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Characterization of Mertainen Iron Ore Deposit for Mineral Processing

Kari Niiranen[1] **and Viktoria Töyrä**[2]

[1]Market and Technology, LKAB (Luossavaara-Kiirunavaara AB), Kiruna, Sweden
[2]Business Area Iron Ore, LKAB (Luossavaara-Kiirunavaara AB), Kiruna, Sweden

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Abstract: In 2006, LKAB tackled a challenging expansion strategy that included studying known iron ore deposits in Northern Sweden to investigate the possibilities of increasing the ore resources and, in an extension, to have the opportunity to mine iron ore at several sites in the future. One of the iron ore deposits under investigation is the Mertainen iron ore deposit, in which magnetite is the main and practically the only ore mineral of economic value. The most important gangue mineral in the ore deposit is dark green actinolite. Magnetite is also locally accompanied by some apatite and calcite.

At LKAB, the iron ore deposits and their amenability with respect to mineral processing have earlier been characterized and evaluated mainly based on the grade of important elements such as iron (Fe), phosphorus (P), vanadium (V) and silicon (Si). However, there are drawbacks when the crude ore shows more complex mineralogy and where a specific element is distributed in several different minerals. There are several challenges with the mineralogy of the Mertainen iron ore deposit. A high amount of SiO_2 including alkali (Na and K) might end up in the final concentrate without successful beneficiation process. Another challenge is the loss of fine magnetite material that can occur in the separation via flotation.

A process design for the test work in pilot scale, corresponding to the flotation process at the LKAB's beneficiation plant in Svappavaara suite was established at the Geological Survey (GTK) in Finland. The results from the pilot flotation test work showed that the required silica grade (0.50% SiO_2) was achieved at an iron (Fe) recovery of over 95% with both tested flotation collectors.

Keywords: Iron ore, Magnetite, Silicate flotation, Mineral processing, LKAB, Mertainen iron ore deposit

Charakterisierung der Mertainen Eisenerzlagerstätte für die Mineralaufbereitung

Zusammenfassung: Im Jahr 2006 startete LKAB mit Planungsarbeiten für eine herausfordernde Expansion, welche die Untersuchung bekannter Eisenerzvorkommen in Nordschweden umfasste, um die Möglichkeit zur Erhöhung der Erzressourcen zu untersuchen und in Zukunft die Gelegenheit zu haben, Eisenerz an mehreren Standorten abzubauen. Eines der untersuchten Eisenerzvorkommen ist jenes in Mertainen, in dem Magnetit das wichtigste und praktisch einzige wirtschaftlich nutzbare Wertmineral ist. Das wichtigste Gangmineral in dem Erzvorkommen ist dunkelgrüner Aktinolith. Magnetit wird auch stellenweise von etwas Apatit und Calcit begleitet.

Bei LKAB wurden die Eisenerzvorkommen und ihre Zugänglichkeit für die Aufbereitung in Vorprojekten mit Schwerpunkt auf die Gehalte an wichtigen Elementen wie Eisen (Fe), Phosphor (P), Vanadium (V) und Silizium (Si) charakterisiert und bewertet. Dabei stellte sich heraus, dass die Mineralogie des Eisenerzvorkommens in Mertainen mit mehreren Herausforderungen verbunden ist. Zum einen weist das Roherz komplexe Verhältnisse hinsichtlich der mineralogischen Zusammensetzung auf, indem sich z. B. einige Elemente auf mehrere verschiedene Mineralphasen verteilen. Zum anderen zeigten aufbereitungstechnische Untersuchungen, dass eine hohe Menge an SiO_2 einschließlich Alkali (Na und K) in Silikaten gebunden ist, die ohne erfolgreichen Aufbereitungsprozess im Magnetit-Konzentrat ausgebracht werden. Reinigt man die Magnetscheidungs-Konzentrate mittels Flotation nach, stellen die Verluste von feinkörnigem Magnetit eine weitere aufbereitungstechnische Herausforderung dar.

