

BHP



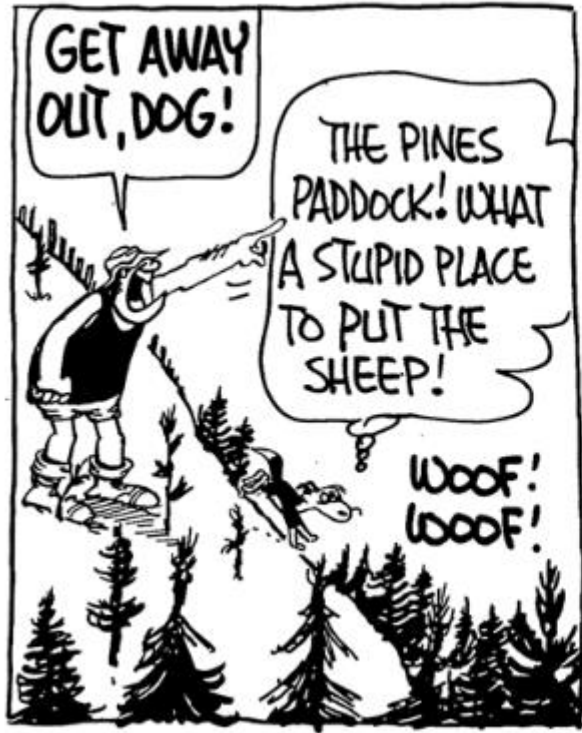
Australian Society of
Exploration Geophysicists

Probabilistic modelling of broadband MT for basement topographic mapping, East Albany-Fraser Orogen, WA

Mark Lowe



MT geophysics camp at sunrise, Rawlinna station, WA



With permission from Diogenes Designs Limited, 2017 [Strip Archive \(footrotflats.com\)](http://Strip Archive (footrotflats.com))

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Mombarriga crew and Ngadju TO's in action

Contributors

This is the work of a host of people but includes

- BHP Metals Exploration team, especially Katherine McKenna, your support is invaluable, thank you!
 - Geophysicists, Geologists, Operations, Business, Geoscience leads, Data scientists... all hands on deck
- Hoël Seillé and Gerhard Visser (CSIRO) – Modelling and many of the slides in the second half of this presentation.
- Tom Hoskins and the Moombarriga Geoscience crew (25+ people over 6 months+, their biggest ever?) – Acquisition and modelling
- Terra Petrophysics
- MIRA Geoscience
- CGG Aviation
- GEM Geosystems
- Daishsat Surveying
- and many others, its still going..
- And yourself for being here and interested today, I hope you can take something away!

Background

BHP Metals Exploration is exploring in the East Albany-Fraser Orogen for basement-hosted Ni-Cu deposits since 2020. An area of ~30000 sq km.

We needed to understand the explorability of the region. This includes understanding the effect of cover on geophysical signatures in basement.

The area is largely unexplored.

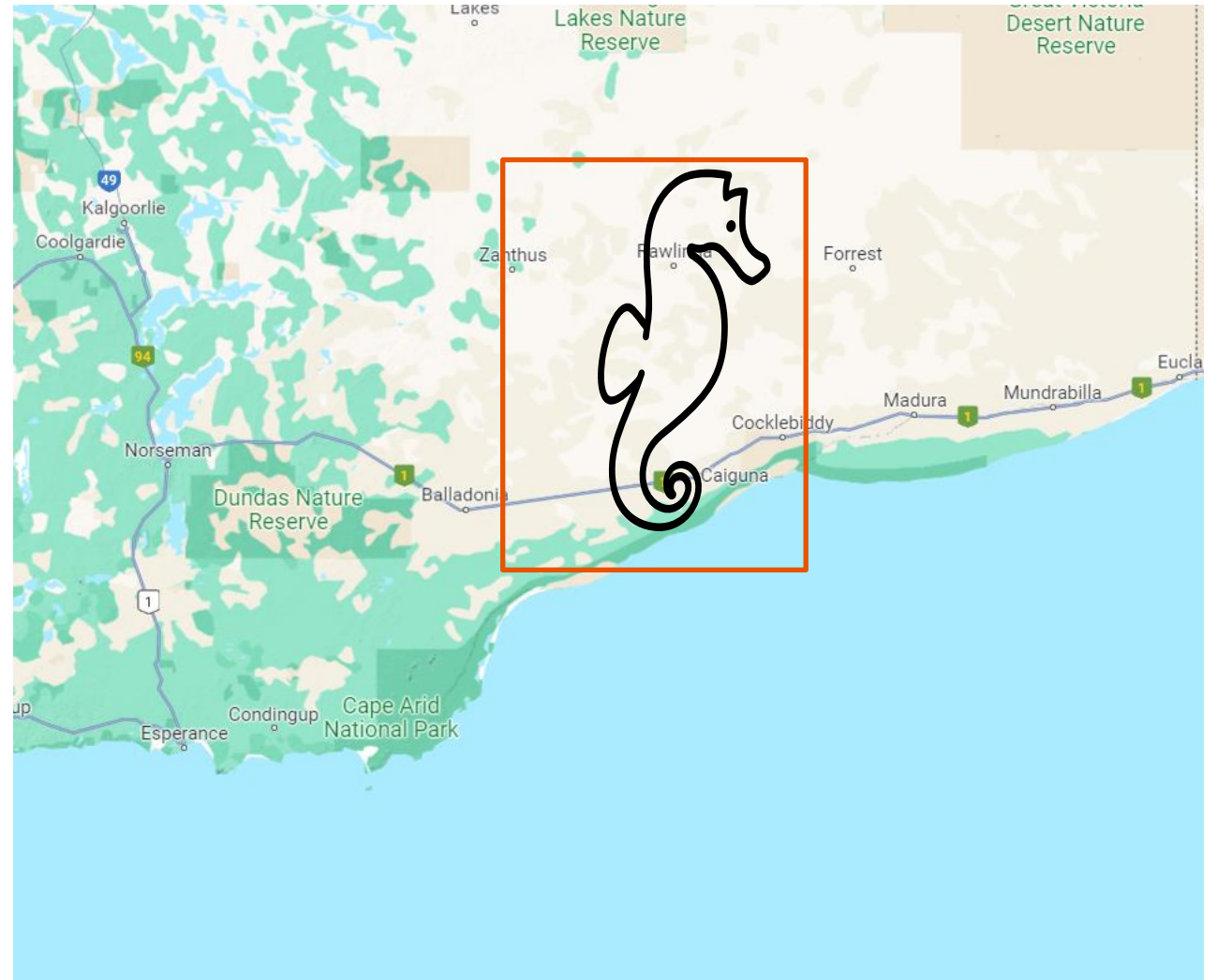
Petrophysics, airborne AGG and broadband MT was used to explore the area during 2021 – 2023.

CSIRO modelled the conductivity of the cover and depth-to-basement using Bayesian probabilistic modelling.

The outcomes were:

- Probabilistic models of the conductivity of cover to 900m, well below AUSAEM depth of investigation.
- Improved understanding of the explorability of the area based on the modelled depth of cover.
- New prospectivity analysis, using calculated basement geophysical residuals from accurate cover models.
- A new exploration process for defining explorability and basement topography in greenfields terranes.

30,000 sq km, no outcrop



Google Maps

Exploration undercover - Challenges

- Sedimentary cover can be km's deep, however the majority in Australia is less than 1km deep.
- We encounter a proportionally greater impact on the importance of cover lithophysics as we go deeper.
 - Petrophysics, sedimentology, hydrogeology, structure, regolith, geomorphology all impact our signal.
- As a result, we need greater Signal/ Noise and full frequency/ full component detection to understand multi-scale mineral systems
- Integrated geophysical modelling, understanding errors and ML-enhanced prediction.
- Localised deep testing with drilling, acquiring petrophysics and hole-adjacent detection including within the cover.

The map on the right shows:

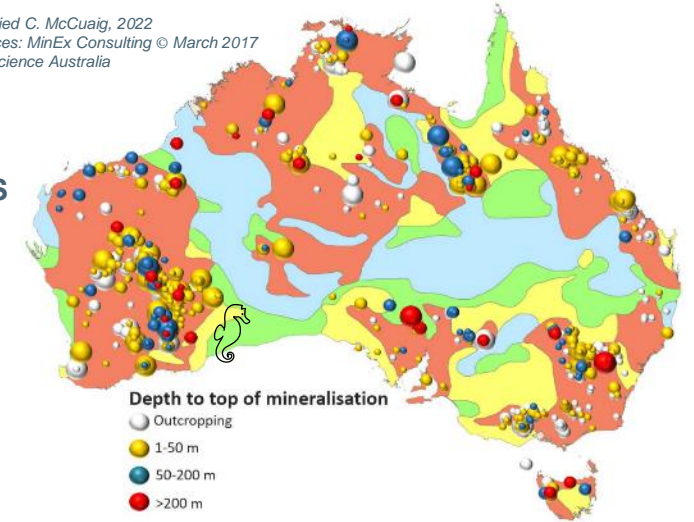
Depth of cover	<150m	150m – 1000m	1000m – 2000m	> 2000m
Proportion of area	35%	21%	12%	32%

e.g. The state of Queensland covers 22.5% of Australia

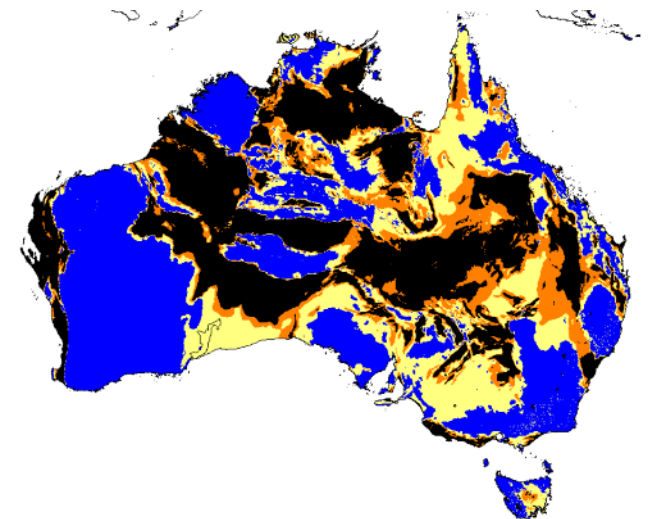
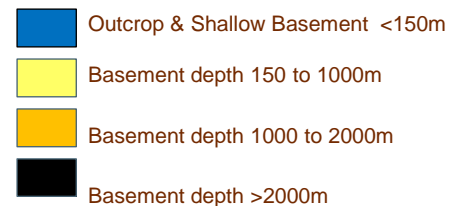
This 'challenge' is more an opportunity.

Modified C. McCuaig, 2022
Sources: MinEx Consulting © March 2017
Geoscience Australia

MAJOR MINERAL DEPOSITS ON DEPTH OF COVER



INDICATIVE DEPTH OF COVER



Geognostics, 2021. OZ SEEBASE® 2021 (March 2021). Geognostics Australia Pty Ltd, <https://www.geognostics.com/oz-seebase-2021>

Precompetitive data

AUSAEM – Tempest, is invaluable for identifying sedimentary profiles, bulk conductivities of broad lithologies, structural offset and basement topography in the first 100-200m, more in resistive regions.

