Geophysical proxies for redox gradients in IOCG systems: Cloncurry District, Qld, Australia.

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SUMMARY

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 to as iron sulphide copper-gold (ISCG) systems, to magnetite-pyrite dominant, and more oxidised, hematite dominant Cu and Au deposits. Importantly, the geophysical signatures in and around (IOCG) deposits are frequently associated with mappable changes in redox. Moreover, redox gradients have predictable geophysical signatures, and thus they can be targeted by mineral explorers using integrated petrophysical and geophysical methods.

Systematic and scale-integrated petrophysical data (>1300 samples form 23 deposits and prospects) such as density, magnetic susceptibility, remanent magnetisation, radiometrics and conductivity were obtained and combined with mineralogical and geochemical data measured on the same samples as part of the Cloncurry district as part of the Cloncurry METAL projects. The data show clear relationships between redox gradients, indicated by transitions between pyrrhotite, magnetite and hematite bearing lithologies, and steep gradients in magnetic susceptibility and/or remanent magnetisation. Moreover, the gradients coincide with Uranium-radiometric spikes present in rock and breccia intervals with complex mineralogy related to transitional redox. This diagnostic radiometric signature together with the coincident magnetic gradients provide a rigid geophysical proxy for differentiation of IOCG related signatures from false positives. Finally, the data provides new insights into economic IOCG mineralisation and new set of tools for targeting IOCG and related deposits in the surface geophysical and downhole datasets.

Key words: IOCG, magnetite, magnetic susceptibility, remanent magnetisation, radiometrics, redox.

INTRODUCTION

Since the discoveries of Ernest Henry, Eloise, Osborne and Maronan, in the late 1980s to mid-1990's, there has been extensive research on the Cloncurry district. Much of this research was focussed on geochemistry and geology. However, these major discoveries were made on the back on high resolution aeromagnetic data acquired over the same period. Although geophysical techniques have found the majority of deposits in the Cloncurry District and elsewhere, the way in which we apply geophysical datasets has not significantly evolved in the last few decades and despite the obvious advances in computational techniques, geophysics is still used mostly to map anomalies and interpret faults.

The classic Status Quo of geophysical exploration for IOCG deposits, is "the combined gravity-magnetic high" (e.g., Funk, 2013). Whilst this paradigm has been successfully applied in IOCG exploration, it does not hold true for all deposits in the Cloncurry district. Deposits may be magnetite-, hematite- or pyrrhotite-dominated or have even a paucity of dense or magnetic minerals (Fig 1). A synthesis of petrophysical properties of several IOCG and related deposits in this region (Austin et al, 2016e) demonstrates that many IOCG's do not show a (significant) gravity anomaly, some do not have a magnetic anomaly, and some have neither. Another problem with the combined magnetic-gravity high concept is that publicly available gravity data is typically of insufficient resolution to highlight all but the largest systems.

Magnetite-rich IOCG deposits, such as Osborne, are geophysically simple, commonly displaying coincident reduced to pole (RTP) magnetic and gravity anomalies. In pyrrhotite-rich systems such as Eloise, remanent magnetisation may cause an offset of the RTP magnetic anomaly relative to the deposit-associated gravity anomaly. In hematite-rich systems, such as Starra, the magnetic signature may be minor or even absent where bulk hematite is of primary, hypogene origin. Whilst these basic geophysical principles are accepted, the recognition of redox gradients within IOCG systems is more meaningful and can be related to the geochemical processes active during mineralisation.

The common criteria for targeting IOCGs are: 1. magnetic (±gravity) anomalies; 2. structural controls, 3. variable Na-Ca-K hydrothermal alteration and 4. evidence of strong redox and/or pH controls on mineral precipitation. At first glance only magnetic and gravity anomalies would appear to be geophysical criteria. Nevertheless, structural analysis of the upper crust can be deduced effectively from regional magnetic data. Hydrothermal alteration can be mapped using hyperspectral imaging, and redox gradients may be delineated using a combination of radiometric and magnetic data. We can therefore use regional scale geophysical datasets to provide the consistent IOCG targeting data for exploration.

As the search space for IOCG deposits gets deeper, satellite and airborne hyperspectral and radiometric methods will become less useful, because both techniques provide information about rocks at the surface. Nevertheless, there remains a great opportunity to utilise existing handheld geophysical tools on drill core to better understand the petrophysics of IOCG systems and how they reflect changes in geochemistry at the core to camp scale.

