

Lemont Geolithium: MT Modelling, integration and analysis

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Background and Goals

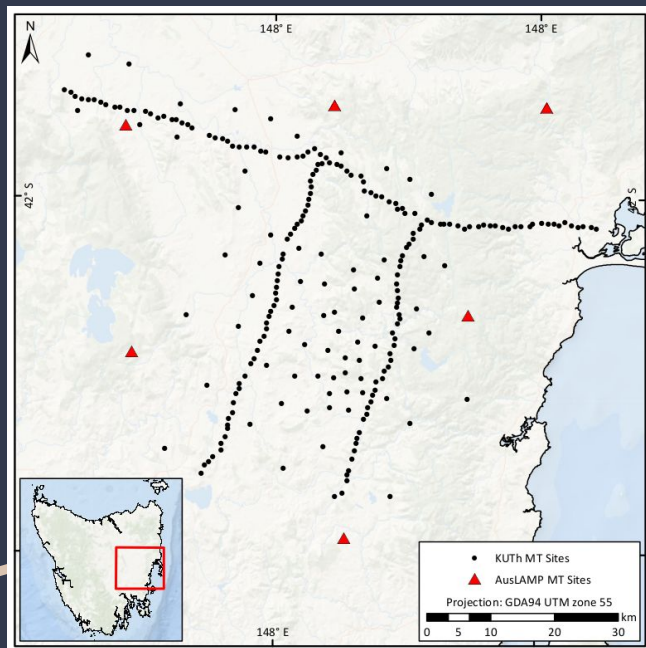


Figure 1. MT site distribution around the Lemont Geolithium prospect, from Ostensen (2021)

The Lemont Geolithium prospect in SE Tasmania has been the site of considerable exploration for two decades, mostly for geothermal energy under KUTH Exploration. This work included the collection of more than 250 MT sites over an area of approximately 100 x 75 km.

More recently, interest in the site has been renewed under Direct Lithium Pty Ltd for both geothermal power and lithium extraction from the brines. Vox Geophysics was contracted in late 2023 to assess and re-model the existing MT data to aid in drill targeting.

This report details the following:

- Results of new 3D MT inversions, comparisons with previous 3D inversions and assessment of robustness of features
- Phase tensor analysis, strike and dimensionality of the subsurface
- Results of new 2D inversions and comparisons with the 3D models
- Results of new probabilistic 1D inversions and comparisons with 2D and 3D models
- Integration with seismic ANT and gravity-derived granite depths for prospectivity analysis

Pre-existing MT data and analysis

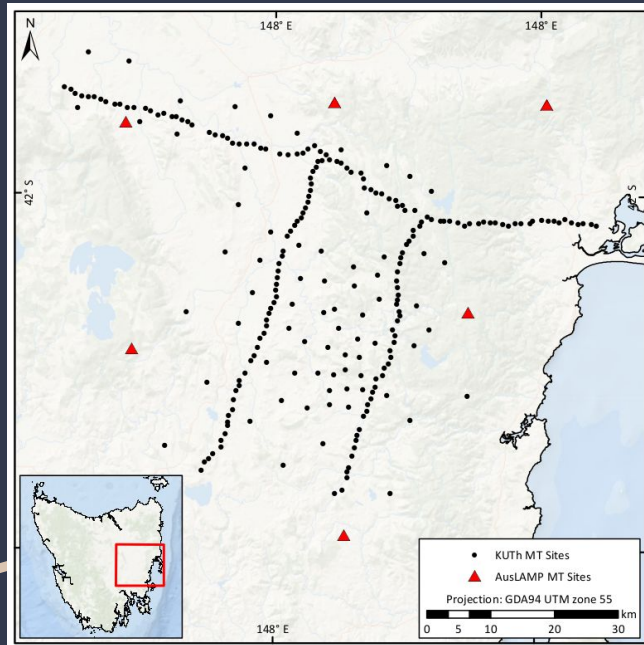


Figure 1. MT site distribution around the Lemont Geolithium prospect, from Ostensen (2021)

Broadband MT data were collected by Moombarriga Geoscience for KUTH in 2008 (54 sites), 2009 (158 sites) and 2010 (43 sites). In 2009, TEM data were also collected at 191 sites to correct for static shift. In 2016, long-period MT data were collected on a 40 km grid across Tasmania as part of the **AusLAMP MT** project, and six of these AusLAMP stations are in the vicinity of the Lemont prospect (Figure 1).

The principal difference between the KUTH and AusLAMP MT data is their frequency content. The KUTH data were designed to image shallow features and therefore contain good high frequency content but no long-period content. The AusLAMP data are designed for broader and deeper imaging and therefore do not contain any high frequency content (>1 Hz) but have good long-period content.

Pre-existing MT data and analysis

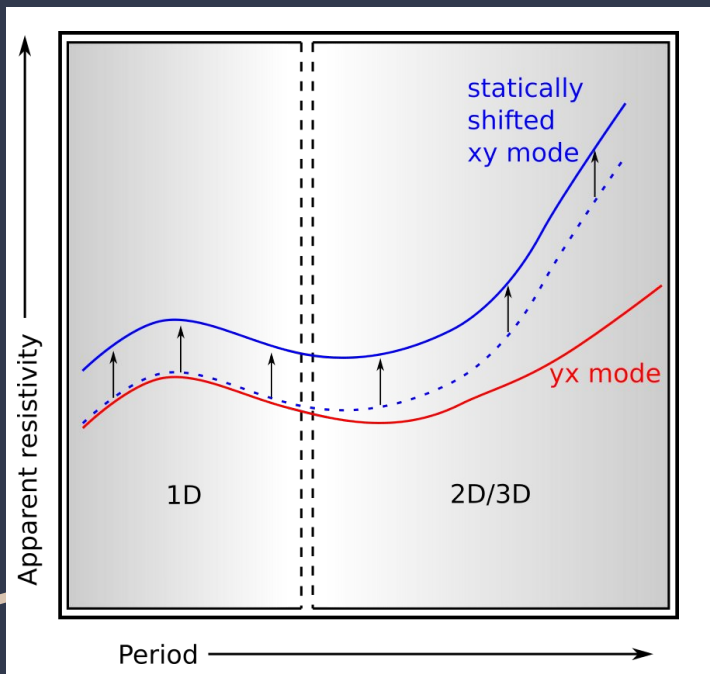


Figure 2. Schematic illustration of static shift in MT apparent resistivity data

TEM data

TEM data were collected at 191 sites coincident with MT sites to correct for static shift. Static shift is a frequency-independent 'shift' of an apparent resistivity curve up or down due to galvanic charge accumulations that are too small to have an inductive response. The consequence of static shifting is that it is not possible to know the objective subsurface resistivity. The TEM data can provide this objective resistivity to correct the MT data.

No previous inversion of the TEM data could be found. New inversions were run using the UBC SimPEG codes. Unfortunately, at all sites modelled, there was insufficient overlap in sensitivity between the TEM and MT data for the TEM data to be useful in correcting static shift. That is, the TEM data lost sensitivity at a shallower depth than that at which the MT data started to gain sensitivity. The TEM models may still be valuable in areas where shallow resistivities (less than ~200 m depth) are of interest.

Pre-existing MT data and analysis

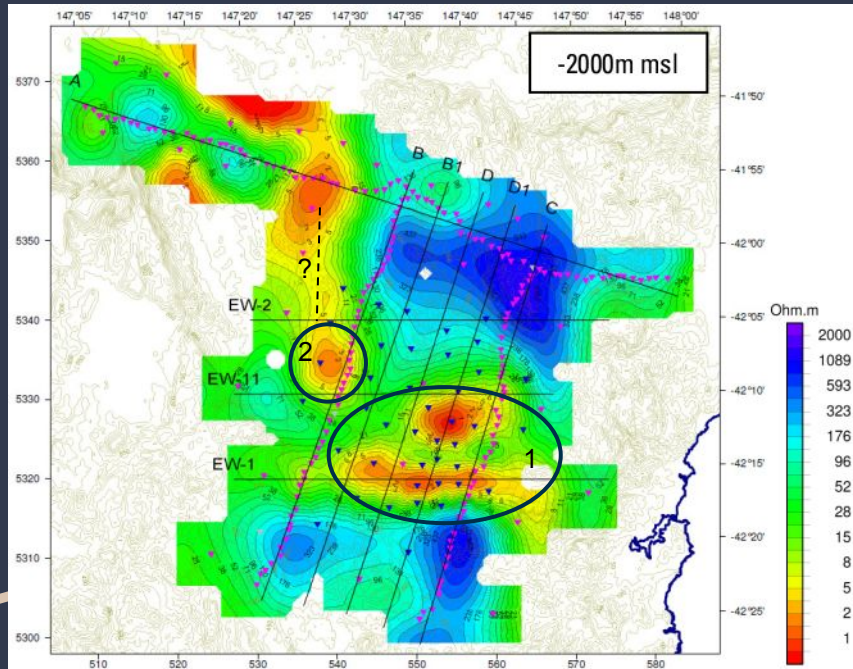


Figure 3. Depth slice at 2000 m below sea level from the 2010 WesternGeco 3D MT inversion

Western Geco Inversions

The first 3D MT inversions of the KUTh dataset were carried out by WesternGeco in 2009 and 2010 using GeoSystem software. The mesh was gridded at 800 m laterally and 100 m vertically. Topography was included, and topography was gridded at 30 m. Static shift was also included as an inversion parameter. With error floors of 3% on the off-diagonal and 20% on the diagonal MT impedance components, the WesternGeco preferred model inverted to an rms of 2.5 after 50 iterations. These inversion settings and procedures all represent good practice that have stood up to the test of time.

From shallow depths to ~2 km below sea level, the principal zones of anomalously high conductivity are (1) an approximately east-west trending zone in the southeast of the model space, and (2) a conductor at approximately the centre of the western profile, which may be connected in a north-south trend to conductors in the northern part of the model space.

Pre-existing MT data and analysis

Ostensen Inversions

In his 2021 thesis, T. Ostensen published new 3D inversions of the KUTh MT data, with the six new AusLAMP MT stations included, using the code ModEM. Due to the different frequency ranges of the two datasets, Ostensen (2021) subsampled both datasets but retained most of the highest frequency data. Although the Ostensen inversions extend to longer periods and can resolve deeper features, both inversions contain approximately the same data in the high frequency range, namely four periods per decade from ~ 300 Hz. Both models should therefore resolve shallower features with similar detail.

Ostensen (2021) ran two inversions from a homogeneous 100 ohm m half-space and two from a starting model taken from the broader Tasmania-wide AusLAMP model. Inversions were run with error floors of both 10% and 15% on the impedance values, with no difference between diagonal and non-diagonal elements. The lateral cell width was 700 m (cf. 800 m for the WesternGeco model). Neither topography nor static shift were included in the inversion. All models inverted to rms values of between 2.26 and 2.41 after 182 to 214 iterations.

While all models have an acceptable data fit, there are significant unexplained differences in the results (e.g., C2, C4 and C5, Figure 4). The models run from a homogeneous half space contain an unusual amount of sharp structure, while the models run from an AusLAMP starting model retain unsmoothed remnants of the starting model and unusual streaking or banding.

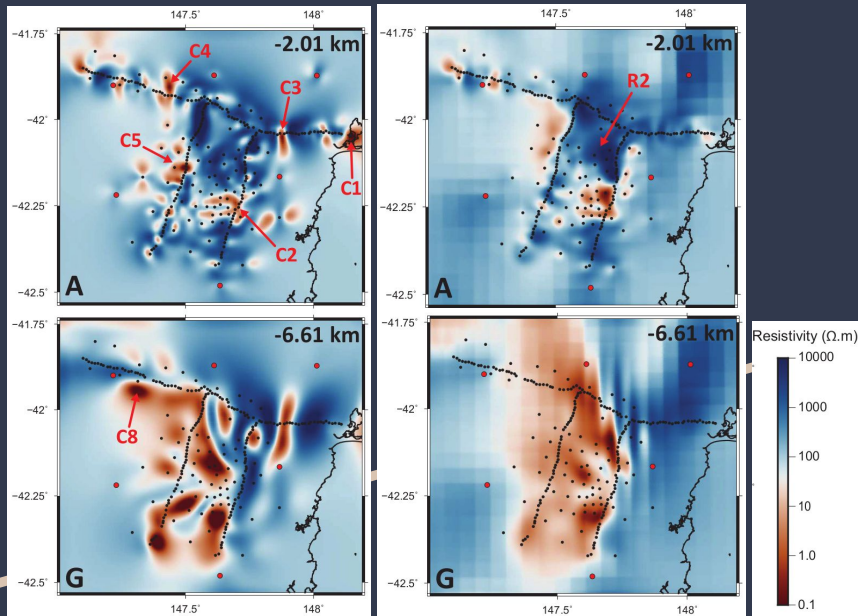


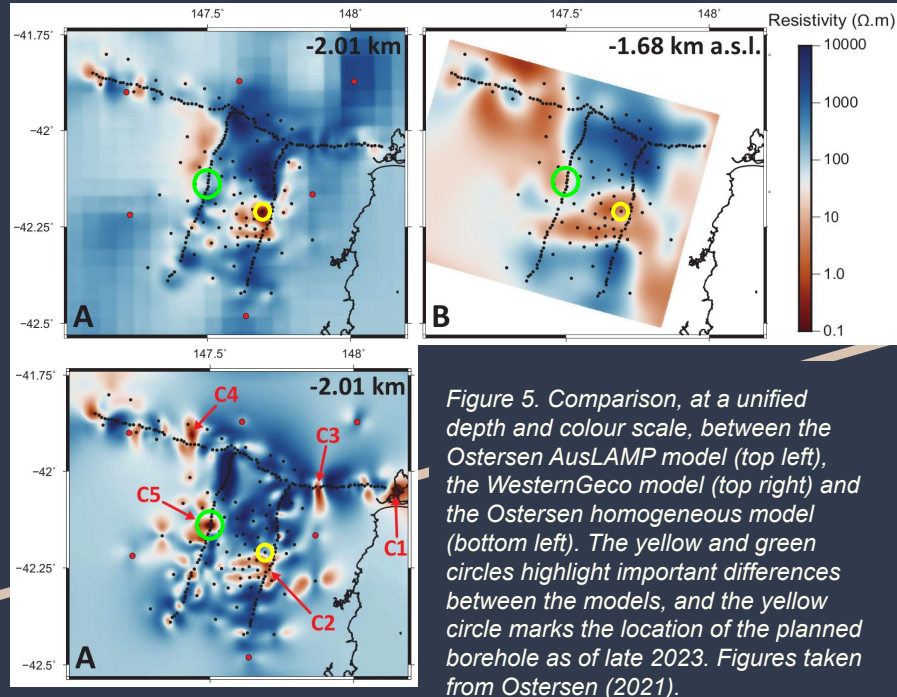
Figure 4. 2 km and 6.6 km depth slices through the Ostensen (2021) models starting from a homogeneous half-space (left) and the AusLAMP model (right). Figures taken from Ostensen (2021).

