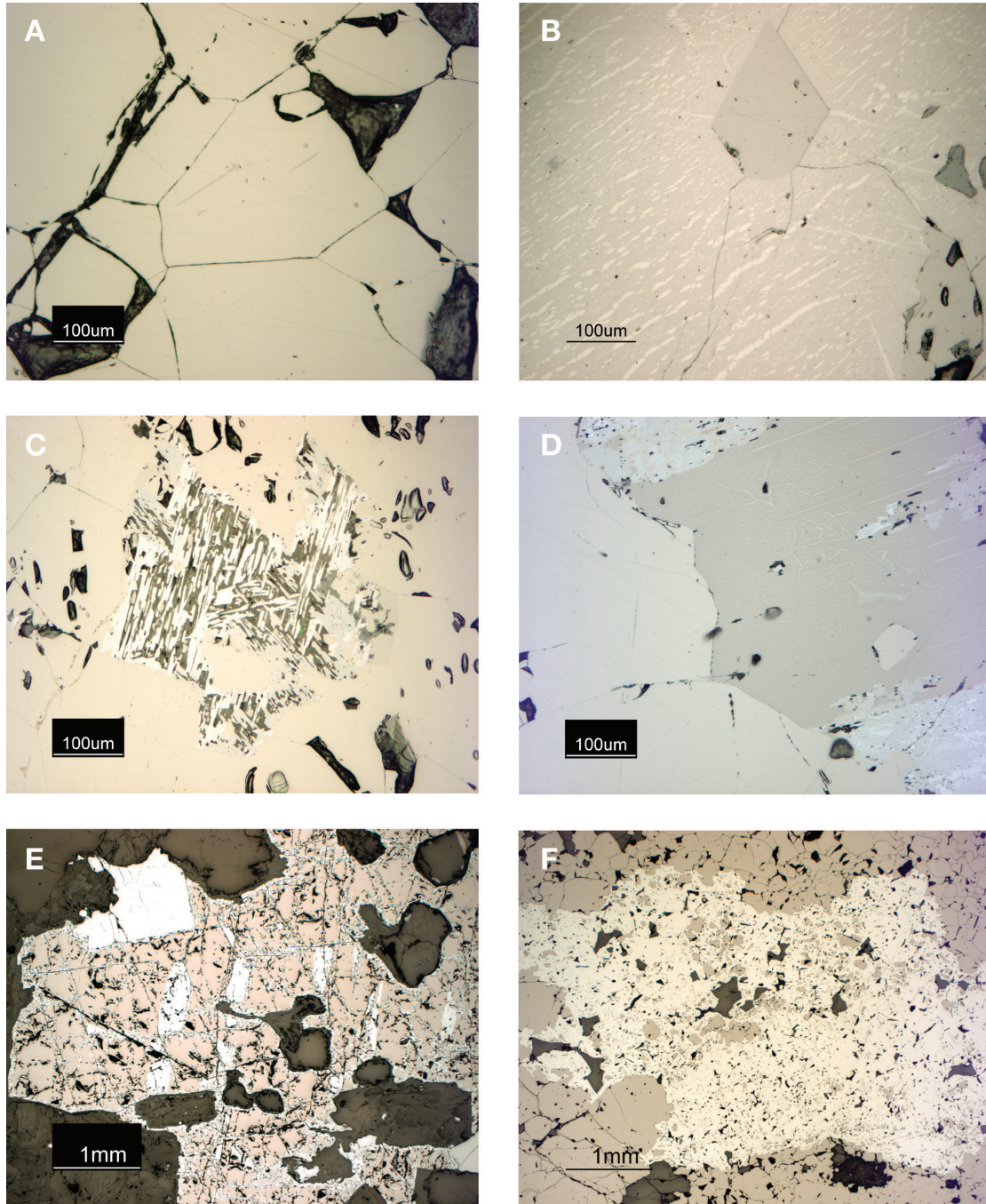
Fig. 7. Photomicrographs of oxidation textures of magnetite and ilmenite at the Malmberget deposit (reflected light). **A)** Exsolution lamellae of ilmenite in magnetite oxidation (stage C_2-C_3) **B)** Hematite lamellas in ilmenite (stage R2) **C)** Increasing intense oxidation will replace magnetite as host by hematite and rutile in areas of former ilmenite (stages C_4-C_5) **D)** Magnetite showing oxidation assemblage of rutile and ilmenite (stages C_4-C_5) and ilmenite with hematite lamellas (stage R5). **E)** and **F)** Martitization of magnetite occurring as oxidation surfaces, along grain boundaries and fractures. The oxidation stages according to (Haggerty, 1991).

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Mineral chemistry

Magnetite and hematite at Hens

Magnetite from the Hens ore body has a low content of practically all the trace elements (tab. 5). However, there is an indication of higher MgO and V_2O_3 contents compare to ViRi ore body (fig 8). Two subgroups can be distinguished for MgO by a distinct higher content (0.037-0.055 %) in some samples. This variation is depending on the samples and probably controlled by the mineral parageneses. The V_2O_3 content forms a narrow group of a low content (0-0.023 %) and a group of a higher content (0.023-0.075 %). Hematite samples shows a higher content of TiO_2 (4.27-5.04 %) and V_2O_3 (0.09-0.18 %) than the coexisting magnetite.

Tab. 5. Representative electron microprobe analyses of magnetite and hematite from Hens ore body

	Hens						
Mineral	Magnetite				Hematite		
Sample no.	H495-8-537	H495-9-601	H495-11-54	H495-12-52	H495-11-52	H495-11-76	H495-11-77
FeO (tot)	93,863	94,391	92,693	93,093	87,322	86,568	87,942
Al_2O_3	0,095	0,151	0,1	0,105	0,066	0,086	0,107
TiO_2	0,019	0,011	0,008	0,038	4,848	5,047	4,407
V_2O_3	0,024	0,004	0,069	0,093	0,119	0,182	0,117
MgO	0,004	0,01	0,039	0,549	0	0	0,046
P_2O_5	0	0	0	0	0	0	0
CaO	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0
MnO	0,026	0	0,067	0,008	0,004	0	0
NiO	0	0,008	0,003	0	0	0	0
Cr_2O_3	0,017	0	0,051	0	0	0,006	0,01
ZnO	0	0	0,012	0,008	0,014	0,004	0,005
CuO	0,057	0,052	0,008	0,062	0,047	0,02	0,023
Total	94,105	94,627	93,05	93,956	92,42	91,913	92,657
Fe_2O_3 (calc)	69,646	70,035	68,811	69,750	58,299	57,418	59,368
FeO (calc)	31,195	31,373	30,776	30,331	34,864	34,903	34,522

Fe^{2+} and Fe^{3+} recalculated

Magnetite and ilmenite at ViRi

The ViRi ore body is characteristic for higher V_2O_3, TiO_2 and Al_2O_3 content compared to Hens magnetite (tab. 6). Magnetite forms two subgroups of low (0-0.072 %) and high (0.14-0.27 %) content of V_2O_3 respectively, (fig. 8). TiO_2 varies from a low to high content and is divided in three different subgroups (0-0.1 %, 0.1-0.97 % and 1.30-2.34 %). The Al_2O_3 content is overall rather low but slightly higher than Hens magnetite. Ilmenite contains a varying content of Mg and Mn and also a higher content of V than the coexisting magnetite
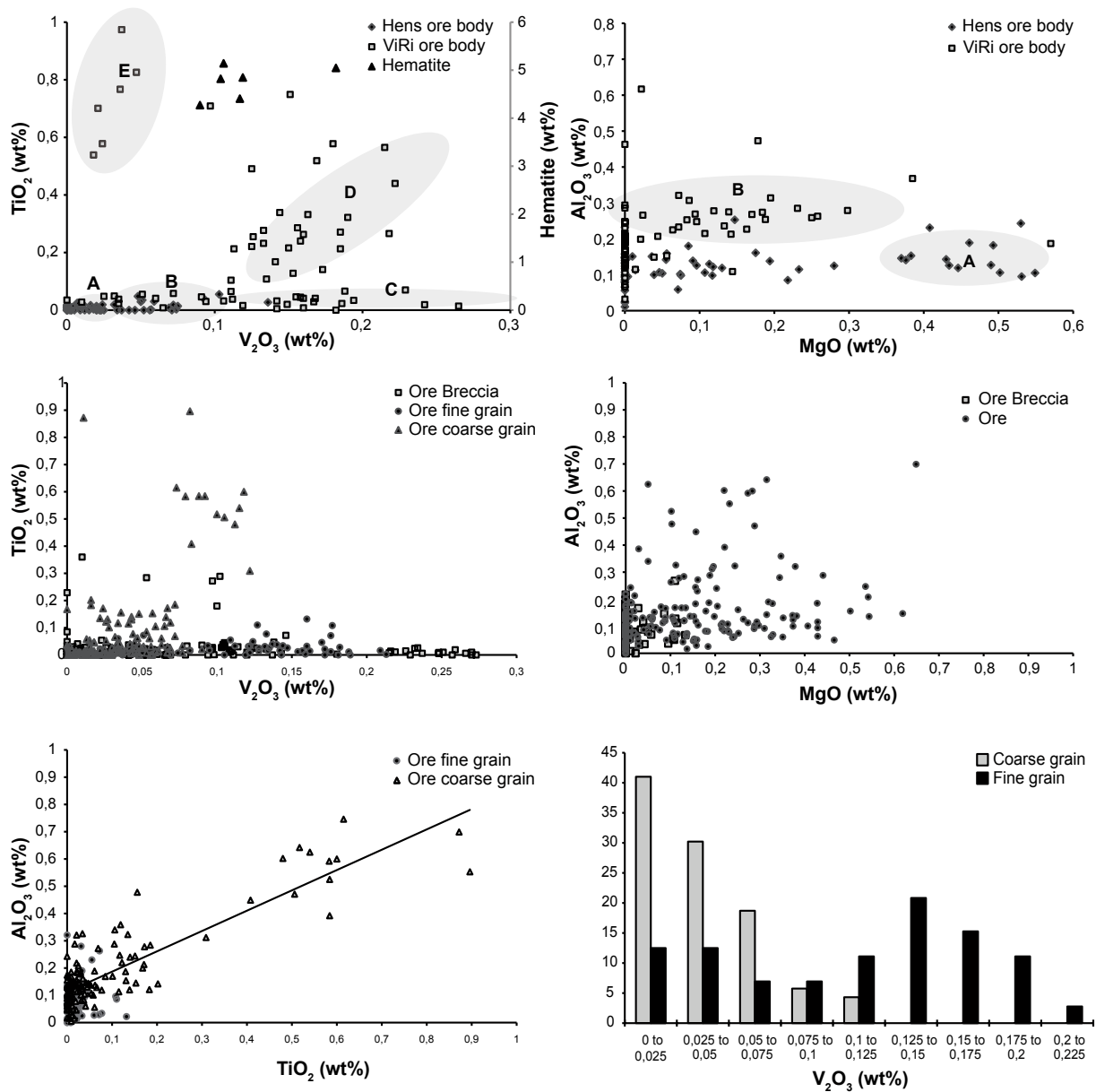
Fig. 8. Mineral chemical plots of magnetite and hematite from Hens, ViRi and Fabian **A)** The TiO_2 content in magnetite (left axis) and hematite (right axis) vs. the V_2O_3 content in Hens and ViRi. **B)** The Al_2O_3/MgO content of magnetite in Hens and ViRi. **C)** The TiO_2/V_2O_3 content in magnetite from massive ore and ore breccia, massive ore is subdivided into "fine grain" and "coarse grain" magnetite textures. **D)** The Al_2O_3/MgO content of magnetite from massive ore and ore breccia. **E)** The Al_2O_3/TiO_2 content in magnetite from massive ore subdivided into "fine grain" and "coarse grain" magnetite textures. Coarse grain magnetite shows a positive correlation of these elements. **F)** A histogram of the V_2O_3 in magnetite from massive ore subdivided into "fine grain" and "coarse grain" magnetite textures.

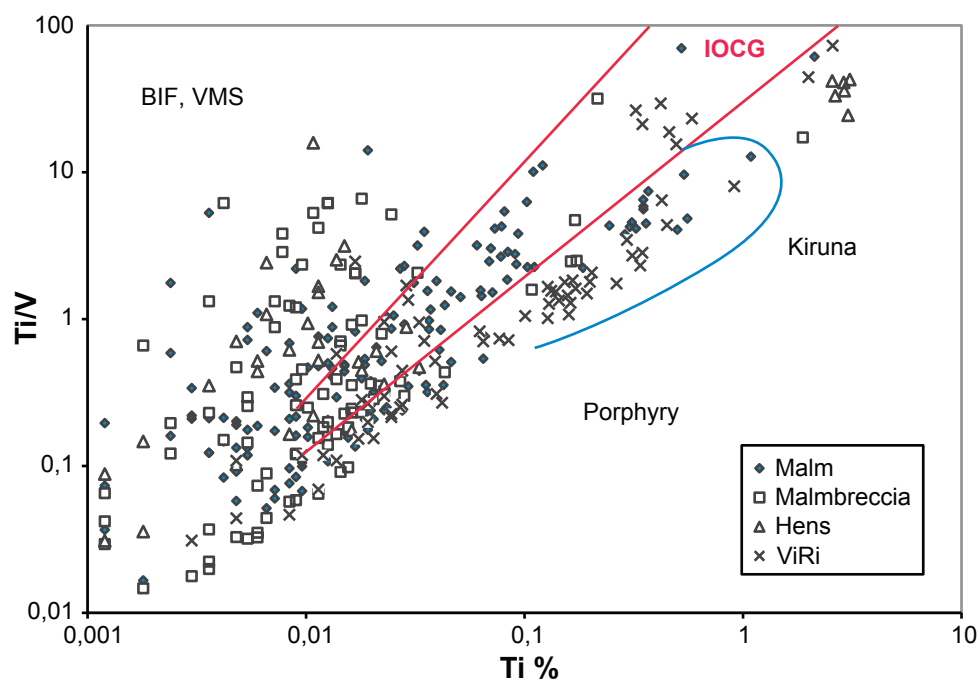Fig 9. Ti vs. Ti/V (%) binary plot for magnetite from Malmberget deposit, fields for IOCG and Kiruna deposits modified from Beaudoin et al. 2006

Tab. 6. Representative electron microprobe analyses of magnetite from ViRi ore body

Mineral	ViRi							
	Magnetite					Mag – ilm – hem assemblage		
Sample no.	V834-2-25	V834-3-664	V834-3-665	V858-4-80	V858-6-256	V858-4-82	V834-2-33	V834-3-684
FeO (tot)	93,977	93,163	91,518	94,038	93,215	92,227	90,608	83,887
Al_2O_3	0,207	0,215	0,463	0,259	0,307	0,215	0,187	5,31
TiO_2	0,019	0,055	0,974	0,491	0,322	1,521	3,326	4,292
V_2O_3	0,242	0,051	0,037	0,125	0,19	0,167	0,066	0,052
MgO	0,044	0,107	0	0,25	0,086	0	0,57	0,024
P_2O_5	0	0	0	0	0	0	0	0
CaO	0	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0	0
MnO	0	0	0,012	0,02	0	0,086	0,182	0,032
NiO	0	0	0	0	0,018	0,013	0	0,013
Cr_2O_3	0,017	0,022	0	0,009	0,024	0	0	0,015
ZnO	0	0	0,036	0,021	0	0	0,044	0,014
CuO	0,035	0,053	0,05	0,026	0,01	0,027	0	0,059
Total	94,541	93,666	93,09	95,239	94,172	94,256	94,983	93,698
Fe_2O_3 (calc)	69,610	69,112	66,431	69,322	68,669	66,333	63,595	53,862
FeO (calc)	31,341	30,976	31,743	31,661	31,426	32,540	33,384	35,421

Fe^{2+} and Fe^{3+} recalculated

Massive ore and ore breccia at Fabian

When comparing the chemical variation between the two types of ore it shows a rather apparent pattern where the *ore* is more diverse in trace elements (fig. 8). *Ore* has a more variable trend for the elements where both TiO_2 and Al_2O_3 are higher for coarse grained magnetite, while fine grained magnetite has a higher content of V_2O_3. Samples that contain MgO are those which are almost free from all silicates (massive).