DEPOSIT FOOTPRINTS

One aspect of many ore deposits (e.g., IOCG's, Porphyry, VMS, epithermal, SEDEX) that is almost universally accepted is they display distinct zones of hydrothermal mineral assemblages (e.g., Kelley et al., 2006), which are colloquially referred to as "footprints". Deposit footprints are most commonly considered to be geochemical and/or mineralogical, but they can also have associated geophysical, structural, biological and rheological expressions. It is rarely recognised that geochemical zonation can be coupled with geophysical zonation in mineral systems, but recognition of geophysical zonation, and its implications for alteration and redox in mineral systems can be very useful in regional targeting. Integrated petrophysical and mineralogical studies, undertaken as part of the previous Uncover Cloncurry (Walshe et al., 2016) and the current Cloncurry METAL projects, have demonstrated that magnetite is predominant in the footprint of many deposits in the Cloncurry area, but the core of many system is often less magnetised. The core may display partial (e.g., Ernest Henry; Austin et al. 2019) or near-complete (e.g., Starra: Patterson, 2016) oxidation of magnetite to hematite. In other cases, magnetite occurs in the wall rock of reduced pyrrhotite-rich systems (e.g., Artemis; Austin et al., 2016a). Thus, targeting magnetite using geophysics is becoming a less and less successful strategy for finding IOCGs.

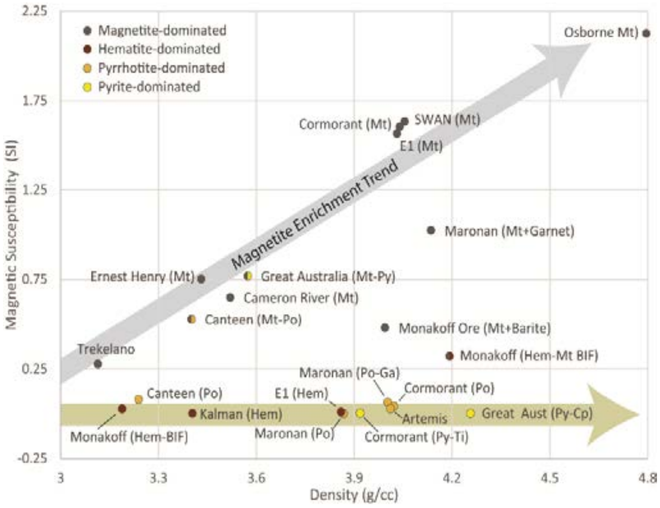

Figure 1: Mean magnetic susceptibility vs density for mineralised samples assessed in this study. Grey arrow = magnetite trend, gold line = pyrite trend.

Whilst geochemistry, mineralogy and petrophysical properties can be mapped at deposit to sub-deposit scales using handheld tools, such as portable XRF, portable ASD, portable Gamma-ray spectrometers, magnetic susceptibility meters, and conductivity meters, industry commonly focuses on mineralogy, geological logging and interpretation of assay data. Despite this trend, geophysics has one huge advantage over geochemistry because geophysics is scalable. Therefore, if we can translate our geochemical and mineralogical understanding into geophysical knowledge, we can explore more effectively using regional geophysical datasets. In this paper we outline some of the results of the Cloncurry METAL integrated petrophysics project, and highlight ways in which magnetic susceptibility, density and radiometrics can be used to describe hydrothermal alteration, and better instruct exploration methodologies.

METHODS

The Uncover Cloncurry and Cloncurry METAL projects have collected over 1300 samples from 23 deposits, from host rock assemblages, through deposit footprints and into the core of each system. Sampling has been conducted in this manner to facilitate an understanding of the ore> proximal> medial> distal> background footprint of the system. Cylinders of 2 cm diameter were drilled from each sample and subsequently 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 balance), magnetic susceptibility (using an AGICO MFK1-A Kappabridge magnetometer), remanent magnetisation (using an AGICO JR-6 magnetometer), radiometrics (using a Radiation Solutions RS-332 gamma-ray spectrometer) and conductivity (using a Terraplus KT-20). Analyses of mineralogy were undertaken using a Tescan Integrated Mineral Analyser (TIMA) and the results were used determine the redox condition during alteration and the paragenesis of each sample, as well as a textural and metasomatic framework for the petrophysical results. Anisotropy of magnetic susceptibility (AMS) measurements made using a MFK1-A magnetometer provide structural context. The data were integrated with basic geophysical interpretation (e.g., lineament mapping) and 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 contrasts in geophysical signatures at the sample, drill core and deposit scales. Therefore, redox zonation can be correlated with structural controls and petrophysical properties. This knowledge can be up-scaled to provide new insights into geophysical targeting of IOCG and related system across the Cloncurry District.

