Anisotropy of Magnetic Susceptibility (AMS) and Paleomagnetism applied to the differentiation of structural and metallogenic controls on Iron Oxide Copper-Gold (IOCG) mineralization: a case study from Monakoff, NW Queensland.

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SUMMARY
The temporal and metallogenetic relationships between BIFs and IOCGs in the Mt Isa Block are controversial and difficult to assess quantitatively. In this study we examine new magnetic data, anisotropy of magnetic susceptibility (AMS) and remanent magnetisation to define potential structural controls on mineralisation, and try to determine temporal relationships between a barren hematite-magnetite BIF and a carbonate-hosted IOCG, Monakoff. The results showed that the BIF was magnetically isotropic, but that it had a high remanent component (Q=13). The remanent magnetisation has Dec= 238.4° and Inc= -38.6°, which is offset from the present field and previous data from Cloncurry, so it likely formed during deposition, or early in the deformation history e.g., D1, D2. Conversely, the ore has very low remanent magnetisation (Q=0.2) but significant AMS, oriented Azimuth=225°, Plunge=75°, which is consistent with NE-SW (D3) shortening. 3-D magnetic modelling, constrained by magnetic property data and geophysical enhancements, showed that the BIF horizon formed a tight synform. However, modelling of the ore body showed it to be sub vertical. Based on the recognition that the ore body formed during D3 shortening, we infer that the ore formed in a zone of dilation sub-perpendicular to the shortening direction, rather than in a layer sub-parallel jog. The results suggest that the intersection of NW-oriented, sub-vertical faults with stratiform BIF horizons, adjacent to mafic volcanics are prospective for Monakoff-style IOCGs.

Keywords: Anisotropy of Magnetic Susceptibility, Remanent Magnetisation, BIF, IOCG, Structural Control.

INTRODUCTION
Iron Oxide Copper-Gold (IOCG) deposits have a wide variety of geophysical signatures and properties (Austin and Foss, 2012). The metallogenesis of some stratiform types of IOCGs (e.g., Monakoff, Weatherly Creek) is particularly controversial with some authors proposing a primary syngenetic control via seafloor exhalative processes (e.g., Davidson, 1996, 2002; Hatton and Davidson, 2004) at ca. 1670 Ma. Others suggest that stratiform magnetite formed much later at about 1570 Ma (Duncan et al, 2011) in a number of IOCGs in the Eastern Succession. Iron-rich types of mineralisation appear to have a variety of styles including: Massive Stratiform BIFs; Metasomatic Massive to Banded Iron formations; Hematite-Magnetite fault-fill; Magnetite-hematite replacement deposits

(Davidson, 1996). However, their temporal and metallogenic relationships are controversial and difficult to determine quantitatively.

IOCGs may contain multiple magnetic minerals (e.g., magnetite, pyrrhotite and hematite) which are often thought to be precipitated via multiple metasomatic events and hence might retain different magnetic anisotropies and palaeomagnetic signatures. Magnetic anisotropy and remanent magnetization are not commonly measured in mineral deposits, and hence, their effect on forward modelling mineral deposits such as IOCGs is not well established. However, several studies of IOCGs in the Eastern Succession have shown that remanent magnetisation is commonly minor (Clark, 1988; 1994; Austin et al., in press), and where present is commonly retained in pyrrhotite (Austin et al., in press).

Here we use detailed rock property data and magnetic inversion to try to distinguish between different structural events and their metallogenic control on the formation of an IOCG deposit. The study presents new magnetic susceptibility, anisotropy of susceptibility and remanent magnetization measurements from the Monakoff IOCG, NW Queensland (Fig 1). We also use geophysical filters to refine the architecture of the deposit in its regional context. The magnetic properties of host rocks, ore and adjacent BIF horizons are evaluated, and their relevance to modelling of the deposit, and implications for its genesis, are discussed.

Fig 1: Location map showing geology of the Pumpkin Gully Syncline (PGS) and known mineral prospects on its limbs.
**METHOD AND RESULTS**

**Re-evaluation of structure using new magnetic data**

The new magnetic data (Fig 2), flown by Xstrata Copper, allow a detailed re-evaluation of the structural position of the Monakoff IOCG. Fig 1 shows that a ridge of the highest TMI values overlies the main ore zone, and is oriented slightly oblique to the linear anomalies on each flank. These observations may indicate that processes responsible for precipitation of the ore are distinct from those that formed the flanking linear highs. Geophysical enhancements, including the second vertical derivative (2VD) shown in Fig 3, to map bedding traces and apparent discontinuities, which are inferred to be faults and shears. There does not appear to be much horizontal movement (i.e., it is mostly vertical) on the interpreted faults but apparent shear sense is shown for reference. These NW-oriented features have not been previously recognised, but may represent an important structural control on the localisation of the deposit. The apparent shear sense on the series of faults is dextral, but it switches to sinistral locally in the middle of the ore zone.