Beim Geologischen Dienst (GTK) in Finnland wurde ein Prozessdesign für das Testverfahren im Pilotmaßstab er-

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Dr. mont. K. Niiranen, M.Sc. (✉)
Market and Technology,
LKAB (Luossavaara-Kiirunavaara AB),
Kiirunavaaravägen 1,
98186 Kiruna, Sweden
kari.niiranen@lkab.com

stellt, das dem Flotationsprozess in der Aufbereitungsanlage von LKAB in Svappavaara entspricht. Die Ergebnisse der Flotationsversuche in der Pilotanlage zeigten, dass der maximal erlaubte Gehalt an Kieselsäure (0.50 % SiO_2) bei einem Ausbringen an Eisen (Fe) von über 95 % mit beiden getesteten Sammlern erreicht werden konnte.

Schlüsselwörter: Eisenerz, Magnetit, Silikatflotation, Mineralaufbereitung, LKAB, Mertainen Eisenerzlagerstätte

1. Introduction

Luossavaara-Kiirunavaara AB (LKAB) is a state-owned Swedish iron ore producer in Northern Sweden with underground iron ore mines in Kiruna and in Malmberget as well as an open-pit operation in Svappavaara. At LKAB, the iron ore deposits and their amenability with respect to mineral processing have earlier been characterized and evaluated mainly based on the grade of important elements such as iron (Fe), phosphorus (P), vanadium (V) and silicon (Si). This kind of characterization and evaluation seemed obviously to be suitable when high grade ores were treated. However, it has drawbacks when the crude ore shows more complex mineralogy and where a specific element is distributed in several different minerals.

The first stage of the more complete characterization and evaluation of an iron ore deposit with respect to mineral processing is to predict the industrial scale plant performance from selected process mineralogical test work at the laboratory scale. In the case that test works in the laboratory scale have a positive outcome, they are followed by enlarged test work and by pilot scale test work as well as full scale tests at the beneficiation plant.

2. Background

In 2006, LKAB tackled a challenging expansion strategy that included studying known iron ore deposits to investigate the possibilities of increasing the ore resources and, in an extension, to have the opportunity to mine iron ore at several sites in the future. One of the iron ore deposits under investigation is the Mertainen iron ore deposit, which is located about 14 km NW of Svappavaara village and 29 km SE of Kiruna. The latest preparatory investigations were carried out in Mertainen deposit from 2007 to 2010.

There are several challenges in the characterization and evaluation of the Mertainen deposit for mineral processing, especially related to the gangue mineralogy. A high amount of silica (SiO_2) including alkali (Na and K) bound to the silicates may end up in the final concentrate without successful beneficiation process and therefore impact the quality of the final products, blast furnace and direct reduction pellets. That might cause problems in the customers' steel production processes. Another challenge related to the mineral processing of Mertainen magnetite ore might be the loss of fine magnetite material what can occur in the separation by flotation [1].

3. Mertainen Iron Ore Deposit

3.1 Geology and Mineralogy

The Mertainen iron ore deposit (IOA) is a Kiruna type Fe oxide apatite deposit (IOA), of which the world class Kiirunavaara deposit is largest and most well-known (e.g. [3–5]). The Mertainen iron ore deposit has the character of a large ore breccia containing also larger lenses or veins of massive magnetite ore situated in its central part (Fig. 1). These richer and massive part of the deposit occurs within a large positive magnetic and gravimetric anomaly sug-

