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MAGNETIC CHARACTERIZATION OF SULPHIDE ORES: EXAMPLES FROM SWEDEN

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Abstract Diagrams of accumulativemagnetic susceptibility distribution are used to evaluate the suitability of four sulphide ores for magnetic methods of beneficiation. The investigated materials are Garpenberg, Aitik and Kedtrask. The samples were divided into susceptibility classes each of which was characterized by its mineral content. The results are presented as diagrams showing mineral appearance in the whole susceptibility range of the ore. The obtained accumulative susceptibility diagrams can be used to predict the outcome of magnetic separation.
The accumulative susceptibility diagrams indicate that the Garpenberg and possibly the Kedtrask materials are suited for magnetic separation, possibly as the primary concentration method. The other investigated materials contain iron-bearing silicates magnetic susceptibility of which is higher than that of valuable mineral and will thus report into the magnetic product making further separation necessary.

INTRODUCTION

We present a method of characterization of magnetic properties of ores and of evaluation of their suitability for treatment by magnetic methods. Distributions of magnetic susceptibility of complex ores could be a useful criterion in predicting the outcome of magnetic separation techniques. These distributions can be fairly easily determined.

The probability of an individual particle to be attracted and captured by a magnetic field increases with increasing magnetic susceptibility. For instance, in a high-gradient magnetic separator (HGMS) nearly all the material with magnetic susceptibility greater than that of the valuable mineral will report into the magnetic product.

It is of major interest to consider the magnetic susceptibility of the valuable mineral as well as the quantity of minerals with magnetic susceptibility greater than this value. Total amount of material reporting into the magnetics will affect the matrix loading and thereby the economics of the process.

For this reason, the occurrence of iron-containing silicates will affect the usefulness of magnetic separation since their magnetic susceptibility is often greater than that of paramagnetic valuable minerals.

MATERIALS

Four materials were used in our investigation. Three of these samples were crude ores and one sample was a flotation concentrate [1]. The ores are complex sulphides but for purposes of this report the main valuable minerals will used for their characterization which is given in Table I.

TABLE I Samples investigated in this study

Sample No.	Main mineral	Origin
1	Galena	Garpenberg
2	Chalcopyrite	Aitik
3	Cu-Pb-Zn flotation concentrate	Garpenberg
4	Pyrite	Kedtrask

The analysis by inductive-coupled plasma spectroscopy (ICP) identified the most dominant elements that are summarized in Table II.

EXPERIMENT

Samples of the ores were crushed and ground for the best possible liberation of the minerals. For the pyrite/pyrrhotite sample, the minimum particle size that can be treated by a separator restricted the choice of fractions. The limiting particle size for the type of dry magnetic separator used (Frantz Isodynamic Separator) is in the region of 53 to 75 μ m. Minimum particle size depends on particle shape and on the difference in specific gravities of the materials.

TABLE II The ICP analysis of samples investigated in this study

Sample no.	Al	Cu	Ca	Fe	K	Mg	% Na
1	-	-	0.2	-	6.1	-	0.5
2	8.1	0.3	1.8	7.3	6.6	1.0	1.7
3	-	10.7	-	20.3	-	3.2	-
4	5.2	0.2	-	52.2	-	0.5	-

Sample no.	Na	Pb	Zn	Ag
1	-	42.5	4.9	10 000
2	1.7	-	-	32
3	-	21.6	8.3	5 000
4	-	0.3	3.3	-

TABLE III Magnetic susceptibility of classes of minerals

Material Sample / class Nr	Average Magnetic susceptibility m3/kg 10-9	Standard deviation	Number of measurements
Galena / 1	194,90	6,80	6
Galena / 2	56,60	2,80	6
Galena / 3	34,90		1
Galena / 4	5,20	0,40	6
Galena / 5	0,05	0,04	6
Galena / 6	-2,97	0,13	6
Galena / 7	-3,17	0,15	6
Chalcopyrite / 1	996,55	2,32	2
Chalcopyrite / 2	687,78	10,88	3
Chalcopyrite / 3	452,59	7,23	6
Chalcopyrite / 4	203,31	7,92	6
Chalcopyrite / 5	125,82	6,01	6
Chalcopyrite / 6	97,03	1,49	4
Chalcopyrite / 7	76,87	0,33	2
Chalcopyrite / 8	23,20	0,16	4
Chalcopyrite / 9	15,59	1,09	6
Chalcopyrite / 10	4,14	0,09	5
Chalcopyrite / 11	-0,22		1
CuPbZn-conc. / 1	823,30		1
CuPbZn-conc. / 2	699,53		1
CuPbZn-conc. / 3	475,74		1
CuPbZn-conc. / 4	276,82		1
CuPbZn-conc. / 5	80,46	1,77	8
CuPbZn-conc. / 6	50,67	1,11	6
CuPbZn-conc. / 7	33,14	0,77	2
CuPbZn-conc. / 8	16,09	0,48	2
CuPbZn-conc. / 9	6,51	0,05	2
Pyrite / 1	713,26	6,02	3
Pyrite / 2	350,99	10,04	4
Pyrite / 3	134,56	6,07	5
Pyrite / 4	125,21	7,56	4
Pyrite / 5	76,88	2,23	4
Pyrite / 6	37,23	0,49	4
Pyrite / 7	19,09	0,75	6
Pyrite / 8	10,72	0,54	6
Pyrite / 9	5,94	0,29	6
Pyrite / 10	3,25	0,19	4

