Magnetotelluric inversion strategies

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SUMMARY
Regional scale geophysical data is widely and publicly available in many countries. Traditionally, these data include transects that span many hundreds of line kilometres. More recently it was recognised that imaging deep three dimensional crustal structures requires new 3D data sets. An example of this is the Australia AusLAMP magnetotelluric grid. We consider this data from a different perspective and ask how sparse regional data can be incorporated in mineral exploration workflows which focus on the top few kilometres of the Earth. We select a reference area of about 100,000 square kilometres in central Australia, which includes the 450 kilometre long Yilgarn Craton, Officer Basin, Musgrave Province (YOM) seismic and MT transect. We test and compare a number of 1D and 2D inversion strategies with broadband MT data and then stretch that geo-electrical model to the third dimension with an additional 18 long period MT stations on a 50 km grid in the Officer Basin and Musgrave block. With additional data from just a few sparse stations, such as those from the AusLAMP project, we show that the value and outcome of MT inversions can be enhanced. The search for new tier one mineral deposits is transitioning to the under explored deeper covered areas at basin margins, and we have demonstrated techniques for building 3D geo-electrical frameworks towards more relevant shallower exploration depths from including exceedingly sparse long period 3D MT data.

Key words: magnetotelluric, 2D inversion, 3D inversion, ModEM

INTRODUCTION
The Yilgarn Craton – Officer Basin – Musgrave Province (YOM) magnetotelluric dataset was acquired in 2011 by Geoscience Australia in collaboration with the Geological Survey of Western Australia (Neumann, 2013, pp.9). Impedance and tipper broadband (BB) and long-period (LP) magnetotelluric (MT) profile data along the Great Central Road were collected, spanning ~480 km across the Musgrave Province in the east, the Officer Basin in the centre and the Yamarna Terrane in the west (Figure 1). The MT data was acquired alongside deep seismic reflection survey data, which we incorporated as structural constraints in inversion starting models. In addition, long-period data from nearby available AuScope AusLAMP stations (Thiel et al., 2018) were included for some 3D inversions. Detailed descriptions of the YOM data and the geological setting can be found in Neumann (2013, pp.24). See Vozoff (1991) for an overview of the MT method.

METHOD AND RESULTS
MT data processing
Information on data acquisition and processing of the raw MT time-series are described in Neumann (2013, pp.9). MT time-series were processed to the frequency domain and made available by Geoscience Australia as industry standard EDI files without any further edit. For further use, we analysed and post-processed the EDI files, which is briefly outlined below:
Constrained MT inversion

<table>
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<td>e.g. noisy data in MT dead bands</td>
<td>phase tensor analysis provides dimensionality and strike information</td>
<td>decomposed data as TE &amp; TM mode for 1D, 2D and some 3D inversions</td>
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Figure 5 shows a map of the phase tensor ellipses (Caldwell et al., 2004) for the YOM BB data for a maximum of 31 periods between 0.0032 to 104.85 seconds. Colours indicate the phase tensor skew, which is a measure of the asymmetry of the tensor, and is suggestive of the geoelectric dimensionality. Here, values > 3 are considered 3D and smaller values are 2D or 1D in case of near circular ellipses. The map suggests two distinctive terrains: the eastern part over the Musgrave Province is mostly 3D, and the western part over the Officer Basin is largely 1D/2D for periods < 10 seconds. Phase tensor analysis provided an estimate of geoelectric strike of ~165° (with 90° ambiguity) for the YOM BB dataset (Figure 2), and correlates mostly with phase tensor ellipses at periods > 10 seconds, which is possibly associated with the Windularra Fault that separates the Musgrave Province from the Officer Basin (cf. Figure 4).

Figure 2. Polar histogram for all periods of the YOM transect, indicating the regional geoelectric strike of ~165°, with 90° ambiguity. The strike angle was used to decompose the data into TE and TM mode.

MT inversion

We initially inverted the profile data using 1D, 2D and 3D inversion algorithms employing standard inversions with half-space starting models, with as input only rotated impedance data using the geo-electrical strike, decomposed into TE and TM mode. Half-space inversion results are shown in the left-hand-panels of Figure 7. It was found that more conductive half-space starting models resulted in more satisfying results when using the NLCG ModEM2D algorithm (Egbert and Kelbert, 2012). For example, a 400 ohm-m half-space resulted in a rather flat-lying conductive layer in the region of the Officer Basin, but with similar good RMS fit (not shown).

