AEGC Australasian Exploration Geoscience Conference | Brisbane 2023

Geophysical synthesis of Cloncurry IOCG Deposits: The Influence of protolith, rheology, structural control and redox.

Dr James R. Austin
Potential Field Geophysics CSIRO
james.austin@csiro.au

SUMMARY

Iron oxide copper-gold (IOCG) systems form in a range of lithologies, including variably metamorphosed felsic and mafic volcanics, carbonates and siliciclastic sedimentary rocks. The chemistry, porosity and permeability of the host rocks control the reactive potential of mineralising fluids. They form across a range of crustal rheologies, from mid-crustal (ductile) to upper-crustal (brittle) conditions. IOCGs are focussed via a range of structural controls, including permeable strata, shear zones, fault jogs, splays and intersections and breccia pipes. The mechanism of fluid localisation controls geophysical zonation (e.g., planar vs concentric zonation). IOCGs also comprise a spectrum of mineralisation assemblages from reduced, pyrrhotite-dominant examples to magnetite-, and more oxidised, hematite dominant deposits. Such Fe-bearing minerals have contrasting magnetic, density and conductivity properties, and therefore redox/pH and geophysical properties are linked. The interaction of major controls, including host rock chemistry, rheology, structural controls, and redox/pH conditions, define the style of geophysical anomaly associated with an IOCG system. The Cloncurry mineral system comprises a spectrum of deposit styles, not observed across the other major IOCG provinces, and provides an excellent window into the array of possible geophysical signatures. This study synthesises findings of Cloncurry METAL, a three-year study which collected integrated petrophysics, mineralogy and structural data from almost every major deposit/prospect in the Cloncurry district. It provides petrophysical properties of the host rocks and mineralised lithologies across the mineral system and explore some of the ways variations in host rock chemistry and rheology, structural controls and redox/pH zonation interact to form contrasting geophysical targets.

Key words: Petrophysics, Geophysics, IOCG, Magnetic Susceptibility, Density, Structural Control, Redox,

INTRODUCTION

The Cloncurry mineral system comprises a range of deposit types with a complex array of geophysical signatures (Austin et al., 2016a, b). Iron oxide-copper-gold (IOCG) systems, in a broad geophysical sense, include a spectrum of mineralisation-styles ranging from reduced, pyrrhotite-dominant examples, sometimes referred as iron sulphide copper-gold (ISCG) systems, to magnetite-pyrite dominant, and more oxidised, hematite dominant Cu and Au deposits. The geophysical signatures in and around (IOCG) deposits are frequently associated with mappable gradients magnetic minerals, monoclinic pyrrhotite, magnetite and hematite. The distribution of these minerals can be linked to gradients in redox and or pH within the mineral system and have predictable geophysical signatures (e.g., Figure 1).

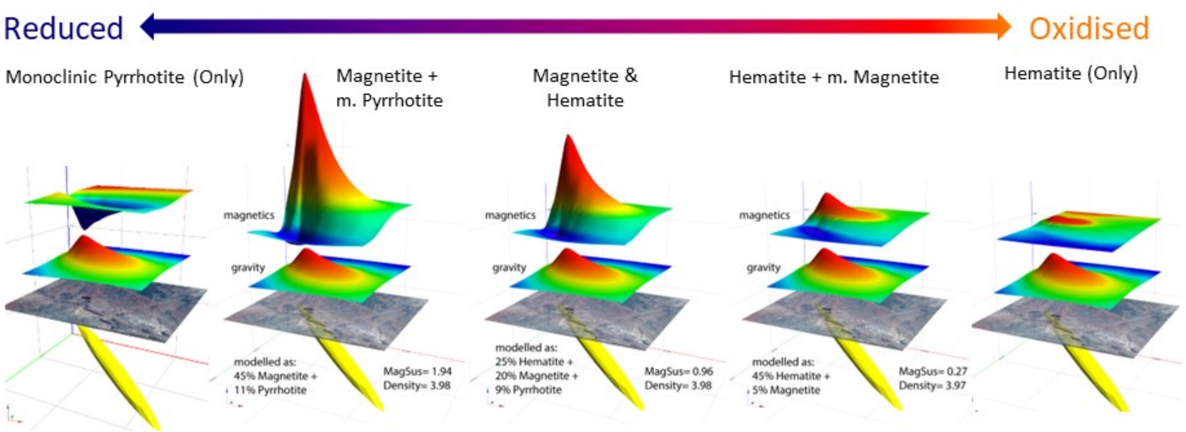

Figure 1: Synthetic models of variability in pyrrhotite, magnetite, and hematite demonstrate that assemblages with comparable density (i.e., gravity signatures) can have highly contrasting magnetic signatures.

Whilst mineralogy, geological logging and assaying are favoured techniques in exploration, geophysical properties have a substantial advantage, because geophysical properties such at magnetics and gravity are scalar. The translation of geochemical and mineralogical understanding into petrophysical knowledge can therefore facilitate effective regional exploration using geophysical datasets. This paper provides a synthesis of the petrophysical properties of Cloncurry IOCG deposits, and their host rocks, which can be used to constrain geophysical modelling. It also provides insights into the petrophysical zonation of Cloncurry mineral systems, the variance in magnetic minerals due to redox/pH/ temperature, and their associated geophysical signatures.

