Advances in Petrophysics

Remanence in Mineral Systems
Geotechnical Applications

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Remanent Magnetisation

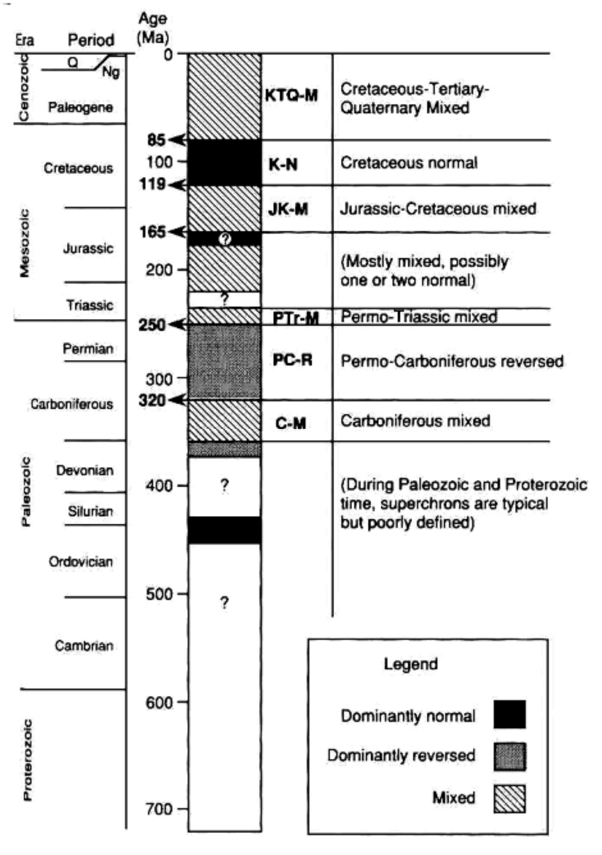
- Remanence requires fine grained magnetite (<20μm) eg rapidly chilled basalt, oxidised mafic intrusions (titanomagnetite) or formation of monoclinic pyrrhotite
- Reduction and of ore-bearing fluids from interaction with graphitic host rocks
- Amphibolite grade host rocks adjacent to granite intrusions and de-sulfidation of ore-fluids during interaction with iron rich units
- Multiphase intrusions/thermal events would be overprinted after each event cancelling out any likely effects of remanence (multi-domain magnetite)
- Pyrrhotite alteration can be remanent and can significantly effect the magnetic inversion models

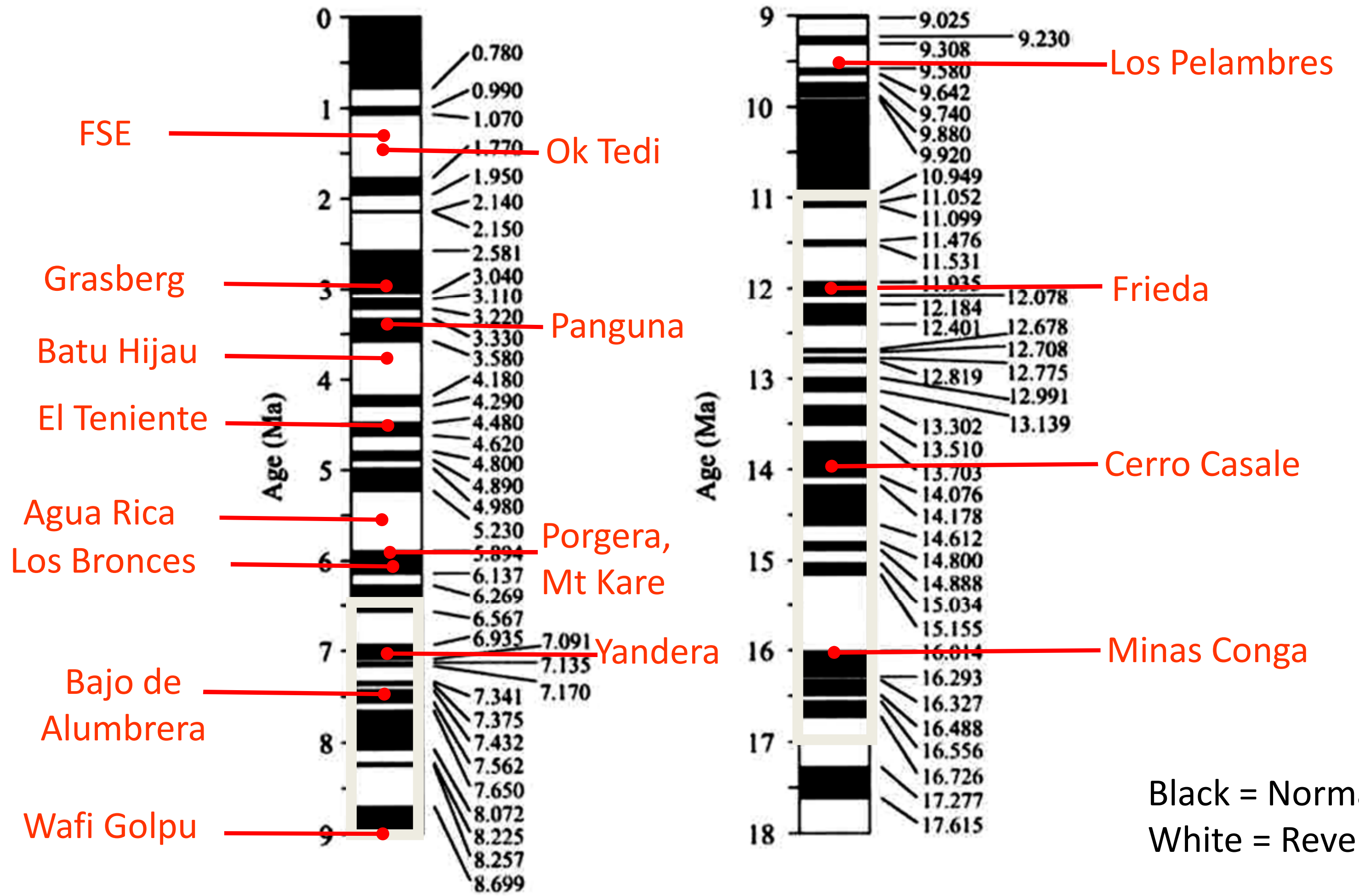
Remanent Magnetisation – Implications for Porphyry Exploration

- Most porphyry system magnetite is coarse-grained, therefore remanence < induced
- During age of mineralisation, earth's field direction was changing and multiphase intrusions/thermal events would be overprinted after each event cancelling out any likely effects of remanence
- Only likely source of remanence features in younger terrains are oxidised mafic intrusions and skarns
- Co-magmatic mafic events likely with world class porphyry districts

No known world class porphyry deposit
with dominant remanent effects

Remanent Magnetisation – Implications for Mineral Systems



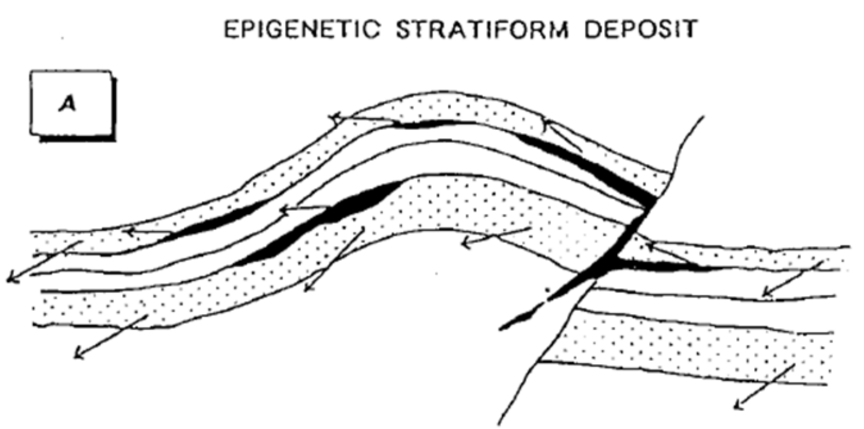


Black = Normal
White = Reversed

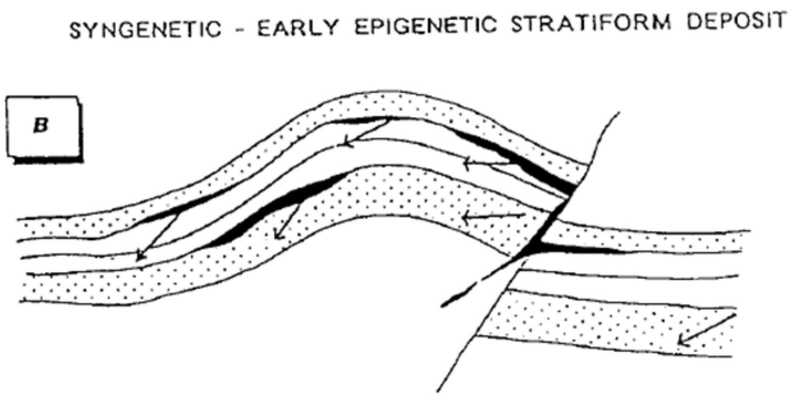
Remanence – Paleomagnetic Dating in Mineral Systems

- Paleomagnetic dating involves measurements for the natural remanent magnetisation (NRM) of a mineral deposit and then establishing the age of the age of the magnetisation
- As mineral deposits are likely to have undergone a complex history of geological events, they may carry a composite magnetic record of several different ages
- In order to separate the magnetising events, step-wise demagnetisation experiment are performed to isolate individual vector components of the NRM

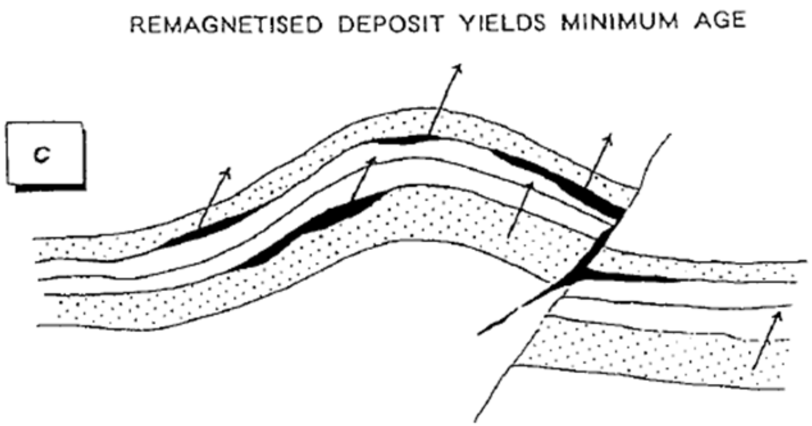
Palaeomagnetic Dating of Mineral Deposits