To improve structural fidelity with a focus on the upper 10 km additionally constrained inversions were carried out leveraging the available seismic information. First, the TWT seismic data was converted to depth using the stacking velocities that comes with the data set. The depth-converted seismic 2D section was then broadly categorized into geological units. This information was saved as a high-resolution image where each geological unit was assigned a unique colour as a proxy for resistivity. Subsequently, this image was translated into starting models for Occam1D (Constable et al., 1987), Rebocc2D (Siripunvaraporn and Egbert, 2000) and ModEM2D using in-house written software. Averaged resistivity values from previous half-space inversion runs and well-log data from Empress-1A (Stevens and Apak, 1999) were used to assign resistivity values for the starting model, shown in Figure 3.

Likewise, for inversion of the YOM profile data with ModEM3D, a 3D starting model was devised, here based on an existing geological GOCAD model as described in Neumann (2013, pp.96). In addition to the existing GOCAD surfaces, we included the Table Hill Volcanics as additional surfaces in the 3D model, constrained by the depth-converted seismic section and well-tops from two nearby wells (Empress-1A and Yowalga-3).

The Cambrian Table Hill Volcanics (THV) consist predominantly of basalt flows and are up to 165 m thick (Neumann, 2013, pp. 37) with an average well log resistivity of ~220 ohm-m at the location of Empress-1A. The unit forms a distinctive, highly-reflective, marker horizon on the seismic section. The THV are also incorporated in the displayed starting model for 2D inversion, cf. Figure 3. To populate the remainder of the 3D GOCAD model with resistivities, averaged values from previous unconstrained inversions were incorporated.

For 3D inversion of the YOM BB profile data, the rotated impedance tensor data was used for equitable comparison with the 2D inversion results. Covariance coefficients within ModEM3D inversion were set to 0.2 for all directions, applied twice. The right-hand-panels of Figure 7 show the results of constrained inversions for 1D, 2D and 3D models.

Lastly, full 3D inversion (unconstrained) was carried out including (i) broadband MT stations of the YOM transect, (ii) long period impedance and tipper data from the YOM transect and (iii) long period impedance and tipper data from the AusLAMP MT grid. One objective of the full 3D inversion was to help demonstrate the additional geo-electrical detail that can be resolved off-line with just a few sparsely located LP MT stations some of which are more than 100 km away from the YOM transect. As has been discussed in Campanyà et al. (2016, Fig. 10) and in Siripunvaraporn and Egbert (2009), joint inversion of the full impedance tensor and tipper can produce superior results where off-line conductors are better resolved than impedance data alone. The question that arises is: how many additional off-line stations are required to further improve characterisation of off-line conductors.

The full 3D inversion was implemented in a multitier fashion to save computational resources but also because it achieved superior data fits, rather than inverting the full dataset at once. In the initial phase the following three datasets were created:

- Merged dataset from BB and LP impedances from both YOM and from available AusLAMP stations.
- Merged dataset as before but with tipper included.
• Only YOM broadband impedances (un-rotated)
The three datasets were then used for sequential inversions resulting in the model shown in Figure 7:
  1. The merged impedances (a) were inverted on a relative coarse mesh resulting in a background model for further inversion. Starting model was a 75 ohm-m half-space.
  2. The merged impedances and tipper data (b) were inverted on the same coarse mesh using the previous inversion result as a starting model. It was found that inverting the merged impedances and tipper data directly resulted in poor fits. Using the previous impedance-only inversion as a starting model achieved superior data fits.
  3. The YOM broadband profile data (c) was then inverted on a finer mesh using the result of the previous inversion (impedance and tipper) as a starting model.