PETROPHYSICS OF THE CLONCURRY IOCG DISTRICT

This section provides a synthesis of potential field petrophysical data collected from the Cloncurry METAL database (Austin et al., 2021a). Other available data include measurements conductivity, radiometrics, anisotropy of magnetic susceptibility, and scanning electron microscope mineralogy maps, pXRF geochemistry and hyperspectral data. In depth explanations of the petrophysical, mineralogical, and geochemical methods and terminology used in this report are available in the database companion (Austin et al., 2021a).

Host Rocks

Host rock petrophysical properties (Figure 2) can be very important in geophysical modelling to establish the level of the background field. Accurate knowledge of this background field is critical to construction of accurate geophysical models of prospects. For host rocks lithologies were grouped based on their mineralogy, paying close attention to the distribution of any high density and/or magnetic minerals. Whilst efforts were made to isolate unaltered samples, it is important to note that the study primarily sampled close to known mines and typically sampled the distal footprint, rather than pure country rock. In some cases, unaltered rocks contain iron oxides (e.g., magnetite in dolerite/amphibolite) and sulphides (pyrite, in black shales), such minerals are more typically considered to be indicative of hydrothermal alteration. Some of the magnetite-altered host rocks highlighted in Figure 2, correspond with sodic and both K-feldspar and biotite-magnetite styles of potassic alteration (Austin et al., 2016a,b; McFarlane et al., 2021a,b; Stromberg et al, 2021). Different footprint assemblages footprint may cause elevated density due to garnet (e.g., Maronan) or elevated remanent magnetisation due to monoclinic pyrrhotite (e.g., Artemis: Austin et al., 2016a,b).

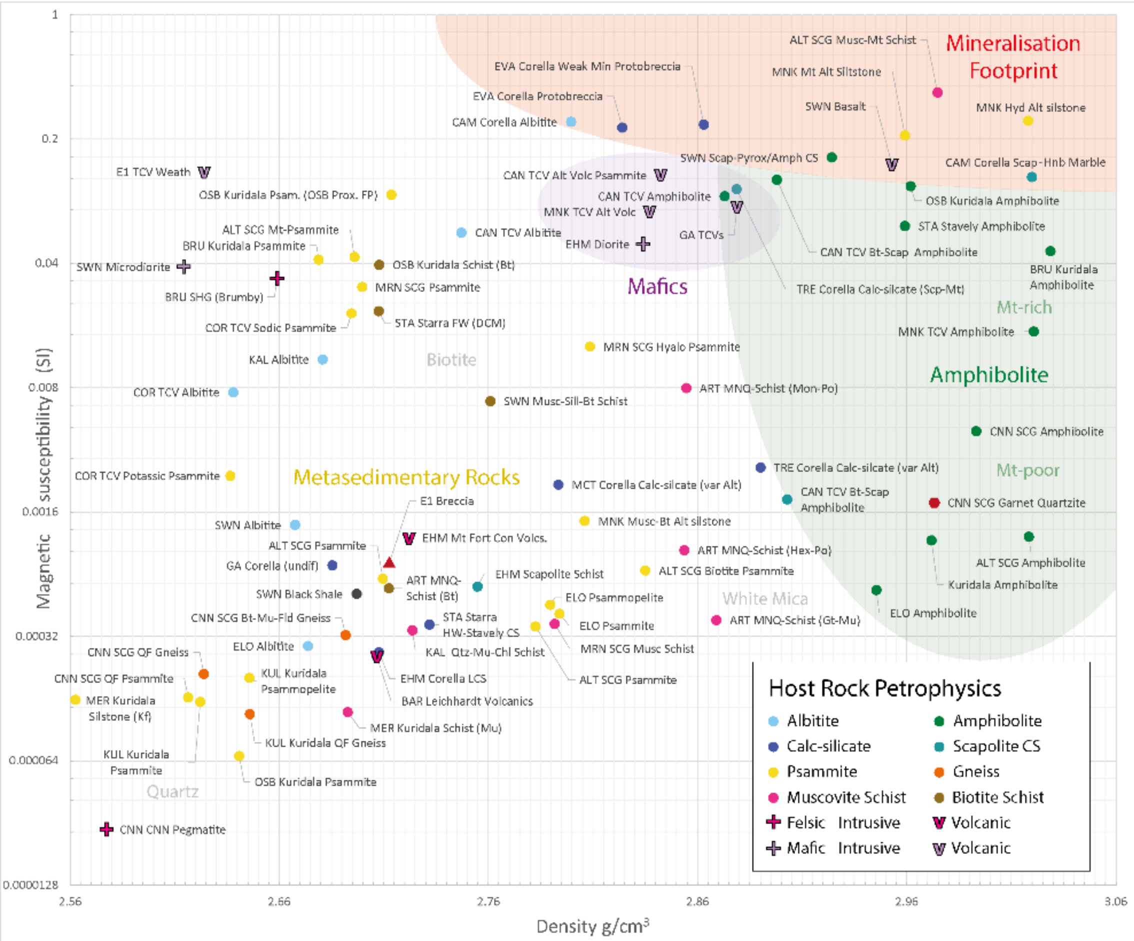

Figure 2. Plot of Magnetic Susceptibility vs density for a selection of host rocks and distal alteration assemblages from the Cloncurry district, shading indicates appropriate ranges for several common lithological classes. Mineralised assemblages

To constrain the petrophysical properties of ore assemblages a cross-section of the most mineralised specimens were obtained by clipping the data to specific mineralisation cut-offs, consistent with what could be considered “ore” in the Cloncurry district. For IOCG style deposits the typical cut-off used is 1.5% chalcopyrite for Cu-dominant systems or 1% in Au-rich systems (e.g., Starra and Eloise). For lead-zinc systems the cut-off is around 5% combined galena-sphalerite. However, many deposits contain multiple mineralisation styles, which have very different petrophysical properties related to variable amounts of iron oxides, sulphides, and other dense minerals such as barite and garnet. Therefore, a selection of different ore types, are provided in Figures 3 & 4, with the specifics of each noted. The deposits and prospects have a large range in density, between 3.1 and 4.8 g/cm^3 due to variability in the concentration of magnetite, hematite, pyrrhotite, galena, sphalerite, pyrite, etc., and in some cases can also be attributed to non-metallic minerals including barite, amphiboles, and garnet.

