Large-scale 3D inversion of helicopter electromagnetic surveys for oil sands exploration near Fort McMurray, Alberta

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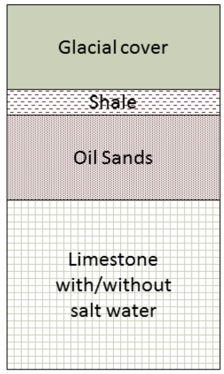
Summary

Helicopter time-domain electromagnetic (HTEM) systems have dominated the airborne electromagnetic (AEM) industry for mineral exploration and environmental studies over the past decade. This is, in large part, a result of the high spatial resolution, excellent depth of investigation, and operational versatility. For oil exploration and related environmental due diligence near Fort McMurray, Alberta, recent interest in HTEM has been driven by the requirement for a cost-effective method for characterizing surface mineable oil sands and shallow steam-assisted gravity drainage (SAGD) prospects. The primary advantage of HTEM is that high-resolution data can be easily and safely acquired over large areas with zero surface disturbances at a fraction of the cost of seismic reflection. Moreover, HTEM data can now be interpreted with full 3D inversion, obviating prior reliance on various 1D methods. In this paper, we present a case study for the 3D inversion of HTEM data for oil sands exploration near Fort McMurray.

Introduction

A typical geological section of the Fort McMurray area, with the associated resistivity, is presented in Figure 1. The McMurray Formation sandstones, which host the oil, tend to be more resistive where the oil is enriched. However, the McMurray Formation can vary in both thickness and depth of burial, and can contain conductive mudstone horizons. Locally, the overburden and/or shale units of the Clearwater Formation may or may not be present. If they are present, they may not be continuous. The Devonian limestone basement is generally resistive, but local increases in conductivity with depth can be attributed to the presence of saline groundwater and/or clays at the contact between the McMurray Formation and the basement.

To date, various AEM data acquired for oil sands exploration have been interpreted using conductivity depth images or layered earth models for each transmitter-receiver pair (e.g., Kellett and Maris, 2002; Cristall et al., 2004; Huang and Rudd, 2008; McConnell and Glenn, 2008; Smith et al., 2008; Walker and Rudd, 2008). These 1D resistivity models are often stitched or interpolated in order to produce a pseudo-3D model over the survey area. However, the geological structures of particular interest to oil sands exploration, such as faults, paleochannels, and variable oil sand and groundwater distributions, are poorly resolved with these various 1D methods, and the geological structures often manifest themselves ambiguously within artifacts or distortions in the 1D-derived pseudo-3D models. Moreover, for coincident loop HTEM systems, only the vertical component can be processed with all of the various 1D methods as the predicted inline component is identically zero above a layered earth model. Yet, the measured inline component contains important information about 3D resistivity variations that is not contained in the vertical component.



Geologic Unit	Resistivity (Ωm)	Thickness (m)
Overburden	100's	0 – 200
Clearwater Formation	2-10	0 – 30
McMurray Formation	100 – 1000	50 – 100
Devonian Basement	1 – 1000	N/A

Figure 1: Typical geological section and related resistivity properties for the Fort McMurray area, Alberta.

3D AEM inversion

The 3D inversion of entire AEM surveys was considered impractical until Cox and Zhdanov (2007) and Cox et al. (2010) introduced their concept of 3D inversion with a moving sensitivity domain. According to this concept, one only needs to calculate the AEM responses and sensitivities for that part of the 3D earth model that is within the AEM system's sensitivity domain for a particular transmitter-receiver pair, and then superimpose the sensitivities for all transmitter-receiver pairs into a single, sparse sensitivity matrix for the entire 3D earth model. We base our frequency-domain modeling on the 3D contraction integral equation method (Hursán and Zhdanov, 2002). For time-domain AEM, system responses and sensitivities are obtained by Fourier transform of the frequency-domain responses and sensitivities, and are convolved with the transmitter waveform (Raiche, 1998). We use a regularized conjugate gradient method for minimizing the Tikhonov parametric functional with either smooth or focusing stabilizers (Zhdanov, 2002). Our implementation has made it practical to invert entire AEM surveys with thousands of line kilometers of data to mega-cell 3D resistivity models within a day using a multi-processor workstation. We refer interested readers to the aforementioned references for further details.

AeroTEM helicopter time-domain electromagnetic system

Today, there is considerable variety in commercial HTEM systems such as AeroTEM, HELITEM (formerly HeliGEOTEM), SkyTEM, and VTEM. Aeroquest have optimized their AeroTEM system (now AeroTEM IV and AeroTEM HD) to provide the maximum amount of information on the subsurface resistivity, and detail their system parameters for subsequent quantitative interpretation. The transmitter consists of a large loop towed by a helicopter with inline and vertical receivers located within the transmitter loop. The diameter of the transmitter loop is 12 m or 20 m. The transmitter waveform is a bipolar symmetric triangular pulse which can be operated at 30 Hz, 90 Hz or 150 Hz base frequencies with a 30% to 50% duty cycle. The transmitter moment ranges from 2.3 x 10^5 Am^2 for the 12 m AeroTEM system to 7.5 x 10^5 Am^2 for the 20 m system. The inline and vertical components of the induced voltage of the secondary magnetic fields are measured during both the transmitter on and off times. There are 16 on time channels and 17 off time channels for both components. Finite transmitter turnoff time may affect TEM data at early times shortly after transmitter turn off when the transmitter turn off time is large. The AeroTEM system allows sufficient time between the transmitter turnoff and the first time-off data sampling to avoid the effects of transmitter turnoff.