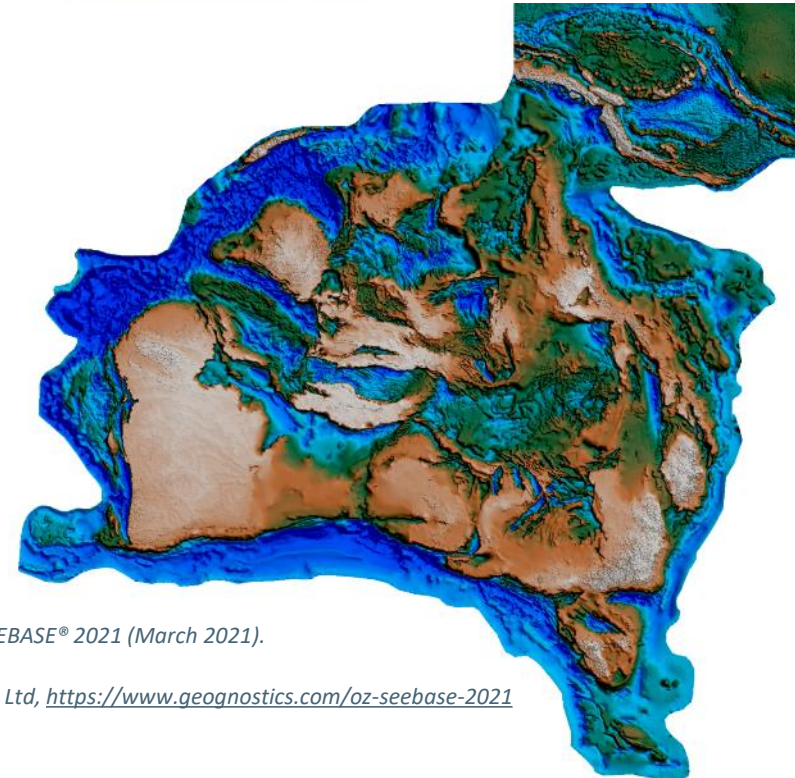
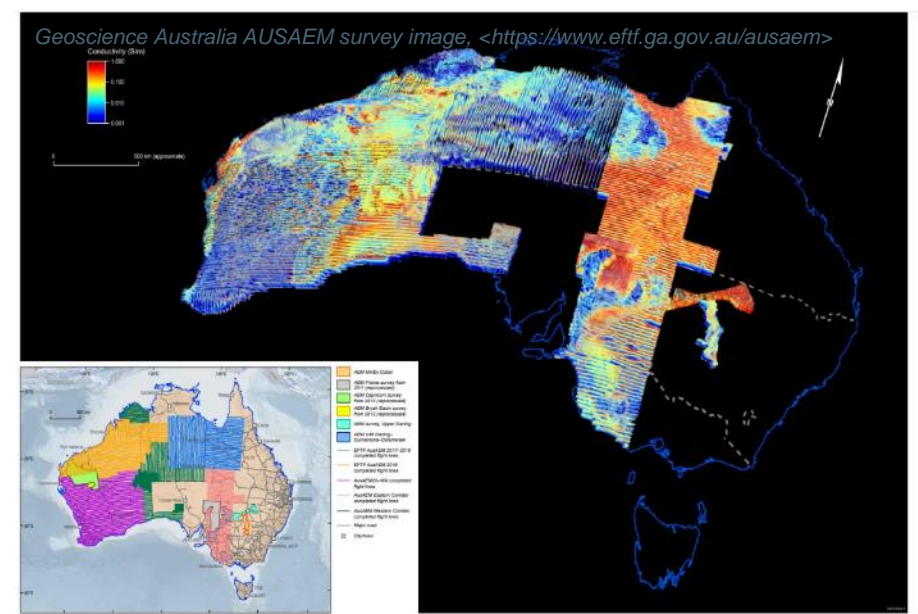
SEEBASE – Very valuable for the deep modelling, km scale, but doesn't retain the necessary vertical/ lateral resolution for many minerals exploration needs within basement.

GA COVER-THICKNESS MAPPING – Integrated models of cover from AUSAEM and drillholes, in NT and QLD, not WA yet?

PASSIVE/ ACTIVE SEISMIC/ MT – brilliant where available but sparse. AUSLAMP at 200km spacing.

GRAVITY/ MAGNETICS – effected by more ambiguity

Need for a technique between 200 – 1000m was between MT and seismic.



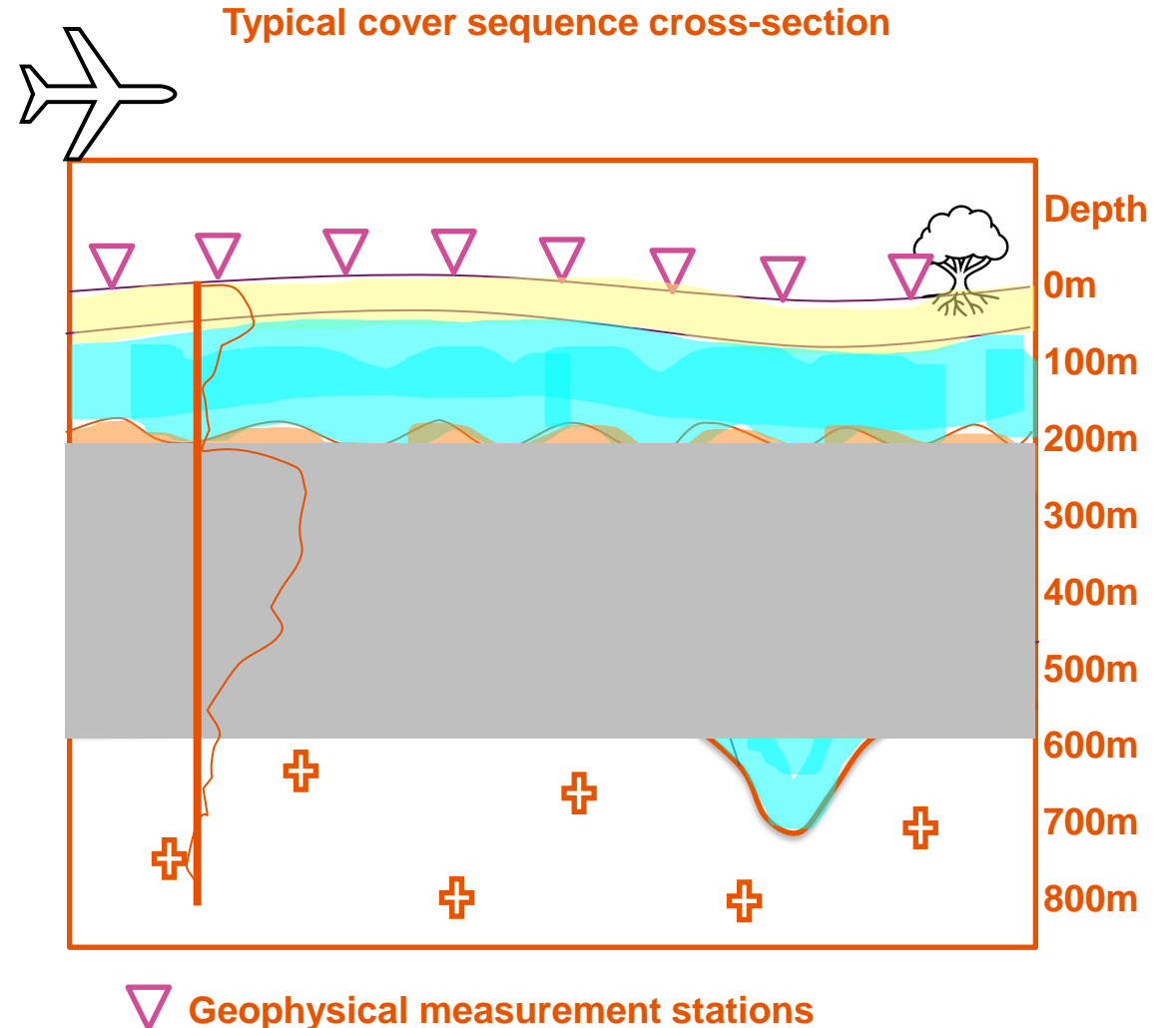
Geonostics, 2021. OZ SEEBASE® 2021 (March 2021).

Geonostics Australia Pty Ltd, <https://www.geonostics.com/oz-seebase-2021>

Looking at the cover differently

A typical precompetitive or exploration dataset contains flight lines of potential fields and AEM.

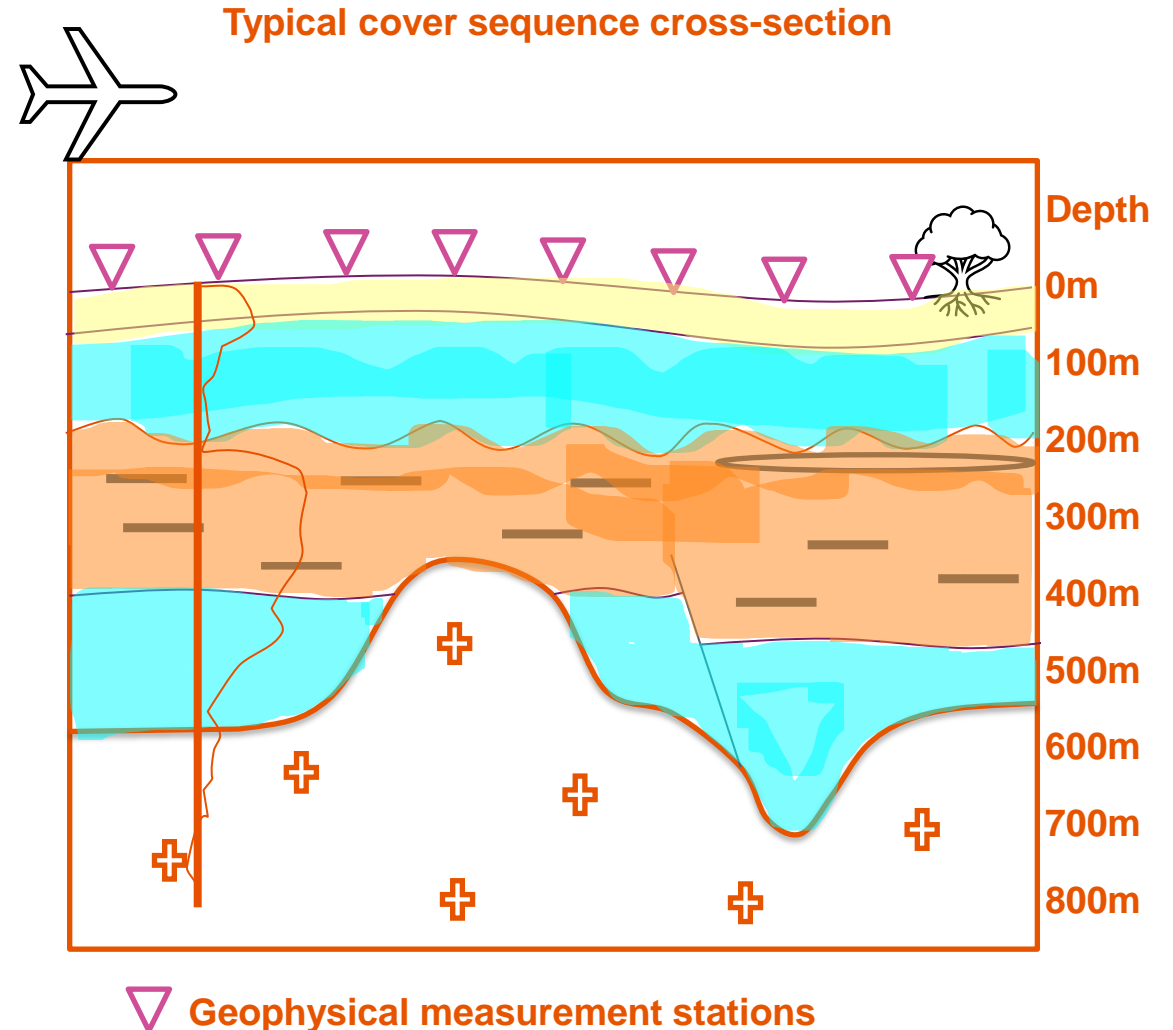
- Lateral/ vertical changes in the basement and upper-most crust are good, but there is a 'gap'. This area is not imaged due to the DOI of EM and the lack of signal/ resolution in potential fields.
 - Petrophysics is used to support this



