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Minerals geophysics

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In 2016 CSIRO Mineral Resources completed the Uncover: Cloncurry project and formally presented their results. To me, the idea that systematic and multidisciplinary measurements on critically selected drill-core and hand specimen samples can be extrapolated to add to the understanding of district scale mineralising processes is one of the ways into the future for mineral geophysics.

Jim Austin and his colleagues at CSIRO have summarised some of their methodologies and findings (with an emphasis on mineral geophysics) for this edition of *Preview*. I invite you to read on.

Integrating knowledge from structural, geochemical and petrophysical analyses at sample to regional scales: new insights into the Mount Isa Eastern Succession

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Background

The Uncover: CLONCURRY project was funded in 2015 by Round 3 of the Queensland Government's Industry Priorities Initiative. The funds gave CSIRO Mineral Resources the opportunity to work with the Geological Survey of Queensland (GSQ) and industry partners, including: Minotaur, MIM-Glencore, Exco-Copperchem, CST, Sandfire, Hammer Metals, Red Metal and Chinova, in developing mineral systems based exploration in the Mount Isa Eastern Succession. The aim was to undertake integrated petrophysical and geochemical/mineralogical micro-characterisation of deposits across the Cloncurry District, and to use those data to better understand the structural, metasomatic and metallogenic processes that led to formation of the diverse styles of mineralisation of the Cloncurry District, within the architectural and geodynamic framework of the Mount Isa Eastern Succession.

The techniques utilised can be summarised in Figure 1, and include petrophysical analysis (e.g. density, remanent magnetisation, magnetic susceptibility, anisotropy of magnetic susceptibility (AMS)), and mineral mapping techniques (e.g. micro X-ray fluorescence (µXRF), rapid scanning electron microscopy (SEM) and micro X-ray computed tomography (µCT), and hyperspectral mineral mapping).

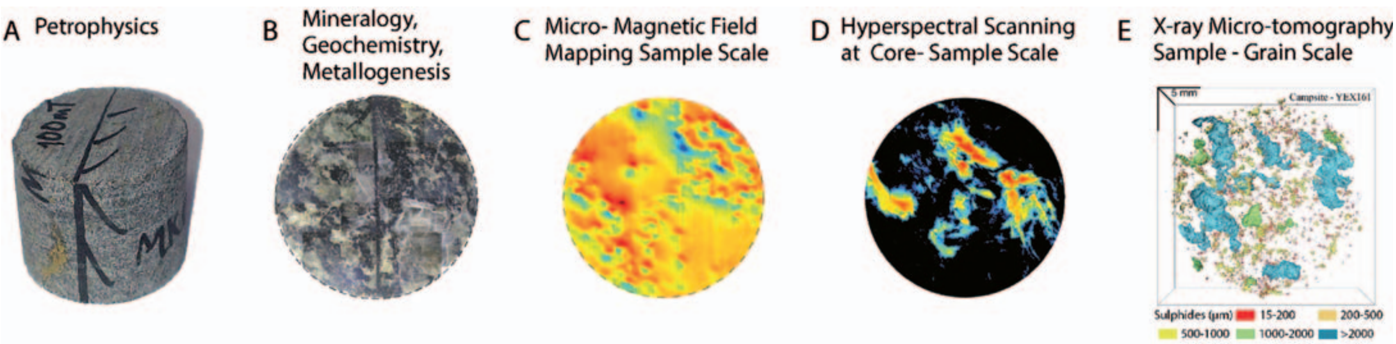

Figure 1. *Samples obtained for petrophysics were subjected to suite of geochemical and mineralogical analyses, and utilised for various mineral mapping techniques (e.g. micro-magnetic field mapping, hyperspectral mineral mapping and X-ray micro-tomography).*