Case study – Fort McMurray

We consider a 175 line km survey of AeroTEM IV data acquired over an oil sands prospect near Fort McMurray as a demonstration survey to Husky Oil. Paleochannels are clearly obvious in the data (e.g., Figure 2). For quantitative interpretation, these data were inverted for a 3D resistivity model as described by Cox et al. (2010). As can be seen in Figure 2, the predicted data has been able to capture the subtle trends of the observed data. The resulting 3D resistivity model (Figure 3) is able to resolve the resistive (i.e., probably freshwater filled) paleochannel in glacial till, and the Clearwater shale layer. The top of the McMurray formation can be recovered in parts of the survey area.

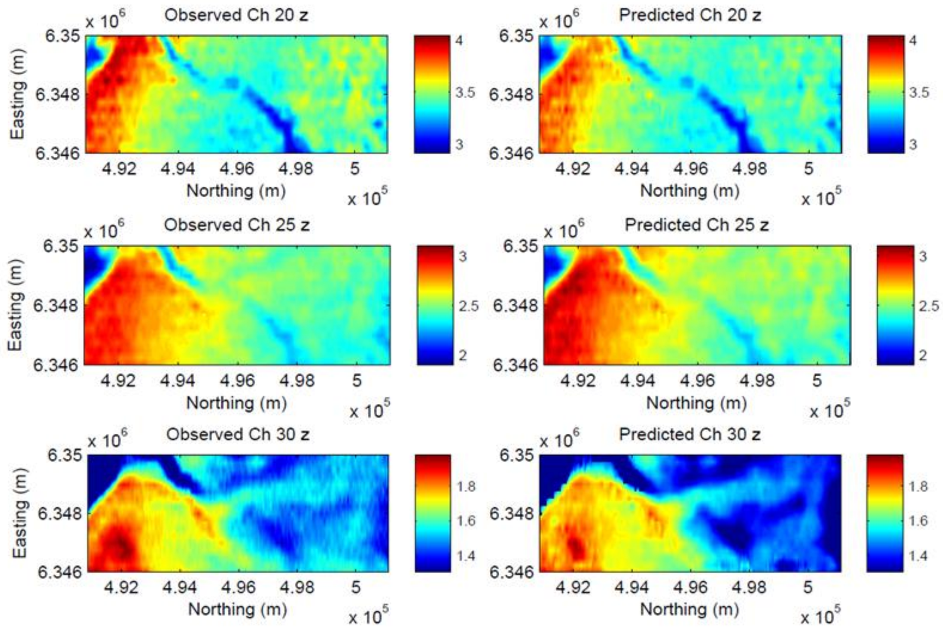


Figure 2: Examples of the observed (left) and predicted (right) data for different channels of the vertical component from the AeroTEM IV survey over the Fort McMurray area.

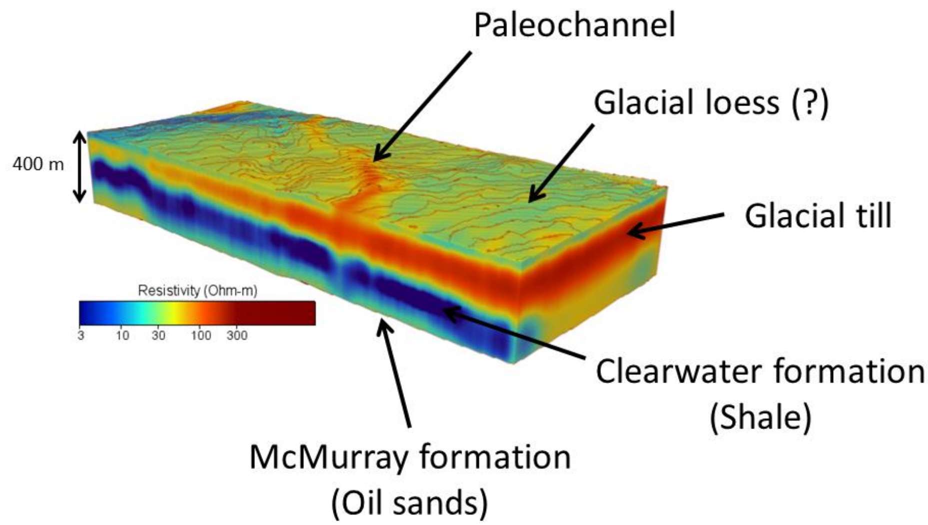


Figure 3: 3D resistivity model obtained from 3D inversion of the 175 line km of AEROTEM IV data. Note that the inversion was able to recover the paleochannel in glacial till, the Clearwater formation, and the top of the McMurray formation.

Conclusions

Recent interest in HTEM for oil exploration and related environmental due diligence near Fort McMurray, Alberta, has been driven by the need for a cost-effective method for characterizing surface mineable oil sands and shallow steam-assisted gravity drainage (SAGD) prospects. To this end, we have presented results from the 3D inversion of 175 line km of AeroTEM IV data from an oil sands prospect near Fort McMurray, Alberta. The model produces from our full 3D inversion has been able to image the near-surface paleochannel with better resolution than various 1D methods. We note that the accurate imaging of such structures is critical for geological hazard identification and mine planning. The 3D inversion has also been able to image the near-surface glacial loess, glacial till, and the Clearwater and McMurray formations. Further analysis and integration of the 3D inversion results with other geological information is ongoing.

Acknowledgements

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