Table 7. Representative electron microprobe analyses of magnetite and ilmenite from Fabian ore body.

Mineral	**Fabian Ore** Magnetite						Ilmenite
Sample no.	V35-1-259	584A-7	V20-1-294	BC6-3-800	V40-1-372	586C-478	V40-1-376
Texture	Fine grain	Fine grain	Fine grain	Coarse grain	Coarse grain	Coarse grain	
FeO (tot)	94,436	93,569	93,144	94,118	93,452	93,881	41,95
Al_2O_3	0,014	0,112	0,096	0,134	0,471	0,24	0,047
TiO_2	0,021	0,059	0,014	0,012	0,506	0,14	47,256
V_2O_3	0,172	0,146	0,128	0,031	0,105	0,043	0,322
MgO	0	0,11	0,067	0,104	0,288	0,203	2,609
P_2O_5	0	0	0	0	0	0	0
CaO	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0
MnO	0	0,053	0	0,009	0	0,009	0,286
NiO	0	0	0,009	0	0	0	0
Cr_2O_3	0,033	0,005	0,044	0	0,034	0,004	0
ZnO	0	0,024	0	0	0	0,036	0
CuO	0,024	0,067	0	0,051	0,008	0	0,021
Total	94,7	94,145	93,502	94,459	94,864	94,556	92,491
Fe_2O_3 (calc)	70,016	69,496	69,105	69,958	68,789	69,631	-
FeO (calc)	31,435	31,036	30,963	31,169	31,555	31,226	-

Fe^{2+} and Fe^{3+} recalculated

The only specific trend for *ore breccia* is an equally distributed pattern of V_2O_3 (0-0.27 %) from low to a high content. The TiO_2 and Al_2O_3 content are low and show no variation for the ore breccia samples (fig 8).

Ilmenite in *ore breccia* and *ore* show the opposite trends for the element Mg and Mn (tab. 7 & 8). Ilmenite in ore is richer in MgO (2.2-2.6 %) and the ore breccia samples show a higher content of MnO (1.2-2.0 %).

Table 8. Representative electron microprobe analyses of magnetite and ilmenite from Fabian ore body.

Mineral	**Fabian Ore breccia**							
	Magnetite							Ilmenite
Sample no.	V38-1-2	V11-1-648	V17-2-503	H20-1-704	V29-3-186	V49-2-126	AP1-8 729	V38-1-4
Type	Massive	Massive	Massive	Inclusion	Inclusion	Inclusion	Inclusion	
FeO (tot)	93,876	93,282	94,25	93,507	94,01	93,676	93,191	46,431
Al_2O_3	0,178	0,055	0,069	0,063	0,069	0,002	0,059	0,018
TiO_2	0,026	0,024	0,019	0,054	0,009	0,021	0,009	52,282
V_2O_3	0,125	0,03	0,004	0,023	0,248	0,133	0,031	0,392
MgO	0	0,106	0,057	0	0	0	0	0,262
P_2O_5	0	0	0	0	0	0	0	0
CaO	0	0	0	0	0	0	0	0
SiO_2	0	0	0	0	0	0	0	0
MnO	0	0	0	0	0,016	0,032	0	2,016
NiO	0	0,003	0	0	0	0,003	0,009	0
Cr_2O_3	0,025	0,062	0,045	0,025	0,019	0,047	0,009	0,001
ZnO	0	0,021	0,022	0,035	0	0	0,009	0,01
CuO	0,021	0,017	0,054	0,055	0,058	0,082	0,03	0,036
Total	94,251	93,6	94,52	93,762	94,429	93,996	93,347	101,448
Fe_2O_3 (calc)	69,502	69,301	70,008	69,323	69,688	69,527	69,143	-
FeO (calc)	31,337	30,924	31,256	31,129	31,304	31,115	30,975	-

Fe^{2+} and Fe^{3+} recalculated

For the other analysed elements no correlation is found for a specific element to a specific type of ore, texture or mineral paragenesis.

Discussion

Oxidation of magnetite textures and products – general aspects

The apatite iron ore in the Malmberget deposit has been exposed for extensive regional metamorphism, deformation and alteration events and as a result were few primary structures and features are preserved in the ore mineralization and the surrounding rocks (Geijer, 1930; Bergman et al., 2001; Martinsson and Virkkunen, 2004). All three different ore bodies in Malmberget deposit in this study have characteristic features regarding mineralization, mineralogy, alteration, chemistry and textures.

Mineralization

The character of magnetite which includes grain size, shape, texture and occurrence is the same for all three ore bodies. The main ore type is massive *ore* which constitutes the major part of each

ore body, massive to its appearance. It has high iron content and contains apatite and amphibole as the main gangue minerals. Ore breccia is characterised by a breccia style mineralization surrounding the massive ore. Magnetite and gangue minerals form breccia infill and comprise several different mineral paragenesis. The iron content is lower compare to massive ore.

Mineralogy

Hematite is only present in the Hens ore body and it occur as smaller separate lenses close to the main magnetite body but also as disseminated grains in the massive ore and in associations to the quartz-plagioclase matrix. The abundant occurrence of hematite in association to iron poor silicates indicate a higher degree of oxidation (Annersten, 1968). Frietsch (1967), Annersten (1968) and Annersten and Ekström (1971) describe the alteration of magnetite to hematite as a high oxygen fugacity condition. The Fabian and ViRi ore bodies have a similar mineral association where the amount of sulphides, Ti minerals and Ti phases are typical common features. The magnetite show no visible inclusions more than some Ti phases that probably is rutile (Annersten, 1968). Pyrite and chalcopyrite occur mainly disseminated interstitial to magnetite grains or as veins. The mineral paragenesis; magnetite + amphibole + anhydrite + pyrite ± calcite ± plagioclase in ore breccia shows a quite common feature with sparsely disseminated or larger amount of anhydrite together with pyrite and chalcopyrite. Sulphides are also a characteristic minor component at Kiirunavaara and El Laco and are interpreted as low temperature hydrothermal products (Nyström, 1985).

Magnetite texture and grain size

The magnetite shows a large variation in texture and grain size which might be explained by metamorphic overprinting. The recrystallization of magnetite is expressed by a varying grain size where the common coarse grained texture is arranged in a foam texture with triple junction configuration of grain boundaries (fig. 5A). The euhedral grains have an equigranular texture with straight grain boundaries. An increasing grain size causes the euhedral grains to develop gently curved grain boundaries to a subhedral grain shape. A common feature is large porphyroblasts in the magnetite matrix. The porphyroblasts occur as single grains or outline veinlike structures with smaller grain of magnetite as interstitials (fig. 5B). This selective growth of grains is caused by on a high temperature and where the surrounding minerals will provide elements to those grains, acting as nucleating agents (Vernon, 2004 and references therein). Small magnetite grains occur as inclusion in larger porphyroblasts (fig. 5C) of plagioclase and amphibole generated by the prograde metamorphism where the small grains been engulfed by porphyroblasts during their growth (Vernon, 2004 and references therein). Smaller anhedral grains occurring particularly at grain boundaries of the silicate matrix are probably formed at a lower temperature after the silicate matrix had developed its granular texture (fig. 5D).

Oxidation textures of magnetite

Iron and titanium oxide minerals reveal a lot of paragenetic information about the rocks containing them and their microtextures provide important knowledge of the prevailing oxygen pressure and temperature (Buddington and Lindsley, 1964). The magnetite from ViRi and Fabian shows oxidation textures of different stages, from homogeneous magnetite, exsolution lamellae of ilmenite to an intense oxidation assemblage of hematite and rutile. The microtextures are trellis and sandwich lamellae of ilmenite in magnetite. Trellis texture defines as thin lamellae along the {111} planes in magnetite and sandwich texture are defined as thicker lamellae along one of the {111} plane (Lindsley, 1991). These lamellae are concentrated in the centre of the magnetite grains. Magnetite exposed to more intense oxidation exhibit an alteration to hematite and lamelleas of rutile and might end up with a complete pseudomorphic replacement by hematite (Mücke and Cabral, 2005). Magnetite from Hens ore body shows an extensive martitization of magnetite. Different textures of martitization are shown as whole grains of hematite, incomplete martitization along grain boundaries, fractures and crystal faces (fig. 7E & 7F) and is assumed to be a late alteration product (Annersten, 1968).

Mineral chemistry - Fe-Ti oxides and iron oxides

Trace element redistribution among ore forming minerals and ferromagnesian silicates during metamorphism seems to be variable connected to temperature, pressure and oxygen fugacity (Annersten, 1968).

Magnetite (Fe_3O_4) and hematite (Fe_2O_3) are both iron ore minerals that can change there trace element content due to the physical properties such as size, charge and bonding of different ions of element that are available (Frietsch, 1970). Magnetite belongs to the spinel group with an inverse structural type and hematite belongs to the hematite group which enables substitution of elements in both the octahedral and tetrahedral positions in magnetite and in the octahedral positions in hematite (Deer et al., 1992). According to Frietsch (1970) the trace element distribution in magnetite is more suitable than hematite for genetically considerations. Definition of trace elements is according to Rollinson (1994) concentrations less than 0.1 %. Elements in magnetite and hematite that are found in considerable larger amount in this study are TiO_2, Al_2O_3, V_2O_3 and MgO which will be referred to as minor element.

The overall trace element chemistry of Malmberget magnetite is similar to other apatite iron ores and matches published data from e.g. Kiirunavaara (Frietsch, 1970; Parák, 1975; Nyström and Henríques, 1994; Müller et al., 2003). Characteristic chemical signatures for apatite iron ores is a high content of V_2O_3 and TiO_2 and a low content of CoO, Cr_2O_3, NiO and MnO (Frietsch, 1970; Helvaci, 1984; Nyström and Henríques, 1994). Depending on the deposit has formed from an iron oxide magma ore from hydrothermal fluids the content of elements is differing e.g. with a higher content of TiO_2 in magmatic deposits (Hildebrand, 1986; Näslund et al., 2000).

The magnetite from the different ore bodies (Hens, ViRi, Fabian) display some sort of systematic chemical variation of the minor elements V_2O_3, TiO_2, Al_2O_3, and MgO. Hens have a low content of practically all the elements and would plot close to the pure end member compositions Fe_3O_4. Fabian and ViRi ore bodies have similar magnetite chemistry with a higher content of minor element compared to Hens but the latter has generally a higher content of the trace elements (fig 8).

Chemistry in relation to ore type (massive ore – ore breccia)

Magnetite from the two ore types massive ore and ore breccia show different chemical composition. Massive *ore* has a content of minor and trace elements that correspond to other apatite iron deposits around the world and the composition of the magnetite could be interpreted as formed either from an iron oxide melt-magma or from hydrothermal fluids at higher temperature.

Ore breccia is characterised by a magnetite which is rather poor in minor and trace elements. The only element which is varying in content in ore breccia is V_2O_3 and the content of this element is dependent on which sample the analysis is from. Some of the samples have a very high content which correspond to the ViRi ore body. It appears to be controlled by the mineral paragenesis and the textures (se below). Ore breccia magnetite is also practically free from TiO_2 which also is manifested by the rare occurrence of ilmenite grains and exsolution lamellae of ilmenite in magnetite in contrast to the massive *ore*. This low content of elements in ore breccia magnetite could be a result of a different ore forming process compared to massive ore. According to Monteriro et al. (2008) is hydrothermal magnetite related to sodic-calcic alteration and IOCG style of mineralisation overlapping with Kiruna type magnetite in terms of Ti, Ti/V. By compare our data to a model by (Beaudoin et al., 2006) *ore breccia* could have formed by a hydrothermal process with fluids comparable to those of porphyry copper or IOCG style (fig. 9). At this rather low temperature of the fluids the substitution of elements is rather limited causing a depleted magnetite composition.

Chemistry in relation to texture (metamorphic features)

The magnetite in the massive *ore* shows a varying chemistry which could be a primary feature or caused by metamorphic recrystallization and redistribution. To be able to explain the variation of elements it is necessary to evaluate these analyses with respect to different kind of magnetite textures and the most obvious distinction is between coarse grained and fine grained magnetite that shows tendency for a systematic chemical variation of Al_2O_3, V_2O_3 and TiO_2.

Al$_2$O$_3$ and MgO content of magnetite

Magnetite grains have been exposed for several different possibilities of substitution, during formation and later reequilibrium with associated silicates. Magnesium can enter magnetite mostly in small amount as Mg^{2+} and will substitute for Fe^{2+}, in spite of the different ion size (Frietsch, 1970). Aluminium is also an element that occurs as an important main component during substitution of different elements of many rock forming minerals (Deer et al., 1992) but are not expected to enter magnetite and hematite lattice in larger amount due to differences of the physical properties compared to iron. The magnetite of massive ore has an Al$_2$O$_3$ content with a slightly different appearance than the other elements if the texture of the magnetite is considered. By comparing aggregates and single grains of magnetite it appears that Al$_2$O$_3$ is strongly depressed in the single grains that occur in silicate matrix. If the single grains are larger and are part of a mineral assemblage where quartz is present a higher Al$_2$O$_3$ content will be the case. Some analyses of coarse grained magnetite have a slightly higher concentration of both Al$_2$O$_3$ and TiO$_2$ which also is indicated by a positive correlation of these elements (fig. 8).

The MgO content in magnetite grains varies independent of ore body, ore type and texture. If the magnetite grain is situated in the massive part of the ore body with a low content of silicates the MgO concentration will be higher.

V$_2$O$_3$

It is a rather distinct difference between the ore bodies and the varying V$_2$O$_3$ content of magnetite in ore bodies, ore type and textures probably mainly due to the metamorphic recrystallization. Näslund et al. (2000) stated that V$_2$O$_3$ is enriched in an iron rich magma produced by immiscibility and according to Frietsch (1970 and references therein) titaniferous magnetite has a high V$_2$O$_3$ content. The vanadium content in coexisting *magnetite* and *ilmenite* and *magnetite* and *hematite* at equilibrium can be an indicator of the prevailing oxygen fugacity and temperature (Schuiling and Feenstra, 1980). In the ViRi ore body, samples of ore breccia and the texture "fine grain magnetite" in massive ore show a higher concentration of V$_2$O$_3$. Magnetite from ViRi and Fabian has a coexisting ilmenite containing higher V$_2$O$_3$ than the magnetite. Schuiling and Feenstra (1980) have shown that ilmenite in magnetite-ilmenite pairs which is fairly close to the magnetite-hematite buffer curve will contain more V$_2$O$_3$ than magnetite because V is then more common as V^{4+} and will substitute for Ti^{4+}. In magnetite-hematite pairs when the hematite-magnetite boundary is approaching, the hematite always concentrates the V. This is due to the fact that V is transformed to V^{4+} and the number of available sites for Fe^{3+} to be substituted by V^{4+} is only 2/3 in the coexisting magnetite. The low content of V$_2$O$_3$ in magnetite in Hens ore body compared to ViRi and Fabian is therefore probably an expression of redistribution of vanadium during formation of hematite which also is supported by the higher content of V$_2$O$_3$ in the coexisting hematite in Hens. Regarding texture the coarse grained magnetite in massive

ore which is not a primary texture has a low content of V_2O_3 and although the fine grained magnetite is more variable it have a tendency to contain a higher content (fig 8). It could not be stated whether all the fine grain magnetite is a primary texture or if some of the fine grain magnetite is exposed for some sort of recrystallization and/or deformation event causing some loss of V_2O_3.