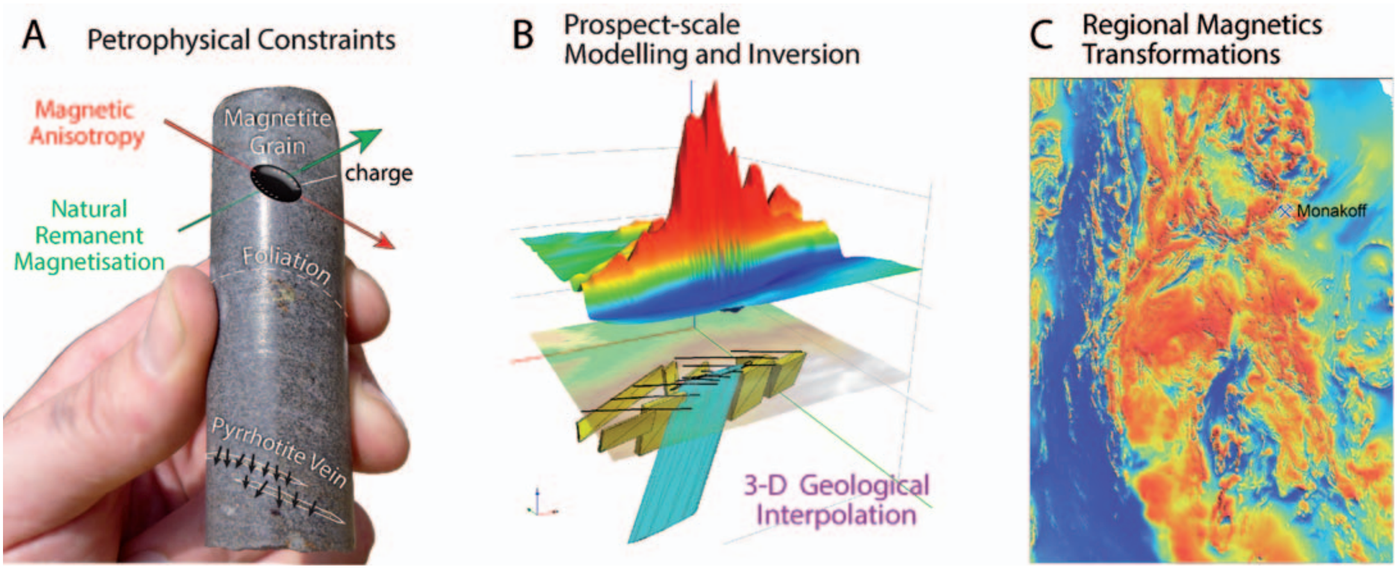

Figure 2. *Petrophysical analyses were used to constrain deposit/prospect scale modelling of specific mineralisation styles, and also to constrain transformations of the magnetic field.*

A strength of this integrated, multi-deposit approach is the creation of an internally-consistent dataset of samples analysed in a consistent manner. This facilitates direct comparisons between deposits, and enables application of insights gained at the deposit scale, resulting in a better understanding of the mineral system as whole (e.g. Figure 2).

AMS data were obtained for at least one specimen from almost every sample obtained from 17 deposits and prospects across the Cloncurry District, possibly constituting the only such dataset compiled across an entire mineral system ever collected.

AMS data are used to quantify structural fabrics within the mineral system, and are used to identify potential structural controls. In many cases it is possible to differentiate fabrics within different parts of the system, e.g. host rocks, mineralised zones, and overprinting relationships. It is also possible to identify fabrics caused by re-activation of pre-existing structures, as well as extensional fabrics. The structural insights provided by the AMS measurements provide a fundamental insight into both the spatial and temporal relationships between deformation, alteration and mineralisation, allowing us to temporally relate structural development to metasomatic and mineralising events across the Cloncurry District.

