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Geophysical Signatures of IOCG & Sedex/BHT style mineralization in the Cloncurry District, Qld.

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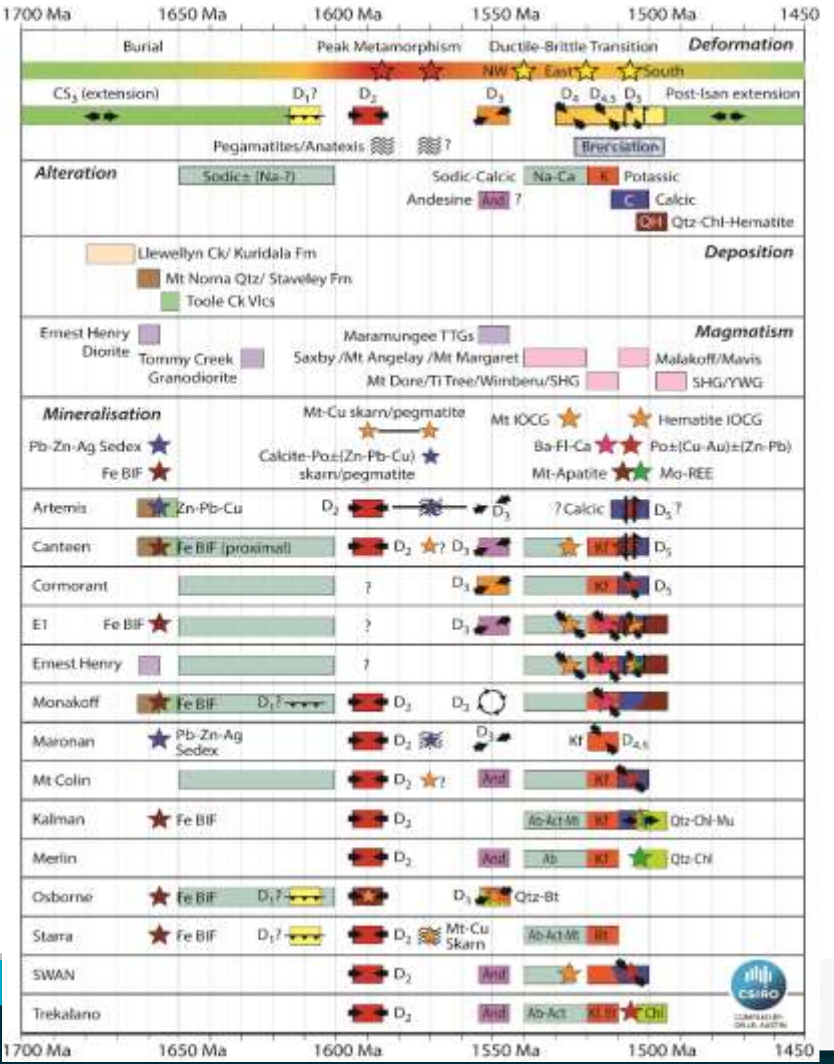
EXPLORATION 17
DMEC CONFERENCES

The "Curry"

- The Cloncurry district is world renowned for IOCG mineralization, but:
- Mineralization styles are diverse, including:
  - Iron-Oxide Copper-Gold (IOCG)
  - Iron Sulfide Copper-Gold (ISCG)
  - Sedex / Broken Hill Type (BHT)
  - Skarns and Carbonate hosted deposits, Intrusion related Cu-Mo.

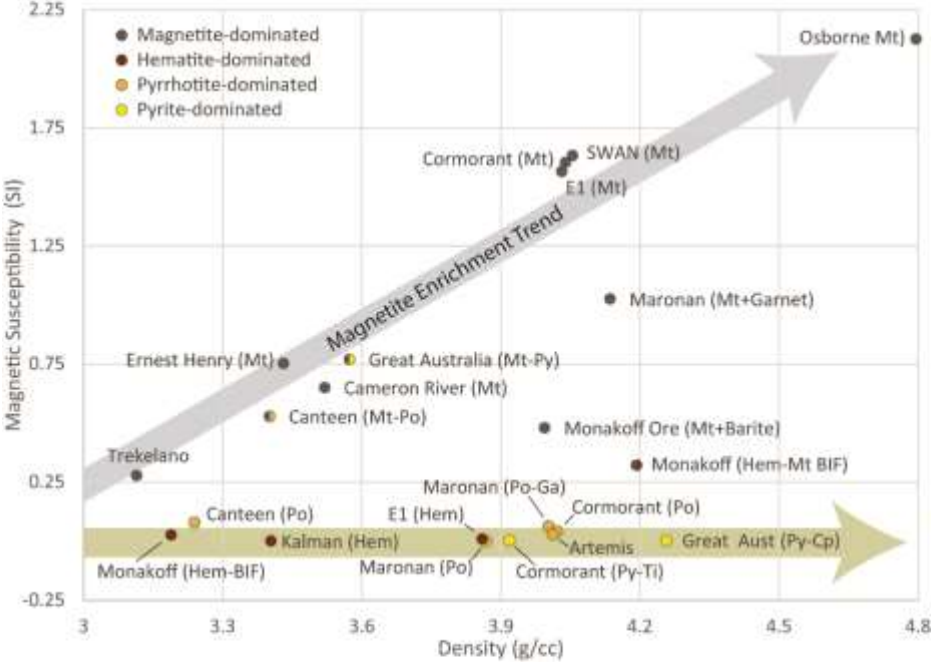
The “Curry”

- The deposits are both mineralogically and petrophysically diverse,
- Highly variable geochemical and geophysical expressions.
- Few deposits are monogenetic, many deposits formed via overprinting of two or more different ore forming systems,
- These occurred during (often interrelated) tectonic, metamorphic magmatic and metasomatic events (Fig 2).



Petrophysics Overview

MagSus vs Density



- Deposits with high density, high MagSus, are dominated by coarse MD magnetite, e.g., Osborne, SWAN.
- Deposits with high density, medium MagSus (e.g., Cormorant, Maronan) may contain magnetite and pyrrhotite.
- Horizons with high density, low MagSus, contain hematite, e.g., Monakoff West BIF.
- Deposits with high density negligible magnetization may contain hexagonal pyrrhotite and /or sphalerite, galena, pyrite and hematite,

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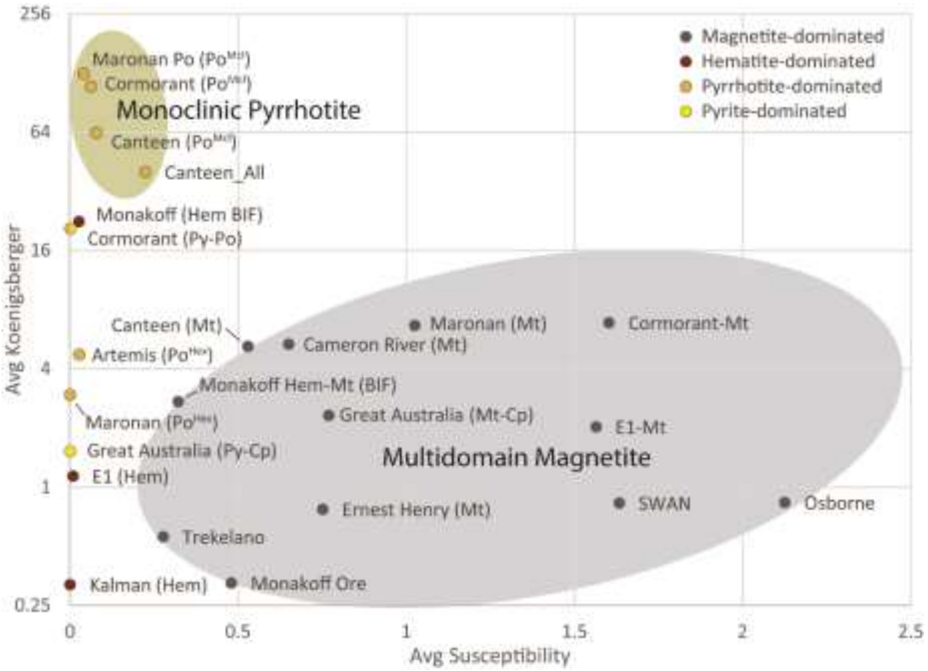
Petrophysics Overview

MagSus vs Remanence



- Deposits with high MagSus, and low Q ratios are dominated by coarse MD magnetite, e.g., Osborne, SWAN.
- Deposits with low susceptibility, and high Q are rich in monoclinic pyrrhotite, e.g., Cormorant, Canteen.
- Deposits with low MagSus, and low Q may contain hexagonal pyrrhotite, pyrite or hematite.

