Electrical Properties of Magnetite- and Hematite-Rich Rocks and Ores

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SUMMARY

Magnetite and hematite are common iron-oxides, being found in sedimentary, metamorphic and igneous environments and being associated with a wide variety of deposits styles, including orogenic gold, iron-oxide copper-gold and iron-ore deposits. While the magnetic and mass properties of magnetite and hematite have been comprehensively studied, there is relatively limited published information on their electrical properties, although anecdotally, it would appear that many geophysicists have encountered the situation in which their 'highly prospective' EM or IP anomaly has turned out to be the result of barren magnetite, and/or hematite.

In 1994, Emerson and Yang extensively studied the electrical properties of magnetite-rich rocks as part of AMIRA project P416. Eight sponsor companies contributed a variety of samples for laboratory measurements of mass, magnetic, galvanic electrical, electromagnetic and induced polarisation properties. A petrological study was also carried out. The electrical properties of hematite have been similarly investigated on behalf of individual companies.

This work has demonstrated that sulphide-free, magnetite- and/or hematite-rich rocks can be moderate to good conductors and also exhibit a measurable IP response. And in some cases, electrical anisotropy may be significant. The electrical behaviour of magnetite and hematite is related to factors such as quantity, grain size and texture and their electrical response can be considerably enhanced by relatively small amounts of sulphides, such as chalcopyrite. Field examples are presented confirming laboratory observations.

Key words: Anisotropy, chargeability, conductivity, hematite, magnetite.

INTRODUCTION

Magnetite and hematite are common iron-oxides, being found in sedimentary, metamorphic and igneous environments and being associated with a wide variety of deposits styles, including orogenic gold, iron-oxide copper-gold and iron-ore deposits. While the magnetic and mass properties of magnetite and hematite have been comprehensively studied, there is relatively limited published information on their electrical properties, although anecdotally, it would appear many geophysicists have encountered the situation in which their 'highly prospective' EM or IP anomaly has turned out to be the result of barren magnetite, and/or hematite.

Magnetite and hematite have been variously described by Carmichael (1989), Ineson (1989) and Shuey (1975), among others. The conductive and chargeable nature of certain types of hematite in iron-oxide copper-gold deposits was discussed by Vella and Emerson (2009) (Carrapateena), Hart and Freeman (2003) (Prominent Hill) and Esdale *et. al.* (2003) (Olympic Dam).

Nelson and Van Voorhis (1983), in a field study using small electrode spacings, measured the IP effects of disseminated magnetite, finding magnetite is not as electrochemically responsive as the common sulphides and graphite. Vanhala and Peltoniemi (1992), in a spectral IP field study, showed magnetite tended to have a lower, but still finite, IP response than sulphides. Malmqvist, in a field study of a small, low grade, titaniferous magnetite deposit, observed a correlation between IP (phase) and magnetic response. Pittard and Bourne (2007) discussed the contribution of magnetite to the observed IP response of the Centenary orebody. And Vella (1995) observed weakly conductive responses from magnetite in unmineralised banded iron formations.

In 1994, Emerson and Yang extensively studied the electrical properties of magnetite-rich rocks as part of AMIRA project P416. The theory and techniques which formed the foundation of this work were derived from an earlier AMIRA project P369 and have been described by Yang and Emerson (1997). The electrical properties of hematite have been similarly investigated on behalf of individual companies.

This work has demonstrated that sulphide-free, magnetite- and/or hematite-rich rocks can be moderate to good conductors and also exhibit a measurable IP response. And in some cases, electrical anisotropy may be significant. Factors controlling the electrical behaviour of magnetite and hematite will be discussed and field examples presented, which confirm laboratory observations.

CHARACTERISTICS OF MAGNETITE AND HEMATITE

Iron-oxides can be classified according to three main solid solution series: the titanomagnetite series (ulvospinel–magnetite), the ilmenohematite (ilmentite–hematite) series and the pseudobrookite series (Figure 1) (Carmichael, 1989).