Pre-existing MT data and analysis

Inversion Comparisons

Ostersen (2021) compared his preferred (AusLAMP) model to the WesternGeco model on a unified depth slice and colour scale (Figure 5, top). While the broad patterns of resistivity are the same, there are significant differences. These differences are magnified when the Ostersen (2021) model run from a homogeneous half-space is added to the comparison. The high levels of structure and extremes of resistivity are not replicated in the WesternGeco model, suggesting that the Ostersen model may have had insufficient smoothing constraints and may have been allowed to iterate too many times., and/or that some of the modelled structure is the inversion attempting to account for static shift effects

Of particular importance for Lemont Geolithium is the contrast highlighted by the yellow circle, which is the approximate location of the planned borehole as of late 2023. This is a strong conductor in the AusLAMP Ostersen model, a moderate conductor in the WesternGeco model, and a boundary between a resistor and a conductor in the homogeneous Ostersen model. The green circle highlights another area of significant difference: the strong conductor C5 on the AusLAMP Ostersen model, a resistor on the homogeneous Ostersen model and a moderate conductor on the WesternGeco model.



New 3D inversions

Model setup

New 3D MT inversions were run using the code ModEM with a goal to accurately model and interrogate upper crustal features that may be drill targets or provide information about the broader hydrogeologic system.

The computational and financial costs of 3D inversions depends on the number of frequencies inverted and the size of the mesh. Data were subsampled to 26 frequencies evenly spaced between 320 Hz and 0.054 Hz (periods between 0.0031 and 18.51 s). At seven frequencies per decade, this provides better data density than the Ostersen and WesternGeco models over the frequency range of interest, and would resolve depths between ~250 m and ~35 km in a 100 ohm m halfspace.

The model space was reduced to the region of interest to decrease the overall mesh size. This allowed for 500 m lateral widths for grid cells (cf. 700 m in the Ostersen models and 800 m for WesternGeco) while maintaining a computationally tractable number of grid cells. Eleven lateral padding cells were included, extending the whole mesh size to 286 x 286 km to avoid edge effects. Vertically, the first eleven layers were 30 m thick; thin shallow layers allow the inversion to account for static shift effects by producing small, near-surface conductors. Below this, vertical layer thicknesses increase by a factor of 1.25 over 40 layers.

Attempts were made to include topography in the inversion but these were ultimately unsuccessful. This experience suggests that the WesternGeco (now CGG) code may be a better choice than ModEM in regions of significant topography, despite its higher cost.

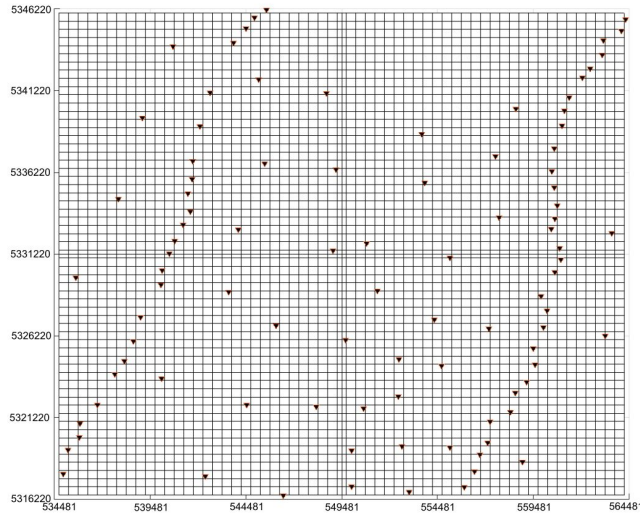


Figure 6. New 3D model mesh with 500 m lateral grid widths, centered on 549481 mE, 5331220 mN (zone 55). Triangles show locations of the 98 MT sites included in the inversion.

New 3D inversions

Data editing

Each individual station was assessed for inclusion or exclusion and for the frequency range that should be modelled based on data quality.

Static shift clearly affects the data and appears to have caused some of the differences between the Ostersen and WesternGeco models. ModEM does not allow for the direct inversion of static shift so in the new modelling it was dealt with partly by including thin near-surface layers. In addition, stations with obvious static shift effects were directly edited, as illustrated by station NSB001A (Figure 7). The unedited data (left) show approximately equal phases for the orthogonal Zxy and Zyx measurements to periods of approximately 0.1 s, implying that the subsurface is 1D at the corresponding shallow depths. At these periods, the apparent resistivity curves are parallel but offset, strongly suggesting static shift. The data were therefore edited (right) to remove the static shift effect. Without external constraints such as the TEM data, there is no way to know the objective correct resistivity. This is also true when static shift is included as an inversion parameter, so inverting for static shift is not necessarily a solution to this problem. In station editing, static shift was corrected to produce a resistivity of ~100-300 ohm m at a period of 0.01 s, taken from an average of the MT responses. Shifts were generally small, as in the example here.

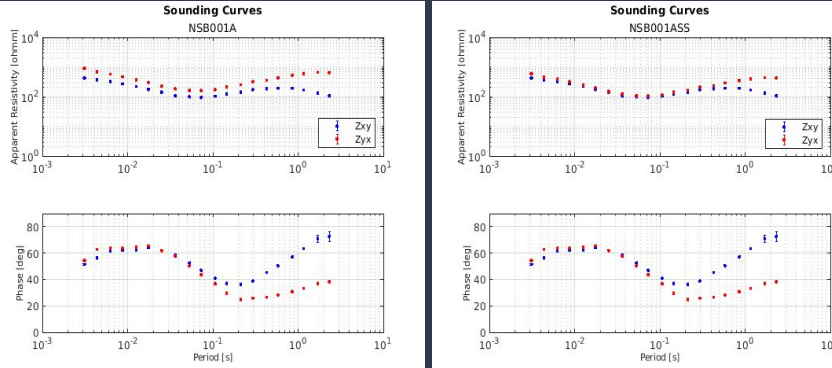


Figure 7. Manual edit of station NSB001A to reduce static shift effects. The unedited data is on the left and the edited data, showing a period-independent reduction in magnitude of the Zyx apparent resistivity curve, is on the right..

New 3D inversions

Starting models and parameters

Results are shown for three models.

The first model, 'Homogeneous Default' is a default model, starting from a homogeneous, 100 ohm m half-space, and with moderate, default settings for spatial smoothing (covariance factors).

The second model, 'Homogeneous Low Smoothing', also starts from a homogeneous 100 ohm m half space but uses low smoothing constraints to allow sharper boundaries between conductive and resistive features.

The third model, 'AusLAMP Default', uses the Tasmania-wide AusLAMP model as the starting model and default smoothing parameters. The AusLAMP model was provided by MRT and was interpolated onto the smaller Lemont mesh.

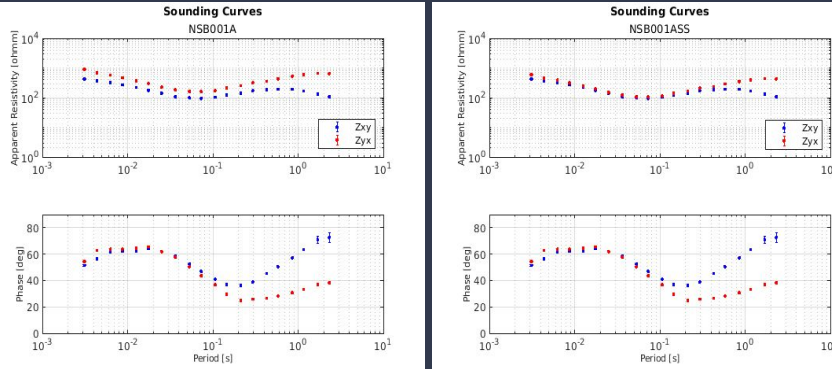


Figure 7. Manual edit of station NSB001A to reduce static shift effects. The unedited data is on the left and the edited data, showing a period-independent reduction in magnitude of the Zyx apparent resistivity curve, is on the right..

Table 1: 3D model parameters

Name	Starting model	Covariance	Starting lambda	Error floors	Number of iterations	Final rms misfit
Homogeneous Default	Homogeneous, 100 ohm m	0.3	10	10%	50	2.7
Homogeneous Low Smoothing	Homogeneous, 100 ohm m	0.1	10	10%	26	3.6
AusLAMP Default	AusLAMP regional	0.3	10	10%	31	3.6

New 3D inversions

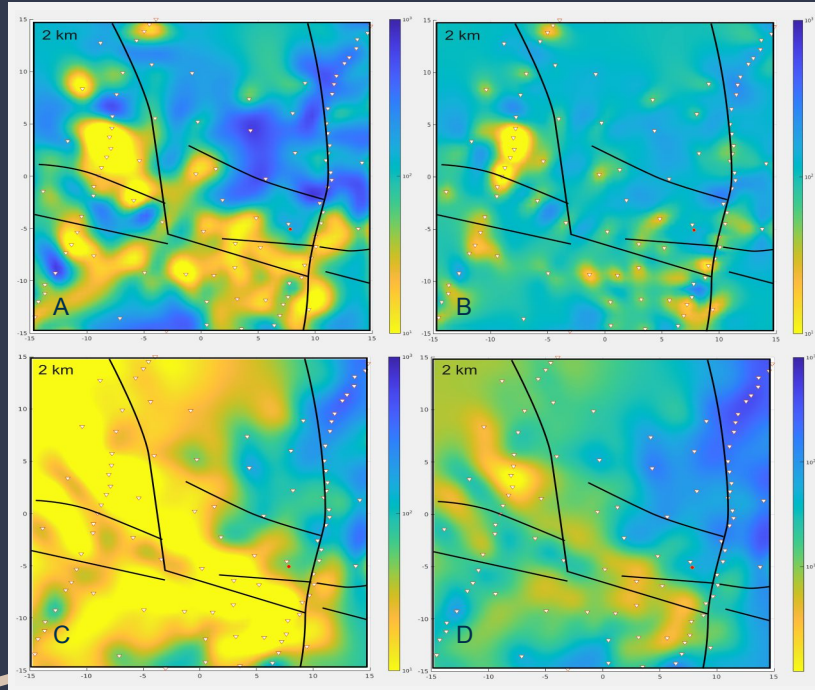


Figure 9. Depth slices at 2 km from the Homogeneous Default model (a), Homogeneous Low Smoothing model (b), AusLAMP Default model (c) and AusLAMP Default model with expanded colour scale (d).

Model results overview

The Homogeneous Default model is the preferred model. The inversion was stopped after 50 iterations at an rms misfit of 2.7. Major model features were not changing and further iterations would have made small reductions to rms by increasing structure in ways that could not be argued to be required by the data. The model is considered unbiased as it was started from a homogeneous half-space and used moderate smoothing parameters.

The Homogeneous Low Smoothing model was manually stopped after 26 iterations at an rms misfit of 3.6. Although the misfit remained quite high, the main regions of high conductivity were similar to the Homogeneous Default model but strong resistors were not being modelled, so the inversion was not providing a comparison model with sharper boundaries as planned.

The AusLAMP Default model reached a local minimum and stopped inverting after 31 iterations at an rms error of 3.6. The AusLAMP starting model contained significant structure at shallow depth, with a strong conductor (10-100 ohm m) at 2-3 km depth in the western part of the model space. Given the longer period range of the AusLAMP data, it is doubtful that this is a robust feature that is required from the AusLAMP data. It is likely that its presence in the model is incompatible with the higher frequency Lemont data and the inversion was unable to progress to a good misfit. The impact of this high conductivity region in the starting model is clear in the inversion response (Figure 9(c)). Nonetheless, the major conductors apart from this region are coincident with those from the other models (Figure 9(d)), providing extra confidence in their robustness.

Preferred 3D model

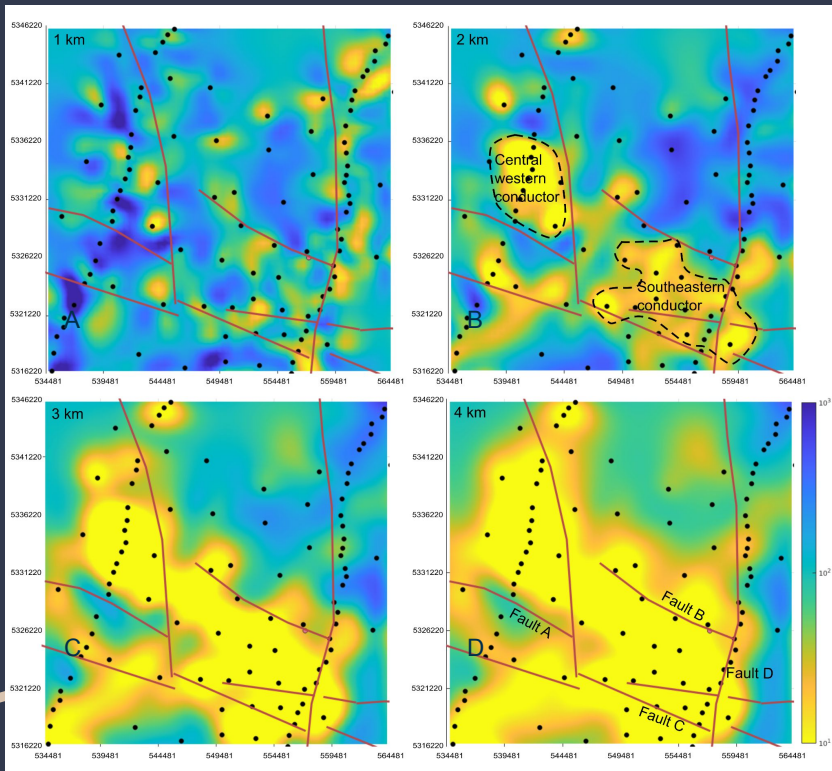


Figure 10. Depth slices through the preferred model

Model results overview

Depth slices through the preferred Homogeneous Default model are shown in Figure 10, with MT stations as black circles, structures in deep red, and the 2023 drill target as a red circle. Since topography is not modelled, depths can be considered to be from the average station height of 365 m.

