Using downhole resistivity to better understand magnetotelluric inversion

Janelle Simpson *
Geological Survey of Queensland
1 William Street Brisbane
University of Adelaide
Adelaide, SA
Janelle.simpson@drnm.qld.gov.au

Graham Heinson
Department of Earth Sciences
University of Adelaide Adelaide, SA 5005
graham.heinson@adelaide.edu.au

SUMMARY

Previous studies have used downhole resistivity logs either as a direct constraint during magnetotelluric inversion or as a qualitative validation of inversion accuracy. This study instead uses synthetic 1D magnetotelluric modelling based on downhole resistivity to better understand results of 1D, 2D and 3D inversion.

One-dimensional models with representative geology for the area were generated directly from downhole resistivity data. These models were used to generate synthetic data, which was then inverted using a range of methods. Synthetic modelling made a significant contribution to selecting an appropriate inversion technique and the quality of the interpretation. Joint use of SimPEG MT1D and Occam 2D inversions proved the most effective combination to understand the geology of the project area.

Key words: Magnetotelluric inversion, down-hole resistivity, synthetic modelling, Occam, SimPEG.

INTRODUCTION

The non-unique nature of inversion is best combated by incorporating independent information during inversion or interpretation. A number of magnetotelluric (MT) studies have successfully used seismic data as additional constraint, either during inversion (e.g. Yan et al., 2017) or during the interpretation process (e.g. Ogaya et al., 2016). Down hole resistivity log data have also been used either as a constraint during inversion (e.g. Yan, 2016) or as a qualitative validation of inversion accuracy (Moorkamp et al., 2013). Another approach is joint inversion of MT with potential field and/or seismic data to better constrain the outputs (Cai and Zhdanov, 2017; Moorkamp et al., 2013).

All of these approaches require the information used to constrain the inversion or interpretation to be coincident with the MT survey. Often, in more underexplored areas these kind of direct constraints are not available. In this study we demonstrate how synthetic modelling of downhole resistivity data can be used to assist with selection of the most appropriate inversion code(s). We also demonstrate how synthetic modelling can guide interpretation to produce not only a more robust interpretation but also a qualitative estimate of interpretation accuracy.

SYNTHETIC MODELLING

Downhole resistivity from the petroleum well Todd 1 (Kress and Simeone, 1993) was extracted for use in this study. Forward modelling (Pethick and Harris, 2015) was used to determine the most appropriate average resistivity structure. Synthetic data were generated from the model using the ModEM 3D inversion code (Kelbert et al., 2014). Random and Gaussian noise at 2.5% was added to the synthetic data. The synthetic data had a frequency range of 10^4 Hz to 0.1 Hz, with five points per decade to represent the attributes of the actual AMT data in the project area. A number of inversion codes were tested to determine which could most accurately recover the original model structure. In addition to selection of the most appropriate code, the synthetic modelling was also used to establish the inversion parameters used in the final inversion of real data. Inversion codes selected for testing were Occam 1D (Constable et al., 1987), MT1D SimPEG (Cockett et al., 2015), Occam 2D (deGroot-Hedlin and Constable, 1990), and ModEM 3D (Kelbert et al., 2014).

Synthetic data were truncated to frequencies higher than 6 Hz for Occam 1D inversions. Models had a maximum depth of 7.5 km with a target depth of 2 km with a stating resistivity of 100 Ω·m. The minimum number of layers needed to achieve an RMS of 1 and reach convergence was nine. Additional inversions were run with number of layers varying from 10 to 100 to establish the effect of the number of layers on the final inversion result.

SimPEG 1DMT inversions used the inbuilt capability to generate synthetic data from a resistivity model during the inversion process. Data error was set at 2.5% and key inversion parameters were determined through a series of tests. Optimal parameters were determined to be: starting resistivity = 100 Ω·m, α_s = 0.001, α_s = 2, β_0 = 6, cooling factor = 2 and cooling rate = 1.

Occam 2D inversions were conducted using data between 10^4 Hz and 6 Hz. All inversions were started using a 100 Ω·m half space. A number of trials were run with differing numbers of layers (n) and error floors; the final inversions were run with n = 60, rho error floor = 5 % and phase error floor = 2 %. ModEM 3D inversions were run using a 100 Ω·m half space mesh size and error floors were set to be comparable to the Occam 2D inversion.