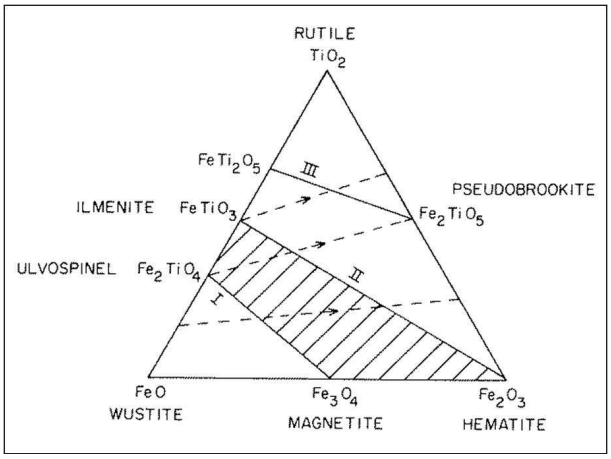

Figure 1. Iron-oxides shown on a ternary diagram of FeO-TiO_2-Fe_2O_3. Dashed lines represent the direction of oxidation (from Carmichael, 1989).

The key characteristics of magnetite and hematite are summarised in Table 1. The values cited in this table are based the authors' experience and should be considered indicative, rather than definitive.

Characteristic	Magnetite	Hematite
Nature	Black, ferrimagnetic metal. Usually titaniferous.	Red to steel-grey to black, antiferromagnetic semi-conductor.
Crystal System and Habit	Cubic. Octohedral and dodecahedral crystals. Also massive, banded or disseminated.	Hexagonal. Thin or thick tabular crystals. 4 types: specular, black steely micro-mosaic, foliated and amorphous red-brown earthy.
Density	5.18 g/cc	5.26 g/cc
Magnetic Susceptibility	10+ SI	~125 x 10^{-5} SI
Conductivity	10,000 S/m (intrinsic crystal conductivity rarely attained in rocks). 10 to 1,000 S/m more commonly observed.	Specular ~10 S/m. Black steely micro-mosaic ≤ 0.1 S/m. Foliated – slightly conductive, but very anisotropic. Red-brown earthy – insulator when dry. A finite resistivity when saturated.
IP Effect	Moderate to strong IP.	Specular - moderate IP. Black steely micro-mosaic – low IP. Red-brown earthy – no IP.

Table 1. Select characteristics of magnetite and hematite.

Four distinct types of hematite have been observed. The textural properties of hematite strongly influence its conductivity and chargeability response. In the case of the foliated hematites, this group can be further divided into two sub-types: micro-platy hematite-martite and micaceous hematite. Based on top grade hematite samples from Brazil, micro-platy hematite-martite, although resistive, does have some capacitive conductivity as frequency increases, in the dry state. In the saturated state, generally being very porous, it will conduct through the pore fluid. The electrical properties of micaceous hematite are not well understood and investigations are continuing.

LABORATORY MEASUREMENTS

Magnetite – AMIRA P416

The following analysis is taken from Emerson and Yang (1994). As part of the AMIRA Project P416, eight companies provided a total of 122 rock samples for laboratory measurements of mass, magnetic, galvanic electrical, electromagnetic and induced polarisation properties. Dr J. Barron carried out a complementary petrological study on 75 of the samples. The aim of the project was to investigate the low frequency electrical characteristics of the samples. The mass, magnetic and petrological work will not be discussed further here.

The rock suites largely comprised iron-rich meta-igneous and meta-sedimentary rocks, some of which had been metamorphosed to quite a high grade and many of which were banded. Magnetites within these rocks displayed varying habits and grain sizes. Most were recrystallised and metamorphic. Of the 122 samples, 21 could be considered significantly sulphidic (chalcopyrite and/or pyrite). Pyrrhotite and hematite were also observed in some samples.

The galvanic and EM conductivities of the barren magnetite samples are shown in Figures 2 and 3, respectively, compared with the inferred volume percentage of magnetite. Despite the variation in conductivities of certain magnetite concentrations, there is a definite trend towards increasing conductivity with increasing percentage of magnetite. This can be seen more clearly from the galvanic data than the EM data, as the measurement range of the galvanic data was larger. Generally, the conductivity increases slowly from background values, for magnetite volumes less than 40%, and then rapidly increases approaching the effective conductivity for magnetite (up to 1,000 S/m), when the volume percentage exceeds 80 or 90%. In the field, EM systems operate at lower than laboratory frequencies, recording lower conductivities and therefore, can respond to concentrations of magnetite less than 40%.

Magnetite tends to occur as euhedral or subhedral crystals, interstitially or as islands in a sea of insulating rock matrix silicates. In massive form, magnetite still tends to be irregularly distributed. Even when magnetite dominates the volume of a rock, imperfect grain boundary suturing and insulating rims can reduce conductivity, as does micro-fracturing. Magnetite, of magmatic origin, frequently contains exsolution lamellae of ilmentite, which can impede its conductivity. Occasionally, magnetite may exhibit a bladed crystal habit, which would favour an anisotropic conductivity higher than magnetite's normal euhedral/subhedral occurrence. Increasing tectonism and magnetite grain size can result in increasing conductivity (EM and galvanic), by providing better grain-to-grain contact external to grains and by better intra-grain conduction for a volume of imperfectly insulated grains (Figure 4).