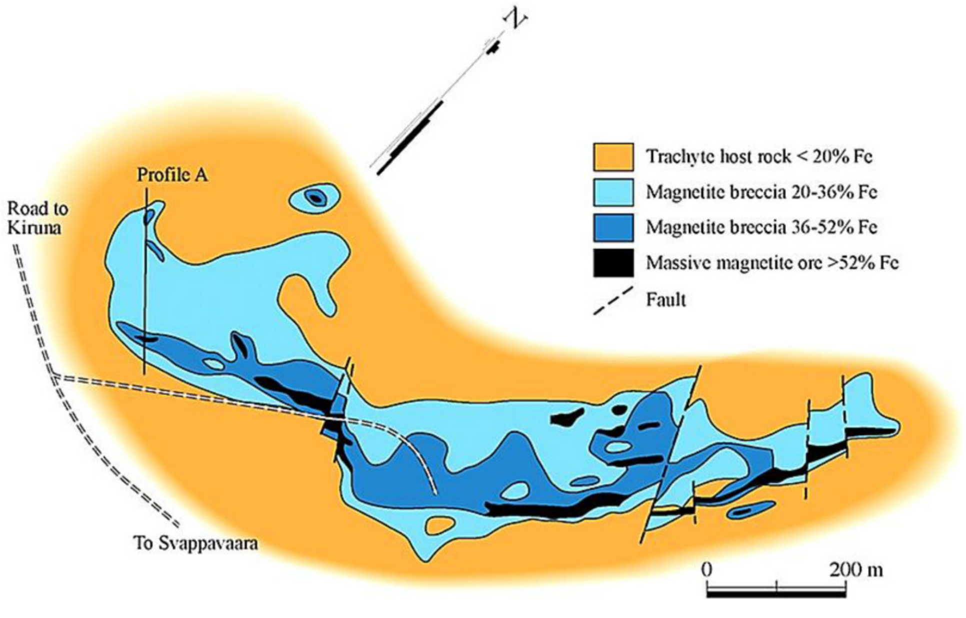

Fig. 1: A simplified geological map of the Mertainen iron ore deposit after Lundberg and Smellie [6]

TABLE 1
Chemical and physical composition of feed concentrate for flotation test work [1]

Fe	P	SiO_2	K_2O	Na_2O+K_2O	P_{80}	H_2O	Specific surface
%	%	%	%	%	µm	%	cm^2/cm^3
70.34	0.0034	1.42	0.06	0.13	43.60	8.85	11,274

gesting the magnetite breccia is very extensive. The high-grade part in the deposit is surrounded by zones of ore breccia with successively lower magnetite content. Mineralization is known to a depth of at least 500 m [6, 7]. Estimated mineral resources (measured, indicated) and inferred of the Mertainen deposit are 229 Mt [8].

Magnetite is the main and practically the only ore mineral of the Mertainen deposit of economic value. A restricted amount of martite (hematite) occurs also very local. The most important gangue mineral in the ore deposits is dark green actinolite, which occurs as dispersed crystals or as coarse aggregates forming bands and veins through the massive ore. Magnetite is also locally accompanied by some apatite and calcite. The average iron content is 35% Fe. The phosphorus content is very low, namely, 0.05% P. However, within certain restricted parts of the deposit the average P content may be as high as 0.2 to 0.9% P [4, 7].

3.2 Ore Types

Historically, mineralization has been divided into three ore types based on their Fe content: the massive magnetite ore (>52% Fe), high-grade magnetite breccia ore (36–52% Fe) and low-grade magnetite breccia ore (20–36% Fe). The Fe content in the host rock is normally under 20% Fe. The massive magnetite ore (or rich ore) is found mainly against the foot wall of the deposit while rich and poor magnetite breccias occur irregularly mixed in the deposits [6]. In a recent study the Mertainen deposit has been divided into seven different ore types based on their geology and mineralogy, on the type of Fe mineralization and alteration, not only on the Fe grade [9].

4. Magnetic Separation

4.1 Sample Preparation

For test work with magnetic separation, 33 samples from drill cores were selected, representing different parts and depths of the Mertainen deposit, at ALS Metallurgy in Australia. Six samples represented the host rock (<20% Fe), seventeen samples represented low grade magnetite breccia (20–36% Fe), six samples represented high grade magnetite breccia ore (36–52% Fe) and four samples represented massive magnetite ore (>52% Fe) [9].

The samples were crushed, homogenized and divided into two subsamples of 150 g. The subsamples were ground to a $P_{80}=45\,\mu m$. After grinding, the samples were screened wet and divided into two fractions: –45 µm and –100/+45 µm. After drying and homogenization, the material was weighed to several subsamples (á 20 g) for wet low intensity magnetic separation with Davis tube magnetic separation. The rest of the material was stored as a backup sample [9].