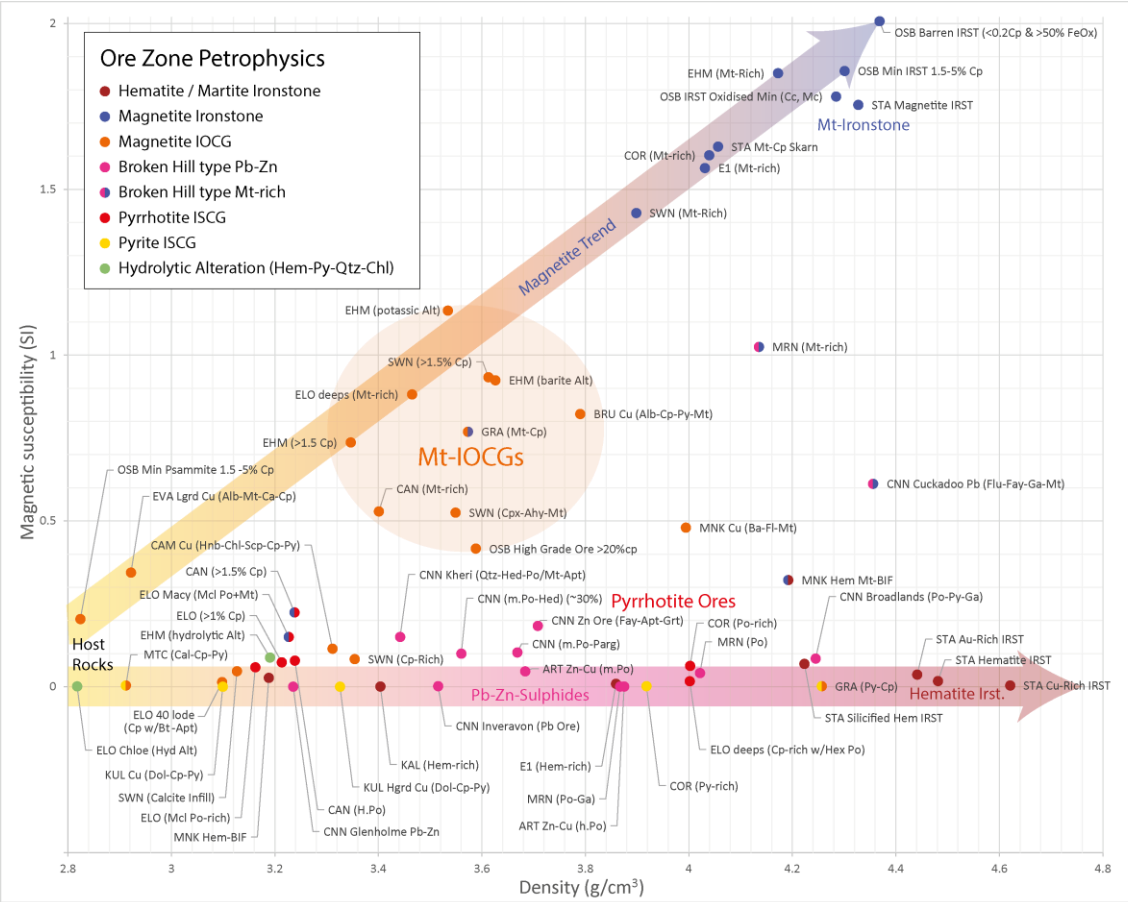

Figure 3. Magnetic susceptibility vs density plot for mineralised assemblages and ironstones from the Cloncurry district coloured by deposit style. Two main trends shown indicate the baseline for non-magnetic minerals and the magnetite trend for near pure magnetite.

Deposits also have a large range in magnetic susceptibility, from negligible (e.g., <10^{-6} SI) to ~2.3 SI (Figure 3: NB figures do not include adjustments for self-demagnetisation effects). In many cases high densities are correlated with high magnetic susceptibilities, and in such cases the dominant dense/susceptible mineral is magnetite. For the most part this is coarse grained, multi-domain magnetite, which does not retain significant, or stable remanence (Figure 4). High densities correlated with moderate susceptibilities, are in many cases due to the presence of monoclinic pyrrhotite. High densities and low susceptibilities may be due to hematite, hexagonal pyrrhotite and other sulphide species including pyrite, chalcopyrite, galena, and sphalerite.

The deposits and prospects assessed have a range of natural remanent magnetisation (NRM) intensities from negligible, up to mean values of 450 A/m, often associated with very high Koenigsberger (Q) ratios of over 100 (Figure 4: NB Q= NRM/Magnetic Susceptibility). Deposits with high remanence and high Koenigsberger ratios are usually dominated by monoclinic pyrrhotite as the magnetic phase. In some instances, high Koenigsberger ratios are calculated for hematite ironstones. However, this is mainly an artifact of their negligible magnetic susceptibility and is commonly caused by near-surface processes such as lightning induced IRM and/or partial oxidation.