TiO$_2$

The oxide mineral phases and their textures indicate the oxidation conditions of the ore bodies, which will also have an implication for the mineral chemistry. The composition of coexisting titanoferous magnetite and ferrian ilmenite can give valuable information of the temperature and oxygen fugacity of the formation and magnetite grain that occur without associated, independent grains of ilmenite probably was unsaturated with respect to TiO_2 during formation at the prevailing temperature and oxygen pressure (Buddington and Lindsley, 1964). Fabian and ViRi ore bodies have a magnetite with a very low content of Ti. Magnetite from Hens ore body is almost practically free from Ti and also lack of ilmenite lamellas. It is instead the coexistent hematite that has a rather high content of TiO_2 (fig. 8A). A high content of Ti in hematite formed at high temperatures is also suggested by Annersten (1968) based on the occurrence of exsolution lamellae of ilmenite in the hematite.

Magnetite with exsolved lamellae (subsolidus) of ilmenite indicates an oxidation at low to moderate pressure and above 600° C with a direct formation of Ilm-Hem$_{ss}$ (Buddington and Lindsley, 1964) and at more intense oxidation the ilmenite will be structurally controlled within the titanomagnetite host (Haggerty, 1991). This is seen in (fig. 7C) as rutile in areas of former ilmenite and hematite which replaces the host magnetite. According to Haggerty (1991) the progressive oxidation of titanomagnetite exhibits a characteristic exsolution sequences for microtextures (C_1-C_7) in the magnetite-ulvöspinel solid solution. C_1 is the homogeneous magnetite and the C_7 stage is an advanced stage of oxidation, characterized by an assemblages of pseudobrookite and hematite in solid solution (Haggerty, 1991). The intergrowth of ilmenite lamellae in magnetite grain corresponds to stages C_2 and C_3 (fig. 7A). A further and increasing intense oxidation will cause magnetite to be replaced by hematite and pseudorutile which corresponds to stages C_4-C_5 (fig. 7C). Analogous high temperature oxidation of primary ilmenite refers to the characteristic stage (R_1-R_7) Haggerty (1991). R_1 is a homogenous ilmenite and R_7 is the highest oxidation stage with coexisting rutile and titanohematite (pseudobrookite). C_7 and R_7 are both present as close associations (Haggerty, 1991). In ViRi and Fabian ore bodies ilmenite is shown as single grain with or without hematite lamellae, stage R_1-R_2 (fig. 7B & 7D). A more intense oxidation of ilmenite is seen as extensive development of titanohematite and ferrianrutile similar to stage R_5 (fig 7D).

The other analysed elements in magnetite and hematite show no systematically variation.

Conclusion

The apatite iron ore bodies (Hens, ViRi, Fabian) in the Malmberget deposit show mineralogical, textural and chemical variations of the ore minerals as a result of recrystallization and oxidation processes.

The ore bodies Fabian and ViRi have similar mineralogical characteristics with the occurrence of Ti minerals, pyrite and chalcopyrite as common minor components. Hens ore body has a different style of mineralisation by the presence of hematite.

All three ore bodies have different chemical signatures and magnetite from the different ore bodies show a chemical variation of the minor elements V_2O_3, TiO_2, Al_2O_3, and MgO. In the Hens ore body the content of TiO_2 is high in hematite and low in magnetite which is suppose to be a redistribution of the element during recrystallization at high oxygen fugacity.

The oxidation textures in magnetite indicate that the ore bodies have been exposed to different stages of oxidation. Magnetite and ilmenite occur as coexisting minerals and show textures varying from the lowest oxidations stage (C_1 & R_1) which is homogeneous magnetite or ilmenite to the highest oxidation stage (C_5 & R_5) which is replacement textures of hematite and ferrianrutile.

The massive ore and ore breccia from Fabian ore body show distinctly different mineral associations and chemical composition of magnetite indicating different origin. The magnetite from the massive ore have chemical similarities with other apatite iron ore deposits around the world and could have been formed either by an iron oxide melt-magma or from hydrothermal fluids at high temperature. For ore breccia the mineral associations and the low content of minor elements in magnetite suggests a generation by hydrothermal processes with fluids of a temperature similar to that of IOCG-style of mineralization.

Acknowledgement

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A quantitative mineralogical characterization of the Malmberget apatite-iron deposit, Sweden using QEMSCAN®

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Abstract

It is necessary to identify and improve mineralogical and textural properties of ore and ore concentrate which can cause process mineralogical problems during upgrading of ore products in the mining industry. A quantitative mineralogical and textural characterisation was performed on ore concentrate from the Malmberget apatite iron deposit by the use of QEMSCAN®. Ore from one ore body were divided in morphologically two different types called ore breccia and ore. Each ore type were crushed and split in three fractions 150 μm, 75 μm and 38 μm. Magnetite, amphibole, feldspar, quartz and apatite are the dominating minerals for the two ore types. Ore has a simple mineralogy while ore breccia is more diverse and comprises different mineral parageneses. The magnetite grains are euhedral to anhedral in shape with a varying grain size. The modal mineralogy shows a high concentration of magnetite in the ore, in all three fractions and for ore breccia the concentration of magnetite is lower with a notable drop for the finest fraction (38 μm). Of the gangue minerals the amphibole/pyroxene mineral classes dominate in both ore types while the presence of apatite is characteristic for ore, and feldspar for ore breccia. The particle liberation of magnetite for ore is high for all fractions but decreases at finer fractions. The ore breccia has a different appearance with two main classes of liberation. It is liberated class of magnetite and a locked class where the liberation of magnetite is low. The mineral associations differ between the ore types, ore breccia being more diverse then ore by the presence of more binary and complex magnetite bearing associations. The most frequent binary association was magnetite/FeTi-oxides (includes ilmenite and rutile) for both ore types and a characteristic complex magnetite/quartz/feldspar association in ore breccia. Two characteristic mineral textures were found. Magnetite occurring as a mixed grain attached to different gangue minerals and as small inclusions or as composite particles mainly in feldspar. Ore breccia is an ore type were some of the magnetite bearing associations will cause an increasing amount of silica in the concentrate or iron content reporting to the tailings.

Introduction

Ever since the production of iron lump ore was replaced by pellet production at LKAB apatite iron ore mines, the focus has been on the concentration properties of the ore and pelletization to achieve a high and even recovery of the products. During mining today at LKAB, Malmberget, ore from different ore bodies are mined and mixed in the process during upgrading which means that different kind of ore types are present. From a mineral processing prospective the concentrate will contain a broad variation of textures and mineral associations causing process problems of a mineralogical character.

Today the mining industry works in different ways to solve these problems. During the last three decades the development of a number of techniques using image analyse systems based on Scanning Electron Microscopy (SEM) technology has occurred for a more rapid quantitative estimation and description of mineralogy and particle textures (Jones and Gravilovic, 1970; Gottlieb et al., 2000; Petruk, 2000; Gu, 2003). This development has led to an improvement in process mineralogical knowledge during upgrading of ore.

It is important to have a precise and detailed mineralogical and textural understanding since these characteristics are closely connected to a concentration process (Sutherland et al., 2001). Many iron ore studies have a tendency to be concerned with the chemical composition rather than the mineralogy, grain morphology and microstructures and these parameters need to be evaluated and understand in process mineralogy (Santos and Brandao, 2003). Referring to Petruk (2000), when a process problem arises according to the mineralogical character of an ore or process product, it is important to gain mineralogical knowledge to solve the problems. However, traditionally mineralogical studies are applied to exploration and ore characterisation but are ignored during later processing (Sutherland et al., 2000).

The aim of this study is to characterise an apatite-iron ore body with respect to process mineralogy. It requires a complete identification of all mineralogical phases, the modal mineralogy, textural behaviour such as mineral liberation and mineral association, all in a quantitative manner. Process mineralogy in this case will be used to create a tool which gives detailed information of the mineralogy and their properties from different kind of ore bodies in the same deposit. These data will both act as knowledge to improve further mineral processing and be a key to solve future process mineralogical questions/problems.

Concept of process mineralogy

To understand the fundamentals of mineral processing it is important to understand and link every single stage in the process chain. It is the mineralogy and the properties of an ore which determines the conditions for further processing (Batterham et al., 1992). To improve

the characterisation of ore and minerals an efficient process can be designed and the mineral treatment can be optimized (Sutherland et al., 2000). Process mineralogy has combined the two disciplines mineral processing and mineral science (Lotter, 2003). Moen (2006) defines process mineralogy as the mineralogy which is applied to the product in specific industrial processes such as the mineralogy in the concentrator, pelletization or in other process stages.

It is required to determine what kind of minerals and textures the ore consists of, due to the fact that the liberation characteristics are close related to the mineralogical texture and these parameters sets the crucial design of further beneficiation (Lorenzen and van Deventer, 1994). A large amount of information about the ore fines needs to be obtained, like particle mineralogy, class, porosity, mineral association, texture, hardness, size distribution, mineral liberation, class densities and mineral composition (Donskoi et al., 2007). According to Sutherland et al., (2000) ore characterisation includes several aspects, such as improved ways of measuring minerals characteristics of ores and ore product, better knowledge of the influence on the measured parameters or better methods for evaluating and present these mineralogical data.

The mineralogy, chemistry and metallurgical properties of an ore and products can be obtained by a combination of different analytical instruments (Henley, 1992; Goodall et al., 2005). Optical microscopy including point counting has traditionally been used for the identification and quantification for both mineralogical and texturally properties, which is a time consuming process (Petruk, 2000) and dependent on the skill of the mineralogist (Henley, 1992). For that reason quantitative estimations, especially during mineral processing has been a limiting factor in the past (Batterham et al., 1992) which today are easier to achieve by the automated SEM based techniques.

Characterisation

The type of information and characterisation this study will measure and evaluate is;
- Modal mineralogy / mineral distribution
- Mineral liberation of important minerals (e.g. magnetite)
- Mineral associations
- Mineral textures

Deposit geology:

In the province of northern Norrbotten, Sweden, LKAB is producing 90 % of Europe's iron ore from two large underground mines, Kiirunavaara and Malmberget. These deposits of apatite iron ore have a similar origin and the genesis of this type of deposit has been debated for more than 100 years. Either a magmatic or a hydrothermal model is suggested but to meet all the characteristic features of the apatite iron ores a magmatic-hydrothermal process is most likely (Martinsson, 2004) at 1.89-1.88 Ga (Cliff et al., 1990; Romer et al., 1994). However,

there are major discrepancies in character between Kiirunavaara and Malmberget, due to later overprinting by metamorphoses, deformation and granitic intrusions, which are stronger for the Malmberget ore (Martinsson, 2004).

In the Malmberget ore field, more than 20 different tabular to stock shaped ore bodies of both magnetite and hematite are spread over an area of 2.5 x 5km (fig 1). The Malmberget deposit was probably from the beginning a more or less continuous and tabular ore lens which was exposed for at least two phases of folding and metamorphism. These events torn the ore lenses apart by strong ductile deformation and today they occupy a large-scale fold structure were the individual ore bodies stretch parallel to the fold axis, which plunge 40º-50º towards SSW (Bergman et al., 2001).
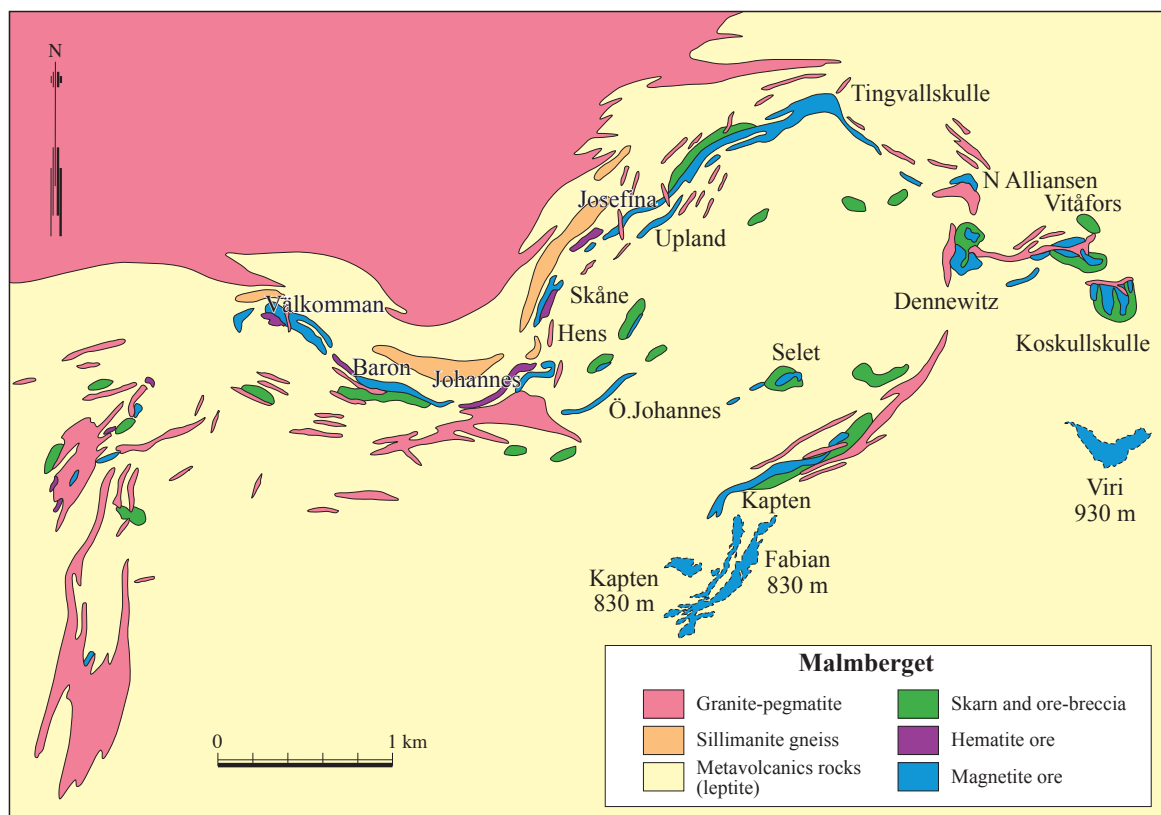
Figure 1. Simplified geological map showing the Malmberget ore deposit modified from Bergman et al. 2001.

The iron ore minerals are both magnetite (Fe_3O_4) and hematite (Fe_2O_3) but the magnetite is more common of the two. Hematite forms several separate ore bodies and portions of others (Geijer, 1930). The main gangue minerals are apatite, amphibole, pyroxene, feldspars, quartz and biotite. Among the accessory minerals are pyrite, chalcopyrite, titanite, zircons and calcite most commonly. Each ore body has their own characteristic mineral, chemical and textural properties.

Due to the strong metamorphic recrystallization of the area, the minerals are recrystallised, coarse grained, and elongated in the direction of the lineation of the rocks.

Material

Ore types:

The iron ore at Malmberget have been divided in morphologically two different types called *ore breccia* and *ore*. The *ore breccia* consists of magnetite, occurring as breccia infill in the wall rocks together with different proportion of gangue minerals like quartz, amphibole, pyroxene, apatite and feldspars. The *ore* consists of massive magnetite, forming large ore lenses and it contains gangue minerals like amphiboles and apatite in smaller amounts. The *ore breccia* borders the massive ore, but occurs also partly as inclusions in the massive ore.

