Application of audio-magnetotelluric method to cover thickness estimation for drill site targeting

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SUMMARY

Cover thickness estimation is critical to mineral exploration effectiveness in covered terrains. Geophysical methods are able to detect physical properties contrasts in different earth materials without seeing them. We present the application of the audio-magnetotelluric (AMT) technique to cover thickness estimation using deterministic and stochastic inversion approaches. The deterministic Occam’s inversion method solves the regularised problem by searching for the smoothest model that fits the data within certain tolerances. The stochastic algorithm uses trans-dimensional Markov chain Monte Carlo techniques to generate an ensemble of millions of conductivity-depth models that adequately fit the data given the assigned noise levels. Statistics are derived from the posterior probability distribution of the conductivity at depth. This approach gives more pronounced layer boundaries that allows more straightforward interpretation of resistivity structure.

We have applied the AMT method to cover thickness estimation for two regional drilling projects, i.e. Southern Thomson Orogen and Coompana Province. The application of the method was validated using drillhole results. Cover thickness estimates compared favourably with drillhole results, demonstrating that the method is a valuable tool to an Explorers’ Toolkit of techniques to reduce the risk in searching for new mineral deposits in covered terrains.

Key words: magnetotelluric, cover thickness, Occam’s inversion, trans-dimensional Monte Carlo.

INTRODUCTION

Knowledge of cover thickness is critical to mineral exploration effectiveness, because 80% of Australia is covered by sedimentary basins and regolith. The ability of mapping cover thickness will greatly increase the confidence of explorers to target relatively easy-to-explore mineral resources in highly prospective areas.

We have actively used a range of geophysical methods to map cover thickness, including airborne electromagnetic (AEM), magnetotellurics, seismic refraction, passive seismic and magnetic methods. These geophysical techniques are applicable to cover thickness estimation because they are able to detect physical properties contrasts in different earth materials. However, each geophysical technique has capabilities and limitations, and these must be understood and considered when designing a geophysical investigation program. It is important that the results from geophysical surveys are integrated with real “ground-truth” data such as drillhole logs to ensure accurate interpretations.

We present the application of audio-magnetotelluric (AMT) technique to cover thickness estimation using deterministic and stochastic modelling approaches. We have applied the AMT method to two regional drilling projects, i.e. Southern Thomson Orogen and Coompana Province. The application of the method was validated using drillhole results, demonstrating that the method is a useful tool for drill site targeting to reduce exploration cost and risk in covered terrains.

MATERIALS AND METHOD

The magnetotelluric (MT) method measures the natural magnetic and electric (telluric) fields of the Earth. The ratio of the two fields, expressed as their impedance, can be used to derive the electrical conductivity/resistivity structure of the subsurface beneath the site of data acquisition. The AMT method samples signals in the audio frequency range of 20 kHz to ~1 Hz, and provides data pertaining to the upper few kilometres of the crust, thus this technique is preferred for mapping cover thickness. For an explanation of the MT theory, refer to Chave and Jones (2012), Vozoff (1991) and other references cited therein.

Data Acquisition

We used Phoenix Geophysics (http://www.phoenixgeophysics.com) manufactured MTU-5A receivers, MTC-150L coils and non-polarisable electrodes to acquire the AMT data. A typical layout of the Phoenix Geophysics equipment is shown in Figure 1.
The instruments were deployed to simultaneously acquire two orthogonal components of telluric data (Ex and Ey), and three components of magnetic data (Hx, Hy and Hz). Two pairs of electrodes, each forming an electric dipole of 100 m, were aligned to geomagnetic north–south and east–west respectively. A fifth electrode was installed as a protective ground for the main recording unit. Two of the magnetic coil sensors were also aligned to geomagnetic north–south and east–west and were accurately levelled. An additional vertical magnetic coil was also installed if logistics and ground circumstances permitted. This allowed for using the relation between the horizontal and vertical magnetic fields, i.e. the vertical magnetic transfer function for further investigation of induced currents (Jones et al., 1989).