4.2 Davis Magnetic Tube Test

The magnetic separation with Davis magnetic tube test can be regarded as one of the most important of the mineral processing tests carried out at LKAB's mineral processing laboratory, especially with a focus on liberation of magnetite and gangue mineral such as silicates and phosphates [5]. It should be noted that there is proof that Davis magnetic tube testing provides results that cannot be directly transferred to technical magnetic separators in industrial scale. For plant design and prediction of final behaviour of intergrowths pilot tests have to be done. In case of enlarged test work for wet low intensity magnetic separation a SALA wet magnetic laboratory separator can be used as well as when there is a need for more material, e.g. for flotation tests.

For this study, 38 iron ore samples (28 magnetic products and 10 non-magnetic products) from magnetic separation tests with Davis magnetic tube were submitted for chemical assays and mineralogical analysis with QEMSCAN (Quantitative Evaluation of Minerals by Scanning electron microscopy) [10].

5. Silicate Flotation Test Work in Laboratory Scale

The mineralogy of the ore to be beneficiated has a large impact on the chemical specification on the final product, i.e. the iron ore pellet or fines [11]. As reverse cationic flotation can be applied to reduce SiO_2 content in magnetite concentrate (pellet concentrate) obtained by low intensity magnetic separation, a laboratory flotation test work was

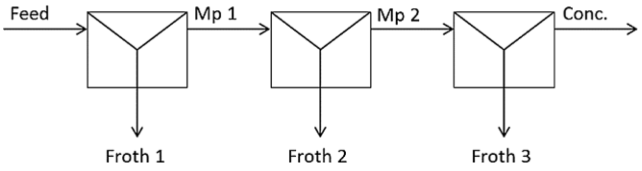

Fig. 2: Flow sheet for the laboratory flotation test work carried out at the LKAB's process mineralogical laboratory in Kiruna [1]

TABLE 2
The parameters for laboratory test work for reverse silicate flotation [1]

	Air	Rpm	Collector dosage g/t	Depressant dosage g/t	pH in pulp (average)	Temp °C
Monoamin	70	1250	40 + 20 + 20	500	8.14	28
Diamine	90	1250	85 + 20 + 20	500	8.20	25
Diamine	90	1250	85 + 20 + 20	500	8.20	22

performed to find a starting point for the collector dosage in the pilot plant test [1, 2].

For the feed for the flotation test work in the laboratory scale the ore samples were obtained from massive magnetite ore and magnetite breccia with higher iron content, which was derived from test mining at Mertainen deposit. The ore samples were crushed to –20 mm and separated with dry magnetic separator. The concentrate was then crushed to –10 mm and beneficiated (comminution and wet low intensity magnetic separation) in the pilot plant in Malmberget. Table 1 presents the chemical composition, the specific surface and the particle size distribution of the produced feed for the flotation test work [1].

The flotation tests were carried out in a Svedala D12 laboratory flotation equipment with a cell size of 3 l. The flow sheet for the flotation test is shown in Fig. 2 [1].

Two different amines were used as collectors (Table 2) and potato starch as depressant (Dextrin). Furthermore, synthetic process water corresponding to the process water in the process plant in Svappavaara site was used during one of the test runs. The test work parameters are presented in Table 2 [1].

The laboratory flotation tests were performed as a stepwise flotation where the collector is added in three steps and the froth product from each step is collected and analyzed together with the final concentrate. The flotation time for each step was 3 min and pH and temperature were measured continuously, but not adjusted during flotation. Chemical analysis of the samples was carried out with XRF. Furthermore, particle size and specific surface were also measured [1].

6. Silicate Flotation Test Work in Pilot Plant

A process design was built up at the Geological Survey of Finland (GTK) corresponding to LKAB's flotation process in the processing plant in Svappavaara site. The feed material was also obtained from massive magnetite ore and magnetite breccia with higher iron content, which was derived from test mining at Mertainen deposit and beneficiated in the pilot plant in Malmberget, consisting of comminution and wet low intensity magnetic separation [1].