Sample preparation

Both ore types were sampled from drill cores. At the mineral processing laboratory at Luleå university of Technology, the samples were crushed in a Retsch jaw crush, +3 mm, split by a Jones splitter and sieved with a Ro-Tap shaker at the fraction 150 µm, 75 µm and 38 µm. At the laboratory at Camborne School of Mines, UK, six resin blocks of powder samples were prepared. First the samples were split by microriffling to obtain representative subsamples, then sub-samples were mixed with graphite to avoid differential settling (Pascoe et al., 2007), aggregation and also to create a random mix of particles. Finally the subsamples were mounted into 30 mm round blocks/moulds and filled with epoxy resin to a height of approx. 6-7 mm. After hardening the blocks were labelled and backfilled with resin to get a size/height of approx. 20 mm. All the blocks were polished, carbon coated and analysed utilising QEMSCAN®.

Analytical methods

The analytical methods which were used are optical microscopy and automated scanning electron microscope (QEMSCAN®). All the samples were analysed at the Camborne School of Mines, University of Exeter, Cornwall Campus, UK on a QEMSCAN® 4300. The measurement mode was PMA (particle mineral analysis), see table 1 for further details. Petrographical studies of polished thin sections were carried out at Luleå University of Technology on a standard microscopy (Nikon Eclipse E600).

Table 1. Analytical settings for the QEMSCAN analysis.

Settings	Coarse 150 µm	Medium 75 µm	Fine 38 µm	Fine 38 µm
PMA	-300/+100	-200/+100	-100/+20	-100/+20
Sample	Ore, Ore breccia	Ore, Ore breccia	Ore	Ore breccia
Number of particles requested	4000	4000	4000	4000
Number of particles measured	1292, 1522	3562, 4002	4012	4025
Field size	2500	2000	1000	1000
Point spacing	5	2.5	2	1
Point across the field	500	800	500	1000

QEMSCAN® (Quantitative Evaluation of Minerals by Scanning Electron Microscopy)

QEMSCAN® was developed by CSIRO in Australia for the global mining industry to analyse ore and mill products in respect to mineral processing to provide rapid, statistically reliable, repeatable mineralogical and quantitative mineral analyses (Sutherland and Gottlieb, 1991; Petruk, 2001). The system can be operated in different measurement modes; field images scan, bulk mineral analysis (BMA), particle mineral analysis (PMA) and trace mineral search (TMS) (Pirrie et al., 2004). The principle of this technology is to use a combination of signals from the backscatter electron detector (BSE) and the energy dispersive X-ray detectors. The backscattered electrons will recognise particles based on density contrast and the compositional differences from the X-ray spectra will create digital mineral images of a sample based on chemical composition (Gottlieb et al., 2000; Sutherland et al., 2000; Goodall et al., 2005). All the analytical data are processed offline by an integrated software application (iDiscover 4.2) to the QEMSCAN system. To be able to identify the minerals and phases in the sample, every analysed pixel and obtained X-ray spectra is compared to a known database of mineral composition *(SIP- Species Identification Protocol)* to get an accurate and complete mineral identification (Gottlieb et al., 2000).

Results

Mineralogy

The mineralogy of *ore breccia* is more complex and comprises different mineral parageneses, including the minerals magnetite, feldspars, quartz, amphiboles, pyroxene, biotite and anhydrite. A small amount of pyrite, chalcopyrite, ilmenite, titanite, and occasionally also zircon occurs. Magnetite grains occur as cluster, aggregate of grains or as single inclusions (fig 2).

The magnetite grains are 0.16-2 mm usually 0.4-0.8 mm in size, euhedral to anhedral in shape and in some samples with an elongated appearance. The grain boundaries have a simple and straight outline. Euhedral single magnetite grains, 0.04-0.4 mm occur both as inclusions and interstitial in grain boundaries. The matrix has a subgranular texture consisting of the main silicate minerals feldspars and quartz. The feldspars grains 0.05-0.4 mm shows anhedral granular outline and the quartz, 0.01-0.12 mm in size occur as rounded grains. The grain boundaries are complex and complicated. The anhedral shaped amphibole grains 0.1-0.2 mm occur in the matrix but are closer associated to the magnetite grains commonly in clusters, there the grain size 0.4-1 mm are larger. The anhydrite occurs as euhedral grains 0.4-0.8 mm. Biotite exists as tabular grains 0.1-0.8 mm, both as single grains elongated in lineation in the feldspar matrix and as grains interstitial to magnetite grains. Pyrite and chalcopyrite occurs disseminated in veins and in grain boundaries or as single grains 0.005-0.04 mm. Occasionally, some larger grains, up to 0.3 mm are found in the feldspar matrix. Ilmenite is present as single euhedral grains associated with magnetite (tab. 2).
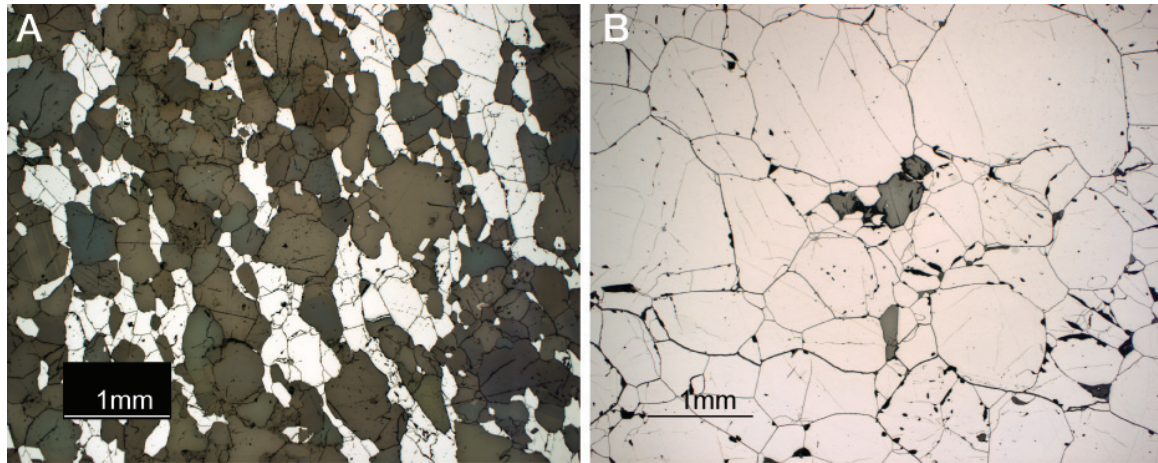
Figure 2. Photomicrographs showing the two ore types in plane polarised light A) ore breccia and B) ore.

The mineralogy of *ore* is rather simple with few silicate minerals involved. The texture is inequigranular and show magnetite grains which are euhedral to anhedral in shape and vary in grain size (fig.2). Coarse euhedral grains 0.8-2 mm are often aligned in a lineation where smaller grains 0.2-0.8 mm are interstitial in an even finer anhedral grained matrix < 0.2 mm. Small anhedral single inclusions 0.02-0.22 mm of magnetite occur in amphibole and pyroxene grains. The coarse magnetite grains can have an elongated appearance and the grain boundaries are overall simple and straight. Apatite occurs as euhedral grains 0.8-4.6 mm extended in linear direction and as single grains 0.1-0.6 mm. The euhedral to subhedral amphibole and pyroxene grains constitute the granular matrix, the grain size is 0.12-0.8 mm and occur also as single grains 0.04-0.4 mm interstitial to magnetite. A minority of feldspar grains 0.2-0.4 mm occur associated with amphibole and pyroxene. Pyrite grains 0.04 mm occurs in amphibole, pyroxene and ilmenite grains associated with magnetite and are single euhedral grains (tab.2).

Table 2. Sample description of the mineralogy and texture of the two ore types.

Sample	Mineralogy	Texture
Ore breccia	Magnetite, feldspar, quartz, amphibole, pyroxene, biotite, anhydrite, pyrite, chalcopyrite, ilmenite	Euhedral to anhedral magnetite grains some with an elongated appearance, smaller magnetite grains occur both as inclusions and interstitial in grain boundaries. The matrix has a subgranular texture. The grain boundaries are complex.
Ore	Magnetite, apatite, amphibole, pyroxene, feldspar, ilmenite, pyrite biotite	Inequigranular texture of euhedral to anhedral magnetite grains. Coarser grains often aligned in a lineation where smaller grains are interstitial in an even finer grained matrix. Coarser magnetite grains can have an elongated appearance. Grain boundaries are overall simple and straight.

Quantification of ore and ore breccia

QEMSCAN®

More than 4000 particles were measured for the each sample and analysed by QEMSCAN®. *Ore* and *ore breccia* was divided in three fractions each se table 1.

SIP file (Species Identification Protocol)

To be able to work with the material a SIP file had to be developed/specified for this kind of ore body and ore type. A characterisation was made from the including minerals and the alteration phases in the samples. The important mineral in this study is mainly magnetite but also other gangue minerals needed to be specified. Each mineral were categorised as a secondary list in the SIP file.

Modal mineralogy

The modal mineralogy and the other quantifications are given as mass percent unless otherwise stated. *Ore* and *ore breccia* are quantitatively distinguished by their differentiated modal mineralogy (tab. 3). *Ore* has a high concentration of magnetite in all fractions (~ 83-90 %) and for the *ore breccia* the concentration is lower (66-68 %), especially for the 38 µm fraction (46 %). The gangue mineral classes are rather equally divided between the fractions in an ore type but the amount of all the minerals will increase due to a finer grain size and especially at the finest fraction (38 µm). Apatite is a characteristic mineral for the *ore* (1.24-1.84 %) and feldspar is characteristic to the *ore breccia* (9.76-19.0 %). Amphibole/pyroxene is present in both ore types in larger concentrations (2.9-17.9 %). Minerals which are present in the samples but do not result in appreciable amounts (0.6-2.5 %) in the concentrate in this study (calcite, other carbonates, mica, chlorite, titanite, zircon, sulphates, sulphides, others) are categorised to 'others' and will not be further discussed (fig. 3).
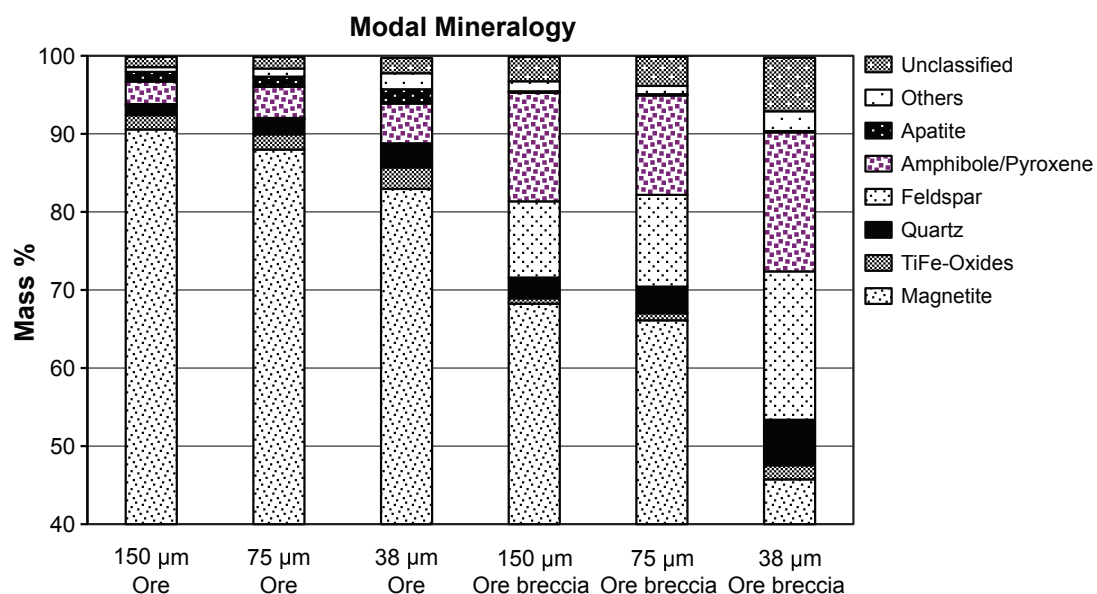

Figure 3. The modal mineralogy of ore and ore breccia.

Table 3. Quantitative mineralogy of ore and ore breccia, subdivided in three different fractions.

Modal mineralogy (mass %)	Ore 150 μm	Ore 75 μm	Ore 38 μm	Ore breccia 150 μm	Ore breccia 75 μm	Ore breccia 38 μm
Magnetite	90,56	87,99	82,94	68,24	66,11	45,74
TiFe-Oxides	1,22	1,25	1,51	0,21	0,25	0,55
Rutile	0,61	0,70	1,24	0,47	0,64	1,25
Quartz	1,27	1,92	2,81	2,67	3,42	5,84
Calcite	0,02	0,04	0,06	0,17	0,13	0,36
Other Carbonates	0,07	0,07	0,11	0,06	0,06	0,10
Feldspar	0,16	0,17	0,28	9,76	11,75	19,00
Micas	0,12	0,09	0,13	0,66	0,27	0,36
Pyroxene	1,09	1,36	1,88	1,08	1,07	1,28
Amphibole	1,79	2,64	3,21	13,01	11,76	16,58
Chlorite	0,28	0,55	1,08	0,17	0,21	0,32
Titanite	0,06	0,10	0,28	0,22	0,35	1,05
Zircon	0,00	0,00	0,07	0,01	0,03	0,30
Other Silicates	1,29	1,44	1,94	3,09	3,72	6,85
Apatite	1,24	1,29	1,84	0,00	0,06	0,11
Sulphates	0,07	0,14	0,10	0,00	0,00	0,02
Sulphides	0,00	0,06	0,25	0,00	0,00	0,01
Others	0,16	0,19	0,30	0,17	0,14	0,26
Total	100,0	100,0	100,0	100,0	100,0	100,0

Particle liberation

The particle liberation expresses how liberated the magnetite is. The liberation of magnetite is divided in four categories, created in iDiscover and based on the amount of free magnetite grains. Liberated is >90 %, high grade intergrown 60-90 %, low grade intergrown 30-60 % and locked is < 30 %. The liberation of magnetite is visualised as an Image Grid report (fig. 4 & 5) and quantified in figure 6. The liberation of magnetite in *ore* is overall high (88-80 %). In the finest fraction a smaller amount of locked minerals is present (15%). The other ore type *ore breccia* is interesting due to containing two characteristic magnetite classes in all three fractions, a liberated class (64-44 %) and a locked class (30-54 %). In the locked class, more than 50 % of the magnetite occurs as minor grains to an associated gangue mineral. The liberation decreases and the locked class increases to a finer grain size.
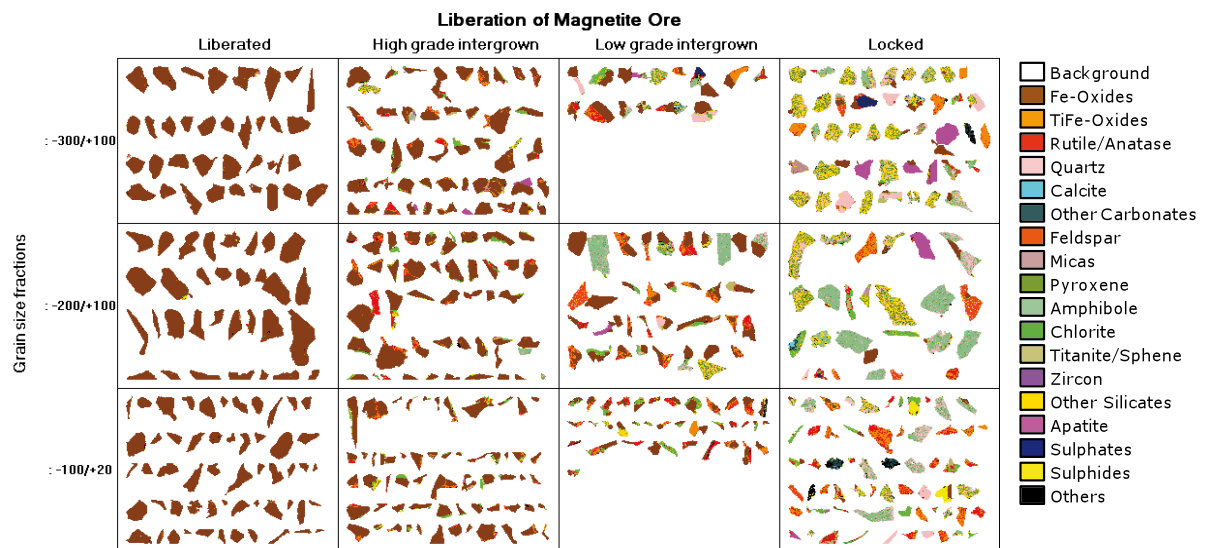

