Airborne Electromagnetic Inversion Applied to Oil Sands Exploration

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Abstract

The industry's standard tools for oil sands exploration have historically been seismic reflection surveying and borehole logging. However, the high electrical resistivity of the McMurray Fm., compared to the overlying and underlying formations, makes it feasible to apply airborne electromagnetic techniques. The main advantages of airborne electromagnetics over drilling and seismic are that data can be quickly and easily acquired on the scale of hundreds of kilometers with zero surface disturbance and at a fraction of the cost. The application of airborne electromagnetics to oil sands exploration is investigated through forward modeling, inversion of synthetic data, and inversion of field data. Forward modeling studies explore and compare the system response to various aspects of the geology. Synthetic inversion studies are performed in order to devise the most appropriate inversion parameters, deduce the imaging capabilities under a variety of geological situations, and to aid in the interpretation of inverse models recovered from field data. The relation between the bulk resistivity recovered by inversion and the detailed resistivity structure recorded by well logs is investigated in particular. Field data are used to validate the synthetic results and show that formal 1D inversion provides the means to interpret the depth to top, thickness, and relative quality of oil sands; both at mineable and shallow SAGD depths.

Introduction

The basic principle of time-domain electromagnetic (TDEM) methods is that a time-varying magnetic field induces eddy currents in the ground that, in turn, generate a secondary magnetic field, which contains information about the resistivity structure of the subsurface earth. In fixed-wing TDEM, the transmitter and receiver are carried by a plane [Figure 1].