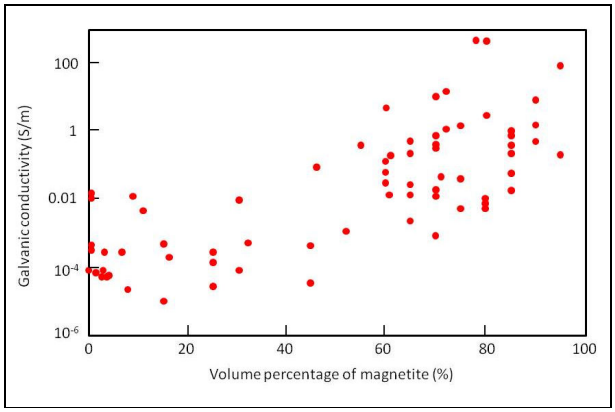

Figure 2. Cross plot of measured galvanic conductivities of barren, magnetite-bearing samples, versus inferred volume percentage of magnetite (from Emerson and Yang, 1994).

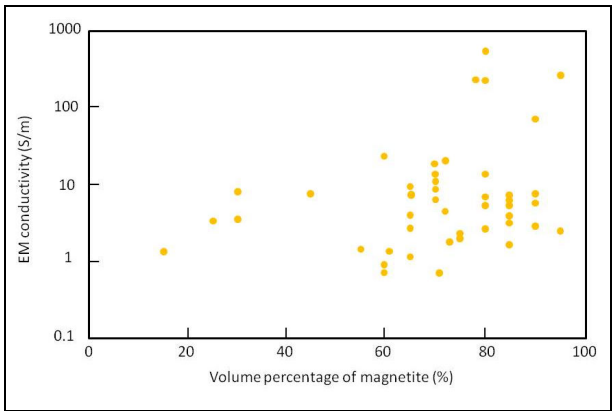

Figure 3. Cross plot of measured EM conductivities of barren, magnetite-bearing samples, versus inferred volume percentage of magnetite (from Emerson and Yang, 1994).

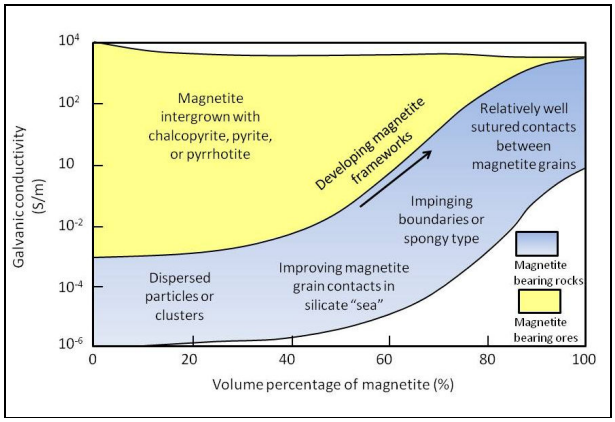

Figure 4. A schematic illustration of galvanic conductivity, against volume percentage of magnetite, as a function of microstructure (from Emerson and Yang, 1994).

On the other hand, compositional banding, as may be observed in iron formations, can impede the establishment of a well-connected network of magnetite grains, therefore reducing conductivity.

Other cubic minerals, such as pyrite and galena, can exhibit similar effects to magnetite. However, tetragonal chalcopyrite and monoclinic/hexagonal pyrrhotite tend to be anhedral and pervasive in texture, with relatively small amounts required to enhance rock conductivity (Figure 4).

Measurements of IP effect showed that magnetite can exhibit a good response in the absence of other polarisable minerals and that this effect increases with an increasing content of magnetite in the rock, although more work is required here.

Magnetite – Hill 50

In 1995, measurements of galvanic and EM conductivity were undertaken on mineralised and unmineralised BIF samples from four separate deposits/prospects, at the Hill 50 Gold Mine, Western Australia. The unmineralised BIF samples exhibited moderate background conductivities of approximately 2 S/m. Significant electrical anisotropy was observed with conductivities being greatest parallel to foliation. Thin section petrography revealed inefficient grain boundary contacts between the magnetites, explaining why the observed conductivities were not higher. Similarly, pyrite mineralised BIFs exhibited modest conductivities, while pyrrhotite, even in small amounts, significantly enhanced the conductivity of the rocks. For more detail the reader is referred to Vella (1995).