At 1 km depth the model is laterally discontinuous. Most anomalies, either conductive or resistive, are controlled by a single station as is to be expected since station spacing is greater than 1 km.

At 2 km depth several key features emerge. The northeastern part of the model space is broadly resistive. There is a strong conductor in the central western part of the model, well constrained by a number of MT sites on the NSA line. Patchy but extensive conductors also appear in the southeast of the model space.

From 3 to 4 km depth these main trends continue, with the central western and southeastern conductors continuing with depth and becoming stronger and more extensive. The conductors link in the model, although they could of course be caused by different features in the Earth.

There appears to be some structural control over the conductivity (see 4 km depth slice). In all models the central western conductor does not continue south past Fault A. In addition, the bulk of the southeastern high conductivity is bounded by Faults B, C and D.

Preferred 3D model

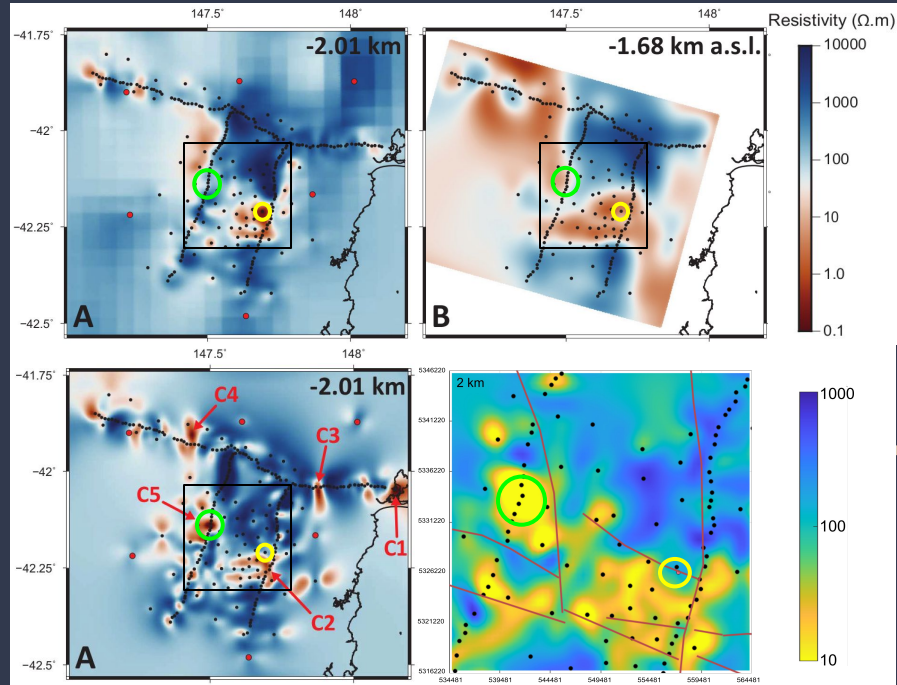


Figure 11. Slices at equivalent depths through the Ostensen (2021) inversion from an AusLAMP starting model (top left), the Western Geco inversion (top right), the Ostensen (2021) inversion from a homogeneous starting model (bottom left), and the preferred Vox inversion from a homogeneous starting model (bottom right).

Model results overview

When the new model is compared with the Ostensen (2021) and WesternGeco models (Figure 11), several features are apparent:

- Broad features and trends are consistent between the models, including high resistivities in the northeastern part of the model space, and high conductivities in the central west and southeast.
- The Western Geco model is the most laterally smooth of all the models, and the Western Geco code likely has higher default smoothness than ModEM.
- The new model is most similar to the Ostensen (2021) model run from a homogeneous half-space, which is to be expected since the two inversions use the same code and the same starting model. The Ostensen (2021) model contains more anomalies that are constrained by only one station, which is likely due to uncorrected static shifts and potentially lower smoothness constraints.
- The central western conductor (green circle) is apparent on all models apart from the Ostensen (2021) AusLAMP model (top left). It is less pronounced in the Western Geco model.
- The site of the drill target as of late 2023 (yellow circle) is a strong conductor only in the Ostensen (2021) AusLAMP model. It is a moderate conductor in the Western Geco model, but this may be partly due to the high smoothness. In the Ostensen (2021) model and all new models it is more resistive than the regions to the east, south and west.

Phase Tensors

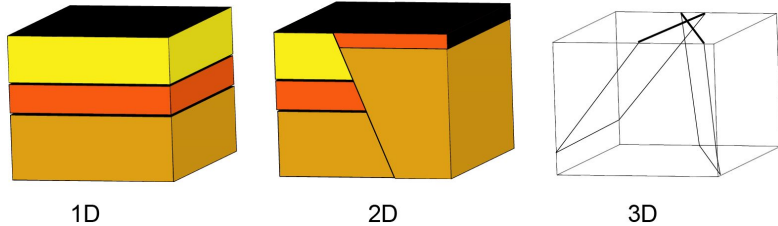


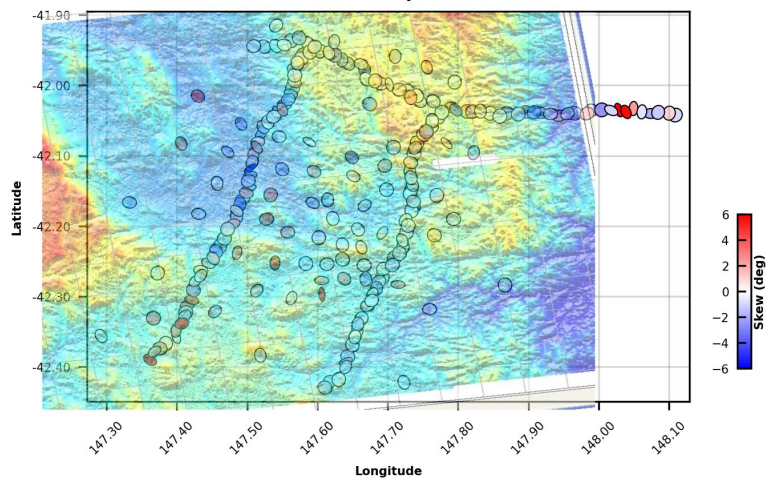
Figure 12. Schematic of one-dimensional, two-dimensional and three-dimensional subsurface geoelectric structures.

Phase Tensor Analysis

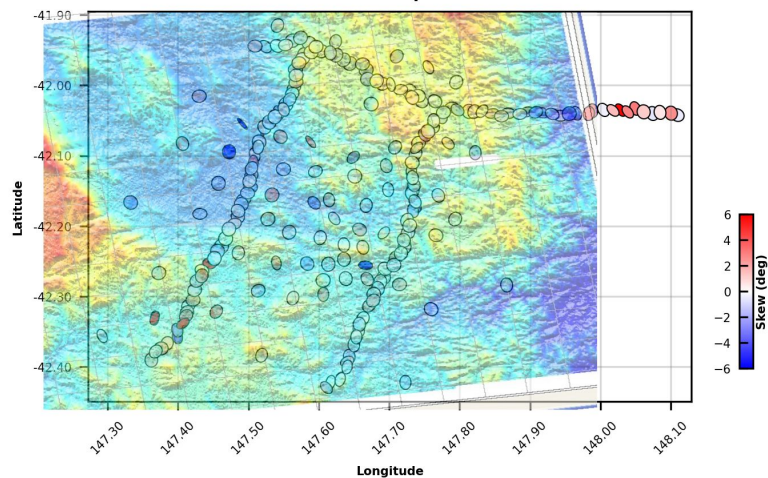
Phase tensors (Caldwell et al., 2004) are a visualisation and analysis tool for MT that provide information on subsurface dimensionality and geoelectric strike direction. When plotted as phase tensor ellipses, they provide a useful visual summary of the behaviour of MT fields. With closer analysis of the phase tensor components, they are valuable for separating out data that can be inverted with 1D or 2D inversion schemes. There are several key parameters:

- The ellipticity is a measure of how circular or elliptical the phase tensor ellipse is. An electrically one-dimensional earth, with conductivity structure that does not vary laterally, will produce approximately circular phase tensors (ellipticity < 0.1).
- The strike is a measure of the direction of preferred current flow. It is ill-defined for a one-dimensional earth, will be consistent laterally and with depth for a two-dimensional earth, and will be variable for a three-dimensional earth.
- The skew is a measure of asymmetry of the ellipse. Ellipses with any notable asymmetry (skew > 3 degrees) denote a three-dimensional earth.

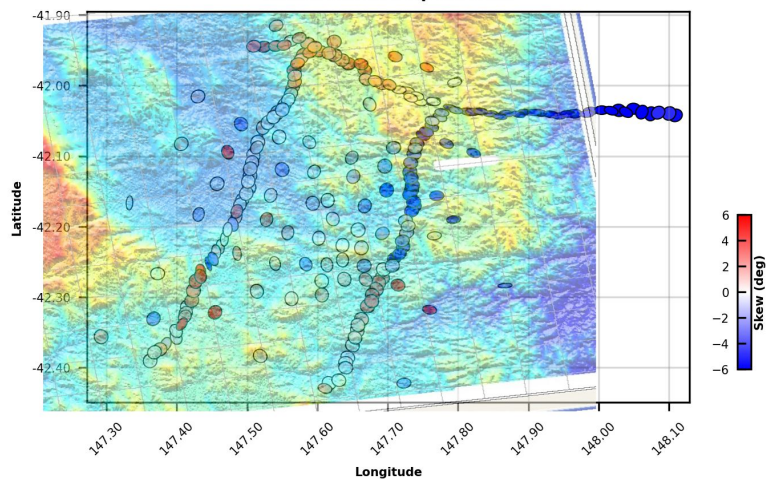
Phase Tensor Map for 0.01 (s)



Phase Tensor Map for 0.1 (s)



Phase Tensor Map for 1 (s)



Phase Tensor Map for 10 (s)

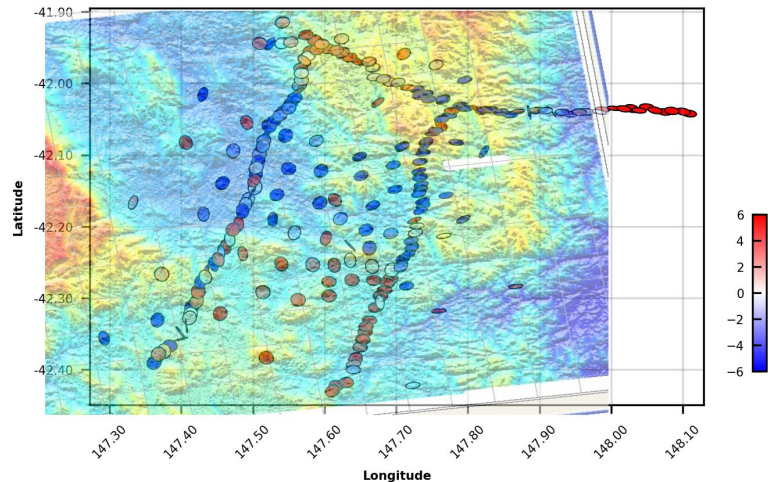


Figure 13. Phase tensor ellipses for periods of 0.01, 0.1, 1 and 10 s, overlain on elevation. Phase tensors are coloured by skew; red or blue colours denote three-dimensionality. The long axis of the ellipse indicates the direction of preferred current flow.

Phase Tensors

Phase Tensor Analysis

Detailed analysis of the phase tensor ellipses, ellipticities, skews and strikes was carried out to investigate subsurface dimensionality and determine any subsets of data suitable of 1D or 2D inversion. Results include:

- Many sites display a section of 1D data at the highest frequencies, from ~300 Hz to between 20 and 1 Hz. This may be a reflection of shallow, flat-lying sediments in some locations. As a rule, the 1D section is less pronounced in the northeast of the model space, where topography is high and subsurface resistivities are also high, supporting this interpretation.
- In the central east and southeast of the model space, many stations display 2D characteristics at moderate frequency ranges (approximately 10 Hz to 1 Hz), with a strike of approximately N70E. This strike is in broad agreement with elevation features (Figure 14) and structural trends (Figure 10).
- In the central west of the model space, in the centre of line NSA, some stations display 2D characteristics at moderate frequency ranges (approximately 1 Hz to 0.1 Hz), with an approximately north-south strike that may be related to structural features (Figure 10) and agrees with the elongated north-south trend of the central western conductor.

Phase Tensor Map for 0.1 (s)

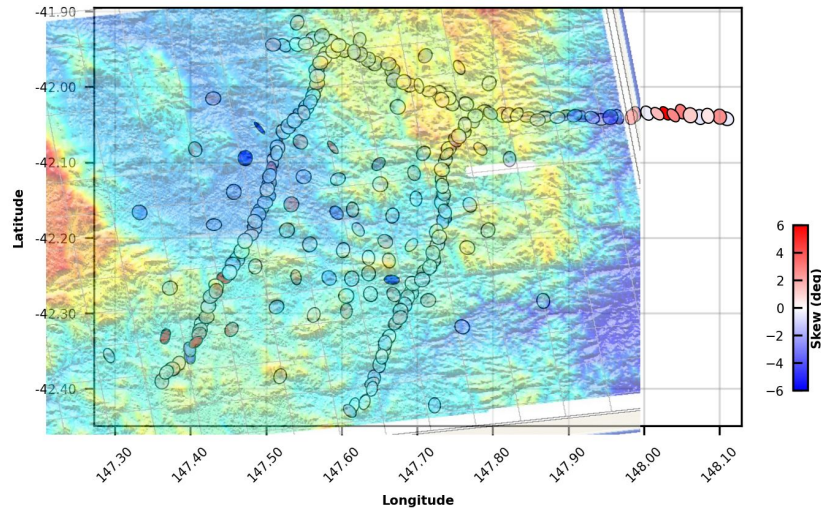


Figure 14. Phase tensor map at 0.1 s period

2D Inversion

2D Inversion, Profile 1

The presence of subsets of data with 1D and 2D characteristics provides the opportunity to run 2D inversions of those data subsets. Where the subsurface structure allows it, 2D inversions offer many advantages over 3D inversions. Because they are computationally much less demanding, 2D inversions can be run on a much finer mesh and model features can be tested more rigorously than in 3D. However, for a 2D inversion to be reliable, only 1D and 2D data can be modelled, the data must be modelled along a profile that is perpendicular to strike, and the electric and magnetic fields from each station must be mathematically rotated to be parallel and perpendicular to strike.