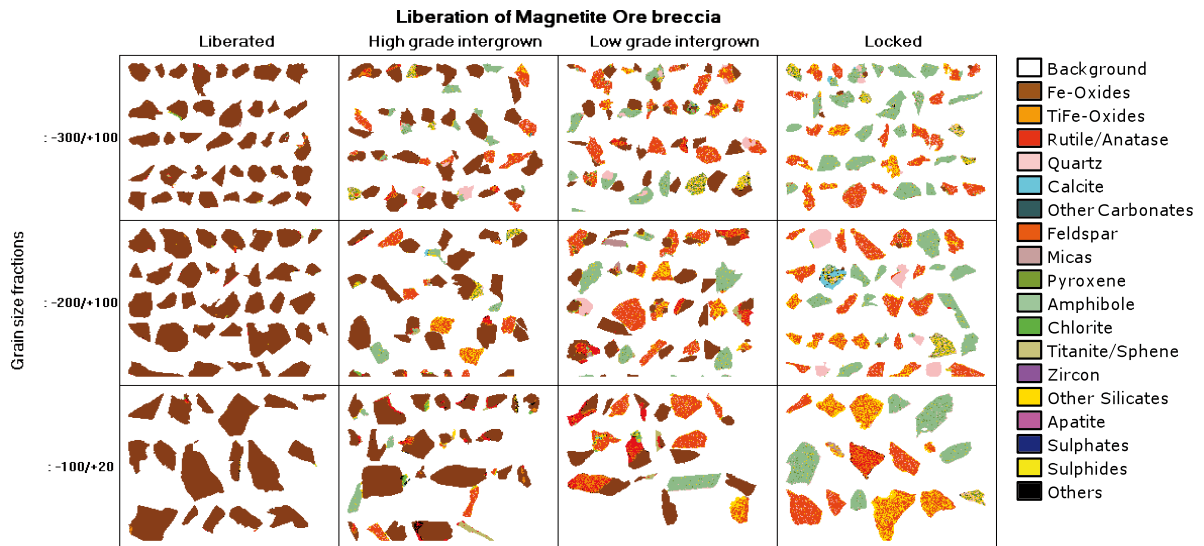
Figure 4. An image grid report created in iDiscover visualising the particle liberation of magnetite in ore. Liberated >90 %, high grade intergrown 60-90 %, low grade intergrown 30-60 % and locked is < 30 %. Fractions: -300/+100 = 150 μm, -200/+100 = 75 μm and -100/+20 = 38μm

Figure 5. An image grid report created in iDiscover visualising the particle liberation of magnetite in ore breccia. Liberated >90 %, high grade intergrown 60-90 %, low grade intergrown 30-60 % and locked is < 30 %. Fractions: -300/+100 = 150 μm, -200/+100 = 75 μm and -100/+20 = 38μm
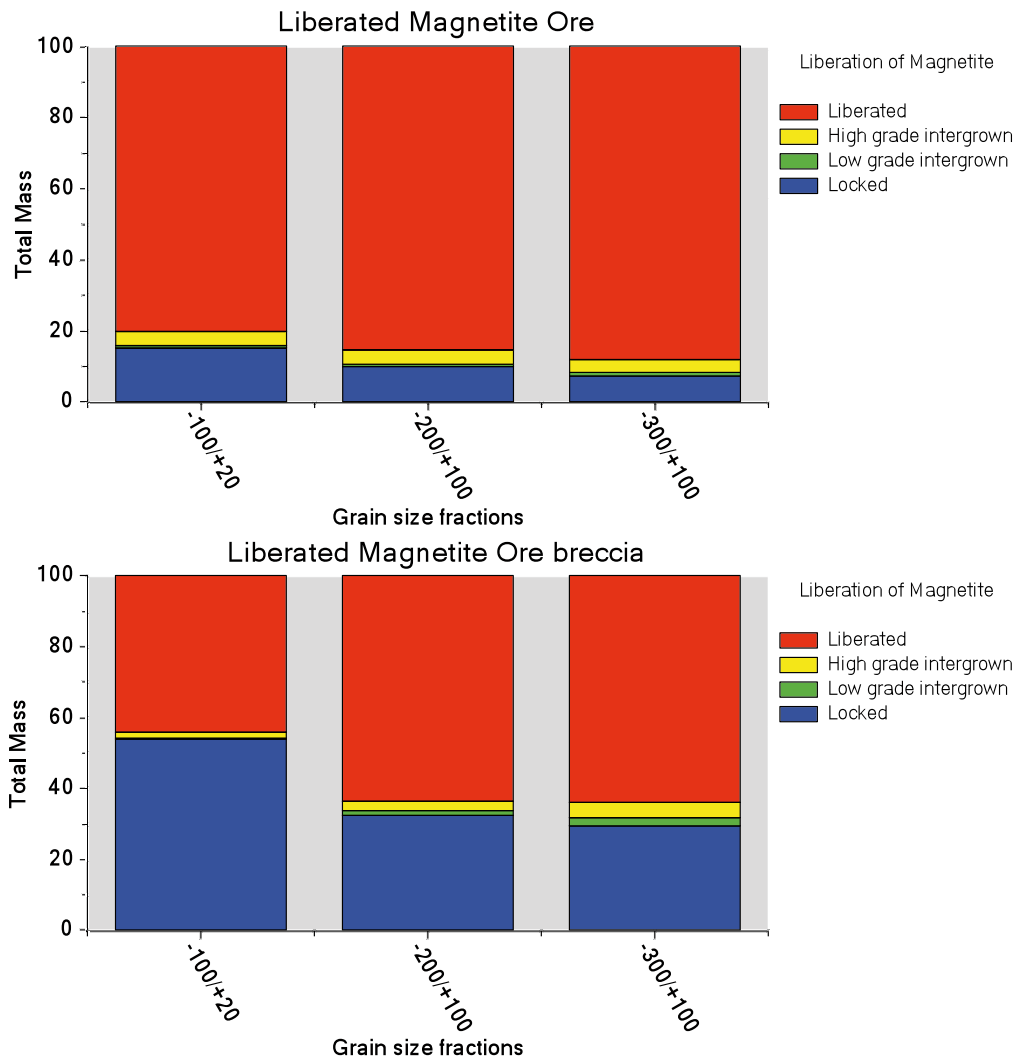

Figure 6. Quantitative particle liberation of magnetite in ore and ore breccia divided in four classes. Liberated >90 %, high grade intergrown 60-90 %, low grade intergrown 30-60 % and locked is < 30 %. Fractions: -300/+100 = 150 μm, -200/+100 = 75 μm and -100/+20 = 38μm

Mineral association

The magnetite that is not liberated occurs in a binary or a more complex association involving two or more other minerals which differ between the ore types. To identify these, an expression was created in iDiscover to identify the associations (fig. 7 & 8) and to quantify them (tab.4). A lot of the gangue minerals were liberated or occurred only as binary and complex association to each other, (5-12 %) in ore and (18-40 %) in ore breccia.
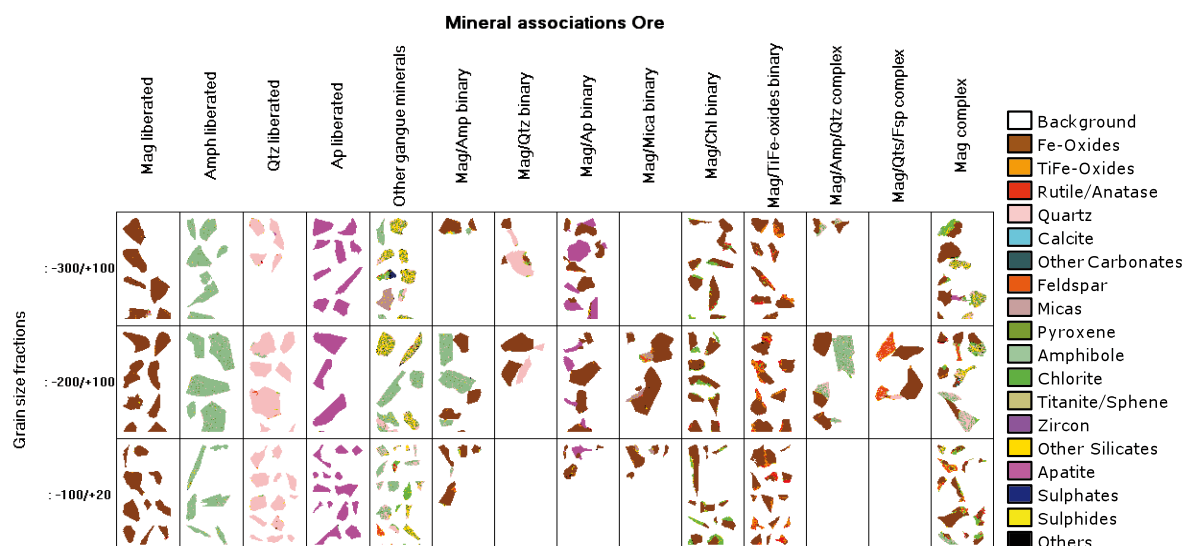
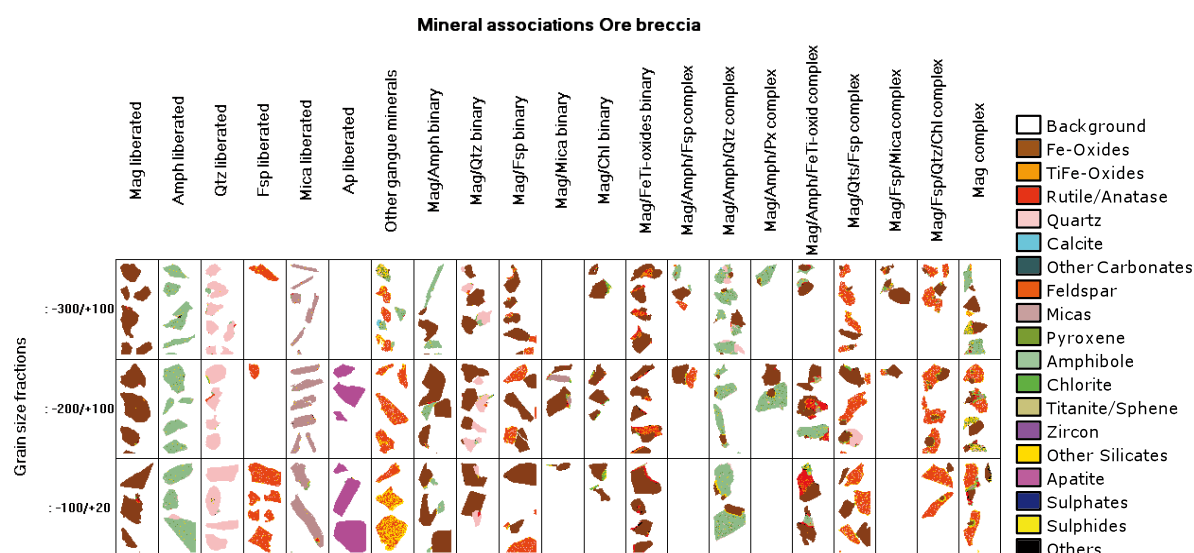

Figure 7. An image grid report created in iDiscover visualising the different binary and complex mineral associations in ore. Fractions: -300/+100 = 150 μm, -200/+100 = 75 μm and -100/+20 = 38μm. Abbreviation, Mag magnetite, Amph amphibole, Qtz quartz, Fsp feldspar, Ap apatite, Chl chlorite.

Figure 8. An image grid report created in iDiscover visualising the different binary and complex mineral associations in ore breccia. Fractions: -300/+100 = 150 μm, -200/+100 = 75 μm and -100/+20 = 38μm. Abbreviation, Mag magnetite, Amph amphibole, Qtz quartz, Fsp feldspar, Ap apatite, Chl chlorite.

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Less then 10 % of the magnetite grains occur as binary or complex magnetite-bearing particles in *ore* and *ore breccia* and are mainly recovered in highest amount, in 150 μm fraction. The most frequent binary association is a magnetite/FeTi-oxides (includes ilmenite and rutile) for both ore types and occur in the largest quantity in the 38 μm fraction. Magnetite/mica binary does not exist in the 150 μm fraction. Some of the binary and complex associations only exist in a certain fraction/s. Characteristic binary associations in *ore* are magnetite/amphibole, magnetite/apatite and magnetite/chlorite but are only present in a minor amount in the samples. The magnetite/amphibole and magnetite/chlorite are more common in 75 μm fraction than the other two fractions. The unspecified magnetite bearing complex accounts for 1-2 % of the samples. *Ore breccia* has more associations of both binary and complex magnetite bearing particles. Magnetite/amphibole binary is the most frequent associations follow by magnetite/feldspar and magnetite/quartz. The character for *ore breccia* is the complex associations, especially mag/qtz/fsp±chl and mag/amph/qtz. The unspecified magnetite bearing complex composes 1-2 % and the finest fraction (38 μm) has a complex magnetite bearing association composed of more diverse minerals.

Table 4. Quantification of binary and complex mineral associations in ore and ore breccia.

Mineral associations (Mass %)	Ore 38 μm	Ore 75 μm	Ore 150 μm	Ore breccia 38 μm	Ore breccia 75 μm	Ore breccia 150 μm
Mag liberated	79,04	84,28	87,36	44,17	63,02	63,49
Amph liberated	0,43	0,35	0,36	9,71	7,75	8,84
Qtz liberated	0,75	0,56	0,13	2,55	1,18	0,47
Fsp liberated	x	x	x	0,08	0,09	0,05
Mica liberated	x	x	x	0,07	0,13	0,41
Ap liberated	1,74	1,26	0,97	0,11	0,06	0,00
Other gangue minerals*)	11,85	7,20	5,01	40,06	21,66	17,83
Mag/Amph binary	0,13	0,43	0,13	0,53	1,45	1,83
Mag/Qtz binary	0,00	0,09	0,17	0,08	0,13	0,29
Mag/Ap binary	0,07	0,16	0,60	x	x	x
Mag/Fsp binary	x	x	x	0,14	0,78	0,81
Mag/Mica binary	0,09	0,15	0,00	0,01	0,08	0,00
Mag/Chl binary	1,37	1,36	0,79	0,03	0,06	0,14
Mag/TiFe-oxides binary	3,10	2,57	2,30	1,13	0,93	1,04
Mag/Amph/Fsp complex	x	x	x	0,00	0,04	0,11
Mag/Amph/Qtz complex	0,00	0,16	0,09	0,08	0,15	0,63
Mag/Amph/Px complex	x	x	x	0,00	0,10	0,07
Mag/Amph/FeTi-oxid complex	x	x	x	0,08	0,14	0,12
Mag/Qts/Fsp complex	0,00	0,10	0,00	0,18	0,55	1,18
Mag/Fsp/Mica complex	x	x	x	0,00	0,02	0,18
Mag/Fsp/Qtz/Chl complex	x	x	x	0,04	0,11	0,16
Mag complex	1,42	1,32	2,09	0,96	1,65	2,35
Totalt	100	100	100	100	100	100

Abbreviation, Mag magnetite, Amph amphibole, Qtz quartz, Fsp feldspar, Ap apatite, Chl chlorite.
*) Includes all the other gangue minerals that are not attached to a magnetite grain.