Integrated structural, metasomatic and metallogenic history of the Cloncurry District

Since the structural data provided by the AMS measurements provide fundamental insights into both the spatial and temporal relationships between alteration and mineralisation, the tectonic evolution of the Cloncurry District is considered in this context. These analyses illustrate that the Cloncurry mineral system is long-lived, comprising several mineralising, orogenic and metasomatic events that are often temporally inter-related, and which overprint each other in a variety of ways, to form disparate deposit styles. In the most simplistic terms, the mineral system was pre-conditioned by early (*ca* 1650 Ma) input of large volumes of Fe plus both Cu–Au and Pb–Zn-rich mineralisation in a syn-depositional exhalative setting. During D_2 (*ca* 1590–1570 Ma) peak temperature and strain conditions (e.g. 630 ± 50 °C and 8 ± 2 kbar at Artemis), there was some remobilisation of metal within the Cloncurry mineral system, via partial melting, metamorphic fluids and/or “skarn” formation. However, the relatively hot, ductile conditions prevented the formation of large-scale permeable fluid pathways, and this, together with a relative lack of magmatic fluid sources, was not conducive to the formation of hydrothermal deposits. Conditions became more favourable during the late history of the Isan Orogeny. During the later history (i.e. post-D_4), strain conditions transitioned from ductile to brittle, and the kinematics gradually switched from shortening ± transpression (D_2–D_4), to strike-slip (D_5) and then to post-Isan extension at *ca* 1500 Ma. This orogenic switch is coincident with intrusion of multiple voluminous phases of felsic magma (e.g. the Williams Batholith), and associated metasomatic events. The majority of hydrothermal mineral deposits formed from *ca* 1525 to 1500 Ma, in conjunction with several different metasomatic overprints, e.g. sodic-calcic (SWAN), magnetite-apatite (Canteen, E1), potassic (Ernest Henry), magnetite-barite-fluorite (Monakoff, E1), calcic (SWAN, Mt Colin), and chlorite-hematite-pyrite (Ernest Henry, Kalman, Merlin, Canteen). In many cases deposits show evidence of two or more styles of mineralisation, e.g. sedex + skarn (Maronan, Artemis), sodic-calcic + calcic (SWAN), sedex + magnetite-barite-fluorite (Monakoff, E1) and skarn + magnetite-apatite + chlorite-pyrite (Canteen).

Strain conditions, structures, magmatic systems, fluids and heat sources varied in magnitude and focus through time, and therefore interacted in different ways to form a range of different deposit styles (Figure 3).

Geophysical expressions of the Cloncurry Mineral System

The geophysical response of a mineral system is a function of the structural and the geochemical development within the system. In this case, since we have used techniques that mainly deal with magnetic properties, the main geochemical/mineralogical events/processes of interest pertain to the precipitation of magnetite and pyrrhotite, plus hematite and pyrite (due mainly to their high densities) and economic sulphides (e.g. chalcopyrite, sphalerite, galena). This is the first time

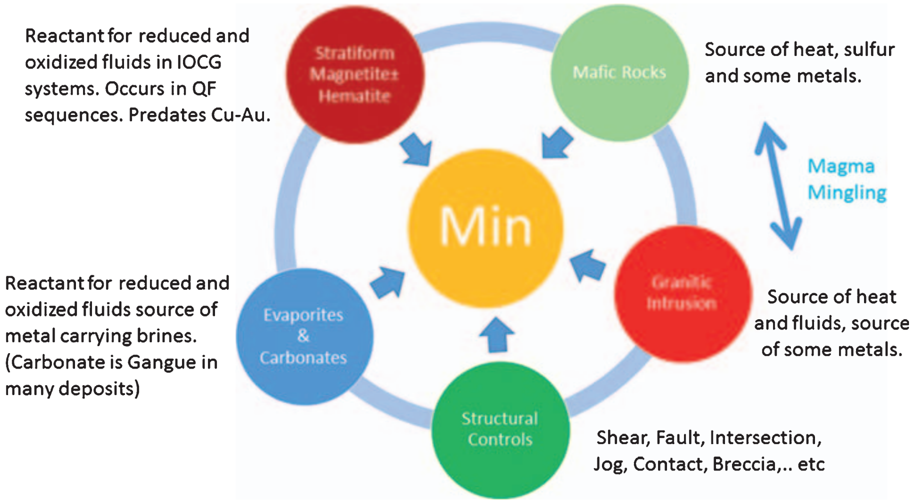

Figure 3. *Schematic highlighting the different ingredients of the Cloncurry mineral system, which combine in different ways to form a variety of different deposits styles across the district. IOCG = iron oxide copper-gold; QF = quartzofeldspathic.*