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Redox

These principles are relevant to Sedex deposits too

Reduced → Oxidised

Ultra reduced (magnetic Pyrrhotite)

Reduced (magnetite+ Pyrrhotite)

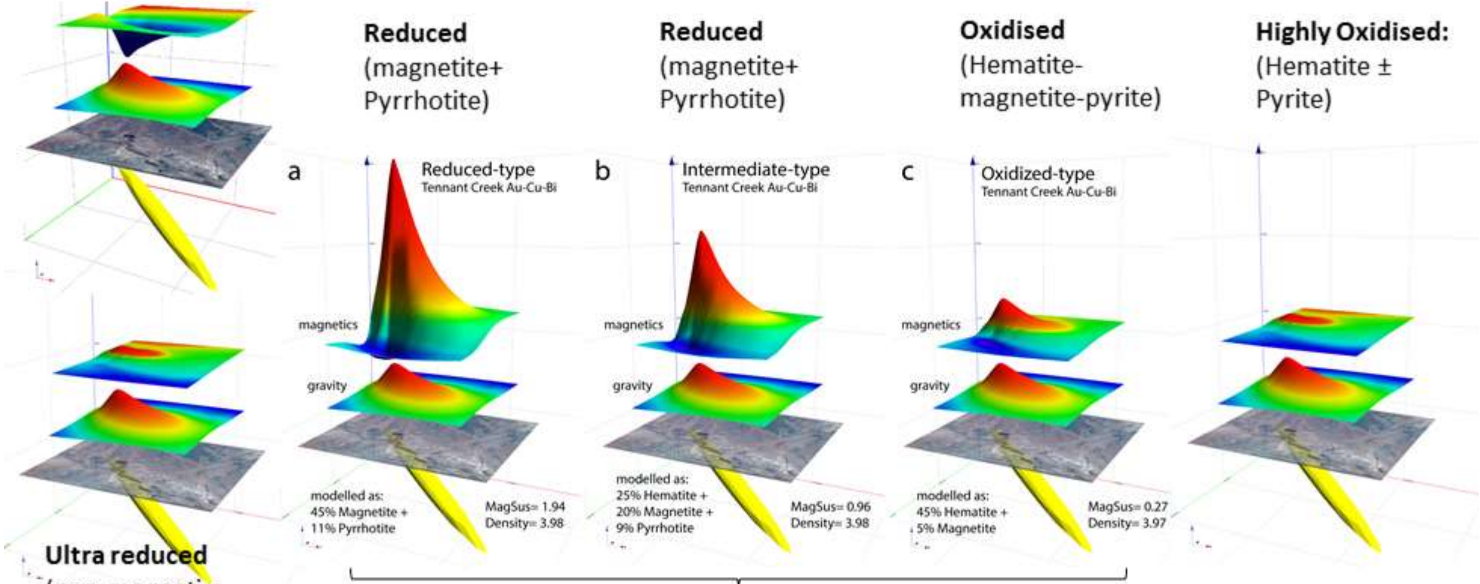
Reduced (magnetite+ Pyrrhotite)

Oxidised (Hematite-magnetite-pyrite)

Highly Oxidised: (Hematite ± Pyrite)

Associated with Cu.

Associated with Pb & Zn



Ultra reduced (non-magnetic Pyrrhotite)

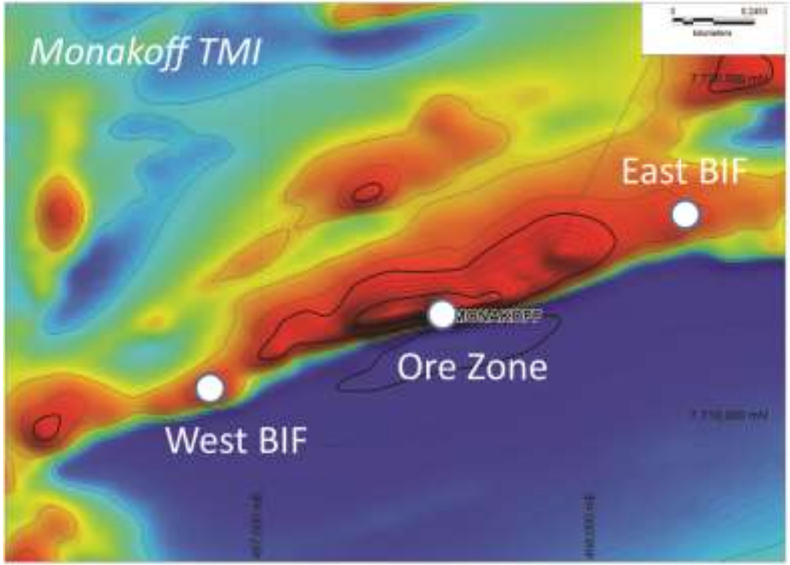
Most known Cloncurry Types

Associated with Apatite ↔ Associated with Pyrite

Sedex / BHT systems

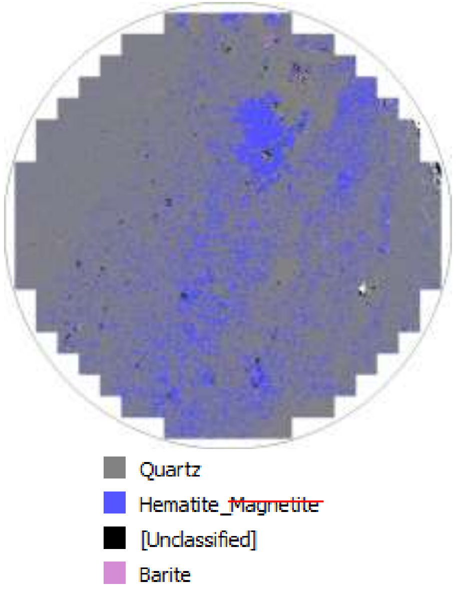
Sedex Zonation

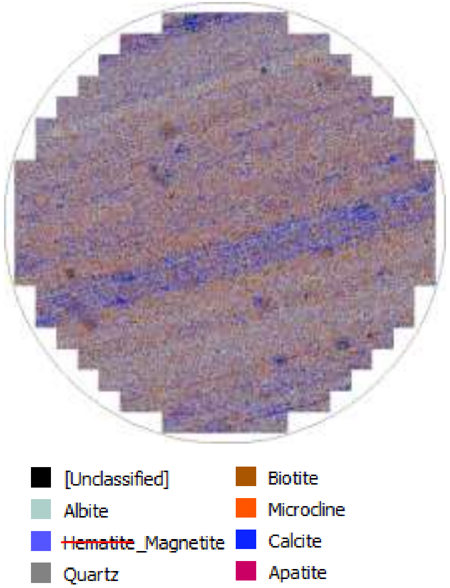
- produce bedding parallel magnetic anomalism.
- Redox controls the species of Fe-oxide, whereby
- Distal deposits are
  - More oxidized (e.g., hematite ± magnetite).
  - Have greater sediment content
  - Subtle anomalies weakly magnetic
  - Can have high Q ratios (e.g., 13, in hematite BIF)
- Deposits proximal to the source are:
  - More reduced (e.g., magnetite ± pyrrhotite)
  - Contain majority of economic metals
  - Can have high MagSus in MD magnetite (proximal to source)
  - Can have extreme remanence in Pyrrhotite (at the source)

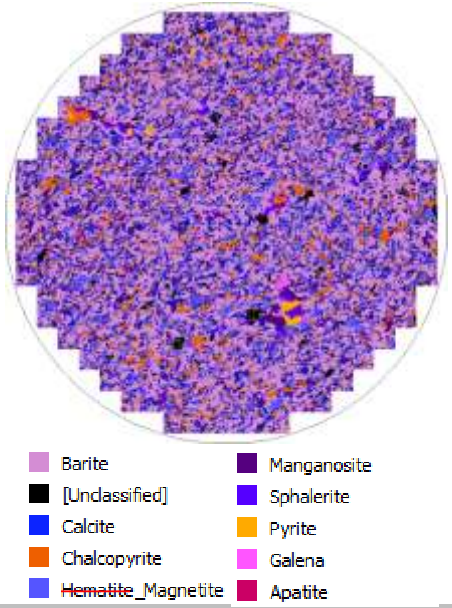


Monakoff	Density (g/cm^3)	Mag Sus K (SI)	Koenigsberger Ratio (Q)
host rocks	2.81	0.0014	-
BIF West (Qtz-Hem)	3.19	0.03	12.27
BIF East (Qtz-Mt-Hem)	4.19	0.32	1.54
Ore (Mt-Cp-Py)	3.99	0.48	0.16

Monakoff zonation







The ore zone:

- totally recrystallized
- barite-rich
- magmatic signature
- Cu and Pb-Zn

?

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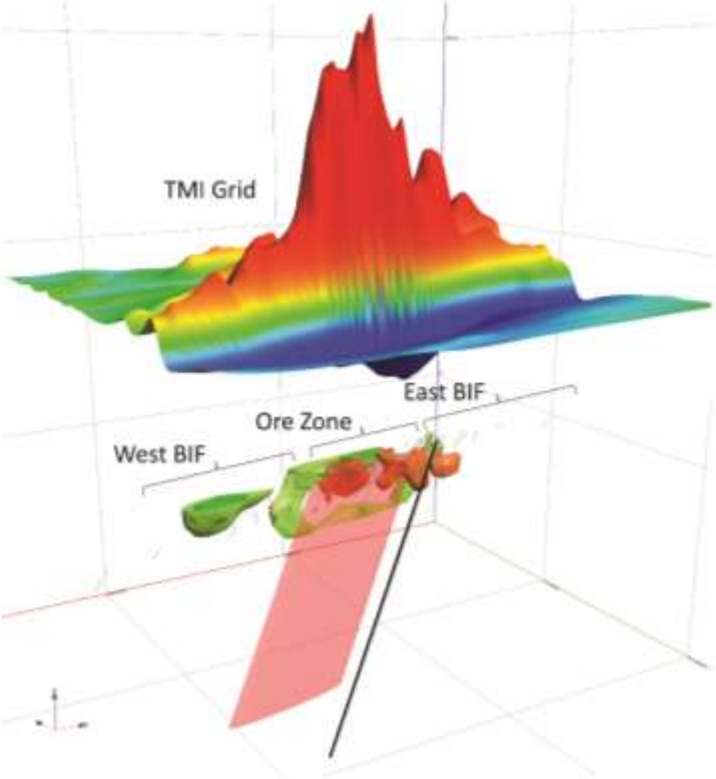
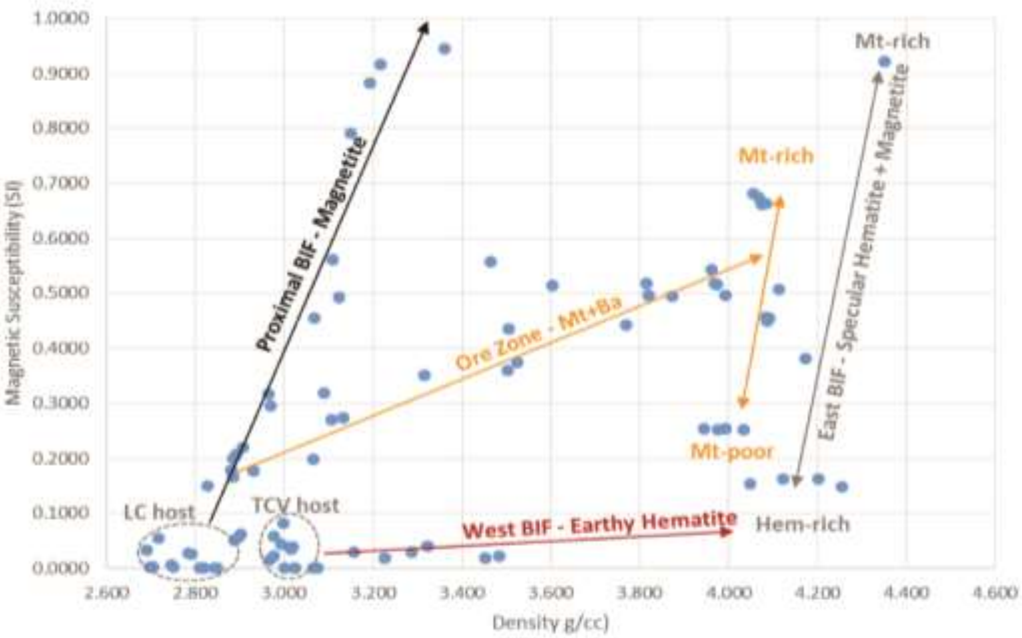
Monakoff overprinted by Magmatic fluids