Looking at the cover differently

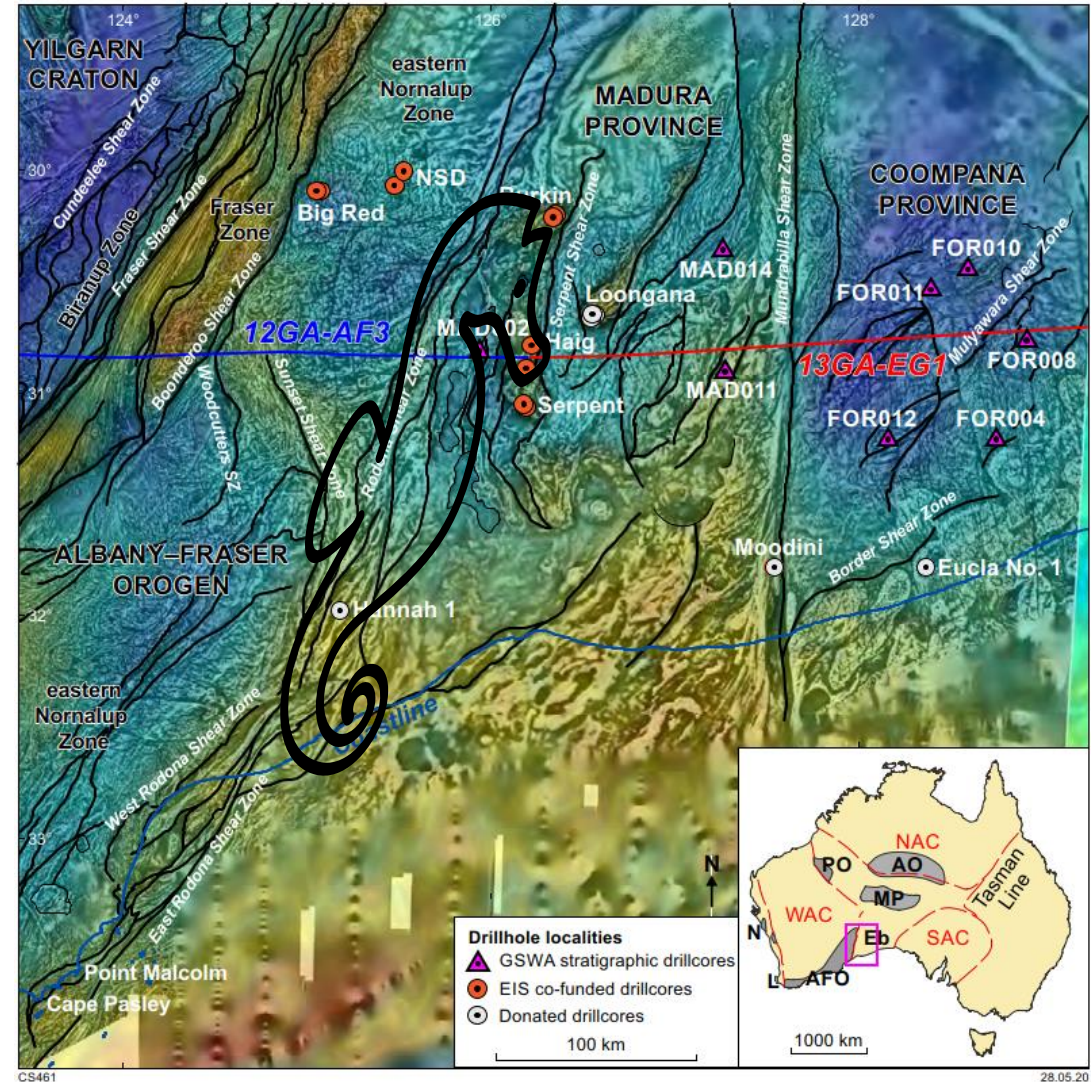
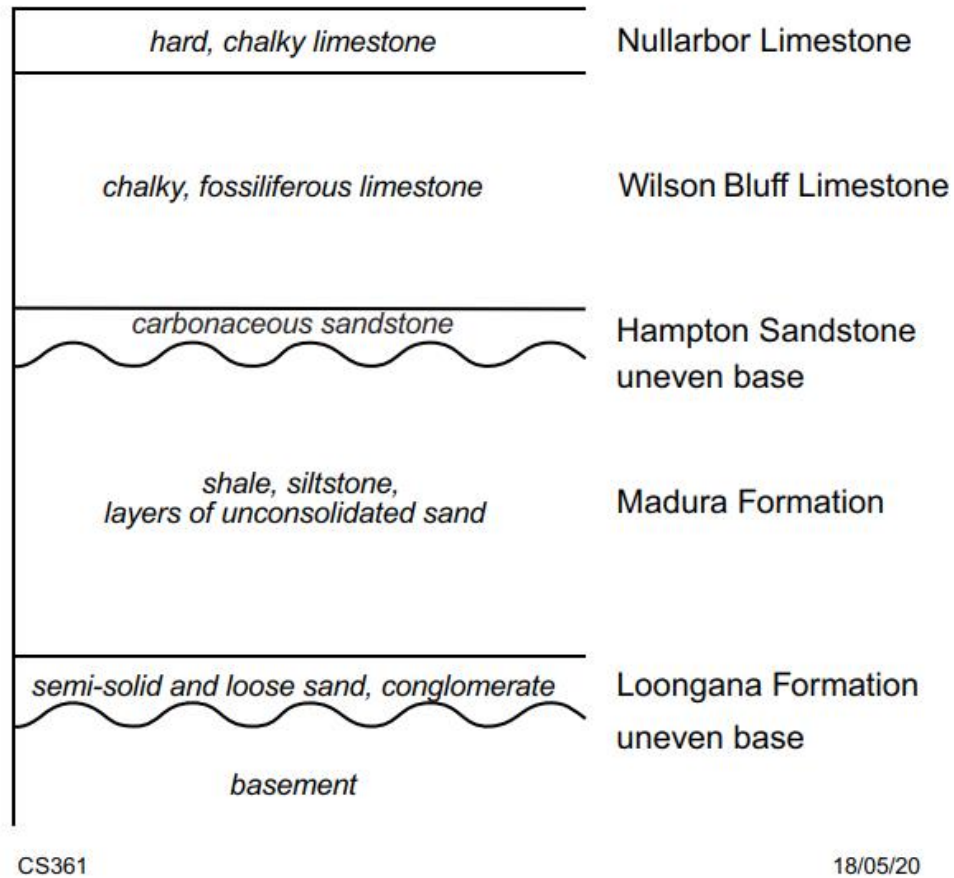
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- Lateral/ vertical changes in the basement and upper-most crust are good, but there is a 'gap'. This area is not imaged due to the DOI of EM and the lack of signal/ resolution in potential fields.
 - Petrophysics is used to support this
- Adding ground stations of electrical data picks up the intermediate layers vertically and laterally depending on the station resolution.
- Without this intermediate depth information, incorrect assumptions about basement topography or cover variation could result in incorrect interpretations of basement geology and false targetting.
- The basement-cover interface is often not the most distinct physical change for one method but can be for others, or alternatively multiple methods can assist in guiding each other. Integrated modelling helps to build the best picture of what the basement topography should be.



Geology of the cover in the East AFO-Madura

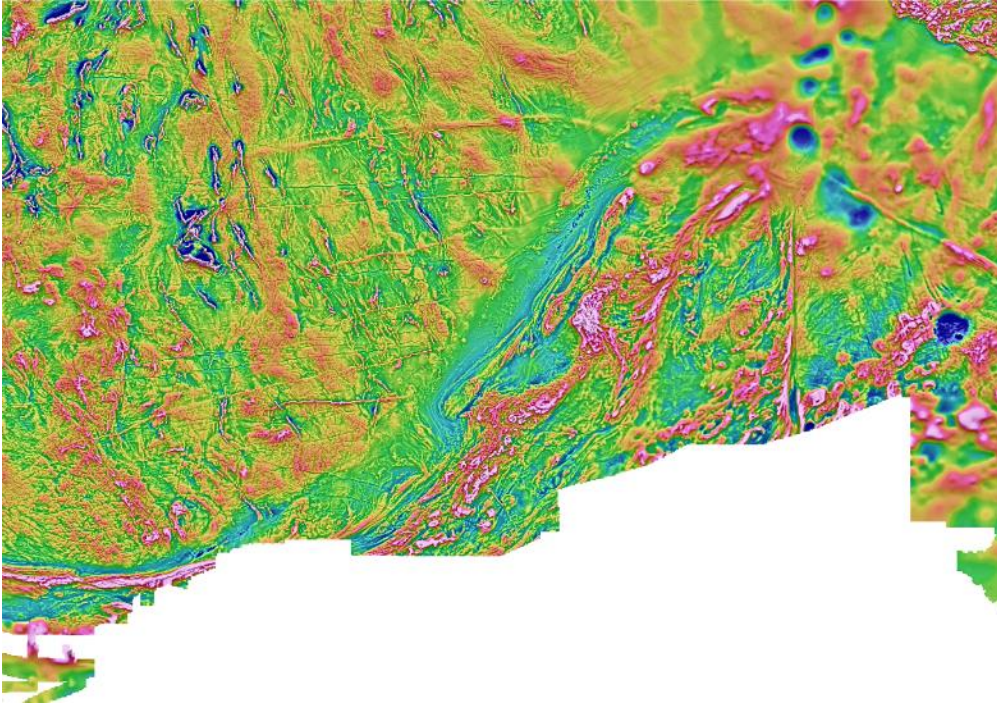
Limestones, sandstones, shale and loose sands/ conglomerate cover the area between 200 – 800m deep.