![Fig 2: Total Magnetic Intensity (RTP) over Monakoff. The central part of the anomaly corresponds to the highest TMI (~57,800 nT), and is oriented slightly oblique to lower TMI linear anomalies on the flanks.](image)

**Density and Magnetic Susceptibility data**

The rock property data (Table 1) show that the magnetic anomaly over Monakoff is caused primarily by two distinct sources, magnetite BIF and the ore zone, both of which have a mean K of about 0.5 SI. Both units have a linear K: density trend (Fig 3). The magnetite BIF tends to be high susceptibility lower density, whereas the ore horizon tends to have lower K and higher density, probably due to Fe being taken up in Fe-sulphides. A comparison of down-hole magnetic data with geochemical results from Williams et al. (2013) reveals that the higher concentrations in metal coincide with a local low in K. This result is also inferred from Figure 3, which shows that parts of the ore with visible (i.e., enriched) chalcopyrite have similar density, but lower K.

**Table 1: Summary of densities and magnetic properties of host rocks, BIFs and ore within the Monakoff deposit.** K was measured independent of AMS and was not corrected for self-demagnetisation. Q is the ratio of remanent to induced magnetisation. P is the ratio of strongest to weakest K, K1:K2.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density (g/cm³)</th>
<th>Mag Sus K (%K)</th>
<th>Koenigs. Ratio (Q)</th>
<th>Anisotropy (P)</th>
<th>Fabric Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact laminted siltstone</td>
<td>2.81</td>
<td>0.0014</td>
<td>-</td>
<td>1.05</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Altered Toole Creek Volcanics</td>
<td>2.81</td>
<td>0.072</td>
<td>0.20</td>
<td>1.07</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Mt + Chi Altered Metasedimentary</td>
<td>2.96</td>
<td>0.25</td>
<td>0.15</td>
<td>1.35</td>
<td>Foliation/Lineation</td>
</tr>
<tr>
<td>BIF (Qtz-Hem-Mt)</td>
<td>3.19</td>
<td>0.027</td>
<td>12.27</td>
<td>1.02</td>
<td>Isotropic</td>
</tr>
<tr>
<td>BIF (Mt ± Po)</td>
<td>3.36</td>
<td>0.51</td>
<td>0.08</td>
<td>1.48</td>
<td>Lineation/Foliation</td>
</tr>
<tr>
<td>Ore Zone (Mt-Cp)</td>
<td>3.99</td>
<td>0.48</td>
<td>0.16</td>
<td>1.58</td>
<td>Lineation/Foliation</td>
</tr>
</tbody>
</table>

**Fig 3: Second Vertical derivative of TMI. Interpreted faults are shown in black, bedding traces in dashed grey, and the anomaly is traced in red, apparent kinematics shown as sinistral/dextral only, i.e., vertical component ignored.**

**Figure 4: Relationships between magnetic susceptibility and density for host rocks, BIFs and ore of the Monakoff deposit.**

**Anisotropy of Magnetic Susceptibility (AMS)**

The AMS results (Table 1, Figs 5 & 6) identify contrasting properties within the host rocks, BIFs and ore horizon. The host rocks are isotropic, except where they’ve seen significant magnetite alteration. The hematite-magnetite BIF is (surprisingly) isotropic despite its obvious structural foliation. Anisotropy in BIFs is related to layering, so the result can be explained by: A. The hematite-magnetite BIF being a pre-existing (syn-depositional) formation with coarse and/or inhomogeneous banding that is not macroscopically representative of the rock; B. due to a discordant hematite-magnetite fault fill with scrambled magnetic grains; or C. a combination thereof.

Both the Magnetite BIF and ore horizon have significant anisotropy, with mean P (K/K1: Anisotropy Factor) of ~1.5. The orientations of K1 (max intensity) are plotted in Fig 6, and consist of 3 apparent foliations, with the remainder...
corresponding to lineations that sit approximately within the foliation. The majority of results plot as steeply SW dipping NW-oriented foliations with associated steeply SW plunging lineation. The remaining data plot as shallow-dipping NE foliations with associated shallow N-NE plunging lineations. The two datasets are essentially orthogonal to each other. A possible explanation is that the second population is caused by uniaxial prolate grains (SD magnetite or pyrrhotite) which cause an inverse AMS fabric (Rochette et al., 1992). However, in this case, it is probably due to variable overprinting of an earlier fabric. We interpret that the anisotropy is due to SW directed shortening which occurred in conjunction with enrichment/reduction of the BIF, and the formation of the ore. Furthermore, we postulate that the structural dilation that hosts mineralisation was in fact caused by strain partitioning in the series of NE oriented faults, which caused a tensional tear, rather than a layer sub-parallel jog (cf., Davidson, 2002).