The test work was divided into 3 different setups. In setup 1 and 2 the dosage of collector and functionality of flotation setup were evaluated. In the last stage, setup 3 presented in Fig. 3, the focus was to investigate how well the closed circuit worked, to confirm dosage selection and to produce magnetite concentrate (pellets concentrate) for further investigations on pelletizing (not presented in this article). The flow sheet for the third set up is presented in Fig. 3. It corresponds to the flotation flow sheet in the processing plant in Svappavaara except for the regrinding mill. The third set up was added as it was desirable to evaluate

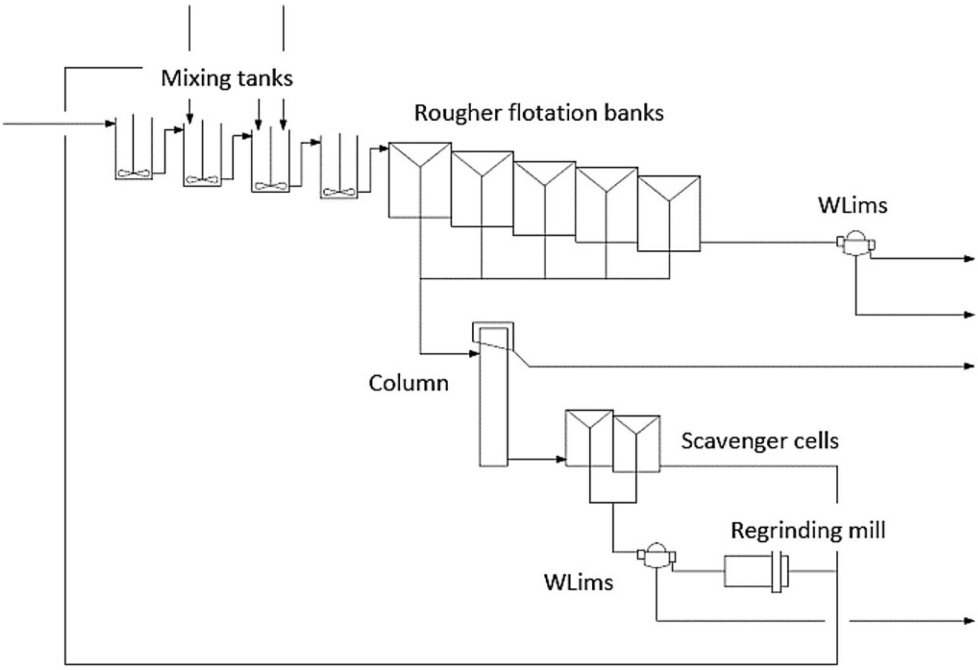

Fig. 3: Flow sheet for the pilot scale flotation test work carried out at the mineral processing laboratory of GTK (Geological Survey of Finland) in Finland [1]

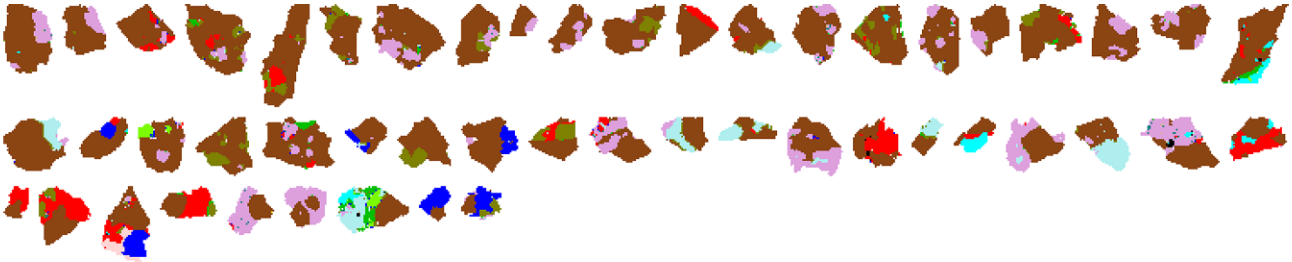

Fig. 4: Typical intergrowths of magnetite and gangue minerals in a magnetic fraction (*brown*= magnetite, *purple*= albite, *red*= titanite, *dark blue*= amphibole, *light blue*= K-Feldspar, *turquoise=calcite*) [10]

the effect of a regrinding step for the recycled material to try to recreate specific surface and increase the iron (Fe) recovery. Sampling was made from every stream, once a day (when possible) in one hour on every 10th minute [1].