Magnetisation directions of the ore and host rocks pre-date structure



Magnetisation directions of the ore and host rocks are similar to structure

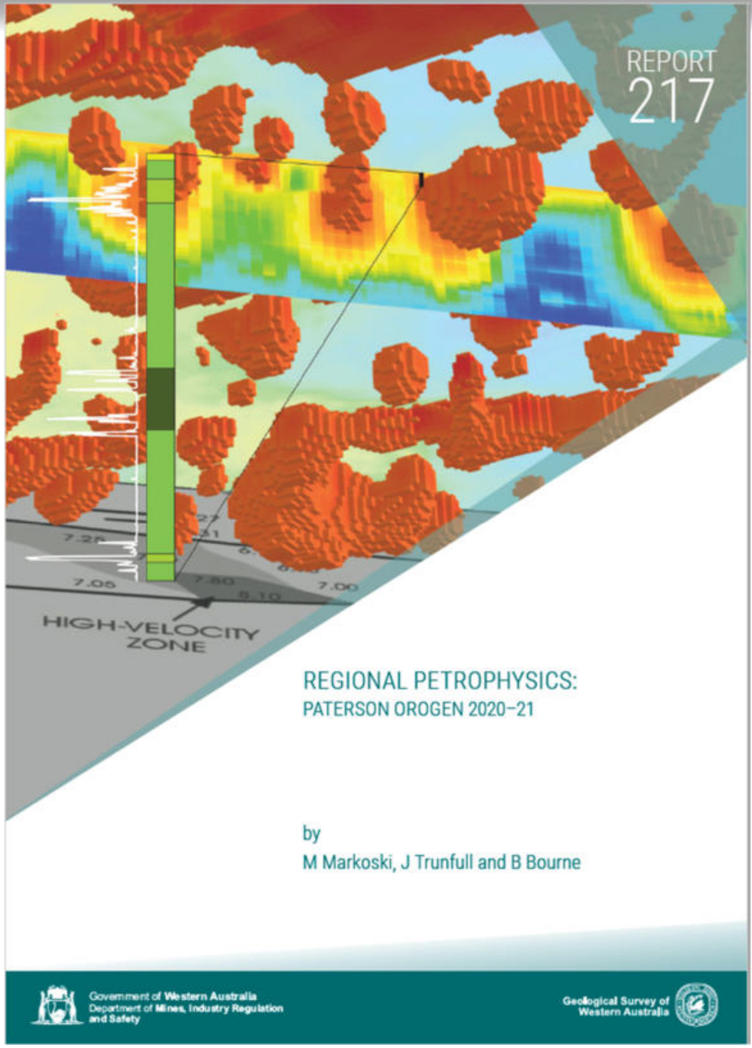


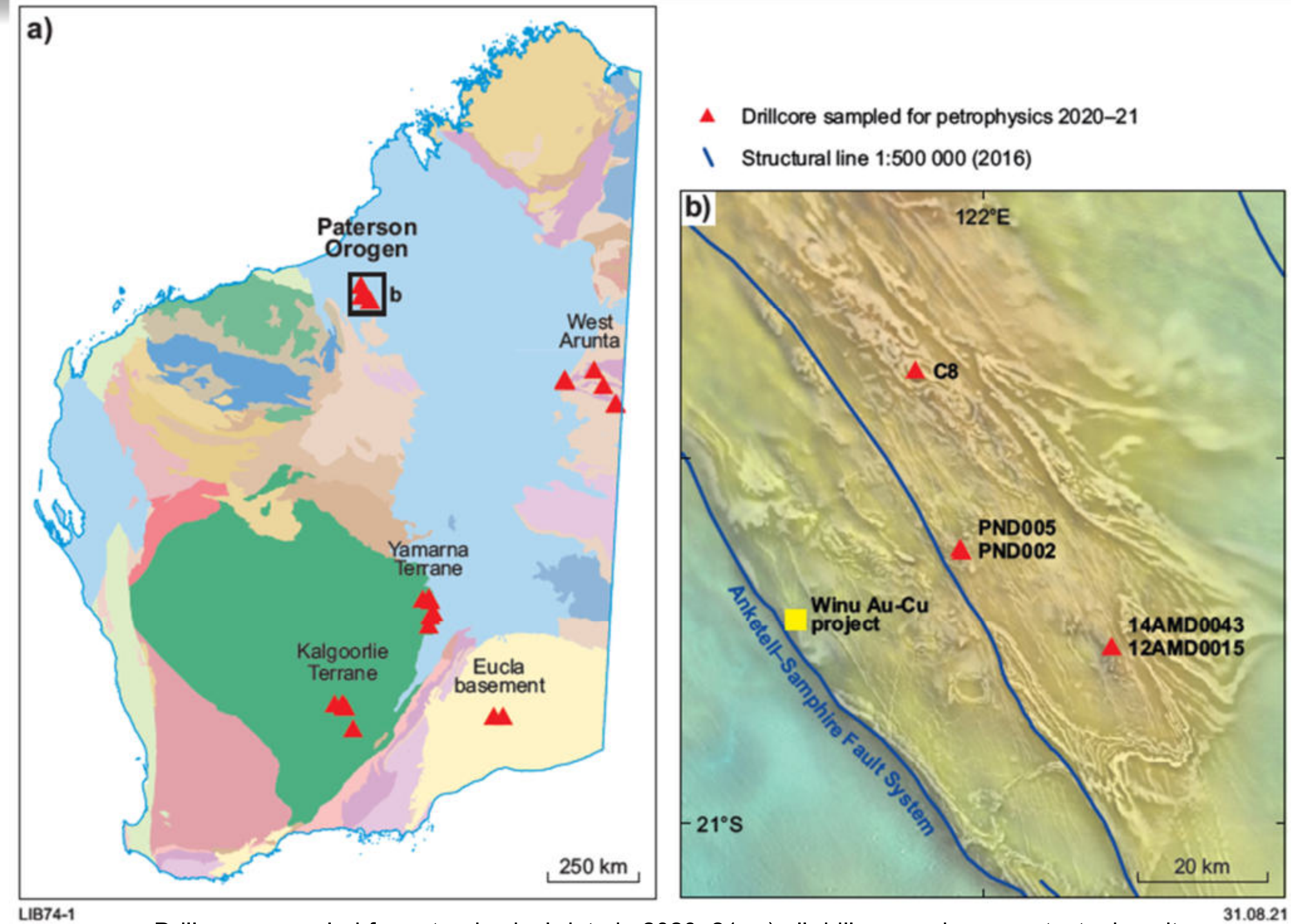
Magnetisation directions of the ore and host rocks post-date structure

Remanence – Paleomagnetic Dating in Mineral Systems

- Accurate dating of mineral deposits can be problematic and time consuming when local stratigraphic relationships permit a broad possible age-range
- Even though age dating has become more common, paleomagnetic studies may offer independent age determination to a wide range of deposit types as well as ways to map the magnetic footprint of deposits and their hosts
- The magnetic footprint may affect how we explore for, and subsequently drill test, these types of deposits
- Success of the palaeomagnetic method relies on several factors including the ore deposit having sufficiently isotropic magnetic fabric to accurately record the Earth's magnetic field direction

Paterson Orogen – Petrophysics (Update)



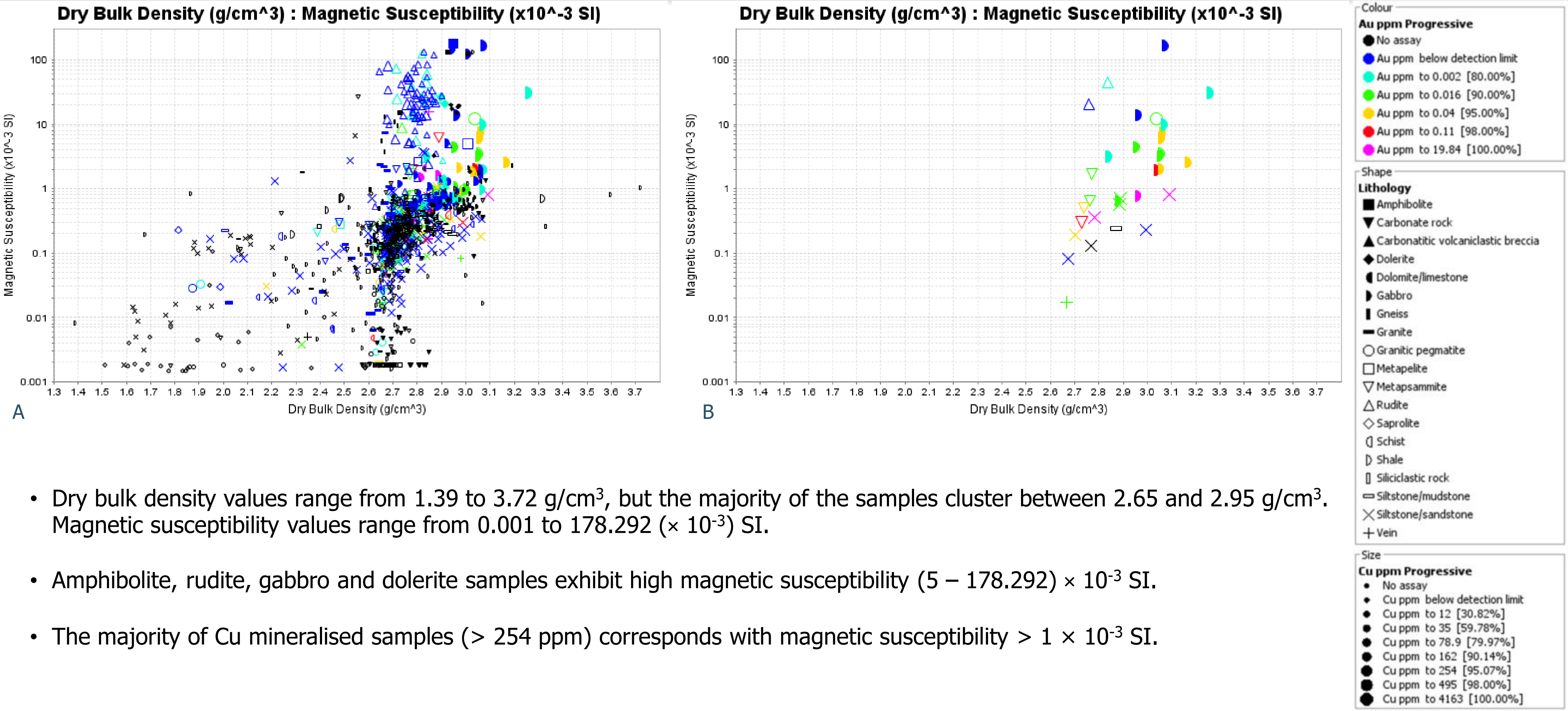


Drillcores sampled for petrophysical data in 2020–21: a) all drillcores, shown on tectonic units map (2016); b) Paterson Orogendrillcores, shown on Bouguer gravity data (colour) draped with 1VD total magnetic intensity data (grey scale)

Petrophysics

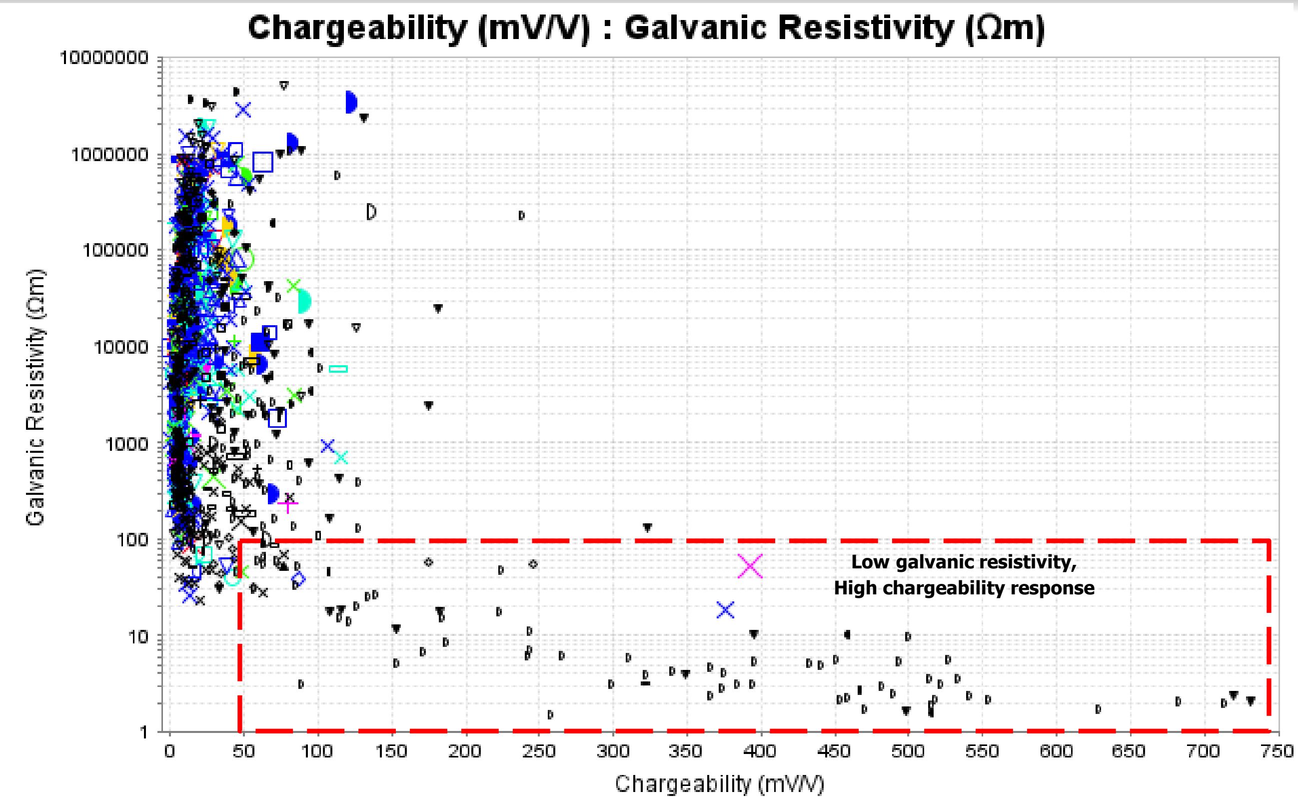
- Terra Petrophysics have completed petrophysics data acquisition on 1180 samples from 19 EIS drillholes from the Paterson Province. (up from 274 in Report 217)
- Petrophysical data acquisition included: induced polarisation response (chargeability), galvanic resistivity, inductive conductivity, magnetic susceptibility, remanent magnetization, wet/dry bulk density/porosity and sonic velocity measurements.

Dry Bulk Density vs. Magnetic Susceptibility



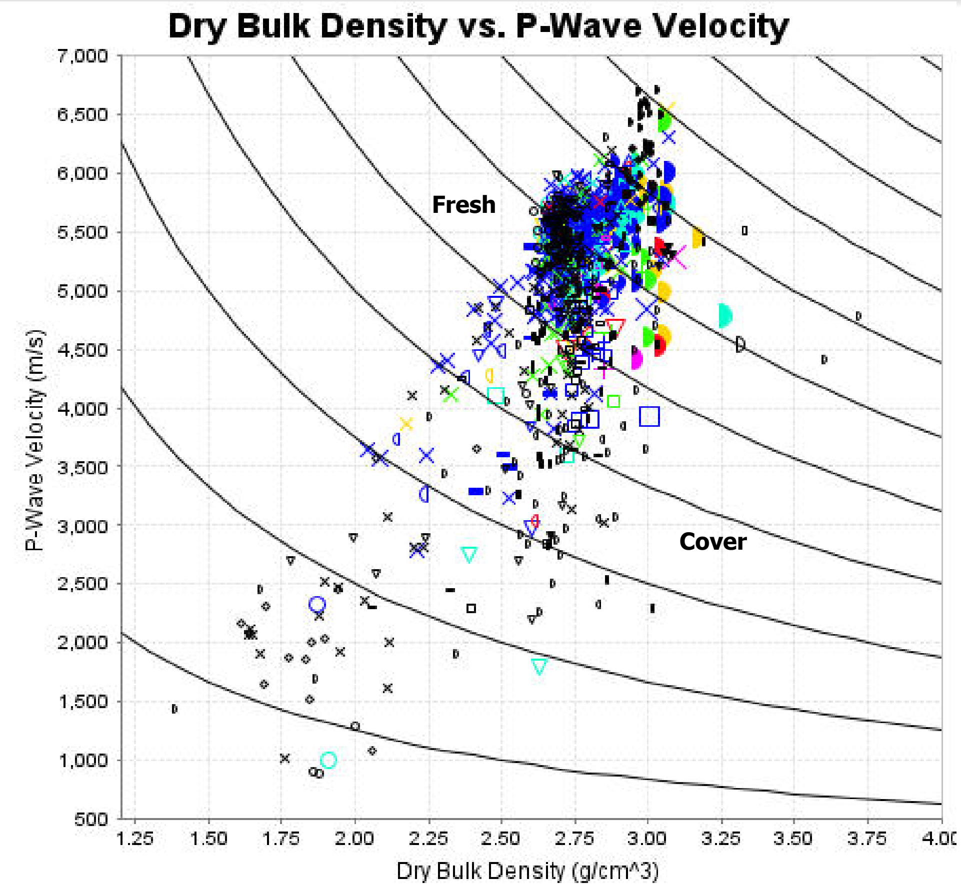
- Dry bulk density values range from 1.39 to 3.72 g/cm^3, but the majority of the samples cluster between 2.65 and 2.95 g/cm^3. Magnetic susceptibility values range from 0.001 to 178.292 (× 10^{-3}) SI.
- Amphibolite, rudite, gabbro and dolerite samples exhibit high magnetic susceptibility (5 – 178.292) × 10^{-3} SI.
- The majority of Cu mineralised samples (> 254 ppm) corresponds with magnetic susceptibility > 1 × 10^{-3} SI.

