Deep geophysical targeting (and ambiguity of results) for hard rock IOCG and soft rock shale-unconformity hosted Cu-Co-Ag deposits at Emmie Bluff in South Australia

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Introduction

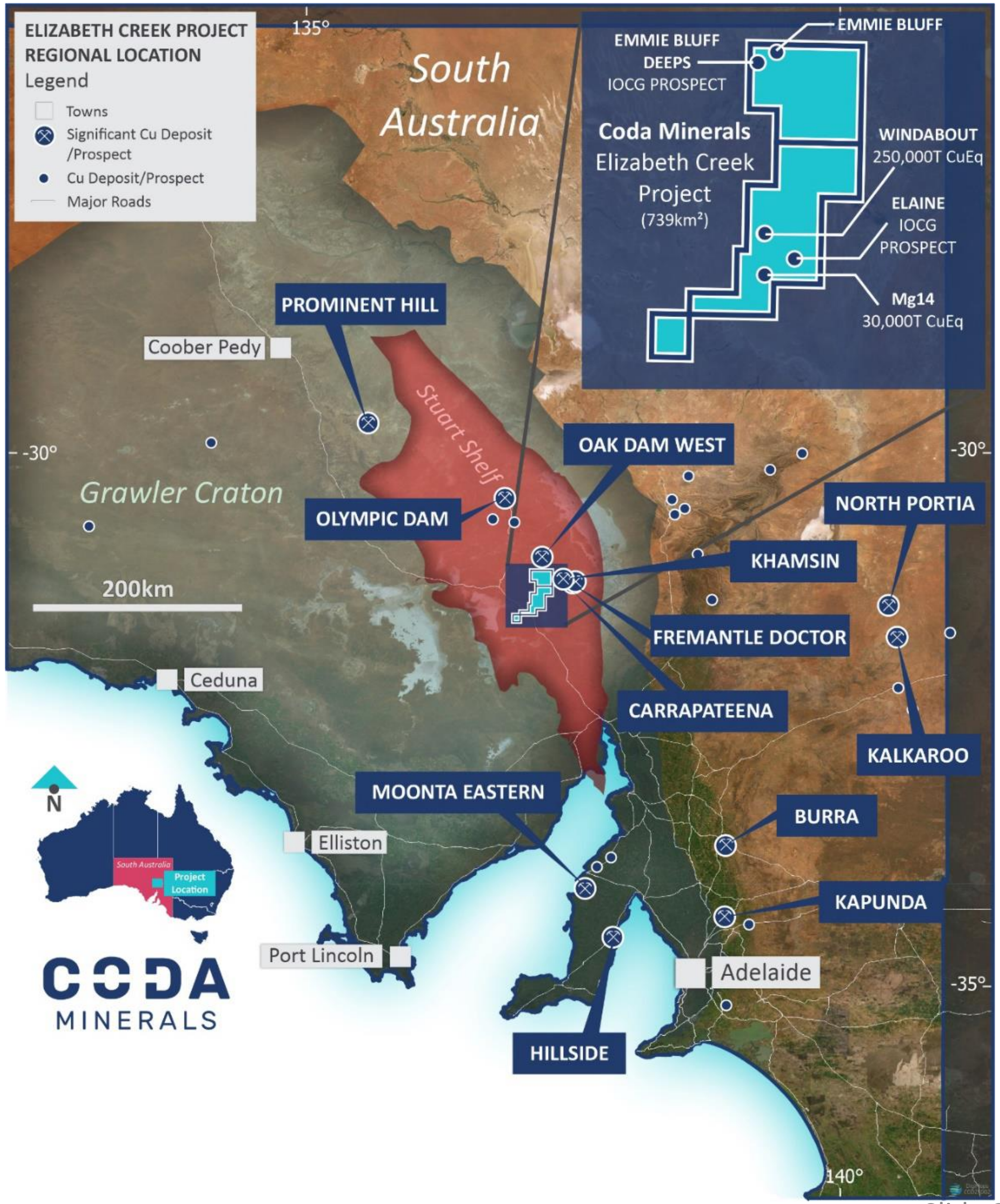
Resource Potentials

Coda Minerals' Elizabeth Creek project in SA contains the **Emmie Bluff** deposit, which is a flat lying shale and sandstone unconformity hosted sedimentary replacement (SEDEX style) Cu-Ag-Co sulphide deposit located at 400m depth. It formed in an isolated Neoproterozoic sag basin along the Pernatty Upwarp of the Stuart Shelf basin to the east of the Torrens Hinge Zone and Adelaide Geosyncline / Fold and Thrust Belt.

The sources of Emmie Bluff sedimentary replacement metals are likely the underlying Pandurra Fm redbeds and possibly IOCG altered Paleo-Mesoproterozoic crystalline basement rocks sitting below the Pandurra.

Emmie Bluff also occurs within the Olympic Dam Copper province, and now also contains the recently discovered **Emmie Deeps** IOCG deposit found at 800m depth. Emmie Deeps likely formed during the same 1.59 Ga IOCG and igneous event that formed other large IOCG deposits in the region.

Both styles of mineral deposits at Emmie Bluff are very deep, well below penetration of surface IP and EM surveying, made more difficult by electrically conductive Neoproterozic and Cainozoic sediment cover, therefore requiring deep reaching geophysical survey methods to help focus exploration drilling and assist with mine development. Example results from recent geophysical surveys will be presented.



Emmie Bluff sedimentary replacement and IOCG deposits

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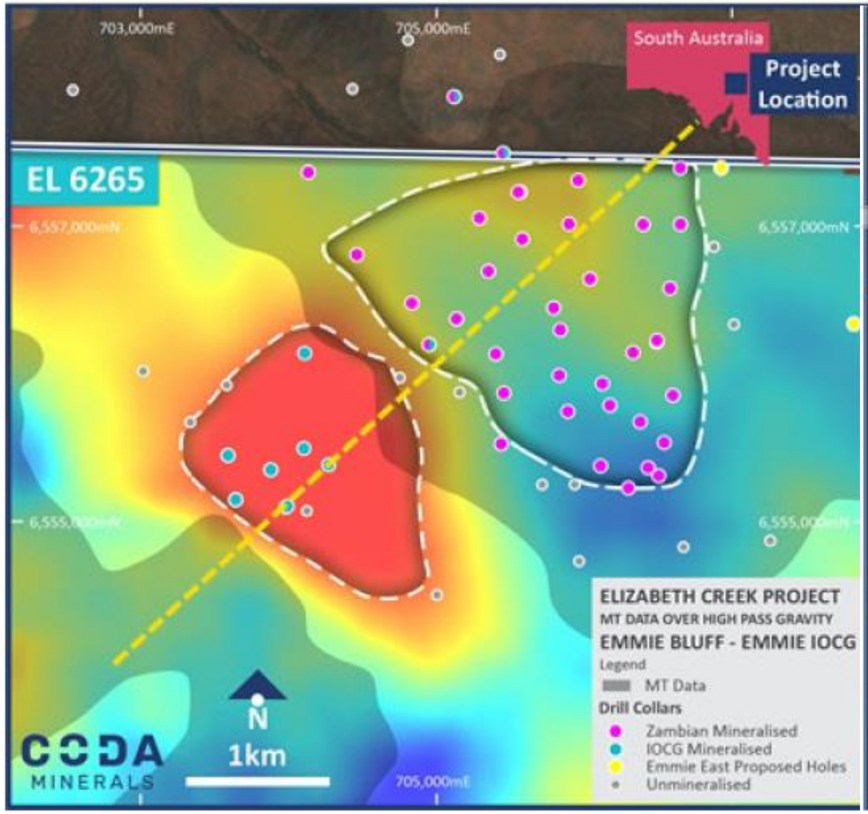

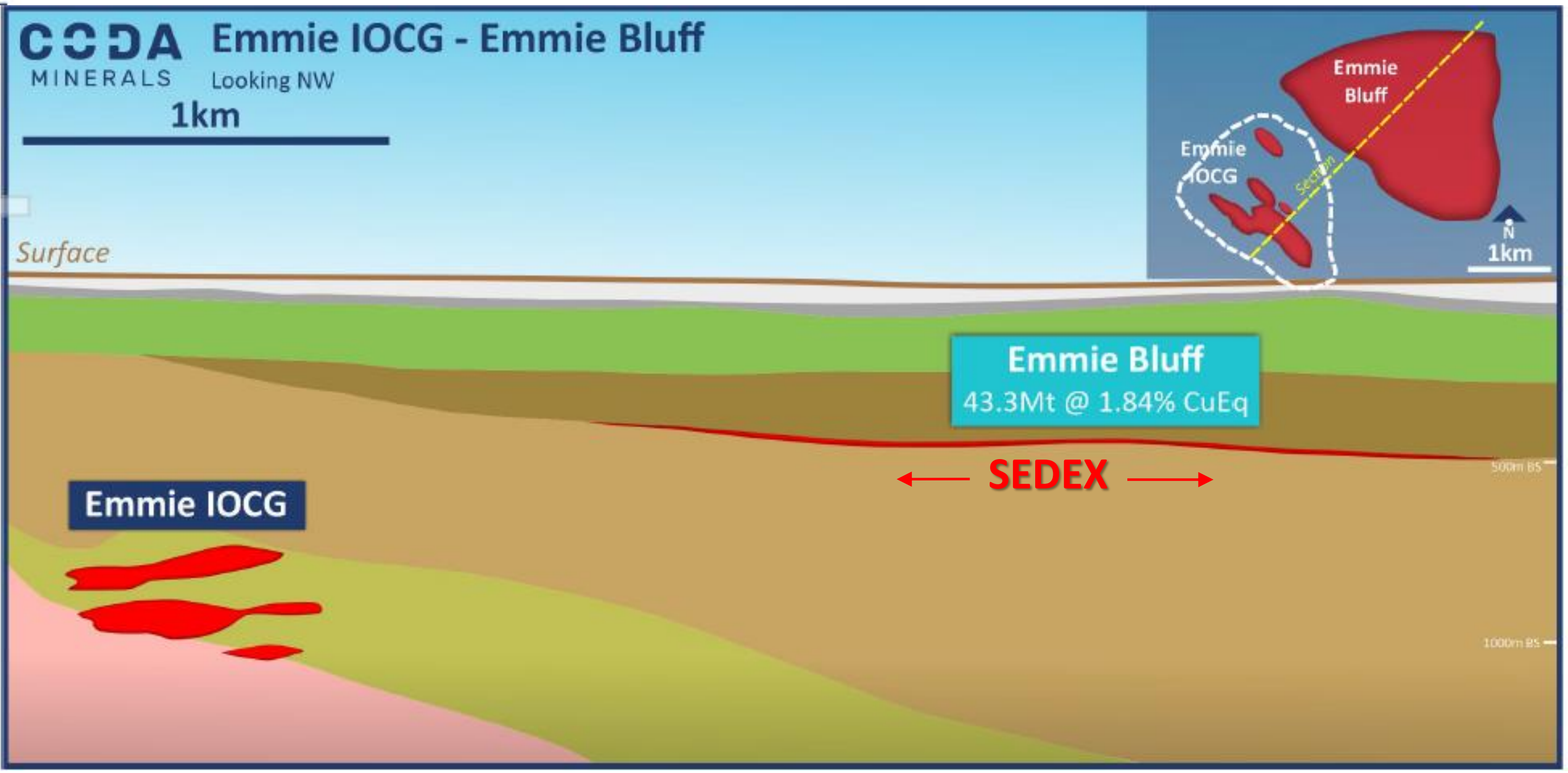

Regional IOCG setting and Stuart Shelf region

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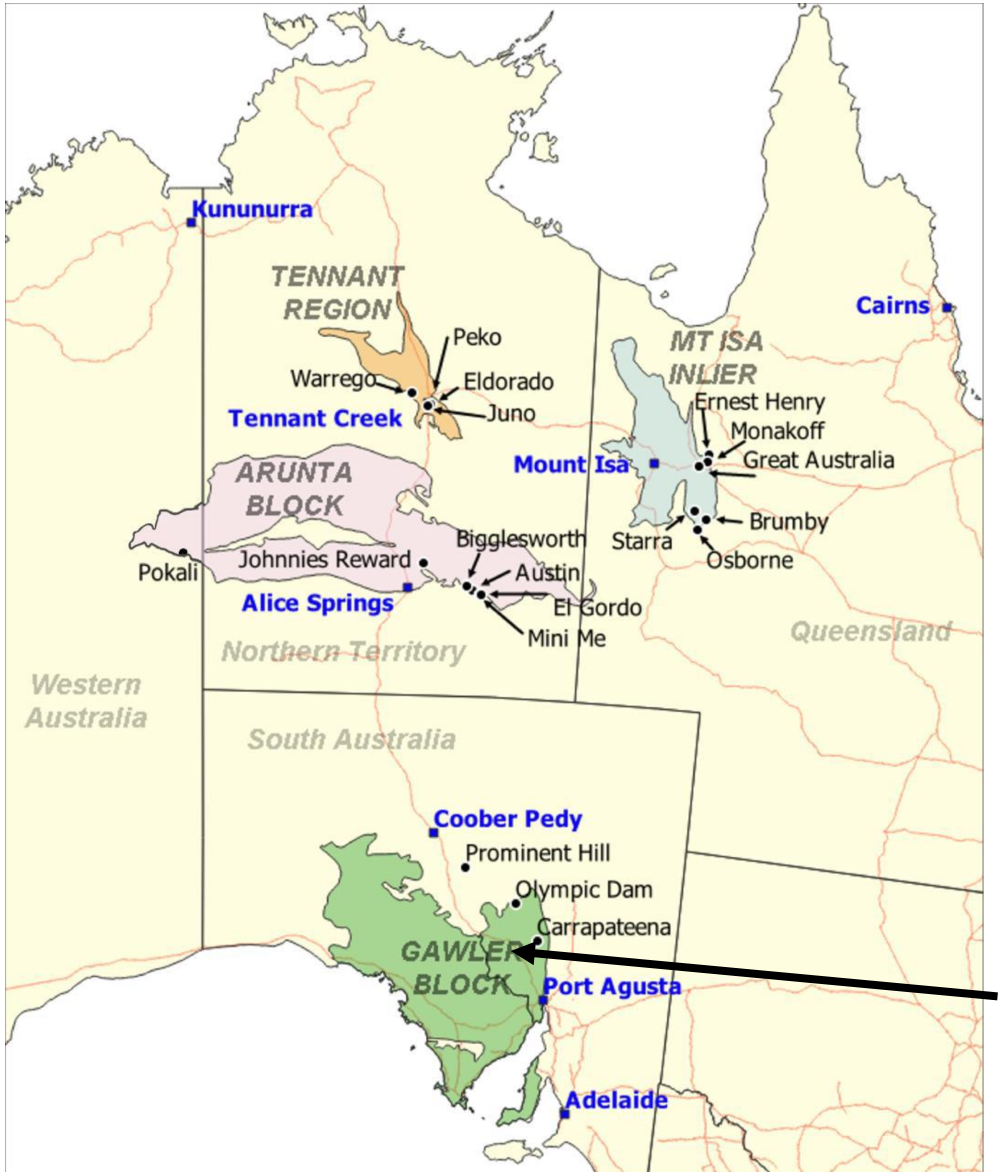
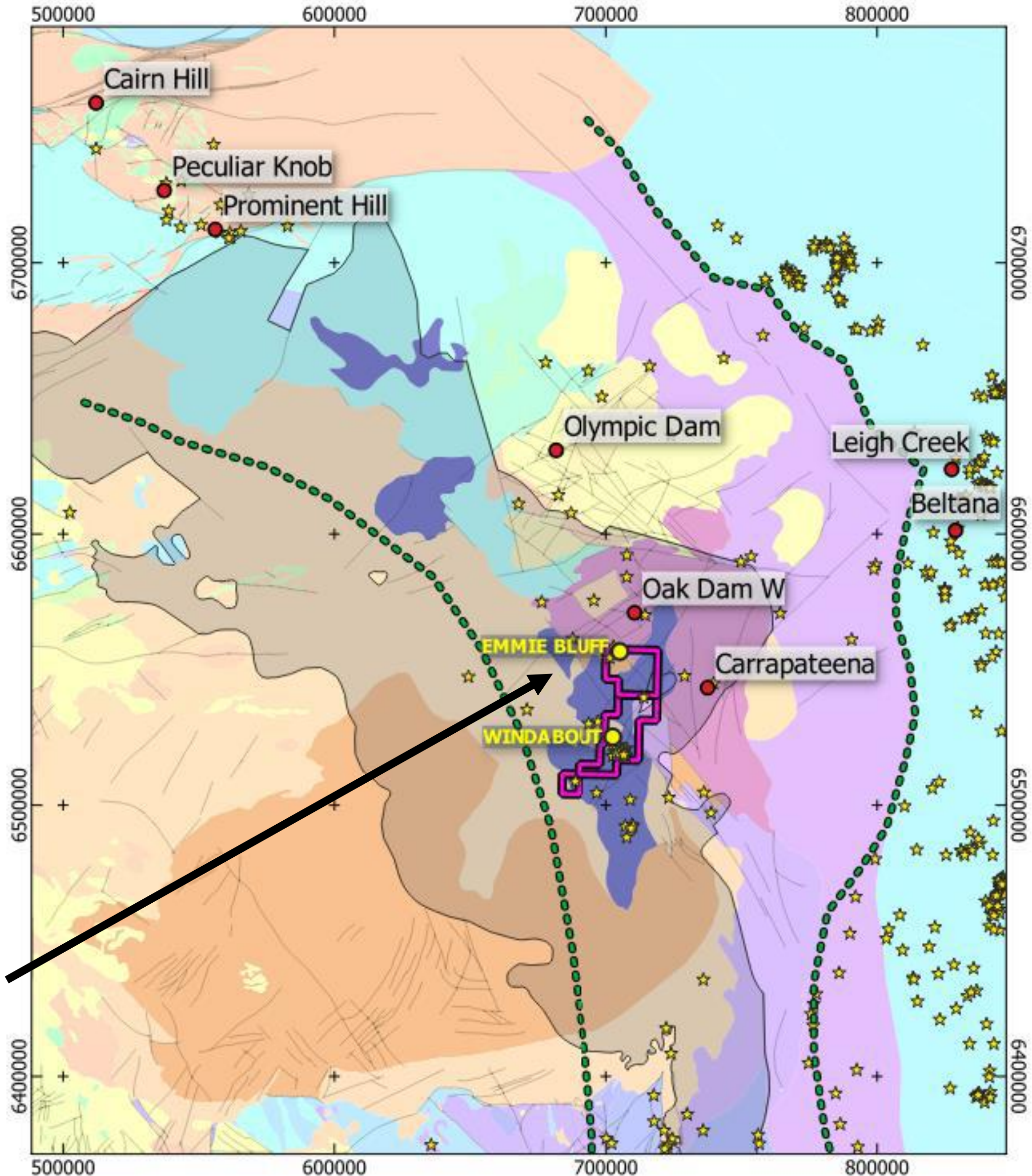
Australian IOCG/ISCG provinces



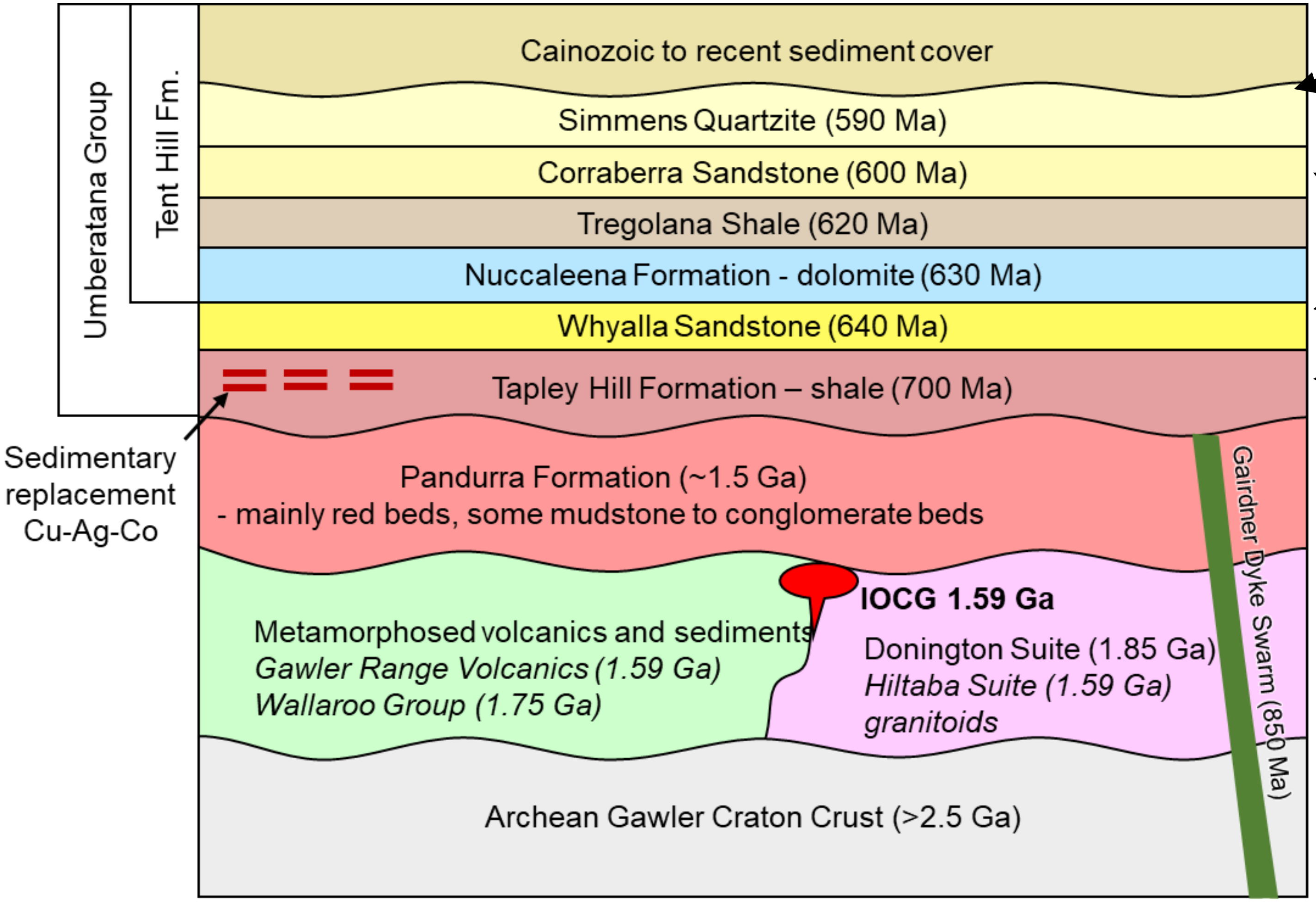
EMMIE BLUFF

Olympic Dam Copper Province

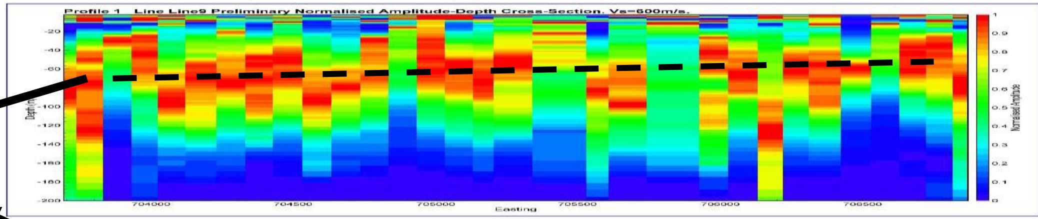


Emmie Bluff stratigraphic column

Resource Potentials



Trial HVSR passive seismic survey line at Emmie Bluff only detects top of Simmens Quartzite