There are several endmember petrophysical associations recognised:

1. Deposits with high density, high susceptibility, and low Q are dominated by coarse MD magnetite, e.g., Osborne.
2. Deposits with high density high susceptibility and moderate Q are rich in pseudo single-domain magnetite (possibly indicative of sedimentary origin), e.g., Cormorant, Maronan.
3. Deposits with high density, low susceptibility, and high Q are rich in monoclinic pyrrhotite, e.g., Cormorant.
4. Deposits with high density, low susceptibility, and moderate to high Q are rich in hematite, e.g., Monakoff, Starra.
5. Deposits with high density low susceptibility, and low Q may contain hexagonal pyrrhotite and /or sphalerite, galena, pyrite and hematite, and an absence of magnetite.

Many specimens contain mixtures of different Fe-oxide and sulphide phases. These different assemblages precipitate in response to variability in the redox/acidity and /or overprinting of various metasomatic events. However, the assemblages usually fall into one of three basic categories, with some overlap:

6. Oxidised assemblages containing hematite, are typically associated with pyrite, and or magnetite. In hematite-rich systems, such as Starra, a gravity signature associated with hematite may be offset from magnetic signature, associated with magnetite which is prevalent in the footwall at Starra.
7. Intermediate assemblages (highlighted in orange in Fig 3) are magnetite dominant. They may contain pyrrhotite or hematite (not both), and other high density minerals including pyrite, apatite, barite, and amphiboles.
8. Reduced assemblages are pyrrhotite dominant, but often contain magnetite. Empirically, hexagonal pyrrhotite is more commonly associated galena and sphalerite, whereas monoclinic (magnetic) pyrrhotite is more commonly associated with chalcopyrite. Monoclinic pyrrhotite has lower susceptibility than magnetite, but much stronger remanence, which may cause unusual RTP magnetic anomalies that are non-coincident with gravity anomalies.

These basic geophysical principles are well known, but the recognition that redox gradients are coupled with petrophysical zonation in deposit footprints is a powerful tool for the discrimination of barren from prospective targets.

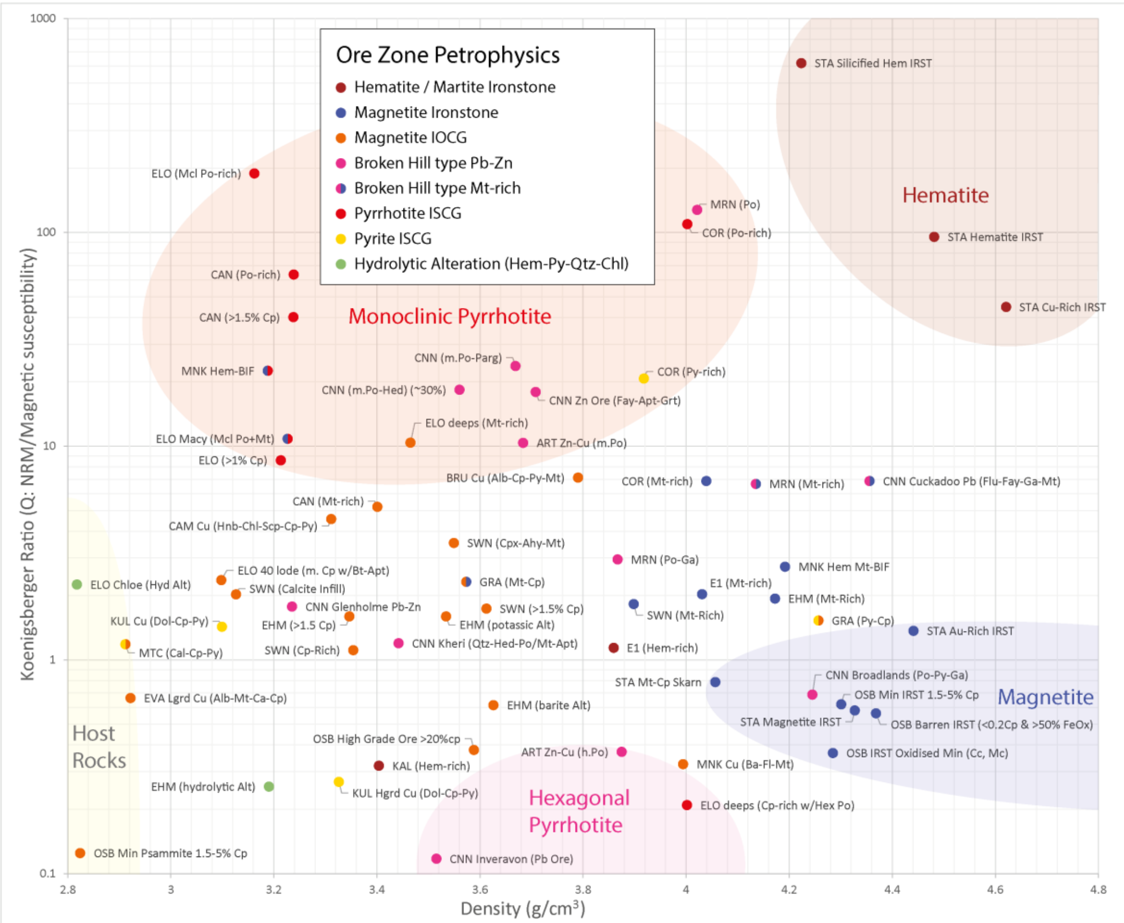

Figure 4: Koenigsberger ratio vs density plot for mineralised assemblages and ironstones from the Cloncurry district coloured by deposit style. Shading indicates appropriate ranges for several common magnetic mineral phases, host rocks and weak alteration footprints.