A series of stations was selected that obey the above criteria along a profile running through the location of the proposed drill hole as of late 2023. For each station, each frequency was analysed and only those that were either 1D or 2D with a strike of $-20 \pm 10^\circ$ were included in the inversion. The inversion was run using the code MARE2DEM (Key, 2016) and topography was included.

Table 2. Data included in 2D inversion profile 1

Name	NSB022	NSOB04	NSOC02	SITE11	SITE12	SITE16	SITE17	SITE18	SITE26	SITE27
Freq. max Hz	320	320	320	320	19	320	320	320	320	320
Freq min Hz	0.86	.107	1.72	.215	.86	.107	0.86	.215	1.72	2.34

Phase Tensor Map for 1 (s)

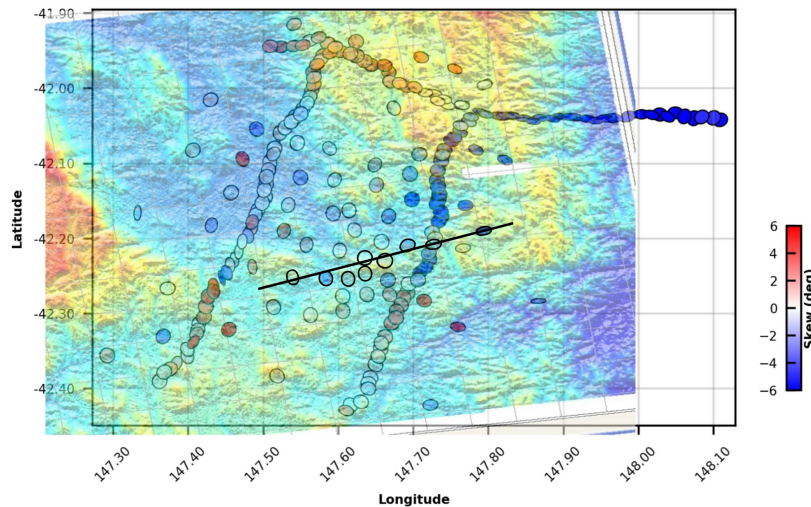


Figure 15. Phase tensor map at 1 s period showing the first 2D inversion profile (black line) and the stations included in the inversion (outlined in black).

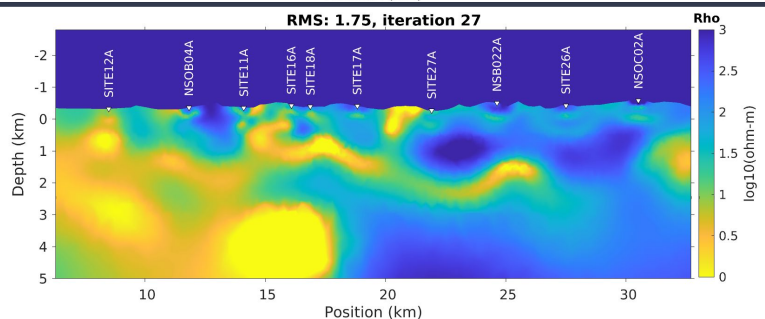
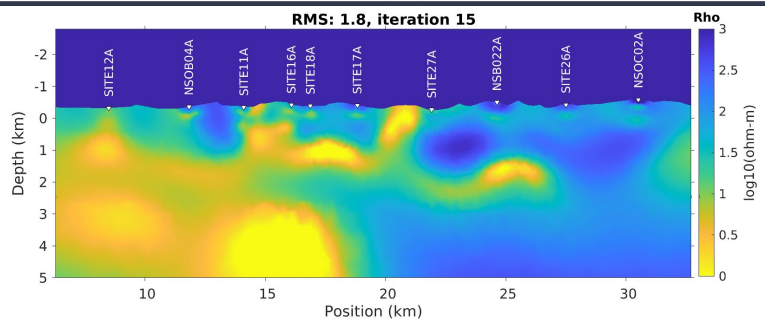
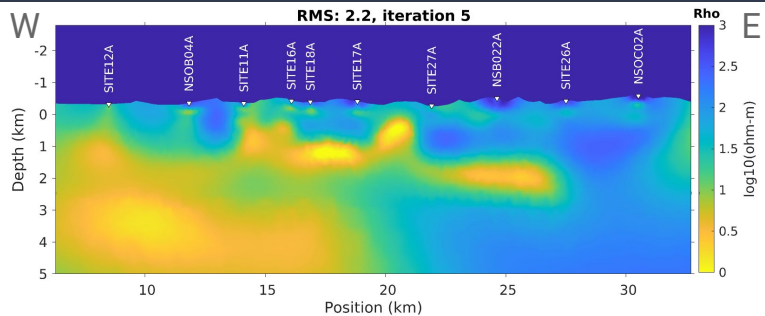


Figure 16. Results of the 2D inversion along Profile 1, showing iteration 5 (rms 2.2, top), iteration 15 (rms 1.8, middle) and the final iteration 27 (rms 1.75, bottom).

2D Inversion results, Profile 1

Profile 1 was modelled with several different parameters and the results of the preferred model are shown in Figure 16. This inversion started from a homogeneous, 100 ohm m half space, included static shift as an inversion parameter, and used default smoothing.

The results of three iterations are shown, demonstrating that the main model features appear early in the inversion runs (iteration 5, top). These features are:

- From ~2 to 5 km depth, the western part of the model space is more conductive than the eastern part
- There is a shallow, stronger conductor in the central part of the model space, extending from Site11 to NSB022. This conductor has resistivity <10 ohm m, lies at ~ 1 to 2 km depth and is less than one kilometre thick in all models. It may rise closest to the surface between Site17 and Site27, though there is a gap in stations at this point.

The three iterations are included to show that, for a well-fitting model such as this, subsequent iterations do not dramatically change the overall resistivity structure but instead tend to sharpen features, increasing the conductivity of conductors and the resistivity of resistors. This illustrates the non-uniqueness of MT inversion. The best constrained parameter in MT is the conductance (conductivity x thickness) and it is clear here how the inversion alters these parameters with little change to data fit.

2D Inversion

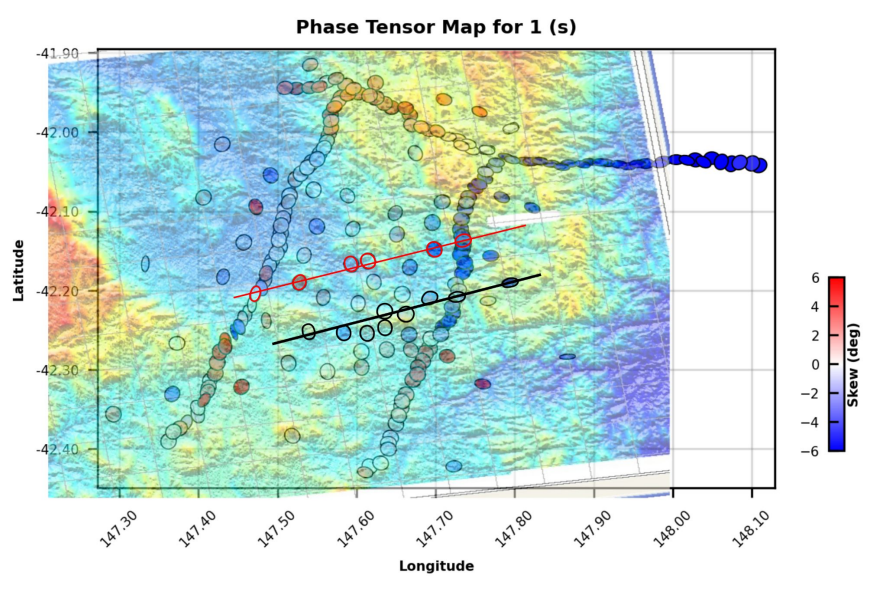


Figure 17. Phase tensor map at 1 s period showing the second 2D inversion profile (red line) and the stations included in the inversion (outlined in red), with the parallel Profile 1 in black.

2D Inversion, Profile 2

An additional 2D inversion was run along a parallel profile to expand and test the results of the Profile 1 inversion.

The criteria for station selection was the same as for Profile 1, and the profile is parallel and to the north of Profile 1. For each station, each frequency was analysed and only those that were either 1D or 2D with a strike of $-20 \pm 10^\circ$ were included in the inversion. The inversion was run using the code MARE2DEM (Key, 2016) and topography was included.

Table 3. Data included in 2D inversion Profile 2

Name	NSA032	NSB013	NSOB02	SITE23	SITE24	SITE33
Freq max Hz	320	320	320	2.34	320	320
Freq min Hz	4.7	.86	.43	.43	.215	.86

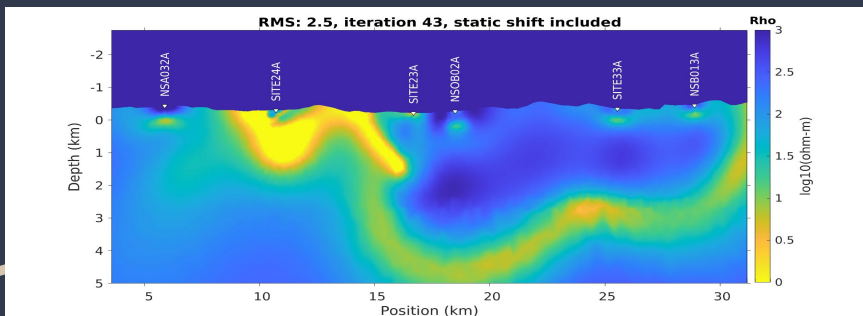
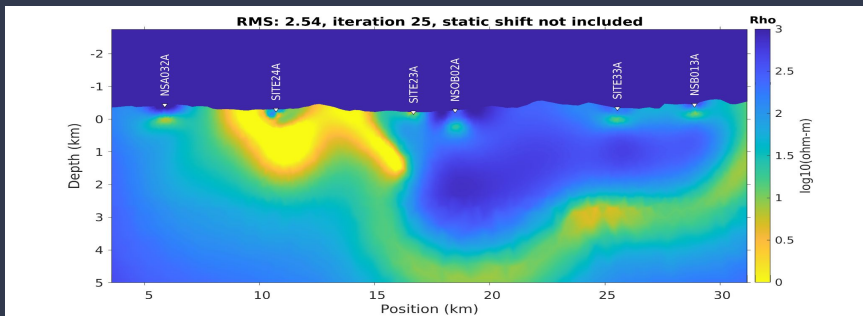
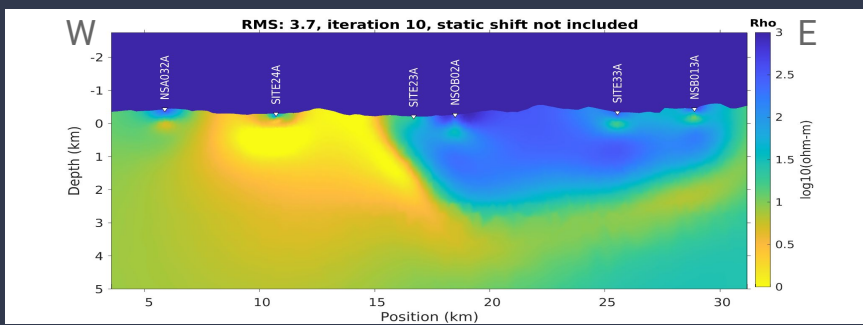


Figure 18. Results of the 2D inversion along Profile 2, showing iteration 10 (rms 3.7, top), iteration 25 (rms 2.54, middle) and iteration 43 after static shift had been included (rms 2.5, bottom).

2D Inversion results, Profile 2

Profile 2 has less data density than Profile 1, with only 6 stations along the ~30 km profile. The final data fit is not as good, with an overall rms error of ~2.5, but there are no systematic misfits to the data.

Similar to Profile 1, the main features included early in the iterations are a more conductive subsurface in the west of the model space and a more resistive subsurface in the east of the model space. With subsequent iterations these regions were refined and the western conductor was modelled as being shallow (not exceeding 2 km depth) and very highly conductive (~1 ohm m), mostly beneath Site24. In the east of the model space, the uppermost 3-4 km is dominantly resistive (~1000 ohm m). Underlying this resistor is a thin band of higher conductivity (~10 ohm m, less than one km thick).

Static shift was included as a parameter into the inversion after iteration 25, but this did not have a noticeable impact on the model features or data fit (Figure 18, lower panel).

The modelled features are in general consistent with those on the parallel Profile 1. The western part of the model contains a lot of high conductivity, which is modelled at shallower depths here than in Profile 1. The eastern part of the model is more resistive (~1000 ohm m) with a thin (one kilometre or less) band of higher conductivity (~10 ohm m). This band sits at ~2 km depth in Profile 1 and ~3 to 4 km depth in Profile 2.

2D/3D Comparison

Profile 1 Comparison

Here, profiles are extracted from the preferred Vox 3D inversion (Homogeneous Default) along the 2D inversion profiles to compare the results.

On Profile 1, the major features are mostly consistent between the 2D and 3D models. The western part of the model space is broadly more conductive and the strongly conductive regions at ~2 to 5 km depth (labelled A and B here) are identified in both models. Towards the east, the higher resistivity at shallower depths at C is consistent between both models. The underlying conductive band D is more clearly identified in the 2D model but is also present in the 3D model. In the 2D model, the deep conductor B has been separated from a shallower conductor at 1-1.5 km depth, while this is modelled as a continuous feature in the 3D model.

The comparison highlights that the 2D inversion models more detail, which is largely a function of its smaller mesh size and the inclusion of more frequencies, both of which are possible due to the lower computational costs of the 2D inversion. The absence of major differences between the models supports the reliability of the 2D model and the absence of any 3D artefacts.

