Integrated inversion of electromagnetic and geological data for regolith characterisation

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SUMMARY

An increase in demand for commodities coupled with a decrease in world-class ore deposit discoveries in the last three decades is the driving force for exploring for a new generation of world-class ore deposits at depth. Exploration through cover is becoming one of the critical challenges for the mineral exploration industry.

This paper explores methods of integrating geophysical, geological and landscape data so as to reduce uncertainty in landscape evolution models interpreted from inversion of electromagnetic (EM) data. Inversion of EM data is, in general, non-unique: many different models will be able to fit the EM data equally well, resulting in large uncertainty. However, EM model uncertainty can be significantly constrained when geological and landscape context are taken into account. This study aims to characterise the regolith (weathered and transported cover), and understand how its conductivity varies with the landscape and with the regolith architecture. This is assisted by logging information from 104 boreholes penetrating through the regolith and into the basement rocks. The study area is associated with the DeGrussa Cu-Au deposit located in the Capricorn Orogen of Western Australia, a regolith-dominated terrain where the regolith varies in thickness between <5 and ~150m.

We first select EM decay curves, extracted from an airborne EM survey, whose locations are close to those of the boreholes. We then use a layered-earth (1D) forward model, and invert those data for the electrical resistivities of each of the lithologies identified on the geological borehole logs. Layer boundary depths are fixed to the borehole depths. We show how the non-uniqueness associated with EM inversion can be reduced by the inclusion of decay curves from geology with different layer thickness ratios.

Lithological models derived from the integration of electromagnetic, geological and landscape data show less uncertainty and are therefore more reliable for mineral exploration targeting.

Key words: mineral exploration, electromagnetics, inversion, regolith.

INTRODUCTION

Most world-class ore discoveries were made close to the surface. Many of these large-tonnage deposits are mined out or are decreasing in production. This situation, coupled with the prediction of a massive increase in demand for mineral resources, is driving investment in the development of technologies and exploration protocols for ore discoveries at depth (e.g., the Uncover initiative in Australia).

Regions that were considered to be unfavorable for ore deposit exploration are now being reconsidered. Among these areas are vast deeply weathered regions called Regolith-Dominated Terrains (RDTs), which extend ~25% of the total continental surface, and were formed under humid sub-tropical to tropical climates, many of which have extensive transported cover (e.g., Australia, Brazil, India, West Africa and China; e.g., González-Álvarez et al., 2016a).

Even if regolith thickness is strongly linked to basement geology, deeply and intensely weathered profiles coupled with sedimentary cover obscure the surface expression of the geochemical features of the basement, and therefore blur and in some cases obliterate the geochemical footprints of mineral systems at depth. A better understanding of the regolith thickness and architecture becomes a critical element to successfully explore these regions for commodities (e.g., Anand and Butt, 2010).

The DeGrussa Cu-Au deposit is one of the most important recent VMS discoveries in Australia (~400,000 Cu tones and ~ 400,000 Au ounces). The DeGrussa deposit is located in the Proterozoic Bryah Basin, Capricorn Orogen. The area is in a RTD at the cratonic boundary north of the Yilgarn Craton. The weathered cover varies in thickness from <5 m above the ore deposit to ~150 m to the west in the Gascoyne palaeochannel system. The Proterozoic rocks in the Degrussa area present numerous metal anomalies (e.g., Cu), as well as in the in situ weathered regolith and sedimentary packages deposited above (Tertiary channels and Quaternary alluvium/colluvium; González-Álvarez et al., 2015).

Airborne electromagnetics can be a powerful tool to correlate the geology between known stratigraphic cover profiles (e.g. Munday et al., 2001). This has the potential to significantly improve the cover architecture reconstruction in 3D, which has important implications for describing landscape and regolith evolution and, therefore, for mineral exploration undercover. Airborne EM can 'map' the surface of the weathering front (Anand and Butt, 2010 and references therein), and define differences in regolith stratigraphy based on properties of the features present that influence conductivity: clay mineralogy, porosity, permeability, groundwater content and chemistry and basement rock lithology (e.g., Palacky, 1987; Munday, 2009; González-Álvarez et al., 2016b).

However, there are few research case studies that have compiled and integrated enough data to tailor airborne EM inversions to specific landscapes. This study aims to contribute to the understanding on how to articulate a truly integrated airborne electromagnetic and geological and landscape data in a crossbreed model.

METHOD AND RESULTS

We are interested in using the EM data to help define the depth of fresh basement rocks, the presence of palaeo-valleys and -hills, as well as the difference between in-situ weathered regolith and transported cover. We have detailed geological logs available along a series of transects, where the rock has been classified into a number of different basement types and regolith types. Figure 1 shows a map of the area, showing the borehole locations. Figure 2 shows a sample subset of the geological logs.