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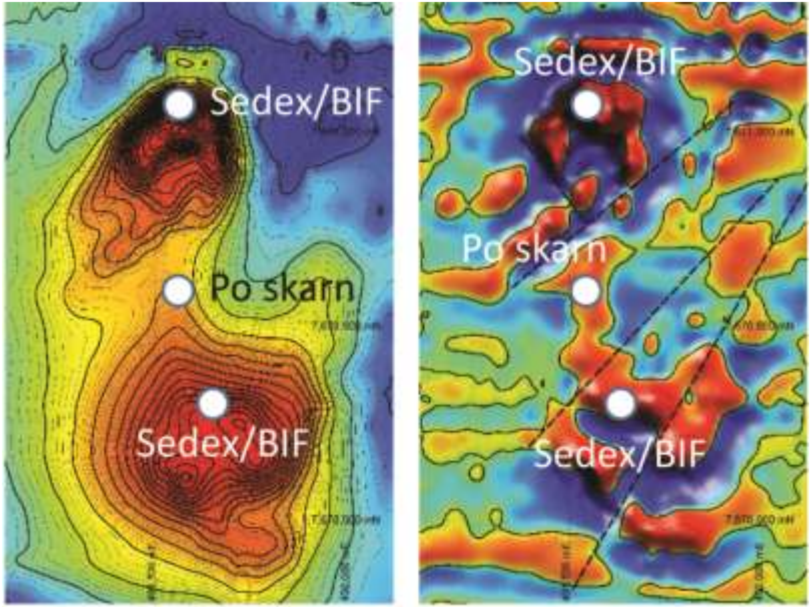
Pyrrhotite ± Pb-Zn-Cu

- Pyrrhotite ± Pb-Zn-Cu assemblages occur at Artemis, Altia and Maronan.
- At Maronan it is located in the central part of the mineralized zone.
- In the Sedex mineralization model the central zone is the most reduced (e.g., pyrrhotite –rich
- Mineralisation occurs in the saddle between the two large anomalies



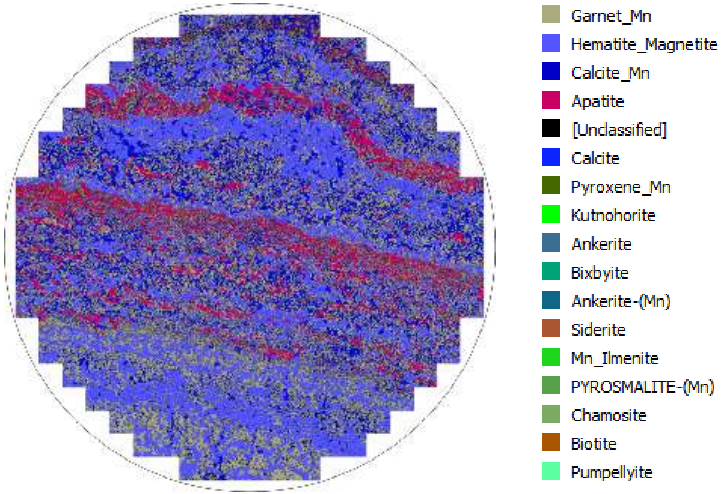
Maronan TMI *Maronan* 1VD

Maronan	Density (g/cm^3)	Mag Sus K (SI)	Koenigsberger Ratio (Q)
host rock	2.91	0.01	11.37
Po skarn	3.27	0.01	62.17
Potassic Alt	2.91	0.37	0.99
Sedex	3.71	0.62	5.32

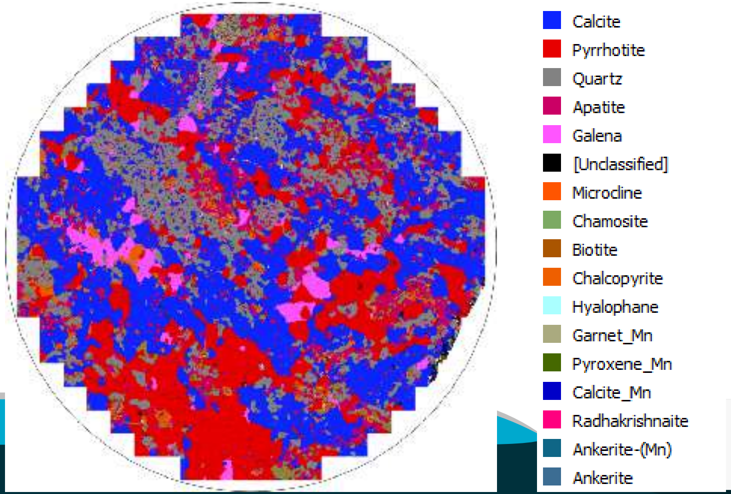
Pyrrhotite melts

- These calcite–pyrrhotite assemblages are sometimes referred to as “skarns”,
- But the core of the system has probably just melted during peak metamorphism.
- The pyrrhotite in the core is associated with main mineralization
- It is mainly non-magnetic (hexagonal)
- We infer that the pyrrhotite changes crystal structure, from monoclinic to hexagonal due to recrystallisation

Mt-rich proximal

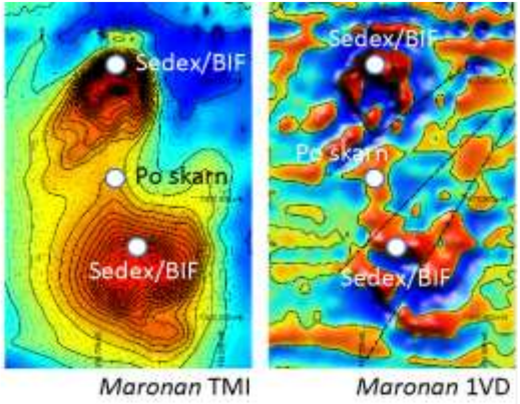


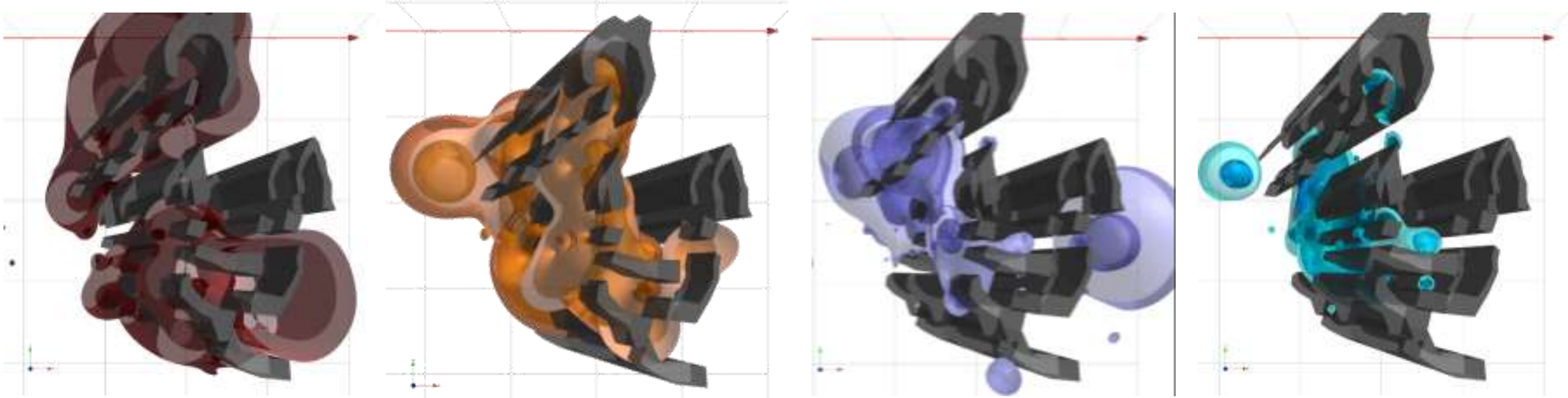
Po-rich core



Mag vs Min - Maronan

- Magnetic zonation and mineral zonation are coupled
- Fe proximal, Pb from proximal to the core
- Zn and Silver occur mainly in the core of the system