Hematite – Carrapateena and Prominent Hill

Laboratory physical property measurements on drill core samples from Carrapateena showed examples of barren (specular) hematite breccias exhibiting an IP effect comparable to their sulphide mineralised counterparts (Vella and Emerson, 2009).

Similarly, laboratory measurements carried out on hematite breccias from Prominent Hill demonstrated that barren samples and mineralised samples are almost indistinguishable on the basis of their density, magnetic susceptibility, conductivity, or chargeability (Hart and Freeman, 2003).

FACTORS CONTROLLING ELECTRICAL BEHAVIOUR

Factors controlling the electrical behaviour of magnetite and hematite are summarised below.

Conductivity of Magnetite and Hematite

- Volume percentage of magnetite/hematite and its distribution (pervasive, patchy or layered, interstitial or matrix, islands etc,);
- Crystal system, grain shape, grain size and grain size distribution;
- Grain style (unbroken/spongy, granular/irregular);
- Grain boundaries (sharp/jagged, rimmed by insulators, inclusions present, well/poorly sutured), defects or inclusions and grain connectivity;
- Development of silicates/carbonates in the rock, and
- Foliation (textural heterogeneity and compositional layering, either relict or intact).

Chargeability of Magnetite and Hematite

- Volume percentage of magnetite/hematite. If very massive, grain to grain current will increase and IP effect will decrease;
- Grain size (smaller grain size, larger IP effect), and

- Rock matrix resistivity, porosity, water saturation and resistivity, and texture and foliation.

FIELD EXAMPLES

Magnetite at Tennant Creek

Airborne EM surveying of a Au-Cu prospect at Tennant Creek showed an anomalous response, coincident with a strong magnetic high (Figure 5). Drilling intersected thick sequences of magnetite and hematite alteration, but no significant mineralisation. Down hole EM surveying revealed an in-hole anomaly, associated with the barren ironstone, providing evidence of the contribution of iron oxides to the observed conductivity response.

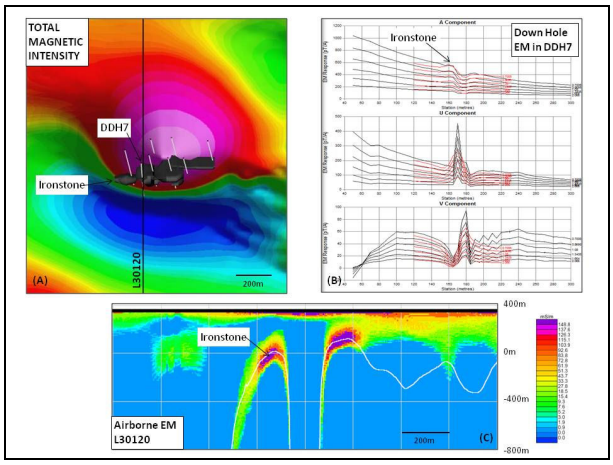

Figure 5. Geophysical responses of a barren ironstone at Tennant Creek. (A) Total Magnetic Intensity. (B) Down hole EM. Black profiles are observed data and red profiles are modelled data (assuming a 200m x 20m, flat-lying plate, of 220S). (C) AEM Conductivity Depth Image.

Magnetite at Centenary

Pittard and Bourne (2007) investigated the contribution of magnetite to the observed IP response over the Centenary gold deposit, Western Australia. Modelling showed the chargeability anomaly to be broader than and displaced from the mineralisation. This was corroborated by down hole IP/resistivity data, suggesting pyrite was not the only contributor to the IP response. Petrophysical measurements and thin section work confirmed that unmineralised, magnetite-bearing samples are chargeable and it is likely that magnetite is contributing to the observed IP anomaly.

Hematite and Magnetite at Prominent Hill

At Prominent Hill, Hart and Freeman (2003) describe drilling a strong phase anomaly, coincident with a gravity anomaly, in the expectation of finding high grade copper mineralisation. Instead, massive, barren hematite was intersected. Down hole IP/resistivity logging and laboratory measurements confirmed the hematite is chargeable and conductive.

CONCLUSIONS

Laboratory physical property measurements and field surveys have demonstrated that sulphide-free, magnetite- and/or hematite-rich rocks can be moderate to good conductors and also exhibit a measurable IP response. And in some cases, electrical anisotropy may be significant. Therefore, care should be taken when interpreting electrical surveys carried out in geological environments containing significant amounts of iron oxides.

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