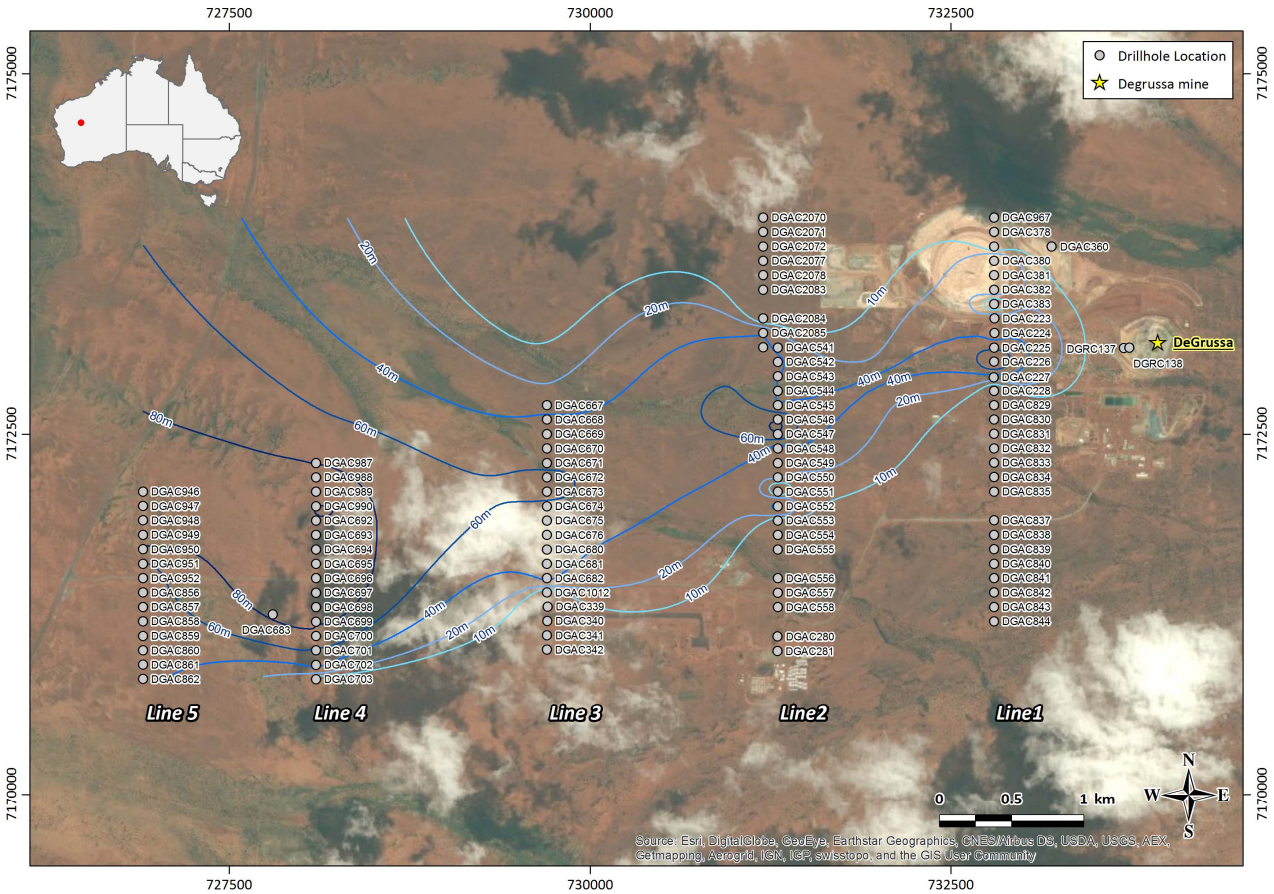

Figure 1 Map showing the study area location, and the logged boreholes. Interpreted palaeochannel depths are also shown as contours.