any study has brought together so much petrophysical data from so many different styles of mineralisation across a mineral district, and the results provide important constraints for future exploration for various styles of mineralisation undercover. The deposits studied have a wide variety of petrophysical properties, primarily dictated by the relative contents of magnetic minerals (e.g. magnetite, monoclinic pyrrhotite, hematite) and other non-magnetic minerals (e.g. hexagonal pyrrhotite, pyrite, galena, sphalerite, barite). Any combination of these minerals can be associated with high densities. High magnetic susceptibilities (and hence high amplitude magnetic anomalies) are invariably associated with coarse magnetite, whereas monoclinic pyrrhotite is associated with moderate magnetic susceptibility and high remanence (and potentially unusual magnetic anomalies). Hematite is only weakly magnetic.

Many specimens contain mixtures of different Fe-oxide and sulphide phases, which are related to redox and/or overprinting. Assemblages within IOCGs in general sit on a spectrum, from highly reduced to highly oxidised (Figure 4). Oxidised assemblages contain hematite, no pyrrhotite, but typically pyrite and variable magnetite. Intermediate assemblages are typically magnetite-rich, and can contain pyrrhotite and/or pyrite. Reduced assemblages are typically pyrrhotite dominant, contain no hematite, but often do contain magnetite. Our observations suggest that hexagonal (non-magnetic) pyrrhotite is typically associated with galena and sphalerite (in sedex/BHT deposits), whereas magnetic pyrrhotite is more typically associated with Cu prospects (in hydrothermal deposits).

The deposits and prospects assessed by this study have a large range in magnetic susceptibility, from essentially negligible (e.g. 10^{-6} SI) to 2.1 SI (Figures 5, 6). In many cases high densities are correlated with high magnetic susceptibilities (e.g. Figure 5), and in most of these 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. High densities correlated with moderate susceptibilities are in many cases due to pyrrhotite. High densities and low susceptibilities are in many cases due to hematite and/or any of the

