Magnetic characterisation of the Osborne IOCG: magnetic fabrics, self-demagnetisation, and remanence: Cloncurry District, QLD

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SUMMARY

Integrated petrophysics linked with structural geology and mineralogy are powerful tools for mineral system characterisation. In this study, open-pit samples and drill core from the Osborne IOCG deposit were measured for anisotropy of magnetic susceptibility (AMS) and remanence. This study focused on the relationships between petrophysical properties and the high amplitude magnetic anomaly of the deposit.

The magnetite-rich “iron formation” typically has high density and magnetic susceptibility, which show a near-linear relationship related to magnetite content ($R^2=0.77$). Samples are magnetically anisotropic, with P-factors ranging from 1.1 to 1.4 and define a NNW-SSE-oriented magnetic foliation. However, the K1 (i.e. the maximum susceptibility) principal component of the AMS ellipsoid is close to horizontal, and therefore does not add to the vertical component of the magnetic field or contribute significantly to the TMI anomaly over the deposit. Koenigsberger ratios (Q) are commonly <0.5. Some Q-values above 2 are observed in mineralisation. However, there is no monoclinic pyrrhotite, and the elevated Q-ratio is instead a result of the very low magnetic susceptibilities, and more likely associated with pseudo-single-domain magnetite.

Remanence is subordinate to magnetic susceptibility at Osborne because multidomain magnetite grains are the main carrier. Therefore, remanence does not contribute significantly to the total magnetisation of the deposit. Statistical linear relationships between density and magnetic susceptibility break down at high K-values of 1.5 ≥ SI. This suggests that neither the AMS fabric nor remanence is the cause of the mismatch between the location of the orebody and the TMI magnetic anomaly, which subsequently made the initial drill siting difficult. Instead, it is related to the self-demagnetisation effect and local modification of the magnetic field, which are both due to the extreme magnetic susceptibilities observed.

Key words: Osborne deposit, magnetic susceptibility, remanence, anisotropy of magnetic susceptibility, self-demagnetisation.

INTRODUCTION

Industry is increasingly aware that the local magnetic field can be modified by strong remanence (often originating from small magnetite grains), but other factors (e.g. magnetic anisotropy and demagnetisation) which cause a similar distortion of the magnetic field are less well understood. Lab techniques by liquid nitrogen treatment are used to discriminate between the soft (viscous) and the hard (true) remanence. Similarly, measurement of properties of magnetic fabric, using anisotropy of magnetic susceptibility, can provide important constraint to magnetic field analysis and modelling. The Osborne deposit is an excellent example where both factors could be used to explain a mismatch between the orebody location and the TMI magnetic anomaly.

Copper and gold mineralisation at Osborne is hosted by two NE-dipping quartz-magnetite ironstone units, within a sequence of mostly psammitic metasediments and minor mafic and felsic igneous rocks. The Proterozoic rocks are covered by 20-40 m of Mesozoic sediments (Clark, 2000). The Osborne deposit (previously known as Trough Tank prospect) was defined by aeromagnetic data in 1974, but the area was abandoned after the drilling only revealed quartz-magnetite ironstones. A renewed interest following discovery of the Starra deposit and revised modelling lead to the Osborne discovery in 1988 (Gidley, 1988; Anderson and Logan, 1992). Clark (1988) outlined that Osborne, with its high magnetic susceptibility and sheet-like geometry, is subject to strong self-demagnetisation. Clark did not include remanence in his models as the available samples only had minor contributions thereof. Ellis et al. (2012) included remanence in their inversions to correct the model to known mineralisation and in the hopes to delineate a possible continuation of the ore body at depth. Both these solutions can estimate ore tonnage but are hard to reconcile with structural geology or insights from geochemical data.

Some insights to links between petrophysics, geochemistry, and mineralogy were provided by the Uncover Cloncurry Project (Gazley et al. 2016). However, few of the samples had been orientated and were only indicative of paleomagnetic and AMS studies. This study is part of the follow-up; the Cloncurry METAL project, which undertook new fieldwork at Osborne in late 2018. More than 50 fully orientated samples from surface outcrop and blocks in and around the pit were collected for analysis. Petrophysical measurements were completed during the first half of 2020 and compiled into an integrated sample database along with 44 samples collected in 2015 from two drill holes (OSHQ0067 and TTNQ364).