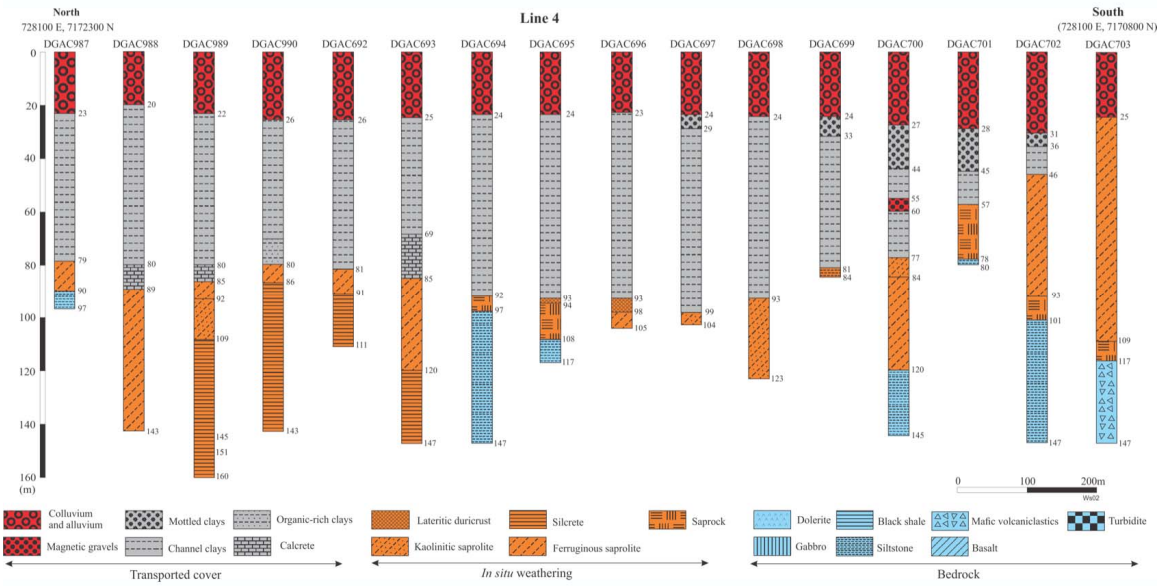

Figure 2 Example drilling logs, showing the lithological units present in the regolith and basement (from González-Álvarez et al. 2015)

The aim is to use the geological logs to constrain depths, and try to invert for a consistent set of resistivities, one for each lithology type, which allows us to reproduce the observed data. That is, we hope to determine the resistivity of each lithology from these inversions. Once we have characterised the electrical properties of the different lithological units present, we can then invert the wider EM dataset for the boundary depths of these different geological units. In this paper, however, we focus on the issue of determining representative electrical properties for each lithology.

EM inversion is subject to an inherent non-uniqueness, where each point on an EM decay essentially only determines a cumulative conductance value down to that depth. Layer resistivities can be modified without changing the fit to the data, so long as these cumulative conductivity-thickness products remain the same. In order to get around this non-uniqueness, we need to find a set of boreholes with different combinations of thickness ratios of the different lithological units. In this way, a change in model resistivities that does not affect the data fit for one decay will, nonetheless, change the fit on another decay with different lithological thickness ratios.

For the layered-earth forward modelling, we have used the open-source code AirBeo (Raiche et al., 2007); for inversion, we use optimization code from SciPy (Jones et al., 2001). The results shown in this paper assume that induced polarization (IP) effects can be ignored, but there are regions in the dataset where negative decays, whose presence is strongly spatially correlated, are clearly indicative of IP effects.

We use a Bayesian framework for our problem (Tarantola, 1987), where the log posterior probability is given by

$$\log P\left(\mathbf{m}\right) \sim \left(\mathbf{f}\left(\mathbf{m}\right) - \mathbf{d}_{obs}\right)^T \mathbf{C}_D^{-1} \left(\mathbf{f}\left(\mathbf{m}\right) - \mathbf{d}_{obs}\right) + \left(\mathbf{m} - \mathbf{m}_{prior}\right)^T \mathbf{C}_M^{-1} \left(\mathbf{m} - \mathbf{m}_{prior}\right).$$

Here **m** is the model parameter vector, **f**(**m**) is the predicted data generated by our forward model, $\mathbf{d}_{obs}$ is the observed data, $\mathbf{C}_D$ is the data covariance matrix, $\mathbf{m}_{prior}$ is a prior model parameter vector, and $\mathbf{C}_M$ is the prior model covariance matrix. In this case, the model comprises only the layer resistivities since the depths are fixed from borehole information. The prior model is derived from the best resistivity values available in the literature (e.g. Munday et al., 2001; Palacky, 1988). The model covariance is a diagonal matrix containing uncertainties in the prior resistivity values.

A number of overlapping AEM surveys were flown on different dates, which allowed us to estimate errors in the data by finding points where flight lines from different surveys crossed. A set of pairs of points was assembled from different surveys, with location differences of less than 2m in plan, and less than 2m elevation difference. Comparing the data from the two surveys gave us an error estimate, which was used to construct the data covariance matrix. The data have also had an along-line smoothing filter applied, so there are in fact additional sources of error which are likely to be underestimated by this procedure.

The posterior covariance matrix, $\mathbf{C}_M^{post}$, estimated from the Jacobian at the best-fit solution,

$$\mathbf{C}_M^{post} = \left(\mathbf{J}^T \mathbf{C}_D^{-1} \mathbf{J} + \mathbf{C}_M^{-1}\right)^{-1},$$

gives a good first-order estimate of the model non-uniqueness. Here **J** is the Jacobian matrix, composed of the derivatives of each data point with respect to each model parameter. Eigenvectors of the posterior covariance that correspond to small eigenvalues represent directions in which large changes in the model produce only small changes in the data fit, and so represent the directions of

non-uniqueness. The condition number of the covariance matrix, i.e. the ratio of largest to smallest eigenvalue, tells us whether the combination of boreholes has reduced the non-uniqueness on the solution.