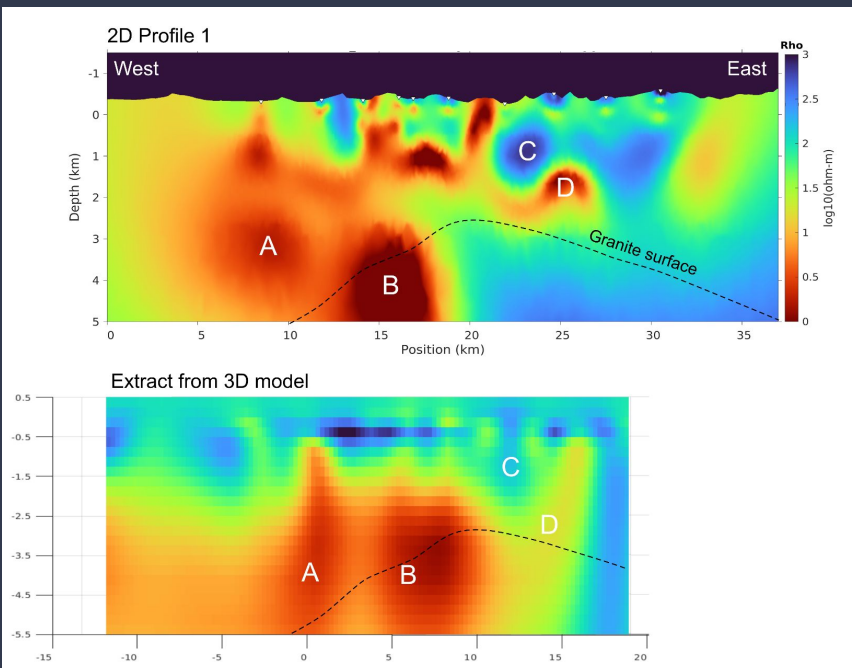


Figure 19. Comparison between the 2D Profile 1 and an extract from the 3D Homogeneous Default model along the same profile, at the same colour scale. The interpreted granite surface is shown as a dashed line

2D/3D Comparison

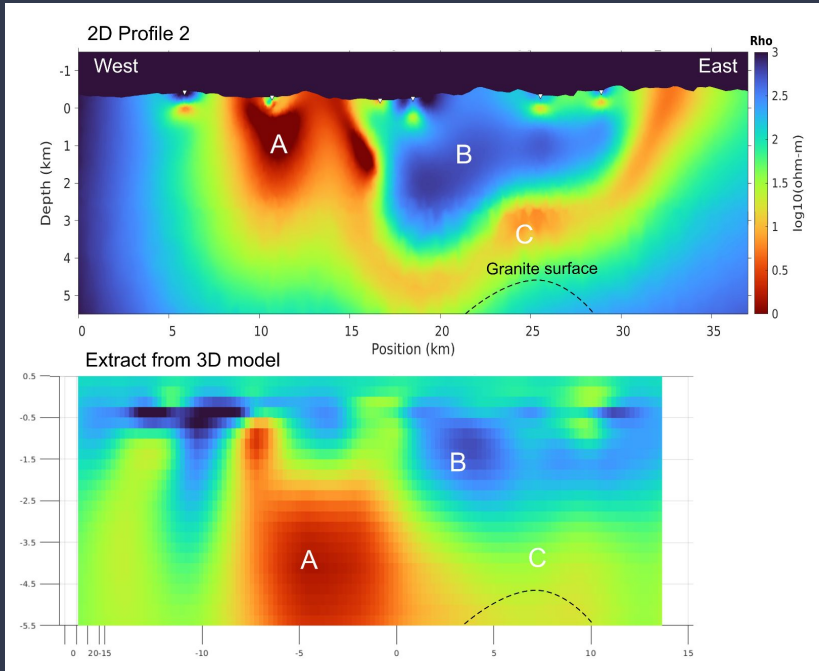


Figure 20. Comparison between the 2D Profile 2 and an extract from the 3D Homogeneous Default model along the same profile, at the same colour scale. Interpreted granite surface is shown as a dashed line.

Profile 2 Comparison

On Profile 2, the major features are similarly mostly consistent between the 2D and 3D models. The western part of the model space is broadly more conductive. The strong conductor labelled A is modelled in both inversions, though it sits at a shallower depth in the 2D model than the 3D model. To the east, the uppermost ~3 km is more resistive (~1000 ohm m) in both models. This higher resistivity region in the northeast of the survey area was a dominant feature of all the 3D inversions (Figs 4, 5 and 9). The underlying conductive band C is also observed in both models, but the 2D inversion models it as a discrete conductive band underlain by a resistor while the 3D inversion models it as a transition to a broadly more conductive region.

As for Profile 1, the features are considered to be in good broad agreement, highlighting the ability of the 2D inversion to model finer detail and also the absence of any 3D artefacts.

1D inversion

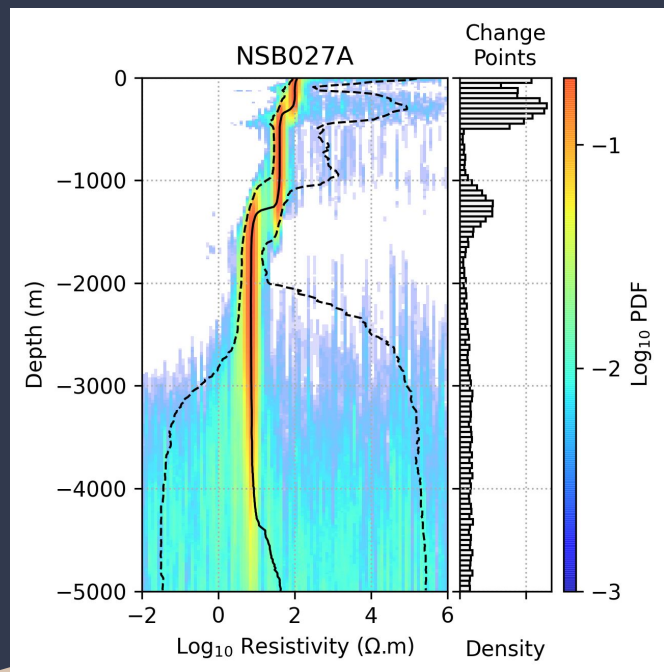


Figure 21. 1D probabilistic inversion of station NSB027, illustrating the colour scale used for the probability density function (PDF) of the models, the change points where boundaries are most likely, and the resistivity models with depth.

1D probabilistic inversion

The presence of 1D data provides the opportunity to carry out probabilistic 1D inversions. Due to the very low computational requirements of 1D inversions, probabilistic inversions can be carried out in a short time frame. These allow interrogation of all the possible models that can fit the MT data, rather than relying on just one deterministic model. Two regions are investigated where conductors reach depths of ~2 km: the southeastern conductor and the central western conductor.

Inversions were carried out using the code of Seille and Visser (2019). Before inversion, data were first analysed using phase tensors such that only 1D data were inverted. The inversions produce a suite of models that all fit the data, rather than only one model. Where the models agree there is good reliability in the modelled feature. The output is presented as a probability density function (PDF) of resistivity with depth (Figure 21). Hot colours show regions where most models agree, and dashed lines show the 95% confidence intervals. In the example shown here of site NSB027, confidence in the model is quite good from 0 to 2000 m, and very good from 1000 to 2000 m, where all models agree on the resistivity structure within a few tens of ohm m. Below 2000 m, the confidence intervals spread out broadly and the PDF shows cool colours, showing that there is low confidence in the model. In many instances in this dataset, this is because data are no longer 1D at depths greater than ~2 km. Finally, the change points show the depths at which boundaries are most likely.

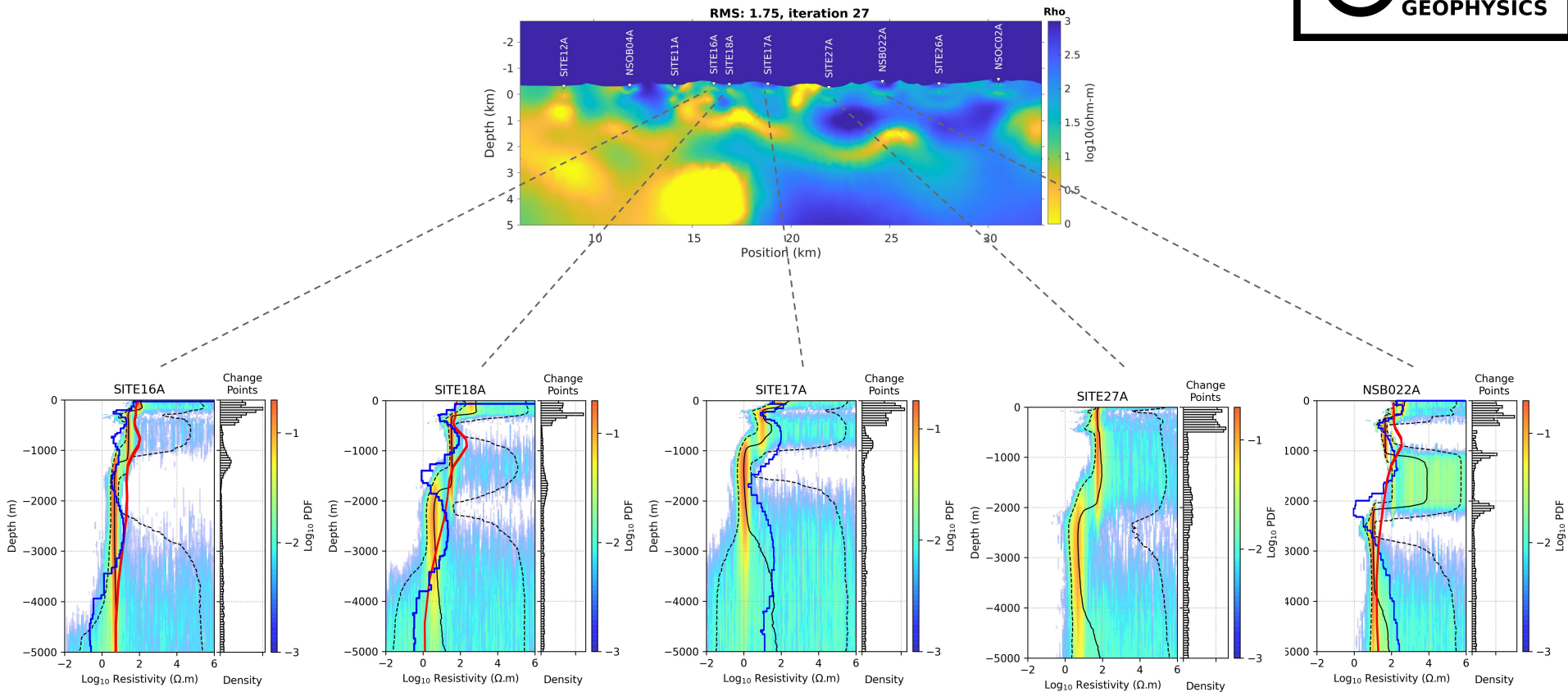


Figure 22. 1D probabilistic models of the stations along Profile 1 that image the southeastern conductor. Profiles through the 2D model are in blue and the 3D model are in red

1D inversion

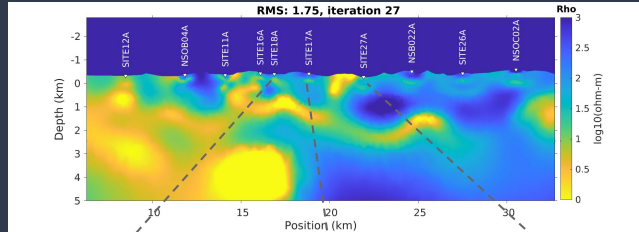


Figure 23. 1D probabilistic models along Profile 1. Resistivity-depth sections through the 2D model are in blue and through the 3D model are in red.

Southeast conductor

The probabilistic 1D inversions support and provide more detail on the results of the 2D and 3D inversions of the southeast conductor. All 1D models lose resolution from ~ 2 km depth, mostly because the phase tensor analysis showed the data are not 1D from this point so the models are poorly constrained.

At Site18, the 1D models are less conductive and more homogeneous than the 2D model at depths shallower than 2 km. 1D model resistivities are best constrained at ~ 600 m depth and are several tens of ohm m; the very strong 1 to 10 ohm m conductors modelled in the 2D inversion are not imaged. At depths greater than 2 km, there is good evidence for a strong (<10 ohm m) conductor.

At Site17, models are in good agreement that there is an ~ 10 ohm m conductor at <1 km depth and an ~ 1 ohm m conductor between 1 and 2 km depth, with a change point at ~ 1 km. At depths greater than 2 km there is less evidence for very high conductivity.

At Site27 the probabilistic model is more poorly constrained. However, there is good agreement that there is an absence of a strong conductor in the uppermost 2 km, with 1D models most dominantly at 100 ohm m and extending to much higher resistivities. The 1D model shows some evidence of a jump in conductivity at ~ 2 km, in agreement with the 2D model, but is poorly constrained.

