# 2.5D vs 1D AEM Forward and Inversion Methods at a Survey Scale : A Case Study

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**SUMMARY**

The McArthur basin/EMU fault study has a classic 2D fault feature and a buried conductor with an off-end effect with other 2D/3D effects away from the EMU fault. The collected AEM data has demonstrable AIP effects. This has stimulated an investigation of a simple 2D geology cross-section of a dipping fault with a strong conductor on one side of the fault.

A forward model of the predicted response near the EMU fault represents a synthetic observed signal from the cross-section in agreement with the AEM data. Our modelling shows that the 1D inversion gives results which do not reproduce the survey data whereas 2.5D performs well reconciling the inverted section with the observed EM response. Away from the 2D geology region and other 2D/3D EM effects, 1D does perform well as expected. Therefore 2.5D gets it right in significantly more situations by honouring the information in the observed data raising questions about the use of 1D.

Emerging AEM systems can provide estimates of economic rock unit thicknesses, dips, faults and anticline/syncline definition at an accuracy that mitigates the need for pattern drilling. The use of 2.5D allows marker beds of more conductive material to stand out at a depth of 500 m or more on sections created beneath individual flight lines. Routine treatment of all survey data is now possible without supercomputing capability.

CSIRO has also recently undertaken comparative studies of the available AEM 1D, 2.5D and 3D inversion codes. Their work raises some stark reminders of what is different in the methodologies and how the progression to higher-order geophysics methods requires not just careful test work but also effective education of the user community.

We explain the fundamental differences between 1D and 2.5D and point out issues with the 1D forward modelling and inversion technology. Importantly, Maxwell’s equations are used to constrain 2.5D whilst empirical methods are commonly used in 1D.

This leads to the situation where a near zero average misfit using stitched 1D models can be achieved with families of 1D inversions, whilst incorrectly predicting the geology. Therefore a low misfit does not necessarily indicate a good solution for 1D. The 2.5D method is a least-squares best fit of the observations and so the quoted misfit for 2.5D is a very different measure than for 1D.

The study demonstrates that 2.5D yields a much more satisfactory geology section and a better reconciliation with information contained in the survey data.

**Key words:** forward models, conductive, chargeable, frequency analysis, mineral exploration, airborne geophysics, solvers.

## INTRODUCTION

This work is prompted by the emerging use of AEM surveying methods and the part this technology could play in further optimizing the costs and time taken to define mineral resources. This paper uses the southern McArthur Basin in Australia’s Northern Territory, as a case study. A fuller exposition of the details and differences of forward modelling of the predicted AEM response, using a 1D method and a 2.5D Finite Element method is made.

In 2010, Brumby Resources Ltd contracted GeoTech to conduct a VTEM survey over their Caranbirini tenements. The survey was designed to search for mineralisation similar to that occurring at the operating world class McArthur River Zinc-Lead-Silver (Zn-Pb-Ag) mine 10 kilometres to the south. The survey was considered to have detected no significant targets. Subsequently the tenements were joint ventured to Marindi Metals Ltd. Around 2015, the Geological Survey of the Northern Territory and CSIRO entered into a 3-year agreement to conduct research on the prospectivity of the Barney Creek formation for Zn deposits that may prove to be economically viable. Intrepid Geophysics helped with this investigation by providing complimentary AEM 2.5D inversion work at the invitation of CSIRO. There is a companion paper at this conference, (Munday 2018 et al).

To date, the combination of AEM surveying and 1D inversion methods has proven useful in defining the regolith geometry and stratigraphic and structural architecture. Many case studies have now proven that AEM can provide this crucial information for mineral exploration (Fraser, 1981; Silic et al, 2015; Silic et al, 2016). In their recent studies, Neroni, Murray and Kepert (2016) showed that constrained 1D AEM inversion in the Hamersley Province, Western Australia enabled exploration geologists to interpret weathering profiles, shallow dipping stratigraphy and steep structures, all of which are crucial aspects of bedded iron ore deposits models.

AEM is evolving into a useful 3D geological mapping tool as well as a discrete conductor detector for direct drill targeting and follow up. Example case studies from all the AEM contractors have been undertaken using 2.5D inversion methods running on common desktop computer equipment. So far, most AEM survey data has been amenable to using our new codes without compromising the frequency decay curves or measured vector components of the EM field response. This paper focuses on just one profile from the Caranbirini VTEM survey, Line 10440 over the EMU fault, Figure 1.