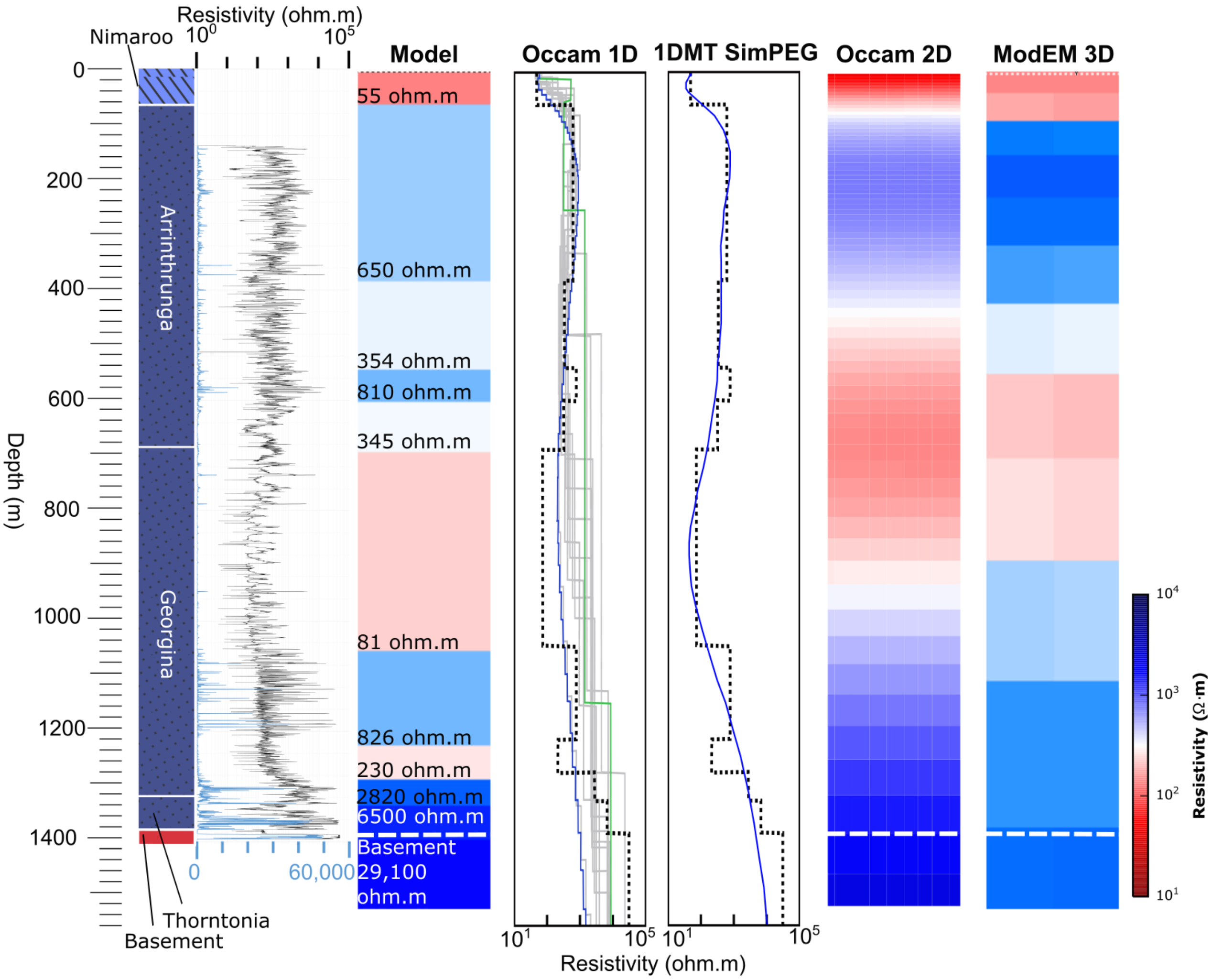

Figure 1: Summary of synthetic modelling. Left to right: down-hole geology; downhole resistivity with linear (blue) and logarithmic (black) scales, Todd 1 simplified resistivity model; Occam 1D inversion modelling, input model in black dashed line, minimum layers model (green), maximum layers model (blue); 1DMT SimPEG model; Occam 2D inversion; ModEM 3D inversion. Input model, Occam2D and ModEM3D all have the same resistivity colour scale. Downhole resistivity from the nearby Bradley 1 well was used to estimate the resistivity data for the surficial Nimaroo formation.

DISCUSSION

The downhole resistivity data from Todd 1 show that there are abrupt changes in resistivity for the area. As a result, even inversion results with excellent data fits may be unsuccessful at recovering geological features. Elevated conductivity is evident in the upper Georgina Limestone and Nimaroo formation.

The inversion codes tested recovered varying levels of the original structure (Figure. 1). Importantly, no code was able to recover the full original structure from a half space starting model. This is due to the combination of noise levels, and difficulties in resolving thin layers at depth. Despite the forward modelling demonstrating that each layer had an impact on the overall MT response, the noise level does not allow the full structure of the models to be resolved. Such limitations from noise together with the smoothing algorithms used to stabilise the inversions are the most likely reason the inversions were unable to resolve the original basin layering.

Synthetic modelling also shows that the recovery of absolute resistivity values from 2D inversion is poor. This is consistent with previous work showing different resistivity distributions for AMT inversions when compared to downhole resistivity data (Bahr, 1997). Together with the poor recovery of depths from the model layering, these results imply that there are likely to be a significant number of models which would adequately fit the data.