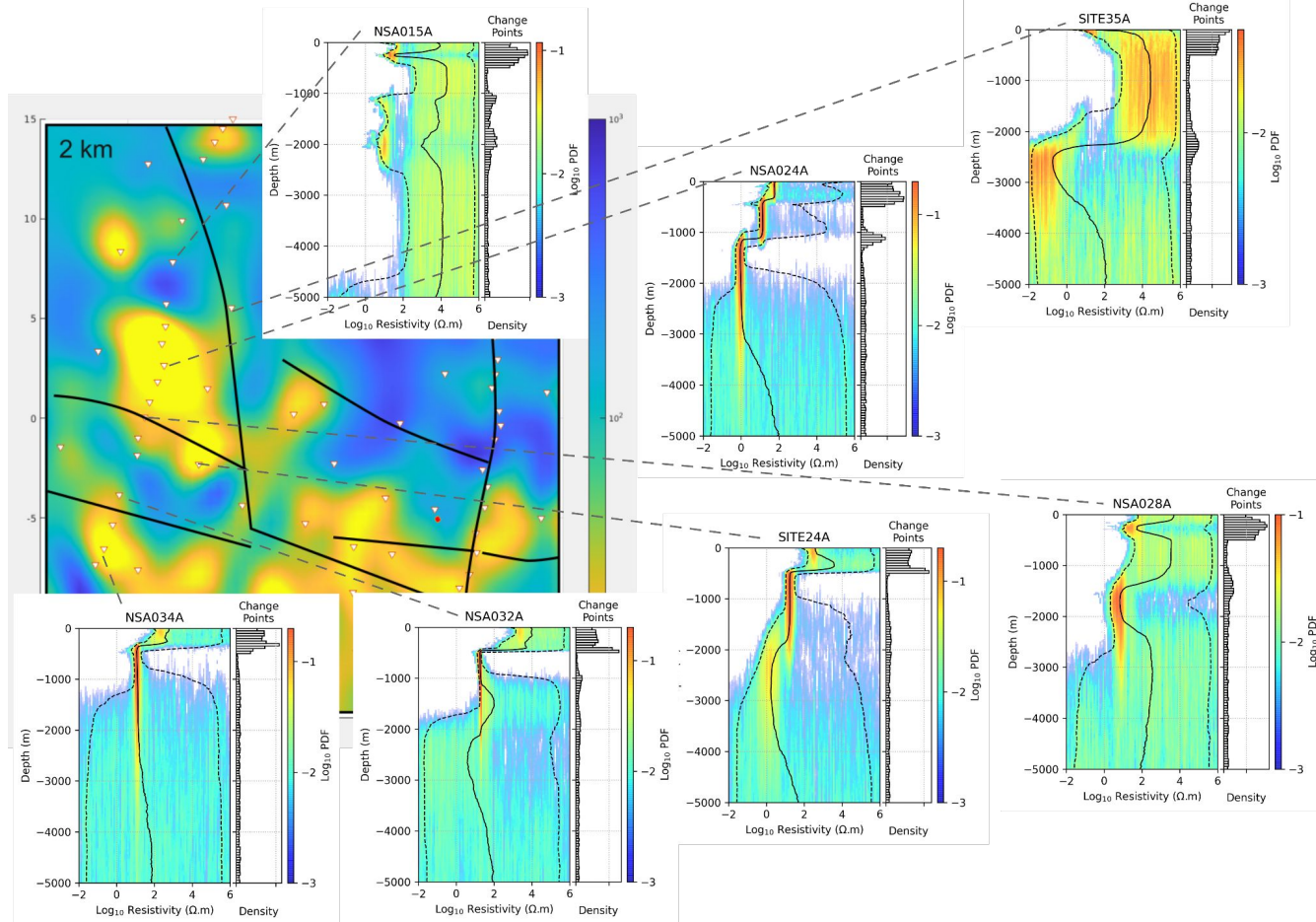


Figure 24. 1D probabilistic models of stations that image and surround the central western conductor with the 2 km depth slice from the preferred 3D model.

1D inversion

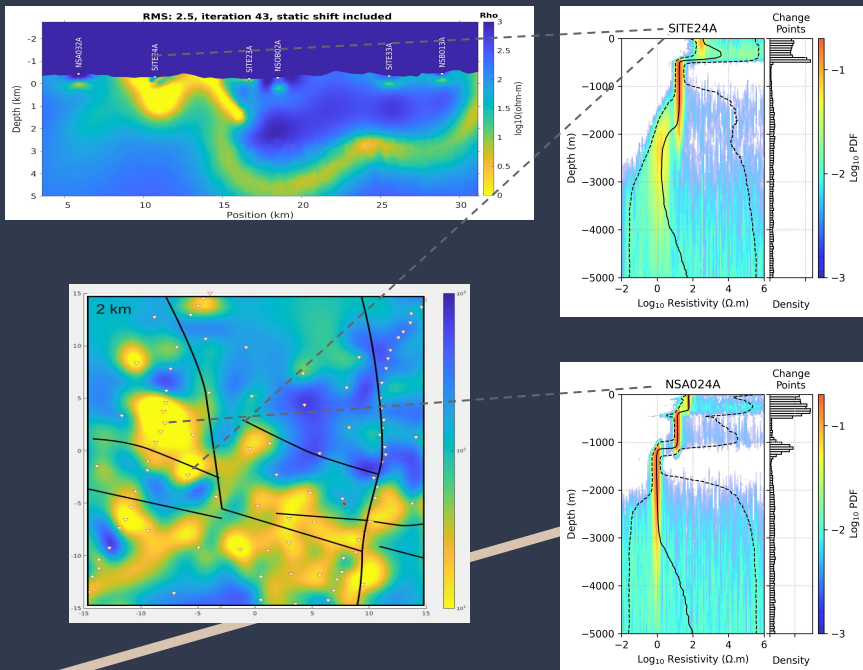


Figure 25. 1D probabilistic models with 2D section and 3D section of the central western conductor.

Central western conductor

The probabilistic 1D inversions support the high conductivities modelled at depths to ~ 2 km at the central western conductor. This region is less one dimensional than the southeastern region so the 1D models are in general less well constrained with broader confidence intervals over a larger depth range (Figure 24). However, at key stations such as Site24 and NSA024, there is reasonable confidence at shallow depths.

At Site24, which is also part of the 2D Profile 2, there is good confidence in the 1D probabilistic model for resistivities of ~ 10 to several tens of ohm m from ~ 500 to 1000 m depth, with a change point at 500 m. There is poor 1D resolution from 1000 m depth but some suggestion in the PDF for higher conductivities (~ 1 ohm m) extending to greater depths, in agreement with the 2D model.

At site NSA024 there is good evidence in the 1D inversions for resistivities less than 100 ohm m from the surface to 1 km, and a tightly bound PDF at ~ 1 ohm from ~ 1 to 1.7 km

Conductors summary

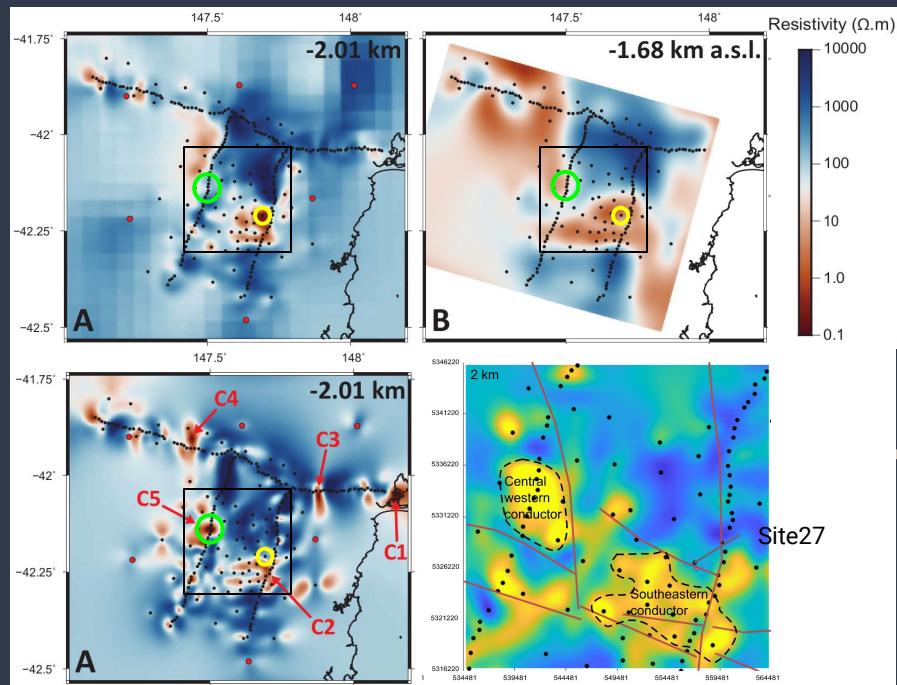


Figure 26. Summary of the important shallow conductors in the survey region

There are two regions of shallow, high conductivity in the survey area.

The central western conductor has been imaged by all models apart from the Osteren (2021) AusLAMP model, which may be biased by its starting model and demonstrates unusual unsmooth behaviour. The WesternGeco, Osteren homogeneous, and new Vox 3D, 2D and 1D probabilistic models all image this feature, so it is considered to be robust. All models image it as a very high conductivity feature, with resistivities as low as 1 ohm m. The 1D and 2D models image it as a feature that extends from close to the surface to ~1 to 2 km depth, whereas the 3D models image it as a feature with greater depth extent, to as much as 4 to 5 km. While its presence is considered robust, its depth extent is not considered well constrained at this time.

The southeastern conductor has been imaged by all models. The main difference between the models is that the Osteren (2021) AusLAMP model images the strongest shallow conductor beneath Site27, whereas other models image this location as more resistive than the regions to the west, south and east. The agreement between the 2D model and all other 3D models leads to confidence that Site27 is not the most conductive target in the southeastern conductor.

ANT seismic

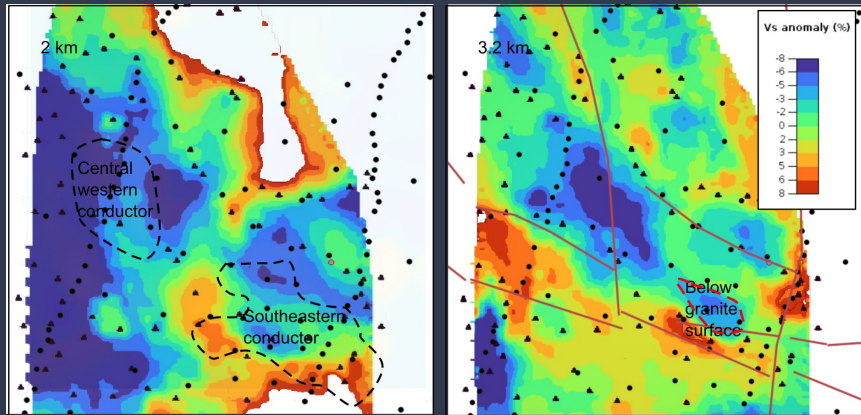


Figure 27. Ambient noise seismic tomography (ANT) models of the survey region at 2 and 3.2 km below sea level, with MT stations and the outlines of the central western and southeastern conductors. At 3.2 km, the slow velocities continue below the granite surface at the location marked in red.

Ambient noise seismic and MT comparison

Existing ambient noise seismic tomography (ANT) models were compared with the MT results. Figure 27 shows ANT depth slices at 2 and 3.2 km below sea level (2 km is the shallowest depth slice available and 3.2 km is the deepest slice available). Blue colours denote low velocity, which may be caused by groundwater.

Velocities at the central western conductor are low, with even lower velocities offset slightly to the east, where there is poor MT data coverage. This coincident conductive and slow anomaly provides support that the feature could be caused by saline groundwater.

Velocities at the southeastern conductor are also mostly low, although they become anomalously high at the southern extent of the low resistivity zone. Velocities at Site27 and the location of the borehole proposed as of late 2023 are higher than those further south, close to MT Site17 and Site18. This is in agreement with the updated MT models which show Site17 and Site18 as having higher conductivity than Site27. The coincident conductive and slow anomalies here also support an interpretation of saline groundwater.

The slow velocities in the southeastern conductor extend to depths of 3.2 km, which is just greater than the interpreted granite depth at this location. This coincides with the deep conductor B imaged on 2D profile 1 and the corresponding 3D section.

Granite relationship

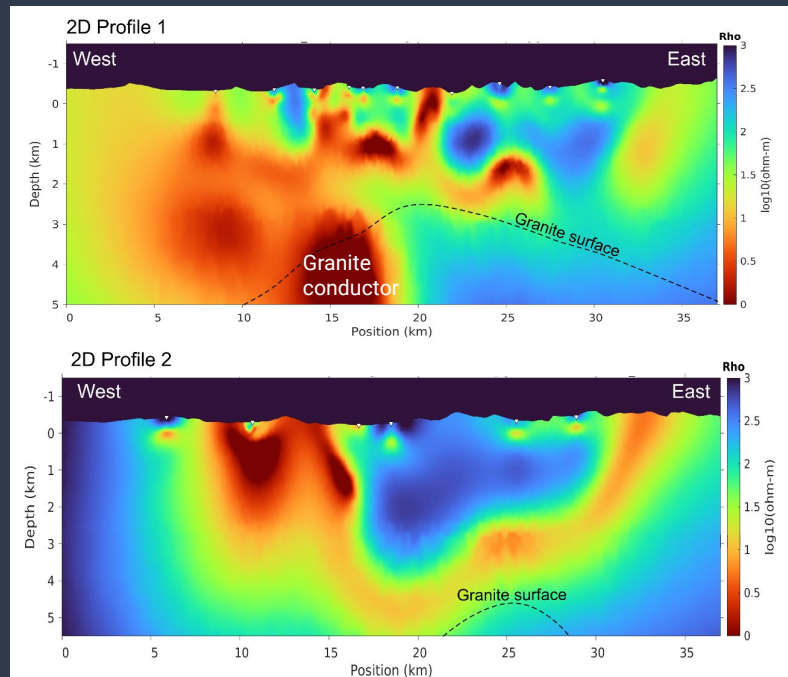


Figure 28. 2D MT profiles with the southeastern and central western conductors and the interpreted granite surface.

Relationship between conductors and granite

Both the central western and southeastern conductors appear robust and could feasibly be caused by saline groundwater. In the eastern part of the model space, both 2D profiles image thin bands of high conductivity that appear in places to be coincident with the top of the granite surface and may be related to fracturing along this surface, or alternatively to clay alteration and weathering of the granite.

No part of the central western conductor is reliably modelled as being below the granite surface. For the central eastern conductor, a strong conductor is modelled in the 2D profile and also in the 3D model that sits largely below the granite surface (Figures 19 and 28). Although the ANT model does not extent to depths greater than 3.2 km, this conductor does appear to be associated with a slow velocity anomaly in the deepest ANT depth slice. This coincidence of high conductivity and low velocity could suggest fractures within the granite causing the granite conductor.