## METHOD AND RESULTS

### 1D & 2.5D AEM Forward Modelling over arbitrary geo-electrical sections

Not all forward modelling of AEM surveys will give equivalent results. As there is existing experience in the broad geophysics community with 1D forward modelling, an explanation of how the 2.5D method works and why it gives different results to the 1D approach is important.
The most common 1D method involves the assumption that at each survey point the EM response can be reproduced by a layered earth model of 10 to 30 horizontal layers. Predicting the response of a geological section is accomplished by creating a series of vertical columns along the section below each survey point and assigning conductivity properties to the chosen number of layers below each survey point. However this forward model prediction is flawed over 3D structures. For example, the predicted response from a 1D forward model over a “thin” vertical conductor will show a single point response over the vertical target and zero elsewhere. This is a direct result of the “false” assumption inherent in the 1D model that the signal at each survey point originates from the vertical column below the survey point and not from the conductivity distribution spatially removed from the point of measurement. However the 1D forward model however is expected to be “reasonably” accurate over those parts of the geo-electrical section where the deviation from a 1D layer model is not too severely disrupted by significant lateral 3D or 2D conductivity variations or over “gently“ dipping 1D formations.

In contrast 2.5D modelling is based on a full wave solution to Maxwell’s equations using a frequency-domain, spatial Fourier domain finite element method over any 2D geo-electrical section under the excitation of a 3D dipole transmitter source, (Sugeng et al, 1992). The geo-electrical section is formed as a mesh with each cell assigned a conductivity value and induced polarization parameters. In the spatial Fourier domain, Maxwell’s frequency domain equations reduce to two coupled partial differential equations for the along strike components of the secondary electric and magnetic fields. These coupled equations are solved using an isoparametric finite-element method with quadratic basis and test functions. This allows the mesh to conform to topography and heterogeneous geo-electrical regions with curved or sloping boundaries. The implicit continuity of the along strike components across discontinuous resistivity boundaries in the conventional 2D finite-element scheme ensures numerical stability and accuracy when modelling problems with extremely high resistivity contrasts. At each survey measurement point contributions to the response from every part of the geo-electrical section are summed, including the EM interactions between them.

The numerical approximation limits the inter-element conductivity distribution to being bi-quadratic. The simple way to improve the fit in areas of high gradients is to reduce the mesh size. For geological applications, the mesh discretization is specified by the user. There is no 2D geology section geometry that cannot be predicted using this forward modelling method. With care, an accurate prediction of the detectability of any configuration of conductive/resistive geology bodies can be confidently calculated.
However, there are very few examples in the literature of methods to independently validate complex EM responses. Examples are mostly confined to simple geometries such as horizontal layers, ellipsoids and thin plates where analytical/numerical solutions are possible.

*Forward Model Challenge*
A simple 2D geology model comprising a dipping fault in a resistive background and a conductive surface layer to the right is shown in Figure 2. The aim is to use this proposed section to show an AEM off-end effect and 2D or 3D effects inside the conductive layer to the right of the fault.
The definition of an off-end effect is, “as the observation system is approaching and is still outside the conductive body, an anomaly of the leading edge of the overall response will be recorded”.
This synthetic case has an off-end effect in both the Z and X components, with peaks of the response in both Z and X components spreading away from the contact from early to late time when the airborne system is over the conductive layer. Interestingly though, in this particular case the late time off–end effect shows a localised peak which superficially can be interpreted as indicating the existence of a separate conductor to the left of the fault.
In contrast to the 2.5D result, when an off-end effect from a large strong conductor is present, the 1D method has to fit the Z channel “anomaly“ at late time, and creates a “ghost” conductor to the left of the fault (Figure 3). There is also a characteristic high resistive zone directly under the leading edge of the fault where it intersects the surface. This is a direct result of 1D being unable to account for or recognize the moving peaks in the Z component as a 3D effect inside the conductive layer (Figure 3).
The impact of adding a dipping conductive unit west of the fault was also investigated (Figure 4). This example shows that the predicted profile shapes cannot be reconciled with the observed data and hence do not account for the off-end effect. As mentioned in the caption, a possible buried conductor to the West of the fault was added, to see if the observed signal could be reproduced.