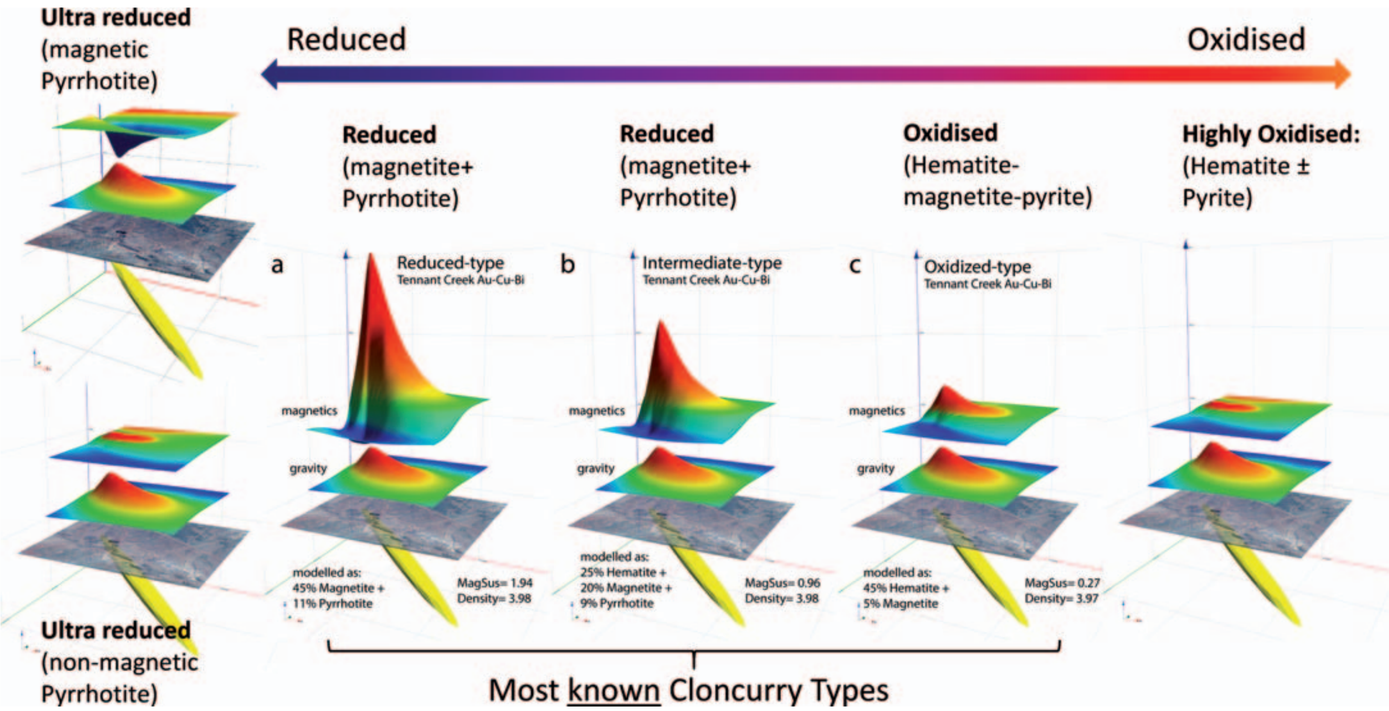

Figure 4. *Synthetic models of the El Dorado deposit, Tennant Creek (based on Austin and Foss, 2014), which contain different proportions of Fe-oxide and Fe-sulphide minerals, based on their Redox state. All the mineral assemblages have comparable density, but the different redox states have very different geophysical expressions.*

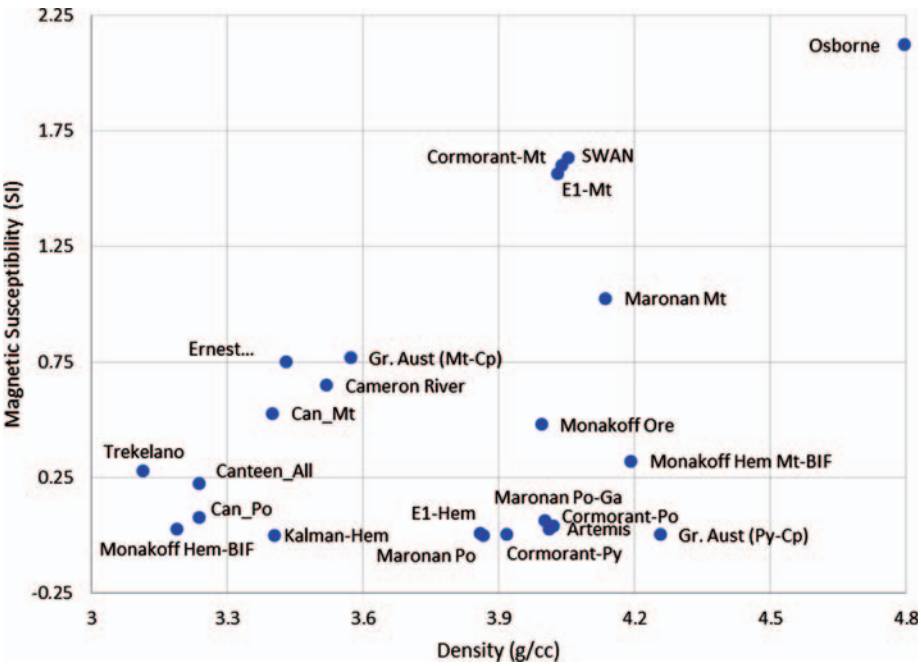

Figure 5. *Plot of magnetic susceptibility vs density for ore samples from deposits/prospects assessed in this study.*