Granite relationship

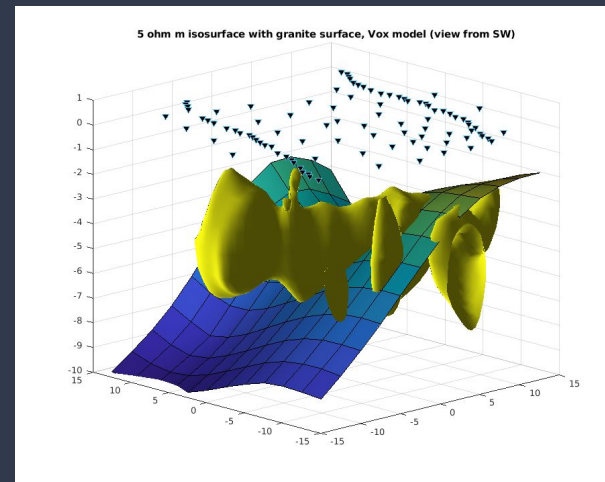
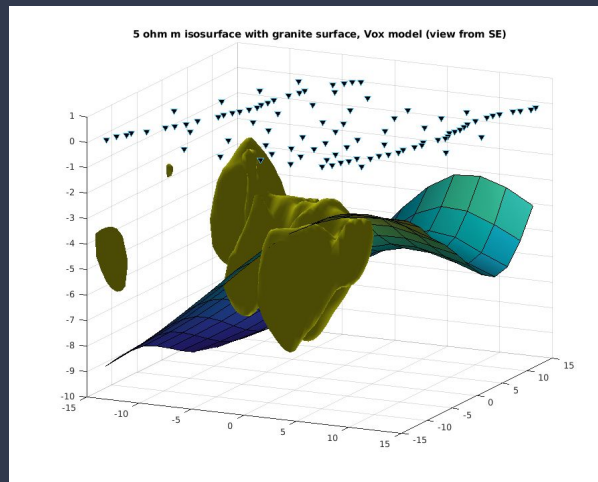
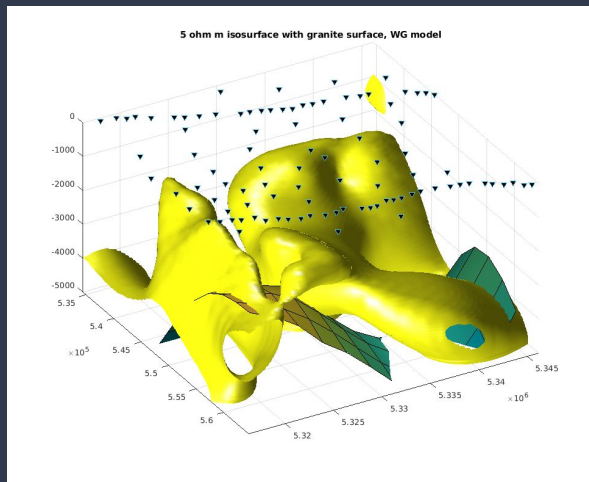


Figure 29. Views of the 5 ohm m isosurfaces of the Western Geco model (left) and the preferred Vox Homogeneous Default model (middle and right) with the top of granite surface displayed. Western Geco model view is from the east. The Western Geco model displays a conductor above the granite that follows the shape of its surface in the eastern part of the model space, in a similar pattern to the narrow banded conductors observed in the 2D models.

Granite relationship – Vox model

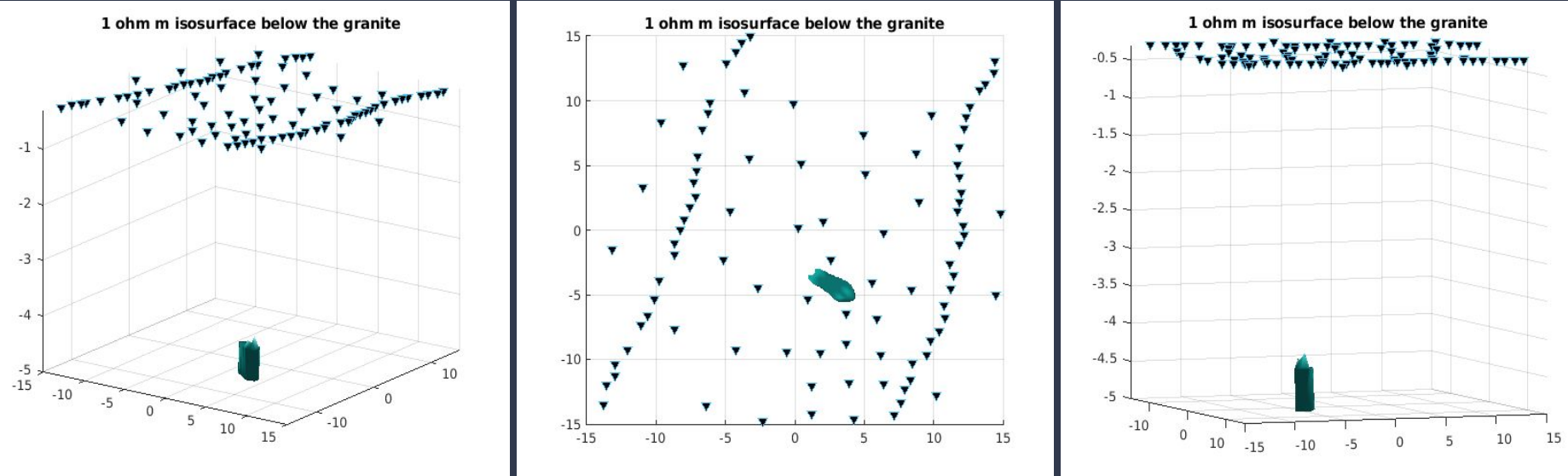
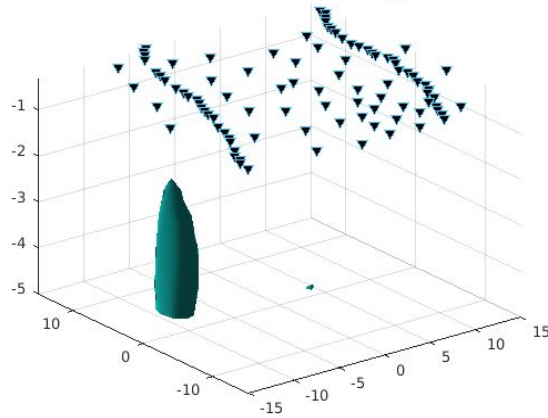


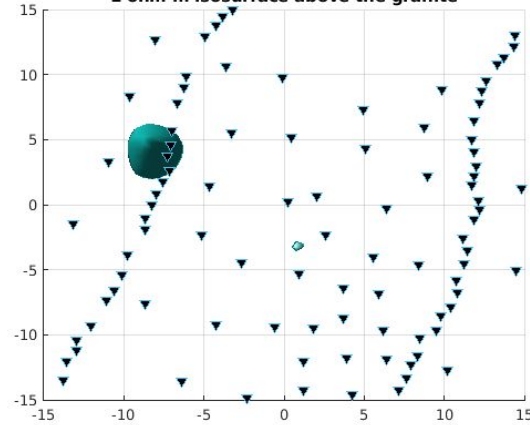
Figure 30. Views of the 1 ohm m isosurface where that conductor sits below the top of the granite from the preferred Vox Homogeneous Default model. Views are from the SE (left), plan view (middle), and from the east (right, to show depth extent of the conductor).

Granite relationship - Vox model

1 ohm m isosurface above the granite



1 ohm m isosurface above the granite



1 ohm m isosurface above the granite

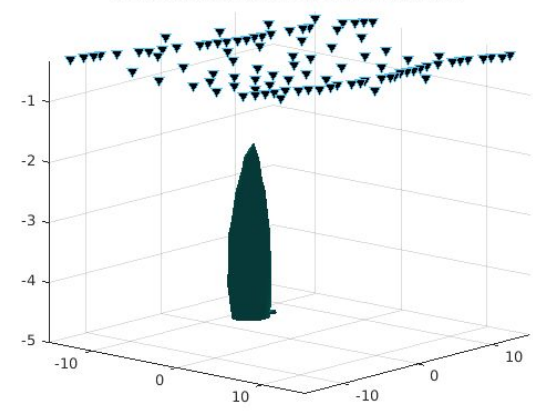


Figure 31. Views of the 1 ohm m isosurface where that conductor sits above the top of the granite from the preferred Vox model. Views are from the SW (left), plan view (middle), and SE (right)

Granite relationship – Vox model

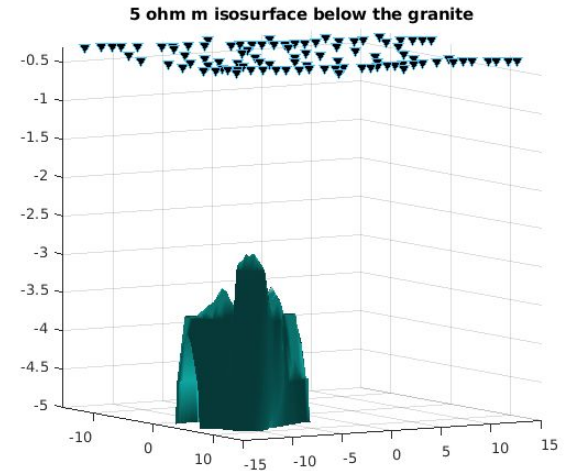
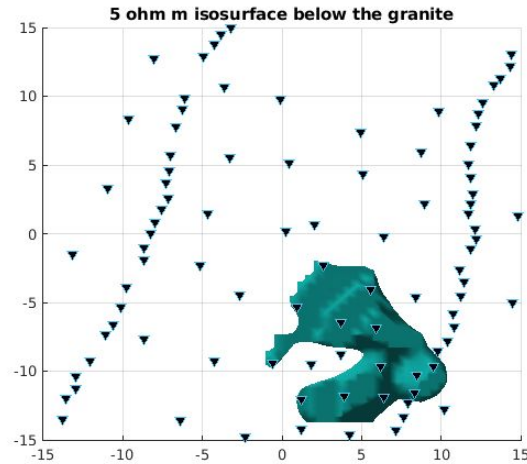
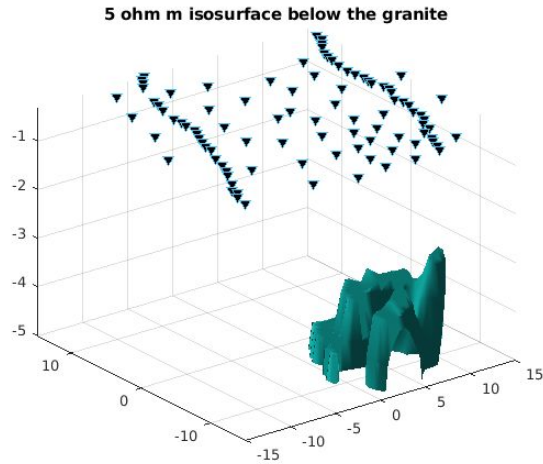


Figure 32. Views of the 5 ohm m isosurface where that conductor sits below the top of the granite from the preferred Vox model. Views are from the SW (left), plan view (middle), and east (right, to show depth extent of conductor).

Granite relationship – Vox model

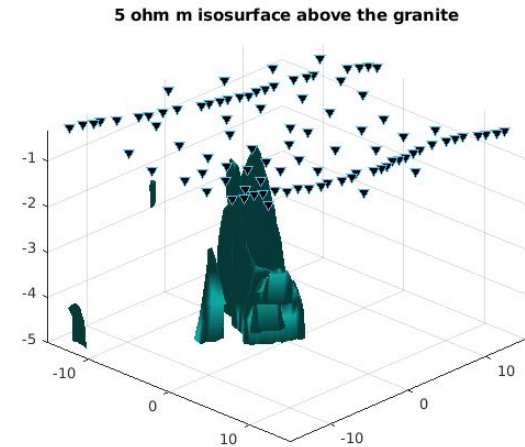
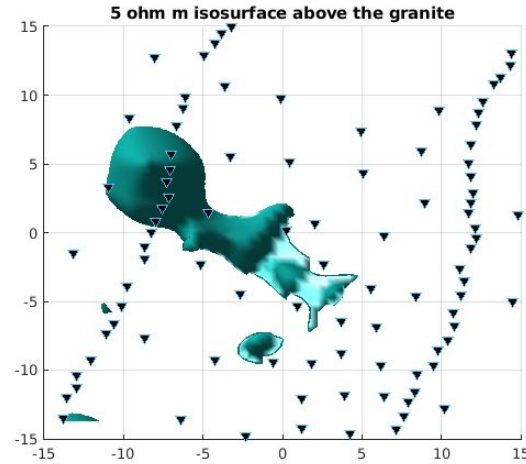
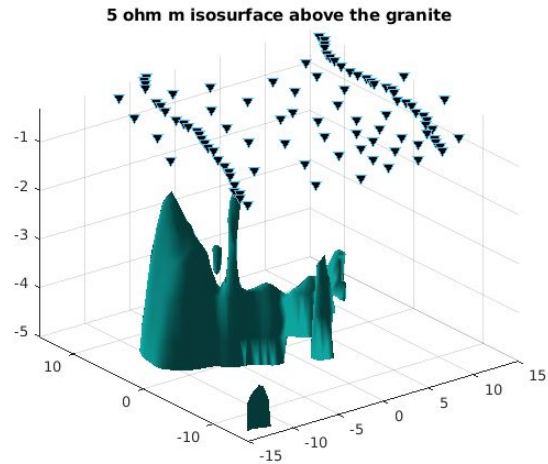


Figure 33. Views of the 5 ohm m isosurface where that conductor sits above the top of the granite from the preferred Vox model. Views are from the SW (left), plan view (middle), and SE (right)

Granite relationship – WGc model

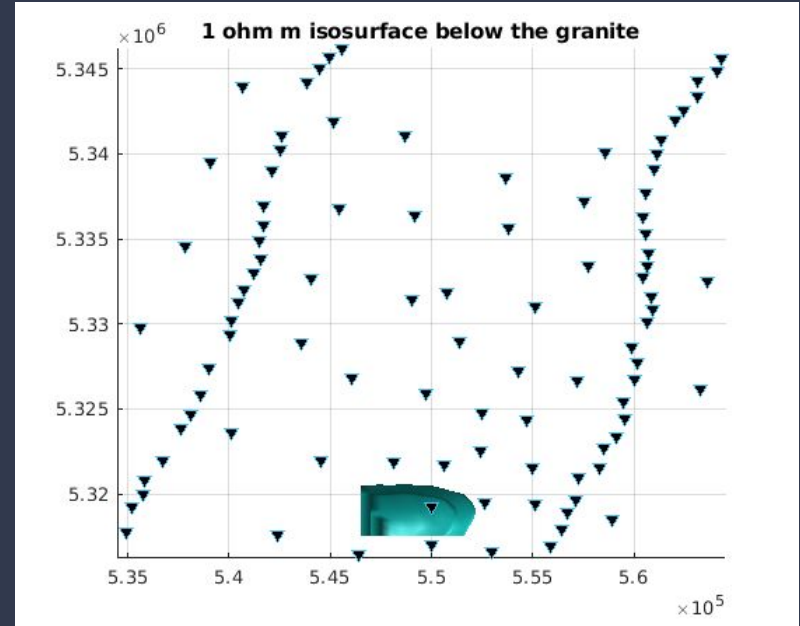
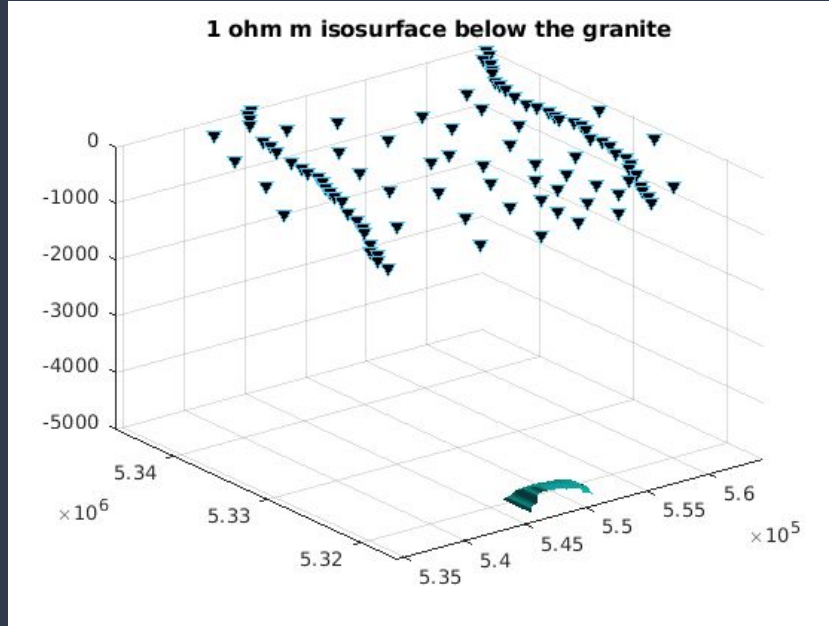