### 1D Inversion
Most 1D inversion codes are designed to fit each sounding in the Z component only (particularly for a centre of loop receiver), independent of its neighbours or with some sort of smoothing/coupling constraint between neighbouring points. As there is inherent ambiguity in this process, there is no reason why this simple process cannot converge to closely fit a 1D multi-layer decay when each sounding is inverted independently of every other one. The 1D GALEI method used initially by CSIRO (1D results 1, 2 and 3), Figure 1, falls into this group. For example, known syncline structures inverted with this method produce a geometry that looks like an anticline or “trouser legs” shape, Figure 5.

Attributes of most 1D inversion schemes can be summarised as follows:

- Generally require a starting model
- Generally require assumptions on number of layers
- Often use constraints such as smoothness
  - Between layers
  - Between adjacent soundings
  - Within an area (LCI and SCI)
- Can provide error analysis for 1D layered models decays

The LCI (Laterally Constrained Inversion) has been used by CSIRO for this analysis (1D results, Figures 4, 5 and 6). It was run using a variety of settings, thus producing a range of possible sections. Typical options include multi-layer, smooth-model mode, where the layer thicknesses are kept fixed and the data are inverted only for the resistivity of each layer. Inversion for flight altitude can also be included. Multi-layer smooth-model inversion is slower to compute but is usually able to provide a close fit to the observed due to a 1D multilayer decay. The layer thicknesses increase logarithmically with depth. The initial model resistivity structure is a homogenous half-space model with an auto calculated starting resistivity. This resistivity is the mean of the apparent resistivity calculated for each sounding or may also be chosen by the user.

Smoothness constraints are applied on the variation of resistivity with depth. In addition, lateral constraints are applied between adjacent survey points or soundings, to facilitate a "smooth" variation in the generated section both laterally and vertically. These smoothing constraints however are not determined by the knowledge or assessment of a possible variation of the actual geo-electrical section within the survey line. This incidentally, also explains the low-pass filtering often observed in 1D inversions with late time channels, that hides or negates the bird motion transference from X to Z and back. – "correlated noise/ or recoverable signal"?

A third 1D inversion methodology is also emerging. This is based upon a stochastic implementation of 1D inversion to explore probability space. Arguably, all the solutions are equally good at fitting the observed 1D Z channel, but with this approach it becomes possible to estimate the most probable model.

However, in the words of Jim Macnae "Weathering / Erosion / Burial /Metamorphism / Alteration / Tectonics / Chunks of rock from space / Chemistry are all the enemies of a flat 1D earth"

*Calculating and reporting Misfits – 1D*

The big question to ask here is – are we interested in the overall average misfits for a profile of AEM data, or going the extra step and examining a moving estimation of the misfit on an anomaly by anomaly basis or inspecting the variations in the misfit along the survey line.

Misfits to 1D inversion results are normally reported on how well each individual "sounding" or decay at each survey data point is fitted with a 1D multi layer decay. However, considering that the EM field over any section that is not strictly 1D in character cannot be reproduced by forward modelling the section using "stitched "1D responses (see previous section), then the reported 1D inversion misfits cannot represent a true misfit to the data.

A more satisfactory method has been proposed and used by SKYTEM. The quality of the fit between the observed data and the predicted data (i.e. the calculated forward 1D model response of the stitched conductivity model resulting from the inversion) can be evaluated by inspecting the residuals but only as a validation how well individual points are fitted with a 1D layered decay. The data residual is calculated by comparing the measured data with the response of the resulting model after inversion. This residual is then scaled. If the residual is near 1, the misfit between the response of the final model and the data is, on average, equal to the noise. A high residual is due to data that has "noise" or deviates from a 1D layered decay greater than the noise model considers.

Nevertheless, this approach still does not and cannot validate the assumption that if the sounding at individual points is "accurately" fitted with a 1D layered decay that the 1D assumption about the section is correct.

The true misfit to the data from a 1D generated section can only be determined by forward modelling the derived 1D section by using a well tested 2.5D or 3D modelling software.

## 2.5D AEM Inversion

The 2.5D inversion is previously described by Paterson et al., (2016), and Silic et al., (2015). The inversion application used in this work is a significantly re-engineered version of ArjunAir (Wilson et al., 2006).

The changes and innovations include:

- a new forward model algorithm (ArjunAir only produced accurate results for flat earth, layer models)
- a new 2.5D inversion solver with adaptive regularisation which allows the incorporation of a misfit to the reference model and the model smoothness function.
- multi CPU parallel processing.
- tiling along profiles, thus removing any constraint on survey line lengths.
- automatic adaptive resolution meshing.

runs on common desktop computer equipment. In this new 2.5D inversion solver, the regularisation parameter is chosen automatically and changed adaptively at each iteration, as the model, the sensitivity and the roughness matrices change (Silic et al., 2015). The estimation of regularization parameter requires calculation of only one forward model and a sensitivity matrix at each iteration and is controlled by an easily understood parameter, Relative Singular Value Truncation (RSVT).

