Assessing the presence of hard rock along a gas pipeline alignment with airborne EM

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SUMMARY

Over the past decades, airborne electromagnetic (AEM) surveys have mostly been used in connection with mineral exploration and a variety of issues in hydrogeophysical mapping. However, increasingly, AEM is used for a wide range of geotechnical purposes: pollution mapping, geotechnical assessment on road and freeway alignments, bathymetry, and depth to bedrock.

We present an investigation using a helicopterborne transient electromagnetic system along the planned trace of a gas pipeline. Oil and gas pipelines are often buried at a depth of a few meters and the cost of construction depends critically on whether the subsurface is composed of soft sediments that can be easily excavated or hard rock formations that require much heavier equipment and possibly have to be blasted. The aim of the AEM survey was to distinguish between the soft, relatively conductive sediments and the hard, relatively resistive bedrock in the upper few meters of the subsurface.

Data were collected with a rather small transmitter moment, but a high repetition frequency that simultaneously allowed high acquisition speed, and reliable data quality. Measurements were inverted with 1D models with both vertical and lateral constraints to produce model sections along flight lines. A novel method of statistical analysis of the set of equivalent models for each inverted model, calibrated against boreholes, improved the estimates of the presence of hard rock along the flight lines.

INTRODUCTION

Airborne electromagnetic methods have occasionally been applied to shallow geotechnical investigations for major infrastructure such as pipelines, railways and tunnels. AEM methods offer particular advantages when on-ground access for geotechnical drilling is difficult, either due to rugged topography, or to delays incurred in obtaining environmental approvals or negotiating access with landholders. AEM surveys can reduce planning risk by predicting likely near-surface ground conditions ahead of construction.

Hodges et al. (2000) have described a frequency-domain AEM survey for pipeline construction in Canada which showed good correlation between shallow bedrock and high AEM apparent resistivities. Data from the highest available frequency (56 kHz) was inverted to produce "depth to bedrock" sections along the pipeline route to aid construction planning. Beard and Lutro (2000) describe a helicopter AEM, magnetic, radiometric and VLF survey along a proposed railway route in Norway. The aim of the geophysical survey was general geological mapping along the proposed route, as well as identification of faults, fractures and dykes which may have been problematic for tunnel construction. Pfaffhuber et al. (2010) use a transient AEM system to assess landslides and potential tunnelling hazards in Norway.

This paper presents a method for automatic estimation of geoelectrical boundaries. A field example is presented from a SkyTEM AEM survey conducted in 2011 along a proposed gas pipeline alignment in eastern Australia. The gas pipeline is to be buried, requiring excavation to a depth of 3 m. The objective of the AEM survey was to identify areas of shallow basement along the profile, which are more likely to require specialised excavation machinery and/or blasting.

Estimating formation boundaries from 1D inversion of electric and electromagnetic data with multi-layer models can be challenging because of the inevitable regularisation of this type of inversion resulting in more or less smeared transition zones between formations.

Conventional wisdom has it that inversion with few-layer models will solve the problem by providing models with well defined layer boundaries. However, in modern profile-oriented, laterally correlated inversion, the number of layers is the same for all models along the profile. This may cause lateral changes in formation boundaries (e.g., pinch-out of a particular geological unit) to be poorly indicated, and sometimes a specific formation will "change layers" along the profile meaning that layer boundaries are no longer formation boundaries.

We suggest a new approach to the definition of formation boundaries. It is based on multi-layer inversion models and finds formation boundaries through a statistical analysis of the set of equivalent models obtained in a stochastic process with a correlation function defined by the posterior covariance matrix of the inversion. The method surmounts several of the difficulties mentioned above and will be applied to the pipeline survey.

INVERSION METHODOLOGY

In this study we shall use the a well-established iterative damped least squares approach (e.g. Inman et al., 1975; Menke, 1989) to the inversion of EM data with a 1D model consisting of horizontal, homogeneous and isotropic layers.

Inversion is carried out using multi-layer models, sometimes called "smooth" models, that divide the subsurface into a large number of layers. In the iterative inversion, the layer boundaries are kept fixed and only the layer resistivities are updated. In this study we have used a 30 layer model with increasing layer thickness with depth: a top layer thickness of 0.5 m and a depth to the bottom layer boundary of 150 m.