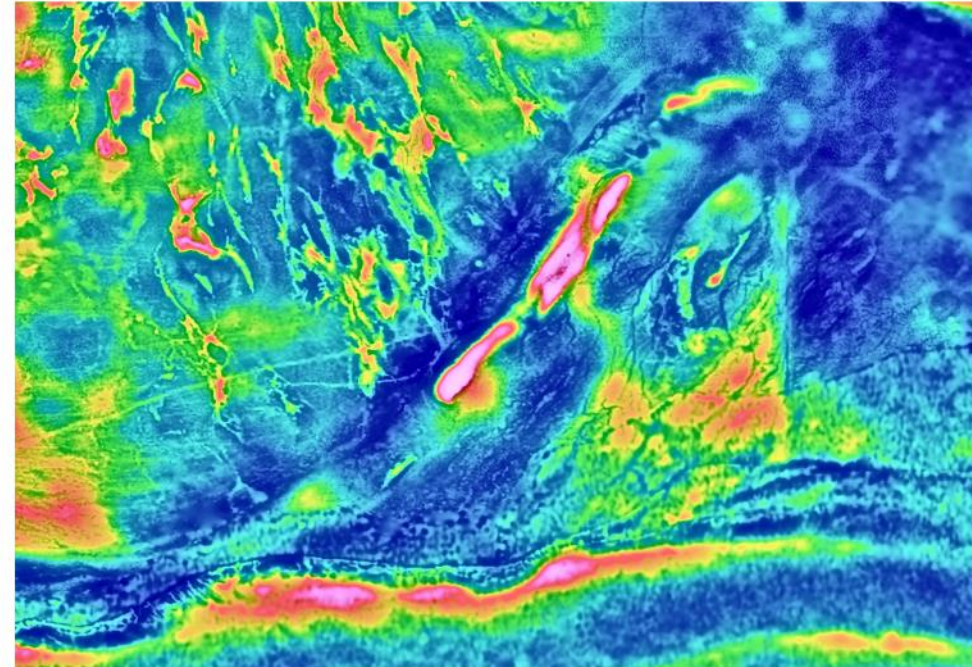
Spaggiari, CV, Smithies, RH, Kirkland, CL, Wingate, MTD, England, RN and Lu, Y 2020, Stratigraphic and co-funded drilling of the Eucla basement — the Proterozoic geology beneath the Nullarbor Plain: Geological Survey of Western Australia, Report 204, 147p.

Geology of the East AFO Madura

GSWA open-file



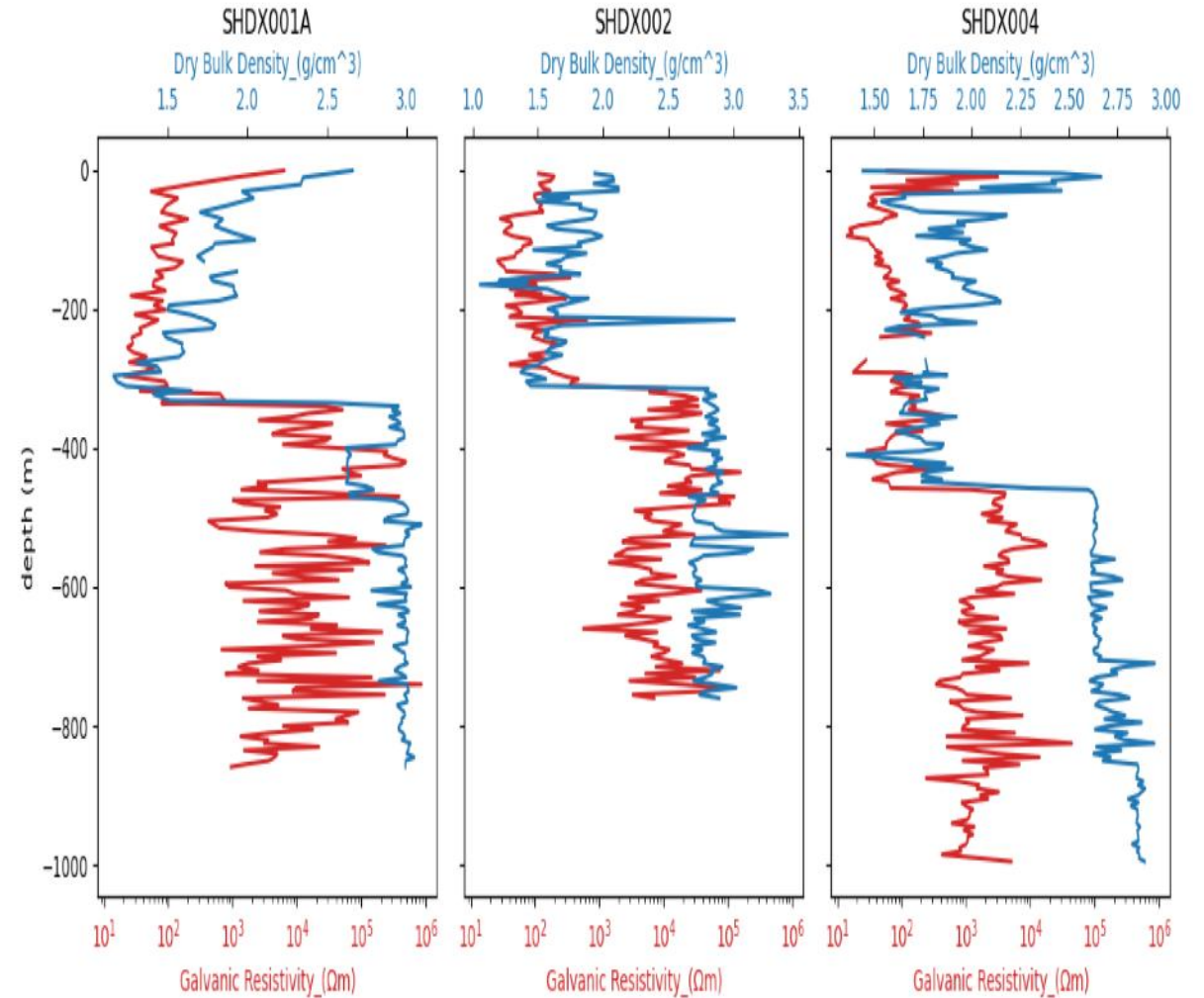
RTP magnetics on 1VD



Gravity draped on 1VD

Petrophysics

The core petrophysics data shows a clear variation of both the Galvanic Resistivity and the Dry Bulk Density at the depth to basement interface. Both datasets detect a sharp physical transition at this boundary, making a joint interpretation of electrical and density suitable to map basement variations.



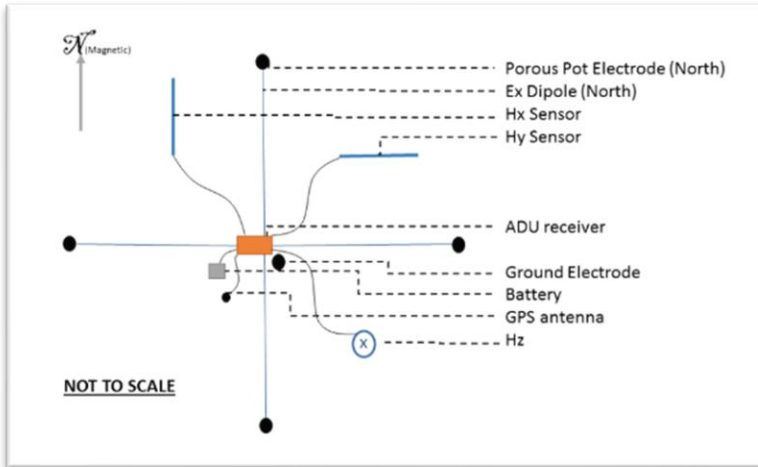
MT Locations

MT Lines were acquired over AUSAEM flightlines for direct comparison between AEM and MT models.

4 lines were completed in early 2022, and 8 additional lines in late 2022- early 2023 at 1000m stations.

Regular repeats were conducted on all stations.

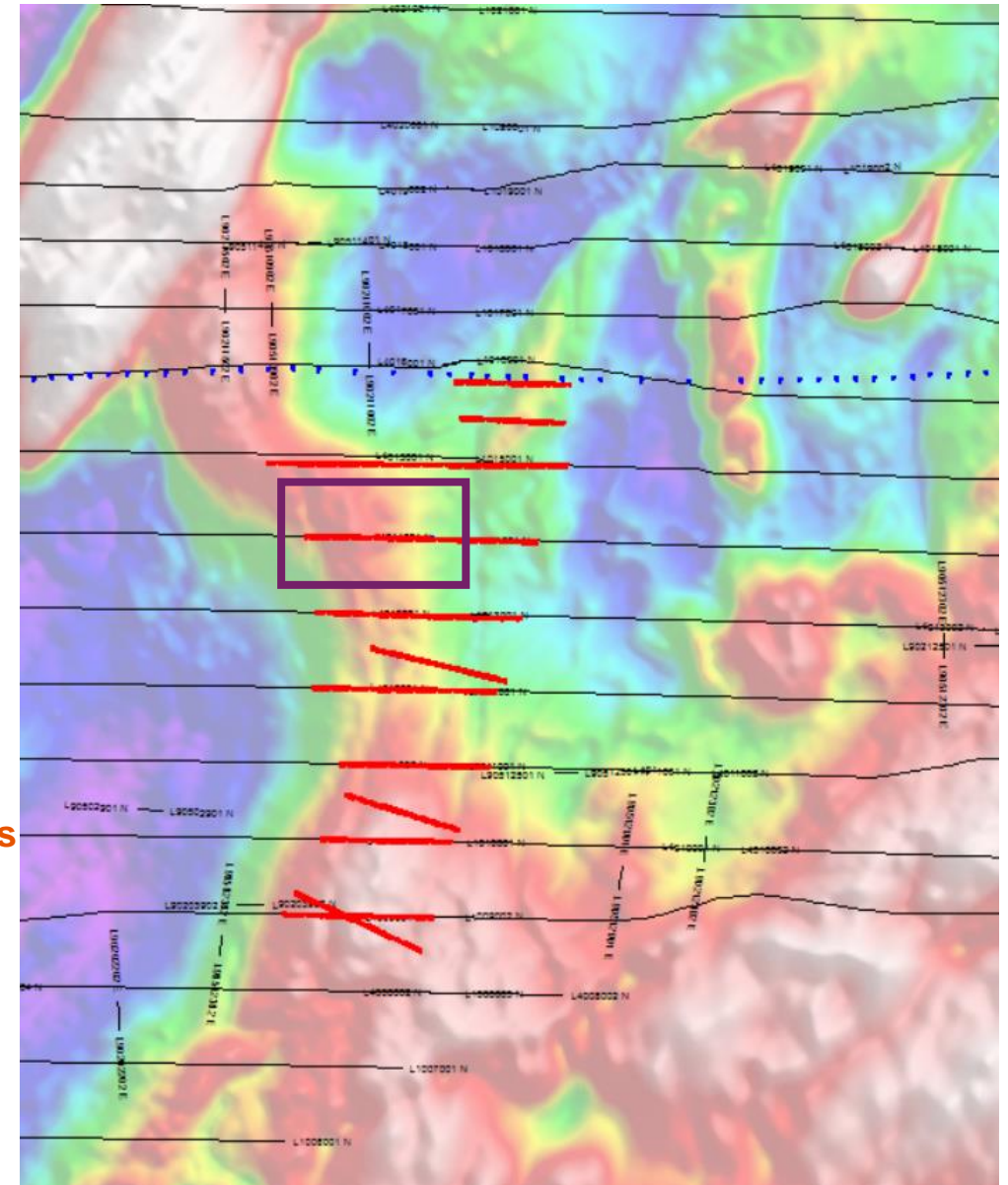
Full tensor data collected. Vertical component MT deadband (1-10s) effected due to prevention of burial of the magnetic sensor.