RESULTS and DISCUSSION

Regional Scale

Regional aeromagnetic and radiometric datasets clearly show a spatial correlation between magnetic and uranium radiometric anomalies in numerous IOCG-style deposits of the Cloncurry district, including Monakoff (Austin et al., 2013d), Canteen South (Austin et al., 2016b), Starra (Patterson et al., 2016a) and SWAN (Patterson et al., 2016b) and also pyrrhotite-dominant Cu±Zn prospects such as Cormorant (Austin et al. 2016c) and Artemis (Austin et al. 2016a). These joint magnetic-radiometric anomalies have long been correlated with magnetite and the radiometric signature reflects the presence of associated apatite and U-bearing minerals. However, their association with magnetite is not universally consistent. For example, there is a broad U-anomaly south of the Artemis Cu-Zn prospect which is implicated as a likely along strike source of mineralising fluids (Fig 2).

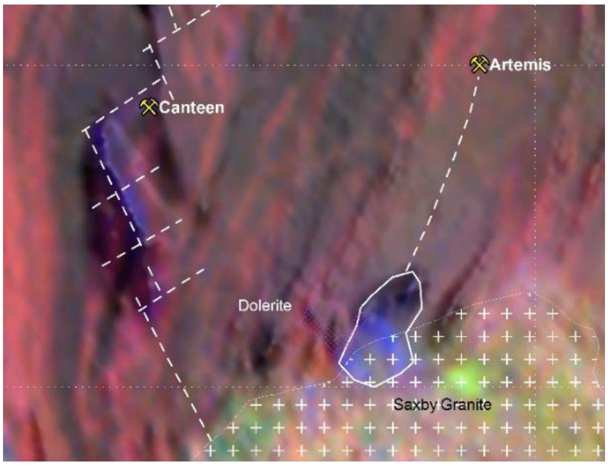

Figure 2: Regional radiometric data visualised as a ternary image, where Red = K, Green = Th and Blue = Uranium, and magnetic RTP used as shading, over the Canteen, Artemis prospects, plus the Weatherly Creek Syncline and part of the Saxby Granite.

This U-anomaly is not associated with a magnetic high, but rather is located proximal to a doleritic intrusion on the margin of the Saxby granite. This spatial coincidence implies that magma mingling could be an important process for the generation of mineralising fluids in the Cloncurry district, as suggested by Oliver et al. (2009).

At the SWAN deposit, several IOCG exploration criteria outlined are observed in only two datasets, i.e., a bullseye magnetic anomaly indicating magnetite breccia, a clear structural control mapped by the fist vertical derivative of the magnetic data and a diffuse uranium anomaly in the radiometric data that is spatially coincident with the magnetic anomaly (Fig 3). In addition, the deposit shows geophysical zonation, which is far more indicative of the mineralisation than a simple bullseye. The aspects of zonation observed at SWAN include a halo of higher amplitude linear magnetic anomalies around the broad bullseye, some of which are coincident sharp uranium radiometric anomalism, indicating potential fluid pathways, in/out of the brecciated, mineralised zone.