Figure 34. Views of the 1 ohm m isosurface where that conductor sits below the top of the granite from the Western Geco model. Views are from the SW (left) and plan view (right)

Granite relationship – WGc model

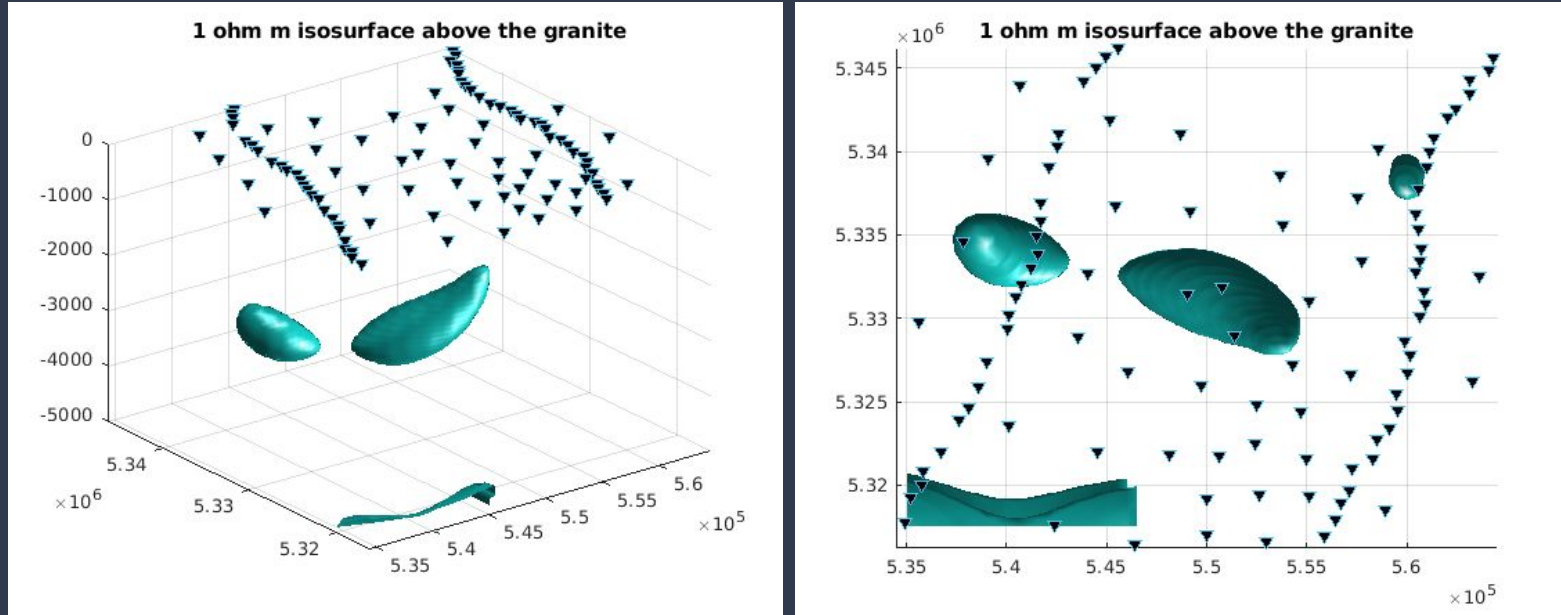


Figure 35. Views of the 1 ohm m isosurface where that conductor sits above the top of the granite from the Western Geco model. Views are from the SW (left) and plan view (right)

Granite relationship – WGc model

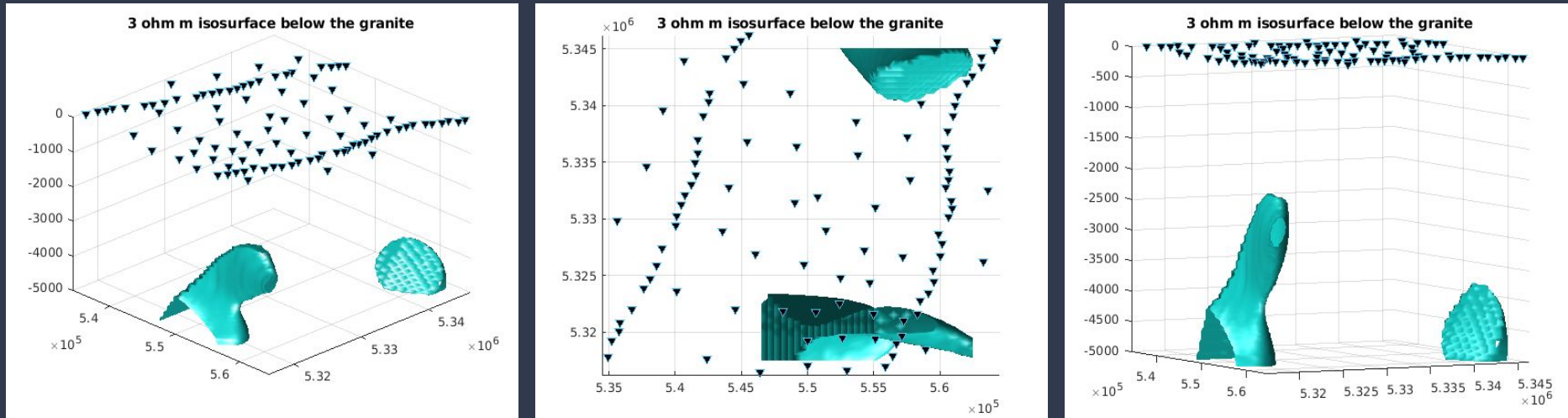


Figure 36. Views of the 3 ohm m isosurface where that conductor sits below the top of the granite from the Western Geco model. Views are from the SE (left), plan view (centre) and from the east (right, to show depth of conductor). There are slightly different absolute resistivities between the Vox and Western Geco model, so the closest comparison to the Vox 5 ohm isosurface is the Western Geco 3 ohm m isosurface. Both of these models image a conductor with similar extent beneath the granite surface in the SE of the model, rising to a depth of ~2.5 to 3 km. The Western Geco model also images a conductor in the NE, but this part of the model is poorly constrained.

Granite relationship – WGc model

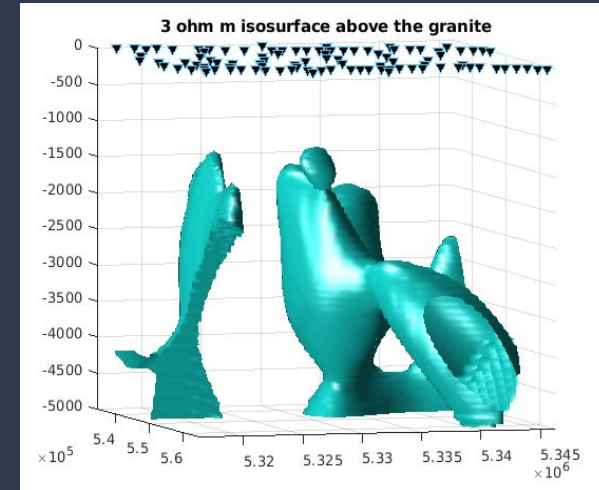
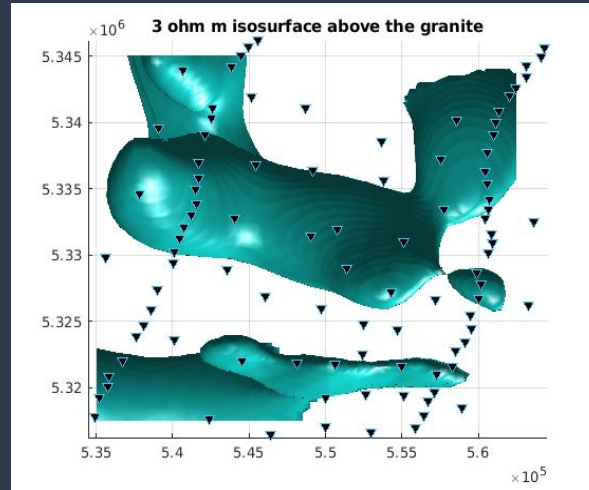
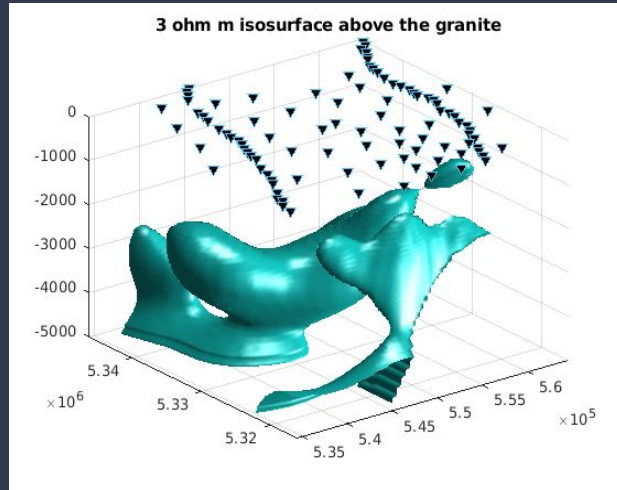


Figure 37. Views of the 3 ohm m isosurface where that conductor sits above the top of the granite from the Western Geco model. Views are from the SE (left), plan view (centre) and from the east (right, to show depth of conductor).

Resistivity volumes

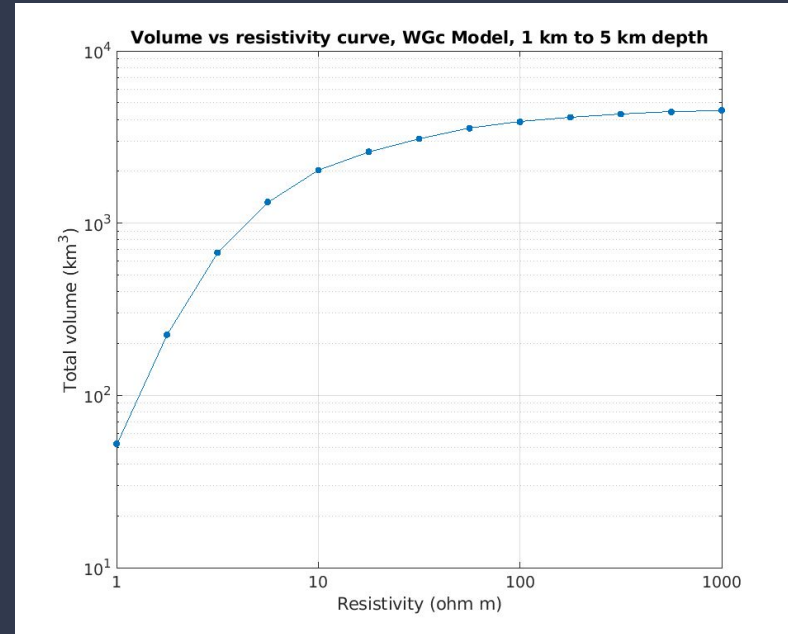
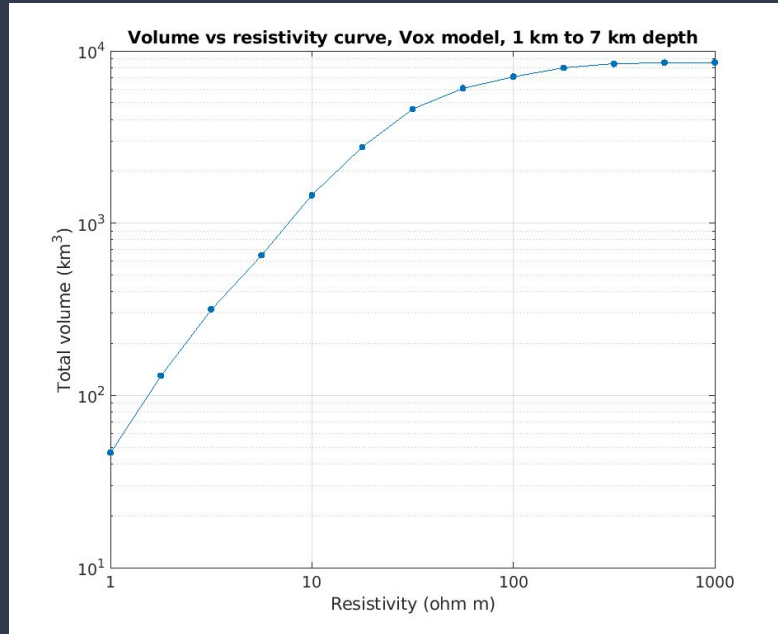


Figure 38. Cumulate volume vs resistivity plots for the Vox preferred model (left, 1 to 7 km depth) and the Western Geco model (right, 1 to 5 km depth). Both models are in agreement that $\sim 50 \text{ km}^3$ of the model space have resistivities $< 1 \text{ ohm m}$.

Model fits, 2D Profile 2