Without constraints, any magnetic modelling studies will be subject to considerable error due to incorrect assumptions of remanence, self-demagnetisation, and anisotropy of magnetic susceptibility effects. This study explores the relationships between measured density, magnetic susceptibility, remanence, anisotropic magnetic susceptibility, and derived parameters thereof. The data is investigated further using assayed mineralogy counting (TIMA; spectral and algorithm identified surface % mineralogy). Geological metadata, i.e., interpretations of structural zonation textures (sample logging) is also used.

METHODS

The fieldwork sampling scheme selected a representative set of samples. The Osborne samples are categorised as follows: barren ironstone, medial footprint, proximal fottprint, and mineralisation.

Density measurements were carried out using a Mettler Toledo MS204TS analytical balance and the Archimedes principle. Magnetic bulk susceptibility was measured using an Agico MFK1-A Kappabridge magnetometer. The magnetic susceptibility and remanent magnetisation results are corrected for volume variations (from the 10 cm^3 sample cylinder standard), using the density measurements' volume determinations.

In addition to bulk measurements, vector measurements were undertaken, which required oriented samples. Samples were oriented using a sun-compass in the field. Three subsamples for each sample were measured for Anisotropy of Magnetic Susceptibility (AMS) using an Agico MFK1-A Kappabridge magnetometer. The AMS data were analysed using Anisoft (version 5.1.08) software (AGICO, 2020), which describes the AMS ellipsoid using a variety of well-known shape parameters based on Jelenik (1981), including degree of anisotropy or anisotropy factor (P), shape factor (T) defining to which extent the rock has lineation ($-1>T>0$) or rock foliation ($0>T>1$), and the orientations of these magnetic fabrics.

Measurements of natural remanent magnetisation (NRM) were carried out for all samples referenced to the orientation data. At least one subsample of each was subsequently exposed to low-temperature demagnetisation using liquid nitrogen (LN2). All measurements of NRM and LN2 were undertaken using an Agico JR-6 Spinner Magnetometer, and the resulting data was analysed with the Rema6 (version 6.3.01) software (AGICO, 2020).

Table 1. Mean values: density and magnetic susceptibility. Count is the minimum number of data points used to retrieve entries in the respective column.

Zonation context	barren ironstone	medial	mineralisation	proximal
Count	20	5	21	37
Density Mean	3.9	2.7	3.5	2.7
Density Median	4.0	2.7	3.2	2.7
Density Max	4.9	2.8	4.7	3.2
Susc Mean	1.6	0.0	0.9	0.1
Susc Median	1.9	0.0	0.2	0.0
Susc Max	2.2	0.1	2.1	0.7

RESULTS

This study provides an expanded petrophysical dataset with statistically validified trends between density and magnetic susceptibility. Osborne typically has high density and magnetic susceptibility (Table 1). In addition, magnetic susceptibility versus magnetite content show a near linear relationship for all samples combined ($R^2=0.77$).

Categorising data by system zonation context, i.e., filtering by geological interpretation of proximity, is depicted in Figure 2. The mineralisation samples are less prone to demagnetisation effects and fit statistically very well (R2 = 0.9) to a straight line. Magnetite-rich and host rock fits poorly and high K-values (barren ironstone) of ≥ 1.5 SI, pull the line down, i.e., indicating demagnetisation effect at the microscale.

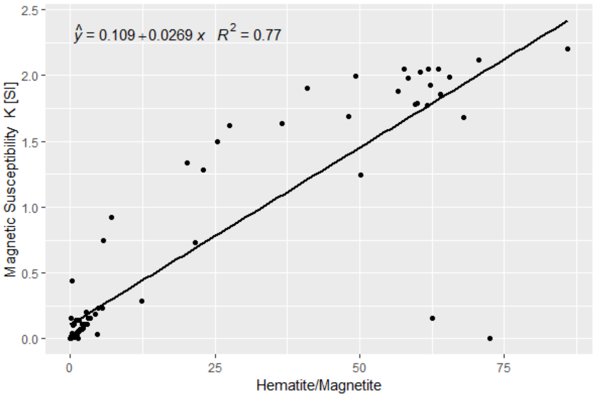

Figure 1. Plot of the density versus % hematite/magnetite from TIMA mineralogy for Osborne samples. Linear relationship and R-value.