DEPOSIT ZONATION

The Cloncurry district is world renowned for Iron-Oxide Copper-Gold (IOCG) mineralization, but the mineralization present is highly diverse, spanning several deposit styles, including: IOCG and Iron ISCG styles, Broken Hill type (BHT), volcanogenic massive sulphide (VMS), skarn and intrusion related Cu-Mo deposits. Whilst some deposits are monogenetic, many deposits formed via overprinting of multiple ore forming systems, which occurred during (often interrelated) tectonic, metamorphic magmatic and metasomatic events. The deposits are both mineralogically and petrophysically diverse, and accordingly have wide variability in both their geochemical and geophysical expressions. Notwithstanding this complexity there are common types of zonation present in several deposit styles which can be recognised in geophysical data. The three common zonation styles in IOCGs (concentric, linear, and lateral zonation) are discussed below in the context of geochemical, structural, lithological, and rheological controls.

Concentric Zonation

There are few sensu stricto IOCG deposits in the Cloncurry district, and many IOCG-related deposits. This represents a problem in terms of targeting because many of the geophysical characteristics one might expect for an "IOCG" may not hold true for all related deposits. There are however several true IOCG examples, including E1, Brumby, and the largest example, Ernest Henry (Austin et al., 2021b). Sensu-stricto IOCG deposits (like porphyries) often display classic concentric or funnel-like zonation comprising numerous alteration styles which can, depending on the host rocks and structural controls, form a bullseye anomaly or circular magnetic high around the deposit (e.g., Clark, 2014). This zonation forms via telescoping of the alteration system from relatively early to late, coupled with changes in crustal rheology, fluid pressure, fluid chemistry and deformation style. However, this simple zonation is often complicated in practise because the porosity and permeability of IOCGs systems is structurally controlled (Figure 5). Because these pre-existing structures control the fluid flow in IOCGs, the simple concentric zonation observed in a porphyry is often not easily observed in IOCGs. Recognition of zonation can, furthermore, be complicated by syn- post ore deformation (e.g., tilting, folding, faulting: Clark, 2014). Nevertheless, it is observed that progressive alteration in many IOCG systems leads to characteristic geophysical zonation.

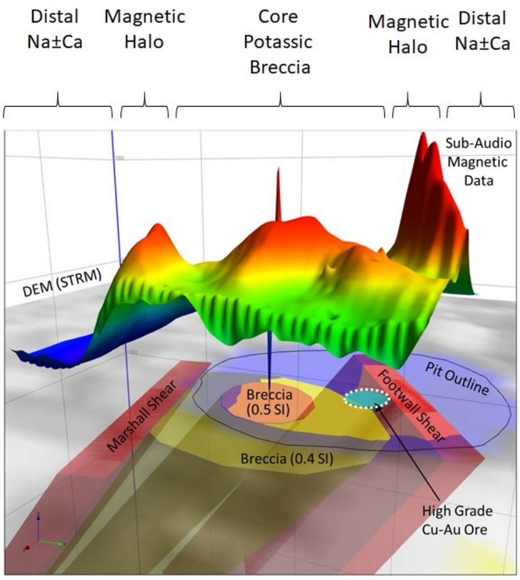

Figure 5. Simplified geophysical model of the Ernest Henry deposit, illustrating pseudo-concentric geophysical zonation.

At Ernest Henry, the progression from early albite-magnetite-dominant alteration to increasingly pyrite and hematite-rich assemblages toward the later stages, is consistent with a system evolving from relatively reduced to relatively oxidised conditions. This type of pattern is simply explained by interaction of an oxidised fluid with a reduced host sequence but viewed within a lithogeochemical framework it is also consistent with the evolution of a fluid from relatively alkaline to relatively acidic via interaction with the host protolith (Schlegel, et al., 2022). A simplified model for the geophysical development of the Ernest Henry deposit is presented in Figure 6. Geophysically, the alteration paragenesis presented will result in a system with a moderately dense, highly magnetic medial footprint, outboard of a weakly magnetised, low density proximal footprint, haloing a highly dense, moderately magnetic core. Late hematite-quartz-chlorite-chalcopyrite (hydrolytic) alteration, which is present, but not pervasive at Ernest Henry results in oxidation of magnetite to hematite, causing subtle suppression of the magnetic signature in the core. This suggests that simple bullseyes magnetic may not be optimal targets for IOCGs exploration and that hematite dominated systems (e.g., Olympic Dam, Ehrig et al., 2012), may represent more fully evolved systems. Whilst hematite is found in relatively low abundance in association with the