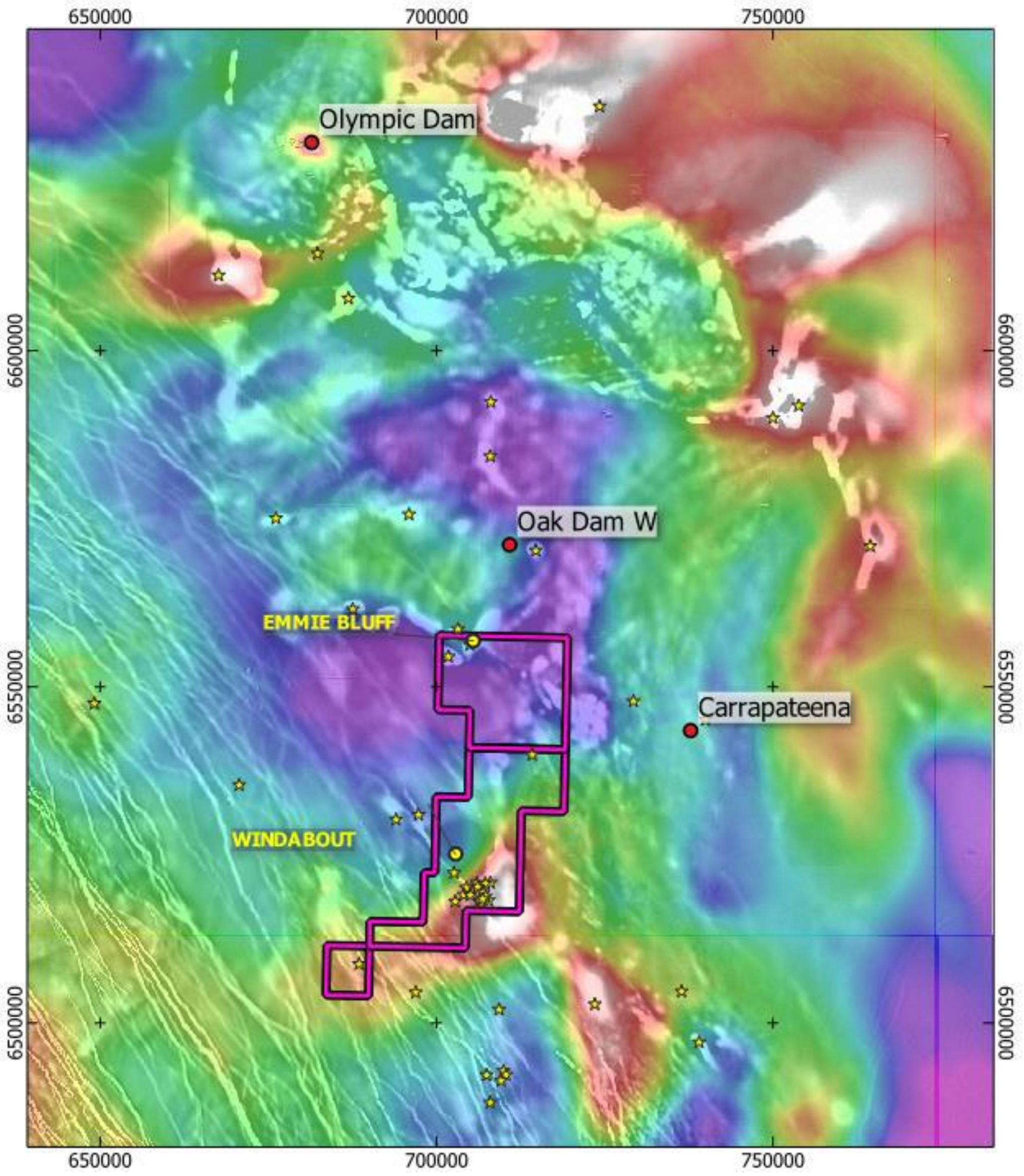
Electrically conductive due to saline groundwater

SEDEX target horizon, electrically conductive shale, enhanced by sulphide minerals

Regional potential field anomaly patterns

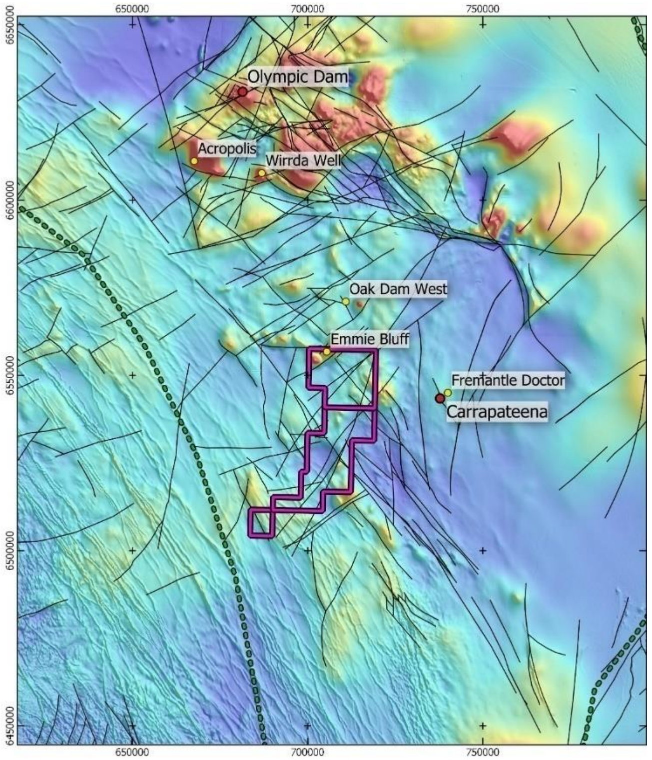
Resource Potentials

Gravity over magnetics

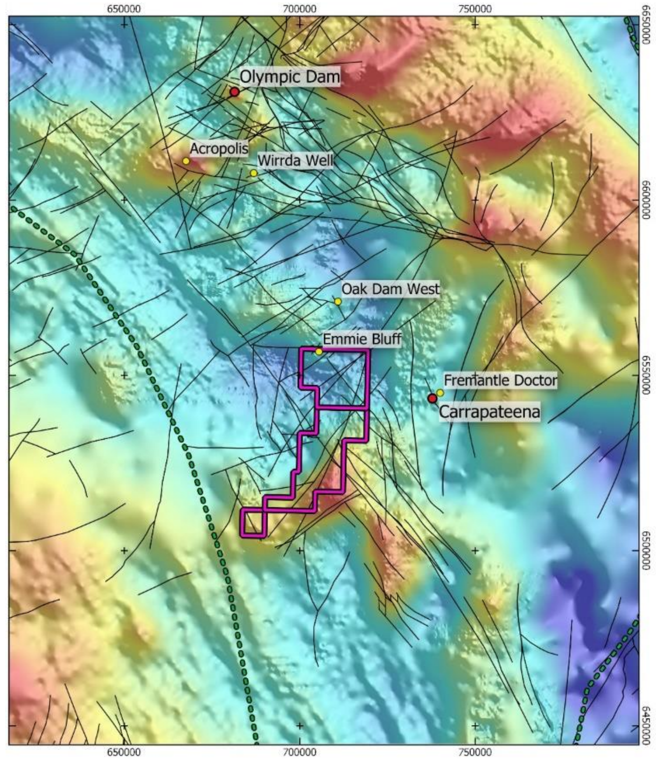


Anomaly patterns caused by igneous and hydrothermal magnetite, dense mafic vs felsic lithologies and hydrothermal hematite, and Paleoproterozoic crystalline bedrock topography below low density sedimentary cover.

TMI-RTP



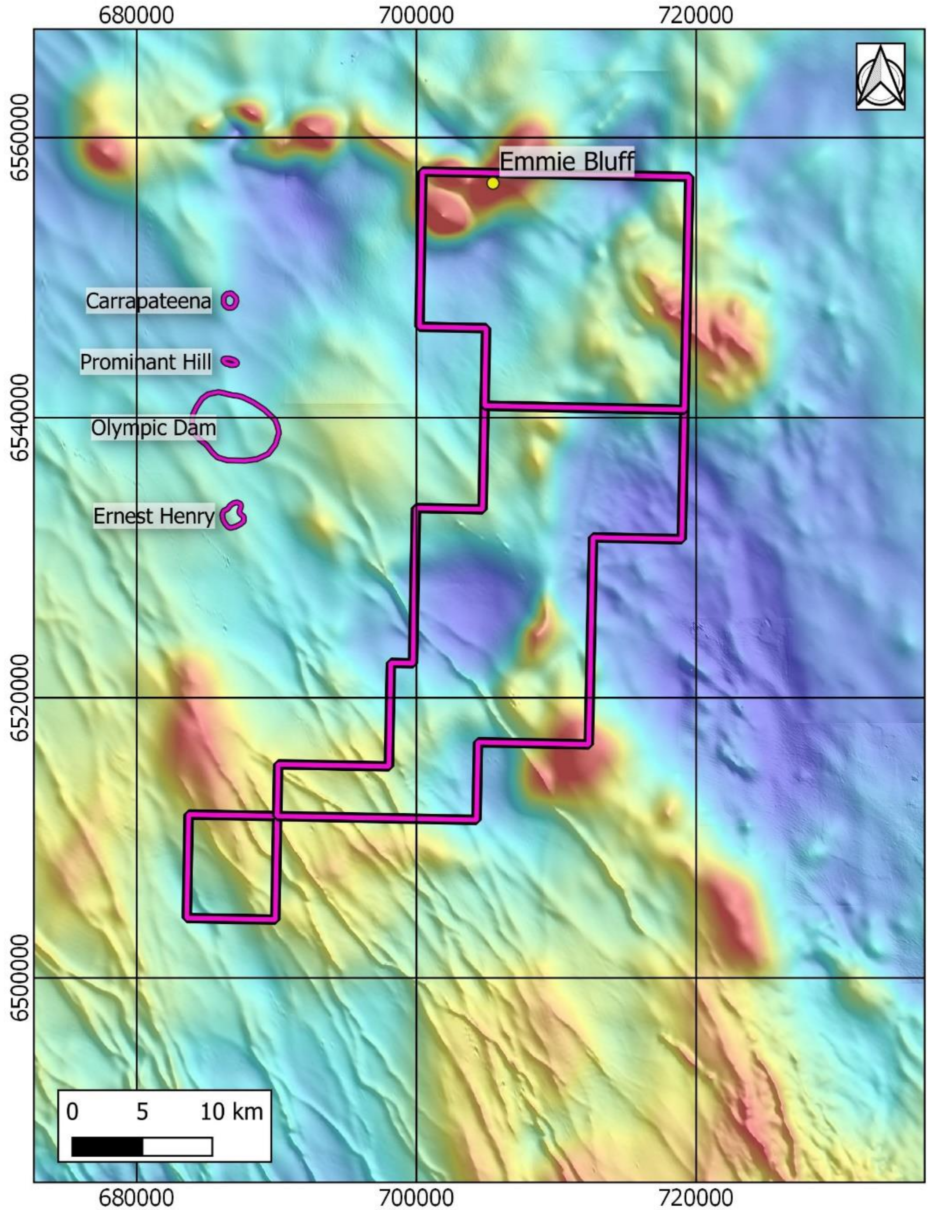
Bouguer Gravity



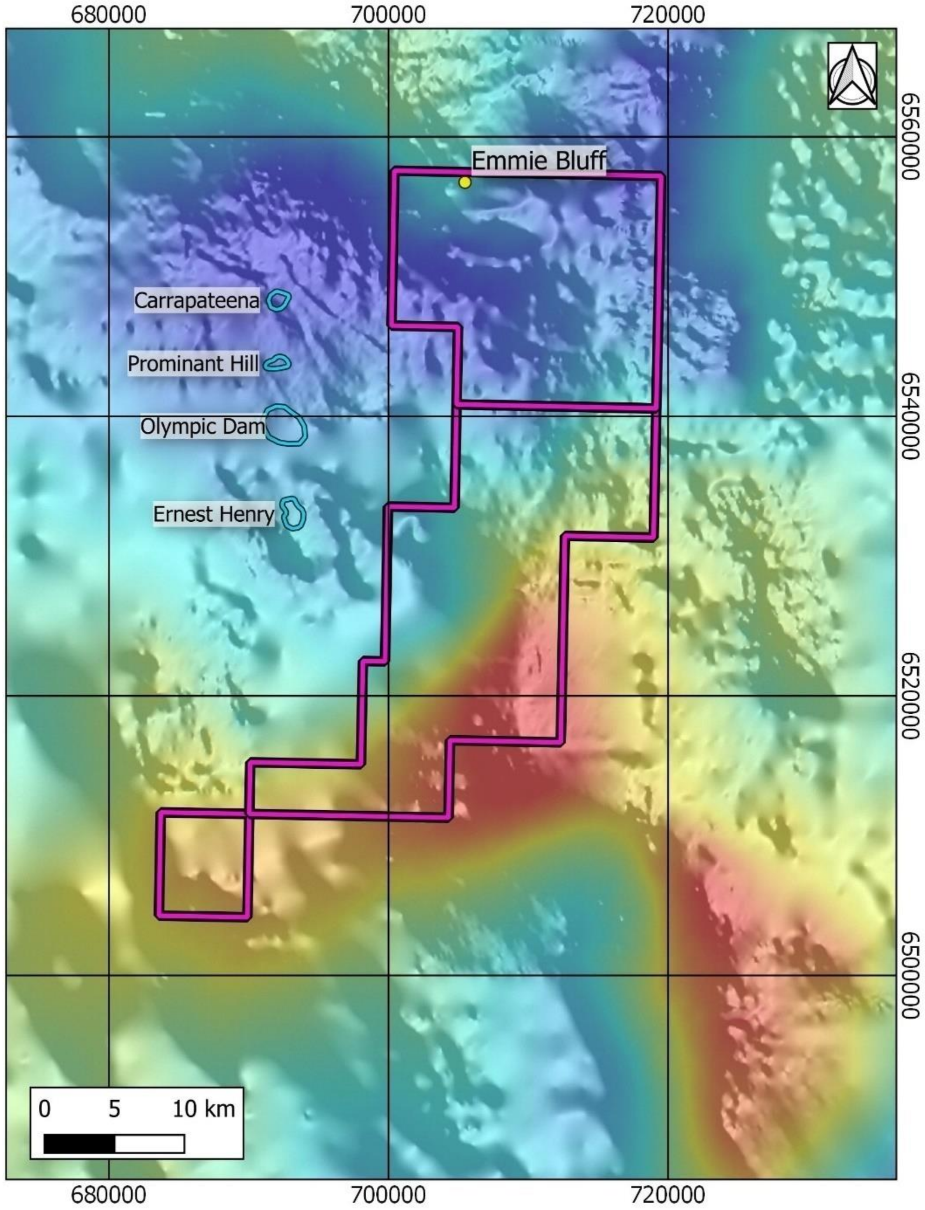
Project scale potential field anomaly patterns vs anomaly footprints of Australian IOCG deposits

Resource Potentials

TMI-RTP

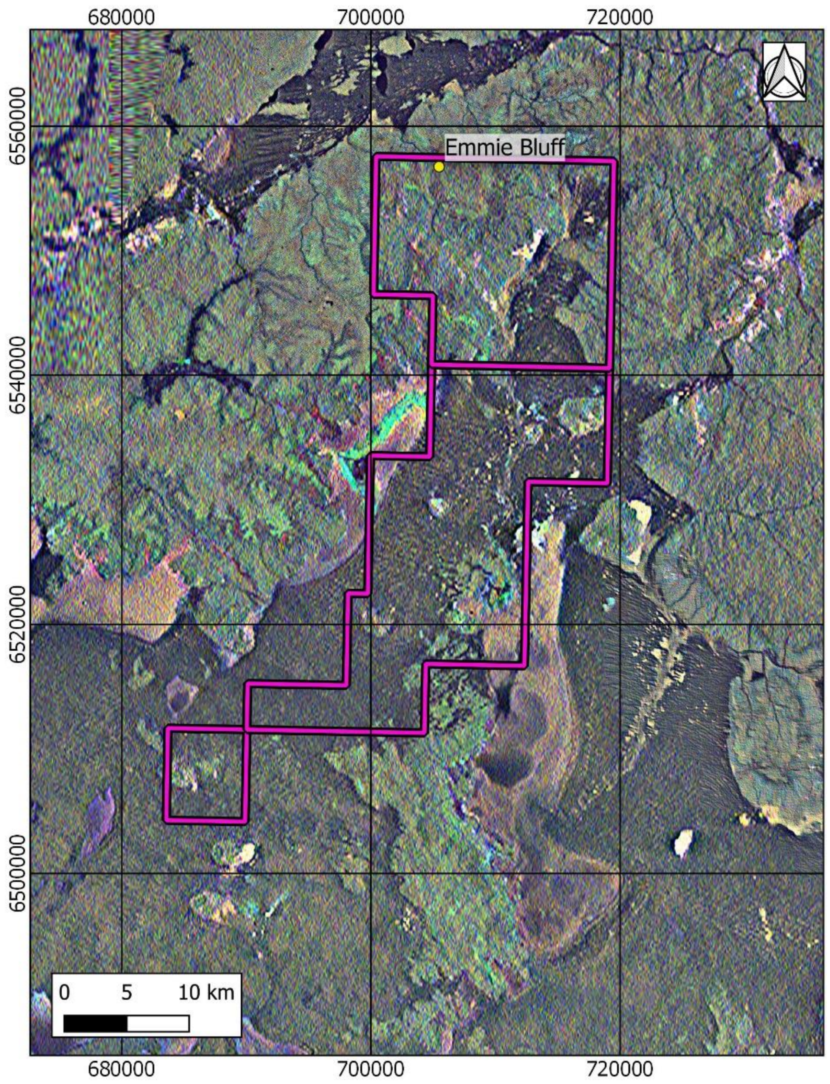


Bouguer Gravity

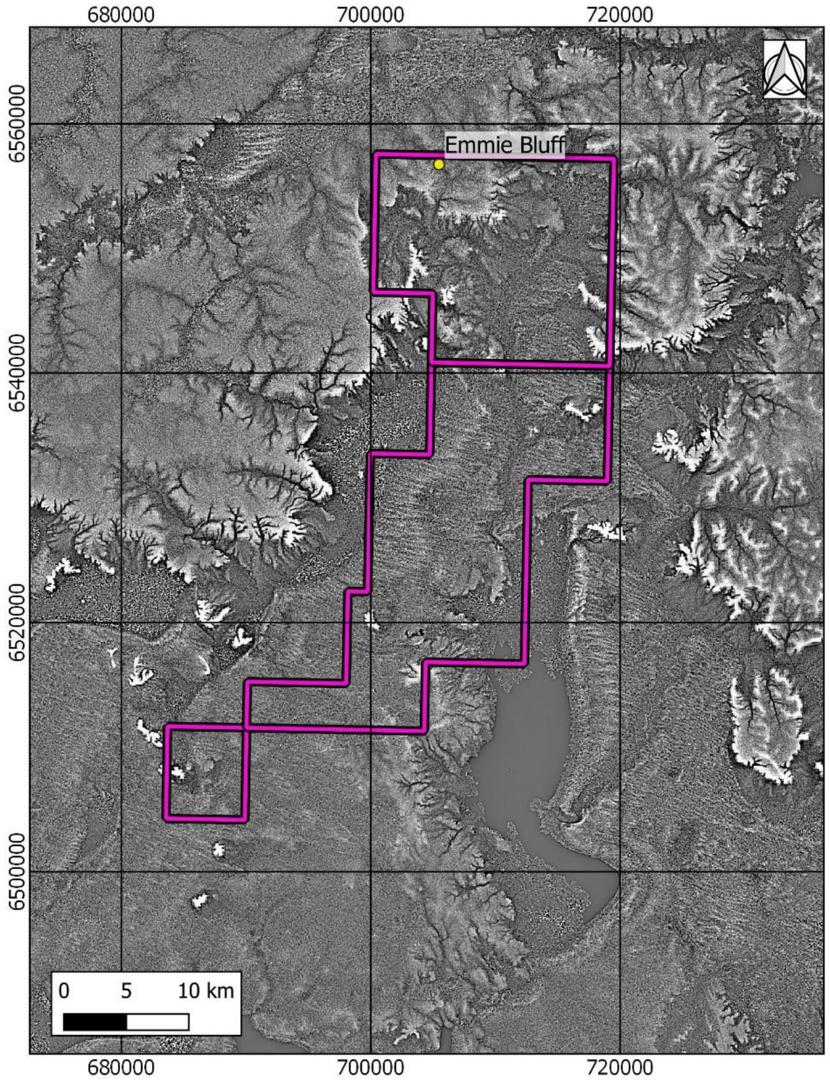


Surface conditions in geophysical and remote sensing images

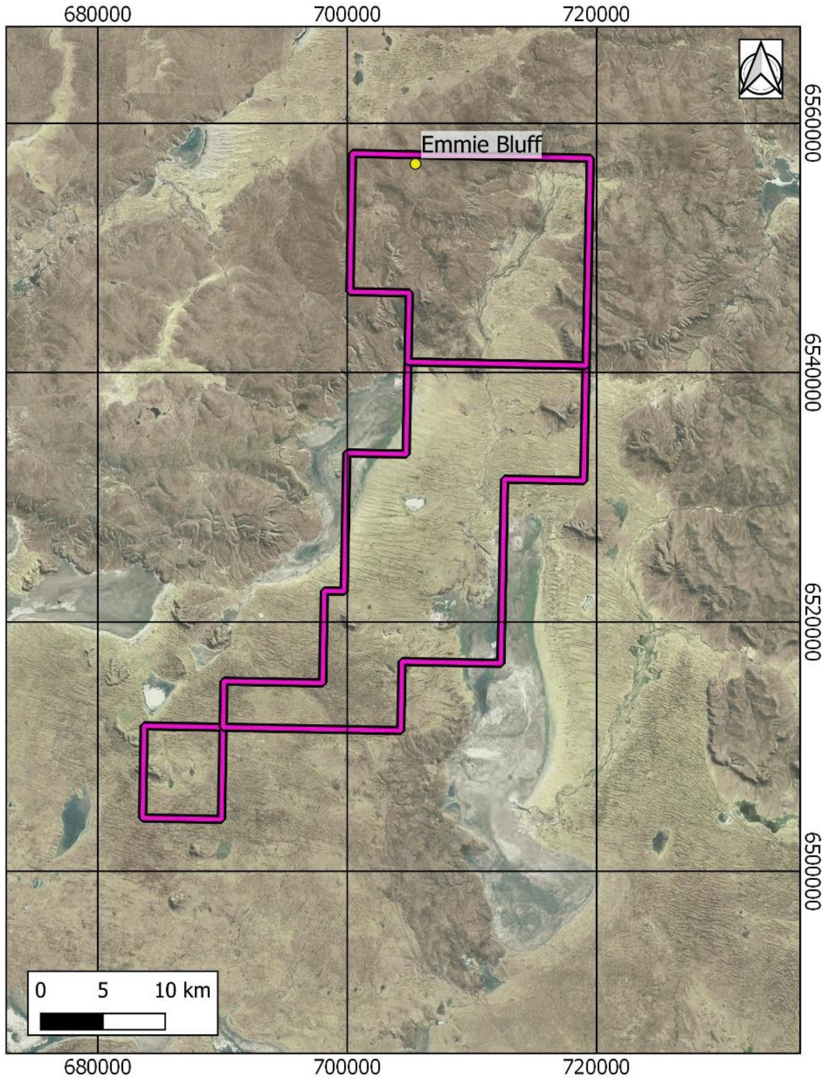
Radiometrics RGB K-Th-U



SRTM elevation



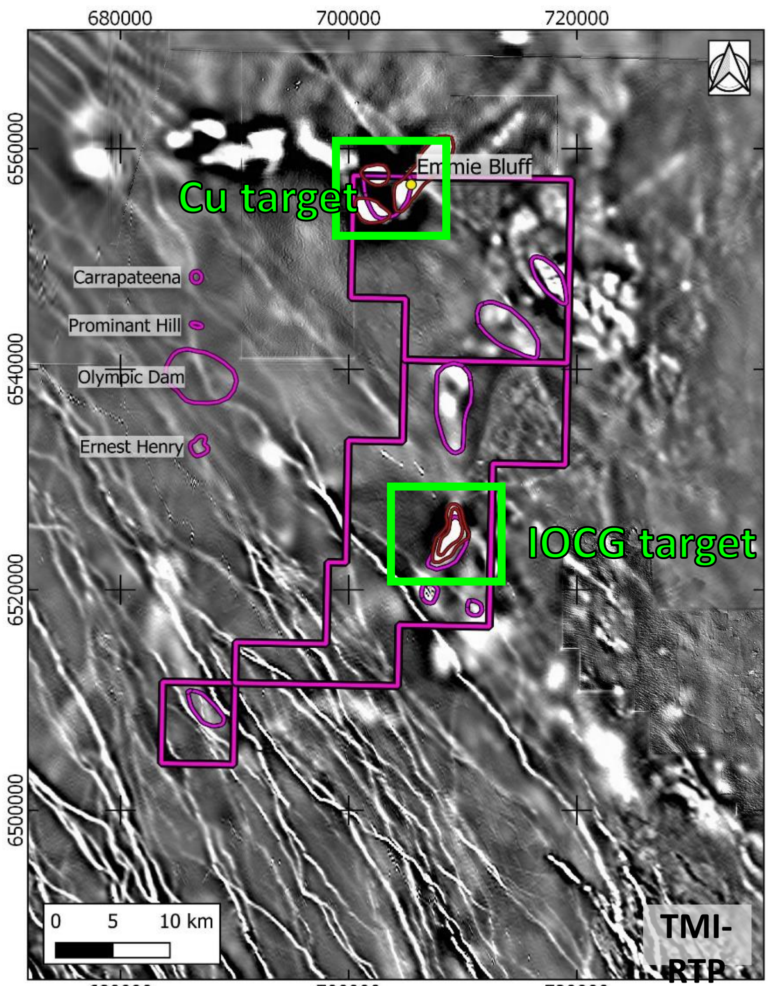
Satellite false colour imagery



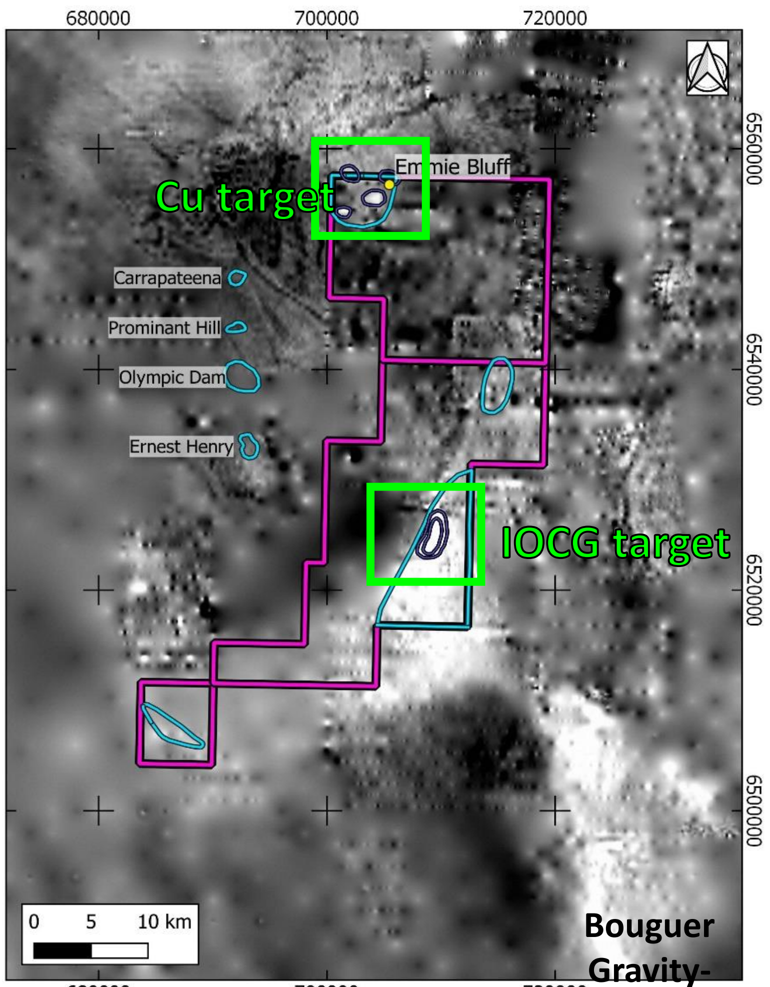
Project scale IOCG magnetic and gravity targeting

