Structural controls of the Ernest Henry IOCG deposit: Insights from integrated structural, geophysical and mineralogical analyses.

SUMMARY

Iron Oxide Copper-Gold deposits (IOCGs) are structurally controlled, and typically display zonation of iron oxides and sulphides, which is potentially related to redox zonation. There are three main factors that determine the location and architecture of an IOCG: 1. fluid pathway(s); 2. trap/host, and; 3. plumbing system (i.e., mechanisms for depressurising the system). Generally, these are loosely referred to as structural controls, but they exercise very different functions within the system. In this study we integrate the results of petrophysical property analyses (including, magnetic susceptibility, remanence, radiometrics and conductivity), structural fabric analyses and TIMA scans that provide information on both mineralogy and texture. The results when placed in an ore-proximal-distal-background framework, allow us to understand the footprint of the system.

The results show that the initial ductile-brittle metasomatic traps (i.e., the NE-trending shear zones) are highly magnetic due to their relatively reduced (magnetite-albite) mineral assemblage and preserve the pre-existing structural fabric. Conversely, the secondary, brittle, trap (i.e., the breccia) is moderately magnetic and weakly oxidised with a magnetite-hematite-pyrite-chalcopyrite mineralogy and has randomised magnetic fabric due to brecciation. The least magnetic, and most oxidised zone of the trap has a quartz-calcite-chlorite-hematite-chalcopyrite mineral assemblage. It overprints the breccia, at the intersection of the trap (NE-trending shear zone(s)) with the fluid pathway (N-S strike-slip fault) and has an N-S sub-horizontal AMS lineation.

The different metasomatic alteration assemblages present at Ernest Henry (i.e., sodic, potassic and calcic alteration) may be related to redox zonation within one event, or represent overprinting of metasomatic episodes. However, the zonation of the system is initially controlled by the pre-existing architecture, a compressive jog within a N-S-trending strike-slip fault. When the trap (the jog) is permeable and/or reactive, the redox gradient lies along the trap, between the fluid pathway and the pressure valves. As conditions become more brittle and the trap becomes impermeable and/or non-reactive, and the system becomes over-pressurised, leading to brecciation at the intersection of the trap with the fluid pathway.

Key words: Redox, Petrophysics, Structural Controls, Geophysical Modelling, IOCG deposit, Cloncurry, Anisotropy of Magnetic Susceptibility (AMS).

INTRODUCTION

Iron Oxide Copper-Gold deposits (IOCGs) are a controversial class of ore deposit, present in the Gawler, the Tennant Creek (cf. Skirrow and Walshe, 2002), and the Cloncurry districts of Australia. IOCGs are structurally controlled and often display zonation of iron oxides and sulphides, and it is postulated that the metasomatic alteration products present (i.e., sodic, potassic and calcic alteration) are related to redox zonation within the mineral system.

In terms of a deposit’s structural context there are three main factors that determine both the location and architecture of an IOCG mineral system. These are: 1. The fluid pathway(s), which bring the fluids into the system (e.g. from the deep crust and/or mantle); 2. The trap, a structural and/or lithological zone of either: relatively high porosity and permeability; relatively rheologically weak or brittle rock (e.g. a fault or shear zone which can be dilated/brecciated during ductile-brittle deformation) or; a zone of highly reactive rock (e.g. carbonates, Fe-oxides and sulphides) which are susceptible to changes in redox; 3. The plumbing system, i.e., the means by which fluids can de-pressurise, escape, and in the process precipitate precious metals. Generally, these are loosely referred to as structural controls, but they exercise very different functions within the system.

GEOLOGICAL BACKGROUND

The Ernest Henry Mine (EHM) is an Iron Oxide Copper-Gold deposit sitting within the Mount Isa Block, 35 km NW of Cloncurry, Queensland, Australia. EHM is commonly thought to be localised within a moderately SE-dipping thrust-jog system, based on a relatively simple lineament interpretation of regional magnetic data (attributed to Valenta, 2000: in Keys, 2008), coupled with geological observations (e.g. Webb and Rowston, 1995), that “the main shear zone foliations and faults at the mine dip moderately SE”. Mark et al., (2006) suggest that “the breccia-hosted orbody plunges down-dip within these fabrics”.