The first step was to attempt to fit the borehole-constrained EM decays, all at once, by using a single resistivity for each lithological unit. It quickly became apparent that saprolite is not a homogeneous material, i.e. the decays could not be fitted using a single resistivity value for the saprolite in the different boreholes. This was expected, since the physical properties of the saprolite are likely to depend on the basement rock from which the saprolite was derived. For this reason, a separate saprolite lithology has been introduced corresponding to each basement lithology.

Even in the case where depths to layer boundaries are known from borehole information, there is a large ambiguity because of the non-unique solution to the EM inverse problem. An example is shown in Figure 3 (left) where the posterior log probability is shown as a two-parameters slice through the best fit solution to a single decay. This borehole log showed three layers: a colluvium on the surface, a saprolite, and a dolerite basement. As can be seen in the figure, there is a large range of parameter combinations of the two layer resistivities which could fit the data. The plot on the right of Figure 3 shows how the uncertainties are reduced when two decays are used, both with depths constrained by borehole information, both with the same lithologies present, but with differing layer thicknesses.

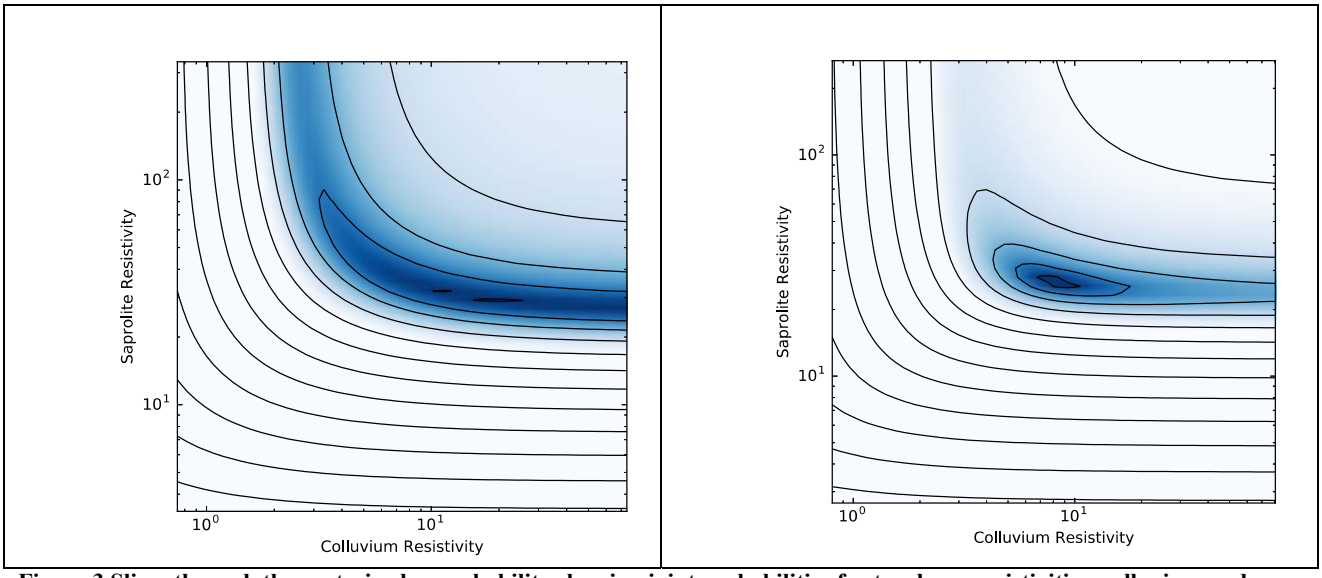

Figure 3 Slices through the posterior log probability showing joint probabilities for two layer resistivities, colluvium and saprolite, of a 3-layer case when depths are fixed by borehole information. (left) Inversion of the decay over a single borehole. There is a large ambiguity in the resistivity values because of the inherent EM non-uniqueness. (right) Two boreholes inverted simultaneously provide a much smaller uncertainty when the layer thickness ratios are very different.

CONCLUSIONS

Inversion of electromagnetic data is plagued by the problem of non-uniqueness, where many different models all result in a similar fit to the data. However, this non-uniqueness can be significantly reduced by incorporating geological and landscape information into the inversion. An example was shown, of how borehole information about lithologies and depths of interfaces can be used to constrain EM inversions, and on how non-uniqueness can be reduced with the right combination of prior information, in this case the use of a set of decays over boreholes with different layer thickness ratios. The resulting reduction in uncertainty improves the usefulness of EM data for mineral exploration.

ACKNOWLEDGMENTS

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