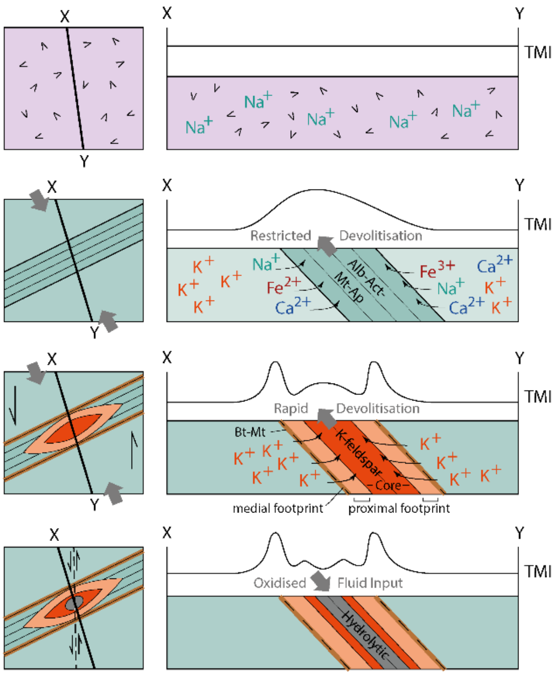

Figure 6. Schematic illustrating the geophysical zonation of a magnetite-series IOCG within a lithogeochemical / reactive transport framework (based on Ernest Henry, Austin et al., 2021b)

latest alteration stages at Ernest Henry, most known Cloncurry IOCGs (cf. Starra, McFarlane et al., 2021a) are hematite poor. Notwithstanding this, it is possible, that more evolved IOCG's are yet to be found in the Cloncurry district.

Structurally/Stratigraphically controlled linear zonation

Stratiform ironstones are common in the Cloncurry district, and are associated with numerous styles of mineralisation, including Pb-Zn-Ag rich Broken Hill type (BHT) deposits (e.g., Cannington), Volcanogenic Massive Sulphide (VMS) styles (e.g., Maronan, Altia, Pegmont); barite-fluorite-magnetite hosted Cu (e.g., Monakoff), and both magnetite (e.g., Osborne and Hematite (e.g., Starra) dominated "IOCGs". In the case of IOCG and related deposits, paragenetic studies favour iron oxide pre-dating ore. In some cases, stratiform ironstones appear to be syn-sedimentary (e.g., those present in the Soldiers Cap Group and Kuridala Fm.) and syngenetic with mineralisation, particularly lead and zinc-rich styles. An example of stratiform zonation from a Cu- dominated system (Monakoff) is presented here.

Monakoff sits within an approximately E-W stratigraphic horizon at the contact between the Toole Creek volcanics and Mount Norna Quartzite. Its magnetic anomaly is linear and parallel to stratigraphy. However, the amplitude of the anomaly varies substantially from the distal parts along strike, into the core, which is an order of magnitude higher (Figure 6). An unusual barite-fluorite-magnetite chalcopyrite (± relict sphalerite and galena) assemblage in core of the system is highly magnetic (ca. 0.5 SI). Barren ironstone horizons, typical of distal parts of VMS systems, occur along strike either side of the deposit. These distal ironstones produce low amplitude, but laterally extensive magnetic anomalies, associated with relatively modest magnetic susceptibility. Magnetite is present but with increasing distance from the deposit hematite is dominant. The variation in iron oxide species from core to distal is consistent with a redox or temperature control, i.e., mineralization closer to the source is relatively reduced (e.g., magnetite ± pyrrhotite) and more distal deposits are oxidized (e.g., hematite ± magnetite). In general, this is coupled with corresponding zonation of metals, with greater economic minerals closer to the core of the system.

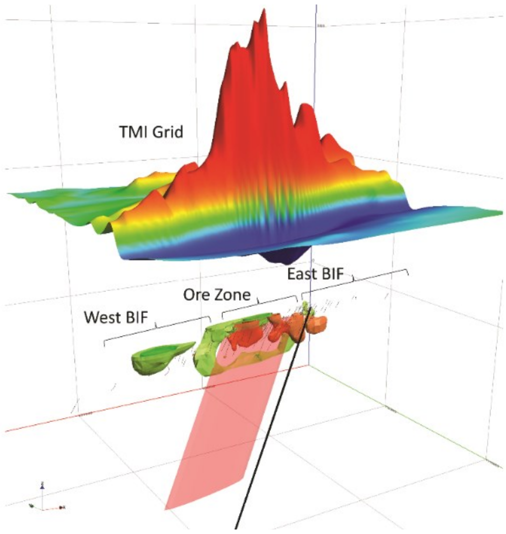

Figure 7. Monakoff Cu-Au deposit magnetic anomaly, magnetic model (red) and leapfrog ore shells red and green.

Whilst there is on-going debate on the genesis of Monakoff, these observations are consistent with both partial replacement of an existing ironstone horizon by an IOCG style fluid and/or a VMS style system in which reduced, highly magnetitic, magnetite-rich assemblages occur proximal to sources and hematite-rich, weakly magnetic stratiform anomalies are distal along-strike. Regardless, the geophysical zonation characteristic of an alteration and/or temperature and/or redox gradient that is indictive of mineralisation processes.