Mineral texture

Two characteristic mineral textures were identified in the samples (fig. 6). Magnetite occurs as a mixed grain attached to different gangue minerals with the mineral associations occurring in different proportions. The other is small magnetite grains which occur either as an inclusion or as a composite, mainly in feldspar. Magnetite as mixed grain occurs in several mineral associations in both ore types. In ore breccia the inclusion and composite textures are typical textures for the particle liberation of the locked class in all three fractions.
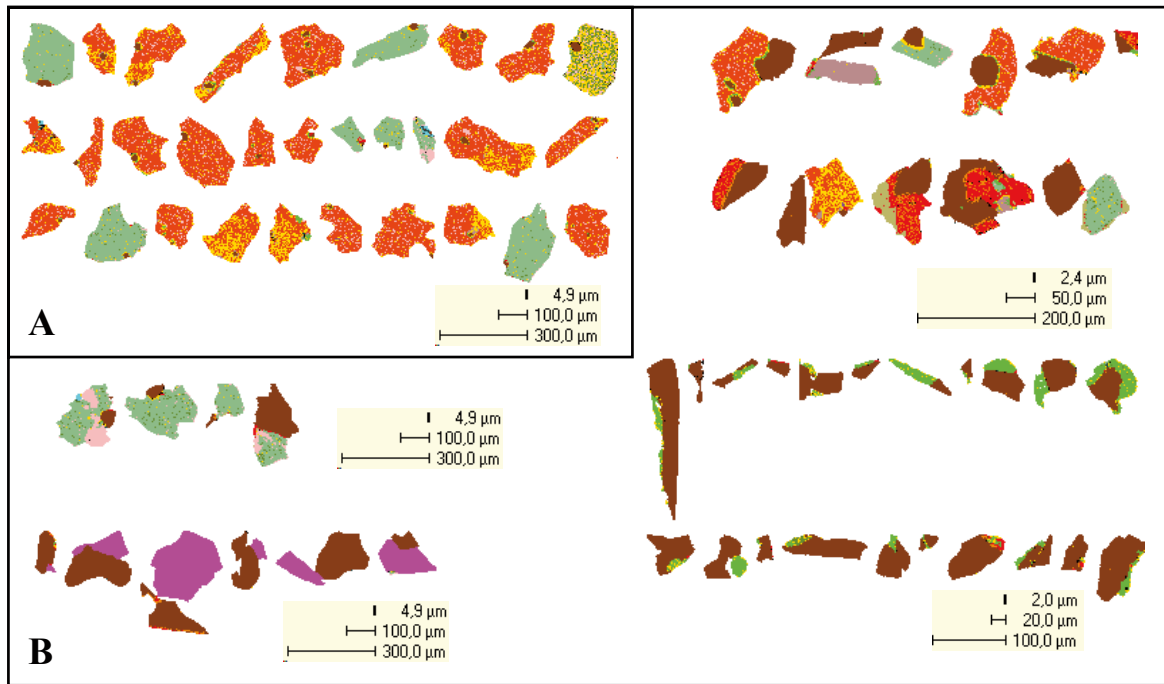
Figure 9. A particle view image created in iDiscover showing the different mineral textures. A) Magnetite as inclusion and composite particles. B) Magnetite as mixed grains to different gangue minerals.

Discussion and conclusions

This mineralogical study of iron ore is the first one using QEMSCAN® analysis on the Malmberget deposit to quantify the modal mineralogy, particle liberation, mineral associations and mineral textures of two different ore types. *Ore* and *ore breccia* represents two main ore types in the Fabian ore body. Separation of these two ore types allows the possibility to identify and track mineral associations and textures which can cause process mineralogical problems. Identifying textures and quantifying them could be valuable in more than one aspect. Both the spatial distribution of ore textures within deposits and their relationship to downstream processing are of importance to improve the mineralogical knowledge.

It has become more and more important to interpret and draw conclusions about textural information in process mineralogy (Pirard et al., 2007). Ore breccia is an ore type that will be part of the concentrate in varying amounts during concentration. The results show that there is a

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rather distinct difference between these two ore types, both in their mineralogy but particularly in their textual properties. The ore has a rather simple mineralogy while ore breccia is more diverse and comprises different mineral parageneses. The *modal mineralogy* classification makes it possibly to identify all the included minerals and track mineralogical changes over longer periods (Sutherland et al., 2000). The *particle liberation* is high for ore, being much lower for ore breccia and has a decreasing liberation to a finer fraction in each ore type. This has to do with grain size, mineralogy and textures of the magnetite and the gangue minerals. The magnetite grains will easily fall apart during crushing and create a large amount of highly liberated fines due to a primary coarse grain size but also by its simple and straight grain boundaries. Ore breccia has more binary and complex magnetite bearing particle associations and a typical mineral association is magnetite/feldspar. This is explained by its *mineral texture* which is characterised by small magnetite grains occurring as inclusions or composite particles in mainly the feldspar grains, generating a large amount in the locked class category of the liberated magnetite. These grain boundaries are more complex and complicated which also is seen in magnetite/quartz *mineral association*. Both ore types have a binary magnetite/FeTi-oxide association which also is the most common one. This association could be a source of high Ti content in the final concentrate product. Since this process only includes one crushing-stage a lot of the gangue minerals were liberated and represents a rather high amount in all fractions.

From a process mineralogical point of view ore breccia is an ore type were some of the magnetite probably will not be liberated during further crushing and milling. Irrespective if magnetite of this type will be part of concentrate or the tailings these particles will probably cause either an increasing content of silica in the concentrate or iron content in the tailings.

Further work

This study has shown that the mineral characterisation was possible for different kinds of ore types. A larger and more process conformed study has started where the aim is to achieve a method to identify mineralogical signatures for different ore types and ore bodies to create a toolbox to solve concentrating problems of mineralogical character in the beneficiation process.

Acknowledgment

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III

Applying traceability in a mine-to-mill context
by using Particle Texture Analysis.

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1   ABSTRACT

This study shows possibilities to have traceability in the mining industry. Here, traceability is used in two ways; first tracing the ore feed through a concentrating plant, and secondly to find traceability between the mine and the concentrator plant by parameters and signatures like particle mineralogy, mineral association, texture, size distribution, mineral liberation. This case study is located to an apatite-iron ore deposit at Malmberget, Sweden and divided in two parts. The first is an attempt to find a way of characterising an apatite-iron ore body both mineralogically and texturally in a quantitative manner by using analytical methods like optical microscopy, microprobe (EMPA) and an automatic SEM based system, Particle Texture Analysis (PTA).

The same analytical method is used in the second part, which is an attempt to find traceability in the concentrator by taking samples from two grinding section and compare them by using PTA. The mineralogy was evaluated and characterized by modal mineralogy, mineral liberation and mineral association. Magnetite has a simple outline and straight grain boundaries and the gangue minerals have a finer particle size with a more complicated texture. The PTA analysis shows that apatite is associated to magnetite as mixed particles, while smaller grains of magnetite are inclusions in feldspar. Result from particle texture analysis shows that there is a connection which link the mine-to-mill context, in both cases the content of gangue minerals increases in finer fraction. Differences in the modal mineralogy of magnetite and gangue minerals in different particle sizes are closely connected to the texture. Overall the results are indicating that the liberation is very high in *ore, ore breccia* and the feed to the concentrator.

This paper will confirm an attempt to find traceability at early stages in ore beneficiation and the results indicate that there is good possibility to achieve traceability in continuous processes.

2   INTRODUCTION

The key factor of having a good and an even production is to have a good control over the process and the raw material. As a result traceability has become important in any process, since it offers the opportunity to tie process data throughout the process to a certain product/batch. Therefore, traceability offers the possibility to understand how the origin of variation and learn how to adjust the process to avoid production of defective products. The raw material that is used in different production is not always the same. A system is necessary to collect different data and to be able link the information to each other. According to Moe (1998) a traceability system is mostly important to manage traceability.

LKAB (Luossavaara-Kiirunavaara AB, Sweden) is one of the world's leading producers of upgraded iron ore products. The customers expect good qualities of the products which demand a detailed knowledge of the processes from mine to customer. To achieve this it is important to have traceability of ore feed and control over the production process but it will also demand a good knowledge of the raw material. Production at Malmberget comes from several ore bodies that are mixed in the process and this means there will be ores having different Fe-content and levels of contaminants (Martinsson and Virkkunen, 2004). Traceability can be explained in several ways see (Töyrylä, 1999) and also traceability can be used by different methods see (Kvarnström and Oghazi, 2008). Traceability is much easier to apply in batch processes than in continues processes. In food and pharmacy industries it is very common to use different traceability tools (Mousavi et al., 2002) but in the mining industry, which is mostly a continuous process, traceability is a difficult task. In continuous process there are different factors that makes the traceability complicated, there are reflux flows and mixing of streams that makes it problematic to achieve a high level of traceability (Kvarnström, 2008).

This paper can be divided in two steps. The first step is to characterise each ore body at Malmberget by identify significant mineralogical and textural signatures. In the second step the focus has been to investigate the raw material that comes from the mine and continues to the concentrator. To identify these signatures different analytical tools have been used to examine the liberation, texture and mineral associations. The main task is to find a method to connect these signatures from "mine to mill" and see if there is any relation between the process stages.

3   GEOLOGICAL SETTING

3.1   Deposit geology:

In the province of Northern Norrbotten, Sweden, (fig 1) LKAB is producing 90 % of Europe's iron ore from two large underground mines, Kiruna and Malmberget. These two apatite-iron ore deposits have a similar origin and were formed by magmatic-hydrothermal process at 1.89-1.88 Ga (Bergman et al., 2001). However, there are major discrepancies in character between them, due to later overprinting by metamorphoses, deformation and granitic intrusions, which are stronger for the Malmberget deposit (Martinsson and Virkkunen, 2004).

More than 20 different tabular to stock shaped ore bodies are known in the Malmberget ore deposit, occupying an area of 2.5 x 5km. The Malmberget deposit was probably from the beginning a more or less continuous tabular ore lens which was exposed to at least two phases of folding and metamorphism. These events torn the ore lenses apart by strong ductile deformation and today they occupy a large-scale fold structure were the individual ore bodies stretch parallel to the fold axis, which plunge 40°-50° towards SSW (Bergman et al., 2001).

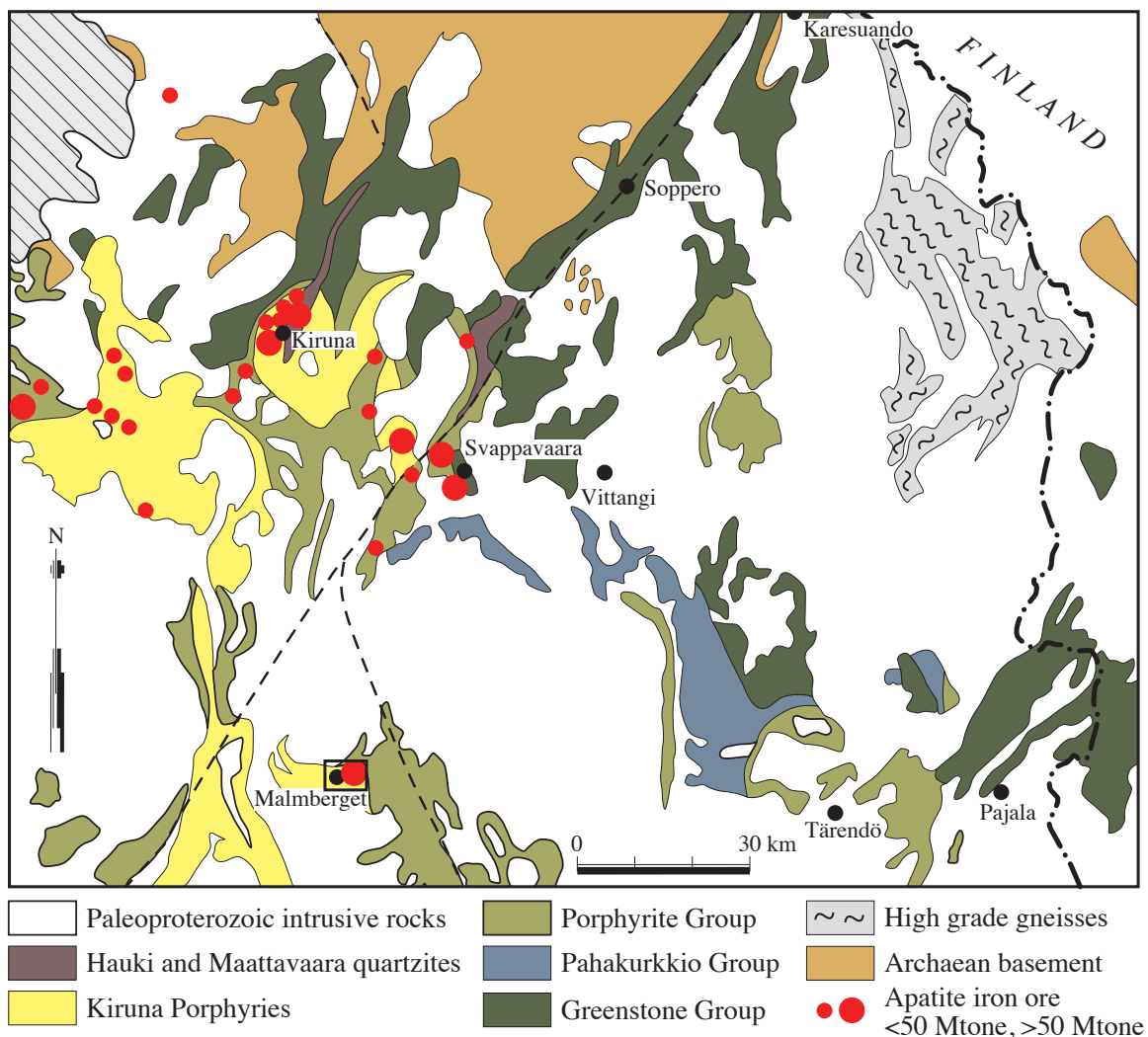
Figure 1. A simplified geological map, Northern Norbotten ore province, the apatite iron deposits marked in red.

The iron ore minerals are both magnetite (Fe_3O_4) and hematite (Fe_2O_3) but the magnetite is more common of the two. Hematite forms several separate ore bodies and portions of others (Geijer, 1930). The main gangue minerals are apatite, amphibole, pyroxene, feldspars, quartz and biotite. Among the accessory minerals are pyrite, chalcopyrite, titanite, zircons and calcite most common. Every ore body is characterised by their own mineral, chemical and textural properties.

Due to the strong metamorphic recrystallization of the area, the minerals are recrystallised, coarse grained, and elongated in the direction of the lineation of the rocks.