To avoid geologically irrelevant models, constraints on the vertical variability of model resistivity are imposed through the use of a broadband model covariance matrix (Serban and Jacobsen, 2001; Christensen et al., 2009). It has superior robustness and is insensitive to the model discretization. The strength of the regularisation has been chosen pragmatically by inspection of the resulting model sections.

In most parts of the survey area, the lateral changes are gradual, but because of the local character of the data noise in space and time, individual inversion of the sounding data does not ensure lateral continuity of the model sections. It is therefore reasonable to impose continuity by lateral correlation of the models and we have used the Lateral Parameter Correlation approach of Christensen and Tølbøll (2009). We have chosen to use the same broadband covariance matrix for the lateral correlation as for the vertical smoothness. In this way, we obtain smoothness in the areas where it is justified. All models in the area were correlated with each other and not separated into flight lines.

STATISTICAL ESTIMATES OF FORMATION BOUNDARIES

Inversion results in a single final model for every data set, and though the final model is the best fitting model of the inversion, it only represents one model among all the equivalent models, i.e. the models that fit the data within the data uncertainty. The off-diagonal elements, the covariances, of the posterior covariance matrix carry information about the coupling between model parameters, i.e. they describe how the other model parameters would change if one parameter is perturbed. This information is what characterises the equivalent models. Though the covariance matrix is derived under an assumption of linearity, it still contains multidimensional information not contained in the parameter variances.

A sampling of the space of equivalent models is obtained by multiplying the squareroot of the posterior covariance matrix with a vector of Gaussian distributed random elements with zero mean and a standard deviation of unity (Tarantola, 1987) to produce a vector of model perturbation that is added to the inversion model. Repeated a large number of times, the models constructed in this way will span the set of equivalent models. Inversion and analysis, and consequently the posterior covariance matrix, refer to the logarithm of the resistivity, so we have

$$\triangle \log \boldsymbol{p} = \sqrt{\boldsymbol{C}_m^{-1}}\, \boldsymbol{r}_g$$

$$\log \boldsymbol{p}_{eq} = \log \boldsymbol{p} + \triangle \log \boldsymbol{p} \quad \Rightarrow \quad \boldsymbol{p}_{eq} = \boldsymbol{p} \cdot \exp\left(\triangle \log \boldsymbol{p}\right)$$

where $\boldsymbol{p}$ is the parameter vector (the MLM layer resistivities) and $\boldsymbol{r}_g$ is the Gaussian distributed random vector. Numerical experiments have shown that 1,000 realisations is enough to produce a representative sampling of the set of equivalent models.

Statistical analysis based on the realisations of equivalent models

The idea behind finding statistical estimates of the position of formation boundaries is to analyse the set of realisations of equivalent models in terms of whether they fulfil a certain explicit criterion or not. In this survey, we consider the criterion: What is the likelihood that the resistivity is below a limiting value all the way from the top, down to a certain layer boundary ?

For each of the realisations, the models that fulfil the criterion are counted and the overall likelihood can then be found. In the following we (arbitrarily) use the criterion of the likelihood being above 0.5.

THE SURVEY

The survey was carried out along a proposed pipeline alignment more than 500 km in length. Geological conditions along the alignment are highly variable, ranging from exposed crystalline basement, to thick sedimentary sequences. Areas of near-surface crystalline basement are most problematic for excavation.

The airborne TEM survey was carried out with the SkyTEM system (Figure 1), a helicopterborne TEM system designed and developed for hydrogeophysical and environmental investigations (Sørensen and Auken, 2004). As the objective was to provide resistivity information at the very near surface, data were acquired using only the Super Low transmitter moment, with a peak current of 10 A in a single transmitter turn. Instrument parameters are listed in Table 1.