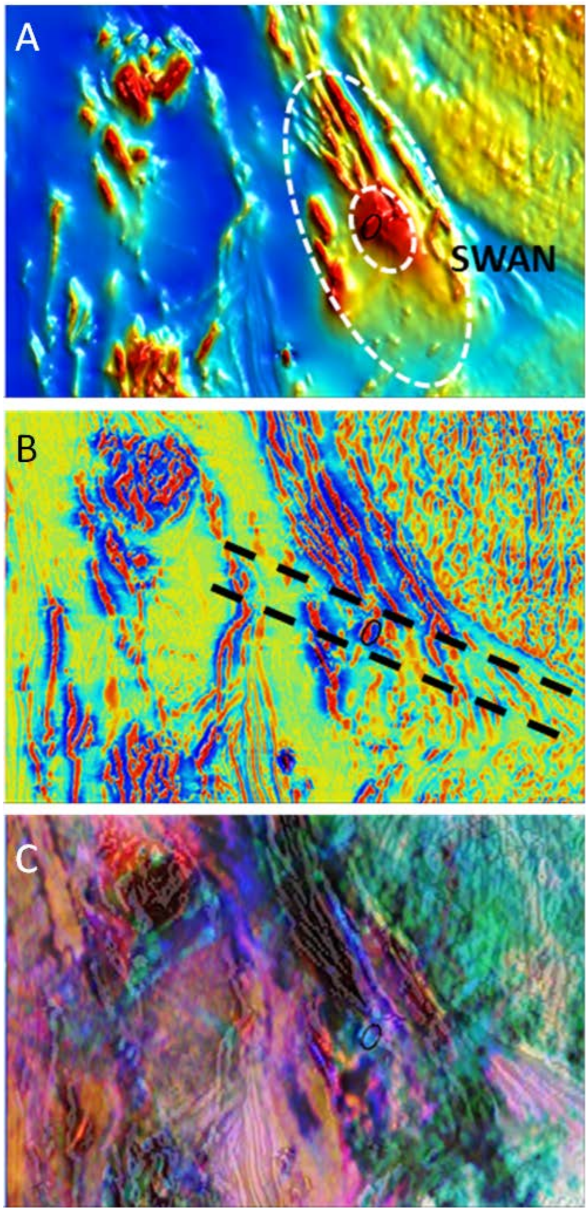

Figure 3: Geophysical imagery over SWAN: ***A. reduced to pole magnetics; B. second vertical derivative magnetics, and; C. ternary radiometrics, where K:Th:U = Red: Green: Blue.***

Sample Scale

The Cloncurry METAL project is attempting to develop techniques to map redox gradients/spikes using handheld tools by utilising integrated mineralogy, radiometric and magnetic data. The results (Fig 4) identified high uranium^2: potassium (U^2/K) ratios (typically >5) in numerous samples from deposits displaying strong IOCG affinities, including Kalman, Ernest Henry, E1, Monakoff, Cormorant, Canteen and SWAN.

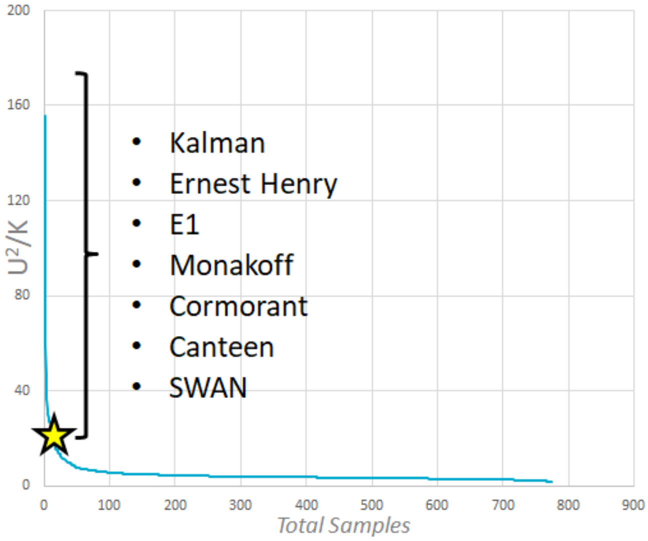

Figure 4: Plot of Uranium squared over Potassium for all radiometric data collected in this study.

Samples with high U^2/K ratio are limited to < 5% of all samples and they show atypical mineral assemblages compared to samples from the same deposit/prospect. General observations from the SEM-TIMA mineral maps from these samples are that: all contain carbonate (dolomite or calcite), all contain apatite, some also contain Uranium-bearing minerals such as allanite, monazite and celestite, and many contain magnetite and/or hematite. These lithologies display mixed redox signatures, for example many contain magnetite and pyrrhotite, and in some cases, both magnetite and hematite. The iron oxides can be readily mapped based on diagnostic petrophysical properties (e.g., magnetic susceptibility, remanent magnetisation, density, and conductivity). Therefore, we can detect aspects of possible redox gradients using geophysical tools.