The complexity of the predicted geology section is simultaneously expressed as the increase in the model norm. This follows directly from the fact that there is a global matrix with all the model detail expressed at each iteration of the solver via the finite element nodes.

We have named this new code "MOKSHA" which loosely translates to "lifting the fog of confusion".

*2.5D assumptions*

The geo-electrical section is 2D in and away from the vertical plane below the flight line.
The 2D geo-electrical section is modelled using a 3D dipole source.
The response of the 2D section can generate non-zero X and Z components and a zero Y component if the calculation is for receivers located along the flight line.
2.5D is expected to be accurate for reasonably 2D geology within the footprint of the airborne EM system.

Wherever possible, the 2.5D AEM inversion uses both the X and Z signal components in a joint inversion to incrementally produce a best estimate conductivity depth section. The Z (and X) component data are typically inverted using 10 m survey stations, a 30 to 40m mesh dX and a 2 to 5m mesh dZ at surface increasing logarithmically downwards to depths exceeding 750m. Using both X and Z components not only results in better signal/noise ratios but more importantly generates a more constrained solution for the geometry of the causative source (Silic et al 2016). This is because the X component response is very sensitive to lateral conductive variations within the geo-electric section for all airborne EM systems. However it is important to note that for a forward model or inversion with the receiver at or close to the middle of the transmitter loop the X component will have an essentially zero response over a 1D source.

Some aspects of the 2.5D inversion process still present a challenge. First is the initial starting model. The usual guideline employed is to set a resistive uniform half space that just exceeds the average resistivity of units of interest within the AEM system's depth of investigation. If this is not followed then parts of the half space may not evolve and the inversion scheme may fail to produce the correct geometry. The second important factor is the starting RSVT factor, or the proportion of the GSVD weights that will be used to establish the background. If too much of the detail in the observations influences the early stage solution as a result of inadequate damping of changes to less data sensitive deeper parts of the section then a failure to converge might also occur. The inversion may get stuck on the detail before resolving the background. Nevertheless, these potential failures to produce an adequate misfit between the calculated and observed data are easy enough to recognize as large sections of the survey data will show spatially coherent "large" misfits.

*Signal to Noise*

As soon as multiple vector components are used, the overall signal to noise ratio for the in-plane vector increases by as much as 40%. The simple derivation of this outcome follows from the fact that the signal parts in each of the X & Z measures reinforce each other and the signal and the noise part of each measure is "stacked". If the noise is "random" then it tends to cancel.
In the case where X & Z have similar amplitudes, the vector sum of orthogonal components is SQRT (2), i.e. approximately 40%. While this is a poor-man's derivation, it does illustrate the benefits of using all the measured components in your inversion scheme, and the possibility of deeper coherent predictions of geology.

*Calculating and reporting Misfits – 2D*

Given the 2.5D global fitting of the observations (the influence of each cell conductivity is evaluated for each observation), 2.5D misfits are typically tied back to profiles for each time gate or frequency. The local shapes for each time gate's anomalies are required to fit the measured X and Z profile shapes, starting from broad-based background wavelengths, to shorter wavelengths and deeper sources as the inversion progresses. Given this, a Root Mean Square of the same data residual (difference between each observed vs predicted forward response) is also considered to be a meaningful and useful measure of the "convergence to a best fit conductivity geology model". As a result a "bad" misfit is not judged on just the overall estimate of the RMS error, but rather on how well the calculated response fits the survey data in both the spatial and temporal sense within the estimated systems noise levels .

## Using 2.5D Forward Model to check 1D Misfits

Given that the 1D and 2.5D forward modelling technology is quite different then a forward model of a predicted 1D inversion resistivity section using both 2.5D and 3D codes is a reasonable way to check the misfit of the X & Z channels with the observed data (see previous section on 1D misfits). If the 1D section is correct, the shape and amplitude of the measured signal at each time gate or frequency should be reproduced within a reasonable estimate of the system noise levels.
Figure 6 shows the predicted profiles for the Aarhus 1D with IP inversion result. Generally, away from the 2D or 3D geology where the section is predominantly 1D, the forward model from 1D resistivity values produces a good fit with the observed data. However, there is a poor fit for the Z component profiles in the vicinity of the dipping fault (2D /3D structure) and over the 1D inferred central "folded" conductive feature. The fit is poor for both the amplitudes and the spatial variation of the signal. For the X component (not shown here) the misfit is even worse. 2.5D inverted sections over these areas reproduce the survey data .

