Characterising Magnetic Susceptibility and Remanent Magnetisation of Magnetite and Hematite Rich Drill-Core Samples at Blötberget

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SUMMARY

Petrophysics prove powerful as a complement to geological and mineral exploration geophysical studies. Statistical relationships between magnetic properties and thin section analysis can be used in a methodology to characterise iron oxide ore deposits. In this study drill core samples are studied and reveal noticeable changes in susceptibility across the Verwey transition temperature (153°C), Curie temperature (580°C) and Néel temperature (680°C). High temperature measurements allow for the contribution of magnetic susceptibility to be separated out, and directly related to ore content in drill core samples. This study shows that a mere 20 samples were enough to delineate a linear relationship susceptibility and magnetite content at Blötberget, Sweden with R^2=0.73. In 6 out of the 20 measurements a similar relationship with R^2=0.81 was indicated for hematite. Low temperature measurements also found that samples within this lower-amphibolite facies setting held a Morin transition suppressed to -60 °C, or missing. It has been suggested that the temperature discrepancy is likely an effect of elevated traces of Vanadium and Titanium. It is also possible that suppression is caused during the formation of martite and/or Fe(III) replacement by Fe(II).

Key words: Iron-ore, magnetism, susceptibility, Curie, anisotropy.

INTRODUCTION

Laboratory magnetic measurements can complement geological and mineral exploration geophysical studies. Analysis of statistical relationships between magnetic properties and thin section analysis can prove useful for this purpose. A methodology is developed in the current study, with the aim to characterise the Kiruna-type REE-bearing apatite iron-oxide deposits at Blötberget in central Sweden (e.g. Geijer and Magnusson 1944; Jiao, 2011).

The purpose of this study has been: a) Characterise magnetic properties in support of exploration. b) Correlate results from an independent petrographical study of vol% and wt% which are based on microscopy point counting (BGU, 2015). It estimates the vol% and wt% of the other previously unknown samples by applying a linear trend with additional magnetic susceptibility measurements.

METHOD AND RESULTS

Thirty-seven drill core samples, received from Nordic Iron Ore, were used in this study. Samples contained a range of magnetite from 0 up to 81 weight percent (wt%) and hematite from 0 up to 83 wt%.

The MFK1-FA (Advanced Geoscience Instruments Company) is a laboratory instrument that enables semi-automatic magnetic susceptibility measurements and attachments enable measurements in 3D and high/low temperatures. In this study bulk susceptibility, magnetic anisotropy and temperature dependent susceptibility were measured using this equipment.

Magnetic susceptibility measurements were carried out as a function of temperature, using an MFK1-FA susceptibility bridge. The measurements show that magnetite with strong susceptibility contribution overshadows the hematite contribution in the samples. Susceptibility drops are noticeable when crossing the Curie temperatures; 580ºC and 680ºC for magnetite and hematite, respectively. Although the bulk susceptibility of magnetite is several orders of magnitudes larger than that of hematite, the signals from the two phases are readily distinguishable from the drop in susceptibility across their respective Curie temperatures. The wt% magnetite, identified in thin sections, was compared with drop in susceptibility across the 580ºC (Fig. 1). A linear relationship is identified (Fig. 2) between the magnitude drop in susceptibility and magnetite content with R^2=0.73. The same procedure (Fig. 3) was performed for hematite in 6, out of the 20, measurements. Thus another linear relationship (Fig. 4) with R^2=0.81 for hematite. A lower detection limit of 7 wt% hematite was identified when characterising susceptibilities associated with hematite using this method. Low temperature measurements identified Verwey transition for magnetite at -153ºC and note that the Morin transition (-14ºC) for hematite in the Blötberget samples was supressed by -60ºC (Fig. 5), or missing.

The degree of magnetic anisotropy (Fig. 6) in susceptibility was measured on non-orientated 3x3x3 millimetre cubic samples. Two groups emerged in the results a) Low bulk susceptibility with exceptionally high degree of anisotropy (P_j) of 2 or more and b) high bulk susceptibility with low to intermediate degree of anisotropy (P_j) below 2. The strongest degree of anisotropy was detected in a low grade pure magnetite sample, high grade hematite sample and one strongly sheared foliated hematite ore with spectrolite (flaky hematite) present.