Mag Sus (Magnetite) Lead Zinc Silver

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Iron Oxide Copper-Gold & Iron Sulfide Copper-Gold Systems

IOCG & ISCG alteration systems

- hydrothermal mineralization:
  - Highly variable
  - 50 Ma Post-peak metamorphism
  - Synchronous with felsic magmatism
  - Structurally controlled
  - Occurred during transition from convergence to transpression then extension

- Mineralization was associated with a number of different alteration types:
  - magnetite-apatite and the sodic (±calcic) alteration
  - Potassic Alteration
  - Pyrrhotite-Calcite Alteration
  - Pyrrhotite-Albite Alteration
  - Quartz-Chlorite-Hematite alteration (retrograde)

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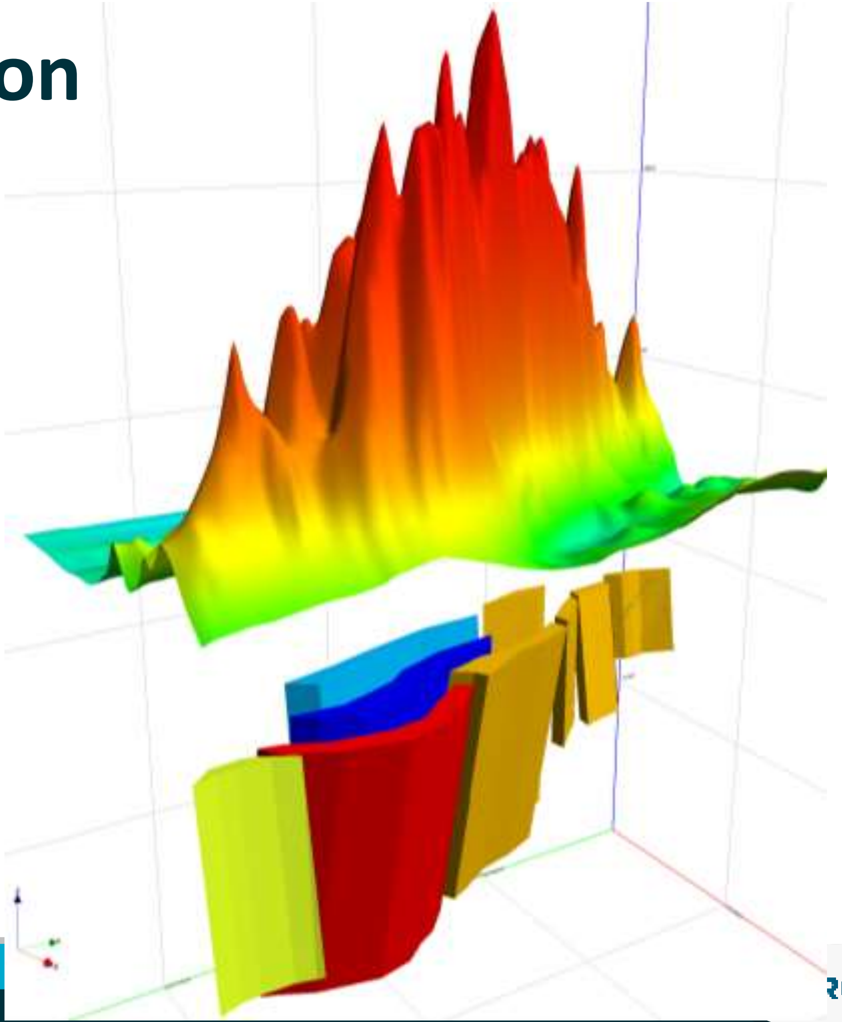
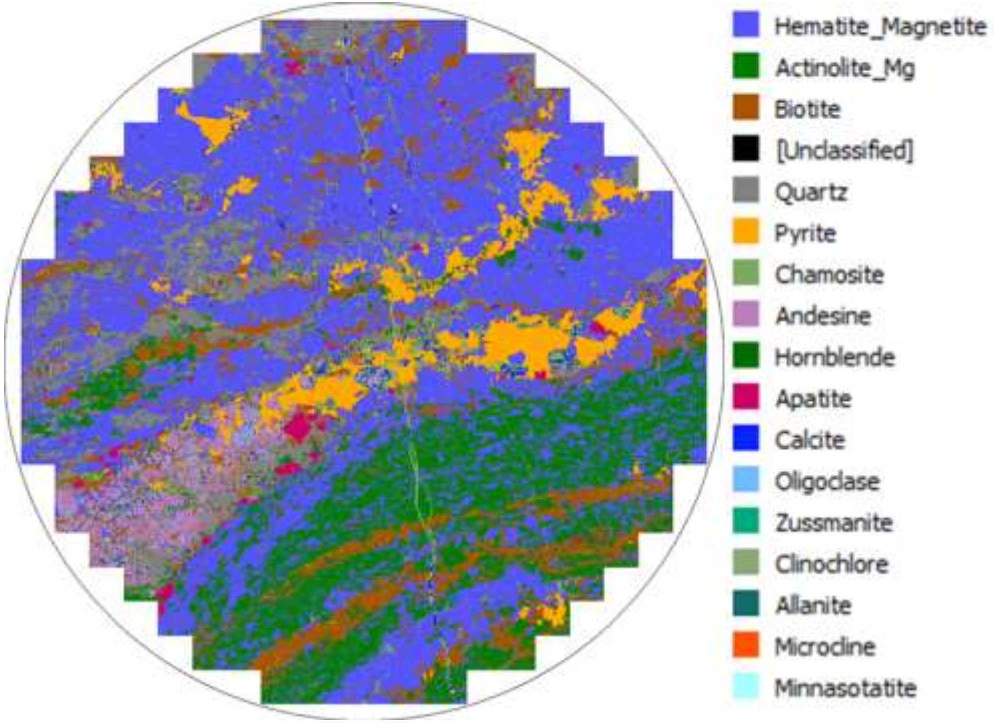
Magnetite-Apatite Alteration

- Magnetite-apatite assemblages are common in IOCG-style deposits, particularly Kiruna-type
- associated with extreme susceptibility,
- relatively minor, (viscous) remanence, typical of multidomain magnetite.
- large magnetic anomalies
- The biggest include Osborne, and Canteen (right)



Magnetite-Apatite Alteration

- Lots of coarse MD Magnetite
  - Sample EHM005 from Ernest Henry had a magnetic susceptibility of ~1.8 SI and a Q ratio of ~0.5
    - (NB: remanence is amplified by ~300% due to DIM, so the *in situ* Q would be 0.1-0.2).
  - Similar samples drilled from the pit at E1 had mean susceptibilities of 1.5 – 2.0 SI, and Koenigsberger ratios of 0.1 – 0.2.
    - NB: because these were surface sampled, they are not affected by DIM.



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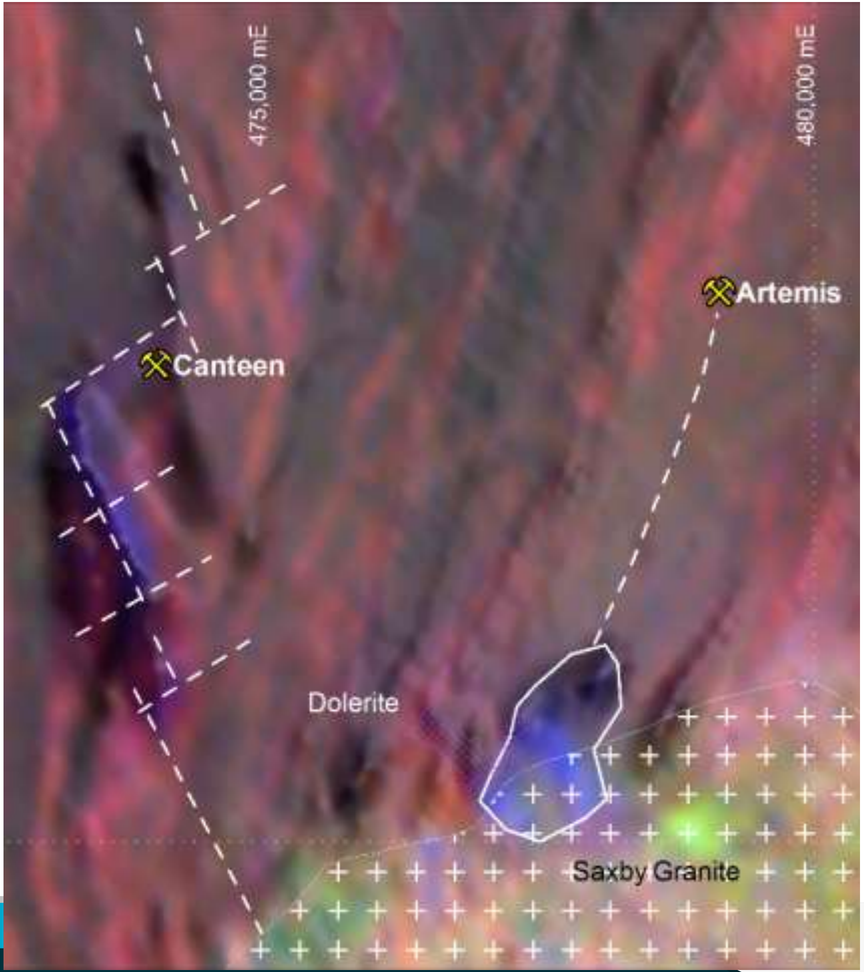
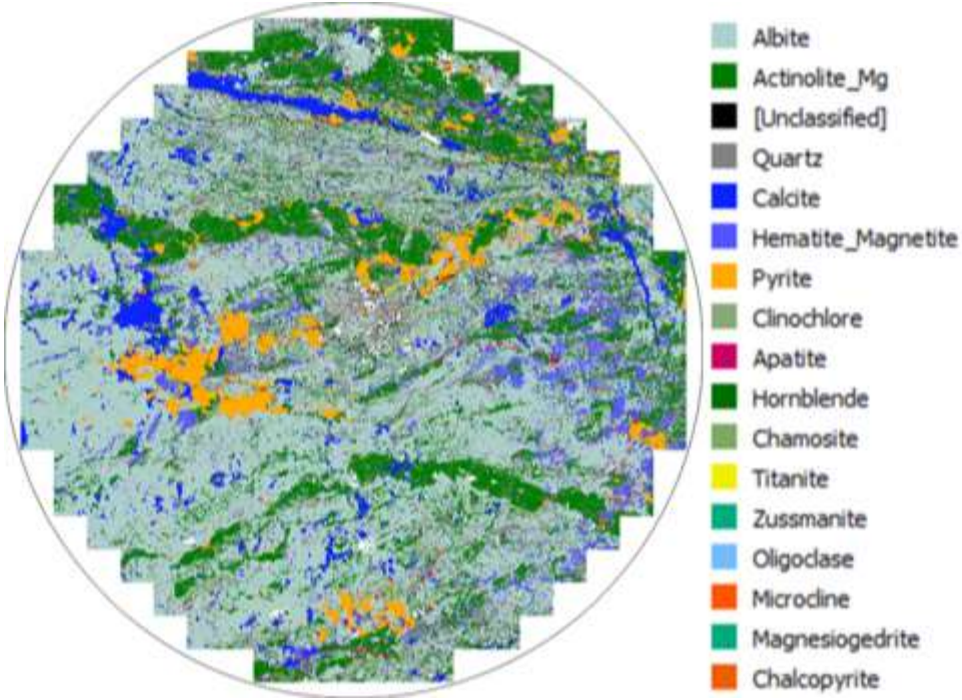
Radiometric Expression