## Airborne Induced Polarization Effects

Data acquired by airborne EM time domain systems, particularly in-loop systems, reflect mainly the EM induction related to ground conductivity and airborne inductively induced polarization (AIP) related to the relaxation of polarized charges in the ground (e.g. Kratzer and MacNae 2012). As seen in figure 7, the presence of AIP from a near surface body dampens the conductivity response. The in-loop system in particular is optimally configured to excite a unique AIP effect including, but not exclusively, negative transients at mid to late times. In many cases these AIP effects are closely related to near surface sources.
The widely used theory to explain the IP effect is the empirical Cole-Cole relaxation model (Cole and Cole, 1941) and in frequency domain assigns a complex conductivity to the geo-electrical section, with the real conductivity modified, by the chargeability, the IP time constant and a frequency factor. Inversion of the airborne EM for both IP and conductivity effects can then proceed by simultaneously inverting for these four parameters. Such a scheme has been implemented within the 2.5D inversion code by restricting the identification of the IP effects to within a specified depth from the surface and by placing "strict" limits on some of the

IP parameters, particularly the IP time constant and the frequency factor. An example of such an inversion is shown in Figure 8, where the IP effect near a surface contact is reproduced by the calculated response. Further schemes are currently being implemented to deal with the complex issue of simultaneously resolving the conductivity of the geo-electric section and its IP parameters.

## CONCLUSIONS

The various 1D AEM codes in common use can be tuned to minimize the predictions of misleading geology. However, little comfort should be taken from a predicted tight misfit for a 1D code, as this is not a measure of a predicted geology section's reliability when it is not truly 1D.

The 2.5D finite element modelling technology fully accounts for the physical phenomena articulated by Maxwell's equations and numerically approximated by the finite element method.

When the 1D assumption is not met, CDI's and 1D inversions will be unreliable and 2.5D or 3D inversions are required to resolve the more complex geometry. For example:

- In contrast to the 1D inversion result, the EMU fault, when subject to a 2.5D analysis, appears as a very clean dipping fault to the East, without any "ghost feature" dipping to the West.
- There are conductive beds overlying the main MacArthur basin away from the EMU fault identified by both the 1D and 2.5D inversions.

Joint resistivity and AIP forward modelling in 2.5D has been achieved. 2.5D forward and inversion technology when augmented by the new AIP method shows that:
The forward model can reproduce the observed late time negative Z component due to the early time IP response.

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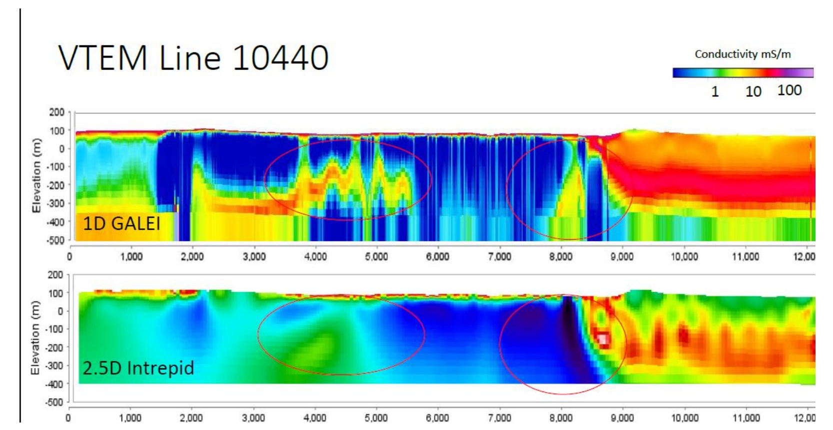


Figure 1. Comparison between initial 1D GALEI and 2.5D inversion results.
Note for the 2.5D plot

- the cleaner result in the basin proper
- absence of the "ghost" feature west of the fault