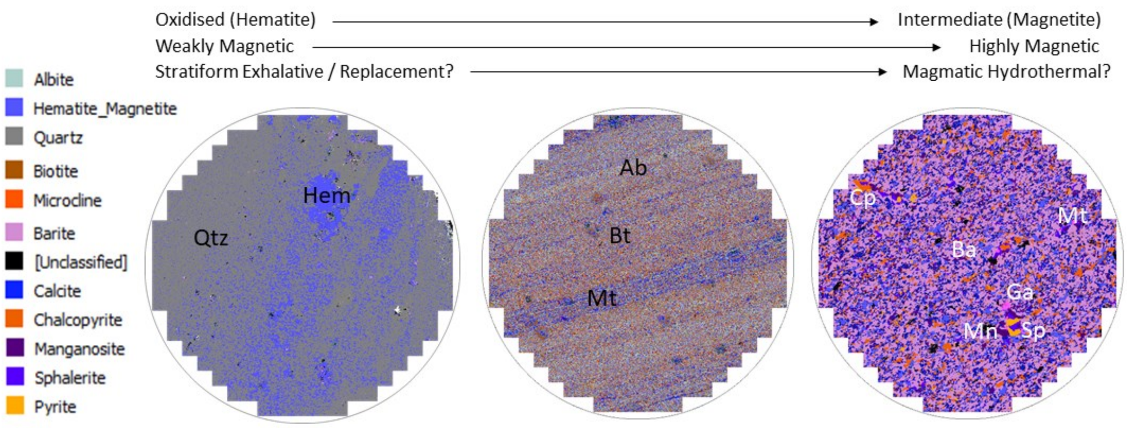

Figure 8. Transition from highly oxidized (left) to relatively reduced assemblages (middle) is consistent with a redox gradient coincident with stratigraphically contained gradients in total magnetic intensity at Monakoff.

Lateral (Lithologically Controlled) Alteration Gradients

The Starra IOCG deposits are structurally controlled (Mc Farlane et al., 2021a), magnetite-hematite deposits that sit along a major shear zone separating distinct calc-silicate and gneiss lithologies. Downhole logging of magnetic susceptibility, density, radiometrics, and assay data (Figure 9) provide insights into geophysical zonation at Starra-276.

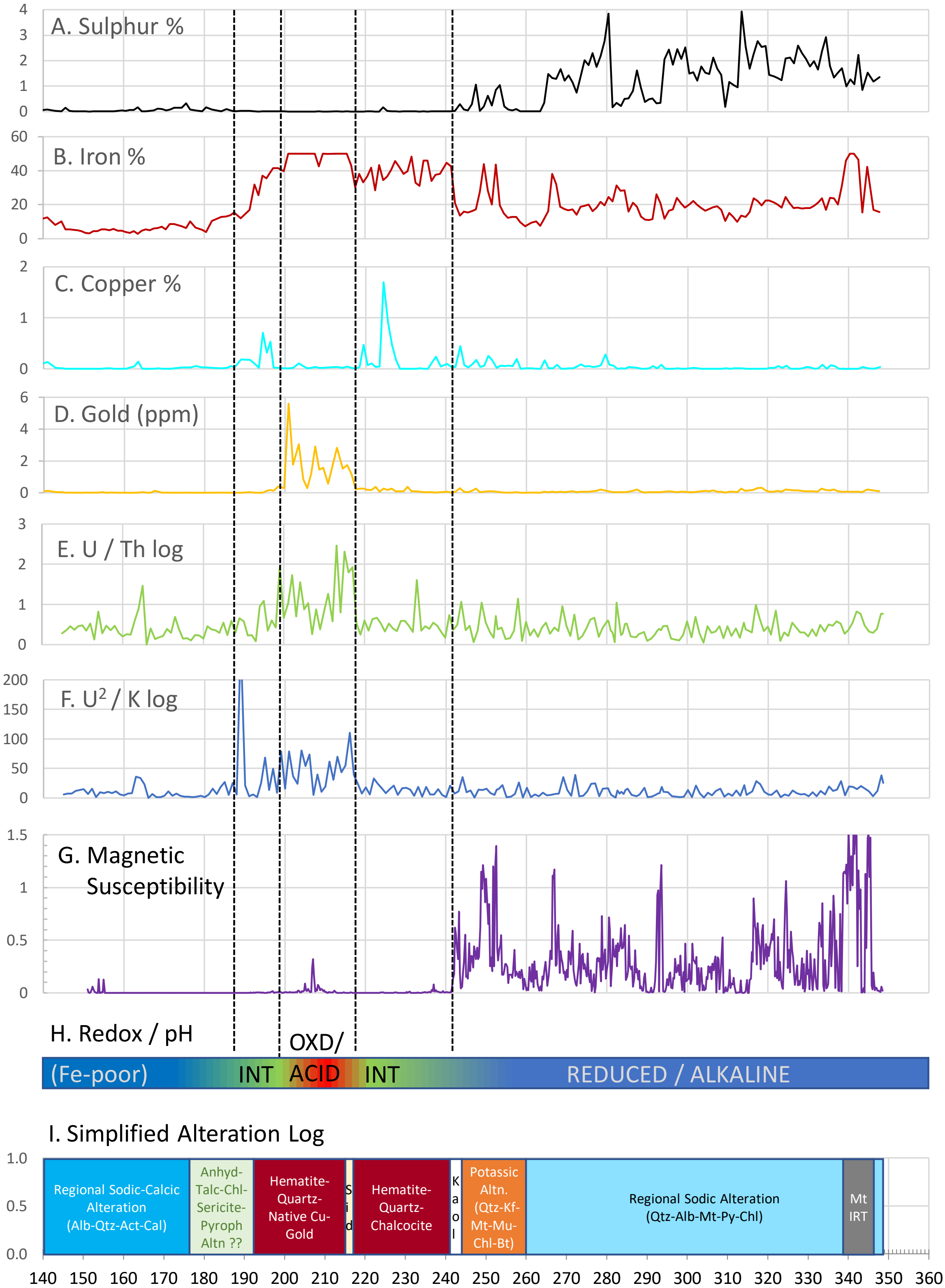

Figure 9. Compilation of log data from drillhole STQ1098 from Starra-276, including sulphur (A), iron (B), copper (C) and gold (D) assays, radiometric ratios U/Th (E) and U²/K (D) that are used to characterise redox (H)), magnetic susceptibility (G) and simplified geological log (I).