Resource Potentials

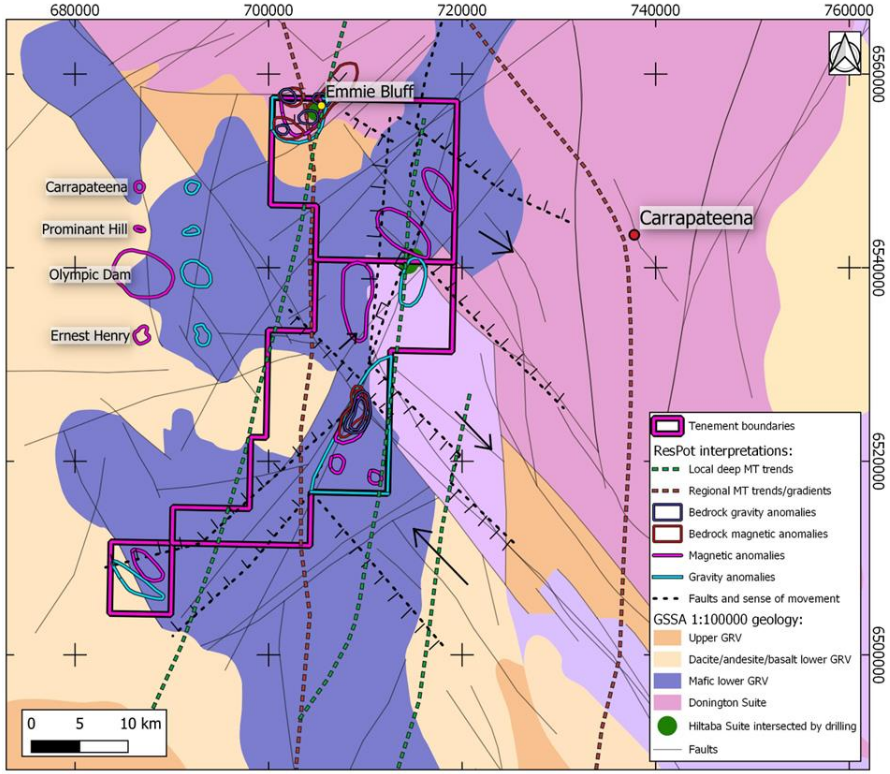
TMI-RTP-HP



Gravity residual



Bedrock geology and interpreted large scale structures

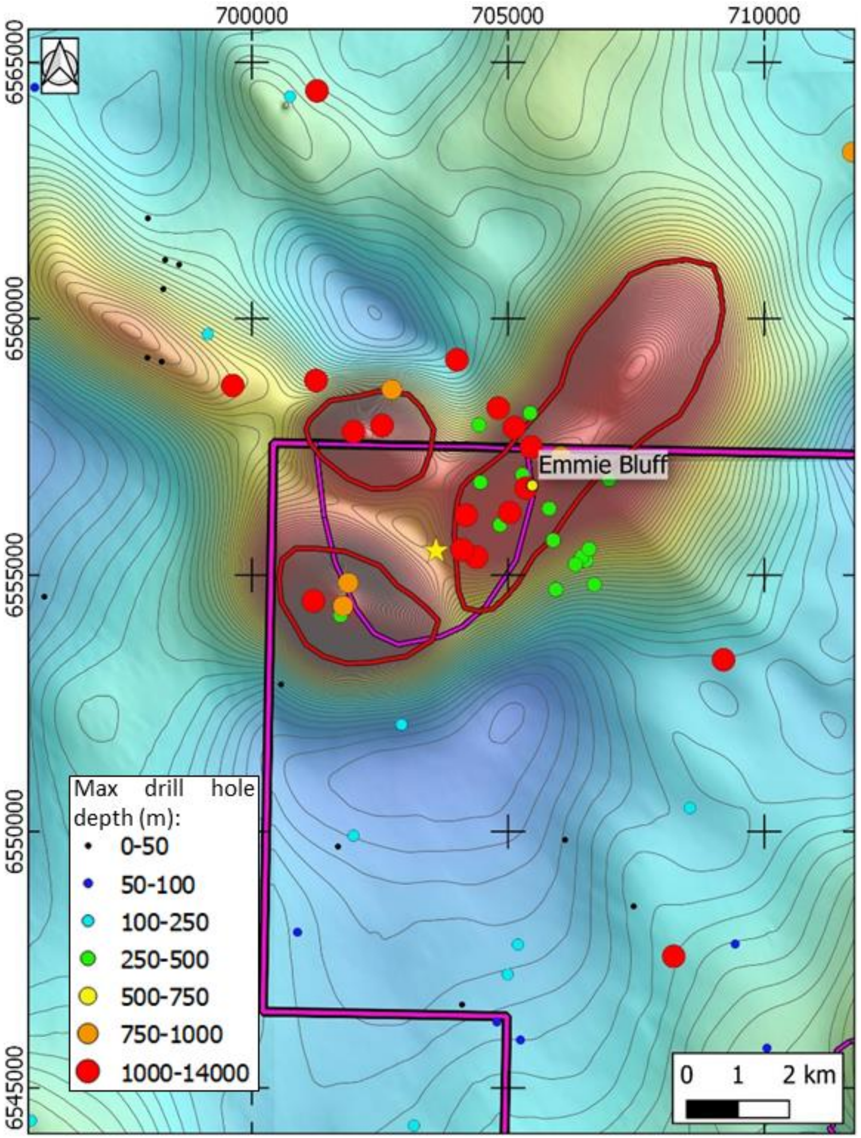


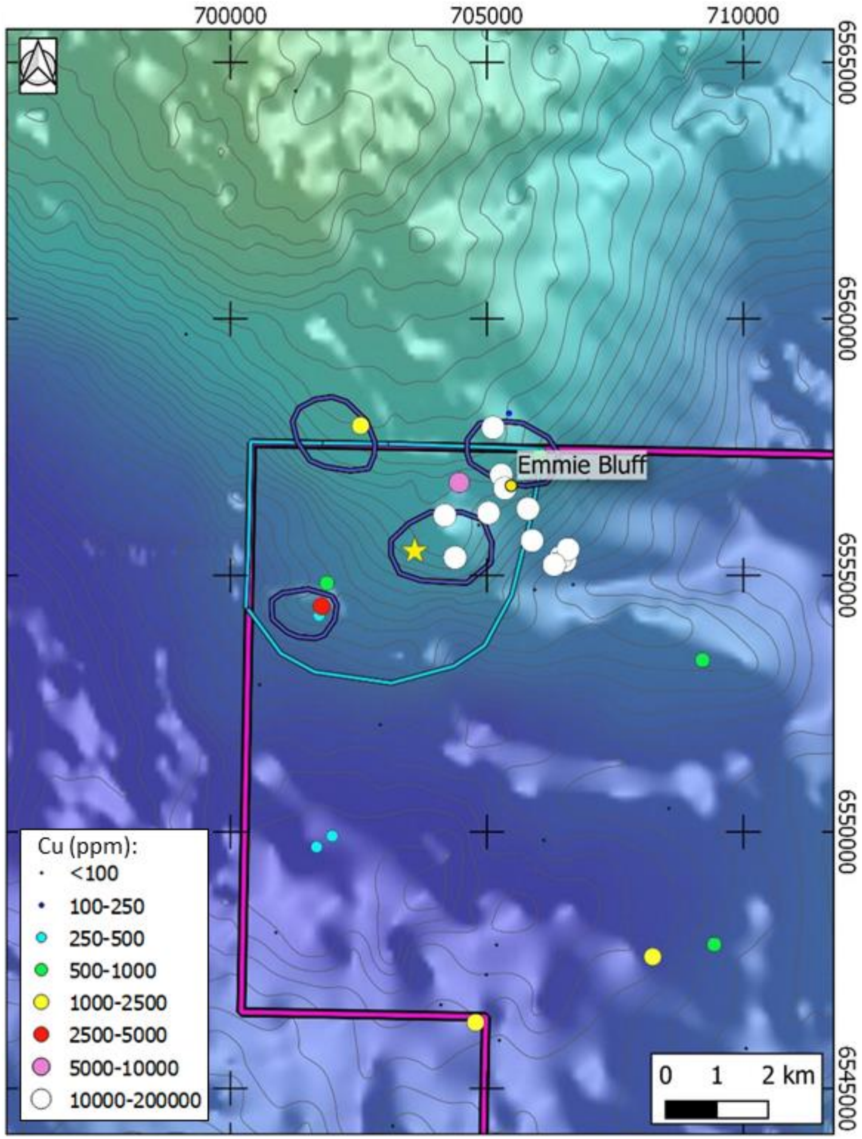
Emmie Bluff IOCG prospect scale deep targeting under cover

Resource Potentials

Known hematite altered meta-volcanics, meta-sediments and granitoids in crystalline basement below >500m of cover.

TMI-RTP

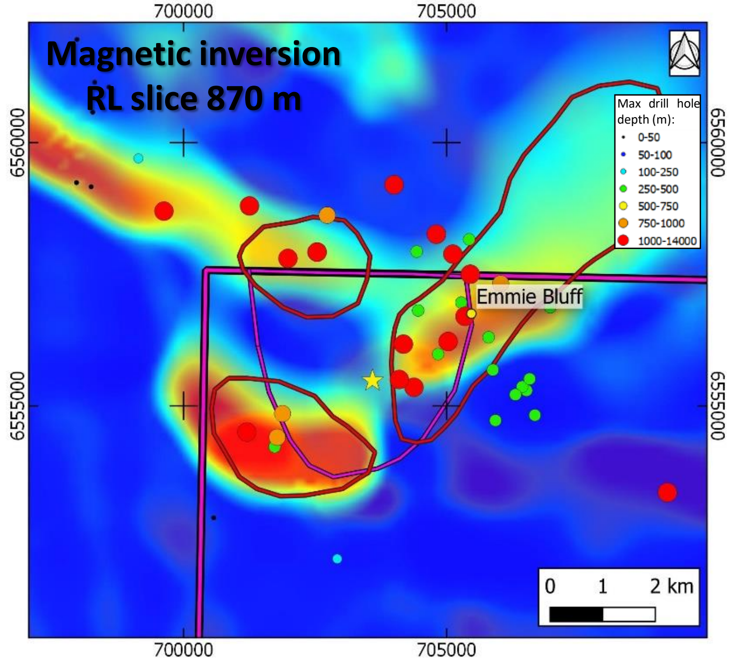


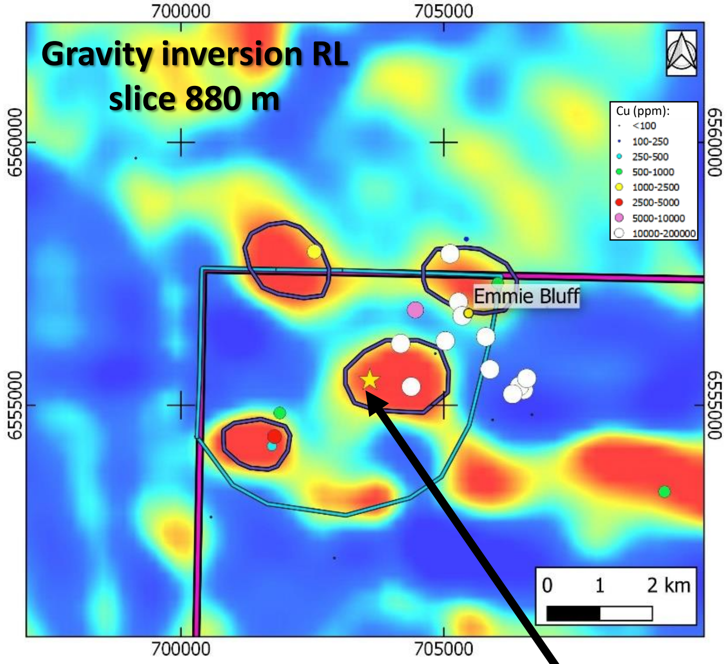


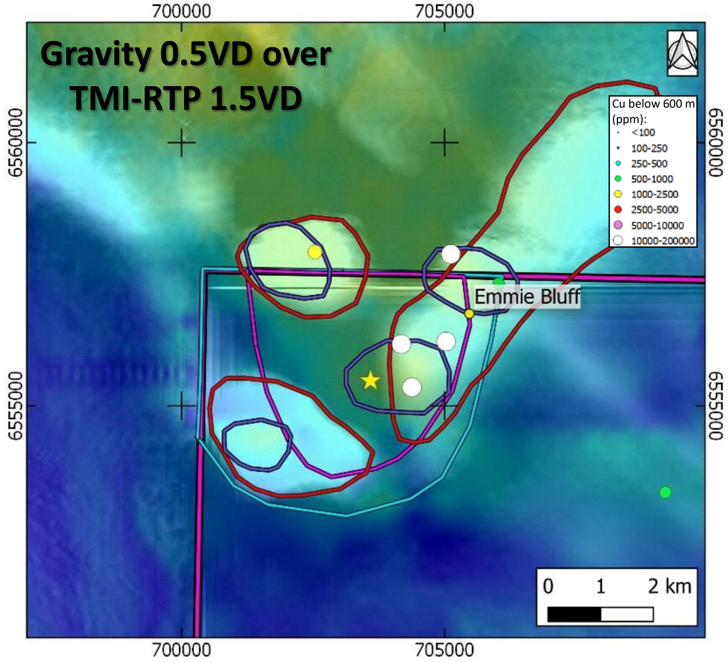
Bouguer gravity

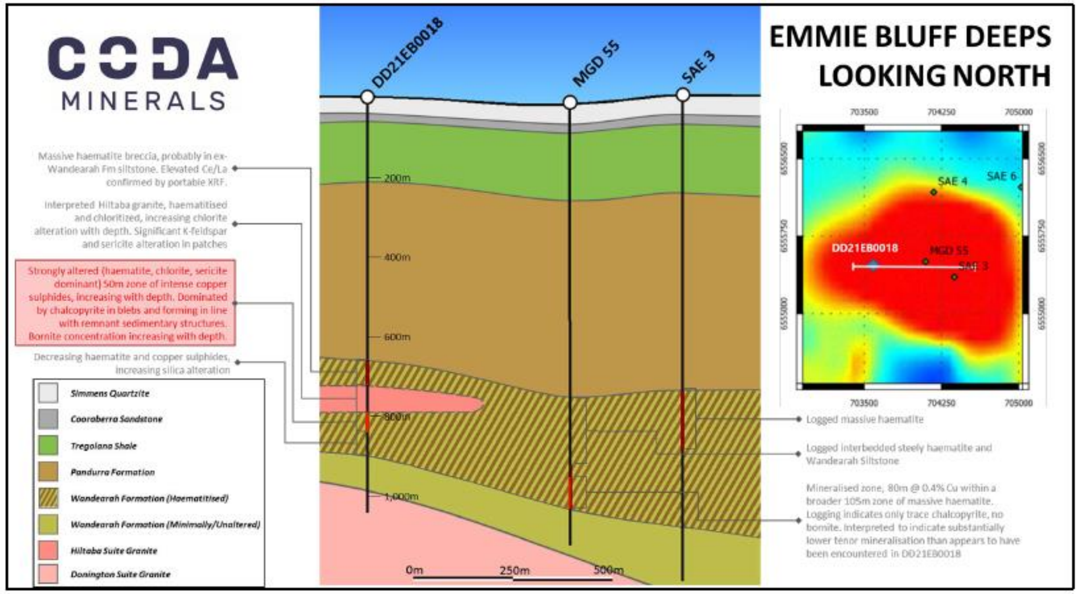
Deep drilling for IOCG and discovery of Emmie Deeps in June 2021

Resource Potentials









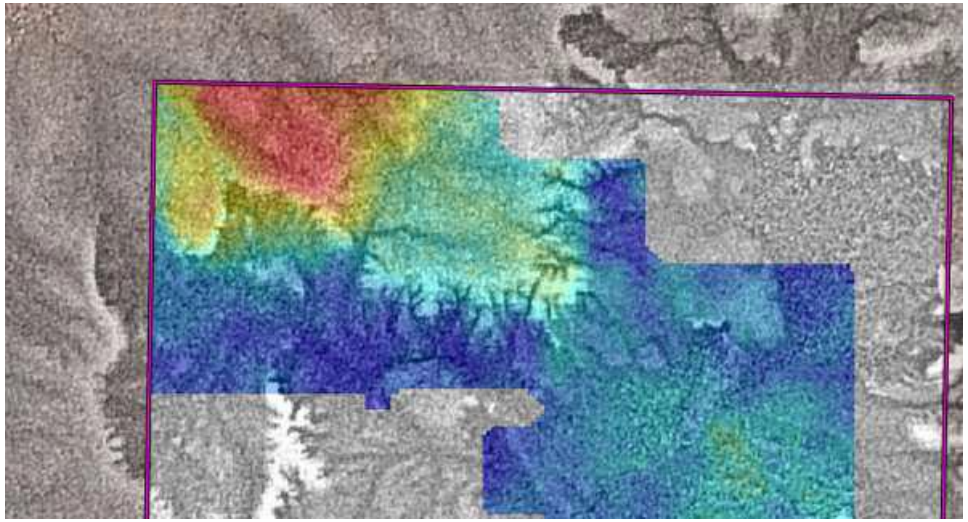
Drill planning on part of gravity anomaly with no coincident magnetic anomaly

Cu mineralisation started in hematite altered gneissic rock, CODA pushed hole deeper than planned 750m depth due to good looking alteration and intersected intense visual Cu sulphide minerals at 800m.

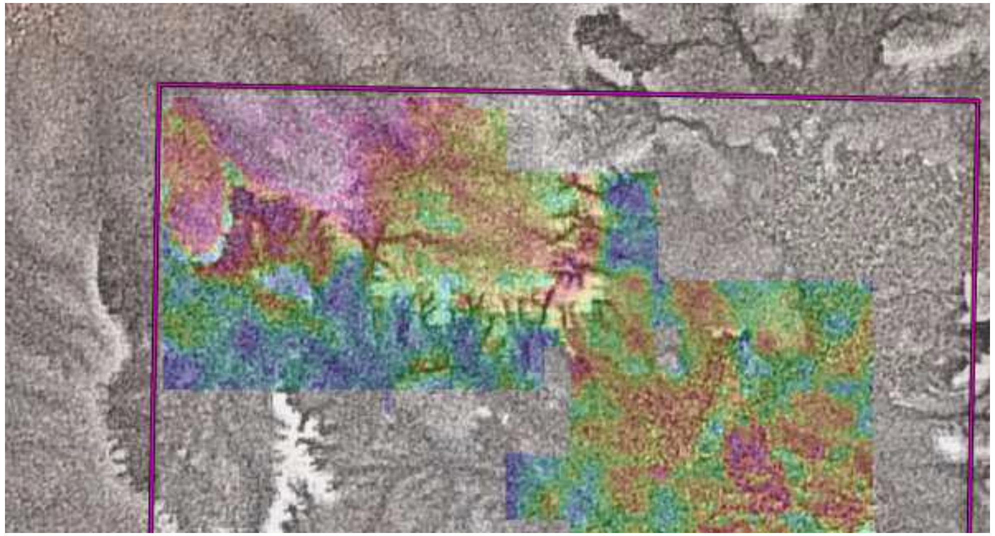
Windowing out higher resolution gravity stations for more detailed processing, imaging and 3D inversion