Moombarriga Logistics report 06/2023

- AUSAEM
- ▼ BHP stations
- ▼ GSWA stations

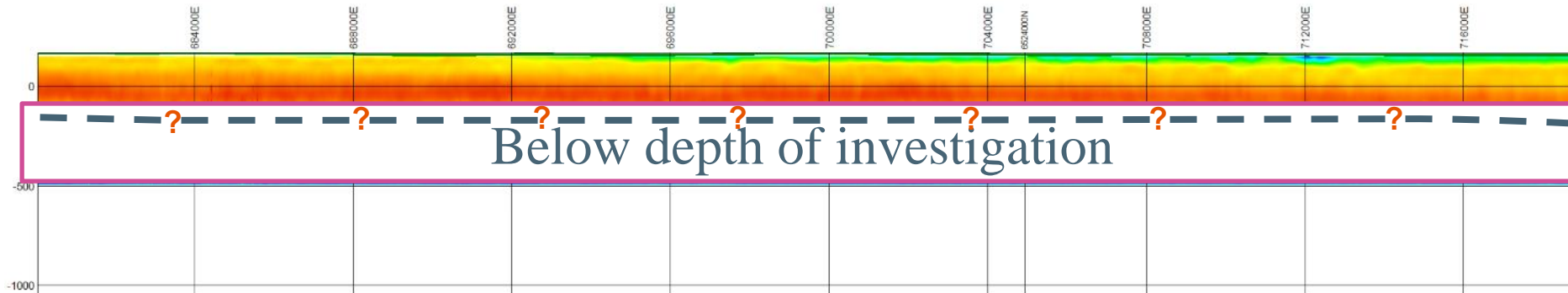
MT Station locations and AUSAEM flightlines shown on regional gravity



MT Locations – we went straight over AUSAEM lines

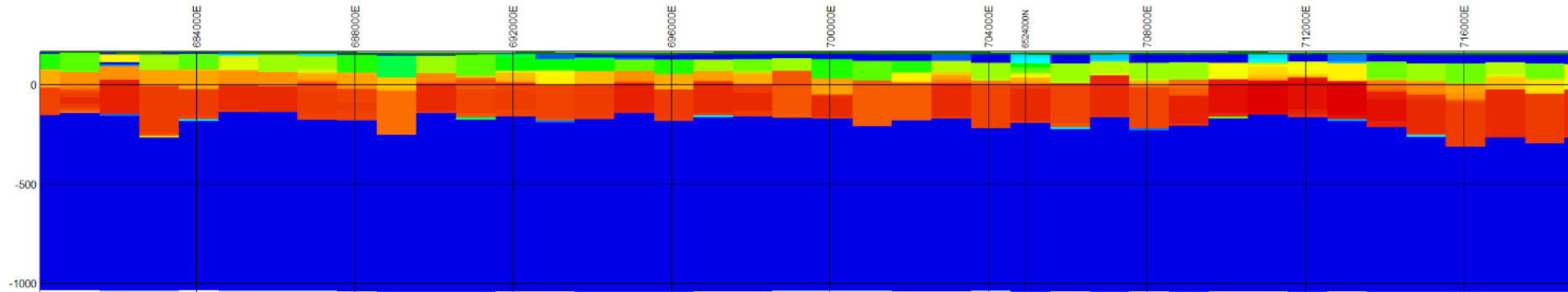
Electrical contrast between sands, clays and crystalline basement is adequate.

Acquiring MT provides opportunity to identify the effect of the deeper cover units on future active ground electrical surveys.



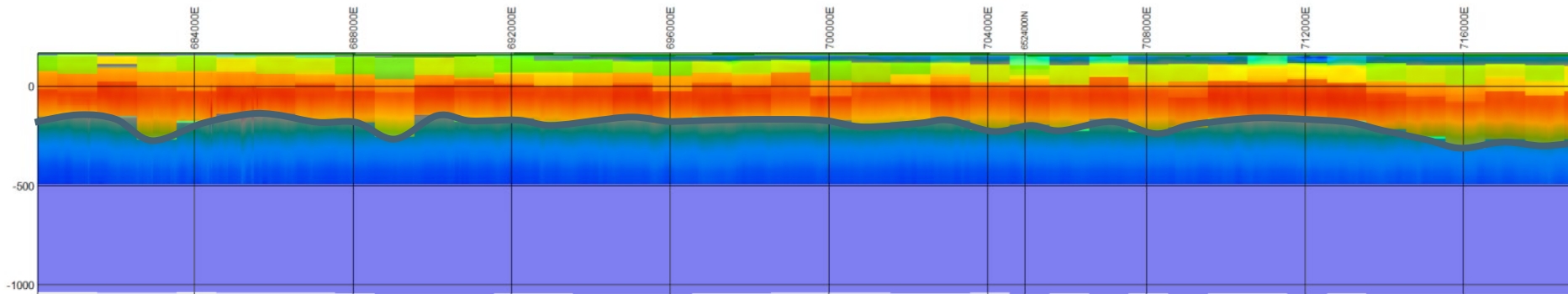
Tempest AUSAEM line 1014001 GALEI.

1km spaced broadband MT over the same line



p50 (median) conductivity LEI of MT.

1km spaced broadband MT over the same line



Merge of the AUSAEM and MT.

MT data QC

- Excellent data quality.
- Frequency range of 10 kHz to 0.001 Hz.
- Data editing consisted in removing few noisy data present at some MT sites generally in the “dead bands” (frequencies bands with a lower signal to noise ratio).
- For the purpose of this study, we use the data comprised in this frequency band

$$8 \text{ kHz} < f < 0.001 \text{ Hz}$$

- High frequencies $f > 8 \text{ kHz}$ were affected by systematic noise. Low frequencies ($f < 0.001 \text{ Hz}$) were not included because of lower quality data.

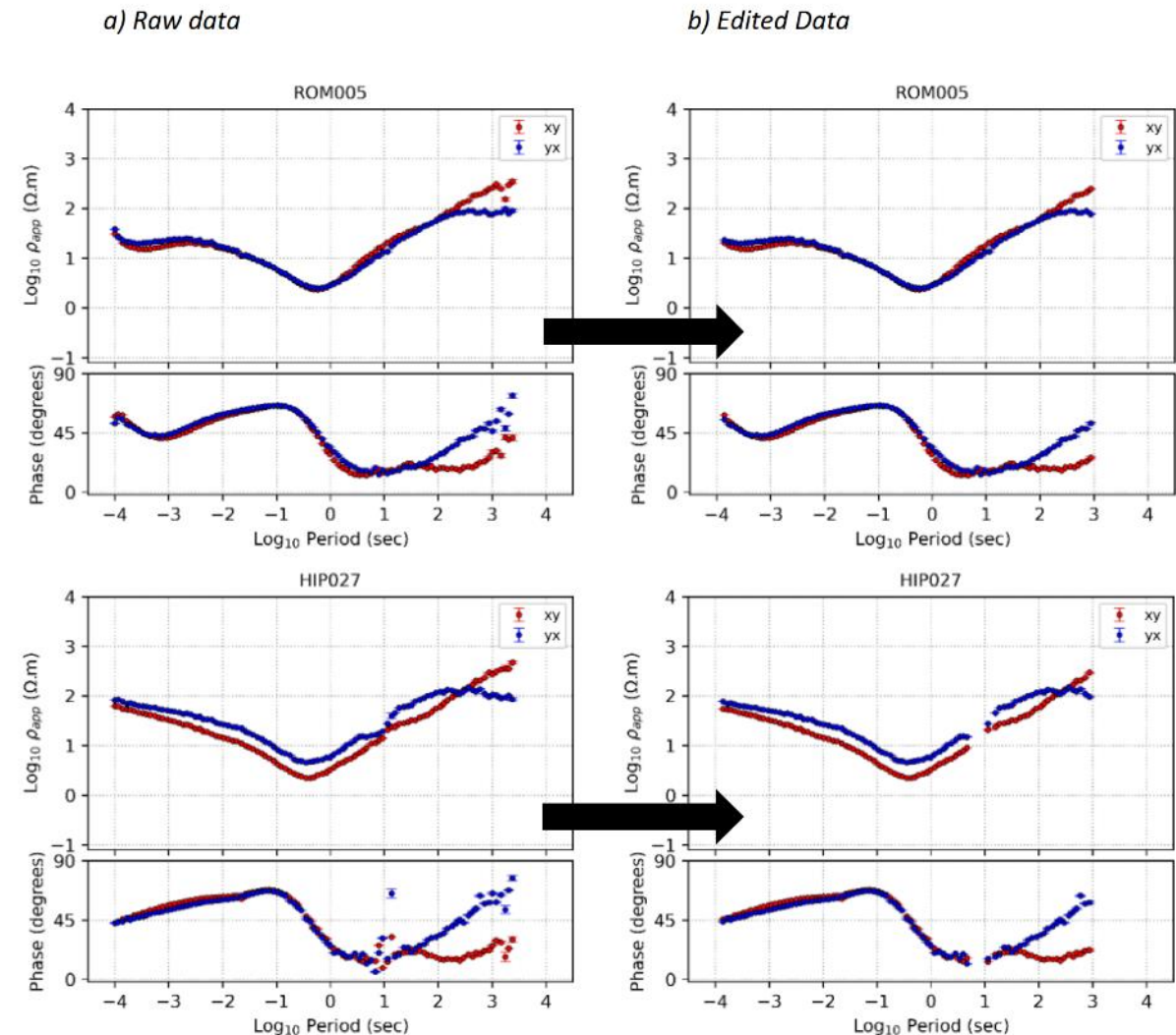


Figure 7. Example of the data editing process for 2 MT sites (top: ROM005; bottom: HIP027). a) raw data, b) data edited prior to the analysis and inversion.

MT data analysis in frequency domain

The directionality and dimensionality of the MT data was analysed.