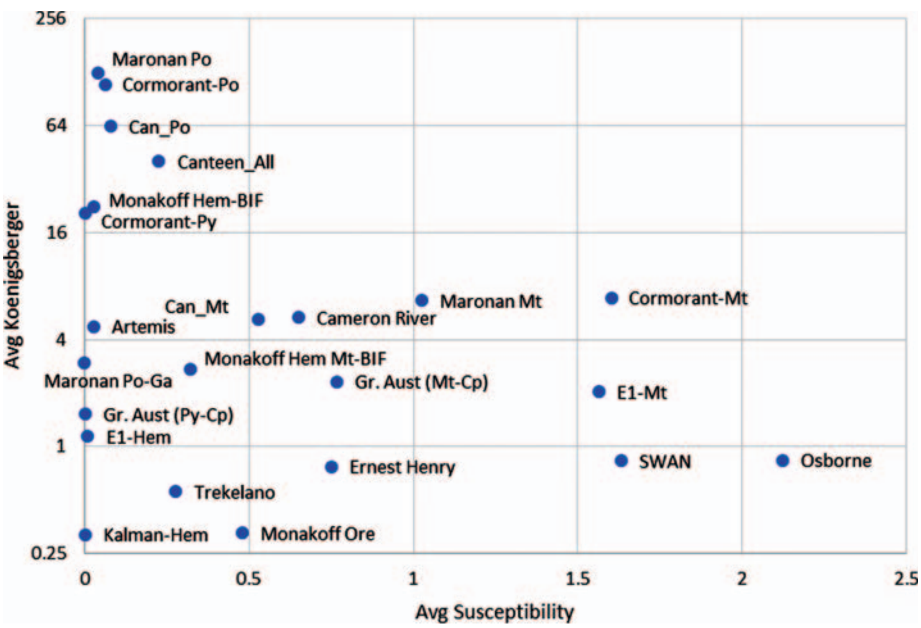

Figure 6. *Plot of the ratio of NEM to magnetic susceptibility (Q, Koenigsberger Ratio) vs magnetic susceptibility for ore samples from deposits/prospects assessed in this study.*

other sulphide minerals. The various deposits have a range of natural remanent magnetisation (NRM) intensities from negligible up to mean values of 450 A/m, with associated Koenigsberger ratios of up to 130 (Figure 6). Deposits that have high Koenigsberger ratios are usually dominated by monoclinic pyrrhotite as the magnetic phase. Where monoclinic pyrrhotite is the dominant phase it is possible that targets can be mis-modelled due to their magnetisation being different to the Earth's local magnetic field.

In terms of petrophysical properties there are several recognised associations:

1. Deposits with high density, high susceptibility, and low Q are dominated by coarse MD (multidomain) magnetite, e.g. Osborne, SWAN.
2. Deposits with high density, high susceptibility, and moderate Q are pseudo single-domain magnetite-rich (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, Canteen.
4. Deposits with high density, low susceptibility, and moderate Q are rich in metamorphosed hematite, e.g. Monakoff West BIF.
5. Deposits with high density, low susceptibility, and low Q may contain hexagonal pyrrhotite and/or sphalerite, galena, pyrite and hematite, with a relative absence of magnetite.

Comprehensive reports are available for all 16 individual deposits and prospects across the district, as well as several summary documents. For further information contact james.austin@csiro.au or ben.patterson@csiro.au.

Reference

Austin, J. R., and Foss, C. A., 2014, Understanding iron oxide copper-gold (10CG) magnetic targets from the inside out: case studies from northern Australia: Annual Geoscience Exploration Seminar (AGES), 18–19 March 2014, Alice Springs.

Jim Austin is a structural geologist and geophysicist whose main interest is in the application of magnetic methods to mineral exploration. Prior to joining CSIRO he worked with the Predictive Mineral Discovery CRC, for the Encom-Mapinfo Geoscience Consulting Group, and also as an exploration geologist in Broken Hill, the Mount Isa Inlier, Papua New Guinea and the Thomson Orogen. In his current role at CSIRO he is focussed on understanding the geophysical properties of Iron Oxide Copper-Gold (IOCG), Sedex, BHT (Broken Hill Type), BIF (Banded Iron Formation) and Magmatic Ni-Au-PGE systems, partnering with exploration companies around Australia.