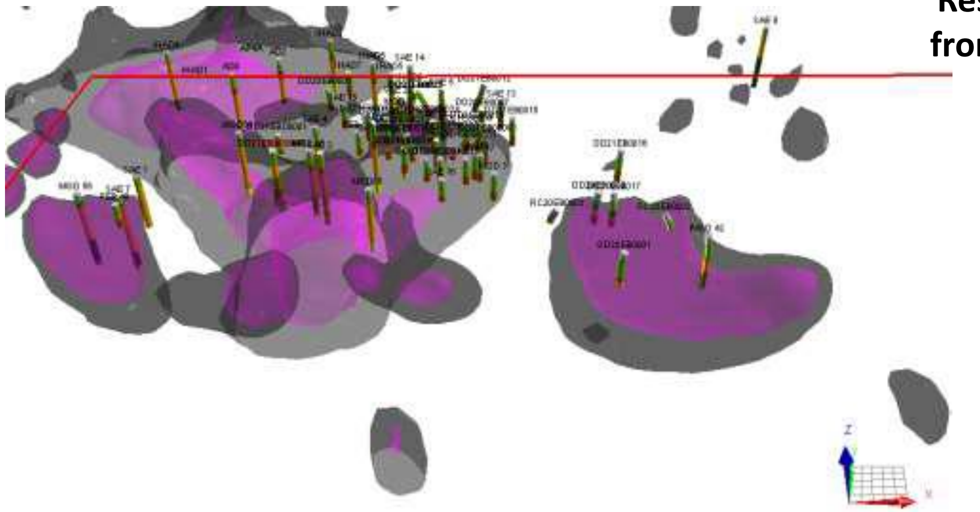
Resource Potentials

Bouguer density of 2.67g/cc affected by terrain

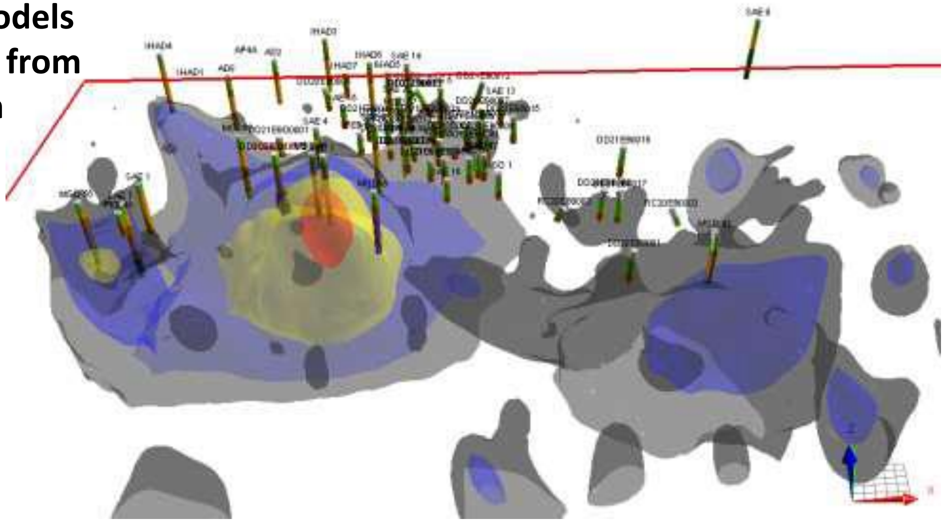


Terrain effects subdued using a lower Bouguer density of 2.3g/cc





Resulting 3D gravity models from data above, views from above facing north

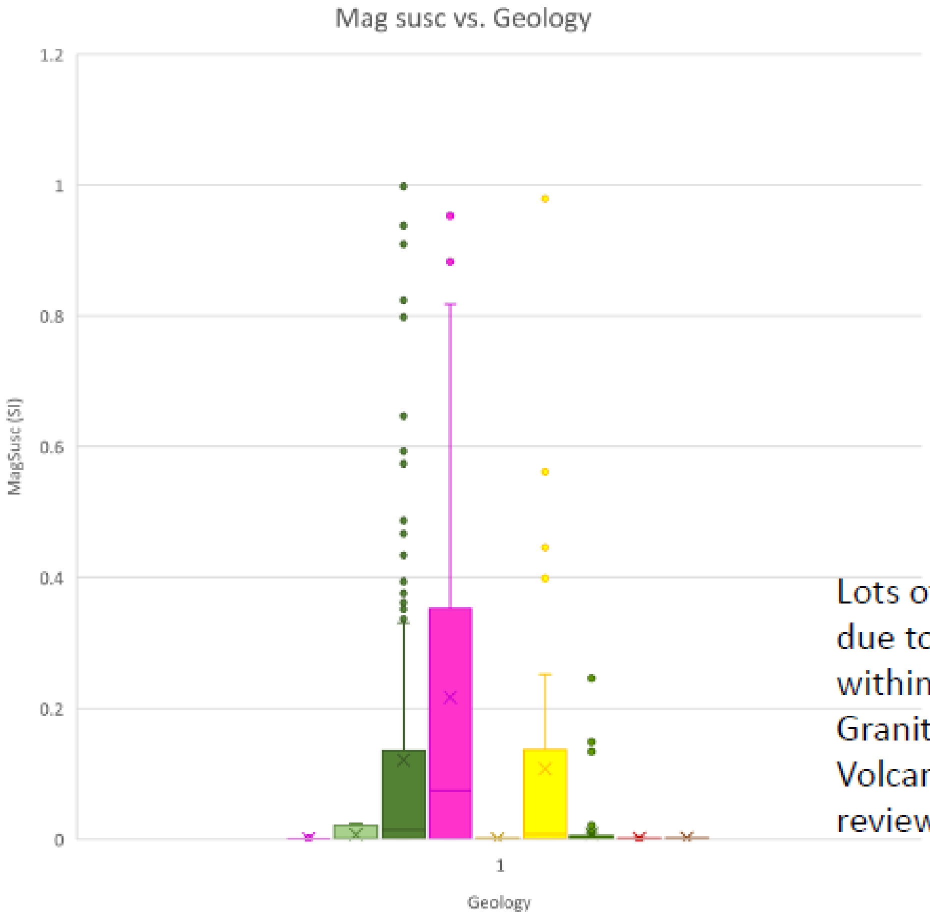


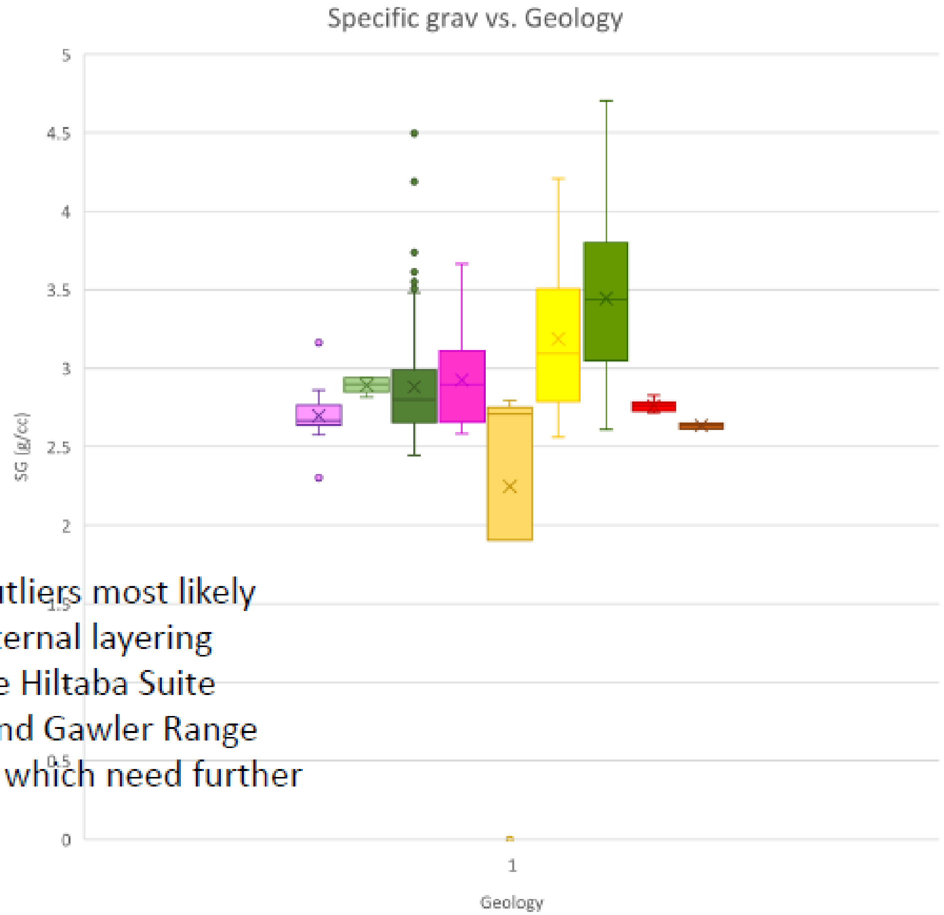
Magnetic susceptibility and density data from Emmie Deeps core

Resource Potentials

Density anomaly mostly caused by hematite altered and replaced meta-sediments, metasedimentary gneiss-schist, and iron oxide altered granite in the Paleo-Mesoproterozoic crystalline basement.

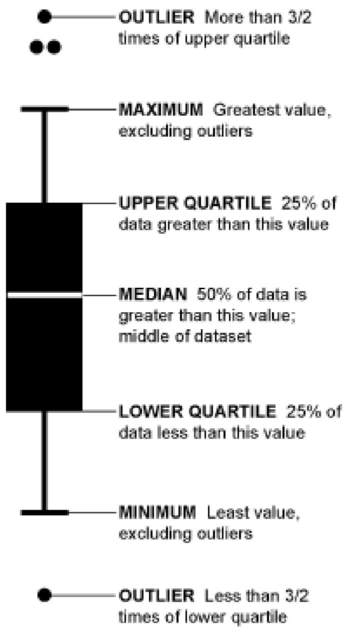
L-d	Donnington Suite Granite	
M	Mafic (undifferentiated)	
Ma	Gawler Range Volcanics	
Mh	Hiltaba suite Granite	
M-p	Pandurra Fm	
Mws	Wandearah Sediments	
Mwsh	Wandearah Massive Hm	
Nft	Tapley Hill Fm	
Nhh	Whyalla Sandstone	





Lots of outliers most likely due to internal layering within the Hiltaba Suite Granite and Gawler Range Volcanics which need further review.

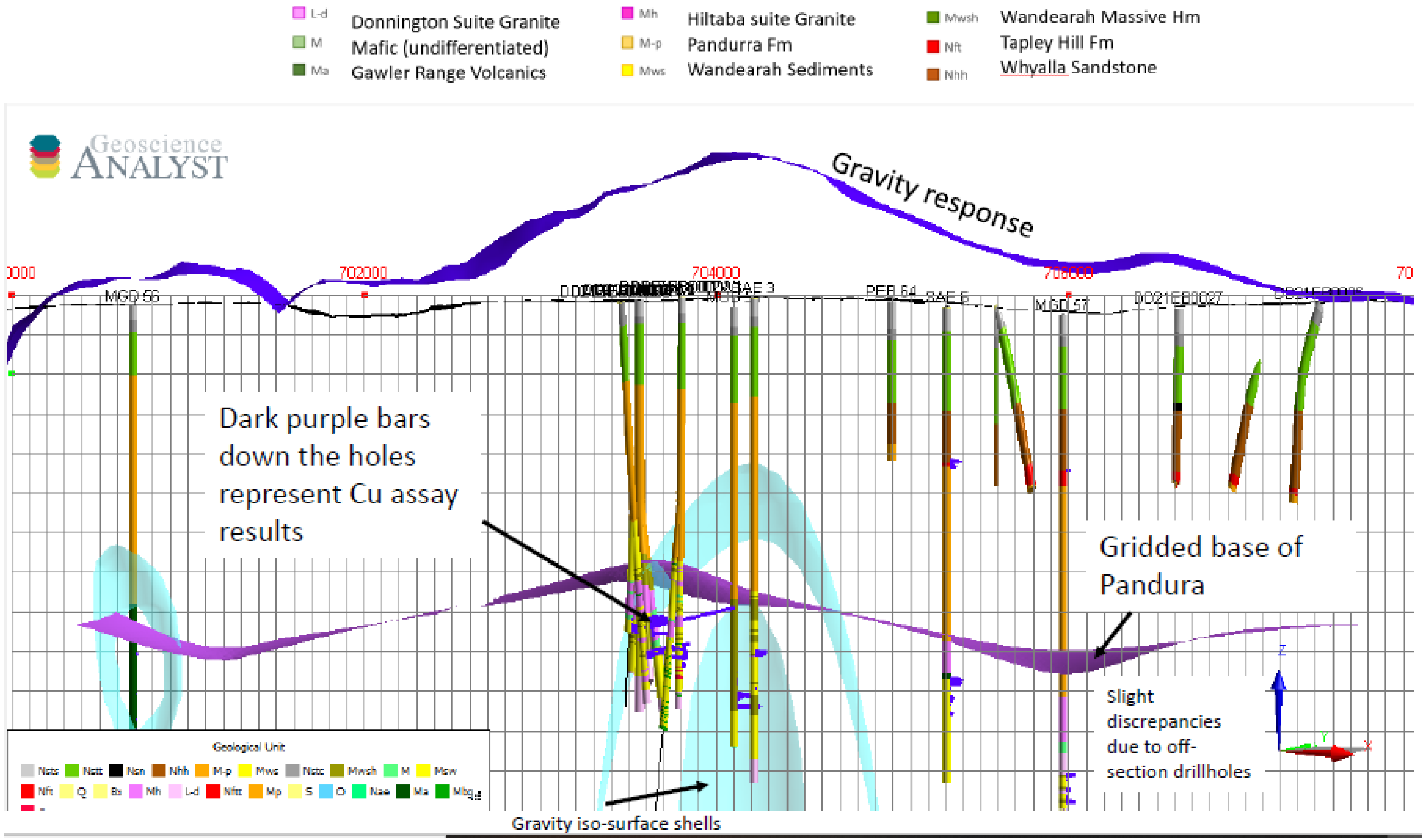
Box plots



Some gravity anomaly response is related to bedrock topography

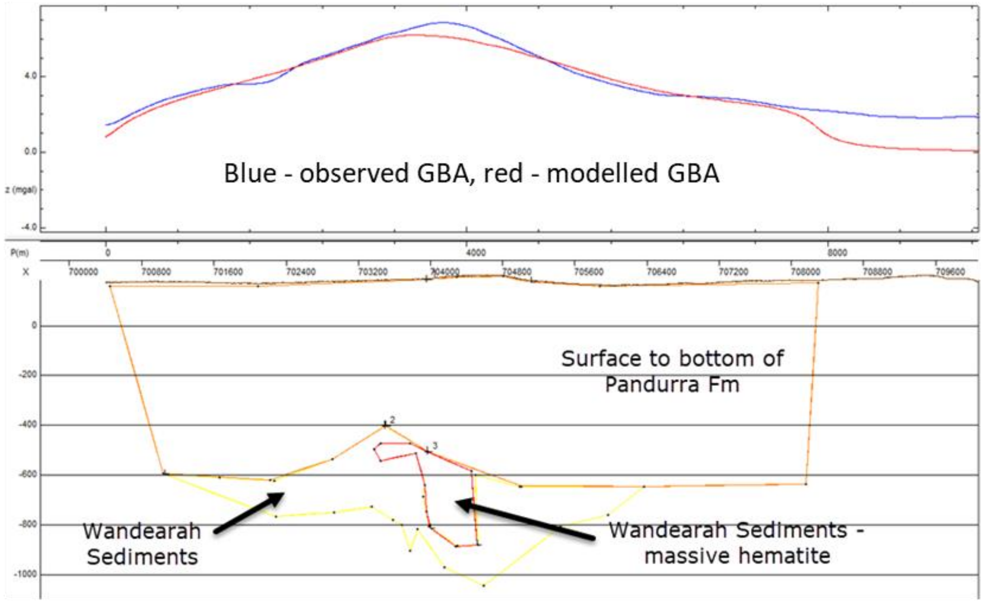
Resource Potentials

Copper mineralisation occurs in and along western side of gravity anomaly high and 3D inversion model body, likely related to sub-vertical faults acting as fluid conduits.

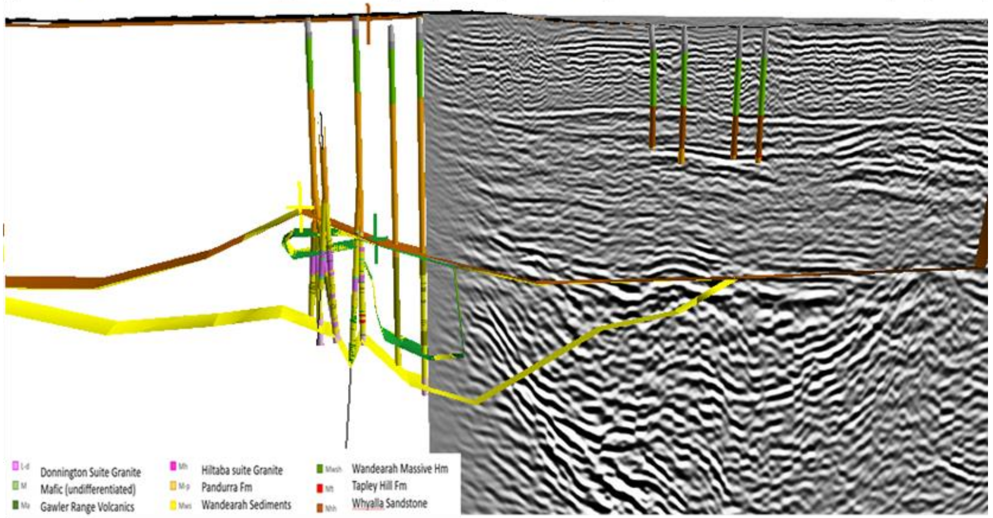


2.5D gravity model with basement topography following drilling and seismic interpretation

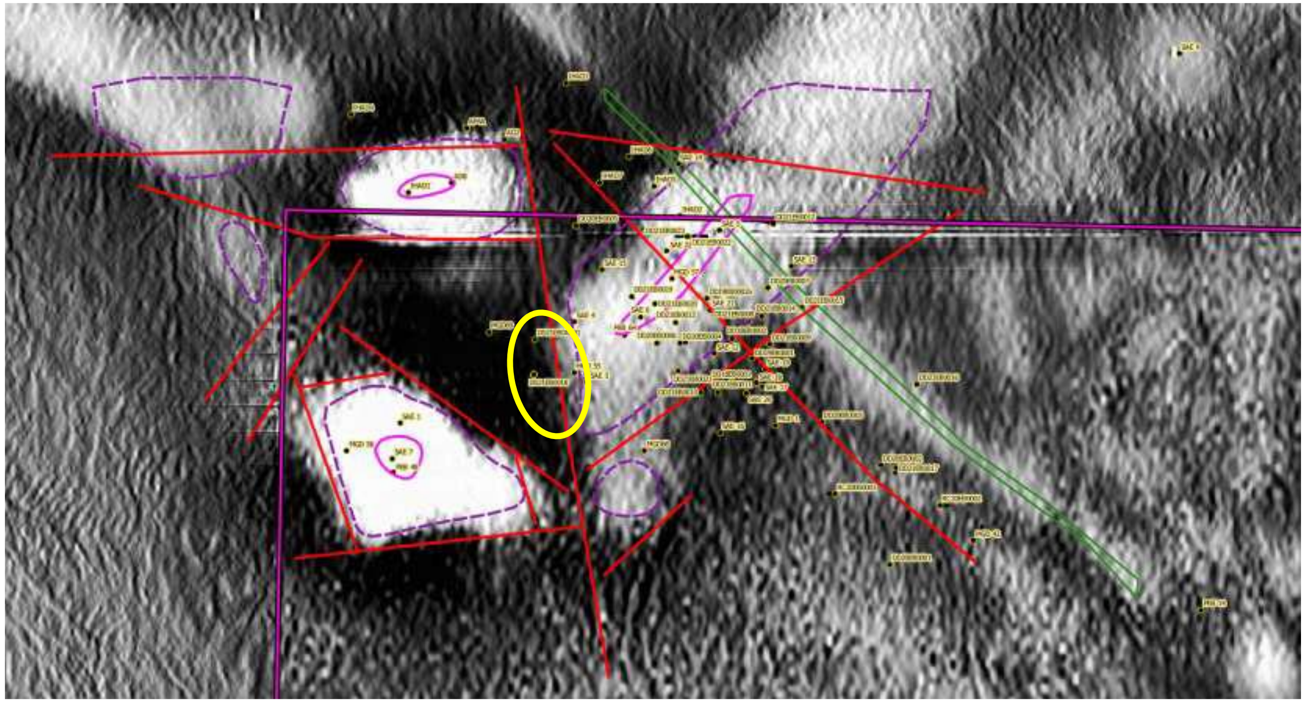
2D model cross-section, looking north, 6,555,400N



3D view looking north, 6,555,400N (with 200m envelope)



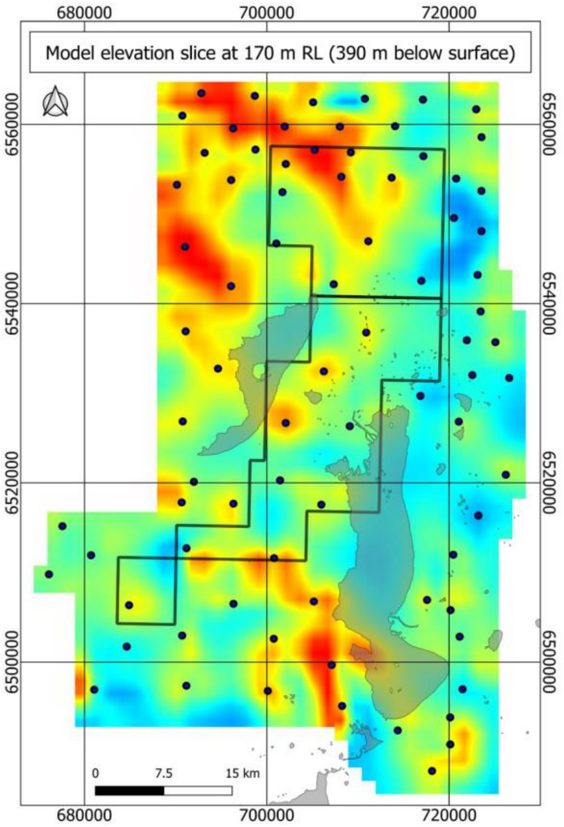
Magnetic 2VD image and line work showing interpreted controlling structures

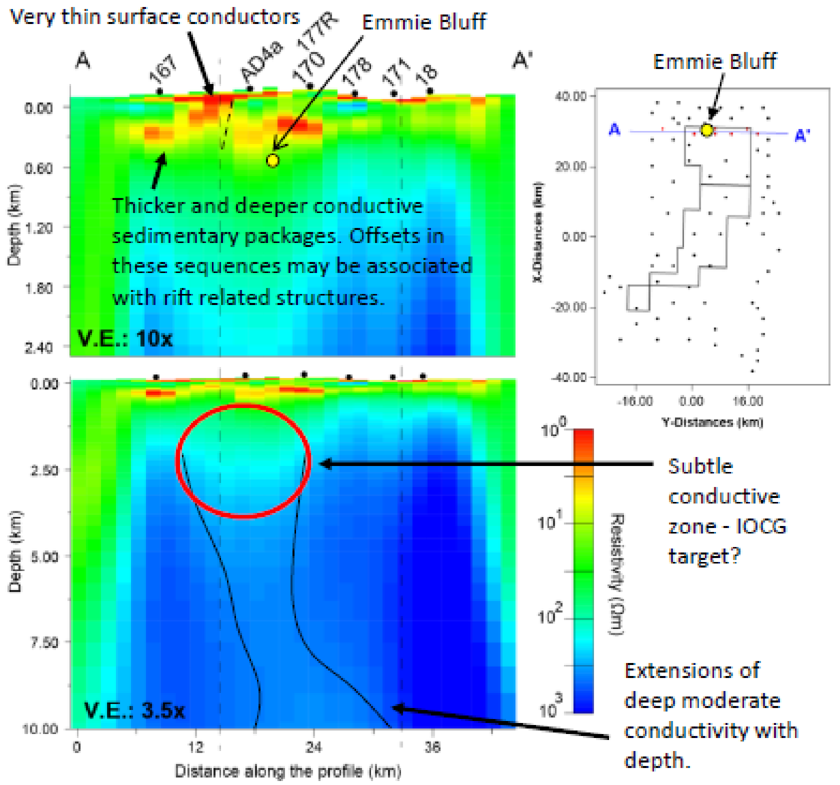


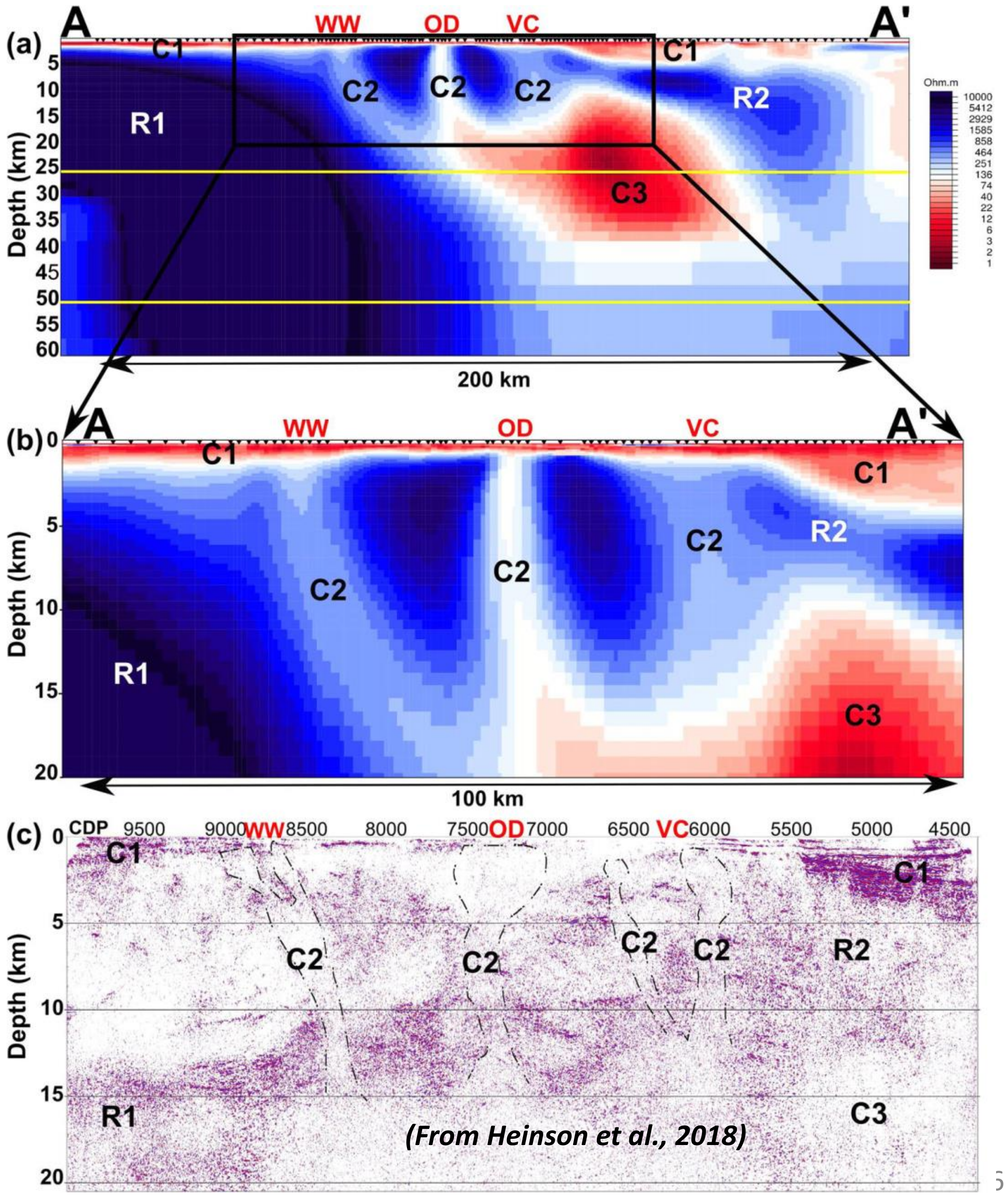
MT "Fingers of ~~G.O.D.~~ (Satan) for crustal scale IOCG targeting

Resource Potentials

Open file Zonge and Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) data were acquired, reprocessed and 3D inversion modelled using ModEM code in 2019. Weak fingers of Satan…