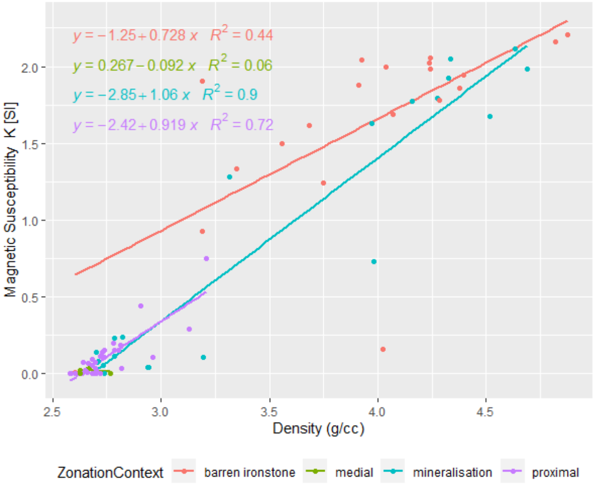

Figure 2. Plot of the density versus magnetic susceptibility with linear relationships and R values for the Osborne samples. Colour coding by the system zonation context.

The data was broken down into system zonation context, with the mean, median, and maximum for remanence calculated (Table 2). The data show high remanence in the barren ironstone and a stepwise decrease in mineralisation, proximal and medial. As indicated by Austin et al (2017), the Koenigsberger values (Q-ratios) are low for Osborne when compared with other IOCGs

Treatment with liquid nitrogen resulted in lower means for NRM by one order of magnitude regardless of lithological zonation. In Figure 3, 4, and 5, the relationships between remanence (NRM), remanence post liquid nitrogen treatment (LN2), density, and magnetic susceptibility are plotted for all samples. Point size has been used to visualise Pyrrhotite content and system zonation context by colour coding. In Figure 5, another colour scheme is used for Q-ratio cut-offs of 1, 10, and 100.

Table 2. Mean values: remanence (pre- and post- liquid nitrogen (LN2) treatment). Count is the minimum number of datapoints used to retrieve entries in the respective column.

Zonation context	barren ironstone	medial	mineralisation	proximal
Count	18	5	21	37
NRM Mean	34.6	0.3	23.6	2.0
NRM Mean (LN2)	7.2	0.1	6.2	0.6
NRM Median	25.9	0.3	1.8	0.2
NRM Median (LN2)	6.1	0.2	0.4	0.0
NRM Max	125.5	0.6	97.7	37.9
NRM Max (LN2)	19.2	0.2	26.5	8.7
Qratio Mean	0.5	0.4	0.4	1.3
Qratio Median	0.5	0.2	0.3	0.2
Qratio Max	1.5	0.8	1.2	14.5

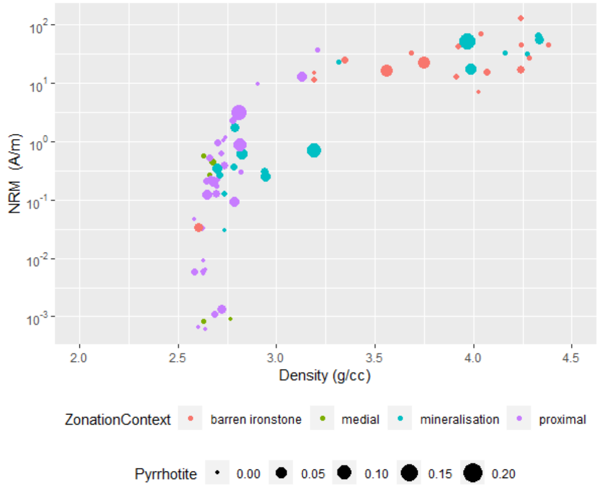

Figure 3. Density vs. NRM (J). Colour coding by the system zonation context. Pyrrhotite % from TIMA.

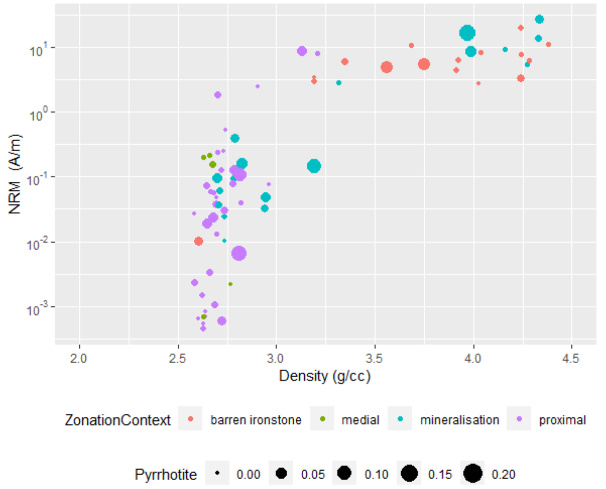

Figure 4. Density vs. NRM (J) after liquid nitrogen treatment. Colour coding by the system zonation context. Pyrrhotite % from TIMA.