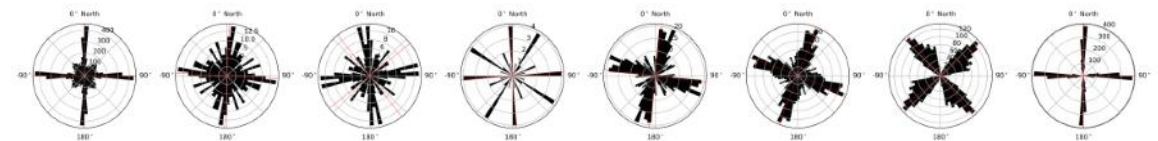
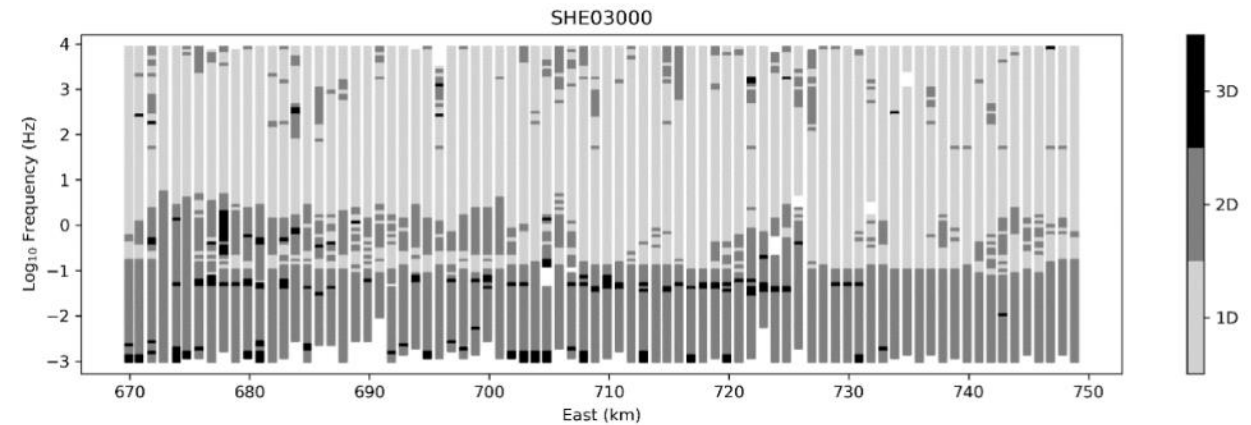
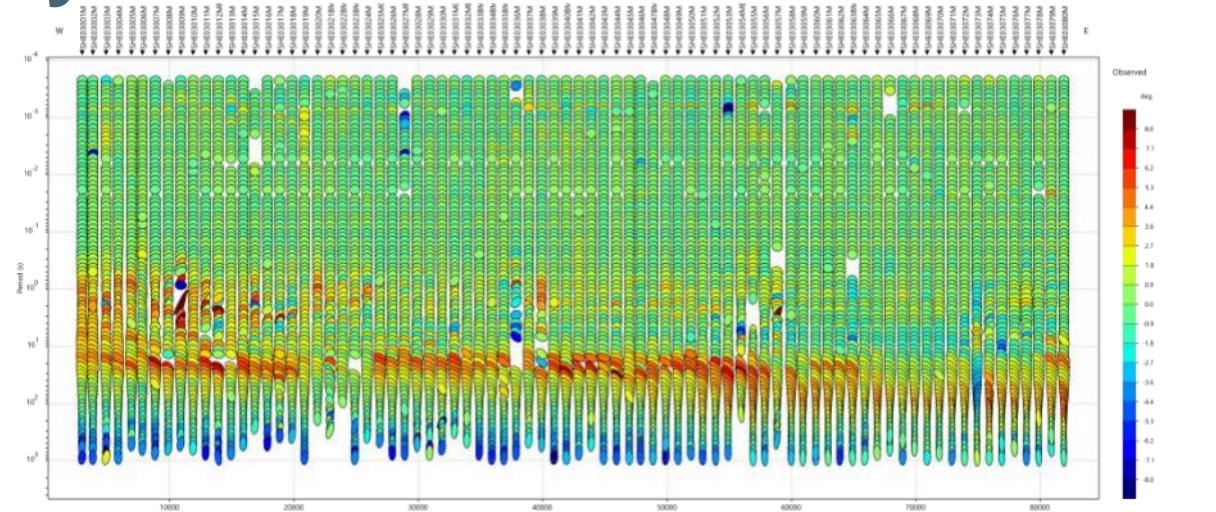
Phase tensor (PT) dimensionality: Determine if the data is sensitive to 1D/2D/3D structures, using Phase tensor ellipses (right).

Rose plot: Visualize the PT strike direction (right bottom):

Tipper: Relates horizontal and vertical magnetic fields; it indicates direction of resistivity gradients. Usually using induction arrows. (not shown)

A 1D behaviour is observable at high frequency, we therefore expect 1D modelling approach to be suitable to map the cover and the cover-basement interface.

Few 2D effects are observable at high frequencies (within the cover), and could indicate the presence of vertical and elongated bodies within the cover.



Bayesian MT inversions

The solution of the probabilistic inversion is a collection of models that satisfy the data within its error. All models fit the data and it allows us to characterise the non-uniqueness and uncertainty.

Deterministic inversion has one misfit per model, but here we determine the misfit over the collection of many models.

The data fit is defined by the following likelihood function (Tarantola, 2005):

$$p(d|m) \propto e^{-\frac{1}{2}(d_{obs}-g(m))^T C_d^{-1}(d_{obs}-g(m))}$$

The determinant of the impedance tensor is used for running the probabilistic inversions because it is rotationally invariant.

A transdimensional Markov chain Monte Carlo (MCMC) algorithm (Seillé & Visser, 2020) is used to invert. There can be any number of layers and the number of layers and depth of layers is traded off for misfit. This is how we can detect where we have interfaces.

For each station the inversion was run using 60 Markov chains of 3×10^6 iterations to ensure all the MT sites across the survey have converged.

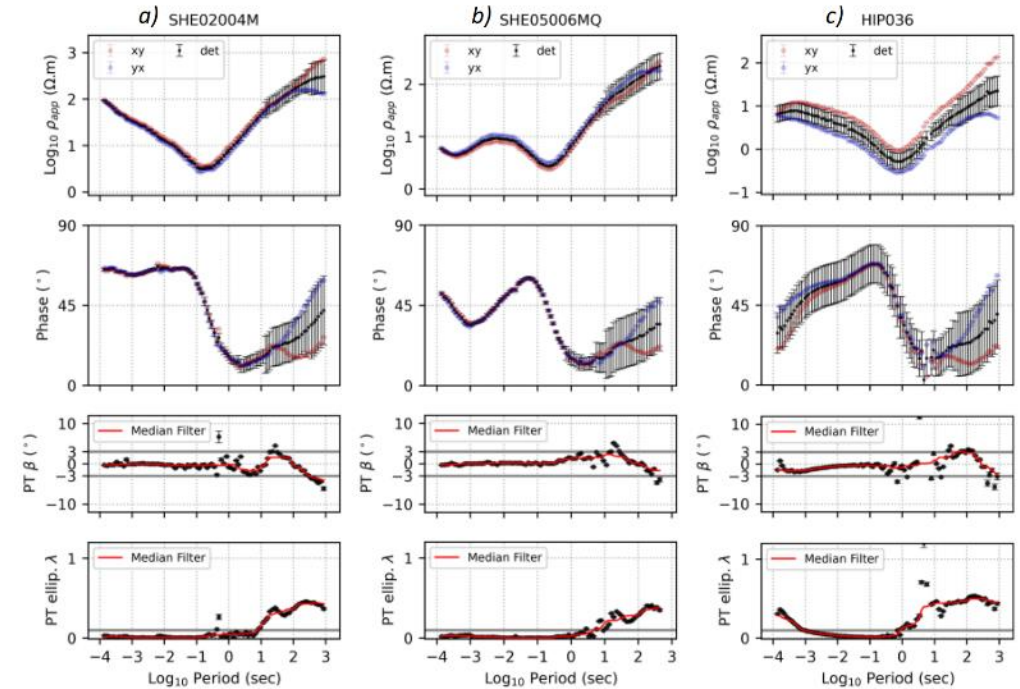


Figure 11. Examples of MT data used for the Bayesian inversion. Top panels: Apparent resistivity and phase. Bottom panels: Phase tensor ellipticity λ and skewness β . a) MT site SHE02004M; b) MT site SHE05006MQ; c) MT site HIP036. Non-1D effects due to structures located in the basement, or to the basement geometry itself, are observable at lower frequencies. The error bars in the determinant of the apparent resistivity and phase are increasing accordingly.

MT inversion results

Stitched cross sections:

The statistics of the posterior distribution of some of the sites can be stitched laterally along cross sections.

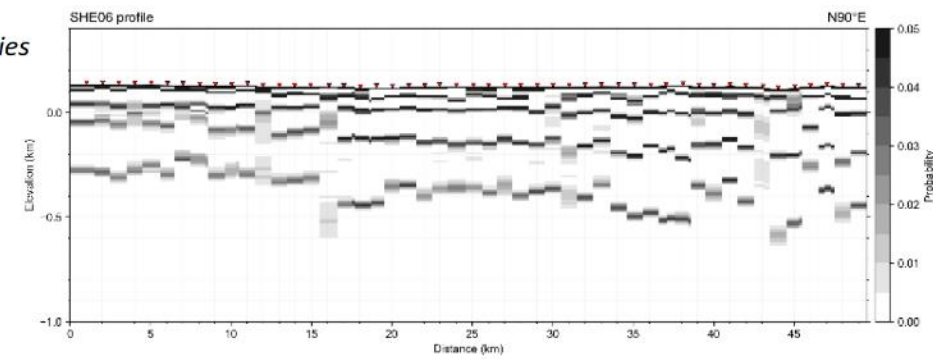
Figure shows:

- a) The change points probability distributions
- b) 5th percentile (lowest resistivities explainable by the data)
- c) 50th percentile (median)
- d) 95th percentile (highest resistivities explainable by the data)

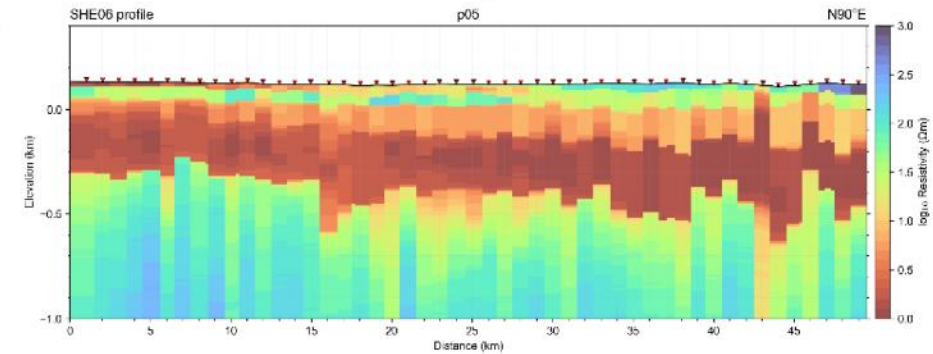
Comparing the extreme percentiles allows to understand what is the range of resistivity allowed by the data, to define the areas that present more or less uncertainty.

This transect shows variations in the cover, with 3 to 4 layers of variable resistivity. Along this profile, the depth to the basement varies from 400 to 600 meters beneath the surface.