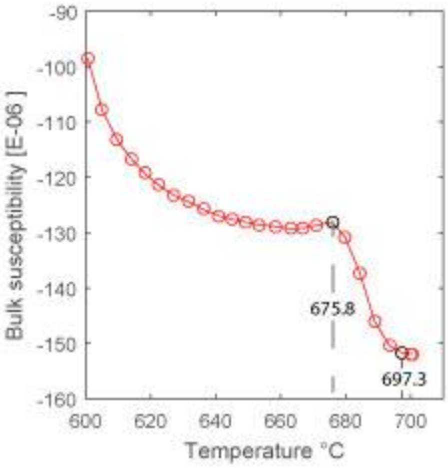

Figure 1. Measurement data from one of the 37 susceptibility temperature dependency sample tests. Curie temperature, approximately 580 °C, averaged at transition. The delta bulk susceptibility is difference between the same points in y-axis

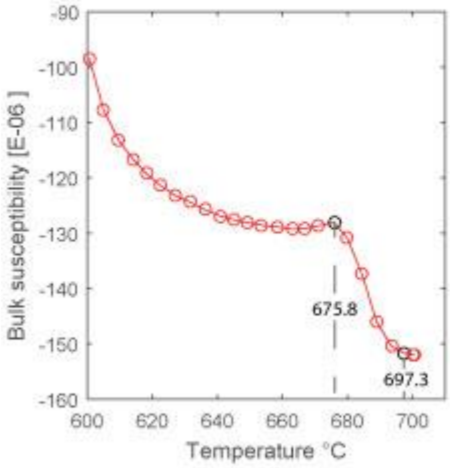

Figure 3. Measurement data for one of the ten samples where susceptibility temperature dependency sample tests. Néel temperature, approximately 680 °C, averaged at transition. The delta bulk susceptibility is difference between the same points in y-axis

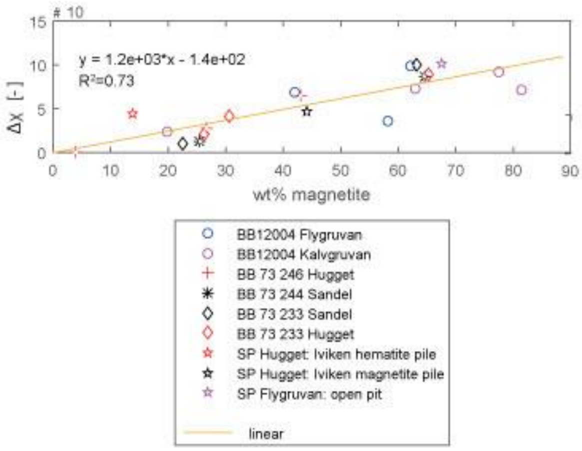

Figure 2. Plotted delta mass susceptibility at high temperature for magnetite (580 °C) transition and respective wt% magnetite. Samples are colour coded for drill core and ore body designation. Linear relation wt% and Curie temperature transitions below 600°C.

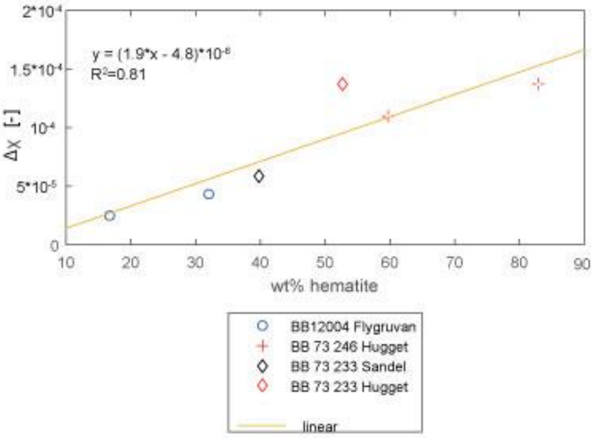

Figure 4. Plotted delta mass susceptibility at high temperature for hematite (680 °C) transition. Samples are colour coded for drill core and ore body designation. Linear relation between wt% and Néel temperature transitions between 600°C and 700°C.