As can be seen in Figure 5, Koenigsberger ratios (Q) are commonly < 0.5. Few samples have Q-ratios of more than 1. Those with Q-ratios above 2 are observed in the mineralized intermediary ironstone. There are only two samples with Q-ratios > 10, both in the intermediary ironstone and proximal to the ore.

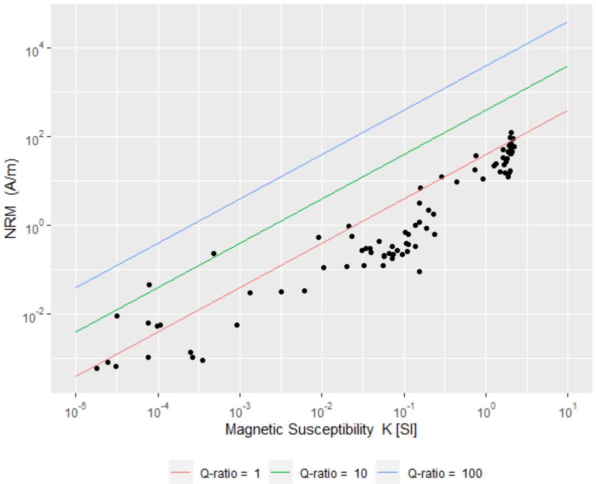

Figure 5. Magnetic Susceptibility (K) vs. NRM (J). In colour code cut-offs for Q-ratios of 1, 10, and 100.

The majority of the Osborne samples have moderate anisotropy with P-factors between 1.1 and 1.4 (Figure 6). Samples with low magnetic susceptibility show T-values with distribution (0>T>1). Samples with magnetic susceptibility K > 1 [SI] (Figure 7) show P < 1.3. A few samples show strong P>1.4, have low susceptibility, and strong foliated fabric, T>0.4. Samples with P-factors ranging including those ranging 1.1 to 1.4 define a NNW-SSE oriented magnetic foliation (Figure 8).

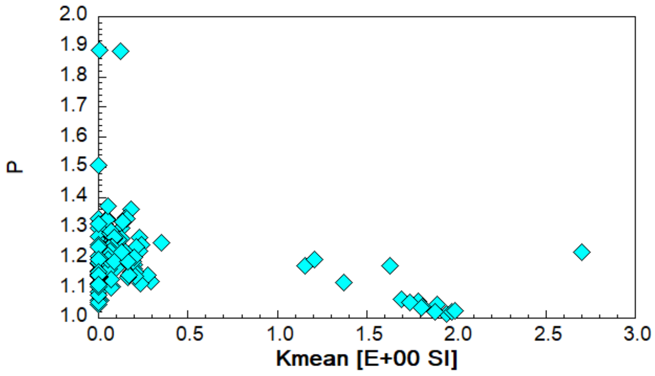

Figure 6. Mean magnetic susceptibility vs. P-factor

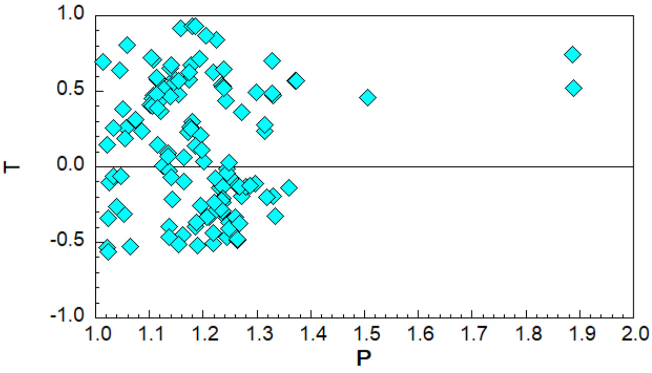

Figure 7. T-value vs. P-factor

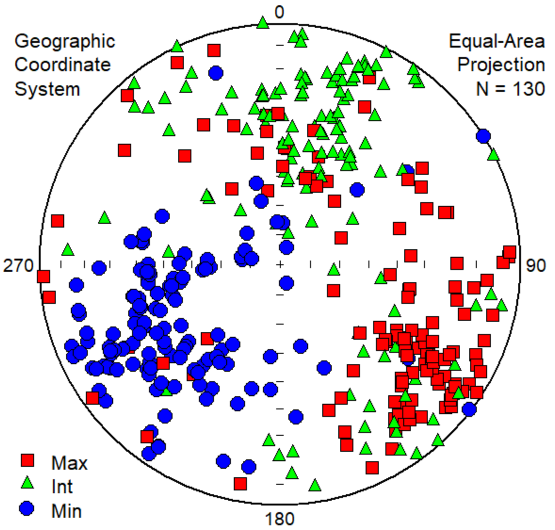

Figure 8. AMS data for Osborne on an equal area stereonet. Orientated AMS data from 130 subsamples from and drill core. Colour coding displaying Kmax, Kint, Kmin vectors.