4   CONCENTRATOR

After blasting and underground primary crushing, the ore is sent first to the cobbing plant where dry magnetic separators make the first separation and send the magnetic product to the concentrator. For concentrating iron ore at Malmberget grinding mills and wet magnetic separators are used. There are several sections in the concentrator, in this study sections 5 and 6 are examined. In section 5 the coarse material at 10-15 mm in size is fed to a primary wet magnetic cobbing separator and the magnetic concentrate flows into a primary ball mill, and the ground product (pulp) is pumped to a secondary magnetic separator. Its magnetic concentrate is then pumped to a secondary ball mill and from their to a tertiary magnetic separation unit, for more information about the flow sheet see (Kvarnström and Oghazi, 2008))

In section 6, ball mill grinding is also in three consecutive steps with wet low intensity magnetic separators in between. However, there is no primary wet cobbing separator in section 6. It is important to grind the raw material approximate 68% < 45µm to liberate gangue minerals, and to reach the desirable size distribution for the pellets feed.
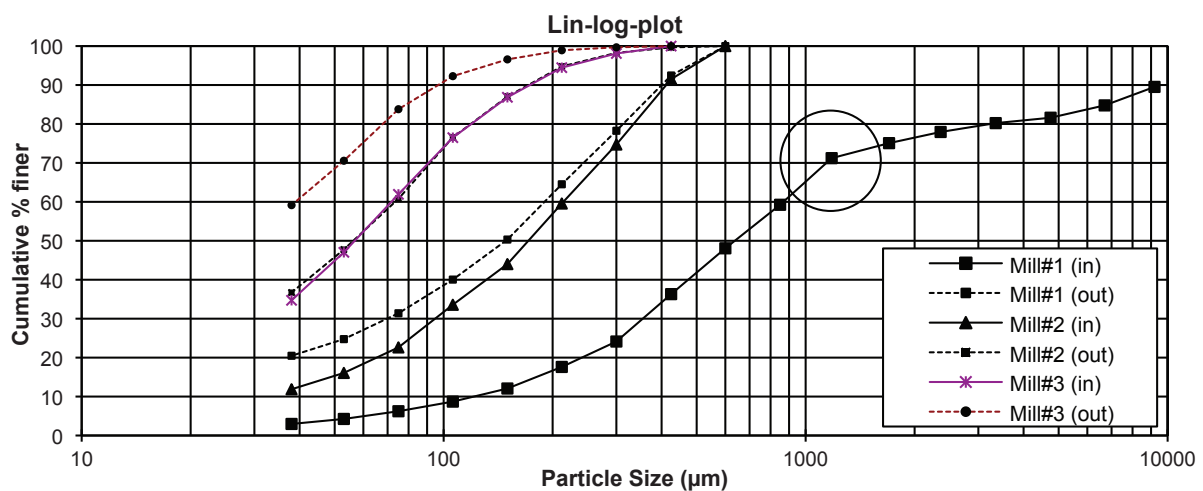

Figure 2. Particle size distribution for section 6. The "hump" is marked with red circle in the figure.

The particle size distribution of ore feed from Malmberget (fig.2) show a characteristic hump around 1 mm where there also are noticeable drops of the Fe content for coarser grain sizes. This could be explained by the average size of the magnetite grains which is around 0.8-1.2 mm and the grains probably quite easy crack along the grain boundaries already in the cobbing plant causing this typically signature.

5   PROCESS MINERALOGY AS A TOOL

To understand the fundamentals of the mineral processing it is important to understand and link every single stage in the process chain. It is the mineralogy and the properties of an ore which determines the conditions for the further processing. To meet these challenges an efficient process can be designed and the mineral treatment can be optimized (Sutherland et al., 2000). Moen (2006) defines process mineralogy as the mineralogy which is applied to the product in specific industrial process such as the mineralogy in concentrator, pelletization or in other process stages.

It is needed to know what kind of minerals and textures the ore is consisting of due to the fact that the liberation characteristics are intimately related to the mineralogical texture (Lorenzen and van Deventer, 1994). A large amount of information about the ore needs to be obtained, like particle mineralogy, class, porosity, mineral association, texture, hardness, size distribution, mineral liberation, class densities and mineral composition (Donskoi et al., 2007)Process mineralogy in this case can be used to create a tool which gives detailed information of the mineralogy from different ore bodies which will be linked to the mineralogy in the concentrator to improve the mineral processing performance. These mineralogical data will be specific in such way it will be possible to express mineralogy both as individual signatures and in a quantitative mode.

Optical microscopy has traditionally been the instrument used for the identification and quantification for both mineralogical and texturally properties, which is a time consuming process (Petruk, 2000). A number of different techniques using image analyses system based on SEM techniques have been developed during the last decades for a more rapid quantitative estimation and description of mineralogy and particle textures (Jones and Gravilovic, 1970; Gottlieb et al., 2000; Petruk, 2000; Gu, 2003). QEMSCAN® and MLA both developed in Australia, is the better known instruments. SEM-PTA (particle texture analyses) used in this study is a similar instrument developed at NTNU, Trondheim, Norway (Moen, 2006).

5.1   Ore types

Two types of ore were identified and used in this study, called *ore breccia* and *ore* (fig 3). The *ore breccia* is largely consisting of magnetite but do have gangue minerals like quartz, amphibole, pyroxene, apatite and feldspars in different proportion occurring as breccia infill in the wall rocks. The *ore* is more massive magnetite that contains gangue minerals like amphiboles and apatite in lesser amounts. The *ore breccia* is bordering the massive ore, but occurs also partly as inclusions in the massive ore.
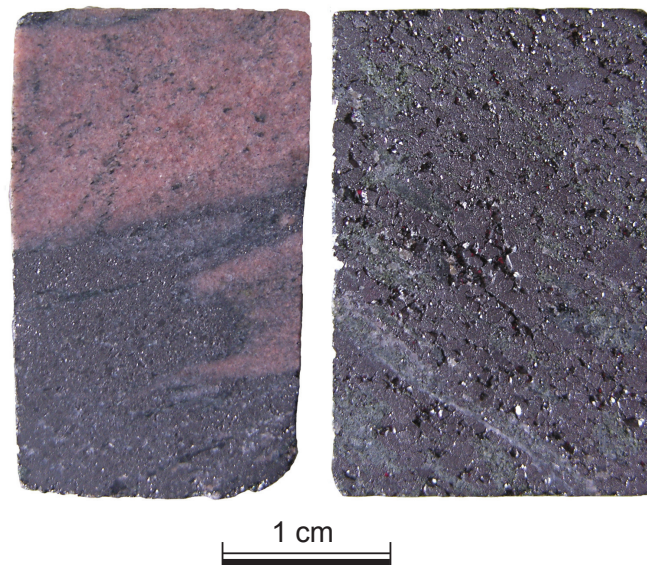
Figure 3. Photographs of the two characterised ore types: ore breccia to the left and ore to the right.

6 EXPERIMENTAL

6.1 Sampling and preparation

The ore samples are from both drill cores and concentrates. The mine is represented by samples from drill cores taken from various parts of the Fabian ore body. Samples from section 5 and 6 in the concentrate were taken before and after each grinding mill.

The drill core samples were crushed in a Retsch jaw crusher, +3mm. The feed samples were weighted and then filtrated at Malmberget. All the samples were then dried and cut by a Jones splitter into suitable proportions in the laboratory at Luleå University of Technology (LTU). The dry material was sieved with a Ro-Tap shaker down to 75 μm and wet sieved further to 38 μm.

It is important that the liberation data for minerals in a sample come from a sieve fraction. Test and comparisons have shown that measured liberation of specific size particles in unsieved samples are not the same as the sieved sample. For unsieved samples the result is not correct due to stereological errors (Petruk, 2000).

Polished thin sections were made of all the samples. To be able to characterise different texture, samples of intact ore were also used in this study. The samples from the drill core were of a larger volume since the sample should be representative for a specific ore type and not only for a specific texture.

7 ANALYTICAL METHODS

The analytical methods which were used are optical microscopy, microprobe (EMPA) and Scanning electron microscopy (SEM-PTA).

7.1 Optical microscopy

Polished thin sections from the ore were optically examined in transmitted and reflected light on a standard petrographical microscopy (Nikon Eclipse E600).

To characterise all the different mineral associations, textures and parageneses, a mineral identification were made of both the silicates and oxides.

7.2 Microprobe

Mineral analyses were performed on a JOEL JXA-8500F electron microprobe at NTNU, Trondheim, Norway. For the microprobe analyses an accelerating voltage at 15.0 kV, a probe current at 95 μA and a < 1μm beam diameter were used.

Totally 186 analyses were made, representing both silicates and oxides on the major minerals to cover all different textural and mineral assemblage variations, observed in the samples. Beside this mineral identification, it also verified that the used sized fraction samples were representative.

7.3 Scanning electron microscopy

The particle analyses were performed on a Hitachi S-4300SE scanning electron microscopy equipped with Oxford Inca Feature software NTNU, Trondheim, Norway.

For the particle analyses an accelerating voltage at 20.0 kV and a probe current at ~0.5nA were used.

7.4 Particle texture analysis PTA

The Particle Texture Analysis (PTA) is developed at the Norwegian University of Science and Technology (NTNU). By using Back Scattered Electron (BSE) from the scanning electron microscopy, images are analysed by means of grey levels and every grain of interest is also analysed by X-rays. All analysed grain size fractions are imported to the PTA software, where images analyses are done offline to process and evaluate if grains occur as liberated or in composite particles.

Standard queries can be done on the output results in a new database that contains information on the mineral liberation of any mineral, mineral association of any mineral and miniature images of particles of a certain texture category (Moen, 2006).

To reduce the unclassified group of minerals an extensive identification of minerals and phases for classification should be done.

8   RESULTS

8.1   Mineralogy and textures

The textures of the *ore breccia* is characterised by magnetite grains with a simple euhedral outline and straight grain boundaries, either as single grains or as aggregates of particles in a matrix of quartz and feldspar. Smaller euhedral magnetite grains are locked as inclusions in and in between feldspar grains (fig 4). This matrix has a subgranular texture and the grains shows anhedral granular outline with complicated grain boundaries.
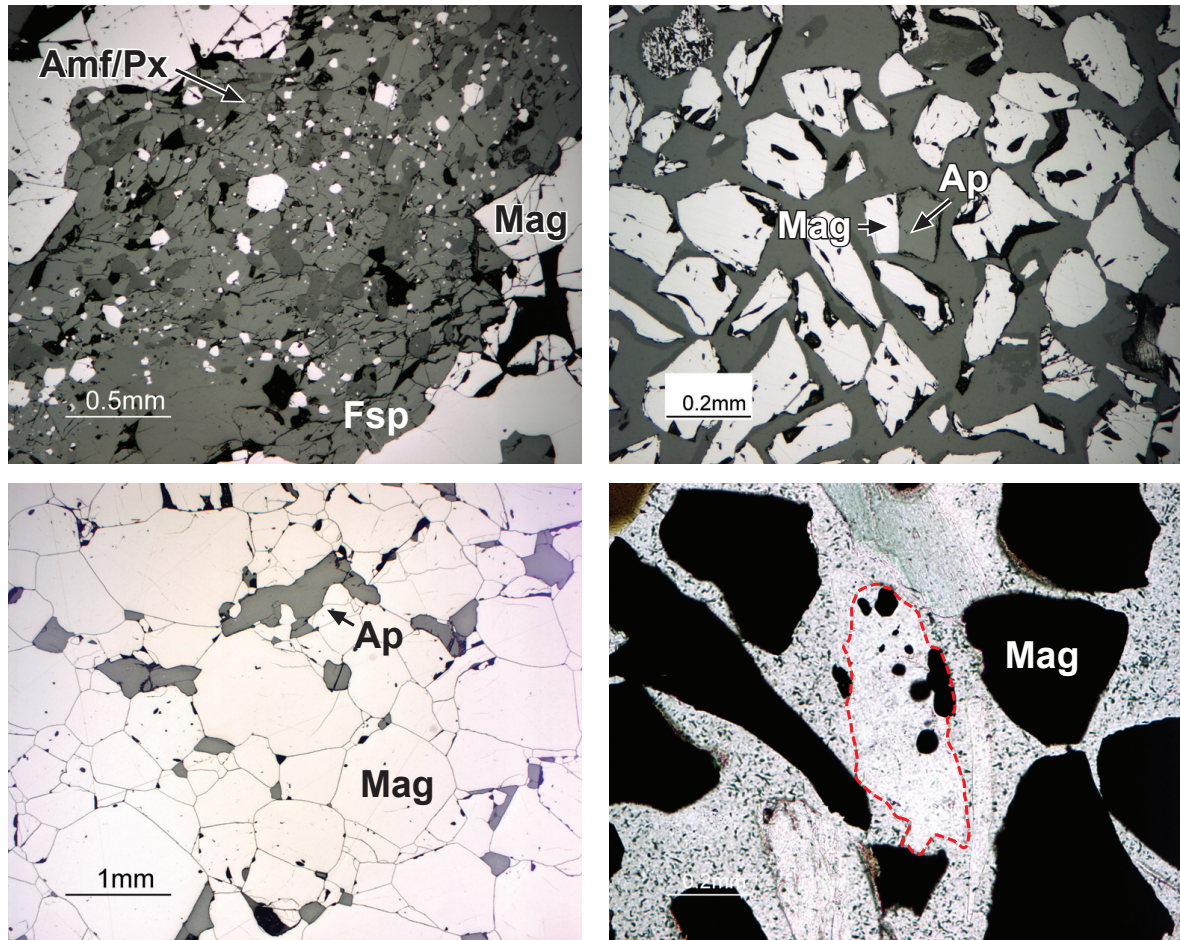

Figure 4. Photomicrographs showing mineral textures and mineral associations from ore and ore breccia. A) Ore breccia texture B) Ore texture C) Magnetite and apatite as mixed grain D) Magnetite grains as inclusion in feldspar.

In the *ore* the texture of magnetite is dominated by grains having simple euhedral outlines with straight grain boundaries (fig 4). The grains are of different size with coarser grains often elongated in the direction of lineation occurring in a finer grained matrix. The mineral parageneses is magnetite associated with apatite and magnetite associated with a larger amount of amphiboles and biotite also elongated in the direction of lineation (tab 1).

Table 1. Sample descriptions of the mineralogy and textures from ore and ore breccia.

	Ore type	Mag	Hem	Ap	Pl	Mc	Qtz	Amp	Cal	Bt	Py	Texture
Mbgt 6500 100.22-100.30	Ore breccia	x		x	x	x	x	x				Single simple outlined mag grain or aggregate in a subgranular matrix of fsp-qtz.
Mbgt 6500 111.00-111.13	Ore breccia	x		x	x	x	x	x				Single simple outlined mag grain or aggregate in a subgranular matrix of fsp-qtz.
Mbgt 6500 112.57-112.63	Ore breccia	x	x		x	x	x	x	x	x		Single simple outlined mag grain or aggregate in a subgranular matrix of fsp-qtz.
Mbgt 6500 374.23-374.35	Ore	x	x	x	x			x		x		Massive mag, fine grained at the contact to amphibole.
Mbgt 6500 383.21-383.27	Ore	x	x	x				x				Massive mag, homogenous, fine grained matrix, elongated coarse grains.
Mbgt 6500 435.56-435.64	Ore	x		x				x			x	Massive mag, elongated coarse grains. Ap and amp grains elongated in the direction lineation.

Mag=magnetite, hem=hematite, ap=apatite, pl=plagioclase, mc=microcline, qtz=quartz, amp=amphibole, cal=calcite, bt=biotite, py=pyrite.