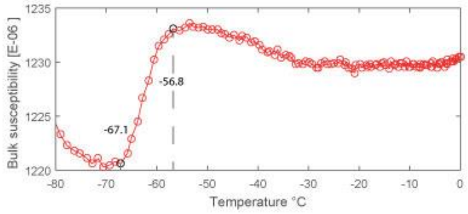

Figure 5. Close-up on supressed Morin transition in one of a high grade hematite ore samples at Blötberget.

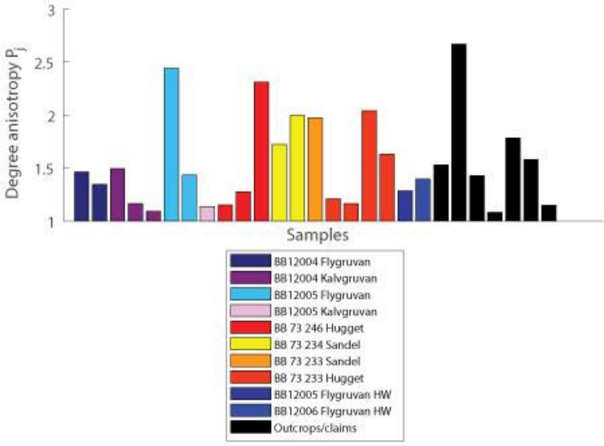

Figure 6. Measured degree of anisotropy (P_j) for samples, colour themed for drill hole and ore body locality or outcrops/claims.

The 7400-S Series vibrating sample magnetometer (Lake Shore Cryotronics) was used for measuring the micromagnetic properties (Table 1). Similarly to the MFK the VSM work at room temperature. Fields of up to 1436 kA/m (1.8 T) were used to determine magnetic saturation (M_s). To determine the coercivity of remanence (H_{cr}), an initial 1197 kA/m (1.5 T) field was applied in one direction, and afterwards the resulting magnetisation was progressively removed by applying increasing reversed fields.

For high fields saturation magnetisation (M_s) and coercity (H_c) follows a non-linear behaviour i.e. a hysteresis loop. Magnetic granulometry of a subset of samples inferred from a Day Plot (e.g. Day et al 1977, Dunlop 2002), which shows the magnetic squareness (M_{rs}/M_s) and magnetic hardness (H_{cr}/H_c), reveals that the magnetic properties of the Blötberget samples (Fig. 7) originates from grains with multidomain behaviour i.e. soft when aligning with external fields). Hematite content only clearly affects saturation capability for one sample with 83 wt% hematite and with 4 wt% magnetite.

Table 1. Hysteresis properties of samples from Blötberget ordered by their weight percentage in magnetite. In grey wt% magnetite derived using linear relationships from temperature dependent susceptibility measurements (see left column, Fig. 2 and Fig. 4).

wt% magnetite	weight [g]	Mrs [emu]	Ms [emu]	Hcr [G]	Hc [G]
3.9	0.1949	0.04	0.59	387.35	82.30
6.9	0.2632	0.07	3.32	109.92	11.79
13.8	0.1595	0.02	0.43	407.86	35.62
22.5	0.2694	0.27	1.79	no value	23.00
25.5	0.0868	0.02	1.20	168.24	5.12
26.3	0.2133	0.04	2.89	403.42	10.40
26.6	0.1362	0.06	5.14	322.63	6.16
30.5	0.1309	0.06	4.25	126.80	6.85
32.5	0.1470	0.10	7.28	101.60	7.24
42	0.1464	0.09	6.28	102.36	7.64
43.0	0.1998	0.15	9.23	118.02	8.79
63	0.1196	0.11	6.25	132.65	10.89
63.2	0.2872	0.18	22.56	329.97	1.85
64.5	0.2145	0.10	13.39	no value	1.32
65.2	0.1626	0.12	11.90	215.60	6.56
77.4	0.3558	0.35	28.37	187.22	9.56
81.4	0.1786	0.15	8.99	128.19	8.83
98.9	0.1240	0.08	10.79	280.67	3.97