Two recent regional drilling projects (Figure 2) were undertaken by Geoscience Australia in collaboration with the State geological surveys, which aimed to improve the understanding of the basement geology, cover sequences and mineral potential in the area through stratigraphic drilling. The Thomson Orogen is one of the most poorly understood regions of Australia’s geology, because almost 99% of the orogen is buried beneath younger sedimentary basins and regolith cover, largely consisting of Lake Eyre Basin and Eromanga Basin rocks. There are generally many tens to a few hundred metres of overlying unconsolidated or indurated Cenozoic and Mesozoic cover. The Coompana Province is a true greenfields frontier because there are no known rock exposures due to extensive Neoproterozoic to Cenozoic cover sediments of the Officer, Denman, Bight and Eucla basins. To reduce drilling risk, we used a number of geophysical methods to estimate cover thickness to inform drilling team for drill site targeting. We also used drillhole results to validate and estimate cover thickness to inform drilling team for drill site reducing drilling risk, exposures due to extensive Neoproterozoic to Cenozoic cover.

Determination of the basement geology, cover sequences and prior knowledge is needed to identify the major discontinuities in the resistivity structure of the Earth, e.g. an

Deterministic Inversion

Occam’s inversion method solves the regularised problem by searching for the smoothest model that fits the data within certain tolerances (Constable et al., 1987). In particular, the regularised inverse problem seeks a model that minimises the model roughness, the difference from an a priori preference model and misfit of the model’s forward response. A Lagrange multiplier serves to balance the trade-off between the data fit and the model roughness and model preference. The utility of this method is that it generally produces smooth peaks in the model that correspond to features that are well constrained by the data, whereas features that are not essential in matching the observations are suppressed or entirely smoothed out (Key 2009).

When inverting 1D datasets, we use the geometric mean of the apparent resistivity \( \rho = \sqrt{\rho_x \rho_y} \) and the arithmetic mean of the apparent phase \( \theta = (\theta_x + \theta_y)/2 \).

Stochastic Inversion

We have developed an algorithm called Rj-McMCMC, which is built upon an open-source library by the Research School of Earth Sciences, Australian National University, called rj-McMC (Hawkins, 2013). The algorithm uses trans-dimensional Markov chain Monte Carlo techniques to solve for a probabilistic conductivity-depth model. The inversion of each station employs multiple Markov Chains in parallel to generate an ensemble of millions of conductivity models that adequately fit the data given the assigned noise levels. The trans-dimensional aspect of the inversion means that the number of layers in the conductivity model is solved for rather than being predetermined and kept fixed. Each Markov chain increases and decreases the number of layers in the model and the depths of the interfaces as it samples.

Once the ensemble of models is generated, its statistics are analysed to assess the posterior probability distribution of the conductivity at any particular depth, as well as the number of layers and the depths of the interfaces. This stochastic approach gives a thorough exploration of the model space and a more robust estimation of uncertainty than deterministic methods allow.

When inverting impedance data, we use the determinant of the impedance tensor \( z = \sqrt{\rho_x^2 \rho_y^2 - \rho_x \rho_y} \). When inverting apparent resistivity and phase data, we use the geometric mean of the apparent resistivity \( \rho = \sqrt{\rho_{xy} \rho_{yx}} \) and the arithmetic mean of the apparent phase \( \theta = (\theta_{xy} + \theta_{yx})/2 \).

Relative and absolute noise standard deviation estimates for the data to be inverted are specified and combined (assuming independence) to generate the total noise estimate that is used in the inversion to calculate the error normalized (L2-norm) data misfit.

For details of the algorithm, refer to Brodie and Jiang (2018).