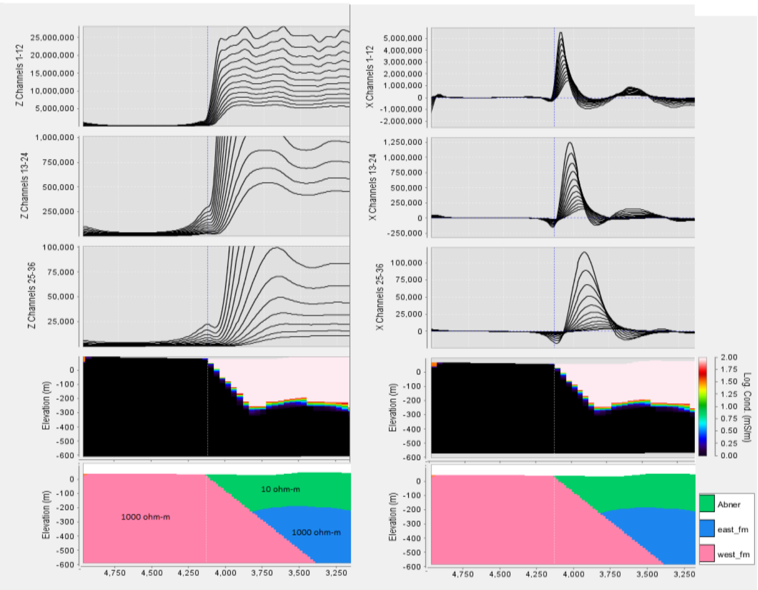


Figure 2. Simple geology model of a dipping fault with a good conductor on the right-hand side at the surface. The Z & X computed forward model response for 36 time gates, with the early times in the top panel. The late time Z shows the pronounced "off-end" effect as does the X component. Inside the conductor and near the edge, moving peaks from early to late time in both the X and Z components map the 3D effect of a current system moving away from the fault edge with time.
The geology model is meant to be an interpretation of the AEM data, once the 2.5D result is taken into account.

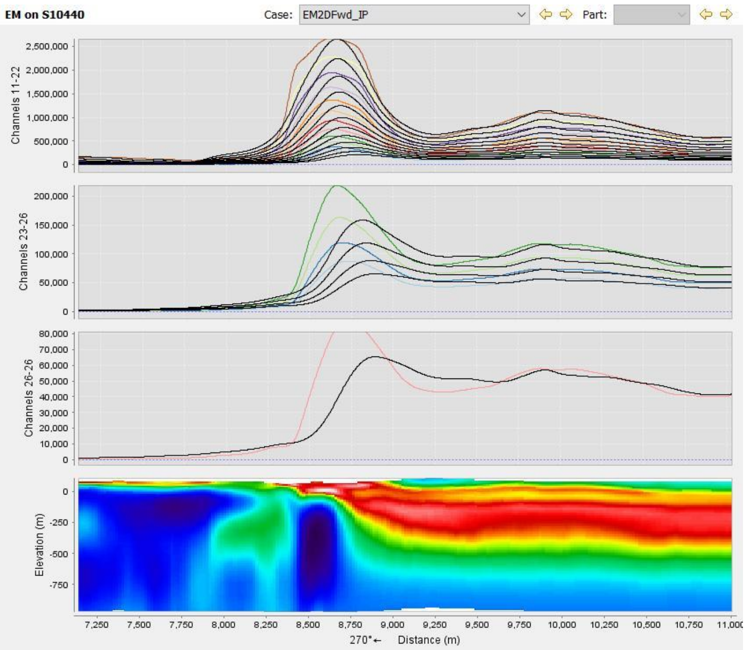


**Figure 3.-Test Line 10440, 1D LCI inversion result – Version 6**
Starting with the 1D inversion result, the 2.5D forward shows misfits of over 100% for the Z component near and over the EMU fault. The data is not fitted in a spatial or temporal sense.
This is in the part of the section, where an off-end effect has been interpreted and fitted with the 2.5D inversion.
The classic 1D prediction, in this context, is the "ghost" conductor to the left and the high resistive blob under the fault/surface contact. Good agreement between data and modelled response occurs some 1.5 kilometres from EMU fault where 1D assumptions are valid.
This is zoomed into the fault section of the line