- Radiometric signatures of different alteration types are not well understood
- There is a correlation between U-rich radiometric signatures and the highly magnetic zone at Canteen
- The U-rich signature at Canteen is correlated with magnetite-apatite alteration within that system
- U-rich radiometric signatures are also correlated with sodic alteration at redox boundaries **(as discussed soon)**
- In this image we can infer that the alteration may be related to Magma Mingling



Sodic Alteration (albite-magnetite-titanite)

- manifested by albite-dominated lithologies
- variable amounts of magnetite as the magnetic phase.
- pervasive, particularly within calc-silicate dominated units, but can be shear zone hosted or vein infill
- Associated with moderate to high susceptibilities
- Remanence is relatively minor, with Q ratios of ~0.1 to 0.2 (after a DIM correction is applied).
- Mag properties suggest moderate amounts of coarse multi-domain magnetite.



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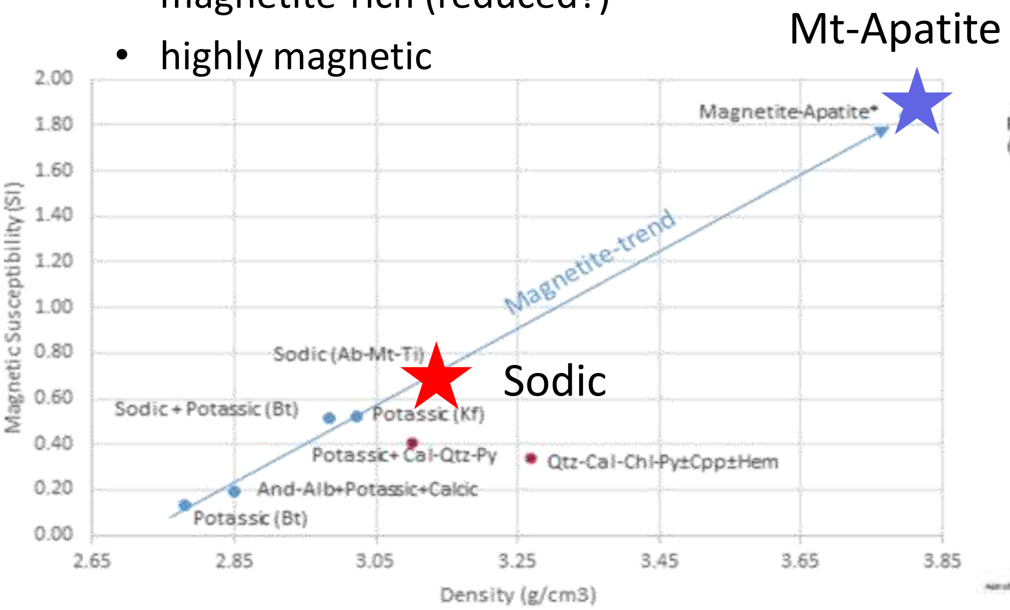
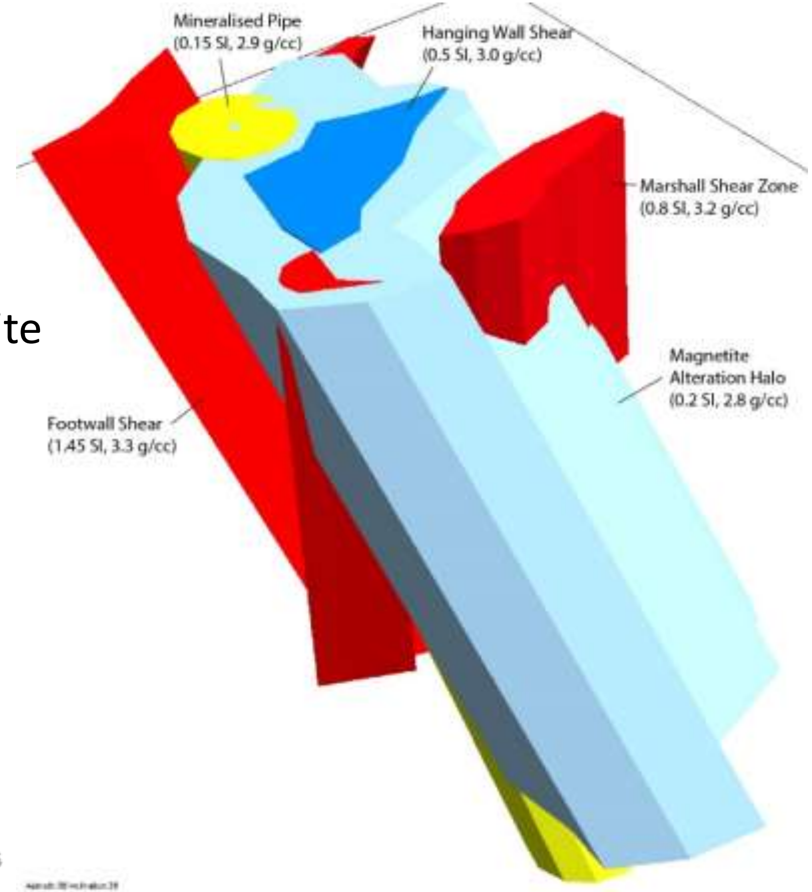
Magnetic Modelling

- Shearzones (in red) are Sodic Altered
  - Have a strong consistent fabric
  - magnetite-rich (reduced?)
  - highly magnetic





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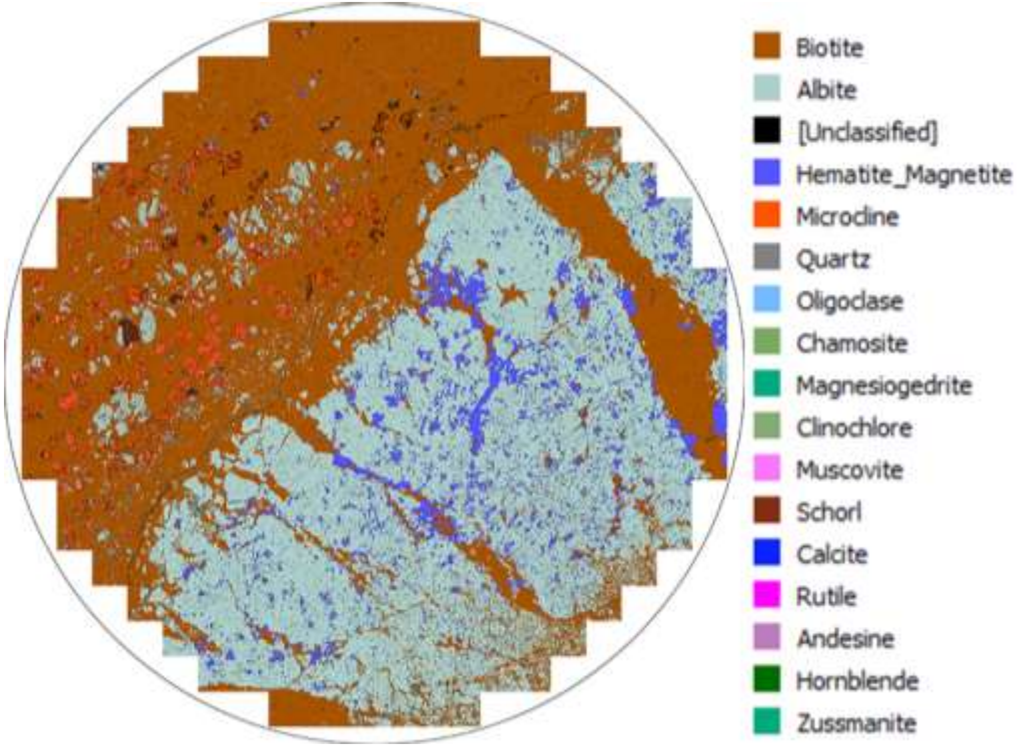
Potassic Alteration