Detailed structural work undertaken by Coward (2001) and Laing (2003) recognised several late brittle faults that strike approximately N-NNW and dip steeply to the E or W. These faults are evident in magnetic data, but seldom discussed by other workers. Coward (2001) suggested that mineralisation was localised at the intersection of the NNW-trending faults with NE-tending shear fabrics, whereas Laing (2003) suggested that the mineralisation was controlled by a 350°-striking (i.e. N-S) sub-vertical fault.
There are numerous models for the emplacement of the breccia which hosts the mineralisation, ranging from structural mechanisms to fluid-over pressuring. Cave et al. (2018) suggest that brecciation resulted from competency contrasts between ductile (incompetent?) metasedimentary rocks and surrounding shear zones with brittle (competent?) volc anics, providing permeable pathways for the subsequent ore-bearing fluids. Conversely, Oliver et al. (2006) suggested that the emplacement of granitic melts into the mid-crust lead to volatile release and fluid overpressure, which may have been the source of mechanical energy for ore genesis and volatile-rich fluids, or at least provided permeable pathways for later ore fluids.

METHODS

220 samples were sampled from 6 separate drill holes which form an approximately N-S transect, from substantially south of the deposit, deep into the hanging wall, through the core of the deposit, and out into the proximal and distal parts of the foot wall. Sampling has been conducted this manner in order to provide insights into the ore-proximal-medial-distal-background footprint of the system. Each sample has been re-drilled into a 2 cm cylinder and cut into 2-4 specimens.

To understand the petrophysical properties of the deposit, each specimen was subjected to numerous analyses, including: measurements of density (using a Mettler-Toledo MS204TS), magnetic susceptibility (using an AGICO MFK1-A), magnetic remanence (using an AGICO JR-6), radiometrics (using a Radiation Solutions RS-332) and conductivity (using a Terraplus KT-20). To provide an understanding of redox within the system analyses of the mineralogy were conducted on one specimen per sample using a Tescan Integrated Mineral Analyser (TIMA). The results were used to provide both textural and alteration context to the petrophysical results. To provide a quantified understanding the structural context of the Ernest Henry IOCG system, anisotropy of magnetic susceptibility (AMS) was measured on 2 specimen from each sample using an MFK1-A magnetometer. The data were integrated with lineament mapping and petrophysically constrained magnetic modelling at the deposit scale.

The resulting data allow us to correlate changes in mineralogy (i.e., alteration signatures) with variability in structural fabrics, and with contrasts in geophysical signatures at the sample scale. Therefore redox zonation can be correlated with structural controls and petrophysical properties. This knowledge can be up-scaled to better understand the 3-D architecture of the deposit, specifically the fluid pathways, the traps and the plumbing system.

We integrate the findings with other geophysical techniques. Simple lineament analysis based on industry standard geophysical filters for potential field data were used to provide a regional structural context (i.e., down-scale from regional context). Petrophysically and structurally constrained 3-D magnetic and gravity modelling were used to place all the results in context (i.e., up-scale results to the deposit scale).

RESULTS

Camp-scale magnetic interpretation

The most striking feature of the TMI map over Ernest Henry are a series of NE-trending magnetic highs, which were the basis (along with structural mapping) for the initial recognition that Ernest Henry is hosted in a thrust zone (e.g. Valenta, 2000).

However, a simple 1st vertical derivative of more recent TMI data provides other interesting clues about the architecture of the system (Figure 1). Locations where magnetised zones are truncated (e.g. either side of the mineralisation) logically are places that physically limit the distribution of magmatic precipitation within the system. Consequently, they are likely to be part of the plumbing system, e.g. pressure release valves. Furthermore, we may deduce additional structures from truncations outside the mineral system to the north and south. At Ernest Henry, several N-NW striking features can be mapped. We postulate that the central structure represents the fluid pathway, or more specifically, it’s relatively late history manifestation in the upper crust. Regional fluid pathways could well be long-lived structures that substantially pre-date the lithologies that host the mineralisation.