CONCLUSIONS

All half-space inversions resulted in satisfactory data fits (i.e. RMS between 2 to 10). Larger misfits were obtained for Rebocc’s smooth 2D inversion and ModEM3D inversions of the rotated profile data; particularly at longer periods (Figure 6). However the results from Rebocc’s unconstrained smooth inversion appears relatively consistent with existing geological interpretations (Neumann et al., 2013, pp. 24). In comparison, ModEM2D unconstrained inversion achieves superior data fits, but it appears to have minimized the error through the introduction of unrealistic geo-electrically patchy regions within the inversion outcome. While the seismic provides clear evidence for near vertical fault systems and large salt walls that cut across sub-horizontal stratigraphy (Neumann, 2013, pp. 45) some patches appear to be related to areas with a combination of small mesh cell-sizes relative to large station separations. These effects occur in the central part of the YOM transect. The large salt wall in the eastern part of the Officer Basin is well defined by seismic imaging and was revealed by all unconstrained MT inversions.

The constrained inversions used starting models based on structural information from seismic imaging. This framework was populated with prior resistivities from previous half-space inversions except for the Table Hill Volcanics which was populated with resistivity directly from wire-line line logs obtained in the well Empress-1A. Inversion results broadly honoured these soft constraints maintaining the relative sharp resistivity contrasts as imposed in the starting model. ModEM2D overall resulted in sharper boundaries, as compared with Rebocc2D, which is a manifestation of the implementation of the different algorithms. Put simply the Rebocc2D inversion imposed higher levels of smoothing employing an Occam style inversion. The unconstrained 3D inversion of the rotated profile data was able to image the high resistivity section overlying the more conductive Officer Basin, which was sharpened using the constrained inversion. Note that the 3D inversion ran on a coarser mesh than the 2D counterparts. Overall, 1D, 2D and 3D inversions of the rotated YOM profile data starting from a geological model populated with prior resistivity distributions tend to achieve superior data fits along with a highly reasonable geo-electrical model when compared to the seismic and electrical wireline logs from drill hole data (Figure 6).

The full 3D inversion result based on broadband and long-period full impedance and tipper data is shown in Figure 7 and exhibits broadly similar features across the YOM transect. Moreover, features offline from the YOM transect reveal an NE-SW trending conductivity structure that largely coincides with the transition from surrounding basins to the Musgrave Block. To extend the recovered conductivity from the YOM transect to the south-western edge of the displayed model, only one additional remote AusLAMP station was required, proximal to the S-E distinct gravity low (cf. Figure 8B).

In summary we created a multithreaded 3D MT inversion approach able to combine broadband MT data from the 450 km long YOM transect with just a few sparse 3D MT stations from the AusLAMP survey to achieve a 3D resistivity model with excellent data fits that spanned many thousands of square kilometres. Given that the data from the 50 km AusLAMP grid will be available in the near future, existing or new 2D MT profiles can be improved by inversion that incorporates a background model based on long-period AusLAMP data. Our next steps will include various 3D constrained inversions for this augmented MT dataset (e.g. the YOM line and AusLAMP grid MT data).

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Figure 6. Representative MT responses of the various recovered models discussed above for broadband station BB64 in the western Officer Basin (marked red in Figure 1). Top panel are apparent resistivities; bottom panel display the corresponding phase responses. Small periods are overall fitted well. Longer period data is poorest for the ModEM3D profile responses, while the mult-tiered ModEM3D inversion exhibits excellent fits across all periods for phase and apparent resistivity at all stations.

Figure 7. Inversion results of YOM profile data across the Officer Basin. From top to bottom, respectively, the panels show inversion results for Occam1D, Rebo2D, ModEM2D and ModEM3D. Left panels show results for a 75 ohm-m half-space starting model; right panels show results using starting models based on seismic horizons and initial resistivity guesses.
Figure 8. 3D ModEM inversion result of YOM broadband data across the entire YOM line, including both Officer Basin and Musgrave Province. YOM broadband and long-period as well as AusLAMP long-period were subject to inversion, using a multitier inversion strategy where first a coarse background model was obtained from long period impedance and tipper data, which was then used as a starting model for inversion of the YOM broadband data on a refined mesh. B: horizontal slice at 2.5km depth through the recovered resistivity model with gravity contours overlain, where white contours indicate low and black contours indicate large Bouguer anomaly values (cf. Figure 1). AusLAMP stations are shown as pink squares. Note that the colour scale is the same as in Figure 7, however resistivities in the Musgrave exceed 10^5 ohm-m.