- Present throughout the Cloncurry district,
- Tends to be less pervasive than sodic alteration.
- It can be both magnetite and pyrrhotite-destructive, e.g., via oxidation
- Can take two main forms:
  - replacement of ferromagnesian minerals by biotite



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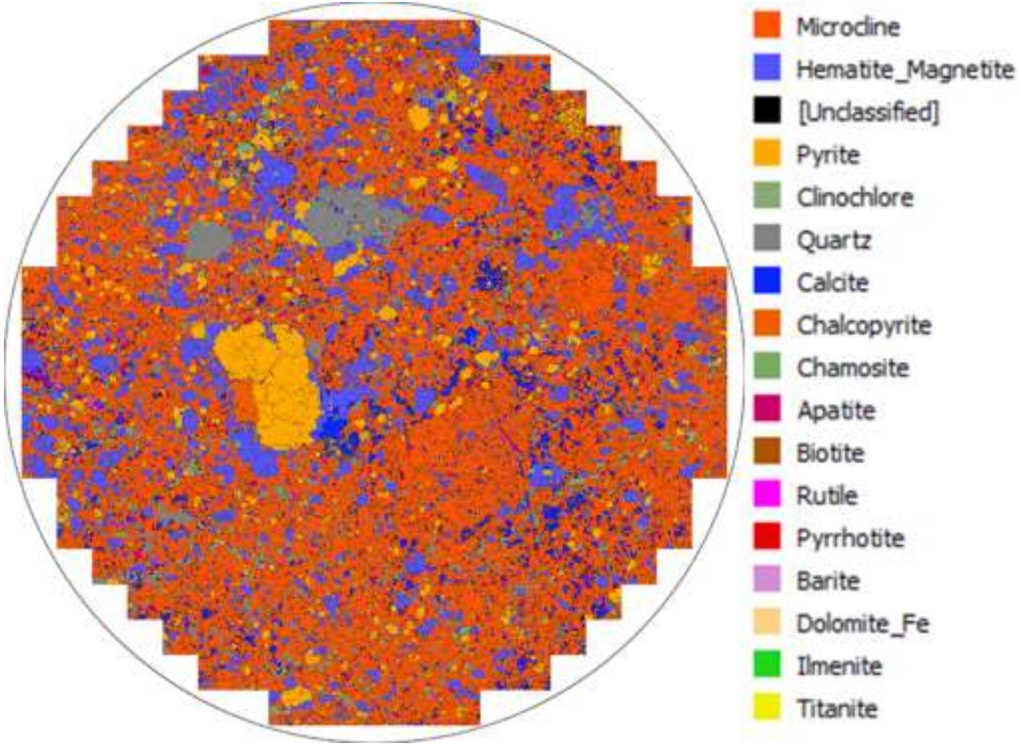
Potassic Alteration

- and/or replacement feldspars (e.g., Albite) by K- Feldspar

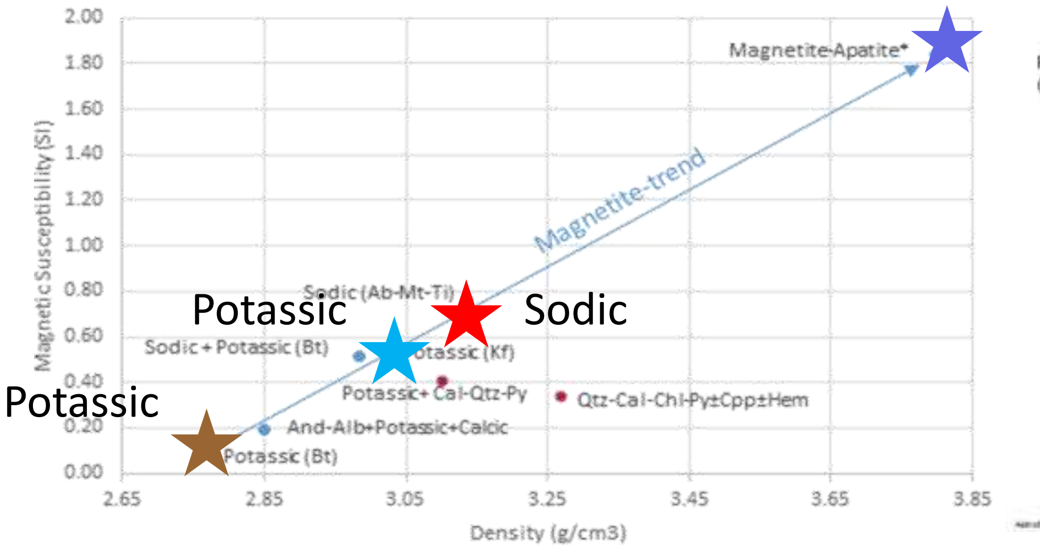
K-feldspar alteration is thought to be associated with hematite (based on the reddish color of the K-feldspar).

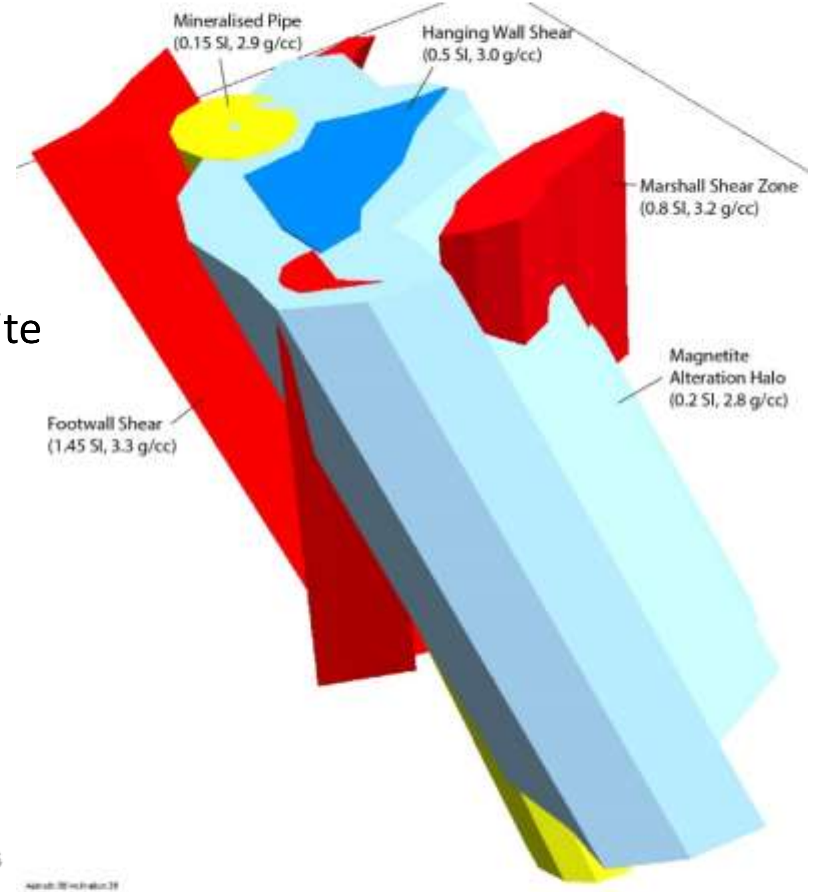
However, magnetite is the dominant magnetic phase in K-feldspar altered lithologies, assessed in this study.



Magnetic Modelling

- Breccias (in blue) are Potassic Altered
    - Moderately magnetic
    - Isotropic (Fabric destructive)





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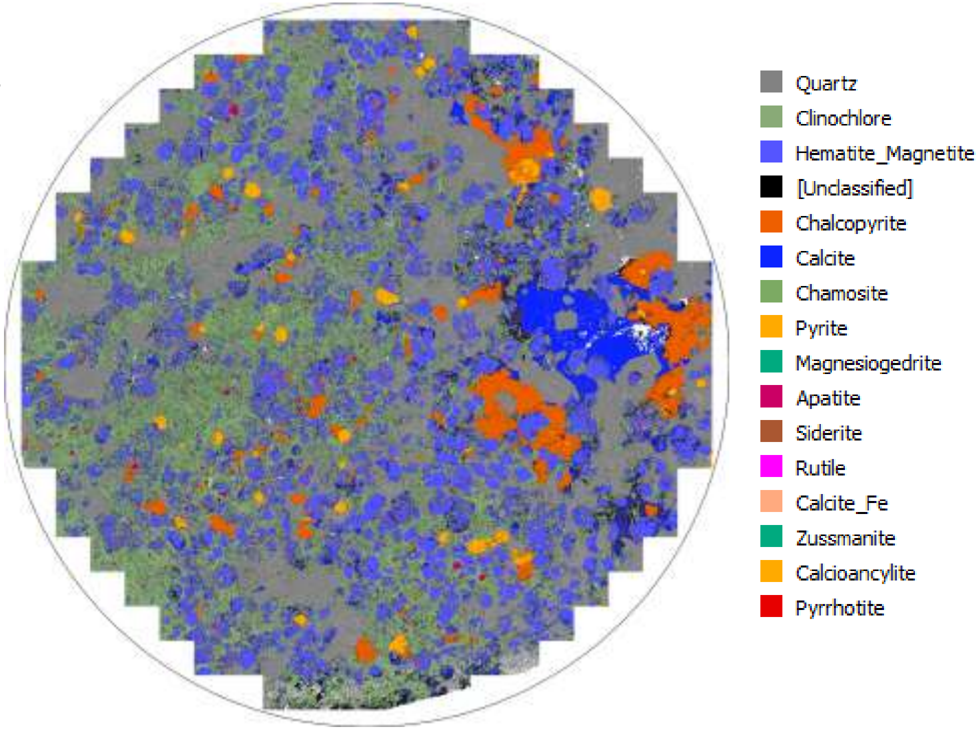
Quartz-calcite-chlorite-hematite alteration

- Late quartz-calcite-chlorite-pyrite-hematite alteration is present in a number of deposits
- associated with copper and/ or molybdenum at Ernest Henry, Canteen, Kalman and Merlin
- most oxidized style observed in the Cloncurry district, as indicated by the presence of pyrite and hematite, rather than pyrrhotite and magnetite
- mineralized samples (with such alteration) sit below the magnetite trend on the density/susceptibility plot.
- iron in magnetite is being converted to;
  - ferromagnesian minerals (e.g., chamosite),
  - chalcopyrite, pyrite and/or hematite during the late alteration history.