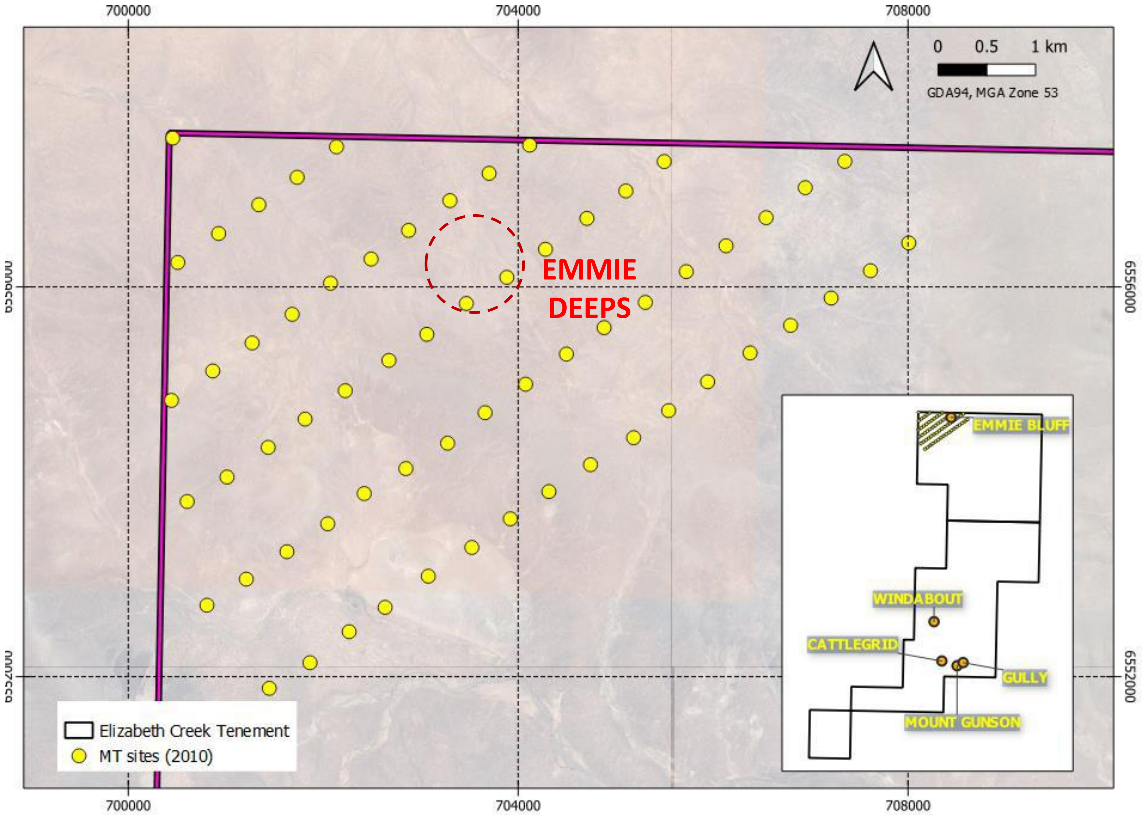


Quantec Spartan MT 2011 acquired for Xtrata

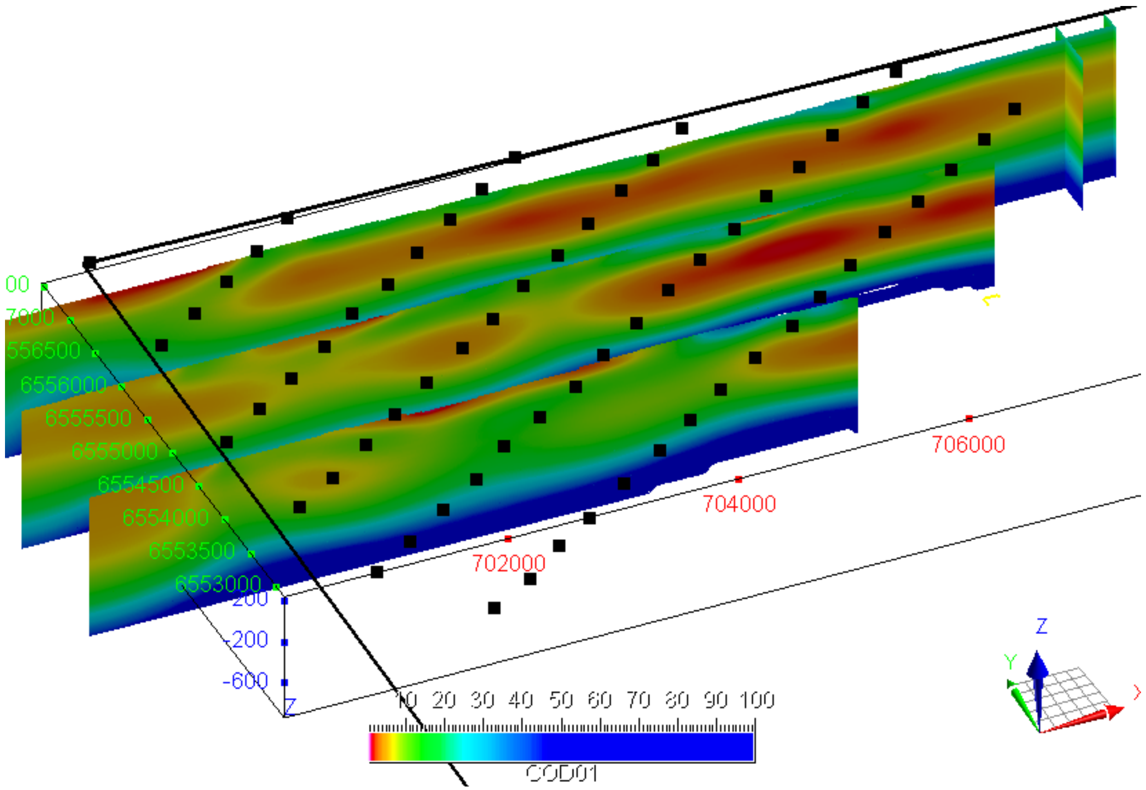
Resource Potentials

Spartan MT data re-processed and 3D inversion modelled using CGG Geotools, some AusLAMP broadband MT stations were also included in the inversion modelling. Highly affected by horizonal conductive layering in Neoproterozoic sediments and some weak conductivity changes in crystalline bedrock, but nothing obvious related to Emmie Deeps mineralisation zone.

MT station locations, data clipped to CODA tenement



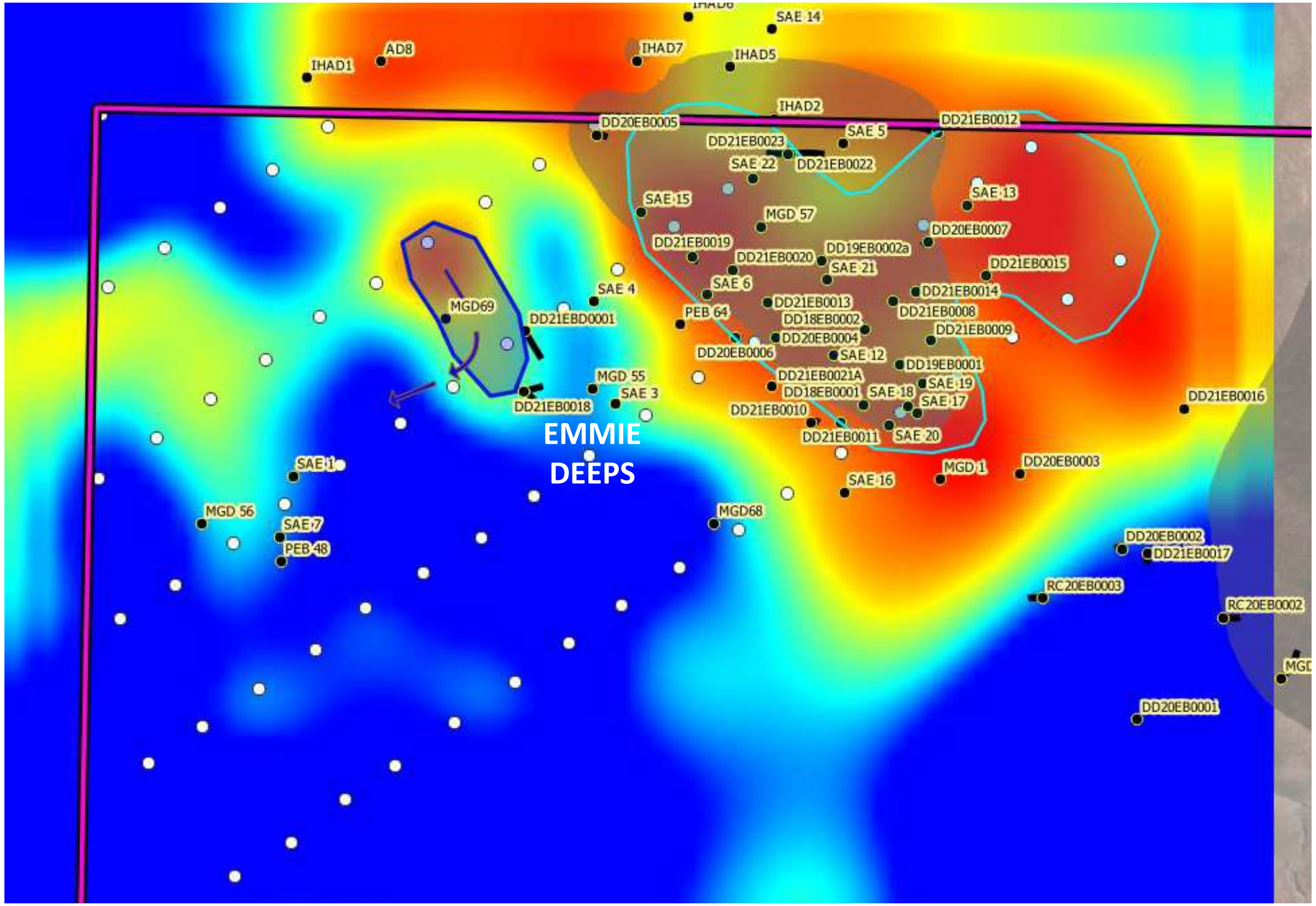
Fence diagram through 3D MT inversion model



MT model depth slice (relative to sea-level)

Resource Potentials

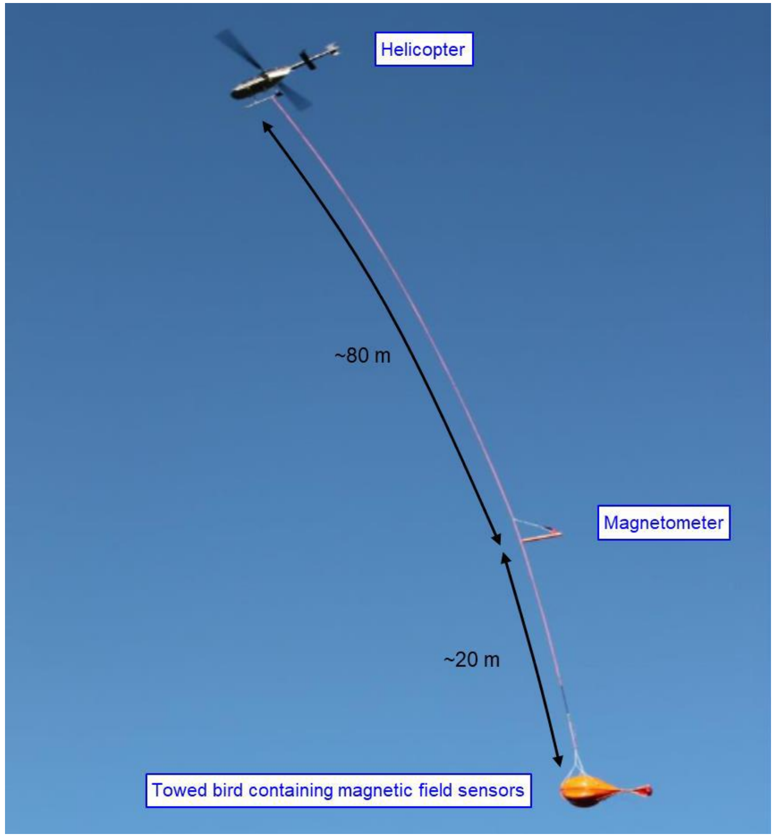
Depth slice at -400m RL through 2D MT model.

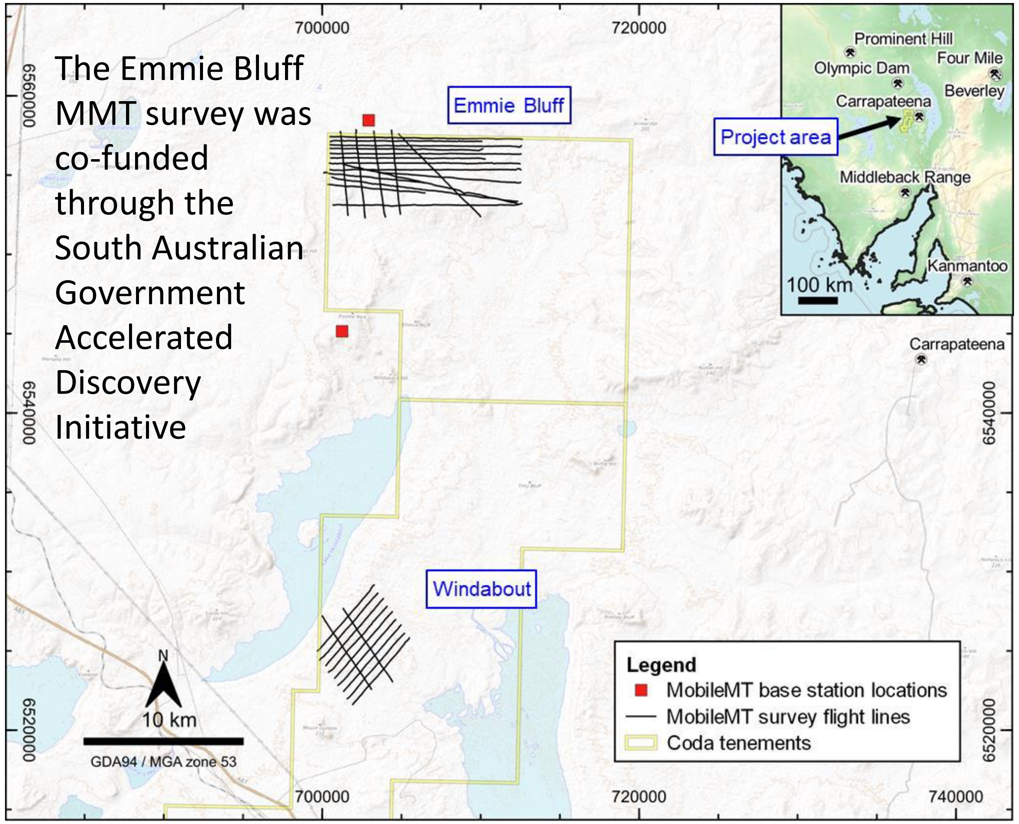


Helicopter MobileMT (MMT) by Expert Geophysics 2022

Resource Potentials

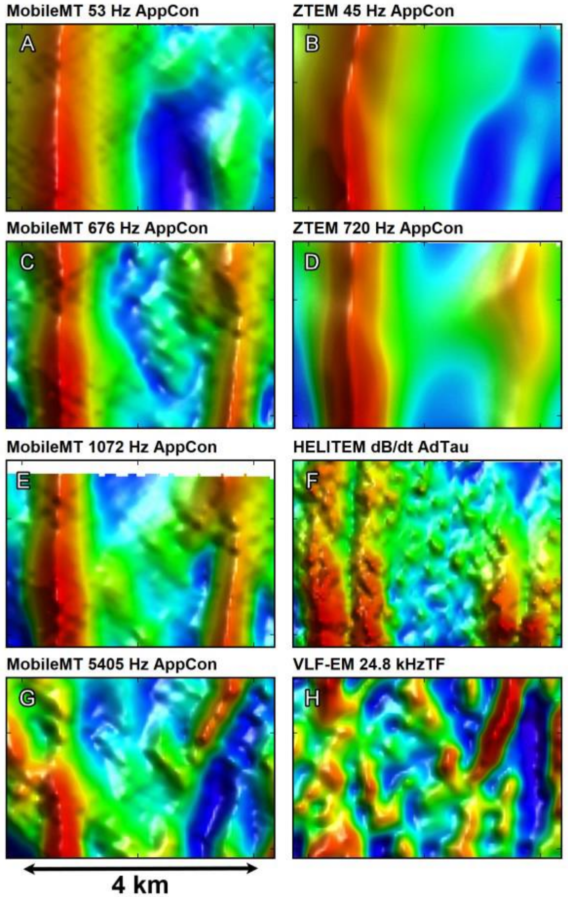
MMT uses the audio-frequency magnetic (AF-MAG) method to measure anomalous vertical magnetic fields caused by interaction between ambient EM fields generated from remote naturally occurring sources (mostly distant lightning strikes) and local variations within subsurface conductivity to about 1 km depth in an electrically resistive environment, or shallower as the resistivity of a survey area decreases. Orthogonal magnetic field induction coil sensors, Hx, Hy and Hz, in the towed bird measure changes in the ambient magnetic field relative to an electric field reference base station, which consists of two orthogonal electric field dipoles, Ex and Ey, which is located nearby to the survey area for measuring variations in the electric field during surveying for later data processing to generate **apparent conductivity** results for each recorded frequency. The frequencies extracted in a survey area for data processing depend on the signal strength and local noise levels at the time of surveying. The magnetic and electric field components for each of the measured frequency components are then used to derive apparent conductivity results from 3-axis tensor data.





The Emmie Bluff MMT survey was co-funded through the South Australian Government Accelerated Discovery Initiative

Athabasca Basin example from Moul et al. (2020)



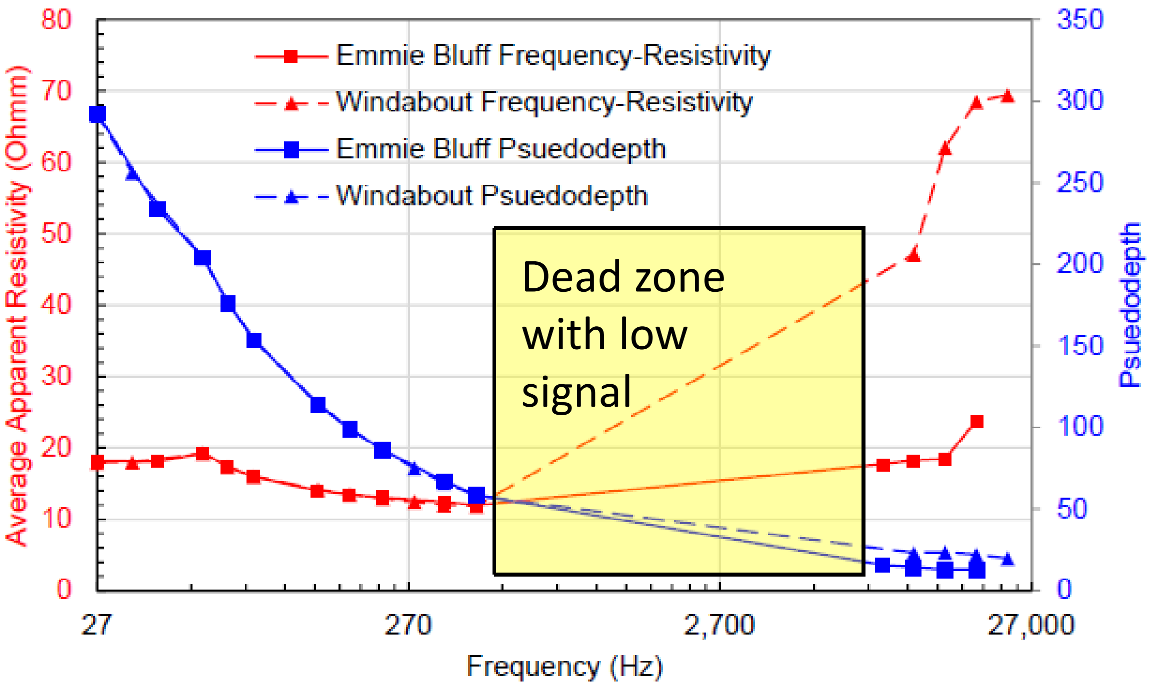
MMT apparent conductivity for each recorded frequency

Resource Potentials

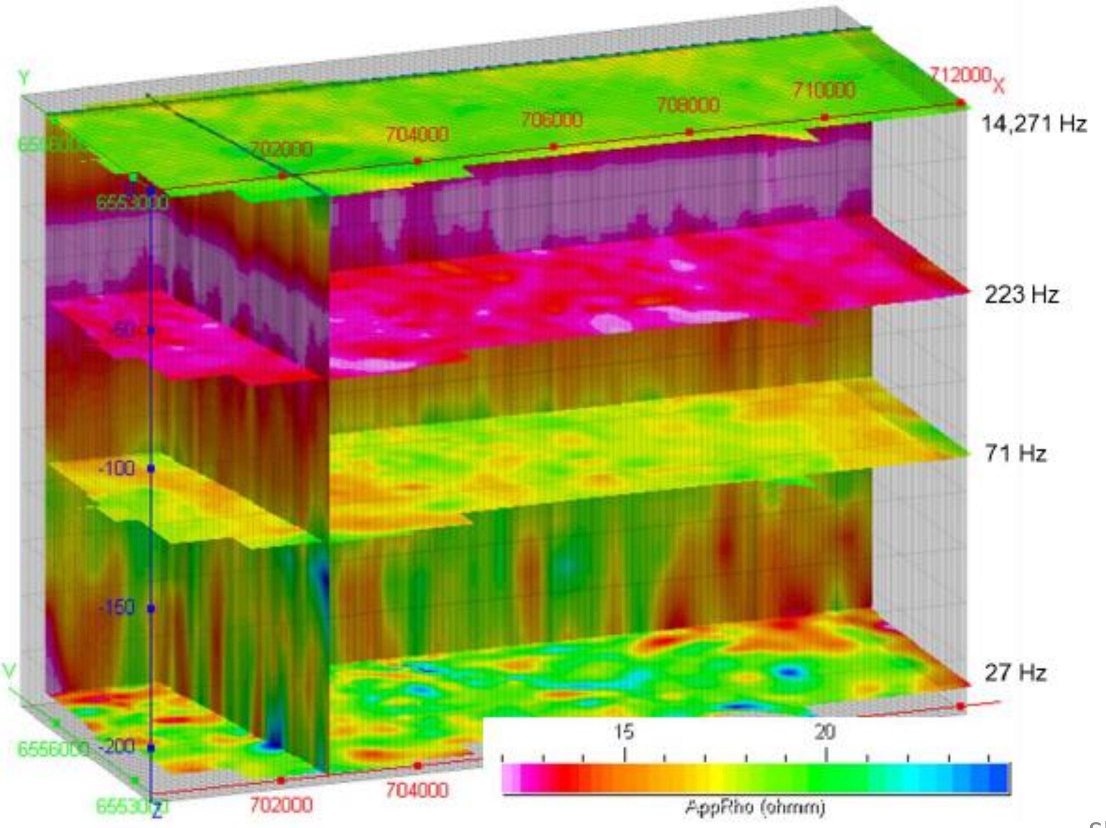
MMT depth of penetration appears to have been limited at Emmie Bluff due to flat geological layers having low resistivity / high conductivity, potentially limiting penetration to only 300m in some places, so just above the Tapley Hill Fm SEDEX target.

Flat lying layers of different conductivity are observed between decreasing frequencies / increasing depth.

A broad dead zone in frequency readings during this survey limited the reliability of inversion modelling results.