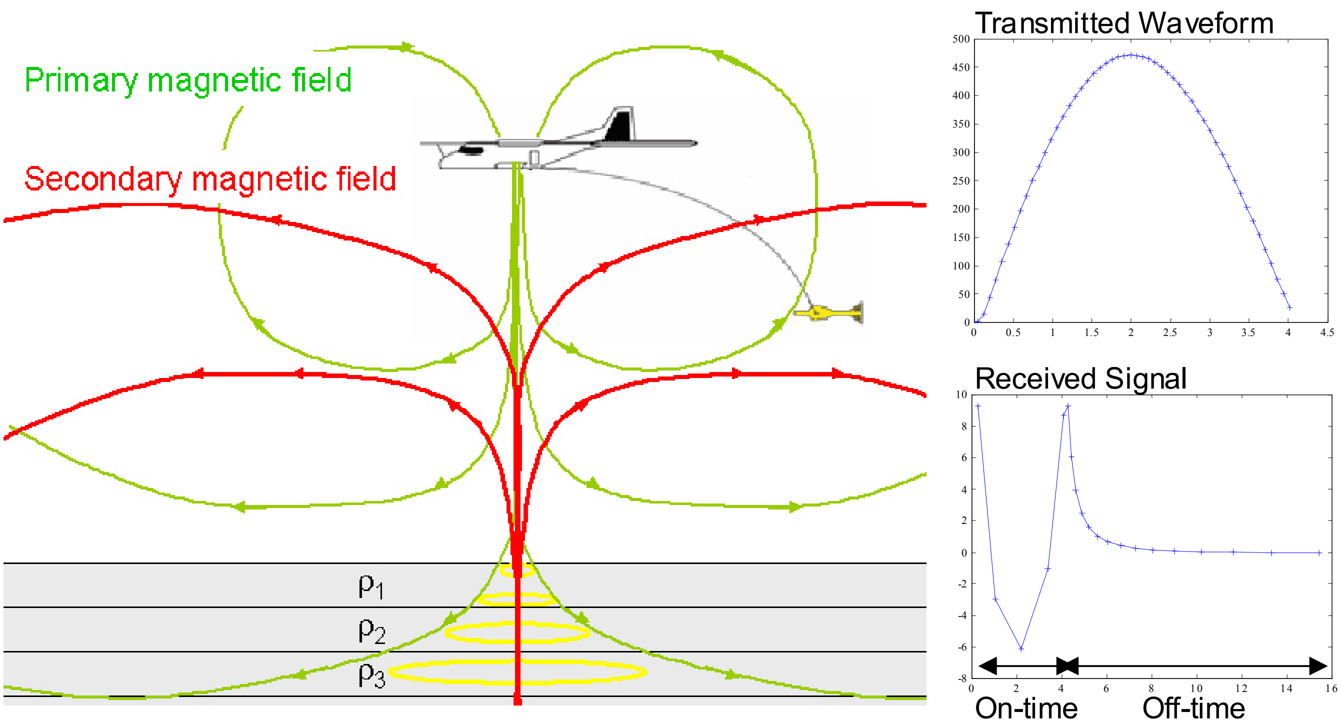

Figure 1. Basic principles of airborne TDEM surveying. Voltage versus time plots illustrate the transmitted waveform and a typical received signal. The present study seeks to invert the data recorded during the transmitter off-time for subsurface resistivity structure.

Airborne electromagnetic surveying techniques have been widely used since the 1950s, mostly in the search for conductive mineral deposits located within resistive Canadian Shield rocks (Fountain, 1998). Traditional methods of interpretation are based upon comparing the data to type curves or inverting for models with only a few parameters, such as the plate-like conductor model. The conductivity-depth transform is a popular interpretation tool that generates an approximate image of subsurface resistivity structure (Wolfgram, 1995). However, the image does not generally contain the detail or accuracy required to reproduce the observed data through forward modeling.

Traditional interpretation methods have been effective in the context of locating discrete conductors in a resistive background but are not as useful when structural and sedimentological details of a resistive unit are required. The fundamental reason for this is that variations in the resistivity and geometry of more resistive units have relatively subtle effects upon the acquired data. Relating these subtle effects to subsurface resistivity structure requires the full power of formal inversion.

Methodology

In contrast to traditional interpretation techniques, formal inversion attempts to estimate general distributions of subsurface properties that are consistent with the observed data. However, many parameters are required in order to allow for models with arbitrary distributions of physical properties. In fact, the number of parameters in such models is typically greater than the number of data. To address the problem of non-uniqueness, as well as the problem of data noise, a general three-step approach to solving the inverse problem is employed (e.g., Farquharson, Oldenburg, and Routh, 2003):

1. the earth is represented with many parameters to allow for arbitrary distributions of physical properties;
2. a model objective function is designed, which measures the complexity of the various possible earth models;
3. the model is found which minimizes the model objective function subject to the constraint of adequately fitting the observed data.

In the case of electromagnetics, the forward modeling operator is a non-linear functional of the resistivity structure. As a result, the inverse problem is non-linear and so an iterative approach is required.

Synthetic Inversion

Studies involving the inversion of synthetic data were carried out for four main reasons:

1. to devise the most appropriate inversion parameters for the present case study;
2. to relate the bulk resistivity recovered by inversion to the intricate resistivity structure contained in well logs;
3. to explore the ability of the system to image the McMurray formation over a range of the geology that is expected;
4. to aid in the interpretation of the inverse models recovered from field data.

Inversion of synthetic data involves four major steps:

1. forward modeling is used to produce synthetic TDEM off-time data from a user-constructed 1D resistivity model;
2. Gaussian noise is added to the synthetic data;
3. the synthetic data are inverted for 1D resistivity structure;
4. the model recovered by inversion is compared to the original resistivity model.

To determine how the bulk resistivity recovered by inversion is related to the intricate resistivity structure contained in well logs, the McMurray Fm. interval of a deep induction log was isolated from the rest of the log and placed within a relatively conductive (100 $\Omega{\cdot}$m) half-space. The TDEM sounding was forward modelled from the well log data and the synthetic data were inverted.

The results are summarized by Figure 2. Figure 2A shows the original well log data in blue and the inverse model in red. It is evident that both the top and base of the McMurray Fm. are well resolved. It is interesting to observe that the bulk resistivity recovered by the inverse model is closer to the low resistivity of the mudstones at the base of the formation than to the majority of the values recorded. This is indicative of the fact that electromagnetic methods are more sensitive to conductive materials than they are to resistive materials. This result suggests that recovered bulk resistivity within the McMurray Fm. will be significantly lower when mudstones are present than when the sands are clean.