The samples contain albite, andesine, oligoclase and anorthite in variable proportions and with a range of timing relationships, and they often show intergrown titanite/rutile and ilmenite. Previous work (e.g., Walshe et al., 2016) has shown that the distribution of andesine-ilmenite assemblages versus K-feldspar-titanite assemblages can be used to define pH and/or redox gradients in IOCG systems. For example, in CO_2-H_2O systems, assemblages with andesine (30 – 50 mole% anorthite feldspar), ilmenite, quartz-calcite-Fe-sulphides ± oxides in excess, indicate relatively acidic and reduced conditions whereas K-feldspar ± albite ± titanite ± biotite assemblages are stable at relatively alkaline and oxidised conditions. Therefore, we can also map other aspects of possible redox/pH gradients using mineralogical and geochemical mapping tools.

Core Scale

Austin et al (2016c) demonstrated that magnetic susceptibility (K) and remanent magnetisation (J) measurements could be used to identify redox boundaries in the Cormorant ISCG prospect (Fig 5). They correlated a redox boundary with sharp transition between a high K, high J magnetite ± pyrrhotite lithology to a low K, moderate J, pyrrhotite- dominant lithology. The boundary can be delineated using the Koenigsberger ratio (i.e., the ratio of remanent to induced magnetisation) which changes from < 5 to *ca* 45 across the boundary. Assay data shows that sulphur, copper, iron and uranium precipitation was concentrated on the boundary, with sulphur preferentially precipitated on the reduced side of the boundary and iron and uranium preferentially precipitated on the intermediate side of the boundary (Fig 5). This data therefore correlated a redox boundary with precipitation of copper and also uranium, which suggests that uranium anomalism in radiometric data, coupled with sharp changes in Koenigsberger ratio, can be used to identify redox boundaries in surface geophysics, and also in downhole data.

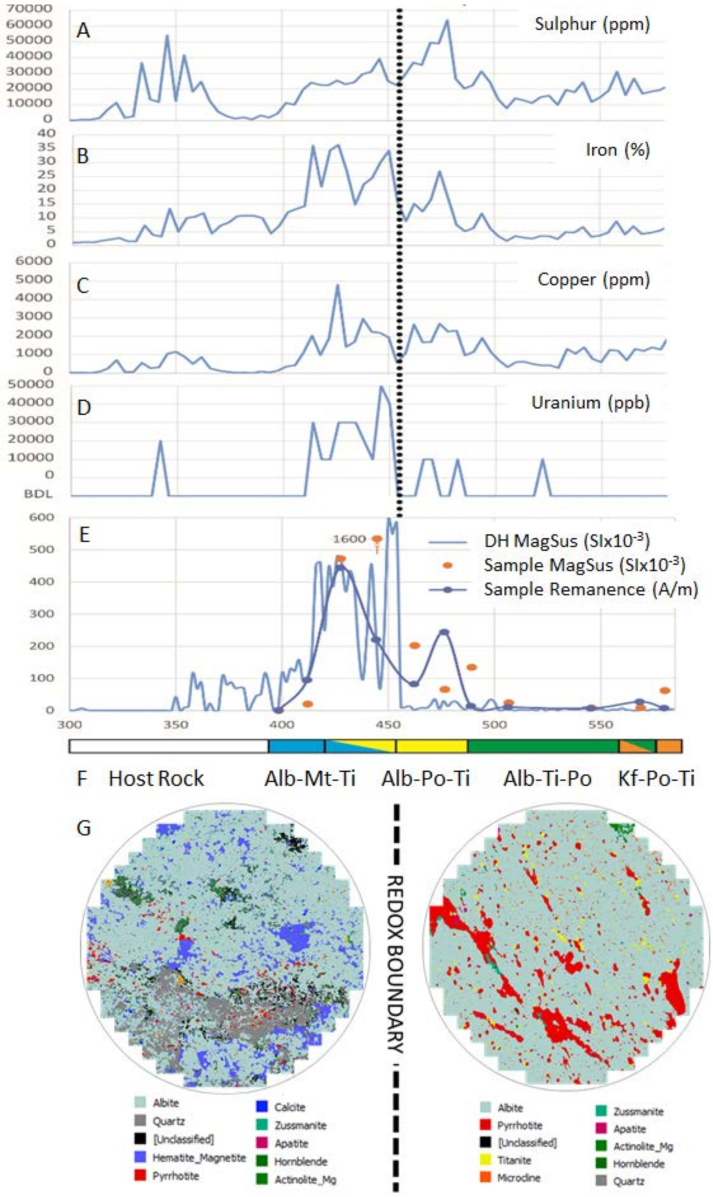

Figure 5: Compilation of data from drillhole MN10 from cormorant prospect. A. sulphur assay, B. iron assay, C. copper and D. uranium assay E. downhole magnetic susceptibility, and magnetic susceptibility and remanent magnetisation on individual samples, and G. mineralogy on each side of the redox gradient.