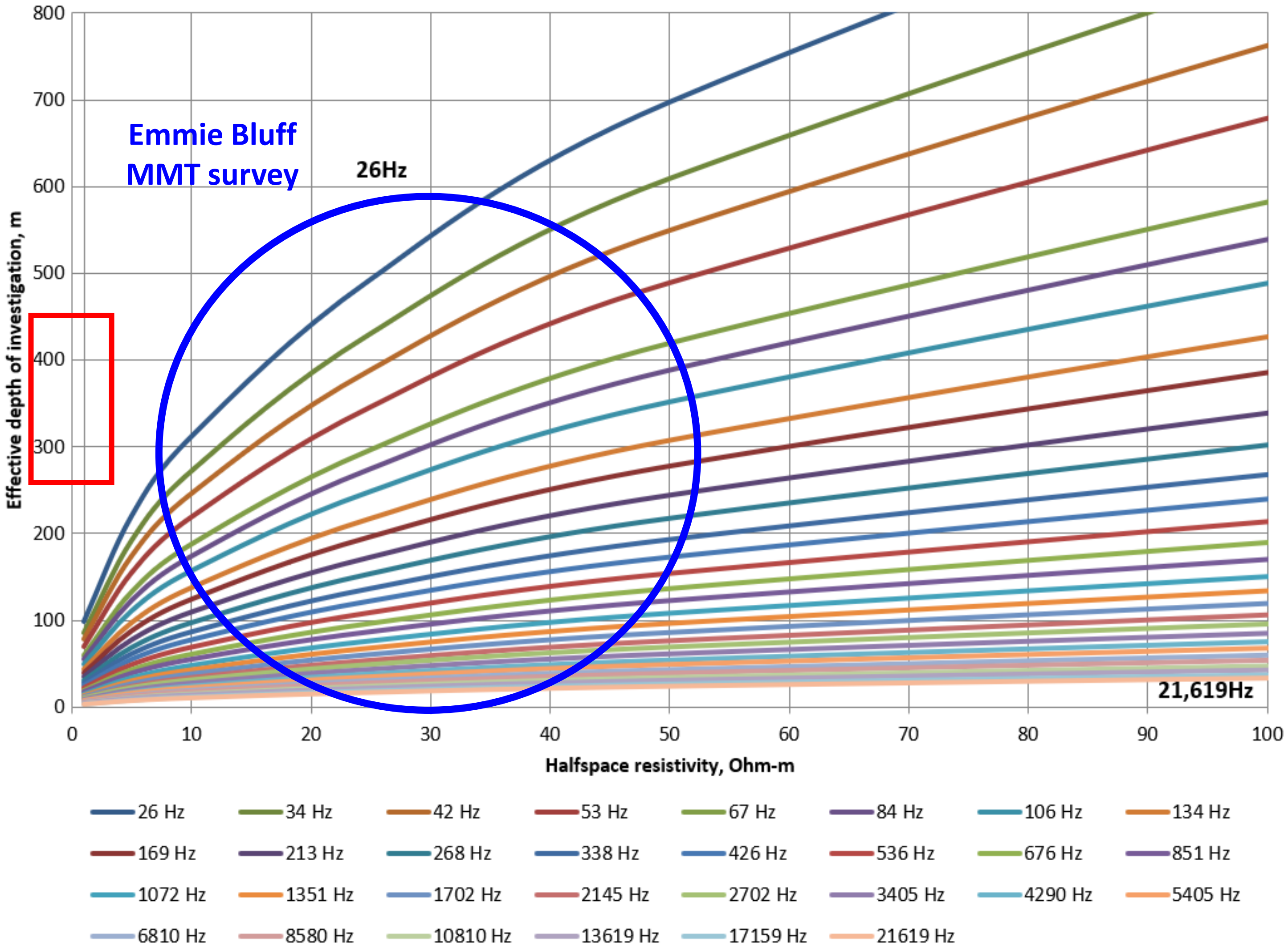


Emmie Bluff MMT apparent conductivity frequencies

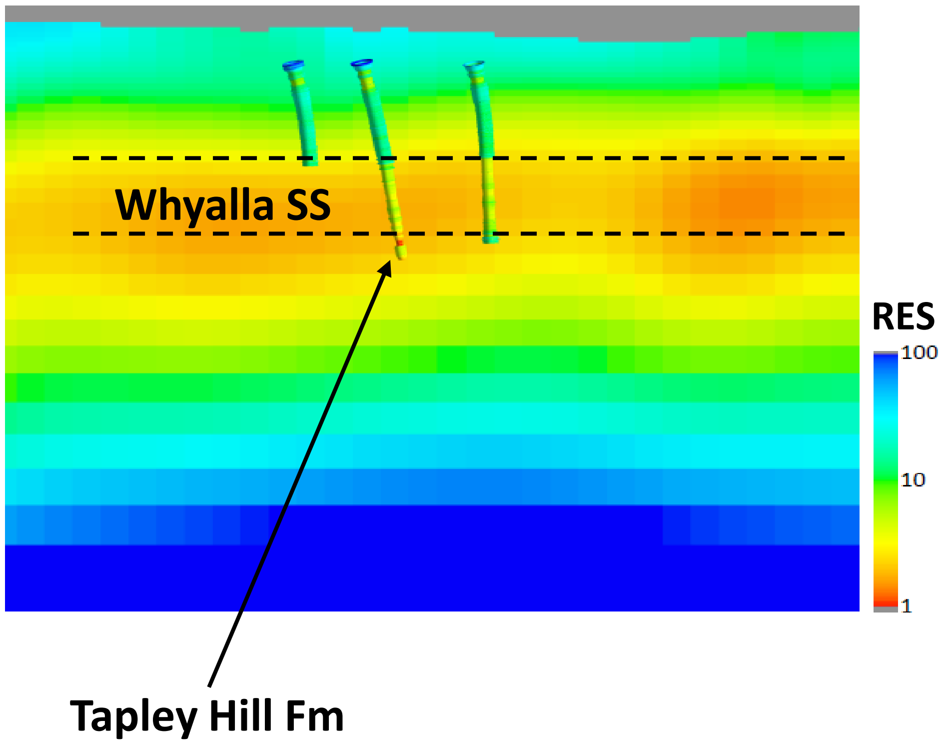


MMT depth of investigation depending on background conductivity

Resource Potentials



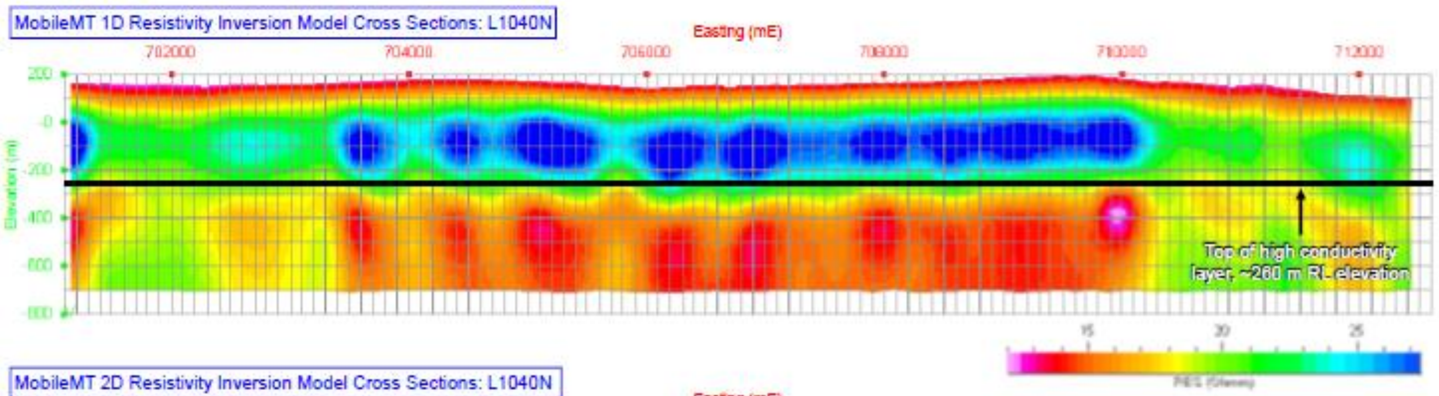
3D MMT inversion cross-section showing conductive Whyalla Sandstone



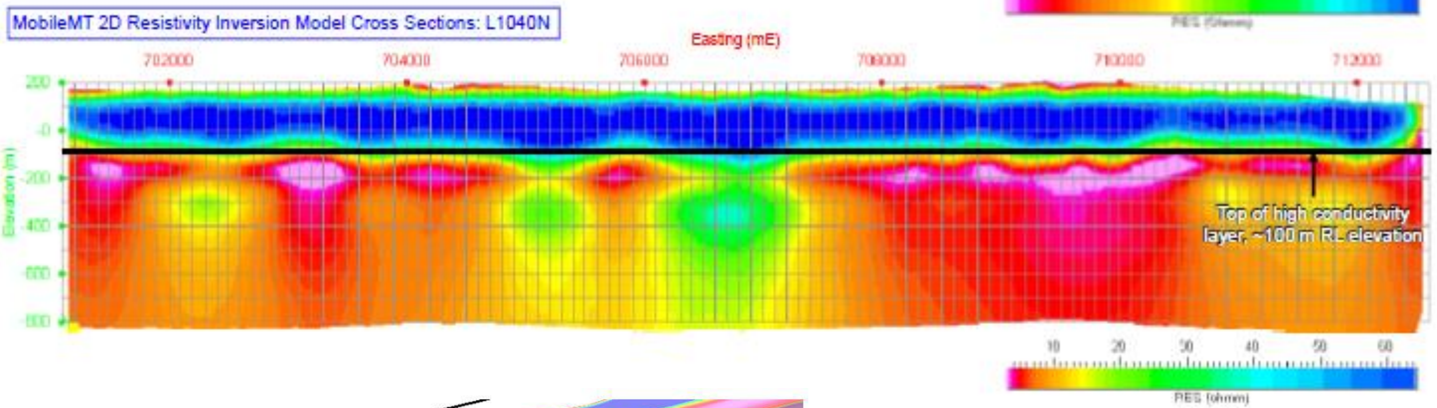
MMT 1D and 2D inversion by Expert Geophysics

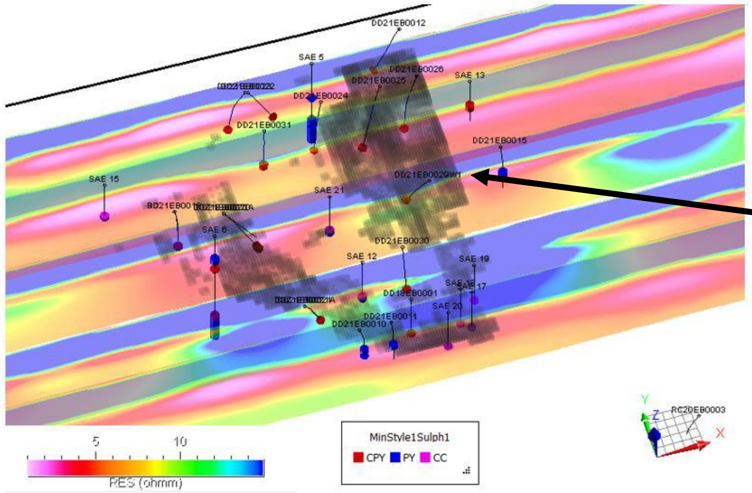
Resource Potentials

The 1D inversion was done using nonlinear least-squares iterative inversion developed by Golubev for MobileMT.



The 2D inversion used MARE2DEM code from Scripps and Lamont-Doherty.





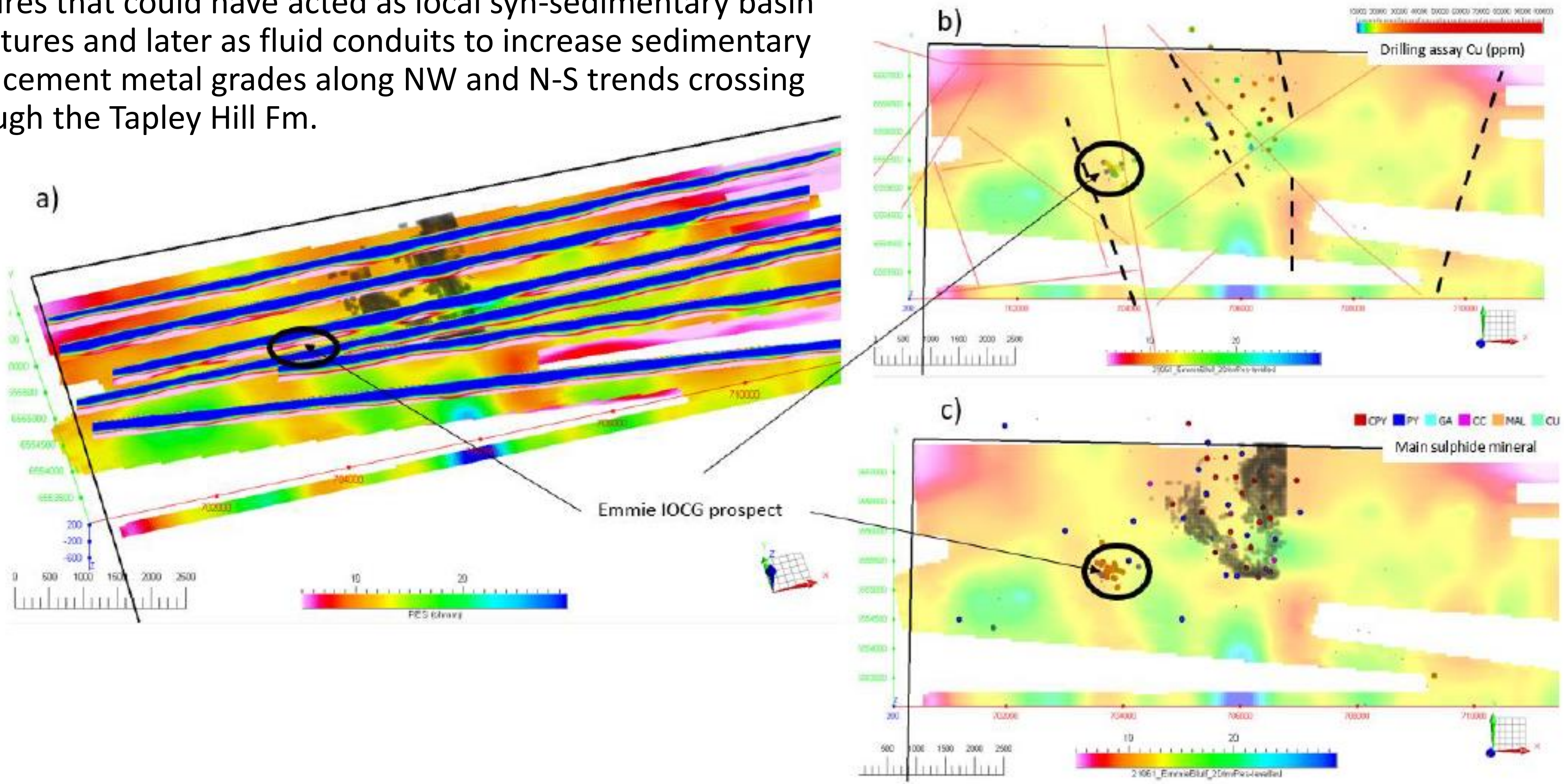
Emmie Bluff resource wireframe

MMT 2D inversion by Expert Geophysics

Resource Potentials

Linear breaks in conducive layers observed in the MMT 2D inversion model results may relate to vertical structural features that could have acted as local syn-sedimentary basin structures and later as fluid conduits to increase sedimentary replacement metal grades along NW and N-S trends crossing through the Tapley Hill Fm.

480m depth slice from land surface though 2D MMT inversion model



3D MMT and joint ground MT+MMT inversion by CGG

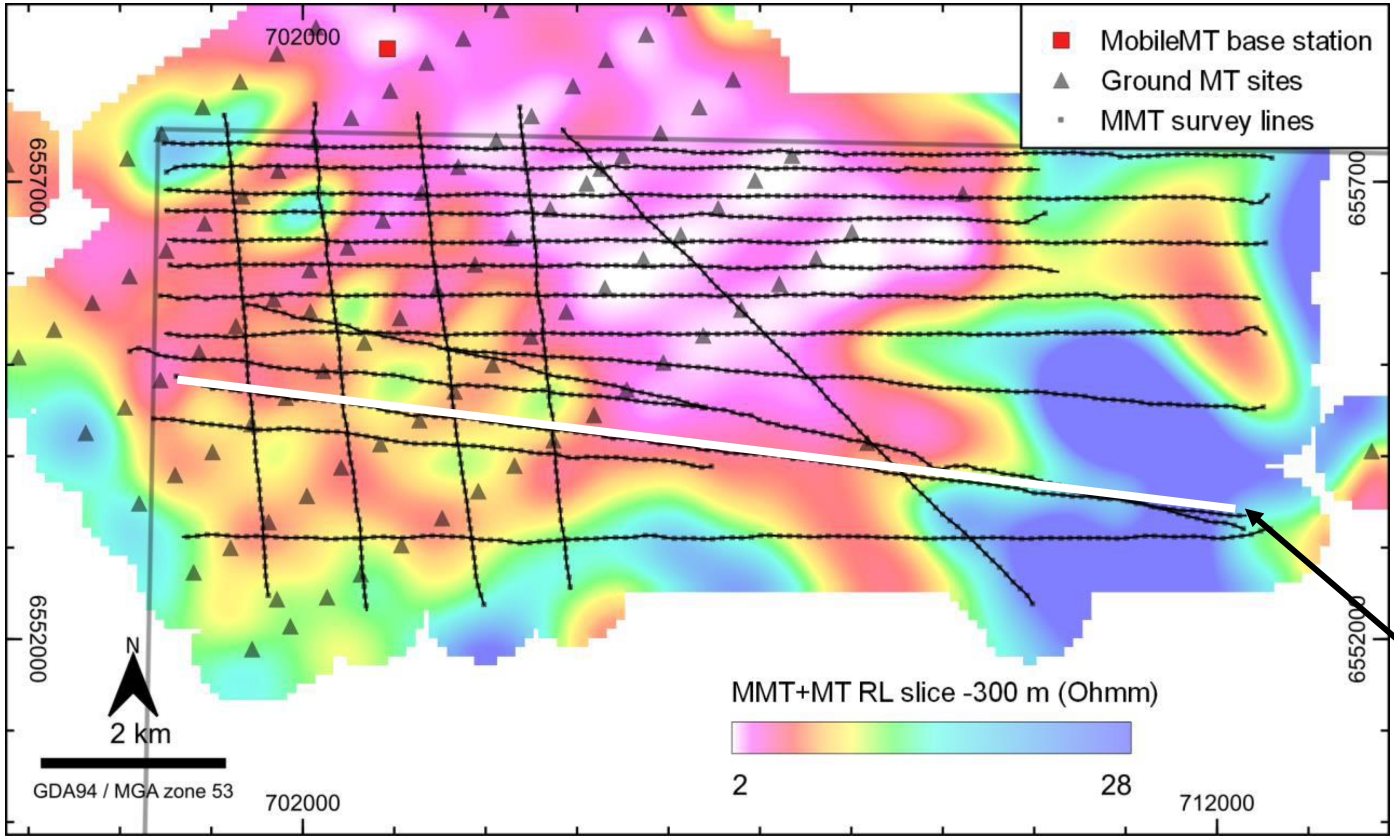
Resource Potentials

3D inversion of the MMT data and joint inversion of the ground MT + MMT data was carried out by CGG using their internal RLM 3D inversion code.

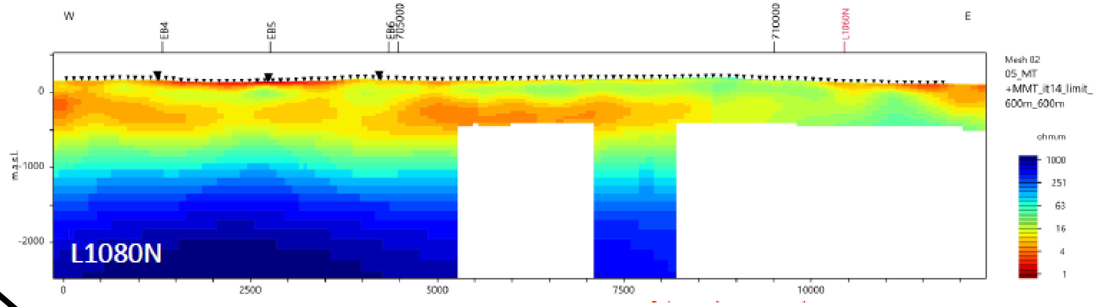
3D MMT inversion results were similar to the 2D inversion results, but 3D results were more depth limited.

Bandwidth of the MMT data was limited compared to ground MT data, so model fit using MMT data was less reliable and it had shallower penetration, but many readings were quickly taken across the survey area compared to wide spaced ground MT readings which used long recording times.

Combining both data sets created unwanted artefacts in the joint 3D inversion results and so they were not used.



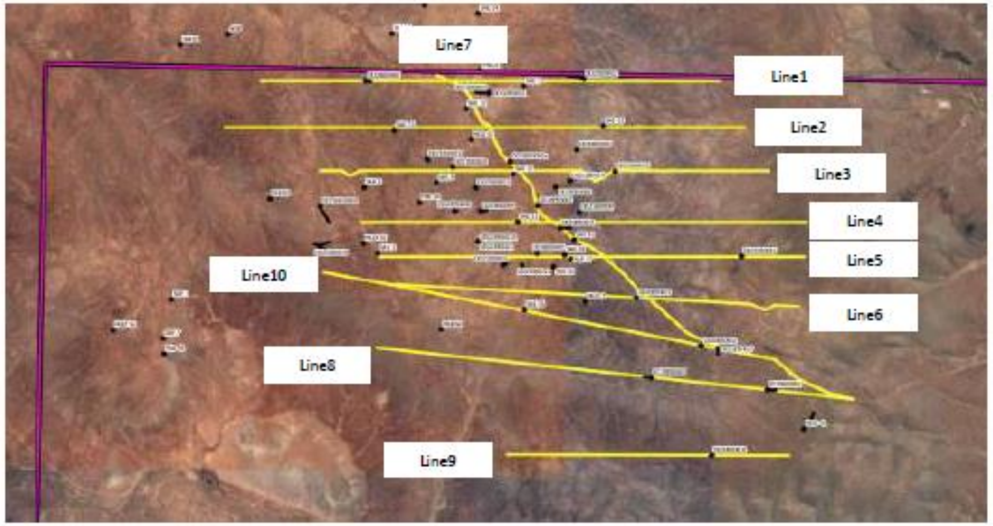
Joint MT + MMT 3D inversion cross-section, with deep gaps caused by lack of ground MT stations.

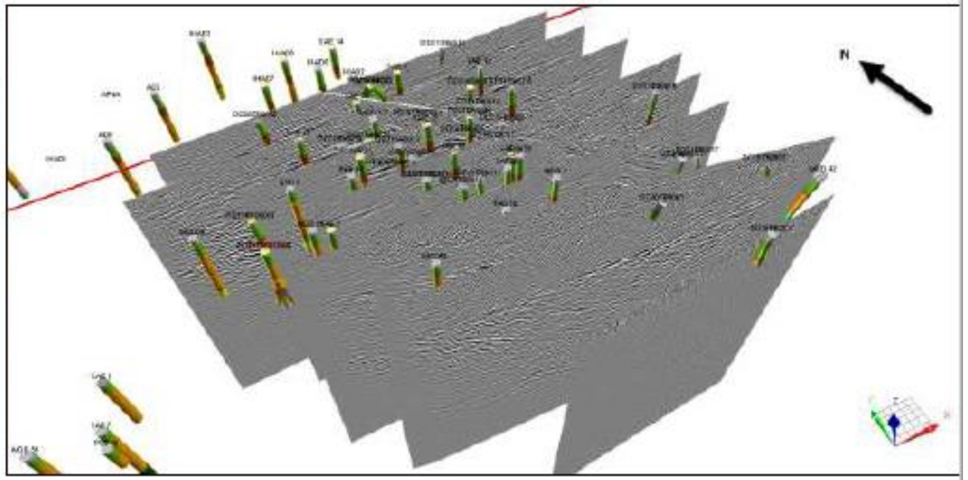


White line shows cross-section location

2D multi-channel seismic (MCS) reflection surveying by HiSeis in 2020

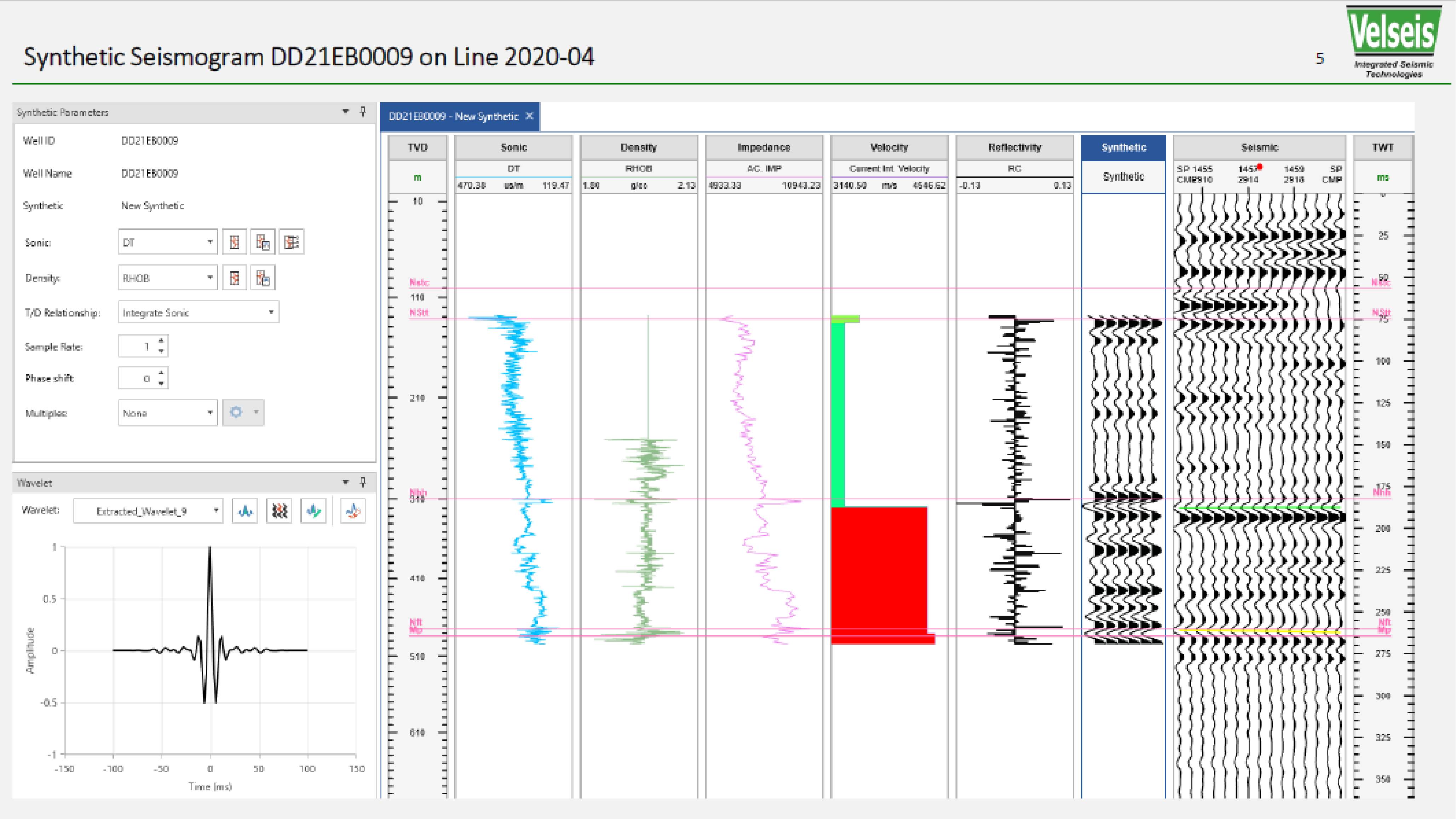
- 6,000 lb vibroseis, 1x 20 sec sweep from 6-120 Hz
- 5m shot and 5m phone spacings offset by 2.5 m, 1,200 phone spread for min fold of 600 and max fold of 3,000
- 3 sec record at 2 ms sample rate
- Initial data processing by HiSeis followed a hard rock workflow focussed on preserving far offset data for detecting steep dipping layers, but this survey area is dominated by flat sedimentary layer reflection surfaces and high-frequency reflection signal.