7. Results and Conclusions

7.1 Mineralogical Investigations and Liberation Analysis

Based on the mineralogical analysis carried out by ALS Metallurgy [10] magnetite is clearly dominating the iron oxide in the Mertainen deposit. Only minor to trace hematite (martite) is present in selected samples, associated with magnetite. Magnetite dominates also the magnetic fraction after magnetic separation with Davis magnetic tube making up between 94 and 99% in the selected samples. The most common gangue minerals in the samples representing magnetic fraction are albite, titanite and biotite. Small amounts of K-feldspar, plagioclase, amphibole, chlorite and epidote as well as calcite and apatite are also present. Silicates (excluding titanite) typically make up between 0.5 wt% and 2.5 wt% of the sample mass in the magnetic fraction. In contrast, the amount of magnetite varies significantly between the non-magnetic fractions.

Furthermore, it can be concluded that magnetite is well liberated in nearly all samples representing magnetic fraction, with typically >90% classified as well liberated. In only two samples representing magnetic fraction, 74% and 83% of the magnetite is classified as well liberated. Unliberated magnetite in magnetic fraction is mainly locked with albite, titanite and biotite, but also with other silicates such as chlorite, K-feldspars, epidote and amphibole. Particle image (QEMSCAN) in Fig. 4 show examples of unliberated magnetite grains mostly with intergrowth with silicates [10].

Unliberated silicates are mainly locked with magnetite in high grade particles (with magnetite occupying >60% of the particle area) in the magnetic fraction. Titanite contributes typically <2 wt% of fraction mass. Furthermore, it is important to note that unliberated titanite is mainly locked with magnetite, either in well-liberated magnetite particles or in binary magnetite-titanite particles.

The intergrowths of magnetite and silicate minerals, mostly with albite but also with titanite and amphiboles is an important texture considering the wet low intensity magnetic separation, which is a crucial part of the beneficiation process in the processing plants in the LKAB sites in Kiruna, Malmberget and Svappavaara. The intergrowths of magnetite and silicate minerals can be expected to end up in the magnetite concentrate (feed for pellets plants) and to increase the SiO_2 content based on the experimental studies on iron ore from Kiirunavaara deposit [5]. Silicates may also increase alkali (Na + K) and titanium (TiO_2) content in the magnetite concentrate, because the silicates are the

TABLE 3

The results from the flotation test work on iron ore from Mertainen deposit in pilot scale for set up 3 presented in Fig. 3 [1]

Collector	Product	g/t	Depressar	g/t	Wt%	Fe%	RFe%	SiO_2%	RSiO_2%	Spec. surface cm^2/cm^3 [a]	Loss of spec. surface	%–45 µm
Mono-amine	Feed	45	Dextrin	464	46.55	70.59	100	1.17	100	11,400 [b]	3300	78.00
	Conc				43.44	71.41	97.50	0.52	42.80	8100		70.50
	Feed	43	Dextrin	483	45.75	69.86	100	1.79	100	11,400	3100	77.00
	Conc				50.88	71.46	96.10	0.52	27.40	8300		76.00
	Feed	53	Dextrin	480	48.15	70.37	100	1.37	100	11,400	2900	79.30
	Conc				44.52	71.43	95.20	0.52	35.60	8500		75.60
Diamine	Feed	109	Dextrin	468	46.34	70.42	100	1.33	100	11,400	3500	78.60
	Conc				54.80	71.47	97.60	0.48	34.90	7900		78.40
	Feed	146	Dextrin	479	45.31	70.15	100	1.55	100	11,400	4100	79.50
	Conc				43.90	71.61	93.80	0.38	22.50	7300		76.40