Deposit Scale

The Starra IOCG deposits are structurally controlled (Davidson et al., 1994) by the Starra Shear, and show signs that redox and/or pH may have played a role in localising mineralisation. Unlike the Cormorant prospect, discussed earlier, which is a magnetite-pyrrhotite system, the Starra line of deposits are magnetite-hematite dominated. Unfortunately, therefore, the Koenigsberger ratio is not ideal to characterise changes in magnetite and hematite content, but the acquisition of magnetic susceptibility and density data from all samples at Starra provides the basis for meaningful interpretation. The Starra-276 study combines 31 outcrop samples (from the ironstone ridge) and 89 samples collected from 3 drillholes along a E-W profile through the deposit. In this work we have built on the workflow used for Cormorant with the addition of 1. high resolution (25 cm) downhole magnetic susceptibility measurements, 2. magnetic fabric (AMS) data and 3. radiometric measurements on core samples. These integrated datasets (Figs 6 and 7) permit the correlation of assay data, with petrophysical data and structural fabric data downhole.

The results illustrate the presence of a steep redox/pH gradient in the upper part of the deposit (Fig. 6). The gradient is indicated by the change from low susceptibility, low strain, 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 characterised by high iron, low susceptibility and high density. In the middle of this ore zone a change from low strain to high strain coincides with a spike in U^2: K ratio. We infer that the radiometric spike coincides with a fluid pathway, and also marks a boundary between highly oxidised, native copper and gold bearing zone and a more intermediate lower iron, copper sulphide bearing zone.

The deeper parts of the deposit again show a pronounced uranium spike near the end of hole STQ1095 (Fig 7). In this case the spike is coincident with a low strain (isotropic) zone, consistent with either an extensional fracture or intense hydrothermal alteration, and displaying low susceptibility and negligible S, Fe, Cu and Au contents. This zone is typified by sample STA026 showing an assemblage of anhedral minerals consisting of calcite, dolomite, quartz, chlorite, and hematite. 30-40 m either side of the radiometric spike, there are two zones which display a strong correlation between magnetic susceptibility, sulphur, iron, copper and gold contents. These zones are typified by samples STA023 and STA027-028, which are quartz-magnetite-dolomite ± chalcopyrite assemblages. The samples appear to be metasomatic in texture, implying they may have formed by replacement of the host rock .However, we infer that the radiometric spike in this case coincides with a major fluid pathway, and the mineralised zones halo a central oxidised structure at a distance of 30-40m.

At Starra-276 the mineral zonation is interpreted as a lateral redox gradient extending from the barren hanging wall rocks 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 redox/pH gradients control mineral precipitation both laterally and vertically in Starra-276. We further infer that radiometric spikes coupled with sharp gradients in anisotropy can be utilised to assist mapping of fluid pathways in IOCG systems.

CONCLUSIONS

This study demonstrates that geochemical and mineralogical footprints commonly preserve coincident geophysical footprints in many IOCG deposits of the Cloncurry district. We have argued that IOCG exploration needs to move beyond the “combined gravity-magnetic high paradigm” and demonstrated that geophysics can be used to map, not just magnetic and gravity anomalies, but structural controls and fluid pathways, three of the main IOCG exploration vectors. Structural controls can be mapped using vertical derivative filters at regional scales, and by anisotropy of magnetic susceptibility (AMS) at the core to sample scale. We have also shown that U-rich radiometric signatures coupled with strain mapping (using AMS) can be used as a proxy for identifying, structural controls/fluid pathways and redox gradients in IOCG systems. Whilst regional radiometrics may appear to be of limited use in undercover areas, adaptation of this method for use as a petrophysical tool in the core-shed has the potential to be a game changer for IOCG exploration. Used in conjunction with complimentary techniques such as magnetic susceptibility, density, AMS, conductivity, downhole geophysical logging, pXRF, mineralogical and hyperspectral scanning and structural geology, it can be used to help identify fertile fluid pathways and geophysical footprints of metallogenic importance.