Reprocessing of 2D MCS survey data to enhance resolution and improve depth control

Drilling constrained data processing and depth conversion caried out by Velseis and Respot in 2021.



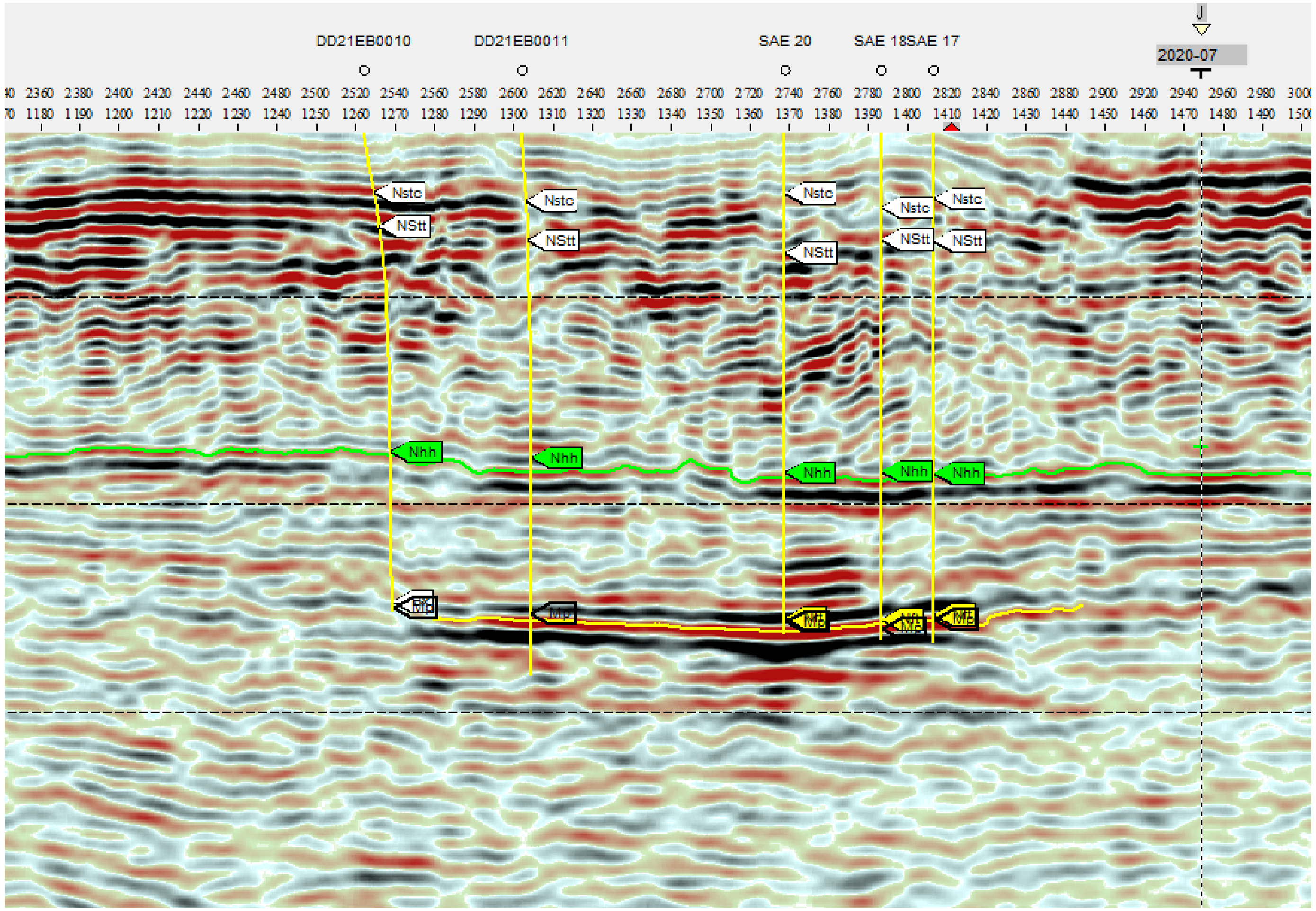
Reprocessing of 2D MCS survey data to enhance resolution and improve depth control

Resource Potentials

Different processing workflow for flat lying sources and higher frequency events, with iterative analysis using drilling data to tie-in stratigraphy and wireline physical properties produced a much more accurate time-to-depth conversion result in the Neoproterozoic to recent sedimentary deposit sequences.

The amplitude response of Tapley Hill Fm located at top of Pandurra Fm was traced along survey lines for targeting isolated depressions untested by drilling for generating SEDEX drilling targets.

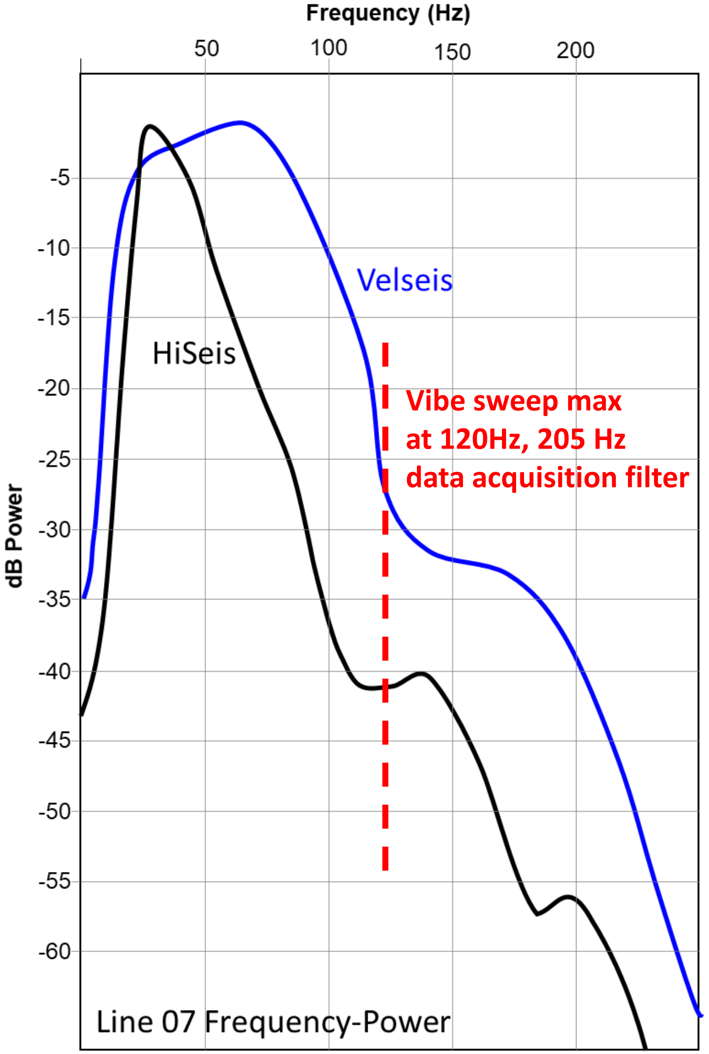
Velseis

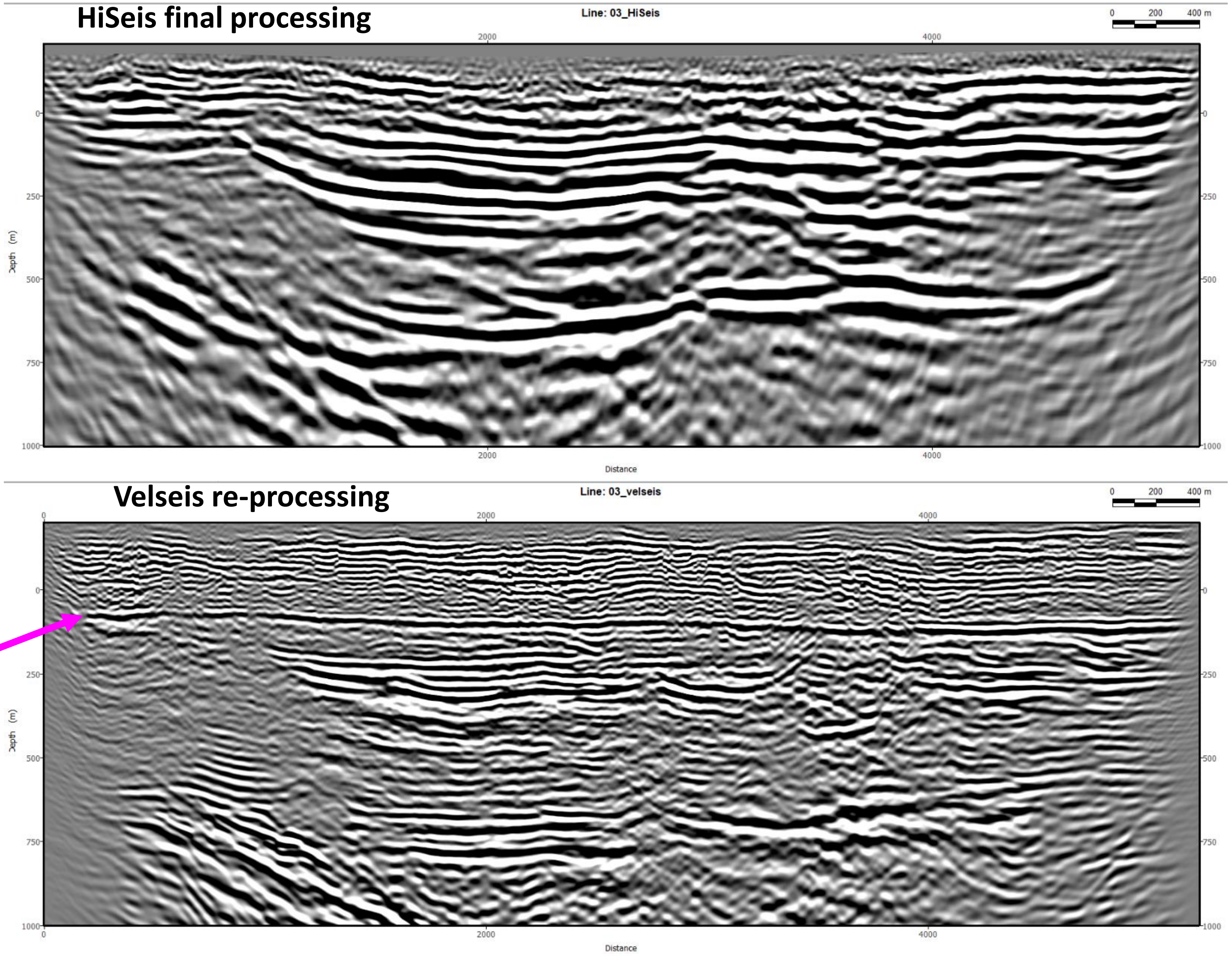


2D MCS data re-processing improved stratigraphic resolution

Resource Potentials

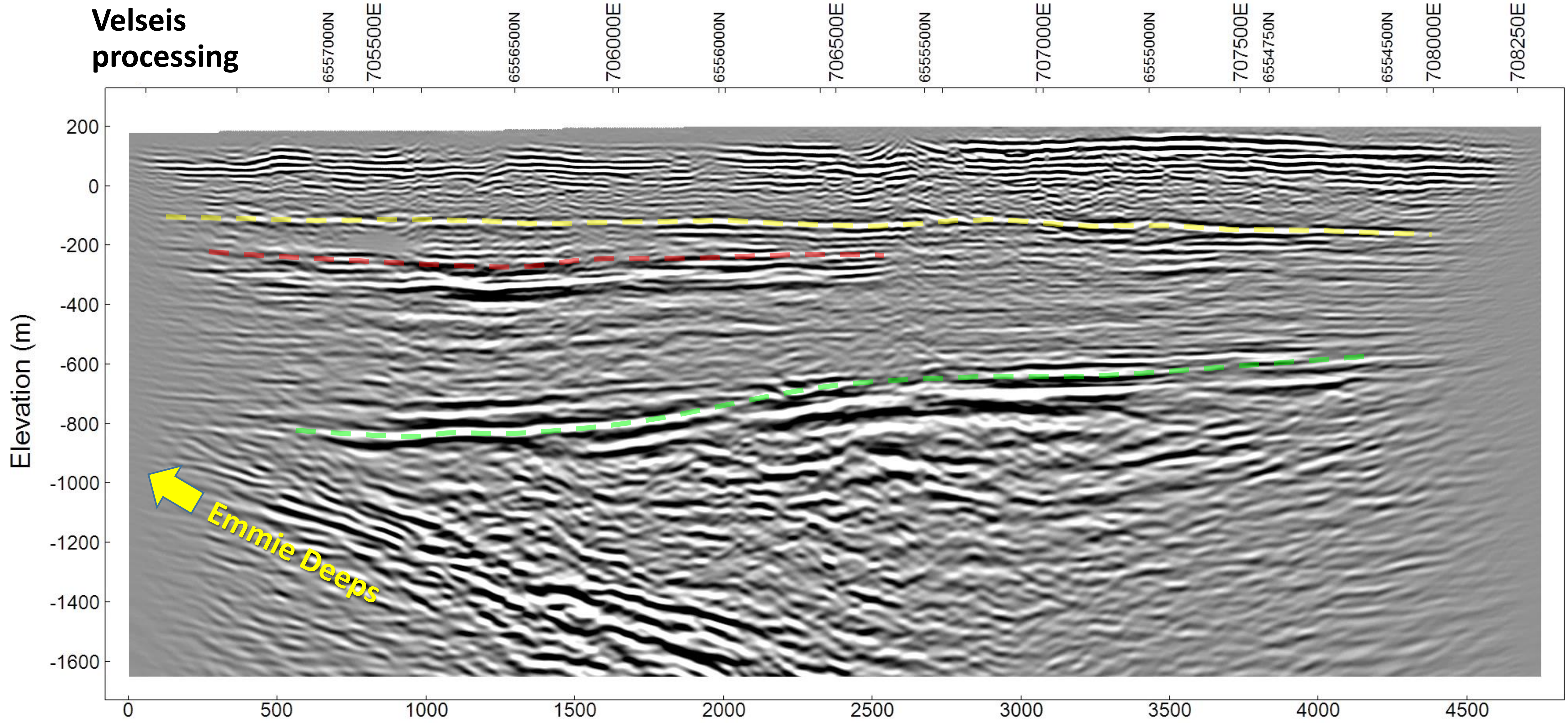
Power-frequency spectra plot of HiSeis processed seismic survey line 7 compared to Velseis re-processing results which contain higher frequency signal for higher resolution imaging.





Top of Whyalla Sandstone, constrained by drilling, shows up as a strong flat reflector

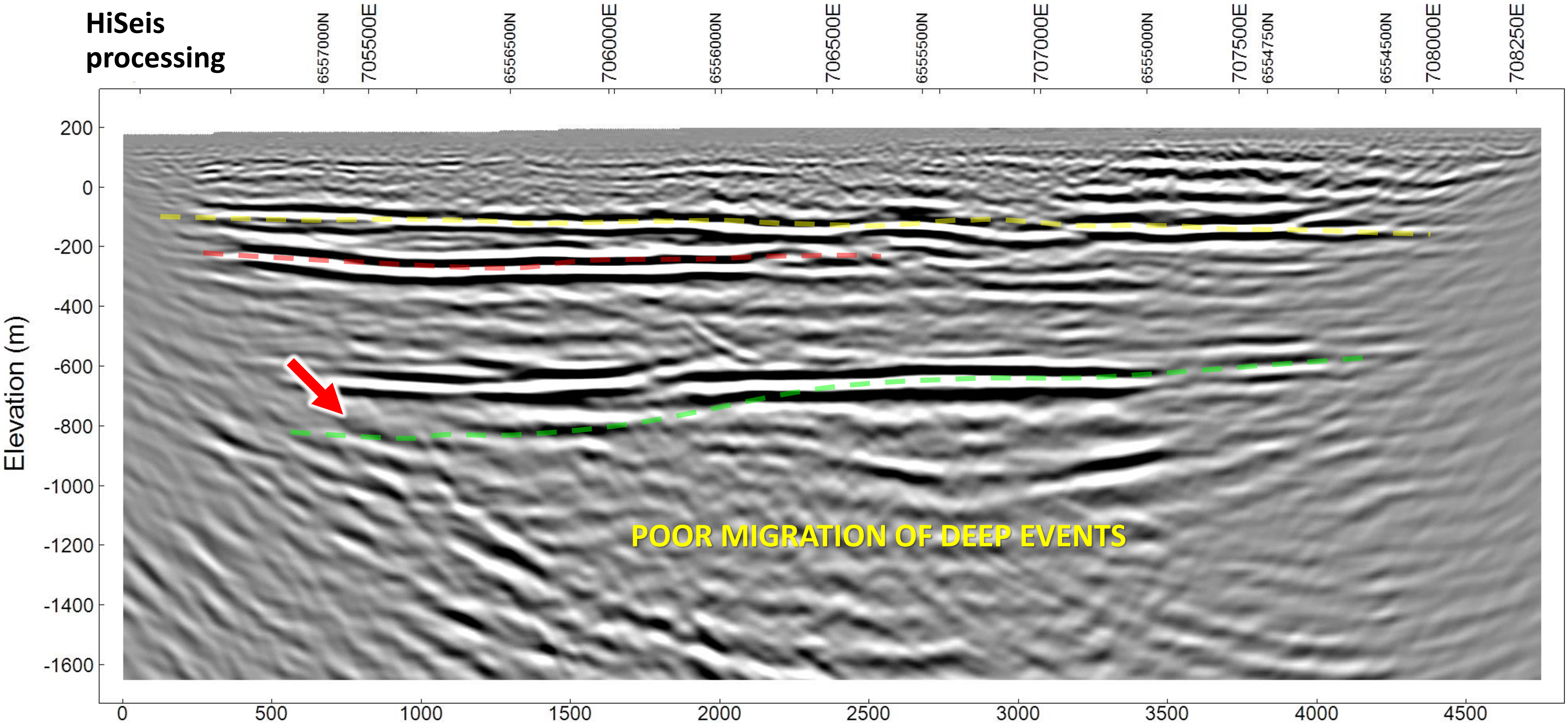
2D MCS reflection data comparison (same scale as next slide)



Velseis reprocessed MCS data along survey line 3. A strong horizontal reflection event at approximately -150 m RL elevation ties in with the Whyalla Sandstone unit (yellow dashed line) logged in nearby drillholes. Other significant reflectors are shown as red and green dashed lines for comparison with HiSeis processed section shown on the next slide.

2D MCS reflection data comparison (compare to previous slide)

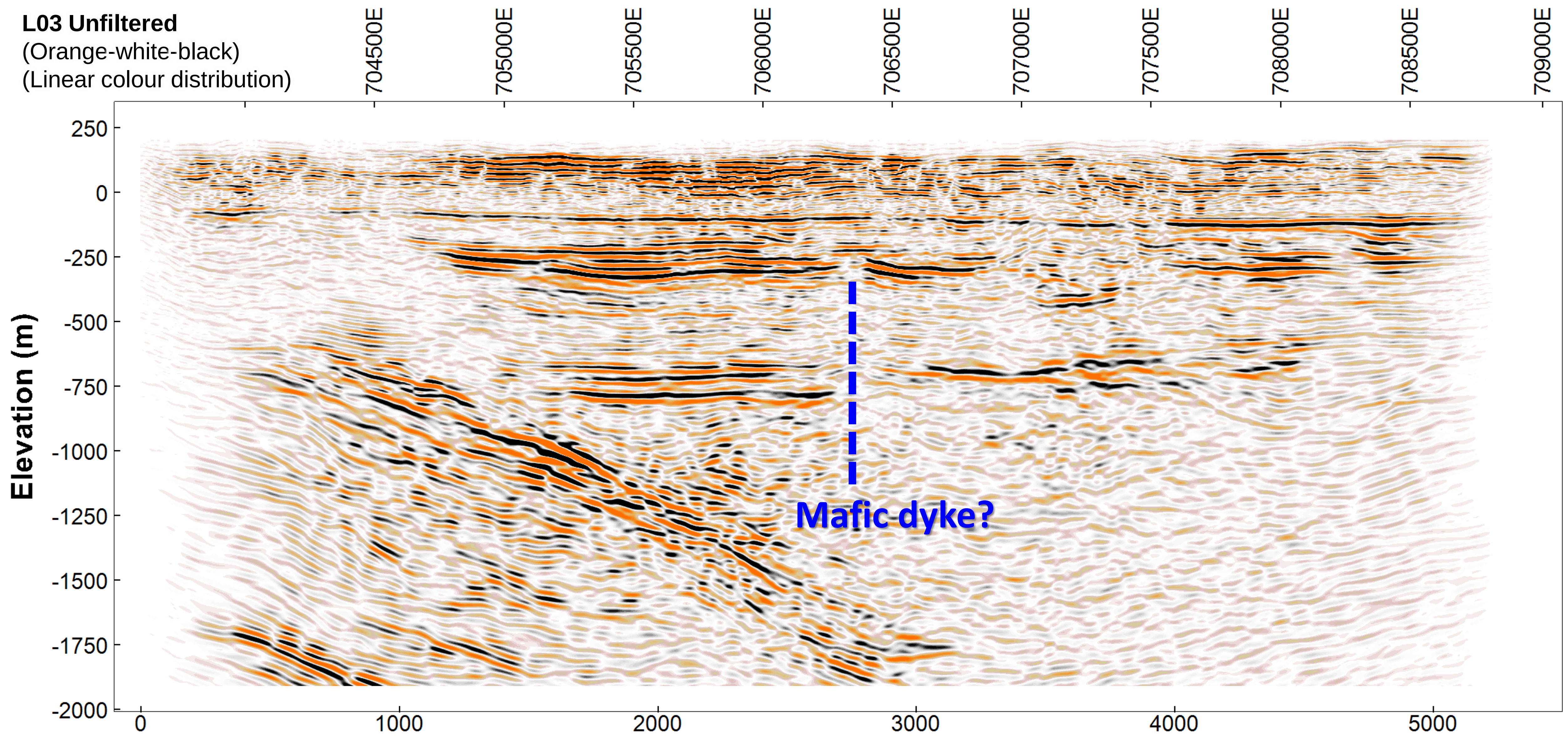
Resource Potentials



HiSeis processed MCS data along survey line 3. The approximate locations of the Whyalla Sandstone horizon (yellow dashed line), and other significant reflectors (red and green dashed lines) traced from the previous slide are copied for comparison against Velseis reprocessed seismic section. The red arrow highlights a significant difference between the picked events.