Chargeability vs. Galvanic Resistivity



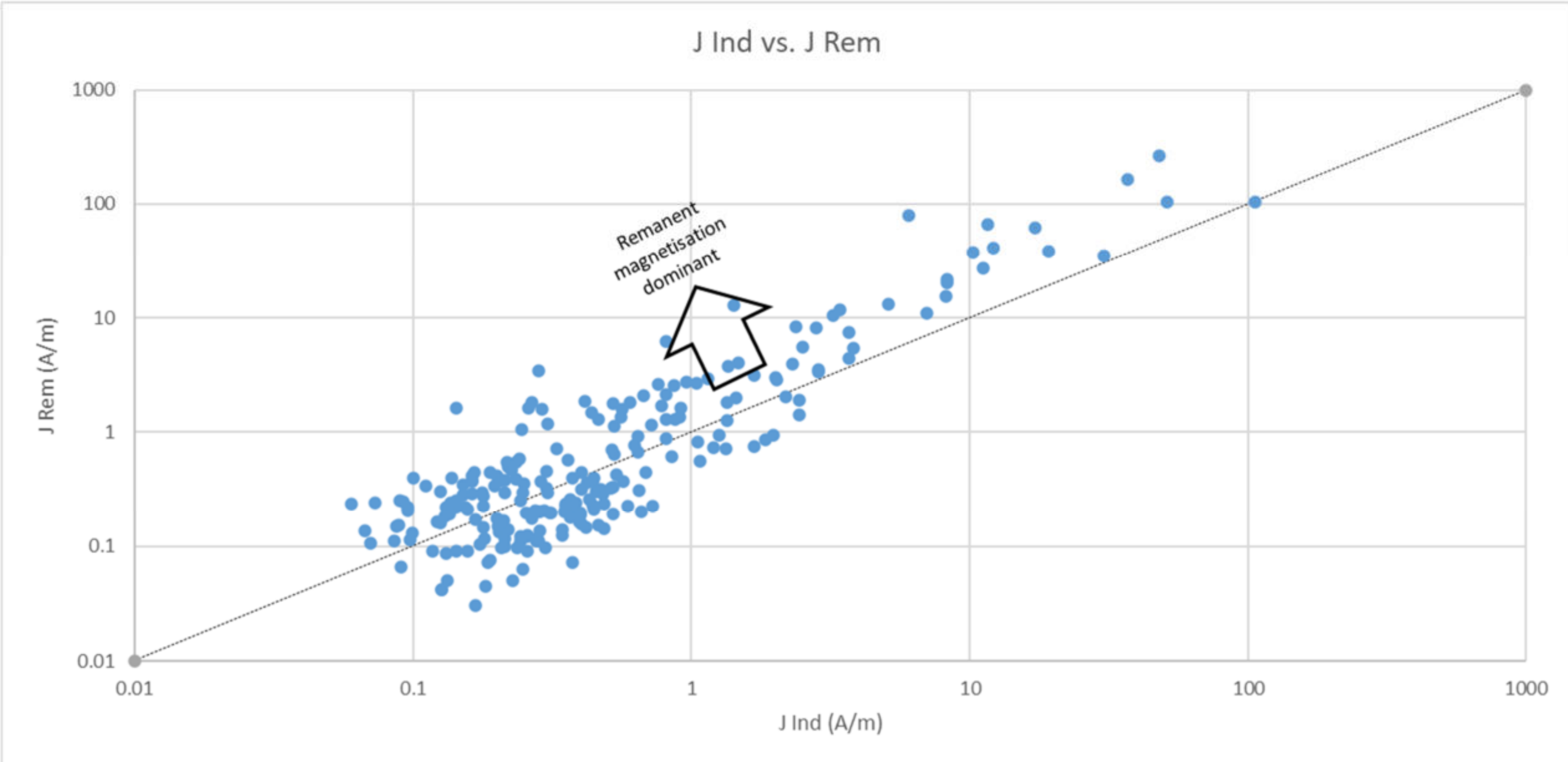
- Chargeability values range between 0.7 and 731.5 mV/V.
- The red square shows shale, carbonate rock and carbonaceous shales which exhibit low galvanic resistivity (< 100 Ωm) and anomalously high chargeability (up to 731.5 mV/V). The high chargeability response in the carbonaceous shales is due to sulphide mineralisation and increased carbon content and the high chargeability response in the shales and carbonate rocks is due to higher clay content from weathering.

Dry Bulk Density vs. P-Wave Velocity



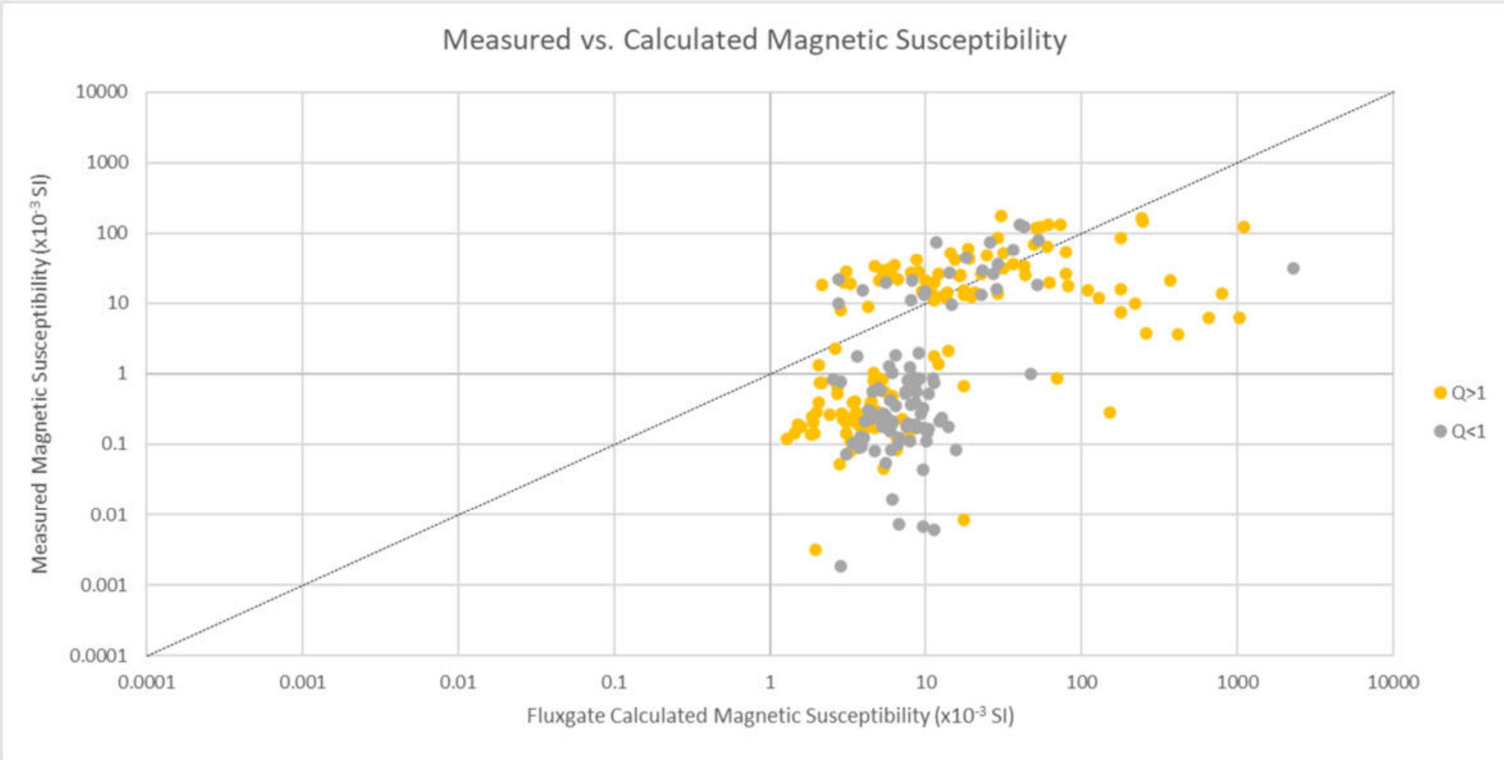
- P-wave velocity values range between 890 and 6710 m/s. Samples spread over 8 acoustic impedance contours.

Induced vs. Remanent Vector Intensity



The components of induced and remanent magnetism were measured for 229 samples. 96 samples are measured to be induced-dominant (Q<1) and 133 to be remanent-magnetisation dominant (Q>1).

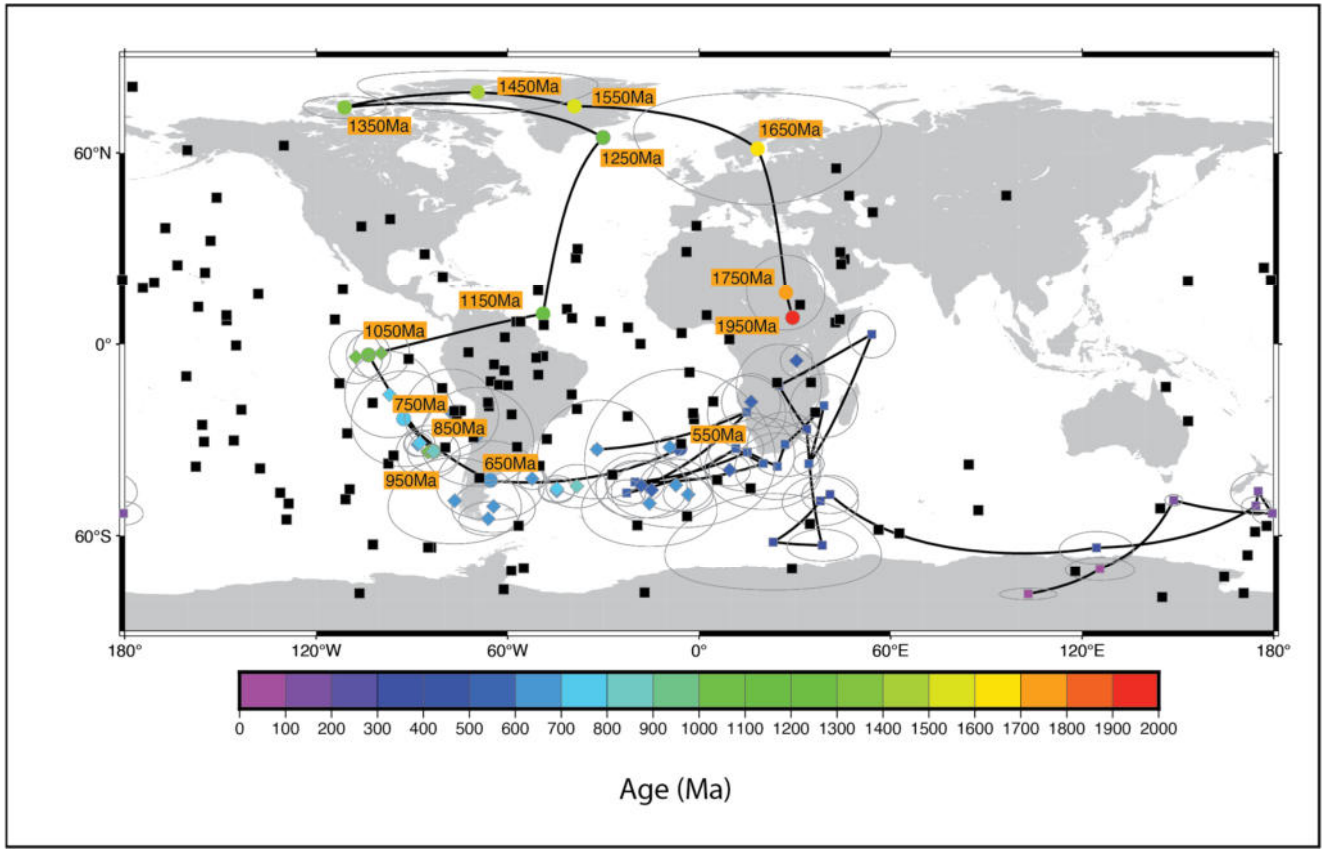
Measured vs. Fluxgate Derived Magnetic Susceptibility