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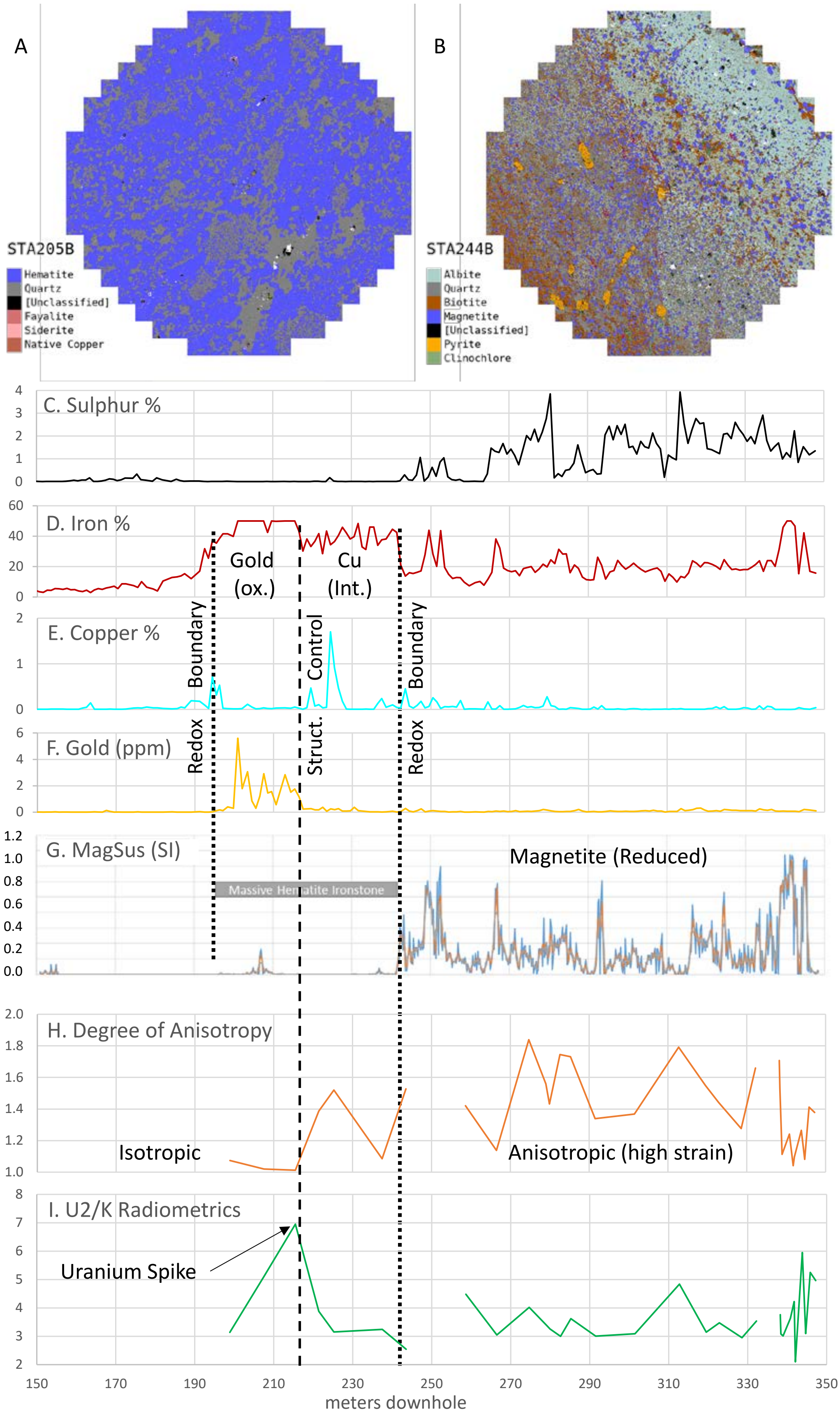

Figure 6: Compilation data from drillhole STQ1098 from Starra-276. A. Ironstone mineralogy; B. Footwall mineralogy; C. sulphur; D. iron; E. copper and; F. gold assay results; G. downhole magnetic susceptibility; H. anisotropy (P) factor of AMS ellipsoid; I. U^2:K ratio of radiometric data.