![Figure 1. First Vertical derivative of magnetic data over Ernest Henry, with a simple lineament interpretation.](image)

Integrated AMS and Mineralogy mapping

AMS data coupled with textural analysis and mineralogy from TIMA data, demonstrate that the albite-magnetite lithologies (Figure 2a, b) present within the hanging wall shear zone have a strong NE-trending, SE-dipping fabric with a south plunging lineation (Figure 2a). The orientation of the lineation suggests the thrust zones formed a jog across two N-S faults during sinistral transpression (Figure 3), as opposed to reverse shearing associated with NW-SE shortening. The fabric in the footwall (Figure 2c) is consistent with pure strain, indicating that the footwall acted as a relatively rigid block during deformation. The nature of the magnetite grains within these lithologies suggest that the magnetite post-dates the formation of the shear zones (as suggested by Cave et al. (2018). Therefore, the shear zones are fluid traps. The NWW-trending upright faults, either side of the deposit, potentially control the precipitation of magnetite-albite within the thrust system, thereby controlling the medial footprint/ reduced zone of the Ernest Henry mineral system.

Between the highly magnetised shear zones there is breccia Figure 2d), which is mineralised and constitutes the bulk of the ore system. This breccia has a randomised AMS fabric (Figure 2e), which is consistent with brecciation of the pre-mineralisation tectonic fabrics. The brecciation is coincident with, or pre-dates pervasive (Figure 2d) to semi-pervasive...
(Figure 2f) potassic alteration which is dominated by K-feldspar in the breccia, but may also be present as biotite alteration. The brecciated, potassically altered zones are still relatively reduced (i.e., contain magnetite) but there is some magnetite destruction to hematite, pyrite and chalcopyrite, which in this case indicates more oxidised conditions in the proximal zone. Alteration was likely focused here due to increased permeability, possibly as a result of over-pressureing and subsequent brecciation. One model for metallogenesis is that reduced fluids (present in the system?) mixed with oxidised fluids (carrying the metals?).

What we deduce to be the last gasp of the system is only represented in a few samples, but preserves a sub-horizontal, N-S lineation (Figure 2g) that overprints the breccia, indicating strike-slip movement within a N-S fault zone. The rock contains quartz, calcite and chlorite and iron oxide (Figure 2h), which in this case is almost entirely hematite, as determined from the susceptibility: density ratio. This style of alteration, although not adequately represented in the sampling contains the highest proportion of chalcopyrite from the samples assessed thus far, and it is the most oxidised assemblage.

Magnetic Modelling

3-D magnetic and gravity modelling were undertaken using ModelvisionPro™, utilising the high resolution ground magnetic and gravity surveys completed by Western Mining Corporation, prior to mining. The magnetic data used were acquired by a SAM (sub-audio magnetic) survey which consisted of 20 m spaced E-W lines that only cover the immediate pit area. The modelling completed in this study was initially conducted on this magnetic data, but due to shear volume of data (which made computation slow), and the unfavourable E-W orientation, a synthetic survey with NNW oriented 100-m spaced lines was generated to complete the magnetic modelling. The gravity dataset (not discussed further here) consists of highly detailed data over the pit area (50 m grid), and more sparsely distributed data around the adjacent areas (100-200 m grid). Both datasets were provided by Xstrata (now MIM-Glencore).

As with any magnetic model there are significant ambiguities, related to trade-offs between depth, dip, shape and magnetisation intensity. However, in the case of Ernest Henry, we have numerous additional datasets that provide constraint to the model. The Ernest Henry drilling database and derived Cu and Au Leapfrog™ interpolations were used to constrain the position of the ore body, the breccia and the high magnetic susceptibility shear zones. Petrophysical properties measured as part of this study (summarised in Table 1) were utilised to guide the rock properties used in the modelling, and previous mapping (e.g. Webb and Rowston, 1995; Coward, 2001) was also used to guide the architecture used.

Table 1. Averaged density, magnetic susceptibility and Koenigsberger ratios of Ernest Henry lithologies.