**RESULTS AND INTERPRETATION**

AMT data were inverted using the Occam’s inversion and the Rj-McMCMC methods. The Occam 1D inversion code produces step-like smooth models from a set of parameters, and prior knowledge is needed to identify the major discontinuities in the resistivity structure of the Earth, e.g. an
approximation of the resistivity value at which the geological structure transition occurs. Instead, the stochastic modelling approach gives more pronounced layer boundaries that allows more straightforward interpretation of resistivity structure.

Across the ten survey sites in the Southern Thomson, the resistivity model produced from the MT responses indicates low resistivity (< 10 Ωm) in the upper tens to few hundred metres, which is interpreted as the Eromanga Basin sedimentary rocks, likely to be unconsolidated deposits or consolidated sediments or rocks saturated with groundwater, e.g. Winton Formation, Wallumbilla Formation and Wyandra Sandstone aquifer. Down to a greater depth, the resistivity value increases from 10 Ωm to 10^2-10^3 Ωm, representing the transition from the underlying Permo-Triassic or Devonian sedimentary sequences, e.g. Cadna-owie Formation (10 Ωm to 400 Ωm; Spence and Finlayson, 1983) to the highly resistive crystalline basement, which is likely to be unweathered igneous or metamorphic rocks. Examples are given in Figure 3 and Figure 4.

In the Coompana Province, the resistivity models show the presence of a moderately resistive layer (~150 Ωm) in the upper few tens of metres (~30 m to 60 m), which is interpreted to be the Nullarbor Limestone. Beneath, it is evident that the MT responses experienced a transition from resistive to conductive rocks, from chalky fossiliferous limestone (Wilson's Bluff Limestone) to a more conductive structure which is characterised by low resistivities less than 10 Ωm. This layer is interpreted to be Pidinda Formation and/or Madura Formation, likely to be unconsolidated deposits, e.g. claystone/siltstone with shale, or carbonaceous mudstone/sandstone. The enhanced conductivity may also be attributed to sediments or rocks saturated with groundwater. Down to a greater depth, the resistivity value gradually increases to 10^2-10^3 Ωm, representing the Loongana Formation (sandstone) and the underlying basement. Examples are given in Figure 5 and Figure 6.

For the purpose of cover thickness estimation, the resistivity contrast between the overlying rocks and the basement is defined at the depth where the apparent resistivity value exceeds 10 Ωm. Due to limitations of the MT technique and uncertainties associated with data inversion, a margin of ±10% is suggested on the final estimates. The averaged estimates from the deterministic and stochastic algorithm compare favourably with drillhole results with an accuracy within 10%.

CONCLUSIONS

We have demonstrated the use of AMT data to map the resistivity structure of the layered Earth for cover thickness estimation purposes. The method was applied to two regional drilling projects, i.e. Southern Thomson and Coompana Province. The application of the method was validated using drillhole results, and the method produced reliable cover thickness estimates. This suggests that the AMT method can be used for drill site targeting and is a valuable tool to an Explorers’ Toolkit of techniques to reduce the risk in searching for new mineral deposits in covered terrains.

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REFERENCES


Figure 3. Left: plots showing apparent resistivity magnitude and phase. Dots showing data points and solid line showing fitted inversion model. Middle: black line showing the smooth model and hachured blocks showing the estimated resistivity structure from the model. Right: the stratigraphy interpretation from the adjacent borehole. Site: GSQ Eulo 1 (Roach et al., 2017).

Figure 4. Plot summarising the results of the Rj-McMCMT inversion: (a) & (b) real and imaginary impedances and error bars (red) and the best fitting model from each Markov chain (blue); (c) data misfit convergence history for each Markov chain; (d) histogram of the number of model layers; (e) the summary median, 10th and 90th percentile, mean and mode models over lying the pseudo-coloured shaded image of the 2D log-PPD histogram; (f) the changepoint histogram showing the probability of where layers interfaces occur; and (g) the stratigraphy log from the adjacent borehole. Site: GSQ Eulo 1 (Roach et al., 2017).
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