Magnetic Modelling

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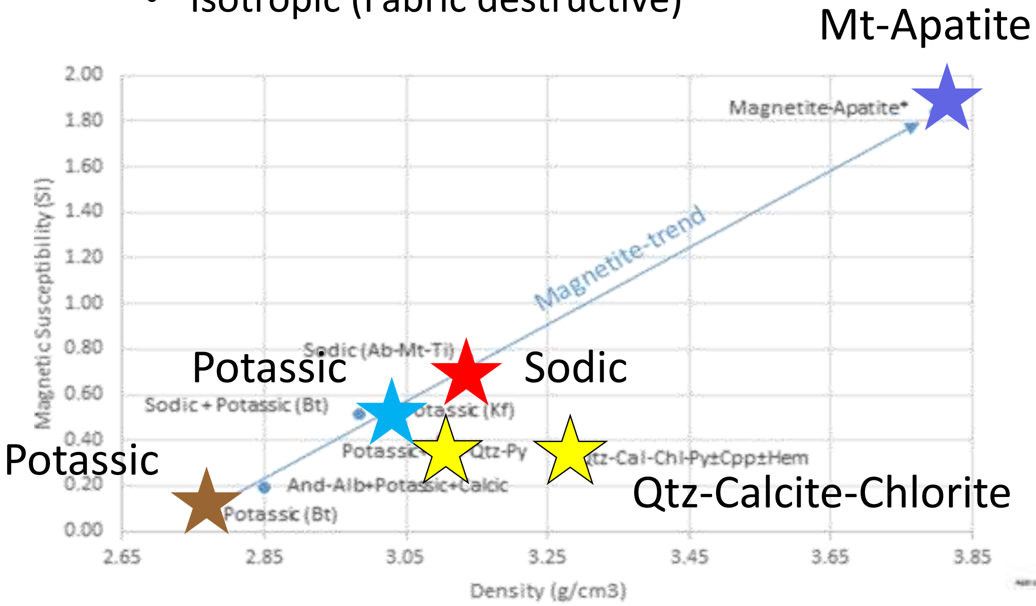

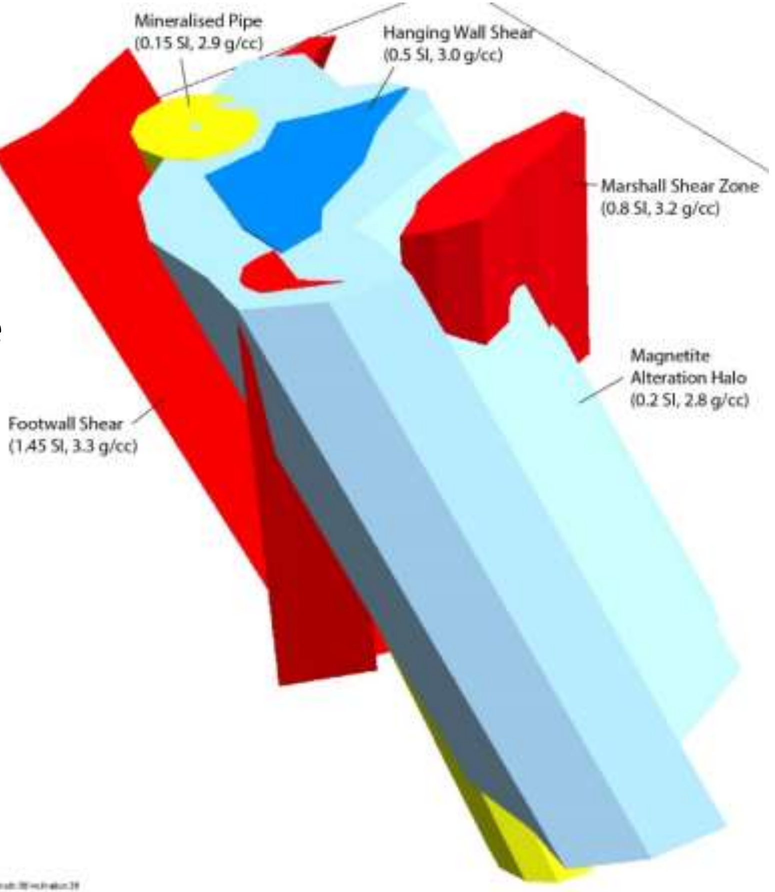

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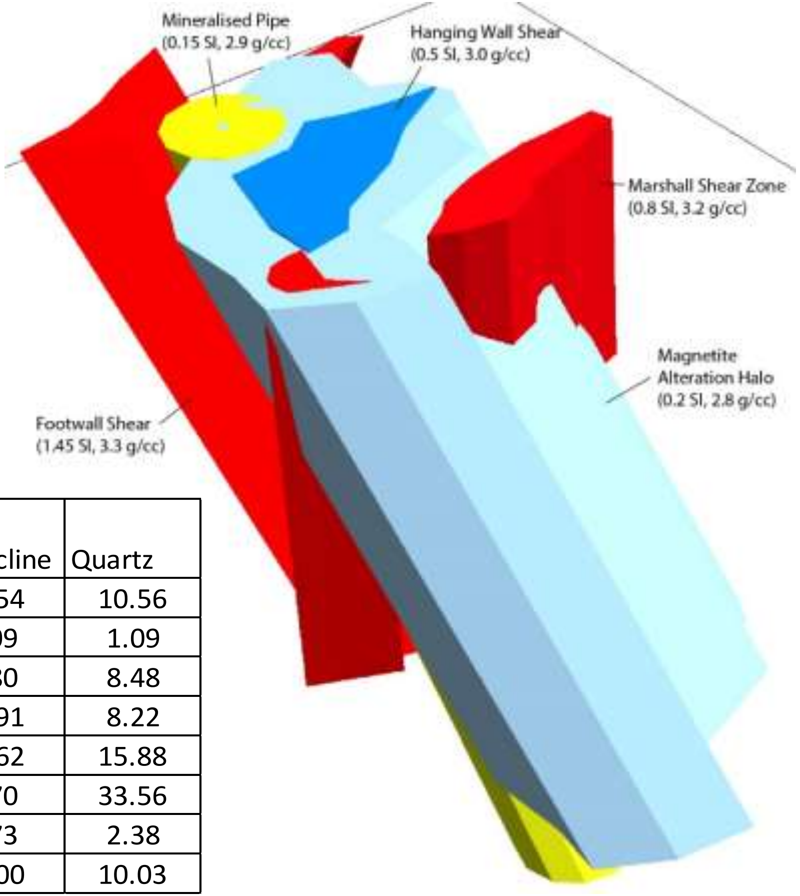
Inverse Bullseye

- Mineralisation is mainly associated with oxidation here
- Mineralisation is associated with the most weakly magnetic rocks

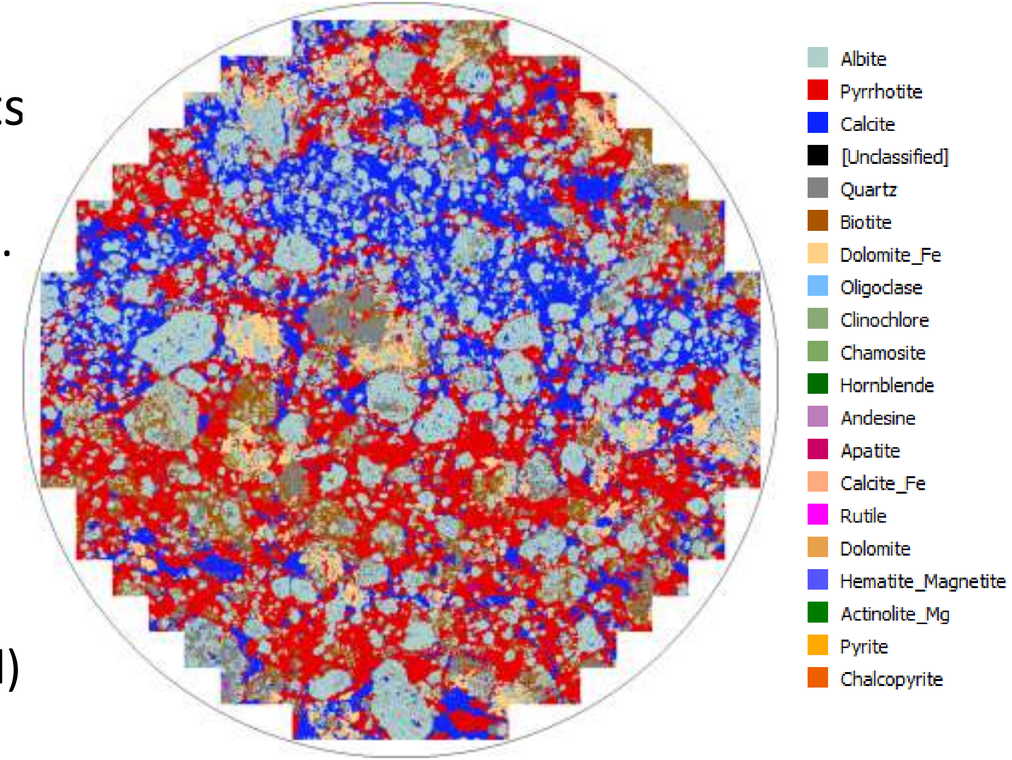


Alteration type	Chalcopyrite	Chamosite	Pyrite	Albite	Microcline	Quartz
And-Alb+Potassic+Calcic	0.00	0.82	0.27	7.41	23.54	10.56
Magnetite-Apatite*	3.80	1.84	1.09	1.09	1.09	1.09
Potassic (Bt)	0.00	0.29	0.07	58.79	2.80	8.48
Potassic (Kf)	0.25	2.27	3.38	2.52	45.91	8.22
Potassic+ Cal-Qtz-Py	2.00	1.19	4.03	0.96	31.62	15.88
Qtz-Cal-Chl-Py±Cpp±Hem	2.88	10.26	13.96	0.16	2.70	33.56
Sodic (Ab-Mt-Ti)	0.00	0.31	0.31	54.96	3.73	2.38
Sodic + Potassic (Bt)	0.05	1.12	0.27	20.11	20.00	10.03