- Samples with similar magnetic susceptibilities plot closer to the trend line. Samples with higher order of magnitude differences between measured and derived magnetic susceptibility may be attributed to remnant magnetisation dominance and associated with cancellation of induced magnetisation. In this case, there is a notable difference between the values, which is expected for remanence magnetisation. For this dataset, the trend is also observed in induced-magnetisation dominant samples.
- Formula for fluxgate derived magnetic susceptibility taken from *Adams & Dentith (2017).*

Remanence – Patterson Paleomagnetic Dating (raw data)

- The inclination and declination from the remanent magnetism have been converted into paleomagnetic poles and plotted on the apparent polar wander paths for Australia.
- Coloured squares and circles are the apparent polar wander path research data used to define solid line (Kirscher et al, 2021) with grey discs showing 95th percentile of data
- Black squares are paleomagnetic poles plotted from the Patterson Province remanent data. All data is raw from the GSWA database and includes some readings on core that may not have drilling direction clearly defined (ie reversed) or dip /azimuth from drilling defined



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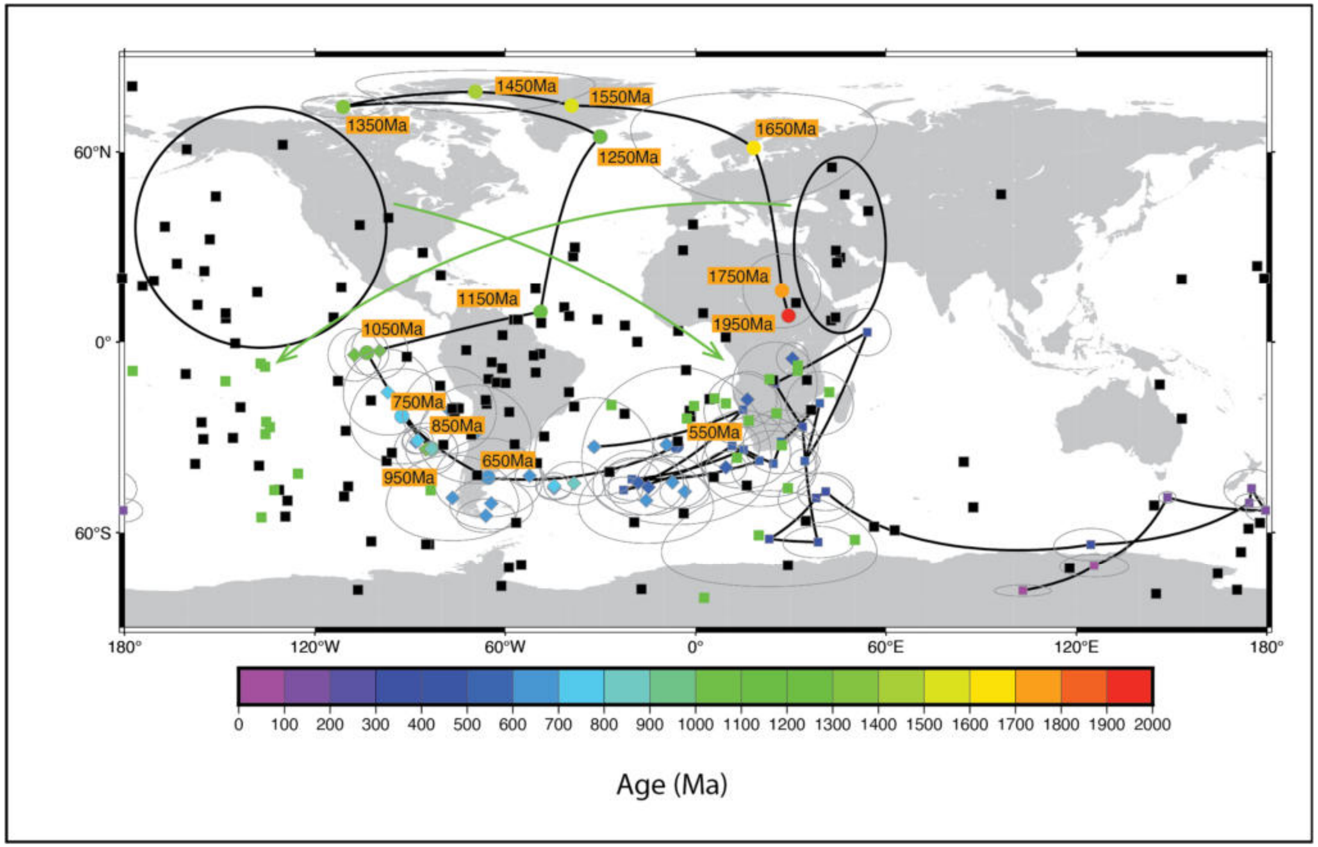
Remanence – Patterson Paleomagnetic Dating (sample reversal?)

- Large black circles could represent groups of data readings on core that may not have drilling direction clearly defined (ie reversed) or dip /azimuth from drilling not clearly defined
- Simply reversing the direction of the data circled (green corrections) seem to plot them in a location that correlates better with geology. These data need to be followed up with an additional validation process



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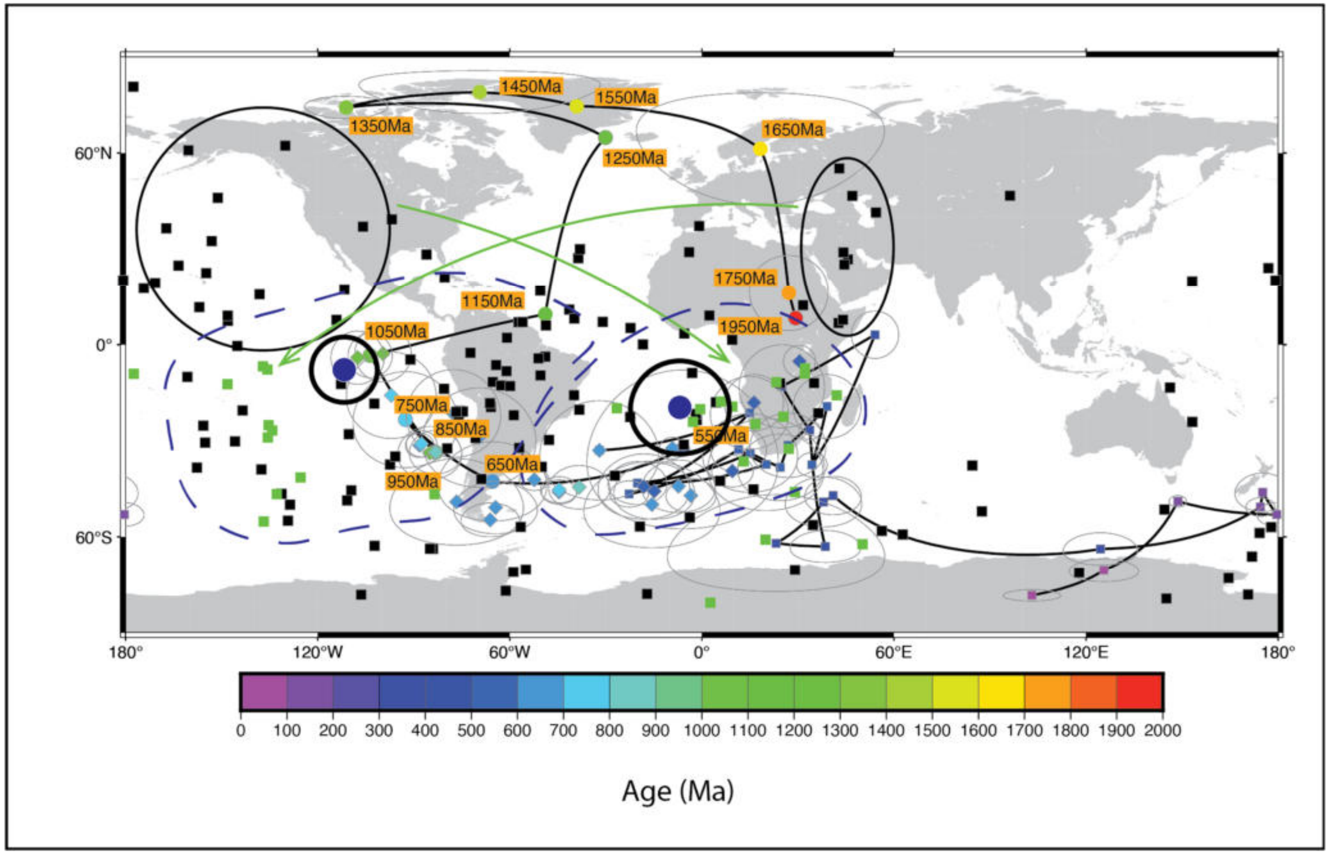
Remanence – Patterson Paleomagnetic Dating (average)

- Dark blue dots are mean paleomagnetic poles from two groups of data as outlined by the blue dashed lines. The main Patterson orogenic age is 550Ma but there seems to be many ages associated with 600-800Ma and older
- Spread in readings are likely from using NRM direction, not breaking each contributing direction down. De-magnetisiation of the sample(s) could assisting in better interpreting these data (drafting MERIWA project)



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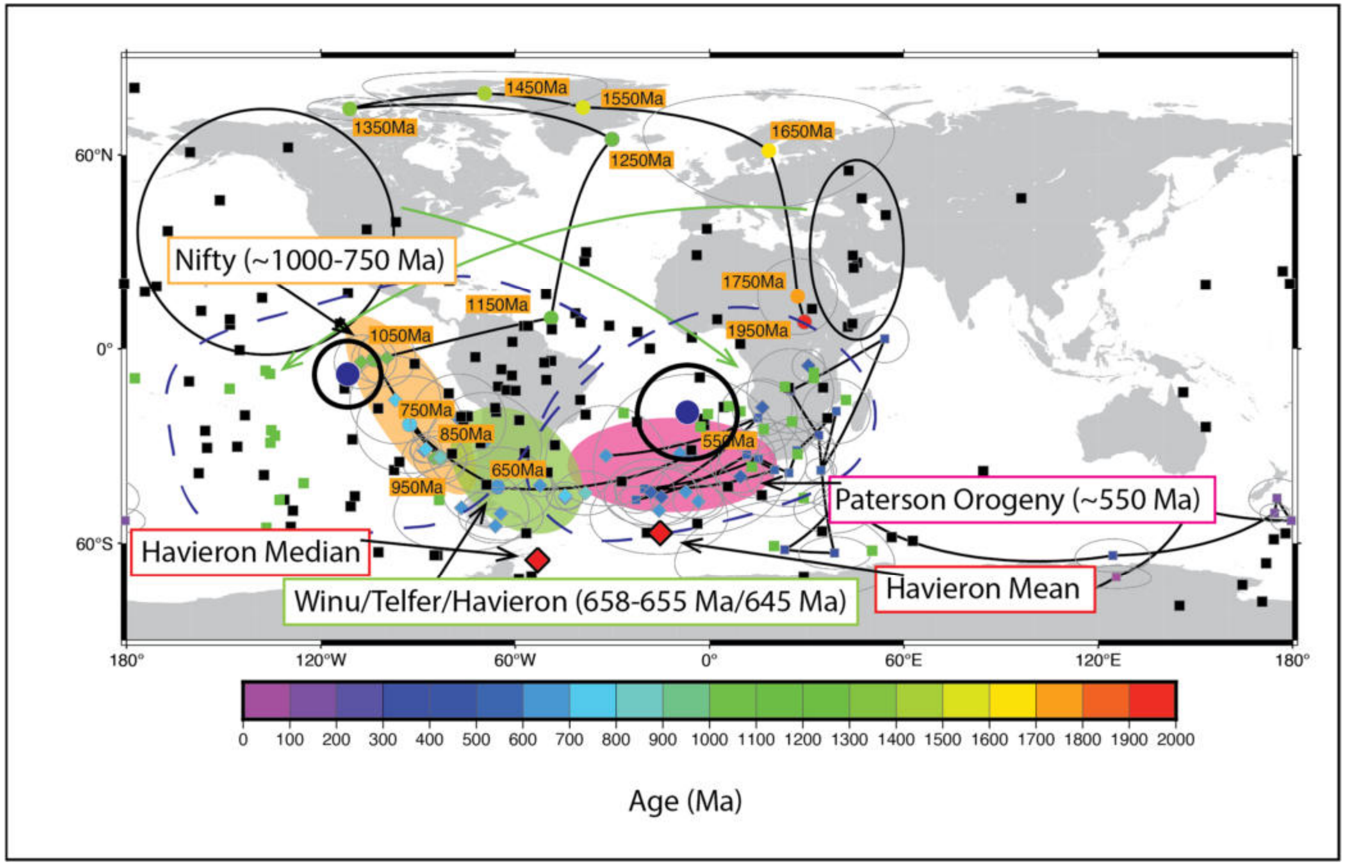
Remanence – Patterson Paleomagnetic Dating (mineralisation)

- The Haverion median (and mean) paleomagnetic poles have been plotted (after Hanneson and Baxter,2022). The median direction was used for the magnetic modelling
- The locations of Nifty, Winu and Telfer have been determined from age dating
- Implications:
  - the presence of remanence in your drilling data could be associated with mineralisation (type?)
  - remanence could effect how you model and subsequently drill test a magnetic target (susceptibility and magnetisation direction)