To avoid the particle size effects during the separation, the ore samples were screened and narrow interval of particle sizes of 53 - 75 μ m was used. Care was taken to keep the same mineral distribution of particle size fractions as in the crude ore.

The flotation concentrate was treated by an organic solvent in ultrasonic bath. This was done in order to remove remaining reagents from the flotation process which may cause unwanted flocculation, and to ensure particle dispersion.

Magnetic separation was carried out in Frantz Isodynamic Separator. Each ore was divided into seven to twelve narrow classes of magnetic susceptibility (see Table III). Minerals in individual susceptibility groups were identified by optical microscopy, and their distributions were determined by particle counting. The occurrence of locked particles was noted.

The mean magnetic susceptibilities of the groups were measured by magnetic susceptibility balance manufactured by Johnson & Matthey Catalytic Systems.

The susceptibility balance operates [2] by measuring the force that a magnet exerts on a sample. The JM balance works on a basis of a fixed sample and moving magnets. Two pairs of magnets are placed at opposite ends of a beam so that the system is in equilibrium. Introduction of a sample between the poles of one pair of magnets produces a deflection of the beam which is registered by photodiodes.

The electric current passed through a coil between the other pair of magnets, producing a force that opposes the force exerted by the sample. The system is thus returned to equilibrium. In equilibrium, the current through the coil is proportional to the force exerted by the sample. The electric current is measured as a voltage drop and is used to calculate the magnetic susceptibility.

Magnetic susceptibility of each sample was measured one to eight times, depending on quantity of sample available for measurements. The average value was used in plots of magnetic susceptibility distribution, as is shown in Figures 1 to 4.

DISTRIBUTION CURVES OF SUSCEPTIBILITIES AND OF MINERALS

Accumulative mass percentage of the ore is plotted against magnetic susceptibility to express the susceptibility distribution of the ore sample. In the same diagram, mineral distribution curves are included. These curves depict the accumulated mass percentage of major minerals. The ore curves are drawn in bold lines while curves representing the minerals are shown as hair lines.

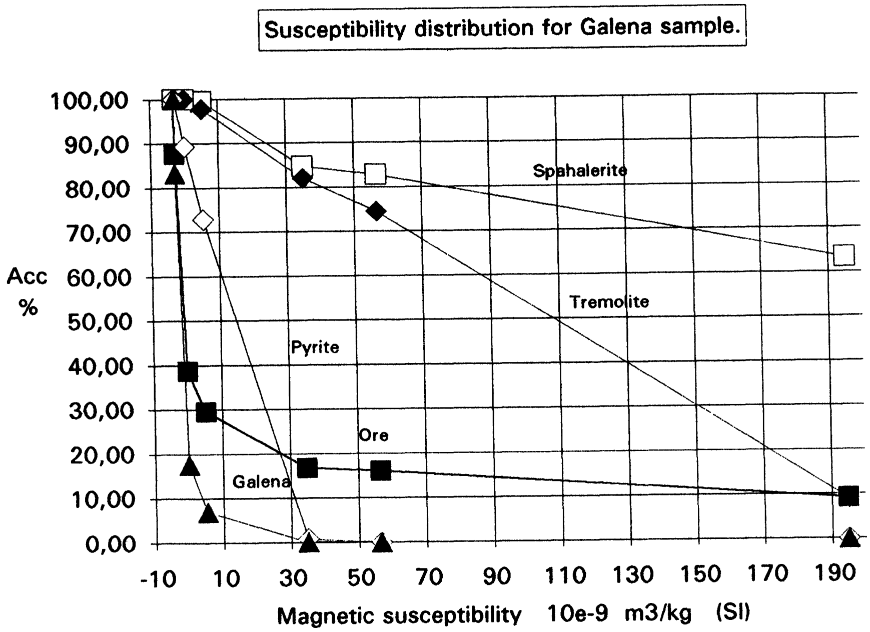

FIGURE 1 Distributions of magnetic susceptibility and of minerals in Garpenberg ore sample.
■ ore, □ sphalerite, ◆ tremolite, ◇ pyrite, ▲ galena.