Figure 2B shows the misfit between the synthetic data and the predicted data normalized by their standard deviation. The **x** component misfit is illustrated by the black line and the **z** component misfit is illustrated by the green line. The fact that both misfits lie within two standard deviations at every time channel indicates that the inversion did a good job of fitting the synthetic data. Figure 2C and Figure 2D show the synthetic data in blue and the predicted data in red for the **x** and **z** components of the measured magnetic field respectively. The fact that the off-time decay curves are very similar emphasizes that the inverse model is consistent with the synthetic data.

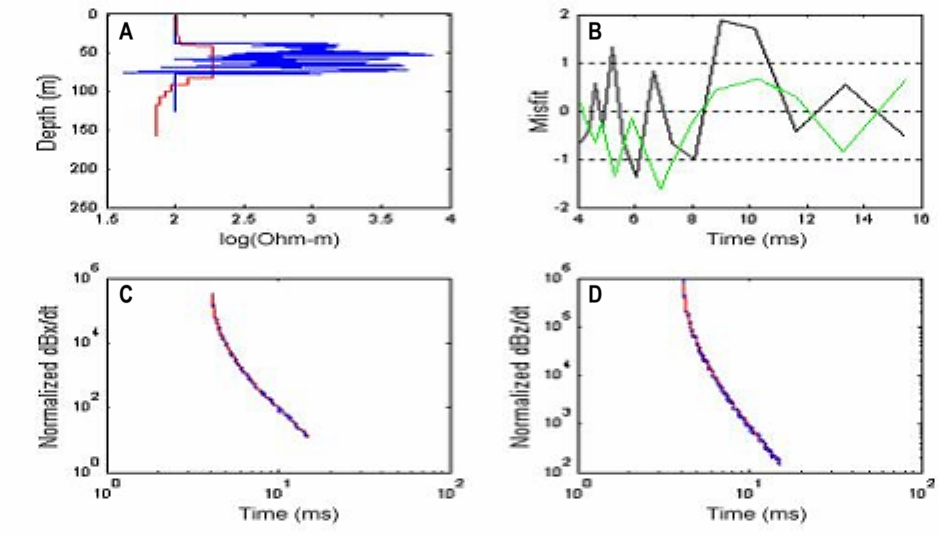

Figure 2. Inversion of synthetic data from the model in which the McMurray Fm. well log interval was isolated and placed within a conductive half-space

The results illustrated by Figure 3 are typical for the case when the McMurray Fm. was modeled as a fairly shallow, resistive block. In the inversion, the thin layers overlying the McMurray Fm., as well as the layers below the McMurray Fm., are averaged together but the top and base of the McMurray Fm. are well resolved. The bulk resistivity recovered for the McMurray Fm. is influenced by the relatively conductive layers that surround the formation. At 137 Ω·m, the recovered resistivity is approximately 30% less than the resistivity in the original model. This reveals an important aspect to be aware of in the interpretation of the inverse models recovered from real data: since the McMurray Fm. is usually bounded by less resistive units, its recovered resistivity will probably be less than its true bulk resistivity. In light of these results, it is anticipated the that the recovered bulk resistivity within the McMurray Fm. will be somewhat lower than well log values when clean sands are present and much lower than well log values when mudstones are present.