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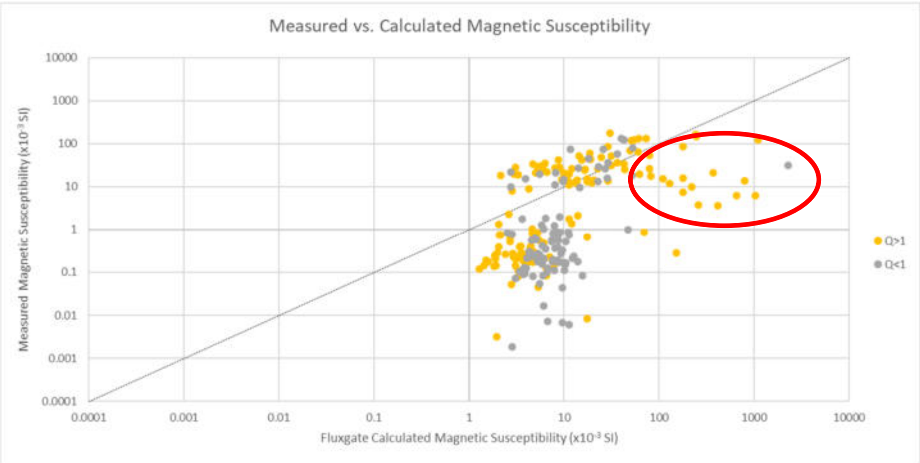
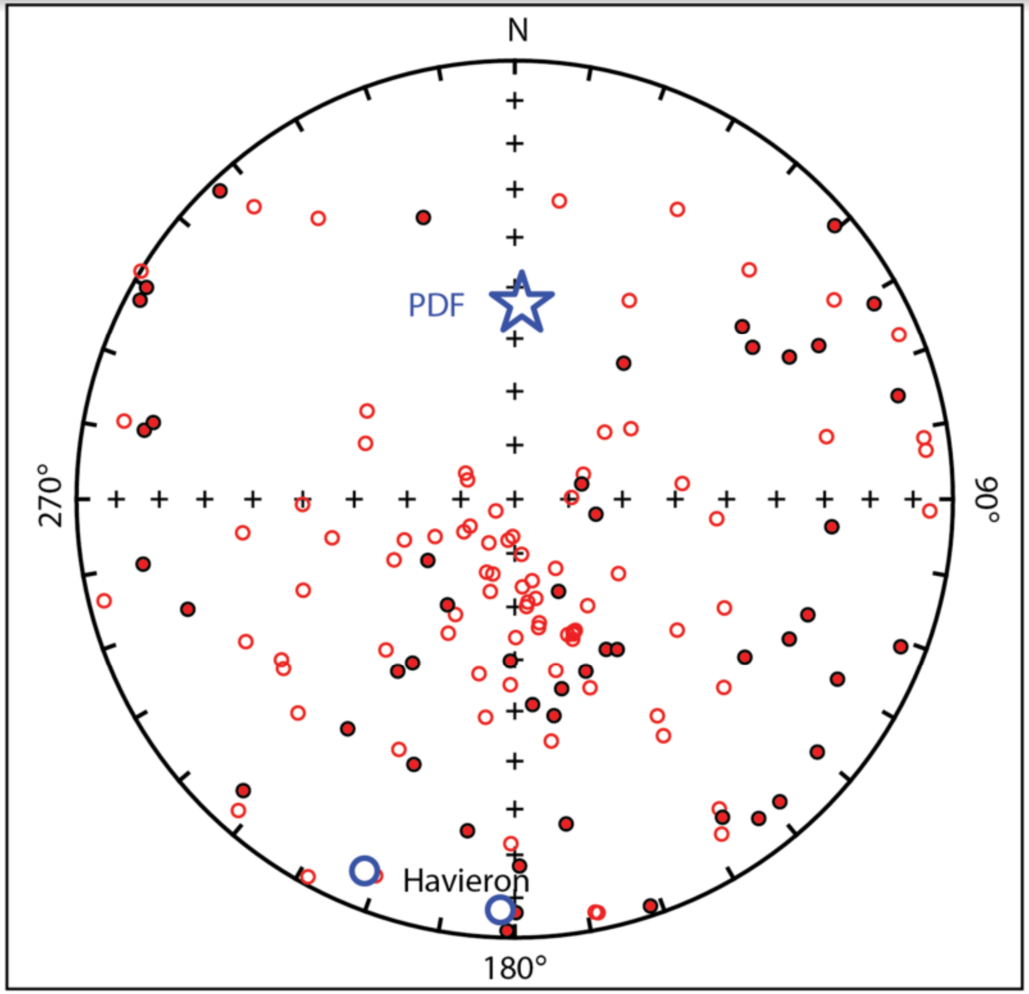
Remanence – Patterson Paleomagnetic Directions

- All data is raw from the GSWA database Magnetisation inclination and declination poles plotted on a stereo net to show direction of magnetic field in remanent samples (only)
- The earths present day field is plotted as a star
- Further supports that remanence could effect how you model and subsequently drill test a magnetic target (susceptibility and magnetisation direction)





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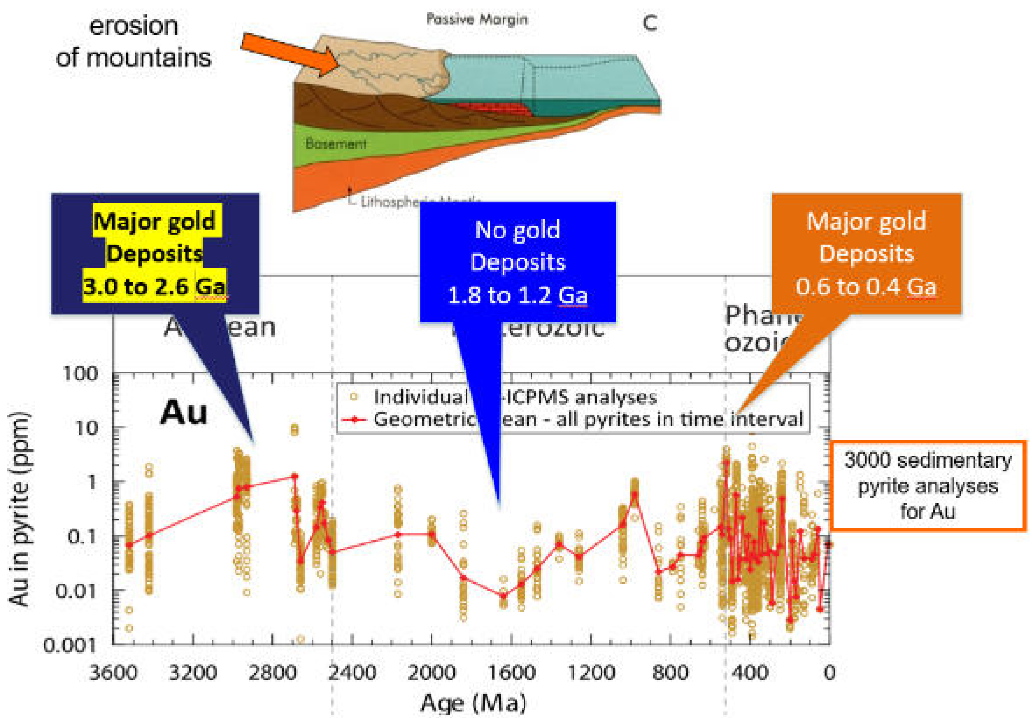
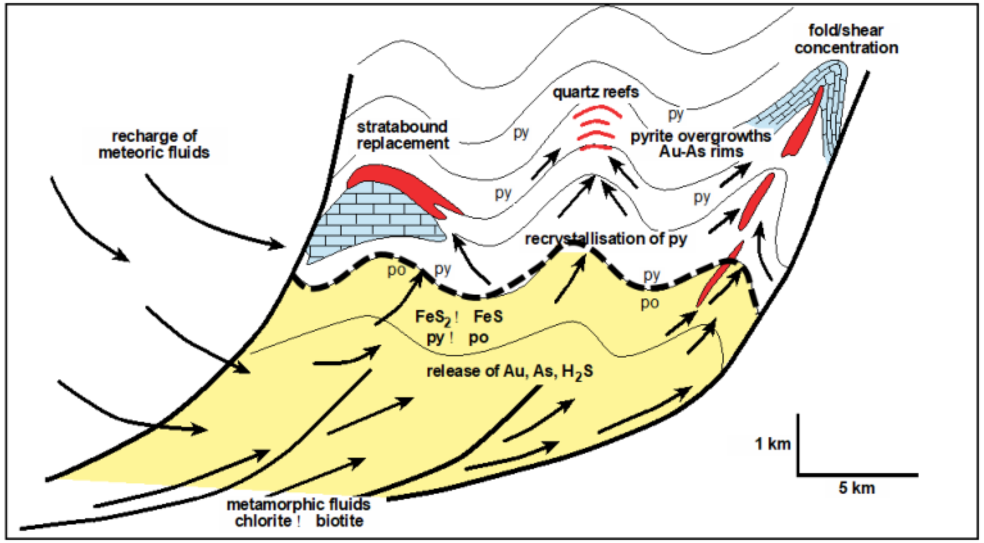
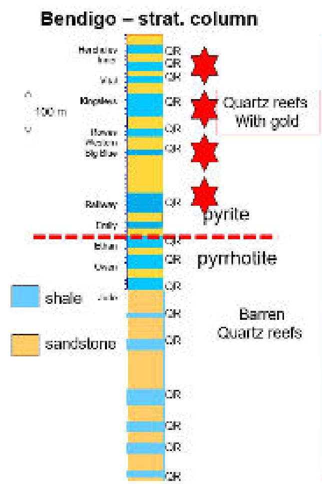
Gold (Cu) in Sedimentary Basins – Peak Ages and Pyrite (Telfer?)

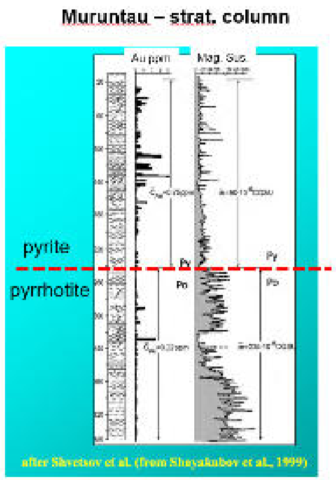
Major periods of Gold concentrated in Global Black Shales



(After Large et.al., 2011,2017)



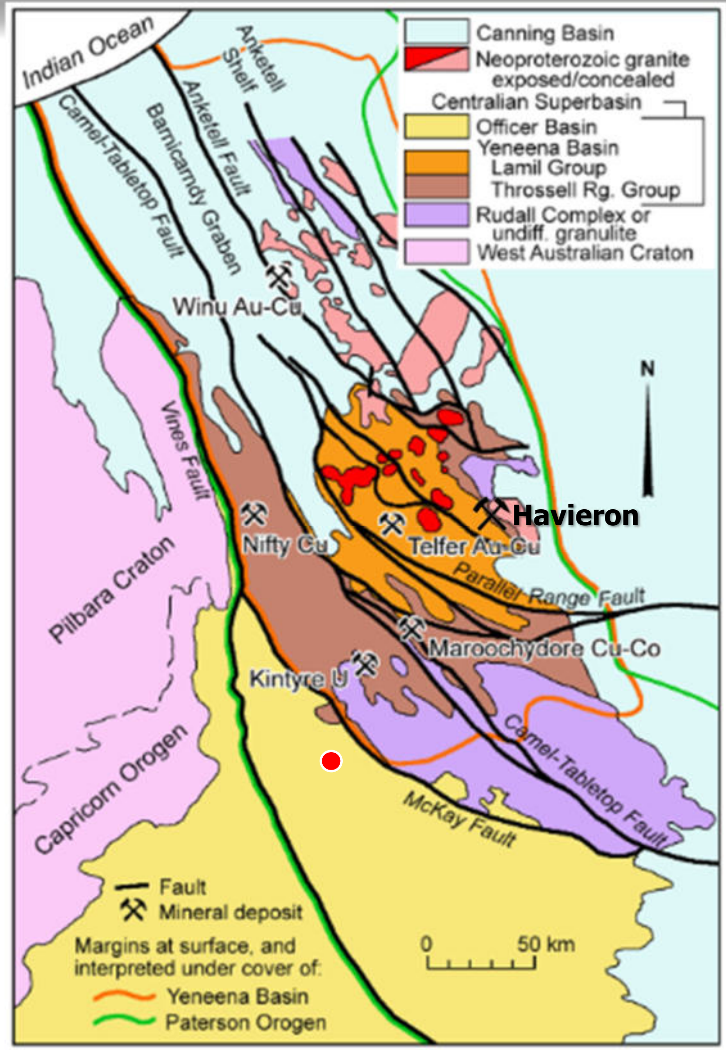




Transition from pyrite to pyrrhotite important in targeting. Pyrrhotite is an important sulphide mineral that is magnetic and targetable at Winu and Haverion