The diagrams provide an aid in determining the suitability of materials for magnetic separation by allowing the degree of recovery and the composition of the magnetic product to be estimated.

Example.

In the diagram for galena, as shown in Fig. 1, the magnetic susceptibility that defines 90 per cent of accumulated sphalerite content ($25x10^{-9}$ m^3/kg) shows that 20 per cent of the sample material has magnetic susceptibilities greater than this value. That is, 20 per cent of the feed will report into the magnetic product.

Since 90 per cent of sphalerite in the sample accounts for about 12 per cent of the total material, some 8 per cent of other minerals will report into the magnetic fraction. For this particular ore, these minerals will be predominantly amphiboles. The estimated results of separation are shown in Table IV.

Diagrams of magnetic susceptibility and minerals distribution give a rough idea of the outcome of magnetic separation. Diagrams that will be shown below depict only the magnetic characteristics of the ore. Other parameters, such as particle shape effects, surface forces, dispersion are not considered in this work.

TABLE IV Estimate of magnetic separation of galena

	Grade		Recovery	
	Zn	Pb	Zn	Pb
Feed	5%	42%		
Magnetics	22%	6%	90%	3%
Non-magnetics	0.6%	51%	10%	97%

RESULTS

Galena Ore

Of the four ores investigated in this paper, the galena ore from Garpenberg is decidedly the most suitable material for beneficiation by magnetic separation.

The main minerals in the sample of the ore are:

Mineral	Grade (w%)
Sphalerite	13.6
Tremolite and actinolite	6.3
Pyrite	6.4
Galena	73.7

The susceptibility distribution diagram suggests that approximately 85 to 90 per cent of sphalerite and 80 to 85 per cent of tremolite will report into the magnetics without a major interference of galena and pyrite. For a higher recovery of sphalerite, an increasing amount of pyrite and galena will report into the magnetic product. High magnetic susceptibility of sphalerite is a result of lattice-bound iron [3]. Pure zinc sulphide is diamagnetic.

Advantage is taken of magnetic properties of this ore in Garpenberg, where the HGMS technique is used [1] to recover sphalerite lost in flotation of galena and to return it to the sphalerite concentrate. The HGMS circuit recovers approximately 90 per cent of the Zn content at 23 per cent grade [1].

Chalcopyrite Ore

The main minerals in the sample of the ore were:

Mineral	Grade (w%)
Magnetite	2.6
Biotite	12.0
Chlorite*	2.2
Chalcopyrite	1.0
Muscovite	6.9
Quartz	71.2

* Various chlorites and talc minerals

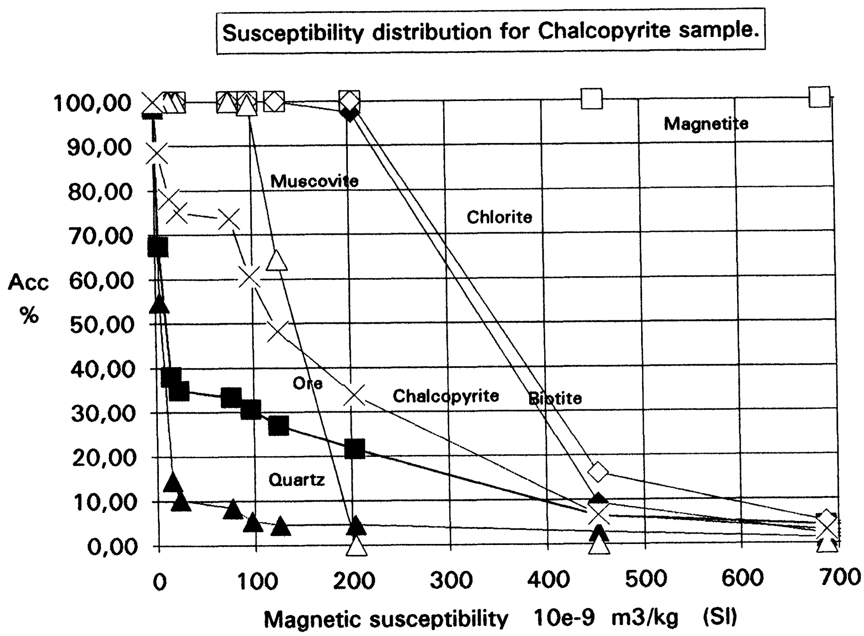

FIGURE 2 Susceptibility and mineral distribution of Aitik sample.