The results of McFarlane et al. (2021a) illustrate the presence of a redox/pH gradient in the upper parts of the deposit coincide with a change from low susceptibility, and negligible S, Fe, Cu, Au contents in rocks in the hanging wall (left), through to moderate concentrations of S, Fe, Cu, and Au associated with high susceptibility and high strain in the footwall. The upper mineralisation occurs in massive hematite, is characterised by high iron, low susceptibility, and high density and coincides with a spike in the U^2:K ratio. McFarlane et al. (2021a) inferred that the radiometric spike coincides with a fluid pathway, and marks a boundary between highly oxidised, native copper and gold bearing zone and a more intermediate lower iron, copper sulphide bearing zone.

At Starra-276 the mineral zonation is interpreted as a lateral redox gradient extending from the barren hanging wall calcsilicate lithologies through the highly oxidised and native copper bearing hematite-rich zone, a gold-hematite, hematite-chalcocite-bornite breccia into a magnetite-bearing footwall. Furthermore, a gradient from deep, magnetite-dominant, copper-sulphide bearing mineralisation at depth to highly oxidised hematite ± native copper ± gold ± chalcocite ± bornite assemblages is also present. These observations suggest that whilst the metal bearing alteration may have been structurally controlled, that lithological factors, e.g., porosity, geochemistry, redox/pH, likely controlled the zonation of magnetic minerals and hence the geophysical signatures at Starra-276.

CONCLUSIONS

The aim of this synthesis is to provide usable, trustworthy constraints for magnetic and gravity modelling. It provides an overview of the petrophysical properties of the various styles of mineralisation present in the Cloncurry district, and the rocks within which they are hosted, based on the Cloncurry METAL database. It presents information on density, magnetic susceptibility, and remanence properties, which explorers can use to constrain geophysical exploration and take the guessing out of modelling. This paper highlights the characteristic petrophysical zonation observed in IOCG style deposits which can be used to better target prospective anomalies in regional geophysical datasets. It also demonstrates that petrophysical analyses, coupled with structural, lithological, and rheological knowledge can provide valuable insights for IOCG exploration in the Cloncurry District, and more generally for hydrothermal mineral systems.

REFERENCES

Austin, J.R., Gazley, M.F., Walshe, J.L. and Patterson B.O., 2016a. Uncover Cloncurry – Summary: Integrated structural, metasomatic and metallogenic history of the Cloncurry District. CSIRO report EP166451, Australia, pp. 45.

Austin, J.R., Gazley, M.F., Walshe, J.L. and Patterson B.O., 2016b. Uncover Cloncurry – Summary: Geophysical Expressions of the Cloncurry Mineral System. CSIRO Australia.

Austin, J.R., Birchall, R., Stromberg, J., Patterson, B., Björk, A., Dhnaram, C., Lisitsin, V., Walshe, J., Gazley, M.G., Le Gras, M., Shelton, T.D., Spinks, S., Pearce, M., Schlegel T., and McFarlane, H. 2021a. The Cloncurry METAL Geodatabase mk1: A scale-integrated relational geodatabase for Cloncurry District, Northwest Queensland. Part I: Cloncurry METAL Final Report 2018/21. CSIRO, Australia.

Austin, J. R., Patterson, B., Birchall, R., Björk, A., Walshe, J., Schlegel T., Stromberg, J., McFarlane, H., Shelton, T.D. and. Pearce, M. (2021b) Metasomatic controls on petrophysical zonation in IOCG mineral systems: An example from Ernest Henry, Cloncurry Mineral District: Part III: Cloncurry METAL Final Report 2018/21: CSIRO, Australia.

Clark, D.A., 2014. Magnetic effects of hydrothermal alteration in porphyry copper and iron-oxide copper-gold systems: A review. Tectonophysics 624-625:46-65.

Ehrig, K., McPhie, J. and Kamenetsky, V.S., 2012. Geology and mineralogical zonation of the Olympic Dam Iron Oxide Cu-U-Au-Ag deposit, South Australia', in JW Hedenquist and M Harris and F Camus (eds.), Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe, Society of Economic Geologists, Inc., pp. 237-267.

McFarlane, H. B., Austin, J. R., Schlegel, T. U., Birchall, R., Bjork, A., Stromberg, J., Walshe, J. Shelton, T.D. and Pearce, M., 2021a. Starra 276: Redox Gradients and Structural controls: Integrated petrophysical, structural and mineralogical analysis: Part V: Cloncurry METAL Final Report 2018/2021 CSIRO, Australia.

McFarlane, H. B., Bjork, A., Stromberg, J., Austin, J. R., Birchall, R. Schlegel, T. U. and Shelton, T. D., 2021b. Mineralogical and structural characterisation of Osborne Cu-Au deposit: Part IIX: Cloncurry. METAL Final Report 2018/2021 CSIRO, Australia.

Schlegel, T.U., Birchall, R., Shelton T.D. and Austin, J.R., 2022. Mapping the mineral zonation at the Ernest Henry iron oxide copper-gold deposit: vectoring to cu-au mineralization using modal mineralogy. Economic Geology, 117, 485-494.

Stromberg, J.M., McFarlane. H., Birchall, R., Schlegel, T., Austin, J.R., Pearce, M.A., and T.D., Shelton (2021). SWAN and Mount Elliot Cu-Au Systems – Multi-scale Investigation of Calc-Silicate Alteration Mineralogy. Part VI: Cloncurry METAL Final Report 2018/2021. CSIRO, Australia