8.2   Particle texture analysis (PTA)

The modal mineralogy shows the percentages of minerals found in the analysed fraction based on examination of a sample from PTA (fig 5). For *ore* and *ore breccia* it is slightly similar results when comparing the fractions 150 μm and 75 μm. Magnetite decreases in the finer fraction and instead different groups of gangue minerals increases. The two particle fractions in the *ore* samples do have the same mineral classes represented but in different proportion. In *ore breccia* more mineral classes are present and the amount of minerals like feldspar and amphibole/pyroxene increases pronouncedly in the finer fraction.
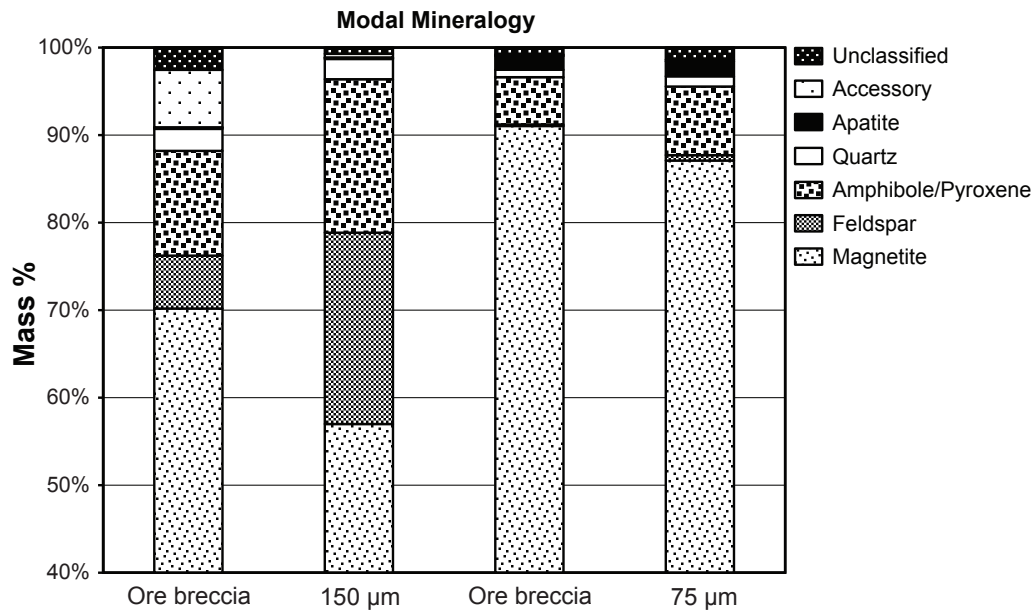
Modal Mineralogy

Figure 5. The modal mineralogy of ore and ore breccia. The mineral classes in the legend follow the same order as the graph. Note that the scale starts at 40 %.

The modal mineralogy (fig. 6 and 7) analysis from the different fractions shows that there is an increase of minerals classes in the finer fraction. The two grinding sections shows slightly different results when comparing the fraction at 38µm. Section 5 shows that the magnetite content is higher in the primary mill than section 6. The reason of higher content in section 5 is that a wet cobbing stage is used before the grinding circuit. There are three major mineral groups in the material that comes in to the primary mill; these are feldspar, pyroxene/amphibole and apatite. The output of the secondary mill contains some more gangue minerals compared to the input of the secondary mill. This is probably due to breakage of larger gangue particles grains into the 38µm fraction.
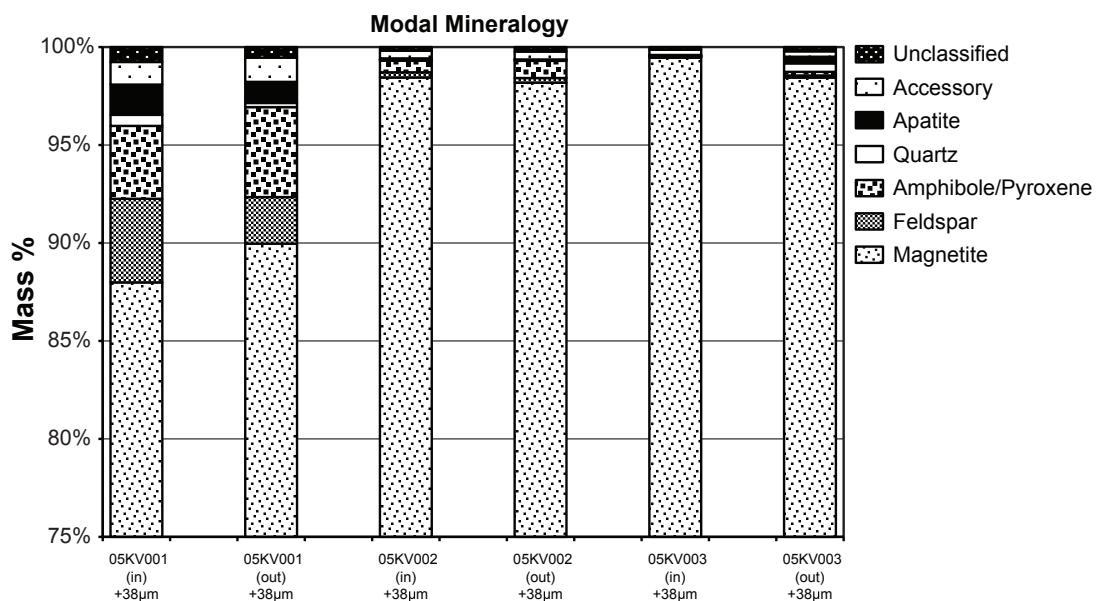
Modal Mineralogy

Figure 6. The modal mineralogy for grinding section 5. Note that the scale starts at 75 %.
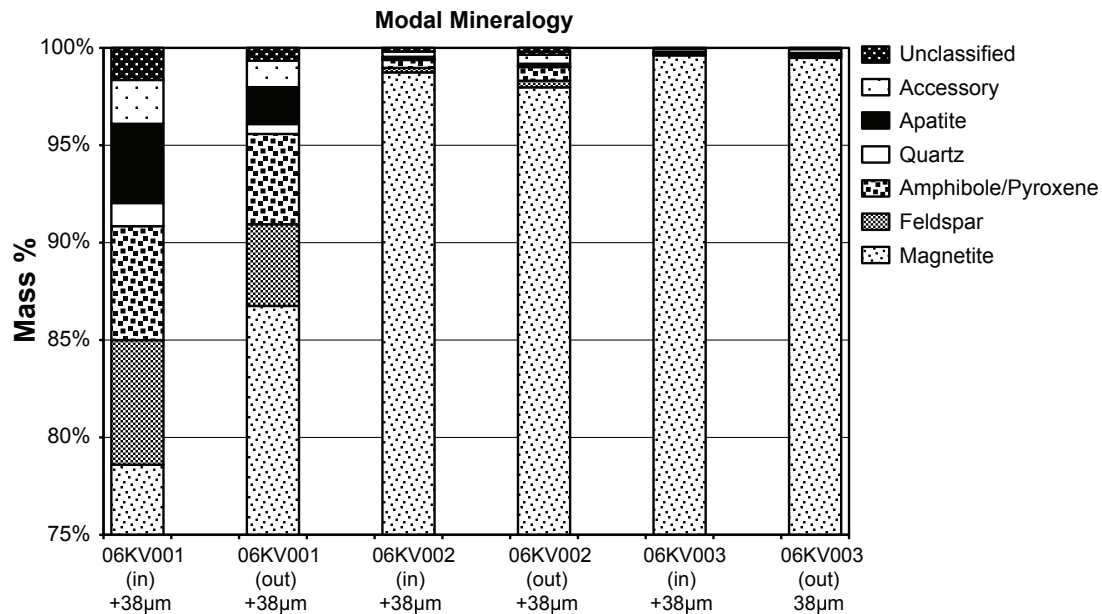
Modal Mineralogy

Figure 7. The modal mineralogy for grinding section 6. Note that the scale starts at 75 %.

Through comparing optical microscopy and particle texture analyses of the sieved samples of *ore*, *ore breccia* and concentrates the results shows a resemblance how minerals are associated to each other and what the grain boundaries and grain shape look like. The mineral liberation of magnetite is high for both ore types and increases for the finer fractions (fig. 8). Magnetite are analysed in perspective of mineral associations and two minerals are characteristic to one ore type each, apatite to *ore* and feldspar to *ore breccia*. Apatite is mostly associated to magnetite and also to amphibole. The amount of minerals association will decrease due to a finer grain size fraction (fig 8). The particles are typically mixed grains and the sizes
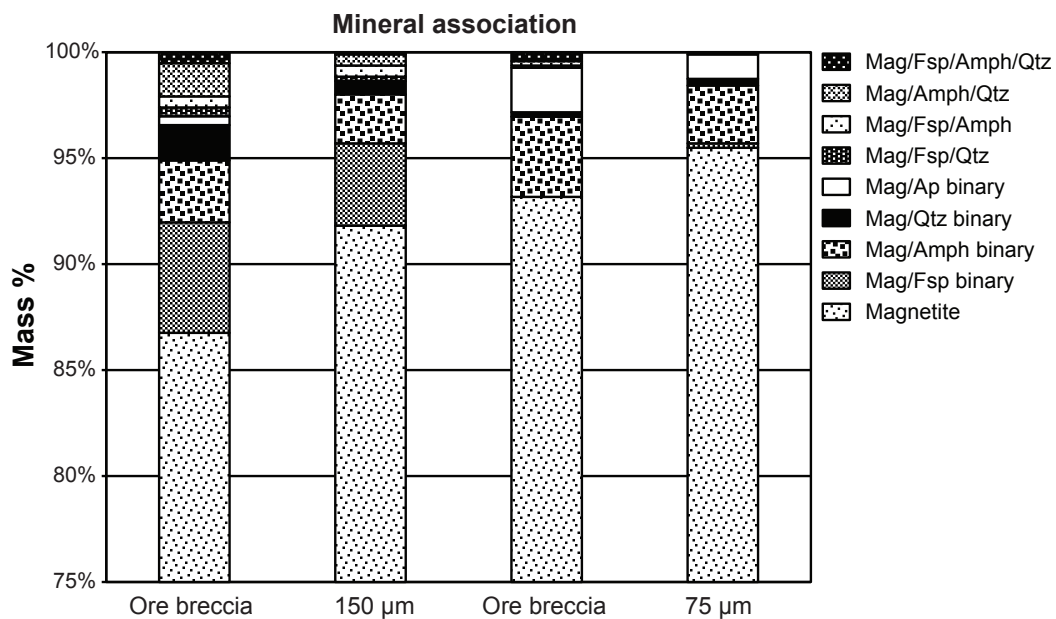
Mineral association

Figure 8. Magnetite from ore and ore breccia associated to other minerals as binary and complex particles. Note that the scale starts at 75 %.

of the two minerals are often a smaller grain of apatite which is attached to a larger grain of magnetite in an equal proportion (fig 4). Magnetite has a euhedral gently curve shape while the apatite and amphibole are euhedral to anhedral, angular shaped.

The *ore breccia* has more mineral associations as binary and complex magnetite-bearing particles represented compared to *ore*. Feldspar to magnetite is the most frequent association. However, quartz and amphibole are often included both as binary association but also as complex magnetite-bearing particles (fig 8). As in *ore* the amount of mineral associations decreases to finer grain size. Magnetite occurs as small inclusions in feldspars and amphibole (fig 4). The grain shapes of the feldspar are euhedral to anhedral.

In figure 9 is shown how magnetite is associated to other minerals for the feed to the primary mill in section 6. It is noticeable that similarities can be found between figure 8 and figure 9. Most of the magnetite is liberated but at coarser size magnetite is more associated to other minerals. The difference between the fractions is small. Closer look with an optical microscopy shows that the magnetite and apatite occur as mixed grain in the samples.
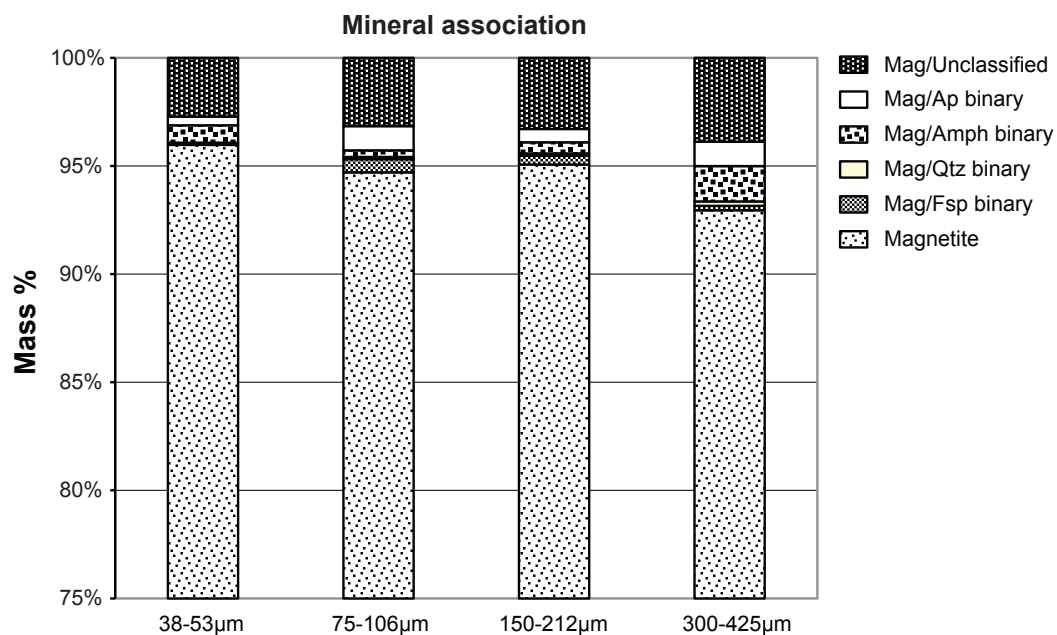

Figure 9. Sample, 06KV001 (in) from the primary mill in section 6. Magnetite associated to other minerals as binary and complex particles. Note that the scale starts at 75 %.

9   CONCLUSION

Through studying the process mineralogy of iron ore it is possible to understand the behaviour of the ore feed during the concentrator and also later on the sintering and pelletising processes. To characterise an ore deposit, mineralogical and especially textural information is a critical factor during the exploration stage but it is also closely interacting with the processing performance (Sutherland et al., 2001). By using an automated system the quantitative information of the mineralogy comes in three general forms; modal information, textural information and liberation information (Sutherland and Gottlieb, 1991). This technique makes it possible to get signatures from both the ore bodies and the ore feed and also achieve traceability between the mine and concentrator. When using an automated mineral liberation instrument it is important to verify the interpretation by another instrument. The usual instrument is optical microscopy but other instrument like microprobe, XRD etc. works as well (Goodall and Scales, 2007).

Some signatures have been identified which can create traceability between mine and concentrator but also through the grinding circuit, these signatures are textures and mineralogy.

The modal mineralogy is the main indicator that makes it possible to find these connections in the process. The modal mineralogy in this study indicates that the magnetite content is high in *ore, ore breccia* and concentrate. Result from particle texture analysis shows that there is a connection which link the mine-to-mill context, in both cases the content of gangue minerals increases in finer fraction. This is probably due to the primary grain size which is larger for magnetite compared to the gangue minerals. Differences in the modal mineralogy of magnetite and gangue minerals in different particle sizes are closely connected to the texture. Overall the results are indicating that the liberation is very high in *ore, ore breccia* and the feed to the concentrator.

The mineral associations are typically linked to different kind of ore types which can be used as fingerprints. A binary association in *ore* shows clearly that apatite is closely connected to magnetite while feldspar is connected to magnetite in *ore breccia*. The binary association of amphibole and magnetite is rather quite common for both ore types and makes it difficult to use as a signature.

By examine the material that comes to the concentrator it shows a binary association of apatite and magnetite.

Two texture associations of interest were frequently found from mine-to-mill, apatite and magnetite as a mixed grain and small magnetite grains occurring as inclusions in feldspar. The grain boundary in mixed grain has often a simple appearance while the texture for feldspar is more complicated. The interpretation is also verified in the optical microscopy. Due to the improved characterisation of mineralogy of *ore* and *ore breccia* it was possible to distinguish these signatures and connect them in the material trough the grinding circuit.

By comparing section 5 and 6, a direct similarity is found between the two sections but also some divergences, which can depend on the cobbing stage or other factors that the grinding mill differs from each section.

The result indicating that the investigating samples from mine-to-mill have a relation to each other by comparing the mineralogy and textures of different ore types and through grinding circuits.

Next step will be a closer look of the PTA results; because of the huge amount of data it is accurate to use tools such as multivariate data analysis. This data can be analysed by bilinear methods also known as principal components. This method is very efficient, since all data are converted to figures that show the connection and relation between different parameters. Some samples from the concentrator have already been investigated by this method but it is important to use this kind of information with the data from different ore bodies and see if there are any more connecting signatures.

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