ISCGs (Pyrrhotite-rich Copper-Gold deposits)

Pyrrhotite Assemblages

- Calcite -pyrrhotite assemblages are present at a number deposits
  - Canteen, Maronan, and Artemis;
  - They don't appear to be co-genetic.
- In all cases, the textures are undeformed.
- However, some assemblages
  - Formed in zones of dilation, e.g., veins and breccia matrix,
  - others appear to have formed by recrystallization. (already discussed)



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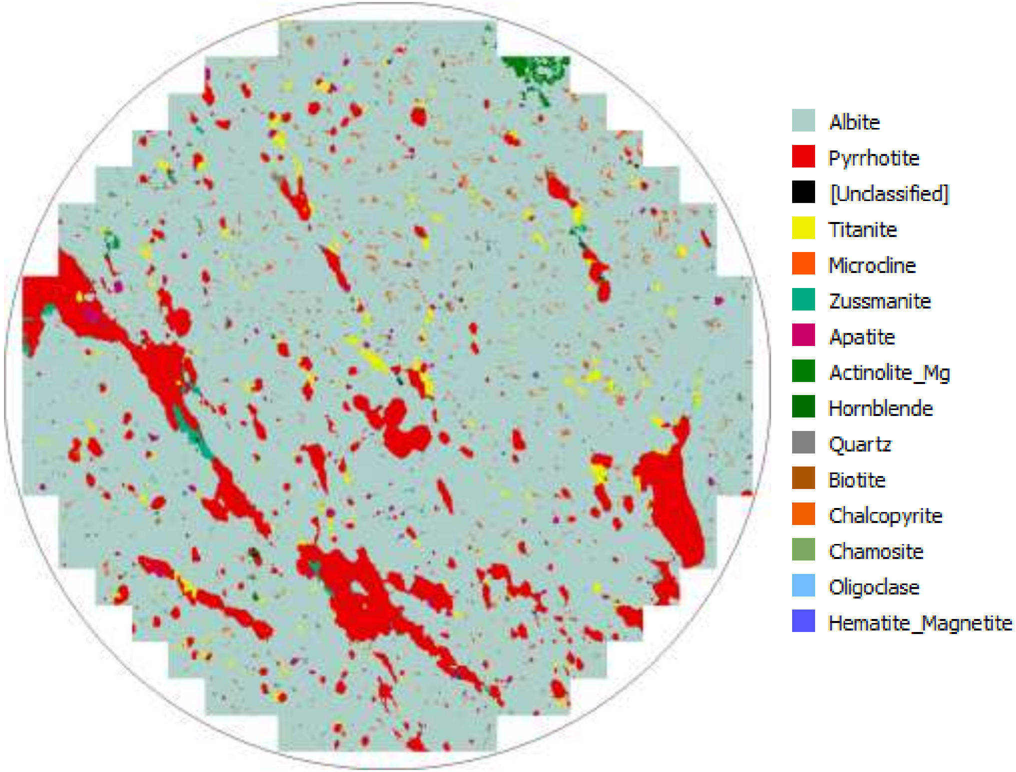
Cormorant

- mineralization is associated with pyrrhotite in microbreccias and veins
- Pyrrhotite is associated with albite, not calcite.
- pyrrhotite, chalcopyrite & titanite are intergrown
- Mineralization is associated with pyrrhotite-dominant vein phases



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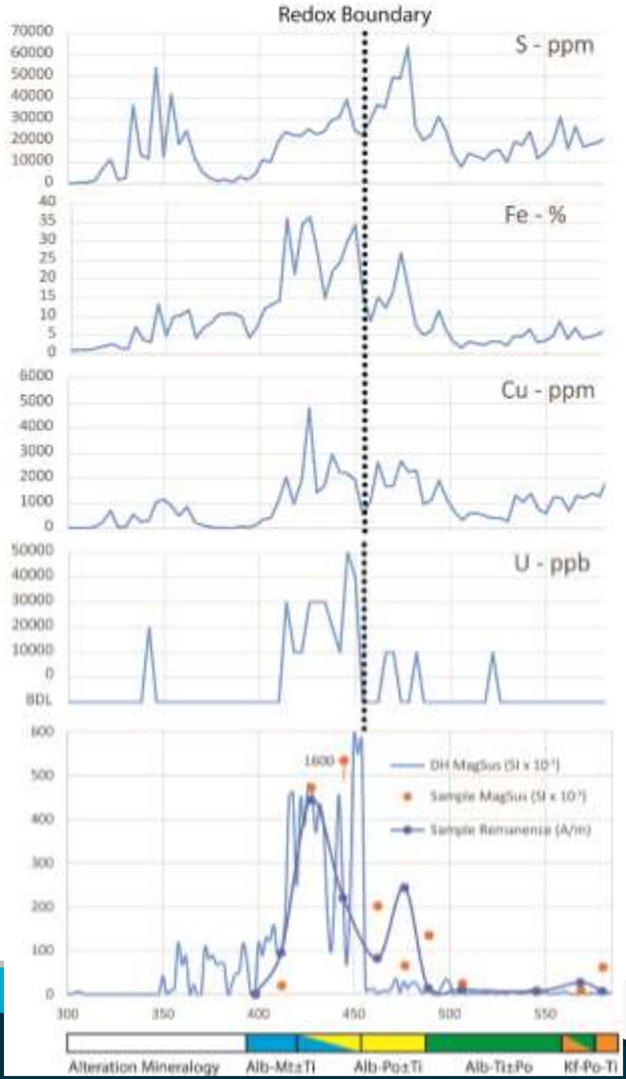
Redox Control on Copper

- Elevated Cu occurs either side of an apparent redox boundary at approximately 450 meters
- transition from magnetite dominant (400–425 m)
- into magnetite-pyrrhotite (425–450 m)
- into pyrrhotite dominant (450–500 m),
- and then titanite dominant lithologies (500–550 m).
- U-rich alteration sits on more oxidized side



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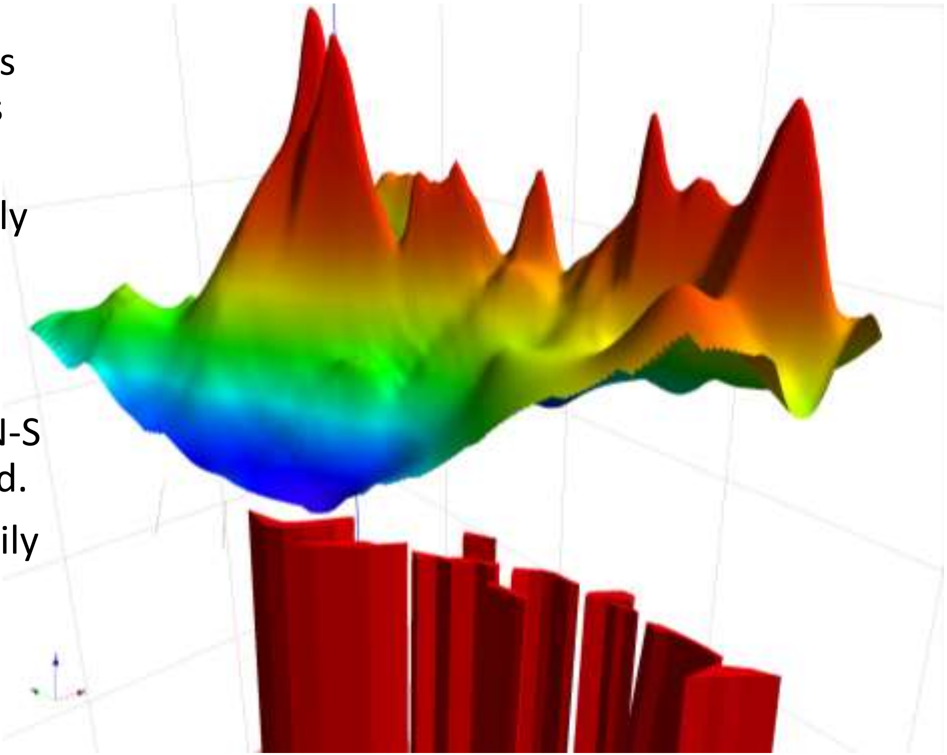
Remanence in Pyrrhotite

- Monoclinic pyrrhotite in several of these deposits (e.g., Canteen, Cormorant, Maronan, Mt Colin) is associated with high Koenigsberger ratios.
- the associated remanence directions are generally sub-vertical upward oriented magnetizations.
- are consistent with metamorphic resetting associated with mafic magmas at *ca* 1114 Ma.
- The magnetizations are sub-vertical and sit in a N-S plane in a similar orientation to the inducing Field.
- So they cause positive anomalies that can be easily distinguished from other anomalies
- therefore we cannot easily use remanence as an exploration tool to find pyrrhotite




Questions?