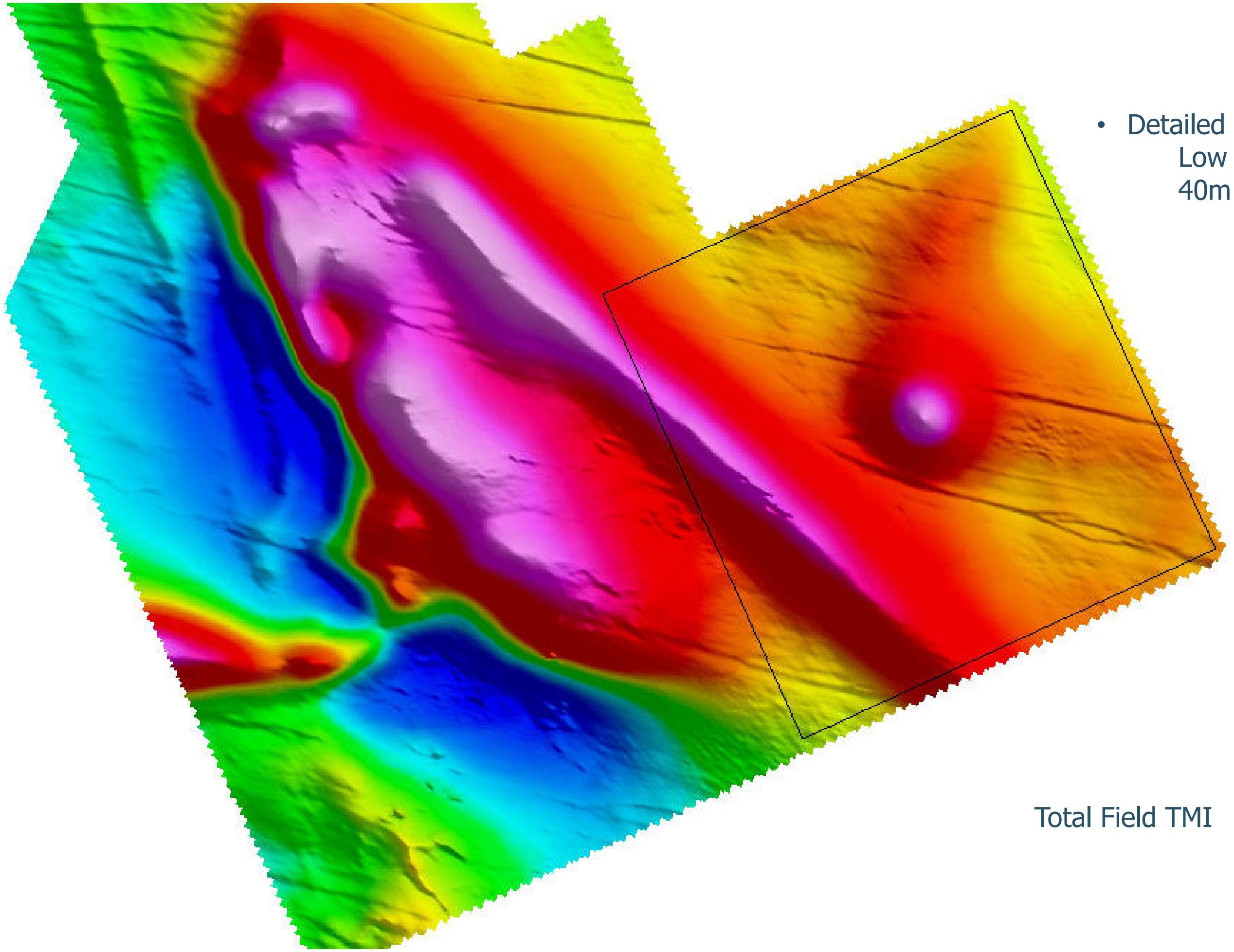
Patterson Orogen – Havieron

- The **high-grade** Au-Cu Havieron deposit exhibits near coincident ovoid magnetic and gravity anomalies and was discovered in 2018, under 420 m of post-mineralisation cover, through geophysical modelling and drilling
- At Havieron, the aeromagnetic image defines a 100 nT near circular magnetic anomaly having a half-width of 800 m
- The gravity gradient appears as a weak 0.5 mGal irregular gravity ovoid in a residual gravity image. The peak of this ovoid is at least 200 m to the south of the magnetic peak
- Including a remanent magnetic vector in the magnetic model simplified the model body and shifted it southward to a position coincident with the residual gravity anomaly



(After Hanneson and Baxter,2022- Preview)

Havieron Deposit - Airborne Magnetic Data

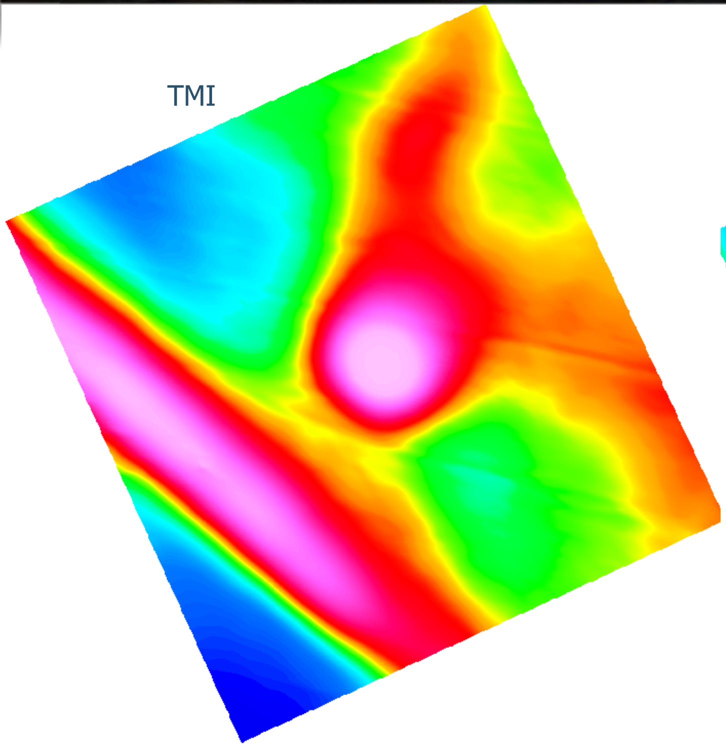


- Detailed UTS open file data
  - Low level 20m
  - 40m line spacing

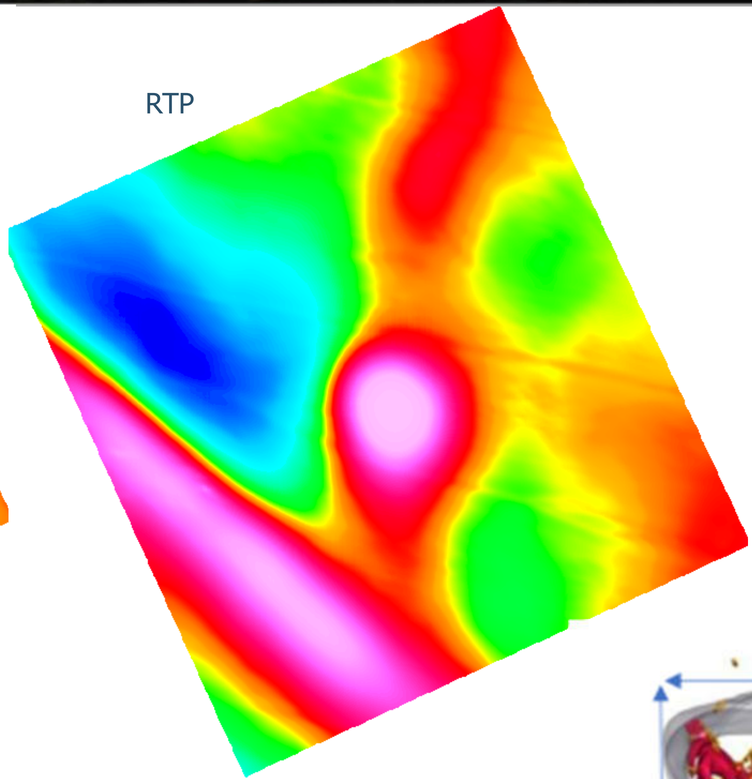
Total Field TMI

Havieron Deposit – Airborne Data

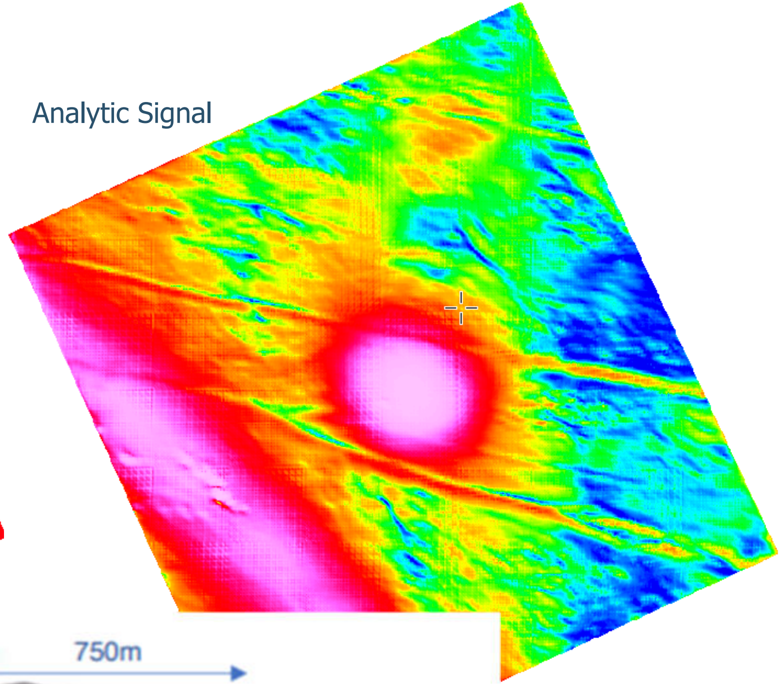
TMI

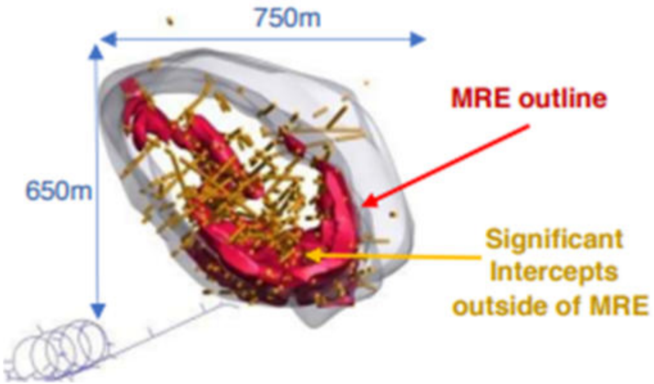


RTP



Analytic Signal





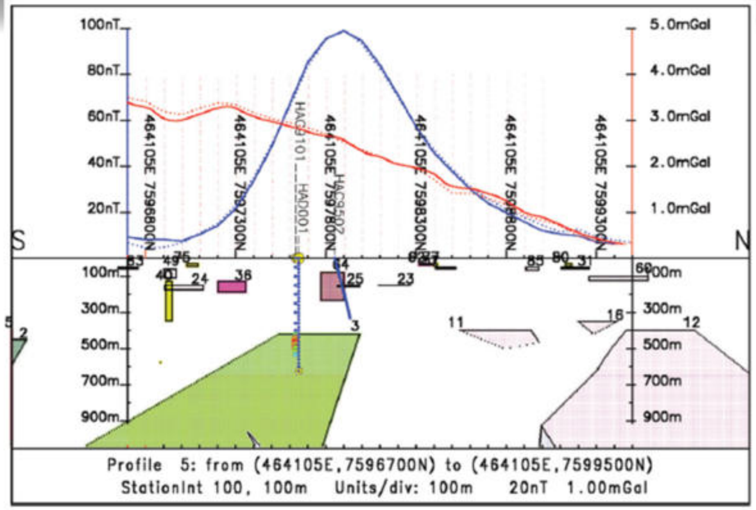
- Detailed UTS open file data
  Low level 20m
  40m line spacing

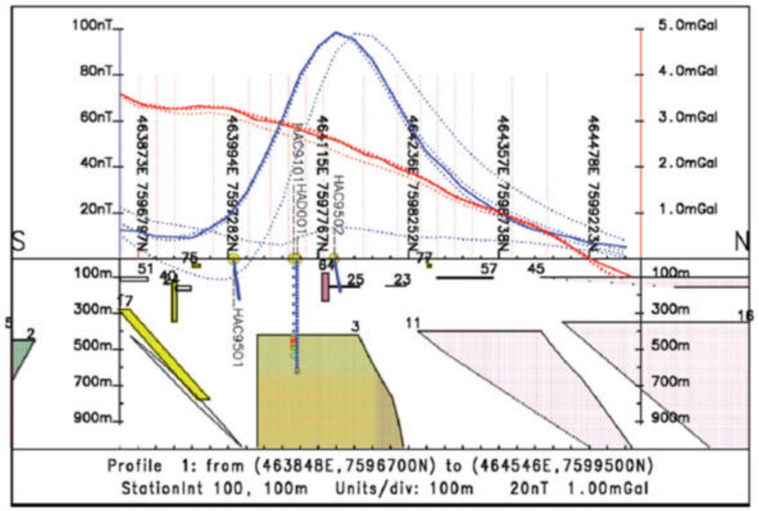
~ 50nT anomaly (airborne 20m flight height)
~100nT anomaly (ground data)

Remanence – Havieron Deposit

- Introducing the remanent vector required shifting the magnetic body southward some 200 m so that the same body, when given a density contrast of 0.11 gm/cc, also simulates the gravity data. The discovery hole was designed to intersect rocks represented by the now coincident source of the magnetic and gravity anomalies.
- The first of the historic holes HAC9101, which seems to have been directed into the magnetic peak, had the potential to make the discovery had it been drilled deeper.
- Discovery hole HAD001, 121m @ 2.9g/t from ~400m

Parameter	Min	Max	Mean	StdDev	Median
Inclination	-83.	73.	-9.44	48.8	-7.0
Declination	77.	349.	202.	71.3	182.
K-Ratio (Q)	0.30	11.6	3.31	3.1	1.9





(After Hanneson and Baxter,2022- Preview)

Conclusions

- Remanence measurements in regional studies are assisting explorationist understand the role of magnetics in targeting mineral systems
- The presence of remanence, or lack of, in your drilling data could be associated with mineralisation (type?)
- Remanence could effect how you model and subsequently drill test a magnetic target (susceptibility and magnetisation direction)
- As mineral deposits are likely to have undergone a complex history of geological events, they may carry a composite magnetic record (NRM) of several different ages
- In order to separate the magnetising events, step-wise demagnetisation experiment are required to isolate individual vector components of the NRM