<table>
<thead>
<tr>
<th>Alteration Assemblage</th>
<th>Density (g/cm³)</th>
<th>Mag Sus K (SI)</th>
<th>Koenigsberger Ratio (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>And-Alb+Potassic+Calcite</td>
<td>2.85</td>
<td>0.19</td>
<td>0.52</td>
</tr>
<tr>
<td>Magnetite-Apatite*</td>
<td>3.80</td>
<td>1.84</td>
<td>1.09</td>
</tr>
<tr>
<td>Potassic (Bt)</td>
<td>2.78</td>
<td>0.13</td>
<td>0.36</td>
</tr>
<tr>
<td>Potassic (Kf)</td>
<td>3.02</td>
<td>0.52</td>
<td>0.83</td>
</tr>
<tr>
<td>Potassic+ Cal-Qtz-Py</td>
<td>3.10</td>
<td>0.41</td>
<td>0.70</td>
</tr>
<tr>
<td>Qtz-Cal-Chl-Py±Cpt±Hem</td>
<td>3.27</td>
<td>0.34</td>
<td>0.47</td>
</tr>
<tr>
<td>Sodic (Ab-Mt-Ti)</td>
<td>3.14</td>
<td>0.76</td>
<td>0.62</td>
</tr>
<tr>
<td>Sodic + Potassic (Bt)</td>
<td>2.98</td>
<td>0.52</td>
<td>3.31</td>
</tr>
</tbody>
</table>

The two most obvious features of the magnetic data and magnetic model (Figure 4) are the ENE- and NE- trending anomalies caused by the Hanging wall and the Footwall Shear zones respectively (as noted previously by Webb and Rowston, 1995). Both shear zones extend beyond the SAM survey to the east, and whilst the shear zones may extend significantly further west than the modelled extent, the magnetisation within the shear zone is limited to a relatively small westerly extent. Hence, it is reasonable to interpret that either the magnetised shear zones are physically truncated along the western margin of the pit, as suggested by Coward’s (2001) mapping, or that the magnetite alteration that causes the magnetic anomalis is zoned, and does not extend significantly west of the pit. The Hanging Wall Shear displays strong induced magnetisation, and is modelled by an elongate body of ~0.7 SI magnetic susceptibility, that dips ~54° SSE, and limits the extent of the magnetised breccias within the system. The Footwall Shear displays strong induced magnetisation, and is modelled by an elongate body of ~1.5 SI magnetic susceptibility, that dips ~51° SE, and sits just beneath the main mineralised zone.

Figure 3. AMS results define a moderately south plumping lineation within a moderately SE-dipping plane, which is consistent with a thrust-jog across sinistral N-S faults.

Figure 4. Magnetic model of the Ernest Henry deposit, shown with sub-audio magnetic data. Viewed from the NE. Scale varies in this perspective view.
Between the shear zones there is a zone of moderate magnetic susceptibility (~0.4 SI), that is zoned, with slightly higher values (~0.5 SI) in the core. This central part of the anomaly is relatively smooth, which is consistent with the rounded shape of the body and zoned/ diffuse nature of the boundaries. This zone coincides with at least part of the breccia at Ernest Henry (the magnetised part). Whilst parts of the magnetised breccia are mineralised, the high grade mineralisation does not appear to coincide with the core of the magnetised breccia. High grade mineralisation (as derived from Leapfrog™ modelling), sits just above the footwall shear, on the margins of the moderately magnetised breccia. The high grade mineralisation is not sufficiently voluminous to affect the magnetic model substantially, but it appears to be only weakly magnetic (based on petrophysical data), which is consistent with it being the most oxidised part of the system.

**METALLOGENESIS**

The architectural framework and localisation of the Ernest Henry IOCG (cf. chemical genesis) is comprised of three main phases. The first critical step is the formation of the NE-striking thrust-jog. This must have formed during sinistral transpression, during the latter stages of ductile-brittle conditions as the crust was exhumed (i.e., D3 of Austin and Blenkinsop, 2010). Exhumation caused the rheological conditions within the shear zone to become more brittle (less ductile), which increased permeability in the shear zones, forming pathways for the early/more distal (i.e., sodic, Fe-rich) metasomatic fluids.