CONCLUSIONS

The magnetic susceptibility at Osborne increases sharply with its magnetite content, but this increase slows down at higher magnetite grade due to demagnetisation effects. The TIMA data does not discriminate between hematite and magnetite, and the exact mix between these minerals has not yet been tested. However, visual inspection suggests that magnetite is predominant, which is consistent with the very high magnetic susceptibilities (between 1 to 2 [SI]), within the Osborne deposit Furthermore, remanence increases linearly with magnetic susceptibility indicating that magnetite is the main carrier.

When treated with liquid nitrogen, remanent magnetisation decreases, indicating that the majority of magnetisation originates from multidomain grains, i.e., soft/viscous. The Osborne magnetisation is predominant induced as indicated by Koenigsberger ratios (Q-values) < 1, especially those with high magnetic susceptibility. A handful of samples show high P-factor in the AMS measurements. Still, these are low in magnetic susceptibility, and the mesoscale effects thereof are overshadowed by higher susceptibility lithologies (i.e., ironstones).

Samples are magnetically anisotropic, with most P-factors ranging from 1.1 to 1.4, defining a NNW-SSE oriented magnetic foliation. However, the K1 (i.e. the maximum susceptibility) principal component of the AMS ellipsoid is close to horizontal, and therefore does not add to the vertical component of the magnetic field or contribute significantly to the TMI anomaly over the deposit.

We are therefore forced to conclude that neither remanence (cf Ellis et al, 2012), nor magnetic anisotropy are significant in the Osborne deposit, but that self-demagnetisation is substantial (e.g., Gidley, 1988; Clark, 2000). These conclusions are consistent with those from the Candelaria IOCG in Chile (Austin et al., 2014) and from the nearby Brumby IOCG (Austin et al., 2013)

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REFERENCES

Advanced geoscience instruments company (AGICO), 2020, viewed 29 March 2021, https://www.agico.com/software.php

Anderson C.G. and Logan K.J.,1992, The history and current status of geophysical exploration at the Osborne Cu & Au deposit, Mt. Isa, Exploration Geophysics, 23:1-2, 1-7, DOI: 10.1071/EG992001

Austin, J. R., Schmidt, P. W. and Foss, C. A., 2013. Magnetic Modeling of Iron Oxide Copper-Gold Mineralization constrained by 3-D Multi-scale Integration of Petrophysical and Geochemical data: Cloncurry District, Australia. Interpretation 1, T63-T84.

Austin, J.R., Geuna, S., Hillan, D. and Clark, D., 2014. Remanence, self-demagnetization and their ramifications for magnetic modeling of Iron Oxide Copper-Gold deposits: an example from Candelaria, Chile. Journal of Applied Geophysics 109, 242-255.

Austin, J., Patterson, B., Legras, M., Birchall, R., & Walshe, J., 2017. Geophysical Signatures of IOCG and Sedex style mineralization in the Mount Isa Eastern Succession, Queensland, Australia. Exploration '17 Workshop: "Improving Exploration with Petrophysics: The Application of Magnetic Remanence and Other Rock Physical Properties to Geophysical Targeting, Toronto, Canada.

Clark, D.A., 1988, Magnetic properties and magnetic signatures of the Through Tank and Starra Copper-Gold deposits, eastern Mount Isa block, Restricted Investigation Report 1745R, CSIRO. Amira Project 78/P96B: Applications of Rock Magnetism, 101 pp.

Clark, D.A., 2000, Self-Demagnetisation in Practice: The Osborne Cu-Au Deposit: Australian Society of Exploration Geophysicists 85, 33-38

Ellis, R. G., de Wet, B. and Macleod, I.N. 2012, Inversion of magnetic data for remanent and induced sources: ASEG Extended Abstracts 2012, 1–4.

Gazley, M.F., Patterson, B.O., Austin, J..R, and Godel, B., 2016. Uncover Cloncurry – Background on Techniques and Methods. CSIRO, Australia, pp. 31. https://doi.org/10.4225/08/58582106f07d6

Gidley, P.R., 1988, The Geophysics of the Trough Tank Gold-Copper Prospect: Australian Society of Exploration Geophysicists 19, 76-7

Jelinek, V., 1981, Characterization of the magnetic fabric of rocks. Tectonophysics 79, 63–67