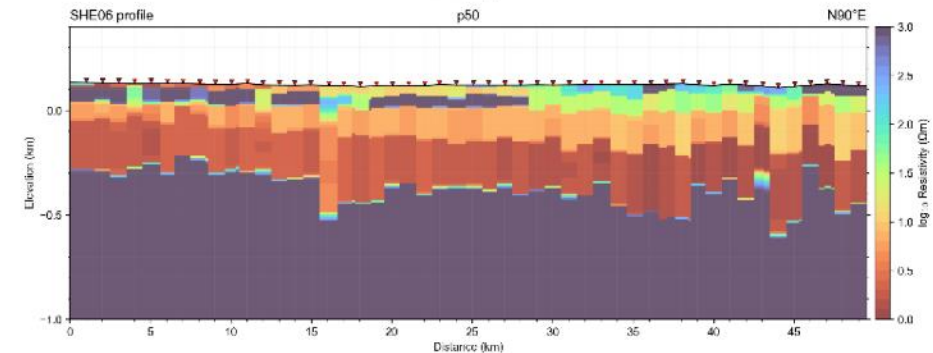
a) Interface probabilities



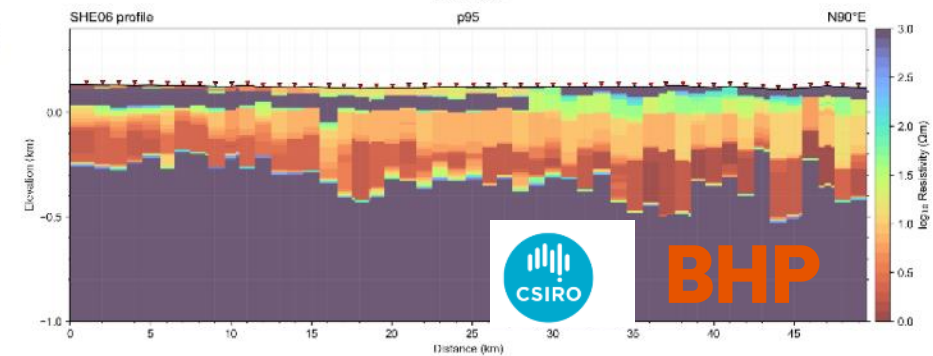
b) p05



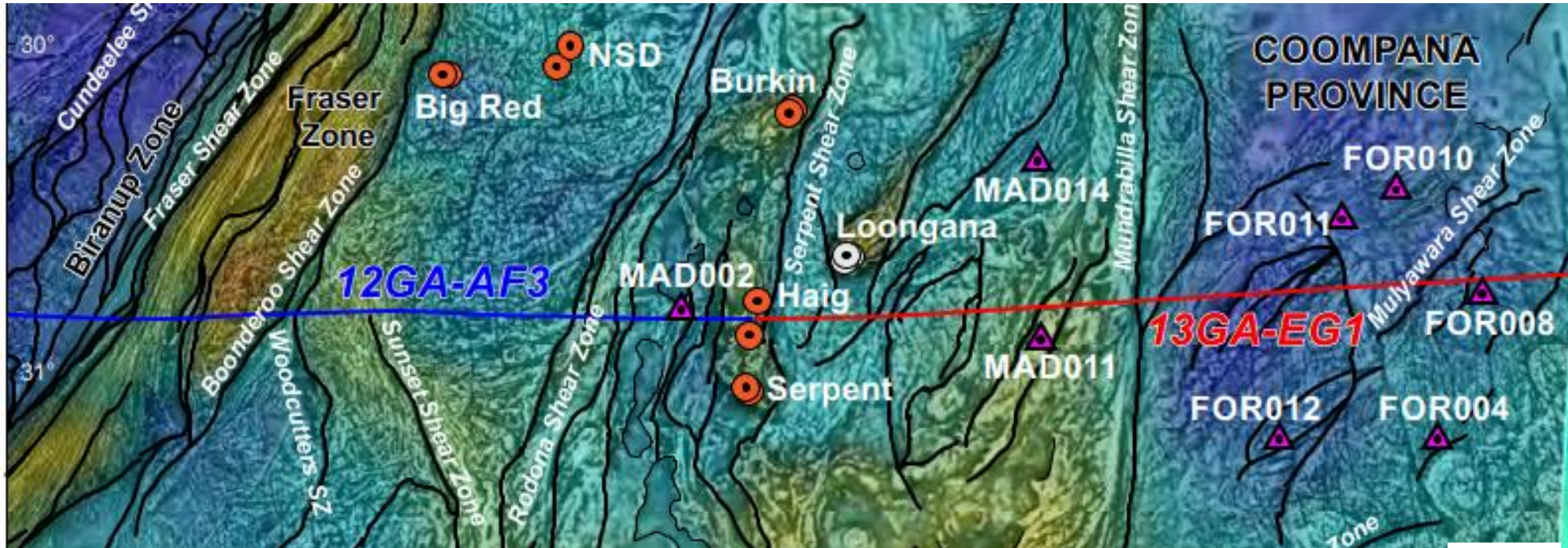
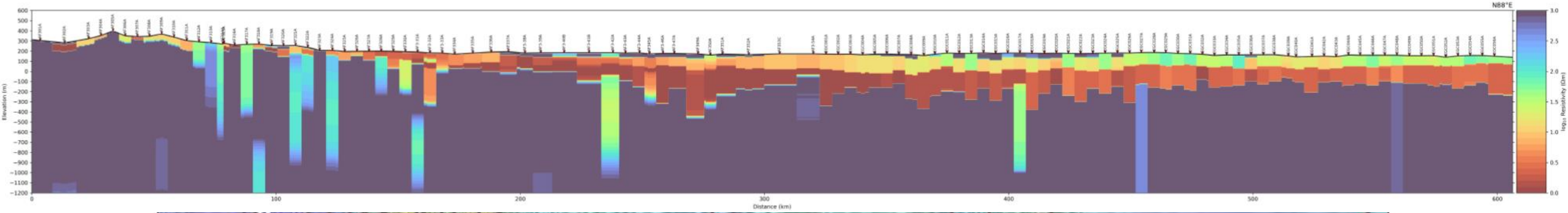
c) p50



d) p95



GSWA line EW along the transline



Spaggiari, CV, Smithies, RH, Kirkland, CL, Wingate, MTD, England, RN and Lu, Y 2020, Stratigraphic and co-funded drilling of the Eucla basement — the Proterozoic geology beneath the Nullarbor Plain: Geological Survey of Western Australia, Report 204, 147p.

Interface analysis/ clustering

Change point analysis:

Collection of models are transformed to produce ρ -z change point scatter plots.

Each point represents the top of a resistivity layer.

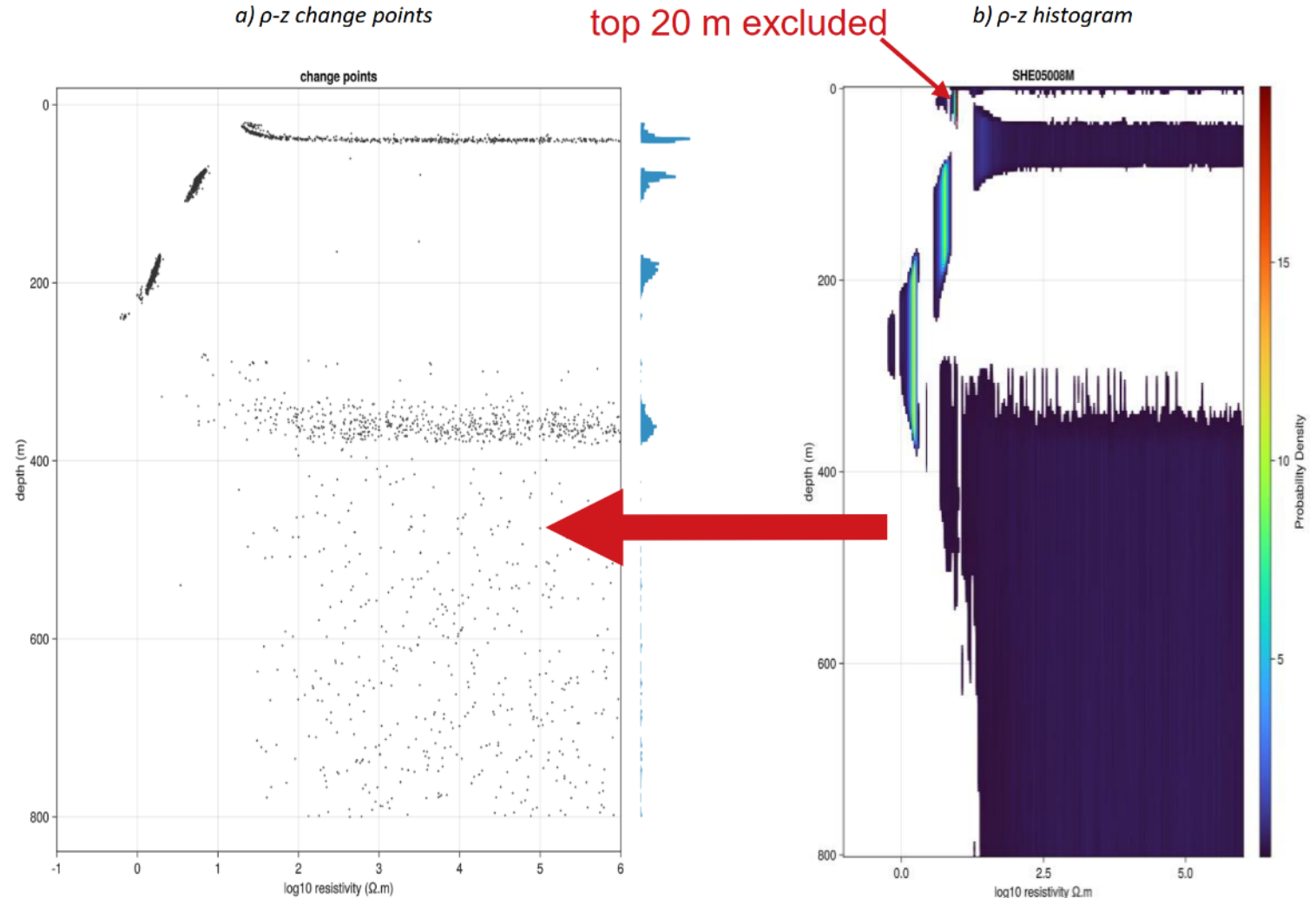
The shallowest 20 m are discarded due to high heterogeneity and low MT resolution.

This transformation discards layer width information but makes characterising transition clusters easier.

Identified resistivity layer transitions:

By manual inspection of these plots, four distinct resistivity interfaces were found to occur consistently in most sites across all lines.

They have been labelled as L1,L2,L3 and L4.