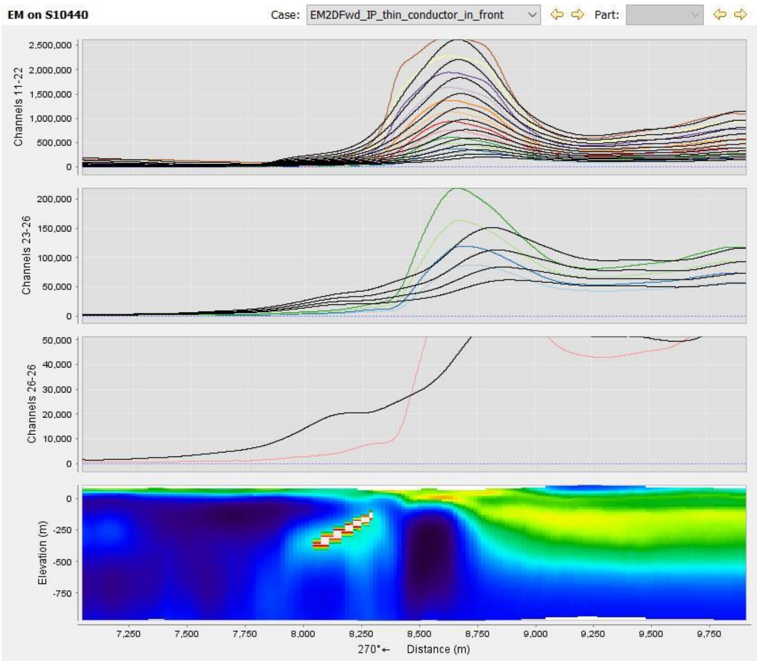


Figure 4. Z component observed (colour) and forward response (black) when a ~25 Siemens "thin" conductor is added to the west of EMU fault set within the 1D generated section.
This example shows that leaving the problems of matching amplitudes aside, the profile shape of the observed data cannot be reconciled with the conductive dipping unit to the west of the fault dominating the response. Simple plate models would also show a similar mismatch in anomaly shape. Estimates for Barney Creek Formation conductivity–thickness product, from areas where there are no potentially overlapping responses from other conductive units is set at about 2-3 Siemens (i.e. low-quality conductor). Within these areas Barney Creek formations do not generate "large" signals at "late" times. Also, note the "off-end" effect and the localized off end peak can be seen in the late-time Z channel. It is very similar to that shown in the synthetic model.

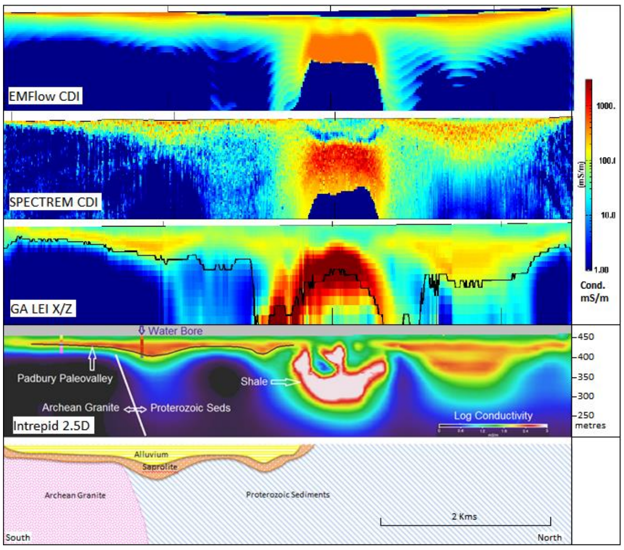


Figure 5. Bryah Basin AEM SPECTREM Survey Example: Comparison of CDI's, 1D and 2.5D Inversions with the previously interpreted geological section along survey line 11050, near the Mt. Padbury paleochannel. Classic trouser leg 1D bodies!

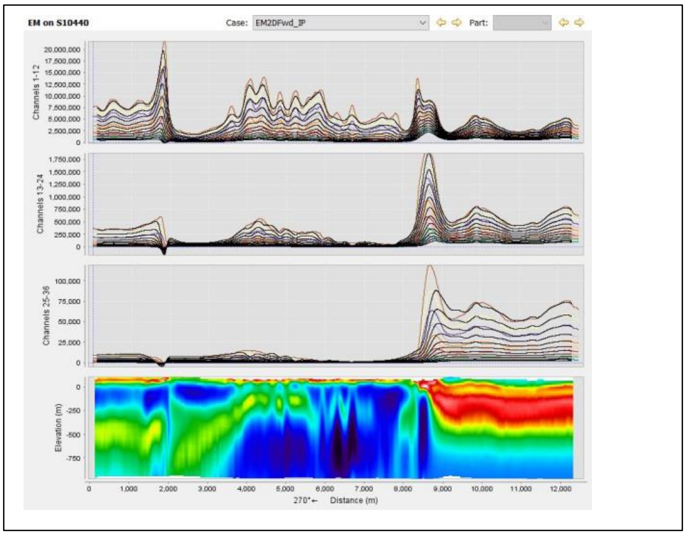


Figure 6. MacArthur Basin AEM, Z component. East-West line over the EMU fault, bottom image is the 1D Aarhus resistivity with IP inversion result, used as a model for a forward response using the 2.5D modelling software that includes the resistivity and the IP parameters. Coloured is the observed and the black lines are the forward response from the model.