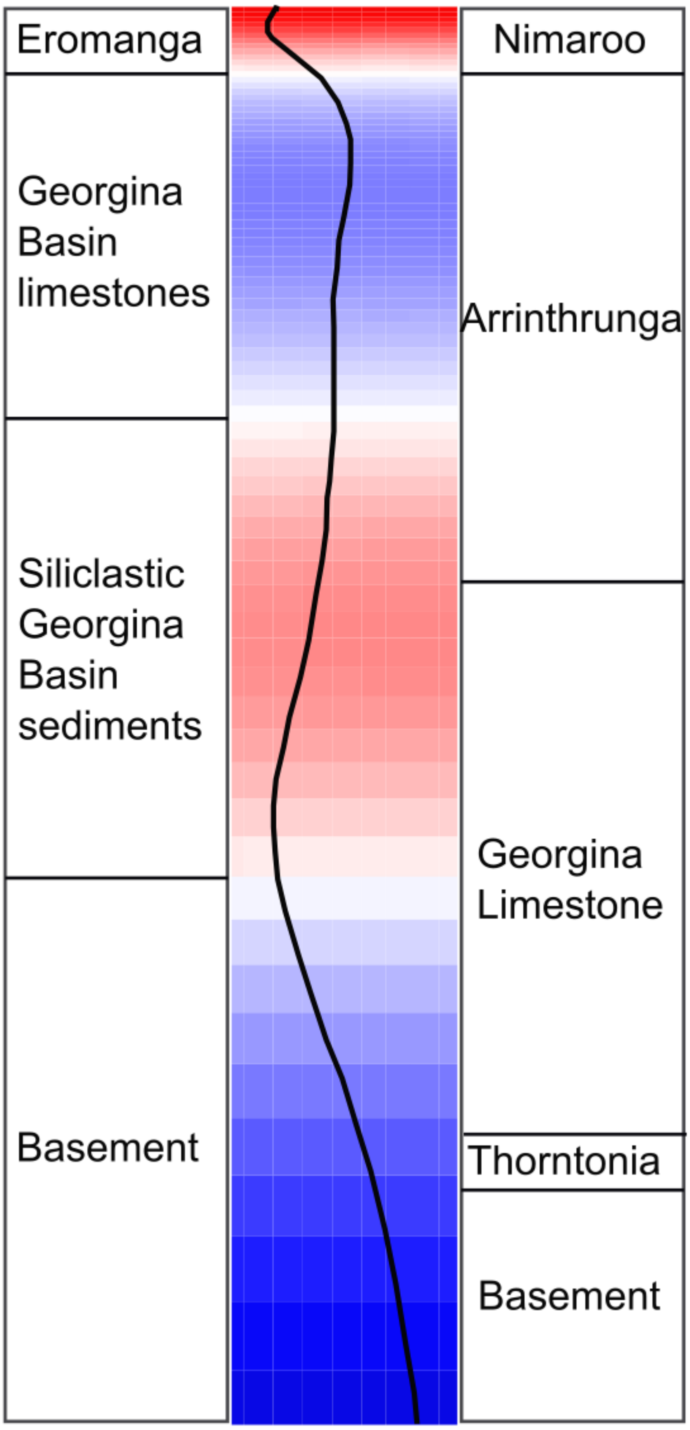

Figure 2: Comparison of original interpretation (left) and final interpretation (right) based on outcomes of synthetic modelling. Central panel shows SimPEG 1DMT inversion (black line) over the Occam 2D inversion.

The two most effective codes identified during synthetic modelling were SimPEG 1D (Cockett et al., 2015) and Occam 2D (deGroot-Hedlin and Constable, 1990). Using the outputs from these two codes in conjunction with the following interpretation 'rules' provide a methodology for a robust interpretation in the absence of a priori geological constraint (see Figure. 2).

1. Interpret shallow conductive feature as Nimaroo Formation - base of layer is accurately recovered by 2D Occam inversion.
2. Use SimPEG inflection points to determine top of Georgina Limestone conductive package – Occam inversion underestimates depth
3. A thin layer (approx. 50 m) of Thortonia Limestone exists at the bottom of the Georgina Basin sequence.
4. Use SimPEG inflection point below conductive layer (deepest most inflection point) to estimate basement depth. Basement expected to be approximately and additional ½ thickness of conductor below the 'base' of the conductor

CONCLUSIONS

In this paper we demonstrate how synthetic modelling of downhole resistivity data can produce better interpretation outcomes. Synthetic modelling allows the interpreter to select the most appropriate inversion technique and parameters. It also produces a set of 'rules' to guide interpretation, reducing the subjective nature of interpretation.

This technique can be applied in areas where directly constraining MT inversion with independent data is not feasible. The technique is most applicable to sedimentary basin environments where a high degree of lateral continuity of geological units is a valid assumption. It also relies on the presence of detailed geological logging and downhole resistivity. Ideally synthetic modelling would be conducted on additional wells in the area to confirm the relationships and signatures established before they are applied to interpretation.

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