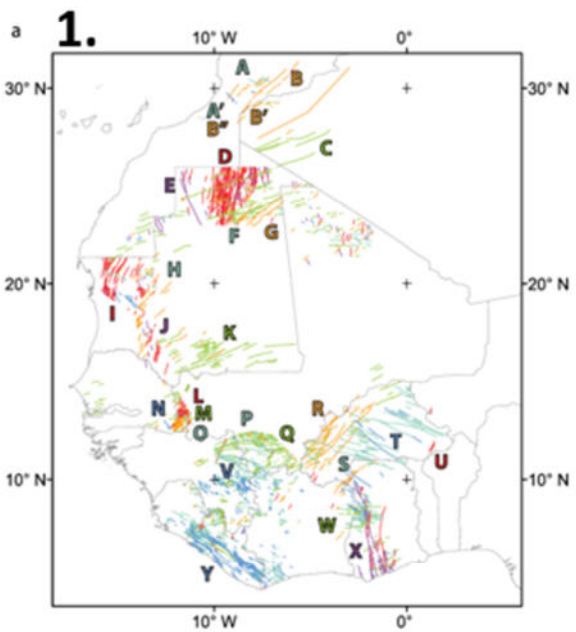
Linkage Project: Exploring the Paleogeographic Relationship of Major Mineral-Bearing Cratons

1. Paleomagnetic field work in West Africa and the Guiana Shield targeting identified dykes of WAXI and SAXI
2. Geochronology, paleomagnetic measurements, establishing full plate paleogeographic models based on new paleomagnetic data for 2.7-1.6 Ga interval addressing the onset of plate tectonics and the supercontinent cycle

3. Innovative paleogeographic approach: Using Quantum Diamond Microscope to locate and use paleomagnetic remanence directions of secondary magnetic phases (e.g., pyrrhotite and magnetite); will be developed on rocks from Australia with the potential of determining the paleoposition of major mineral deposits

Classic
Innovative
Paleogeography

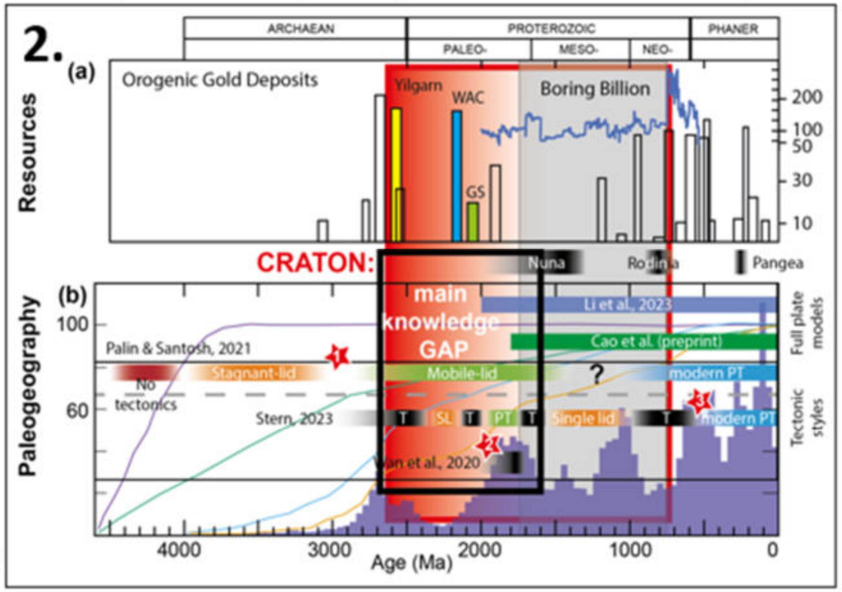
1.



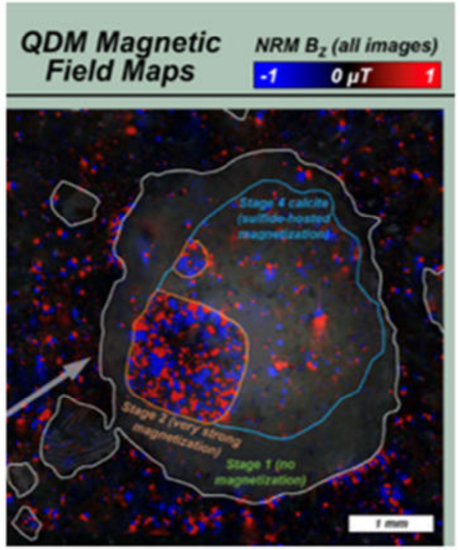
West African eXploration Initiative:
Mafic Dykes in West Africa, Jessell et al., 2015

Most recent full plate models go back to 1.8/2.0 Ga, just
Missing the important 2.7-1.8 Ga interval with the formation of major mineral deposits and major disagreement of the onset of plate tectonics

2.



3.



Locate, date and use secondary magnetic phases
With QDM magnetic field maps, Brenner et al., 2022

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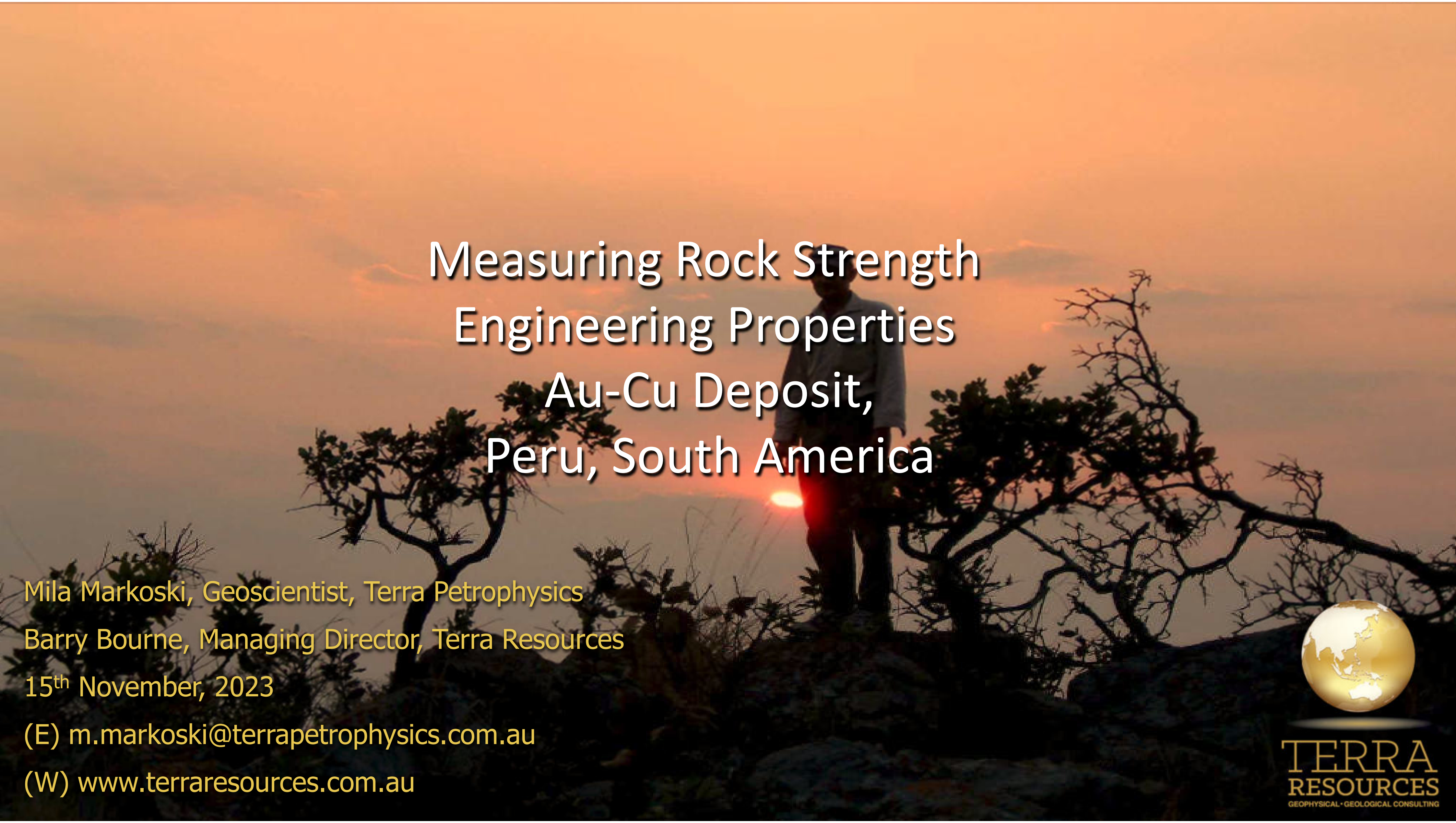

Measuring Rock Strength Engineering Properties Au-Cu Deposit, Peru, South America

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Engineering Properties

- Elastic properties:

→ Young’s Modulus (E): the ratio of uniaxial compressive (tensile) stress to the resultant strain

→ Shear Modulus (μ): the ratio of shearing (torsional) stress to shearing strain

→ Bulk Modulus (K): the change in volume under hydrostatic pressure

→ Poisson’s Ratio (σ): a measure of the deformation (expansion or contraction) of a material in directions perpendicular to the specific direction of loading

- Inelastic properties:

→ Unconfined Compressive Strength (UCS): strength of an intact rock material

→ Fracture Gradient: the pressure gradient at which the formation breaks

Unconfined Compressive Strength (UCS)

- Simplest and most widely used reference system to define rock strength
- The resistance to permanent deformation when under compression
- Measuring Methods: Point Load Test, Schmidt Hammer, Equotip, etc.
- Terra Petrophysics performed research on the use of Schmidt Hammer and Equotip for rock strength testing

Table I

Description of rock strength (ISRM 1980)

Strength description	UCS (MPa)
Extremely low strength	< 1
Very low strength	1–5
Low strength	5–25
Medium strength	25–50
High strength	50–100
Very high strength	100–250
Extremely high strength	> 250

Test and Sample Requirements

- Test points should be away from the boundaries to avoid abnormally low values due to strong dissipation of impact energy
- Hammer axis needs to be perpendicular to the test surface to minimize variations that would arise from oblique impact
- Core should be at ~50mm
- Full core and larger length is preferred
- Specimens should be free of visible cracks

Petrophysics and Engineering Analysis

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- Terra Petrophysics have completed petrophysics data acquisition on 431 samples from 11 drillholes.
- Petrophysical data acquisition included:
- - Magnetic Susceptibility
  - Inductive Conductivity
  - P-wave Velocity
  - Dry Bulk Density
  - Porosity
  - IP/Resistivity
  - Remanent Magnetisation
  - Spectral Radiometrics
- Engineering data acquisition included:

  - Schmidt Hammer Rebound number (R)
  - Unconfined Compressive Strength (UCS)
- Data has been plotted and analysed using IOGas.

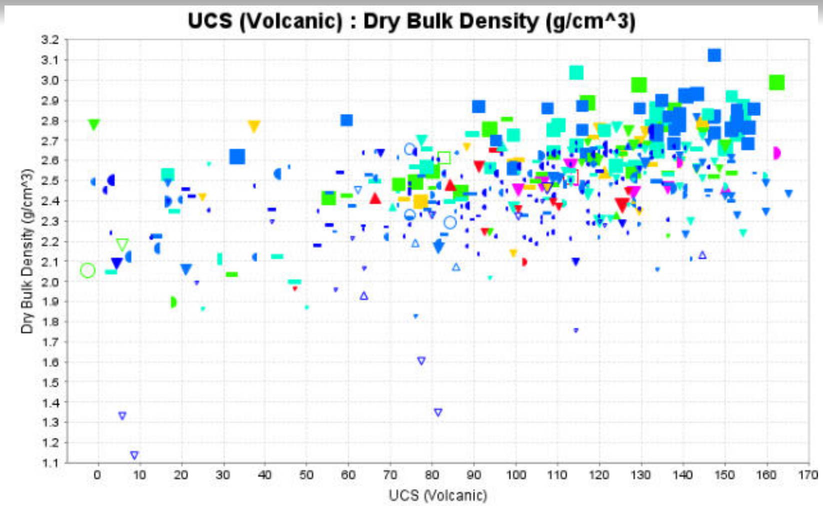
Engineering

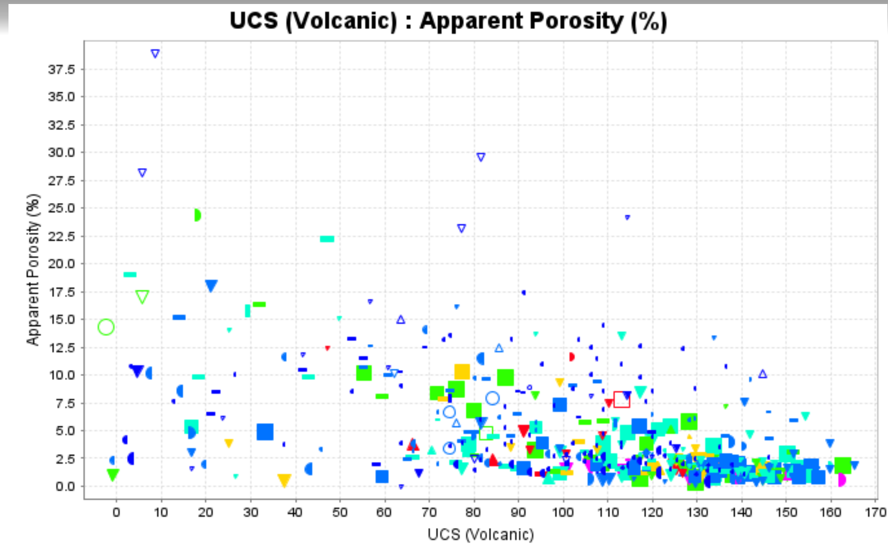
- Rock Schmidt Hammer Rebound (R) numbers were recorded for all samples, except 1 due to a lower limit on the Schmidt Hammer
- 2 measurements/sample and an average R number was calculated
- Unconfined Compressive Strength (UCS) was then derived from the R value using the following correlation equations:

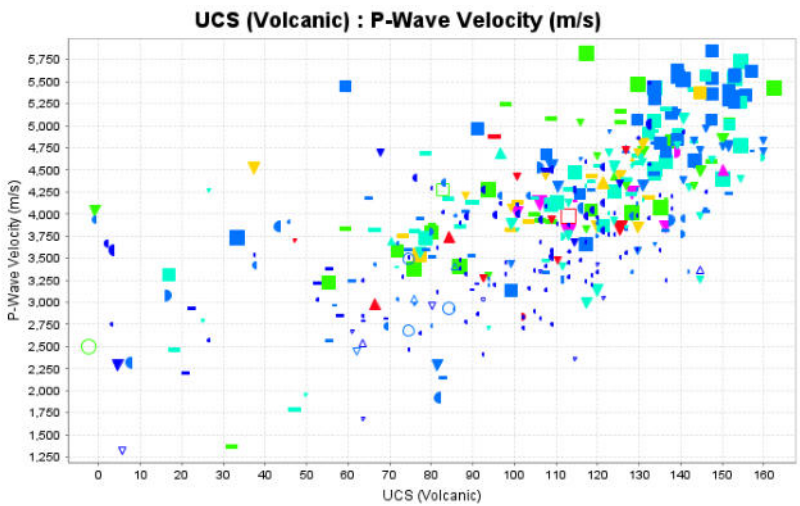
Volcanic rock:	$UCS = 2.75 * R - 36.83$	[3]
Granite:	$UCS = 1.4459 * e^{(0.070*R)}$	[1]
General:	$UCS = 4.24 * e^{(0.059*R)}$	[5]
Vp:	$UCS = 2.304 * Vp^{2.4315}$	[4]

- The obtained UCS values were then plotted against Dry Bulk Density, Porosity and P – Wave Velocity.

Engineering – UCS (Volcanic)







Colour

Au ppm Progressive

- Au ppm to 0.013 [30.00%]
- Au ppm to 0.09 [60.00%]
- Au ppm to 0.174 [80.00%]
- Au ppm to 0.274 [90.00%]
- Au ppm to 0.413 [95.00%]
- Au ppm to 0.864 [98.00%]
- Au ppm to 6.128 [100.00%]

Shape

Lithology

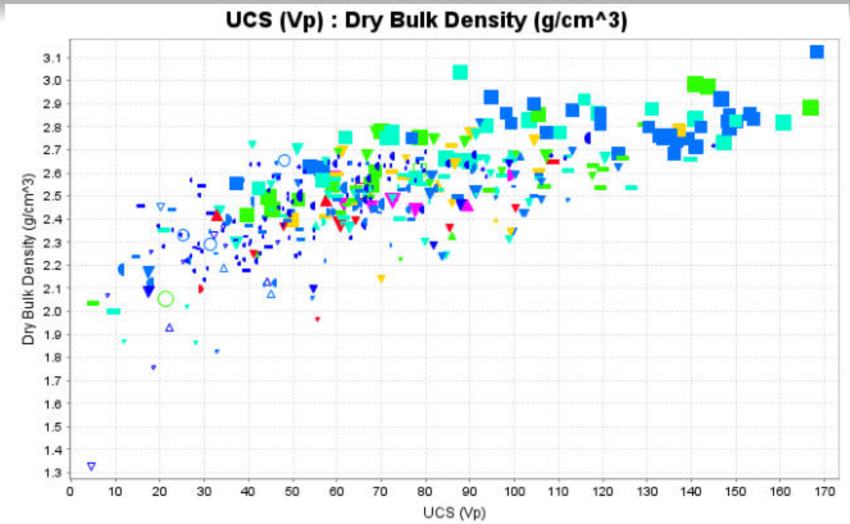
- Early Quartz Porphyry
- Eutaxitic Ignimbrite
- Hydrotermal Breccia
- Limestone
- Lower Andesite
- Phreatic Breccia
- Phreatomagmatic Breccia
- Porphyry
- Quartz Porphyry
- Quartz Porphyry Breccia
- Upper Andesite
- Upper Lithic Tuff

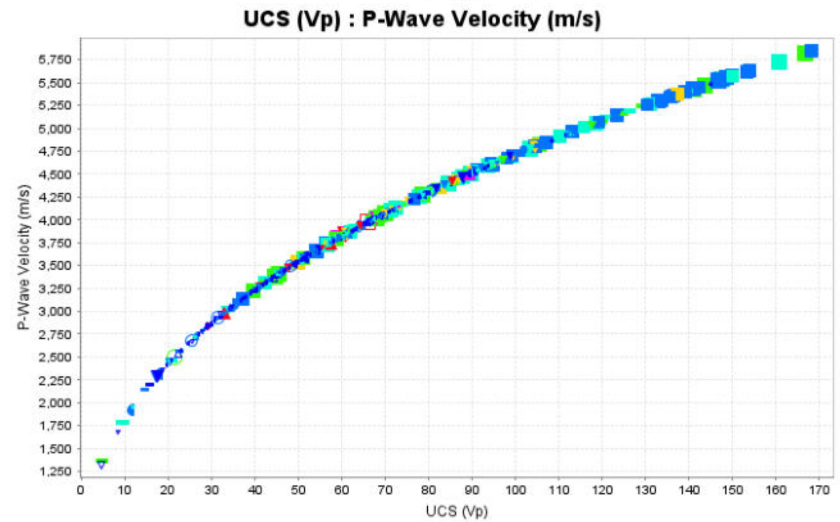
Size

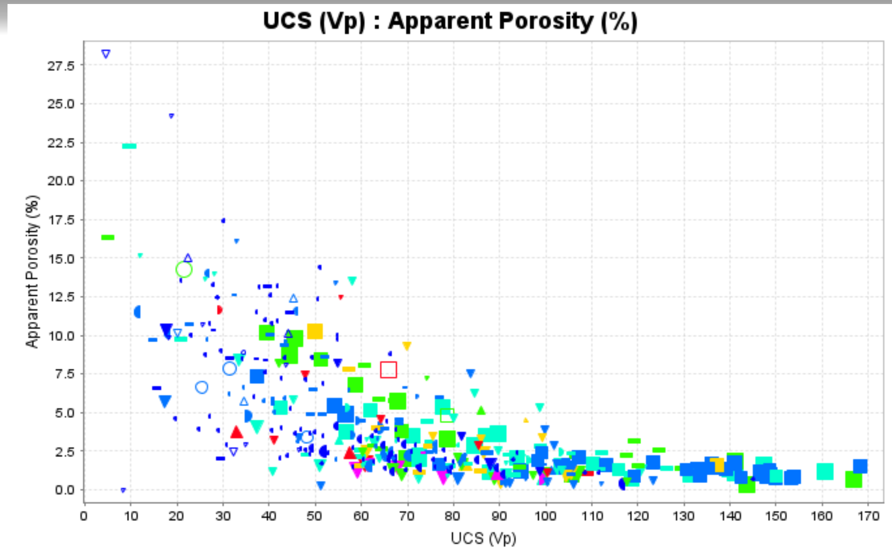
Cu ppm Progressive

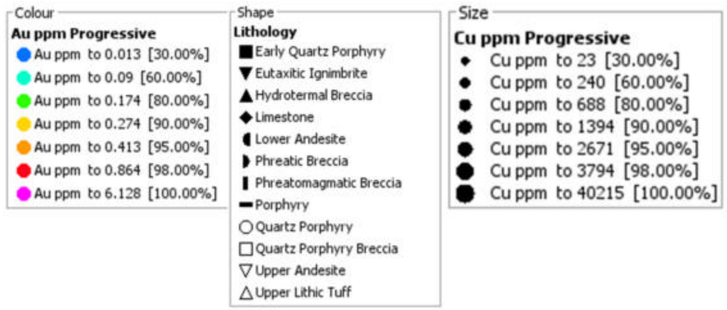
- Cu ppm to 23 [30.00%]
- Cu ppm to 240 [60.00%]
- Cu ppm to 688 [80.00%]
- Cu ppm to 1394 [90.00%]
- Cu ppm to 2671 [95.00%]
- Cu ppm to 3794 [98.00%]
- Cu ppm to 40215 [100.00%]

Engineering – UCS (Vp)









Conclusion

- All plots exhibit positive correlations between the UCS and dry bulk density/P-wave velocity and a negative correlation between the UCS and the apparent porosity
- UCS derived from the equation for volcanics and the Vp equation exhibit values from (5 – 168 MPa) and (-2 – 165 MPa) respectively
- Further research and consulting with geotechnical engineers needs to be conducted to confirm the results and solidify our understanding
- Currently offered as a free service

Acknowledgements

Geological Survey of Western Australia

AGES

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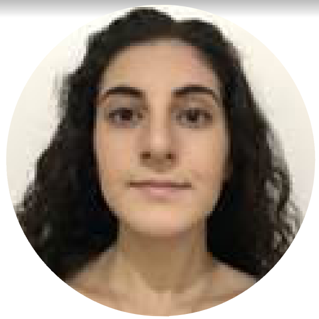
THE UNIVERSITY OF WESTERN AUSTRALIA

Curtin University

Acknowledgements – Terra Team

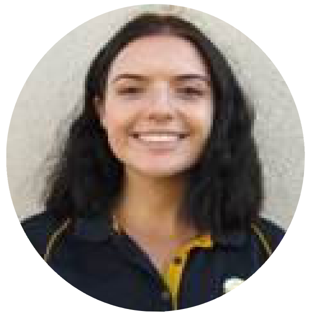


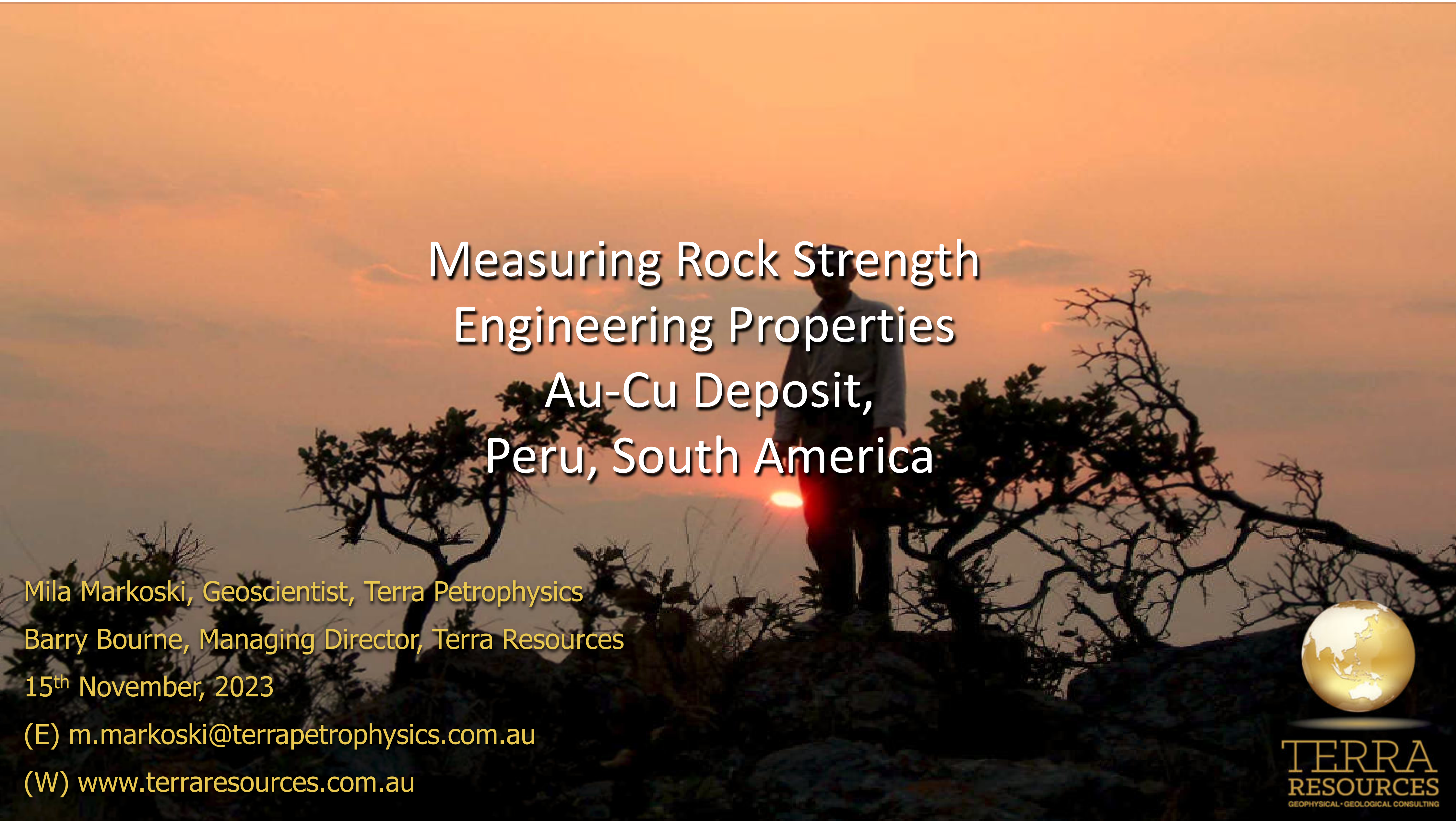










Measuring Rock Strength Engineering Properties Au-Cu Deposit, Peru, South America

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