■ ore □ magnetite
◆ biotite ◇ chlorite
▲ quartz △ muscovite
× chalcopyrite

The susceptibility distribution suggests that biotite/chlorite, chalcopyrite and quartz can be separated by magnetic methods. Separation must then be carried out in two steps.

First, biotite/chlorite minerals must be removed at a lower magnetic field. The valuable mineral chalcopyrite can then be recovered in second stage. However, in order to recover 60 per cent of the copper mineral, approximately 30 per cent of the total material must be captured in the matrix. Taking into consideration low copper grade of the ore and large tonnage of ore to be treated, magnetic separation is probably not a viable technique.

Also, a significant portion of copper will be lost to the biotite/chlorite fraction, making further processing necessary. Investigations using a microscope showed that quartz that appears at large susceptibilities consists of locked particles that include small concentration of magnetite.

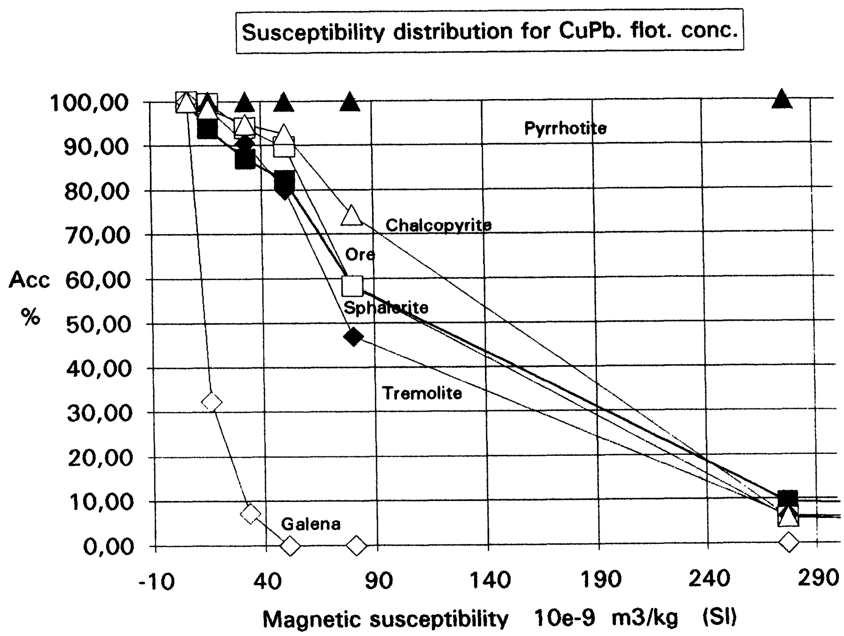

FIGURE 3 Susceptibility and mineral distribution of the Garpenberg flotation concentrate

■ ore	□ sphalerite,
◆ tremolite	◇ galena
▲ pyrrhotite	△ chalcopyrite

Copper - Lead Flotation Concentrate

The main minerals in the sample are:

Mineral	Grade (w%)
Pyrrhotite	5.9
Chalcopyrite	29.4
Sphalerite	18.2
Amphiboles*	18.1
Galena	28.4
*Tremolite/Actinolite	

For this material, magnetic separation of galena from sphalerite/chalcopyrite seems to be possible. It is likely, however, that sphalerite and chalcopyrite cannot be recovered at acceptable grade and recovery.

By comparing the galena curve with that of galena ore it can be seen that galena in the flotation concentrate has a slightly greater magnetic susceptibility. This is probably the result of the presence of the collector reagent which can contribution to the formation of galena flocs which contain minerals of higher magnetic susceptibility.

Pyrite/Pyrrhotite Ore

The main minerals in the sample of the ores are:

Mineral	Grade (w%)
Pyrrhotite/Pyrite	76.0
Sphalerite	5.0
Mica*	18.1
Quartz	28.4

* Muscovite type

Pyrite and pyrrhotite have been considered as one group in this study, mainly because pyrrhotite and pyrite form a mixture of microparticles and the interface between them is diffuse.

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The susceptibility distribution shown above indicates that sphalerite can be recovered by magnetic separation. In this case approximately 90 to 95 per cent of sphalerite content in the sample will report into the magnetic product, together with about 20 per cent of mica. The magnetic product will also contain the pyrrhotite-rich fractions of the ore.