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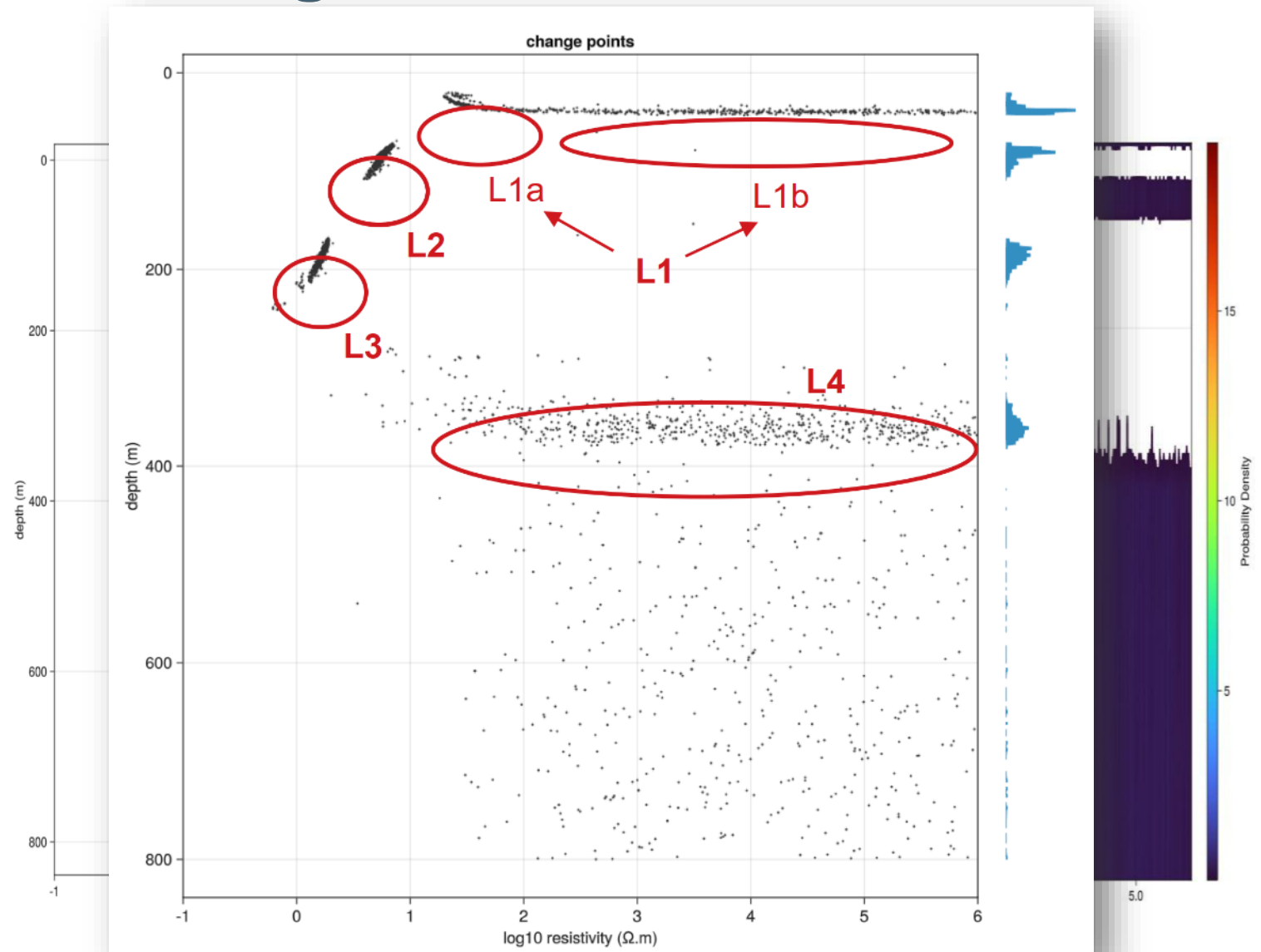
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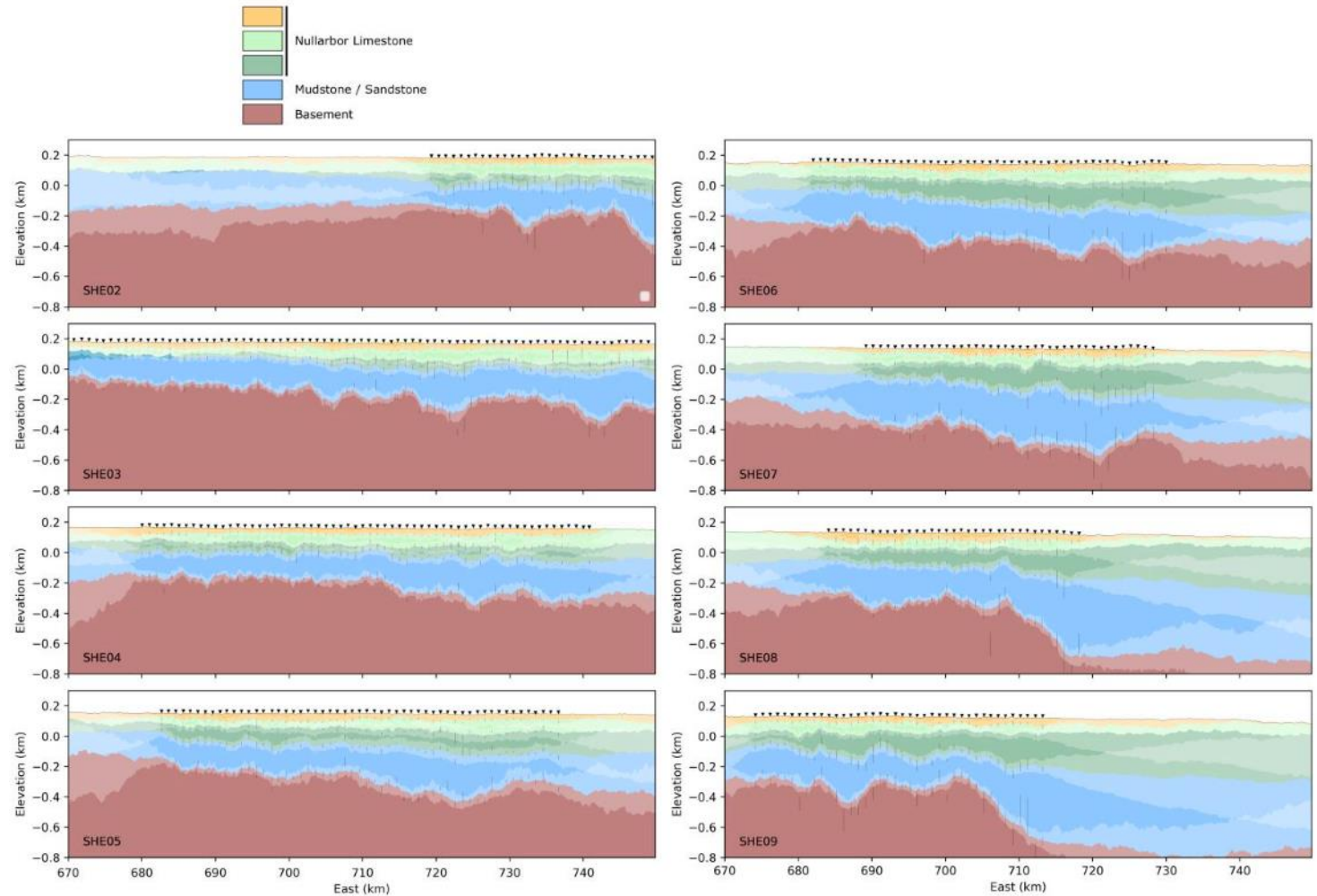
Bayesian Estimate Fusion layering

Identified classified layer transitions:

Each surface defining a transition is plotted with its median (bold line) and its 10th and 90th percentiles (light lines).

The uncertainties of the interface depths are shown as vertical lines, beneath each MT sites.

Where you have no data points on the sides of the profiles the uncertainty/ shading is much bigger and where we have data there is less uncertainty.



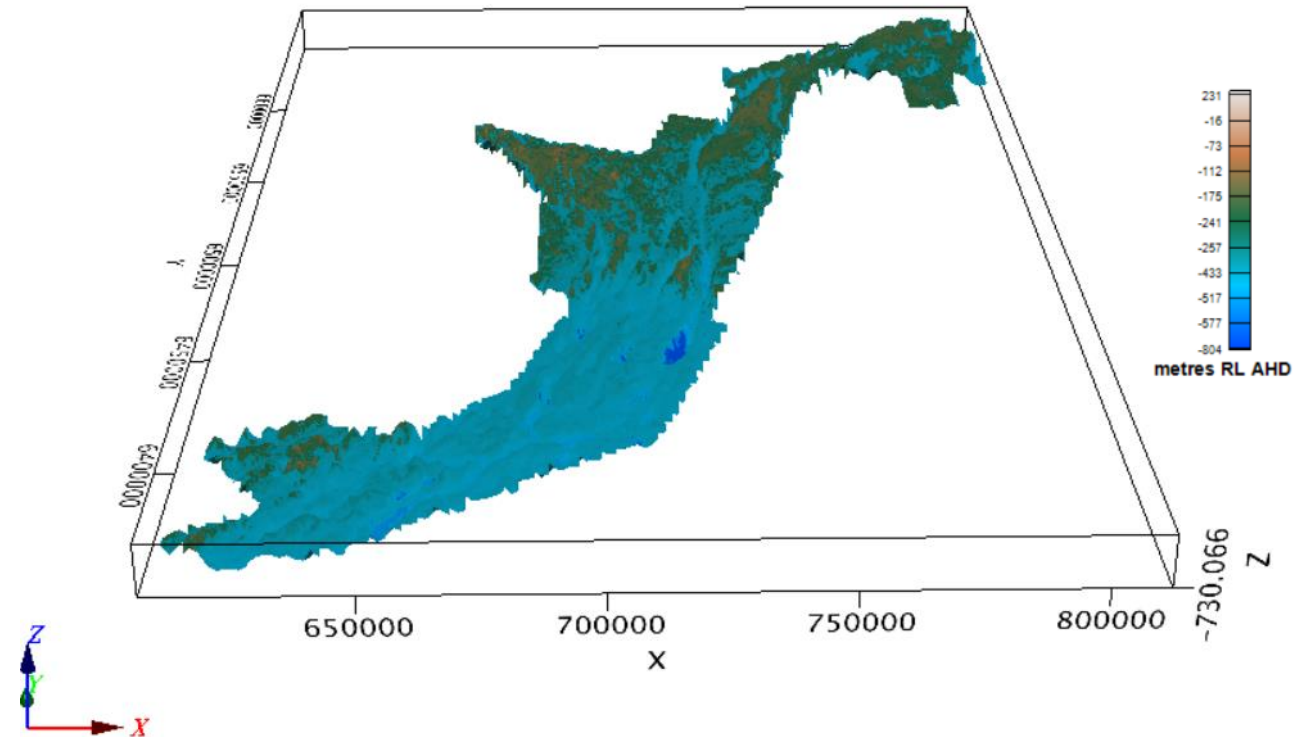
ate Fusion along the SHE lines. The units separating the classified interfaces are colored for visualization. The interfaces uncertainty is plotted as shaded colors around of the surface ensemble, for each interface.

Integrated modelling

Bayesian probabilistic MT models were used to drive a AI/ML predicted surface response using the petrophysical relationship between resistivity and density.

This allowed new forward models and residuals to be calculated for various physical properties, against the new basement surface.

Recent drilling has shown good correlation to the new estimated depths, confirming the applicability of these methods for large-scale basement mapping.



Prediction of basement topography from MT/ AGG. 3D view looking North from coast.

Conclusion

We needed to understand the explorability of the region. This includes understanding the effect of cover on geophysical signatures in basement.

This work resulted in:

- Probabilistic models of the conductivity of cover units in depths to 900m, well below AUSAEM depth of investigation.
- Improved understanding of the explorability of the area based on the modelled depth of cover.
- New prospectivity analysis, using calculated basement geophysical residuals from accurate cover models.
- A new exploration process for defining explorability and basement topography in greenfields terranes.

Next steps

- Applying this technique to other domains.
- Looking at the applicability of other methods for basement topography, such as passive seismic to do a similar thing.
- Looking at the value of probabilistic modelling of AUSAEM and AEM data in shallower basement areas to better define basement topography.

Thank you!

BHP