[a] ±400
[b] average value from total feed

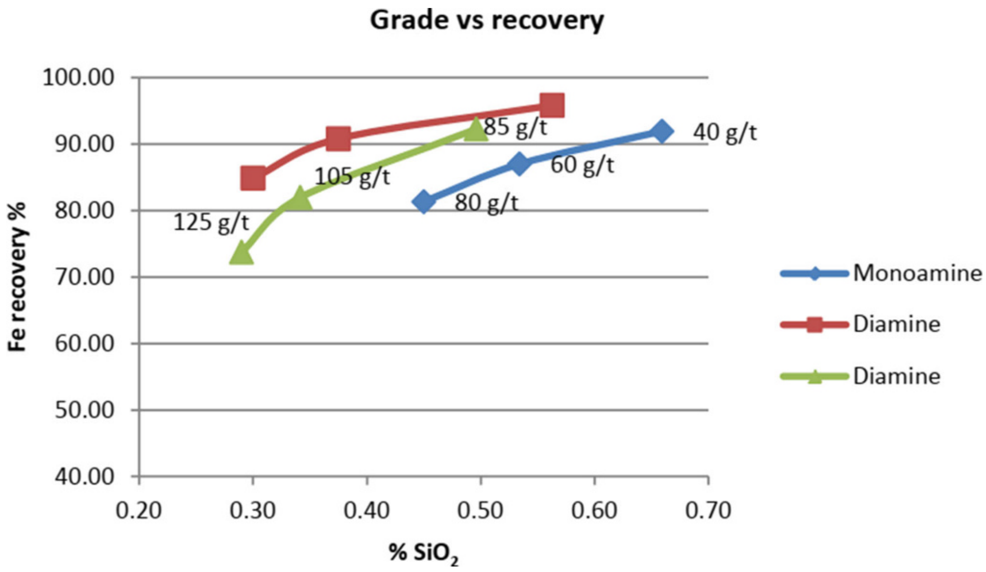

Fig. 5: The dosage of the collector (monoamine and diamine, Table 2) as a function of iron recovery and SiO_2 grade [1]

most important source of these elements in the Mertainen iron ore deposit.

7.2 Flotation Test Work

The aim of the flotation test work in the laboratory scale on magnetite ore from Mertainen deposit was to evaluate the effect of the silicate flotation on the quality of the concentrate. The most important task is to examine the reduction of SiO_2 content in magnetite concentrate (SPC) after reverse silicate flotation. Furthermore, it can be noted that SiO_2 content in SPC (Svappavaara pellet concentrate) should not exceed 0.5% in order to keep the alkali content (Na + K) and titanium (TiO_2) content within the current product specification of LKAB [12].

A laboratory flotation test work carried out at the LKAB's process mineralogical laboratory in Kiruna (Chap. 4) was performed to find a starting point for the collector dosage in the pilot plant test. The dosage of the collector (monoamine and diamines, see Table 2) as a function of iron recovery and SiO_2 grade is presented in Fig. 5. As results of the test work it can be noted that monoamine requires a dosage of about 70 g/t to reach 0.5% SiO_2 with an iron recovery of approximately 87%. The dosage required for the diamine is over 80 g/t with an iron recovery of about 90% in the laboratory scale [1].

The dosage level of the collector for pilot scale test, adjusted to a required level with the monoamine, was about 50 g/t and with diamine approximately 100 g/t to reach SiO_2 content of 0.5% The results from the flotation test work on iron ore from Mertainen deposit in pilot scale are shown in Table 3.

The most important result from the flotation test work on iron ore from Mertainen deposit in pilot scale is that cationic silicate flotation can be regarded as a possible solution for reducing the silica (SiO_2) content in the magnetite concentrate (feed for pellet production). All samples showed SiO_2 content near the reference value of 0.50% (monoamine as collector) or clearly below the reference value (diamines as collector). A similar result was obtained in reverse cationic silicate flotation test work in laboratory scale regarding SiO_2 content for SiO_2-rich ore type B2 from the Kiirunavaara mine [2]. Furthermore, it can be noted that recovery of iron (Fe) is high in all the test runs and both sieve analysis and specific surface analyses shows a loss of fine material during flotation. The performance of monoamine and diamine seems to differ according to particle size. In order to further investigate the potential loss of specific surface, test runs with over dosage of amine were made. High dosage showed an increased loss of specific surface, lower iron (Fe) recovery and a lower SiO_2 grade [1].