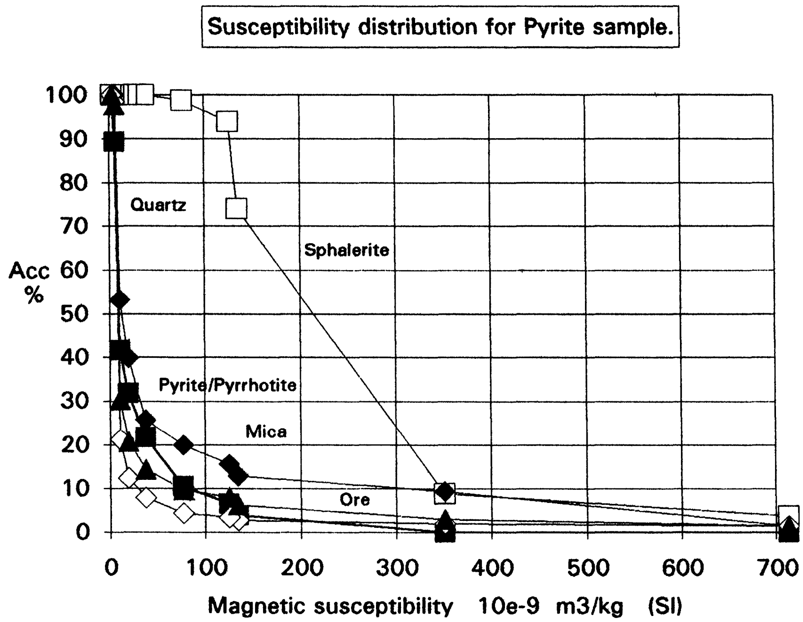

FIGURE 4 Susceptibility and mineral distribution of Kedtrask sample.
■ quartz □ sphalerite
◆ mica ◇ pyrite/pyrrhotite
▲ ore.

MAGNETIC SUSCEPTIBILITY OF MINERALS

As has been mentioned in the experimental section, magnetic susceptibilities of individual minerals have not been measured. Instead, minerals were identified in the susceptibility groups by optical microscopy. In order to evaluate the accuracy of these measurements, our results can be compared with the literature values, as is shown in Table V.

TABLE V Magnetic susceptibility of selected minerals

Mineral	Magnetic susceptibility		
	litterature	average measured	
	10 e-9 m/kg		
Biotite	327	340	
Chalcopyrite	48	120 - 150	
Chlorite	316	360	
Galena	-5	0 - 25	
Muscovite	75	140	
Pyrit	7	15	
Pyrrhotite	2890	3121	
Quartz	-6	5	
Sphalerite	-6	115 - 240	
Tremolite		80 - 110	

The agreement of measured and literature data is acceptable. The literature susceptibilities [4] were often obtained by measuring pure or synthetic minerals. In practice, however, magnetic susceptibilities of minerals vary with concentration of impurities. It is, therefore, natural that a given mineral is characterized by a broad interval of magnetic susceptibility.

CONCLUSIONS

The susceptibility distributions suggest that magnetic separation, with a few exceptions, is well suited for purification of concentrates. The main reason for magnetic separation to fail as a primary beneficiation technique is generally high concentration of iron-bearing silicates in ores.

Silicates have higher magnetic susceptibilities than most of valuable minerals and usually report into the magnetic fraction. Of those materials investigated in this paper the galena sample from Garpenberg and possibly the pyrite/pyrrhotite sample from Kedtrask can yield favourable results by HGMS.

Reliability of our method cannot be evaluated without performing extensive HGMS tests. In the case of the Garpenberg ore some beneficiation data are available [1]. The results of analysis of the feed and of the magnetic product are summarized in Table VI.

TABLE VI Magnetic separation by HGMS of galena ore from Garpenberg.

	Grade (%)			Recovery (%)		
	Cu	Zn	Pb	Cu	Zn	Pb
Feed	1.0	9.0	53.0			
Magnetics	2.5	23.0	24.0	80	90	20
Non-magnetics	0.5	1.0	70.0	20	10	80

Magnetic separation in Garpenberg is performed on flotation concentrate and the separation results and the prediction from the diagram of susceptibility distribution are not directly comparable. The diagram predicts that approximately 85 to 90 per cent of sphalerite have sufficiently high magnetic susceptibility. in comparison with the remaining minerals, to be recovered. Also the Zn grade of the magnetic product was estimated to be around 23 per cent.

Rather high content of lead in the magnetic product from Garpenberg can be explained either as locked particles or as flocs formed by galena particles covered with flotation reagents.

ACKNOWLEDGMENT

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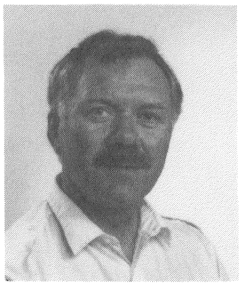

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