This opened up new pathways for deep fluids to pass into the upper crust, and metal bearing fluids were channelled into pre-existing NE-striking shear zones. With continued exhumation and associated cooling, rheological conditions no longer favoured strain being accommodated by ductile shear in the thrust-jog, and instead brittle sinistral strike-slip faults started to develop, overprinting the NE-shear zone. The newly developed N-NNW oriented faults acted as pressure valves, providing a mechanism for the release of water and/or CO2, thereby facilitating precipitation of magnetite and albite. Metasomatic replacement occurred in situ (i.e. was non-destructive), and therefore mimicked the pre-existing structural fabric. At this point the system was isolated from oxidised fluids sitting higher in the crust, because the fluid pathway was isolated from the plumbing system.

As metasomatic replacement occurred within the shear zones, porosity was progressively reduced as the replacement reactions were completed. Decreased porosity in the shear zones isolated the fluid pathway from the plumbing system, and over-pressurisation of the fluids caused brecciation at the intersection of the NW-trending thrust zone (the trap) and the central N-trending upright fault (the fluid pathway). Reactivation and re-scaling of the shear zone and breccia may have occurred numerous times. However, during the brecciation event(s) the fluid pathway and the plumbing are vertically connected and hence some mixing of reduced and oxidised fluids occurs during the formation of the breccia.

The alteration and structural fabrics present in the most oxidised parts of the system most likely reflect post-brecciation reactivation related to the N-S brittle shear within the system (e.g. D3 of Austin and Blenkinsop, 2010). The latest mineralisation is highly oxidised, and consistent with percolation of oxidised fluids down into the system.

**CONCLUSIONS**

Within the Ernest Henry IOCG, the initial mineralisation trap (i.e., the NE-trending shear zones) are highly magnetic due to their relatively reduced mineral assemblage (magnetite-albite) and preserve the pre-existing structural fabric. Conversely, the breccia is only moderately magnetic, weakly oxidized (i.e., magnetite-hematite-pyrite-chalcopyrite assemblages), and the breccia has a random AMS fabric, that clearly post-dates shear zone foliations. The least magnetic, most oxidised zone (i.e., quartz-calcite-hematite-chalcopyrite), overprints the breccia at the intersection of the initial trap (NE-trending shear zones) with the fluid pathway (N-S strike-slip fault) and has an N-S horizontal AMS lineation.

Early during metallogenesis, when the trap (the jog) is permeable ± reactive, the redox gradient lies along the trap, between the fluid pathway and pressure valves. As conditions become increasingly brittle the trap becomes impermeable and/or non-reactive and the system becomes over-pressured, leading to brecciation at the intersection of the trap and fluid pathway. Highly oxidised mineralisation in the core of the system is coincident with late reactivation.

The results indicate that the metasomatic alteration products present at Ernest Henry (i.e., sodic, potassic and calcic alteration) are coincident with redox zonation. However, the zonation of the system is controlled by the pre-existing architecture of the system, a compressive jog within a north-south trending strike-slip fault. Mineralisation occurs during the transition from ductile-brittle to brittle conditions when the D3 transpressional jog transitions to a D4 brittle transensional strike-slip system.

**ACKNOWLEDGEMENTS**

The GSQ are acknowledged for funding this research. Richard Lilly, MIM-Glencore and MIM-Ernest Henry Mine are thanked for allowing the sampling of the Ernest Henry Core.

**REFERENCES**


Figure 2. AMS data (left) and Mineralogy (right) for select lithologies present in the Ernest Henry minerals System. The Hanging wall shear preserves a SE dipping fabric with a south-plunging lineation which is consistent with transpressional strike-slip (A) is albite-magnetite rich (B). The Footwall has a pronounced lineation (F), but no foliation, which is typical of pure strain. Breccias (D) are isotropic (i.e., have random magnetic fabric: E) and display pervasivel (D), to partial (E) potassic alteration. The most mineralised rocks preserve a sub-horizontal lineation consistent with transtensional strike-slip (G), and are highly oxidised, with hematite the dominant iron oxide present (H), based on the samples high density: magnetic susceptibility ratio).