Signal strength is generally high in the area and the SkyTEM data were subjected to a basic data processing. For a further discussion of these steps, please refer to Auken et al. (2009). In the data processing, no bias signal was found and repeated measurements demonstrated that there was no system drift. We use the general noise model

$$V_{noise} = V_0 \cdot \left(\frac{t}{1\,\mathrm{ms}}\right)^{\alpha} \qquad (3)$$

where V_0 is the noise level at 1 ms and α typically attains values between $-½$ and -1. Visually inspecting the data from the survey and adjusting V_0 and α gave a value of $V_0 = 2.5 \cdot 10^{-12}$ and $\alpha = -½$. The values of V_0 refer to data normalised with the Tx moment.

The airborne TEM survey

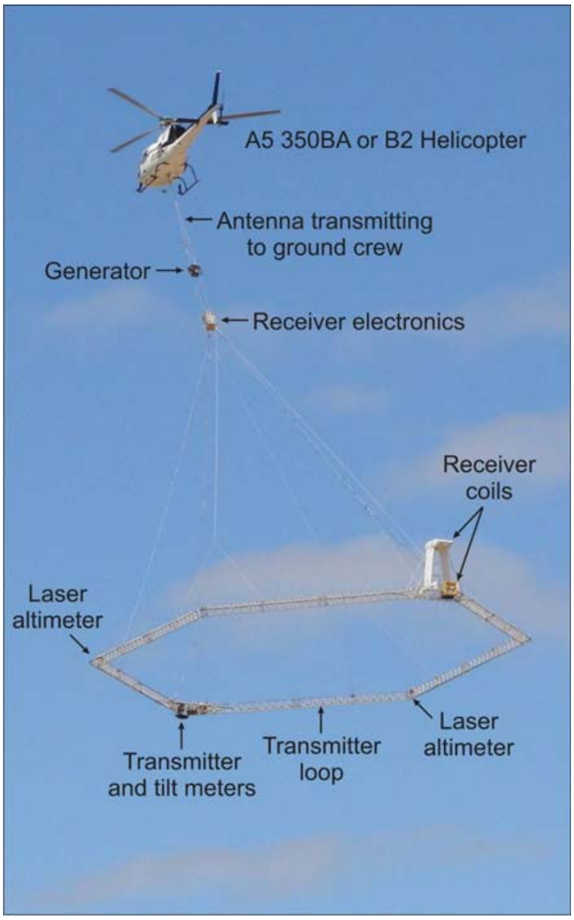

Figure 1. The SkyTEM system at a glance.

SURVEY PARAMETER	SLM
Tx area [m^2]	314
Tx moment [Am^2]	3140
Nominal Tx height [m]	30
Repetition frequency [Hz]	200
Nominal ground speed [km/h]	80
First gate [μs]	12.2
Last gate [ms]	1.41
Number of gates	23
Rx cut-off frequency [kHz]	450
Amplifier cut-off frequency [kHz]	300

Table 1. SkyTEM survey parameters for the super low moment used in the survey.

Inversion, data fit and data inconsistency

The initial inversion was done with a 30-layer model with all layer resistivities having an initial value of 10 Ωm using the fast approximate inversion method for transient data (Christensen, 2002; Christensen et al., 2009). The result of this inversion was used as initial models for a subsequent full-accuracy multi-layer inversion incorporating the lateral constraints.

In general, most of the soundings can be interpreted well with 1D models. Typical values of the normalised data residual are of the order of 1, indicating that the noise model is reasonable.

RESULTS

In Figures 2 and 3, two models sections from the survey are shown; one with fairly low resistivities indicating softer sediments and one with higher resistivities pointing to the possible presence of harder rock. The estimated depth above which the likelihood of the resistivity being above 60 Ωm is higher than 0.5 is indicated with a black line. This is the statistical estimate of the amount of hard rock.

In Figure 2, the estimated depth to hard rock is generally large and there are only 2 minor intervals where there are high resistivities near-surface. The high resistivity zone at around 461700 m is surficial and may represent unsaturated sediments rather than genuine shallow bedrock. The high resistivity zone at around 465000 m extends to some depth, and may represent a genuine bedrock high. This zone presents the greatest excavation risk on this section of line.