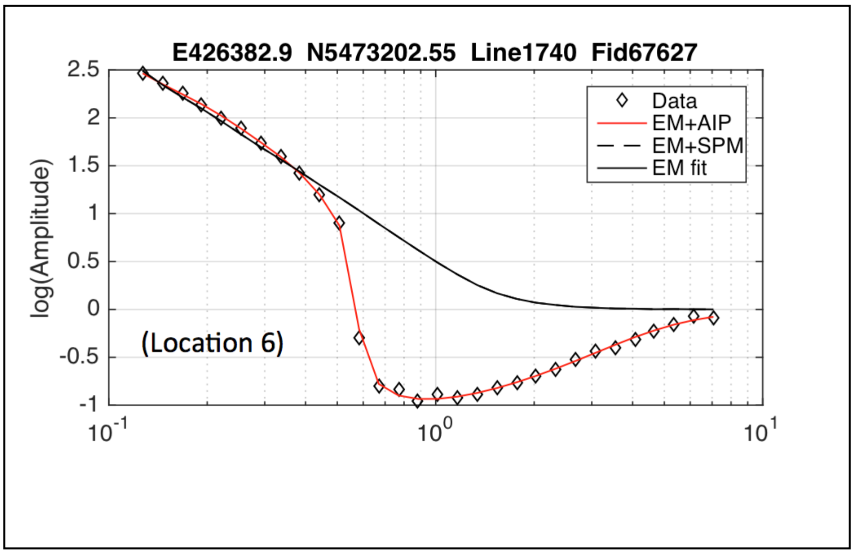


Figure 7. Cole-Cole model has conductivity σ, chargeability η (or mIP), frequency dependence c and IP time-constant τIP.
For AEM, each C-C response needs to be multiplied in frequency domain with the fft of a waveform (injected or induced current) and inverse fft'd to get a (convolved) "typical" response used as one of several basis functions in fitting the data. (courtesy Jim Macnae.)

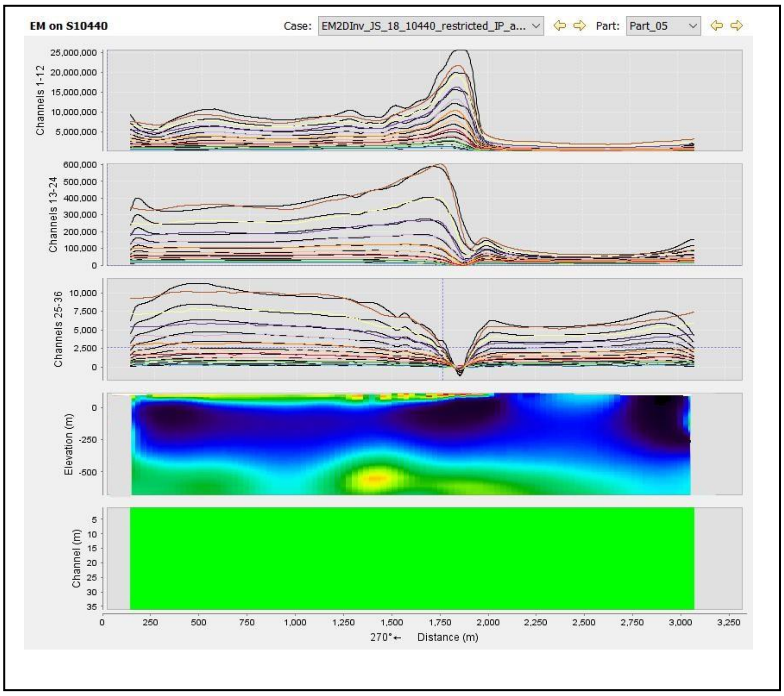


Figure 8. Example of restricting the identification of the IP effects to within a specified depth from the surface and by placing "strict " limits on some of the IP parameters, particularly the IP time constant and the frequency factor, where the IP effect near a surface contact is reproduced by the calculated response. The negative late time response is closely replicated.