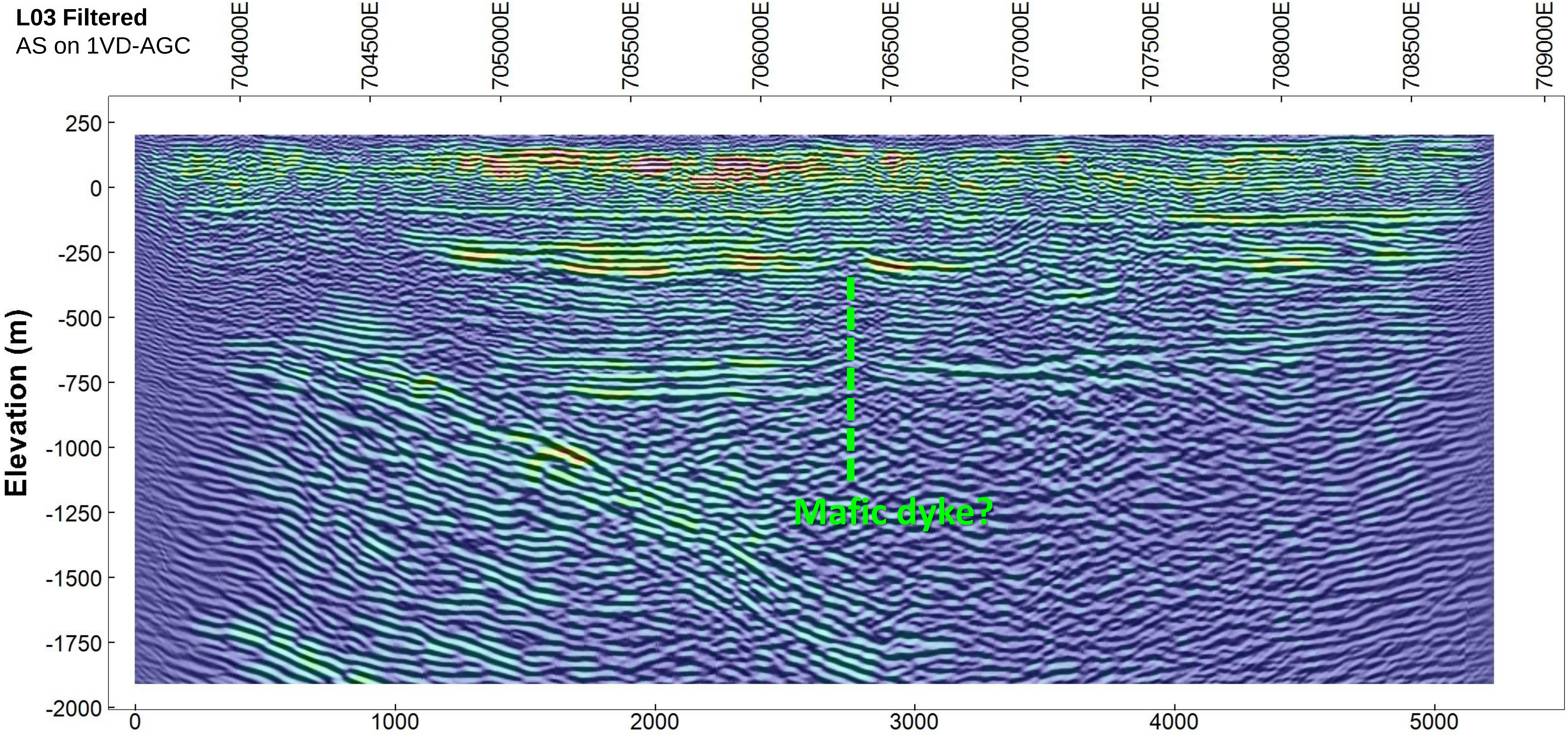
MCS data imaging – raw amplitude

Resource Potentials

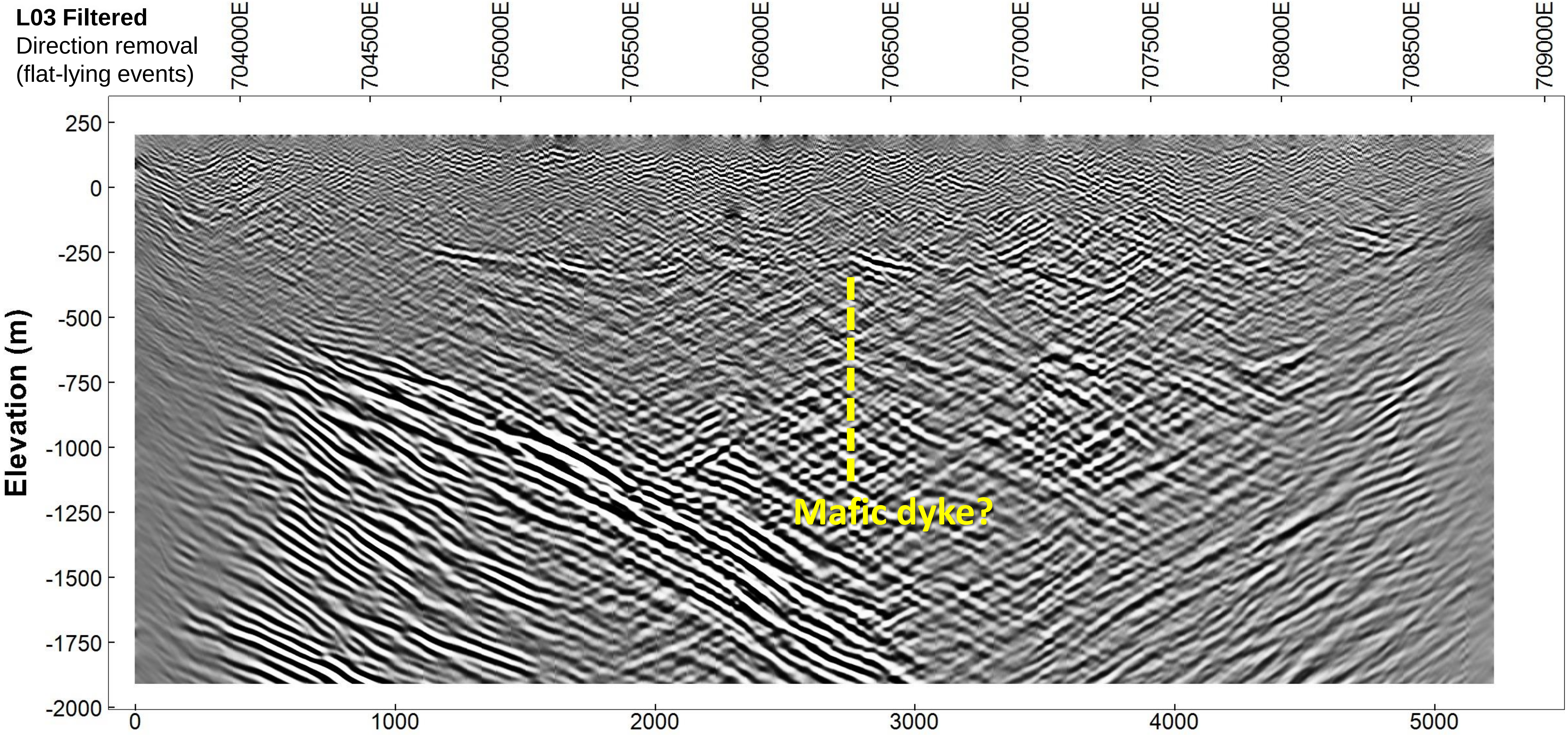


MCS data imaging – ansig over 1VD-AGC

Resource Potentials



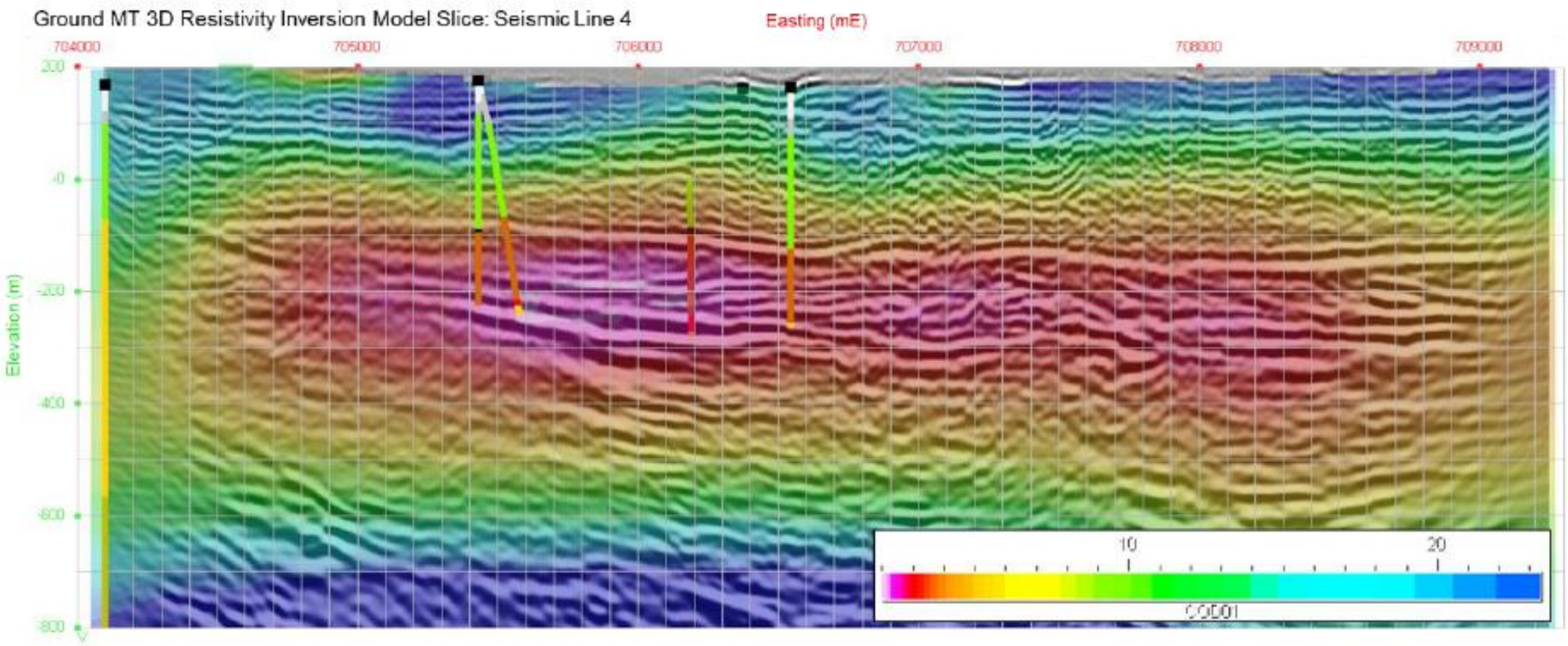
MCS data imaging – enhancement of steep dipping reflectors



Ground MT 3D inversion results over depth migrated seismic sections

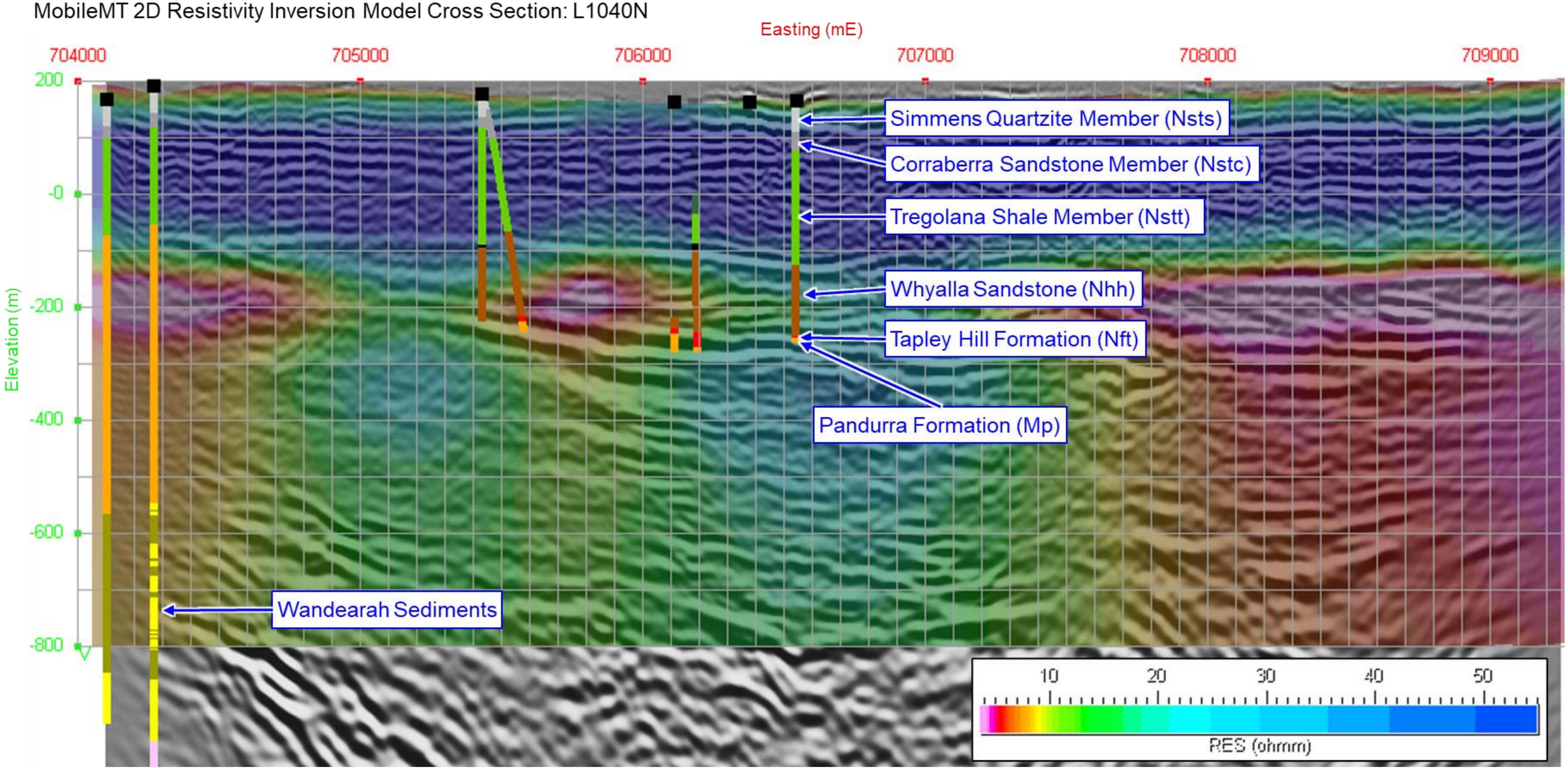
Resource Potentials

Conductive layering follows the Whyalla Sandstone at broad scale, due to saline groundwaters as detected in drillholes and measured in wireline resistivity logs.



MMT 2D inversion results over depth migrated seismic sections

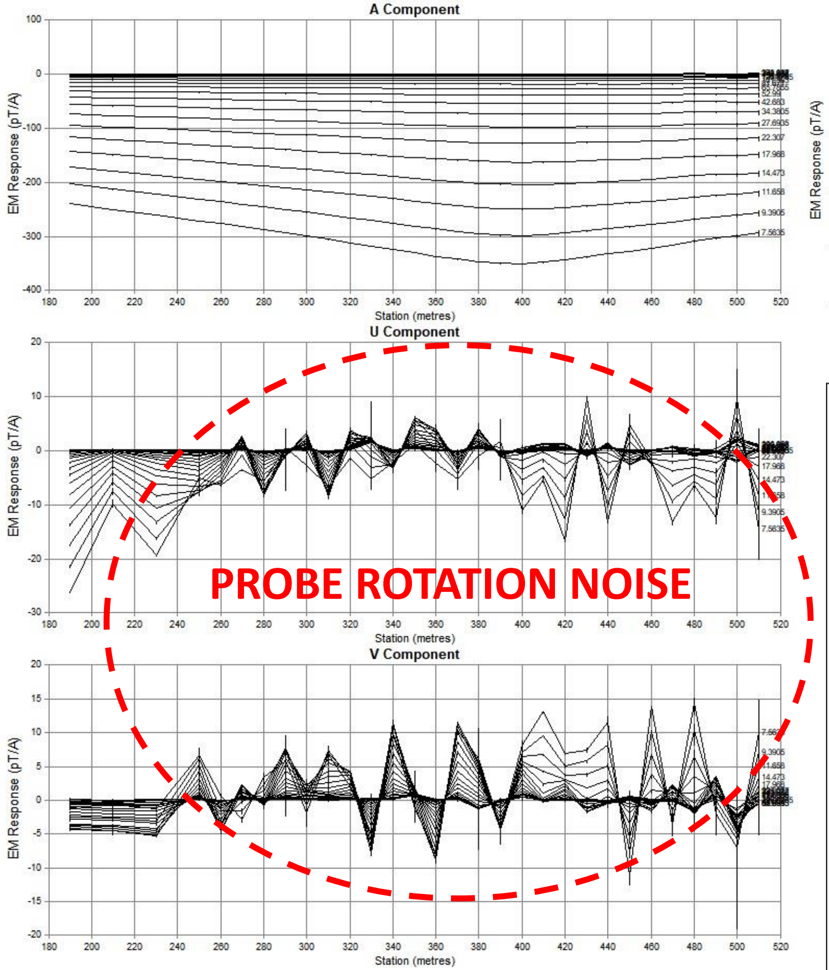
Conductive layering follows the Whyalla Sandstone, but with local breaks possibly artefacts from interpolation between survey lines to make a solid model, or forming real geological breaks caused by vertical structures affecting groundwaters and sulphide contents.



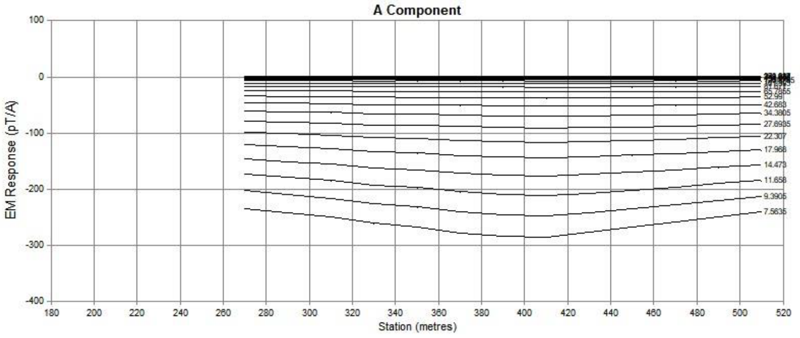
Downhole EM (DHEM) Zonge 2021

Tapley Hill Fm shale is the main EM conductor target horizon, saline groundwaters not detected in the DHEM data, but vertically drilled holes produced bad U and V component data from probe rotation, and so re-surveying the hole using multiple Tx loops was required to vector toward off-hole conductor sources using the A component results (*old school method used before development of 3-component probes*).

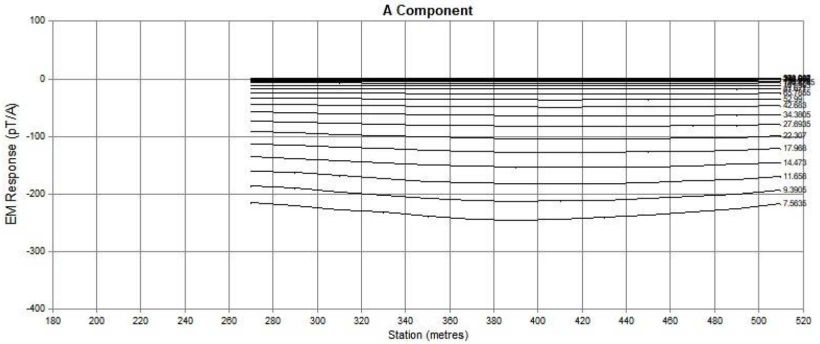
DD20EB0002 DHEM Decay Profiles (Ch20-39)

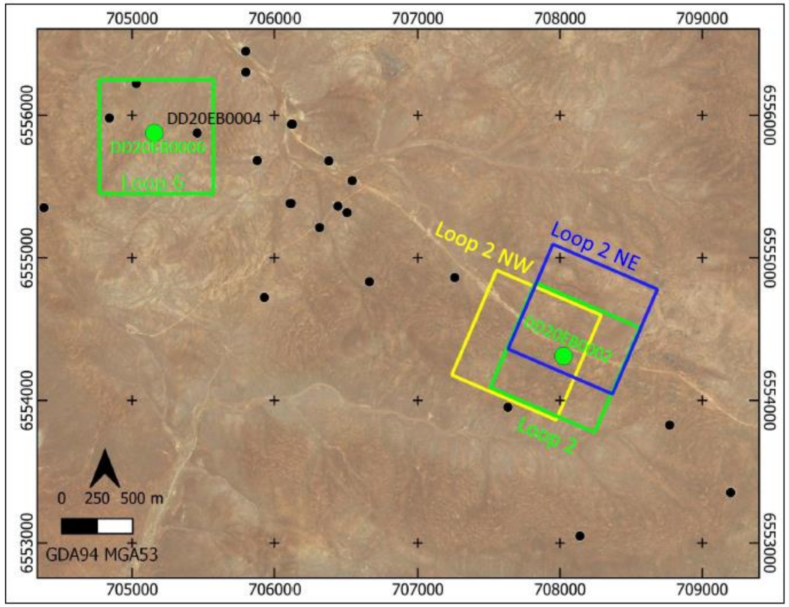


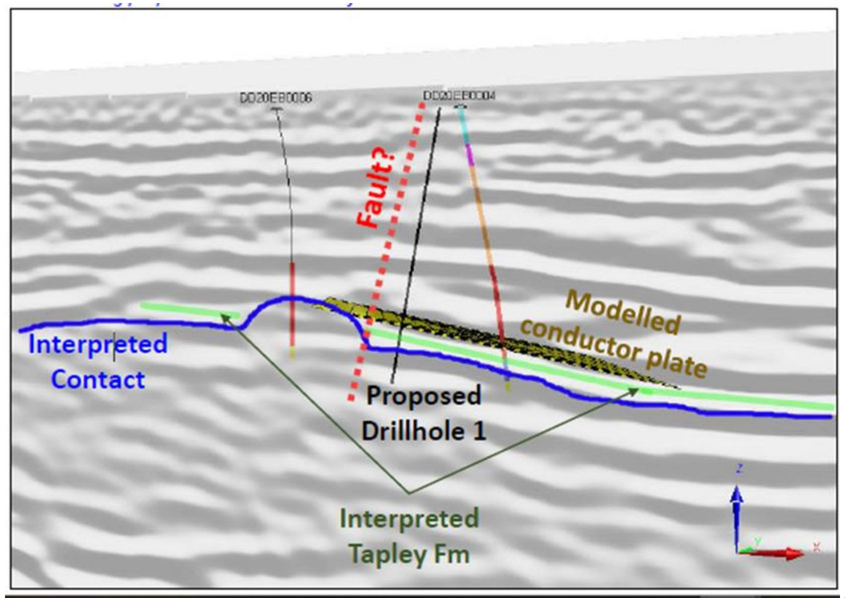
Loop 2 NW –A Component Decay Profiles



Loop 2 NE –A Component Decay Profiles







Conclusions and Recommendations

Resource Potentials

- Classical "bullseye" targeting on a subtle gravity high anomaly and inversion model density high zone has led to the discovery of the Emmie Deeps IOCG deposit which starts at 800m depth. Subsequent deep drilling and comparison of geology and petrophysical results to magnetic, gravity and MT anomaly patterns shows that the Cu mineralisation is structurally controlled in a hematite altered zone with a bedrock high, but it is not directly detected by MT or MMT surveying, and it is not related to obvious MT "*fingers of Satan*" – 3D MCS surveying may help here…
- Some of the gravity high anomaly at the Emmie Deeps IOCG discovery is caused by a rise in the crystalline bedrock topography at the base of the Pandurra Formation, but most of the anomaly high is explained by strong hematite alteration of crystalline bedrock units.
- Detailed 2D multi-channel seismic data re-processing focussing on flat lying stratigraphy, preserved high frequency content and used geological constraints from drilling data to greatly improve reflection resolution and reliability of depth migrated results. More future drillholes should be wireline surveyed for sonic velocity and density, and some VSP surveying using a vibroseis source. Consider 3D MCS surveying over the Emmie Bluff underground mine development area.
- Drilling into interpreted Tapley Hill Formation reflectors showed that the depth position between Whyalla SS and Pandurra Fm was correct, but the Tapley Hill shale beds and related SEDEX Cu-Ag-Co mineralisation were often missing, so MCS data by itself is not a very reliable tool for targeting SEDEX mineralised layers.
- MMT and MT survey results were highly affected by horizontal conductive layering caused by saline groundwater zones in Neoproterozoic sandstone formations overlying the target Tapley Hill Formation shale and deeper IOCG targets, and therefore were not useful for direct targeting of sulphide related mineralisation. Some subtle NNW trending breaks in the conductivity inversion modelled layers may relate to sub-vertical faults that acted as basin controlling features and mineralising fluid conduits extending into the Pandurra Fm and IOCG altered crystalline basement rocks below.
- DHEM surveying to detect SEDEX conductor zones using 3-component probes in vertical deep drillholes was limited to the axial (A) component, because the horizontal U and V component data were unusable due to probe rotation, and therefore "old school" re-surveying of the same hole using multiple transmitter loop positions was required for constraining locations of off-hole conductor sources.