Figure 3 shows a 9 km long section of line over an area in which thin unconsolidated sediments overly crystalline bedrock. Drilling has shown that the depth to bedrock is very variable, ranging from ~ 1 m to > 10 m, and would be difficult to predict on those parts of the line with no drillholes. The bedrock interface determined using our statistical approach is at > 3 m depth along the entire section of line, and is consistent with all drillholes except that at the extreme right-hand end of the section. The mismatch between the AEM interpretation and drilling may be because the bedrock is weathered or fractured and thus conductive. The statistical estimate of bedrock depth shows very good agreement with drilling near 402000 m, and generally shows resistivities < 60 Ωm associated with unconsolidated sediments.

CONCLUSIONS

We have presented a helicopterborne transient electromagnetic survey along the trace of a projected gas pipeline in Australia carried out with the purpose of discerning between soft (conductive) and hard (resistive) formations along the trace to assist in designing the burial of the pipeline.

To assist in the categorisation of the geological formations, we applied a statistical analysis of the set of equivalent models to assess the likelihood of encountering one formation or the other. The method was successful in delineating the possible occurrence of hard formations and shows reasonable correlation with the available drillholes.

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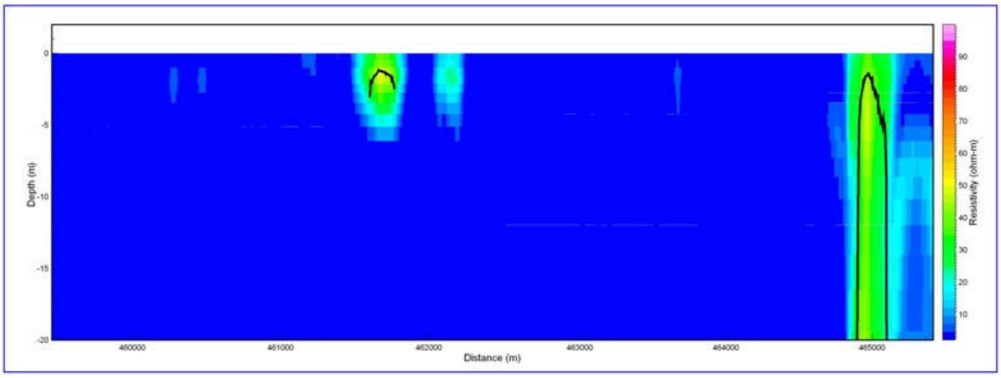

Figure 2. Resistivity cross-section on a ~6 km section of the proposed pipeline alignment. Depth to bedrock estimated using the statistical approach is shown as a black line. This section of line is generally very conductive and is likely to present few obstacles to excavation.

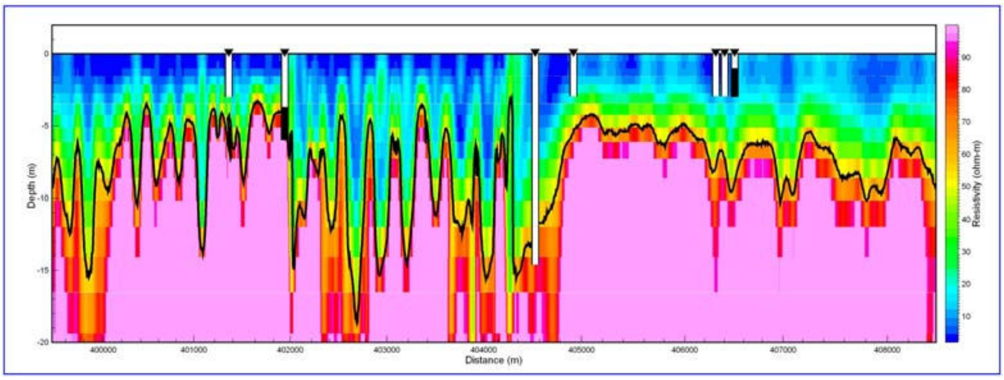

Figure 3. Resistivity cross-section on a ~6 km section of the proposed pipeline alignment. Depth to bedrock estimated using the statistical approach is shown as a black line. Drillhole lithology logs show unconsolidated sediments as white and crystalline bedrock as black. The depth to bedrock estimated from the AEM data is generally consistent with the drilling results and suggests that materials above a depth of 3 m will generally be excavable.