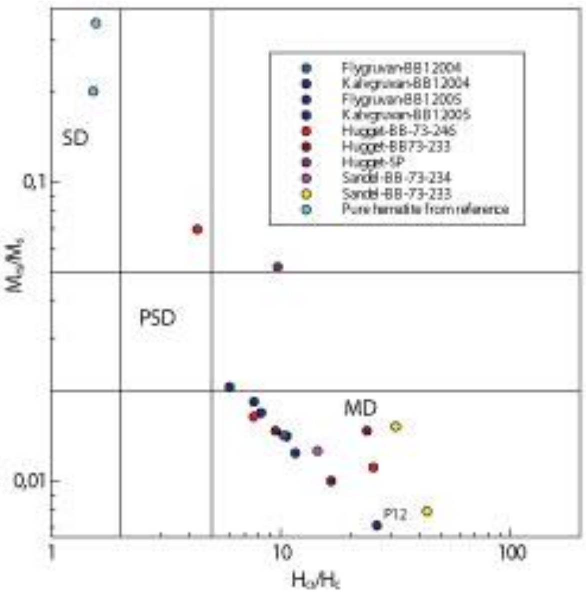

Figure 7. Magnetic hysteresis properties as function of wt% magnetite and locality. Day Plot in log scale with H_{cr}/H_c versus M_{rs}/M_s. Abbreviations SD 'Single domain', PSD 'Pseudo single domain' and MD 'Multidomain'.

CONCLUSIONS

This study has focused on developing a methodology for laboratory magnetic measurements on natural samples to separate and characterise magnetite and hematite in iron-ore. The main results show that high temperature magnetic measurements combined with mineralogy data can quantify both ore types. Furthermore low temperature and magnetic anisotropy measurements can characterise samples with properties that can be related back and specifically targeted for further studies by other geoscientific methods.

The high temperature measurements have shown that the magnetite is close to pure. The Curie temperatures have a narrow Gaussian distribution. In this study the hematite shows a wider temperature span for Néel temperatures than the magnetite Curie temperatures. Low temperature measurements suggest that the Morin transition is lowered to -60 °C or been moved below detection level. Possible explanations for this include: a) There are impurities in the hematite, likely Ti 0.005 mole% or more. b) It is an effect of the formation of martite. c) There is an absence of Fe(III), or replacement of the same by Fe(II).

In this study 3x3x3 millimetre cubic samples were used to measure the degree of anisotropy in iron ore. For Blötberget samples, the P_j parameter can be used to separate out high grade and/or foliated hematite-rich ore.

For the majority of the samples the micromagnetic properties show low coercivity and high saturation magnetisation. This was illustrated by the Day Plot where hematite-dominated samples plot in between pure hematite and magnetite dominated samples. Deviation from a linear trend in the MD-domain for saturation levels are relatable to hematite content.

OUTLOOK

The results from this study is part of developing a research method to link sample characteristics with ore mineralogy.

It yet needs to be proven that linearities, such as those in this study, can be effectively used for estimation of wt% in new samples.

It is also unknown if the lowered Morin temperature occurs in hematite ore at other deposits, and whether such information can provide useful exploration insights.

It is suggested in this study that the high degree of anisotropy for Blötberget samples are linked hematite content and strong foliation within hematite-rich samples. The contribution of anisotropy from crystalline or foliation has not been characterised.

The Day plot diagram was developed for magnetite samples. Can hematite ore be characterised effectively? Measured magnetite-rich samples from Blötberget have multidomain characteristics in remanence, saturation and coercivity. Can these properties be quantified and better linked with grains size, texture and wt% of hematite or magnetite?

There is great potential to distinguish hematite from magnetite and relate it to mineralogy. Most relevant to industry, there is the potential to use the method in iron ore mining for quality control and analysis, to select of high grade magnetite ore with the right properties.

ACKNOWLEDGMENTS

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