Remanent Magnetisation

The results of the palaeomagnetic study (Table 1) provide further evidence that remanence is commonly minor in IOCGs. All the host-rocks, ore and magnetite BIF samples have average Koenigsberger ratios of less than 0.2. The exception is the hematite-magnetite BIF which has an average Q of 13, but which coincides with a relatively low average K. This indicates that the Fe-oxides within this unit are relatively fine-grained, and probably not related to metasomatism which localised ore deposition. The remanent magnetisation has a mean declination of 238.4°, and an inclination of -38.6°, which is significantly offset from the present field, and previous measurements in Cloncurry IOCGs (e.g., Clark 1988,1994; Austin et al., in press), so it likely formed during deposition, or early in the deformation history e.g., D1, D2. The relatively low average Q in the magnetite BIF and ore horizon are consistent with previous studies of IOCGs (Clark 1988, 1994; Austin et al, 2012; Austin et al, in press) and indicate that metasomatic fluids precipitated the magnetite in both units.

![Magnetic Profile (RTP)](image)

**Figure 5:** Cross-section (N-S) through the Monakoff pit showing, magnetic profile, measured density, MagSus and anisotropy of magnetic susceptibility (P), and the location of the open pit.

![Monakoff Open Pit](image)

**Figure 6:** Stereonet showing the orientations of K1 (direction of max K) and planes that define “foliated” fabrics. NB: The easy direction of hematite and pyrrhotite are normal to that in MD magnetite. The results indicate that when the magnetite was precipitated, deformation was normal to a NW foliation, (NE-SW oriented shortening). The lineations (dots) indicate that movement was vertical with minor transpression.

![Stereonet showing paleomagnetic directions for hematite-magnetite BIF horizons to the E and W of Monakoff](image)

**Figure 7:** Stereonet showing paleomagnetic directions for hematite-magnetite BIF horizons to the E and W of Monakoff.

3-D Magnetic Modelling

A 3-D geological model (Fig 8) was constructed using 2VD magnetics to guide surface geometry and rock property measurements to constrain dip. Two main outcomes of the modelling pertain to the structural control on ore localisation:

1. The hematite-magnetite BIF to the east and west of Monakoff was modelled using K=0.03 SI and Q=13 and magnetisation Dec=238°, Inc=38°. The result suggests that the BIF horizon is a tightly folded synform, which is generally consistent with the structural findings of Davidson (2002). The anomaly caused by the northern limb of the fold has a much lower intensity, possibly due to flattening of the magnetisation vector due to folding.

2. The ore zone was modelled using anisotropy of magnetic susceptibility with K1=0.75 SI (mean K x F), Dec=225° and Inc=75°. The ore zone model is (approximately) a lens-shaped body, striking 78° sub-vertical, and it is aligned (unsurprisingly) with the strike of the pit.

The modelling results suggested that the ore body is not stratiform, but that it has formed in a zone of dilation due to SW-oriented shortening, coupled with minor dextral and sinistral transpression along NW-oriented faults.
CONCLUSIONS

The primary quartz-hematite-magnetite BIF is magnetically isotropic suggesting it formed in a low strain environment, e.g., ocean floor, and it appears to have formed pre- to syn-D2, probably syn-depositional. It has very strong remanence (Q = 13) which is typical of syn-depositional BIFs (as opposed to metasomatically altered BIFs).

Secondary Magnetite (± Pyrrhotite) BIF does not retain strong remanent magnetisation (Q<0.2) but does display strong AMS which consists of NW oriented planar fabrics, coupled with SW directed sub-vertical lineations. The AMS results suggest that the magnetite in the BIF and the ore zone formed during NE-SW shortening, which is consistent with D2 (Austin and Blenkinsop, 2010; D2 of Davidson, 2002). The magnetite BIF is likely a reduced zone within the earlier hematite-magnetite BIF horizon formed via metasomatic alteration.

The carbonate hosted ore is texturally different to the BIF horizons and appears to have formed in a zone of dilation during D3 NW-SE shortening. Although it strikes sub-parallel to the hematite-magnetite BIF, its dip is significantly steeper. Its orientation is likely controlled by the D3 deformation, as the dilation vector is directed approximately toward σ3 of D3.

This study shows that AMS studies can be used effectively to discern structural-metallocenetic relationships within complex mineral systems. It provides further support for the theory that IOCG formation involves multiple overprinting events — rather than single discrete events — that concentrate fluid flow in structurally favourable locations. The apparent pre-existence of the hematite-magnetite BIF horizon suggests that the BIF is just one of two or three necessary ingredients for the formation of this type of IOCG.

These results along with previous deposit to regional scale studies (e.g., Austin and Blenkinsop, 2009) suggest that NW-oriented structures are favourable for localising IOCG mineralisation in the Eastern Succession. We infer that structural locations where NW-oriented faults cut hematite-magnetite BIF horizons adjacent to mafic volcanics should be considered prospective for Monakoff-style IOCG deposits.

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