7.3 Conclusions

Although the geology and mineralogy of the Mertainen iron ore deposit differ from the other iron ore deposits operated by LKAB, i.e. Kiirunvaara and Malmberget underground mines and Leveäniemi open pit, it seems to be possible with cationic silicate flotation to reduce the silica (SiO_2) content in the magnetite concentrate produced from this deposit.

The test work in the pilot scale showed that the required SiO_2 content of 0.50% was achieved with an iron (Fe) recovery of over 95%, with both reagents (monoamine and diamines). For monoamine the froth was very stable, thereby accumulating in large volumes. This might cause some problems in full scale operation, because it may clog the froth drains. With diamine the froth was easier to handle and the selectivity was better. There was no notable difference between the use of synthetic process water and the original process water in content and recoveries. It can therefore be concluded that the origin of process water does not seem to have a large effect on the flotation conditions. It seems that diamines are more effective on coarser particles and monoamines on fine fractions.

If the excessive froth formation can be handled, it could be of interest to mix diamine and monoamines in order to enhance the selectivity in all size ranges. However, this needs further investigations and more test work both in the laboratory scale and pilot scale as well as full scale test at the processing plant.

References

1. Töyrä, V.; Adolfsson, G.; Rostmark, S.; Fredriksson, A.: Flotation of silicate minerals from Mertainen iron ore. Mineral Engineering 2014, Conference. University of Technology Luleå, 2014. Preprints
2. Töyrä, V.; Niiranen, K.; Niva, E.; Rosendal, O.: Increasing Silicate Content in the Kiruna Ore—a Challenge for Mineral Processing. Mineral Engineering 2017, Conference. University of Technology Luleå, 2017. Preprints, pp. 149–159
3. Geijer, P.: Igneous rocks and iron ores of Kiirunavaara, Luossavaara and Tuolluvaara. Scientific and practical researches in Lapland arranged by Luossavaara-Kiirunavaara Aktiebolag, Stockholm: Norstedt & Söner, 1910
4. Martinsson, O.; Billström, K.; Broman, C.; Weheid, P.; Wanhainen, C.: Metallogeny of the Northern Norrbotten Ore Province, northern Fennoscandian Shield with emphasis on IOCG and apatite-iron ore deposits. Ore Geology Reviews 78 (2016), pp. 447–492
5. Niiranen, K.: Characterization of the Kiirunavaara iron ore deposit for mineral processing with the focus on the high silica ore type B2. Chair of Mineral Processing, Montanuniversitaet Leoben, Austria, Doctoral Thesis with Appendices, 2015
6. Lundberg, B.; Smellie, J.A.T.: Painirova and Mertainen iron ores: two deposits of the Kiruna Iron Ore type in northern Sweden. Economic Geology, 74 (1979), pp. 1131–1152
7. Martinsson, O.; Virkkunen, R.: Apatite iron ores in the Gällivare, Jukkasjärvi and Svappavaara areas. In: Allen, R. L.; Martinsson, O.; Weihed, P. (Eds.): Svecofennian, Ore-Forming Environments: Volcanic-Associated Cu-Au, Sediment-Hosted Pb-Zn, and Magnetite-Apatite Deposits in Northern Sweden. Littleton, Colo: Society of Economic Geologists, Guidebook Series Vol. 33 (2004), pp. 163–167
8. LKAB: LKAB Annual and Sustainability Report 2019
9. Holm, S.: Mertainen – Davis tube undersökning. LKAB Utredning (Internal Report in Swedish), 2015
10. ALS: Quantitative Automated Mineralogical Analysis conducted on 38 DTR Products (Iron Ore) from Mertainen Deposit, Svappavaara, Sweden for ALS Sweden (on behalf of LKAB), Mineralogy Report MIN2211, Part I and Part II, 2015
11. Adolfsson, G.; Fredriksson, A.: Reduction of Silica in LKAB Pellets through Different Mineral Processing Unit Operations. Conference in Minerals Engineering, Luleå University of Technology, Preprints, 2011
12. Töyrä, V.: Silikatflotationsförsök i laboratorieskala med Mertainen-material från provbrytningen 2015. LKAB Utredning 15-956 (Internal Report in Swedish), 2015