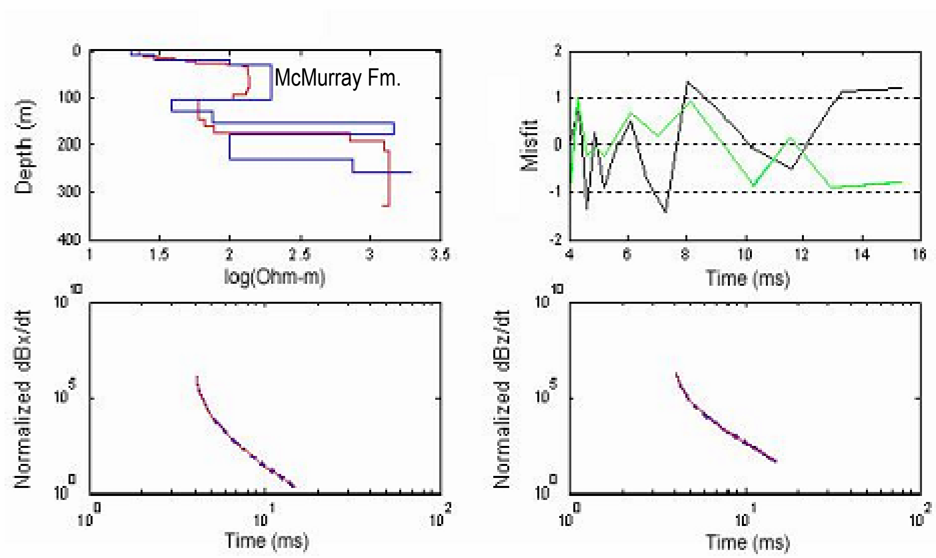

Figure 3. Synthetic inversion results for the shallow McMurray Fm. scenario

Inversion of Field Data

Field data inversions correlate well with deep induction log data, both for the McMurray Fm. at shallow SAGD depths and for the McMurray Fm. at mineable depths. Figure 4 illustrates the correlation for the McMurray Fm. at SAGD depths. Here, a 2D section is constructed by plotting the independent 1D inversion results next to each other. The section shown is approximately 3 km long. Three resistivity logs are projected onto the section for comparison. It is important to note that the flight line did not actually pass directly over the well log locations. The distance over which the three well logs were projected varies from approximately 150 m to 750 m.

The four layers imaged in Figure 4 are consistent with a Quaternary overburden, the Clearwater Fm., the McMurray Fm., and the underlying carbonates. The resistive McMurray Fm. lies approximately between 160 m and 230 m depth. Its top, base, and relative resistivity correlate well with the values recorded by the well logs. The variation of bulk resistivity within the McMurray Fm. provides the means to interpret the relative quality of oil sands over the section. Higher resistivities imply cleaner sands with higher bitumen saturation while lower resistivities suggest a greater mudstone content.

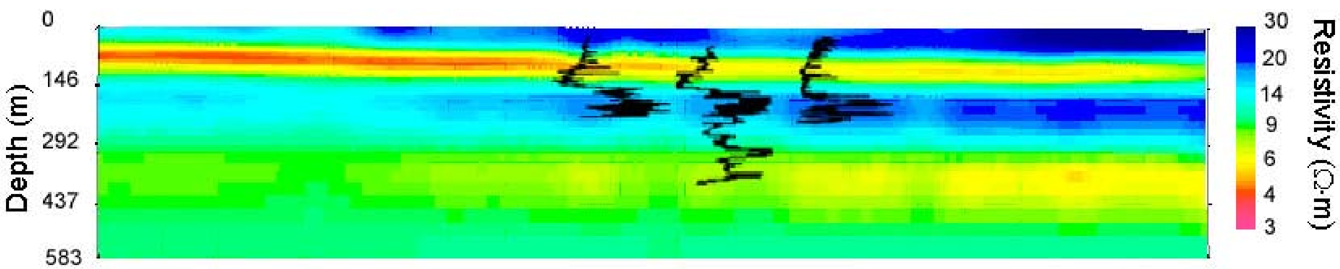

Figure 4. Correlation of independent 1D inversions with resistivity logs for oil sands at shallow SAGD depths

Discussion

The main advantages of airborne electromagnetics over traditional oil sands exploration techniques are that a much larger area can be covered in less time and at a fraction of the cost. Until now, a major factor preventing the wide scale adoption of airborne electromagnetics to explore for oil sands at moderate depths has been the lack of a methodology for interpreting the subtle effects that variations in the McMurray Fm. have upon the acquired data. As suggested by Kellett and Maris, and demonstrated by the present research, formal 1D inversion provides the rigorous imaging capability that is required. This technology may prove to be an effective way to rapidly appraise oil sands leases and more efficiently target drilling programs.

Acknowledgements

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