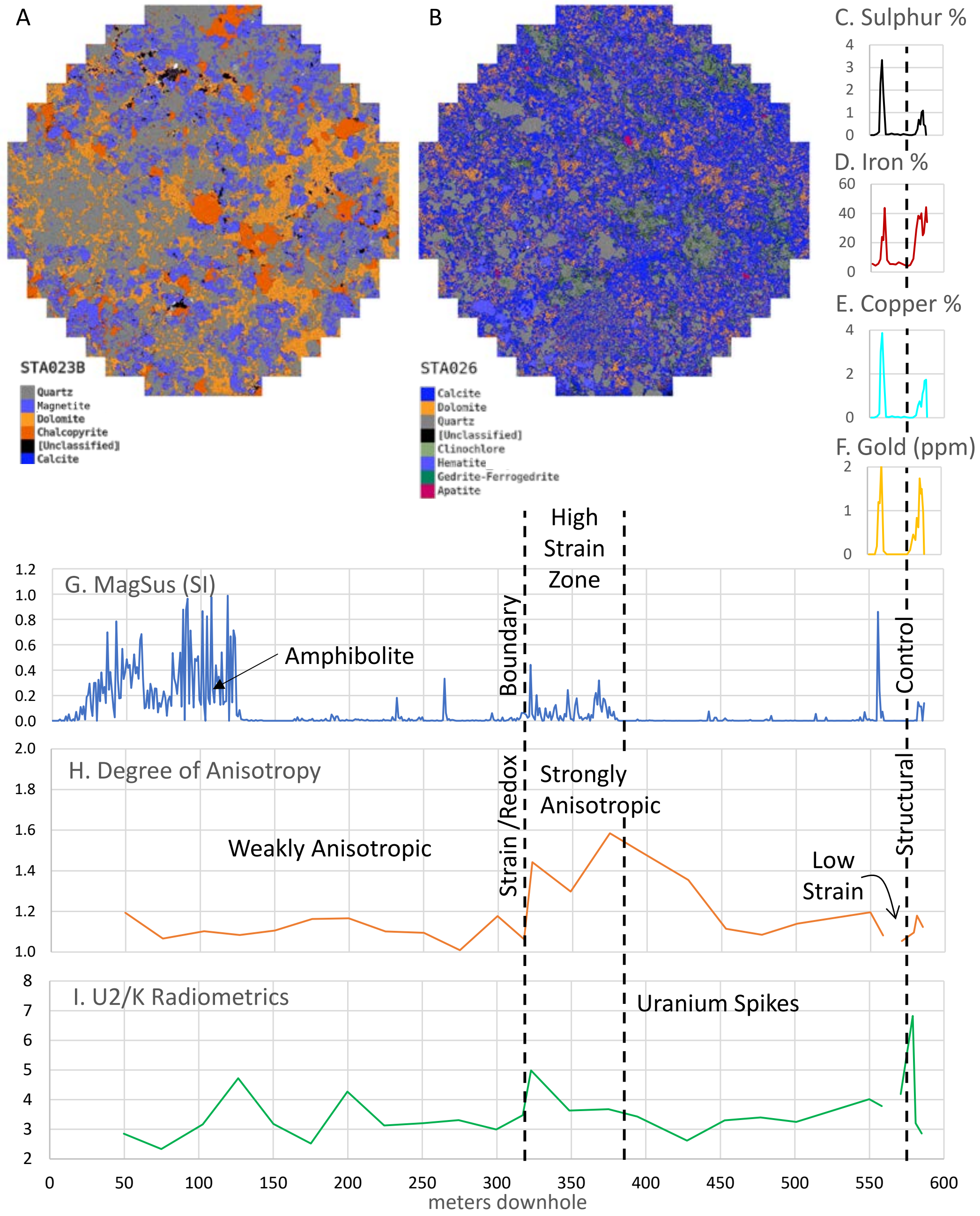

Figure 7: Compilation data from drillhole STQ1095 from Starra-276. A. Skarn mineralisation; B. calcite-quartz-chlorite (fluid pathway) assemblage; C-I as for Fig 6.