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Electromagnetic Methods for Oil Sands Characterization and Monitoring

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ABSTRACT

In this paper we explore how electromagnetic methods can be used at the regional and local scales to delineate the geology of the Athabasca oil sands and how steam-assisted gravity drainage processes can be monitored. Laterally-constrained one-dimensional inversion of airborne electromagnetic (EM) data provides large-scale, regional geologic trends and identifies a paleo-channel. In addition, the data indicate that the cap rock for the steam-assisted gravity drainage method has a uniform resistivity and thickness. Three-dimensional inversion of the airborne data provide a high resolution model at the local scale while borehole data are used to model the oil reservoir and lower layers. We propose using ground-based EM surveys to characterize the oil-rich McMurray Formation and recover a complete background resistivity model. Finally, EM monitoring surveys are investigated for this region and a low-cost survey using surface transmitters and borehole receivers is chosen to monitor steam chamber growth over time. The research shows that periodic EM data collection and three-dimensional time-lapse inversion can provide high resolution interpretations to compliment traditionally collected seismic surveys. Our work also showcases some of the advancements made in recent years for the inversion of EM data.

INTRODUCTION

The Athabasca oil sands in northeastern Alberta, Canada, have an abundant source of heavy oil, or bitumen. To extract the oil, it can either be mined or produced using thermal methods, such as steam-assisted gravity drainage (SAGD). SAGD uses two horizontal wells drilled at the bottom of the main reservoir (Butler, 1994). Steam is injected into the top well and forms a steam chamber. The steam heats the oil, which becomes fluid and drains downwards to be collected and pumped to the surface by the lower horizontal well. As oil is produced, the steam chamber expands further outwards.

Development of the oil sands involves many steps, starting with regional, large-scale exploration that includes acquiring seismic data, and drilling and logging wells. Based on the data, a prospect area is identified and focused studies are performed. Eventually, a company applies for approval to develop the land. Finally, the site will be constructed and production of the heavy oil will begin, along with monitoring the steam chamber growth.

Each of these exploration steps can help characterize the geology and steaming processes at regional, local, and reservoir levels. Here, we focus on a property that lies 45 km northeast of Fort McMurray, Alberta, where the geology is fairly uniformly layered. The Quaternary-aged deposit at the surface contains glacial till with paleo-channels that can incise into the underlying Grand Rapids Formation, which consists of shales and sands. The Clearwater Formation is a uniform shale layer that prevents the steam from the underlying McMurray Formation, the main oil sands reservoir, to penetrate upwards. The McMurray Formation is separated from a Devonian limestone unit by an unconformity. Prairie Evaporites may exist along the unconformity (Broughton, 2013).

The electrical resistivity varies for each of these geologic units and the steaming of the McMurray Formation further decreases its' resistivity (Tøndel et al, 2014). This means that electromagnetic (EM) methods can provide information which complements conventional seismic surveys and well logging that is routinely done.

In this paper, we show that EM methods can be used to characterize the Athabasca oil sands and monitor steam growth. We present the inversion of regional airborne EM data to delineate the upper geologic layers and we investigate the deeper layers using a ground-based survey. Finally, different surveys are investigated to monitor steam chamber growth using EM. Each example is inverted in three dimensions, thus showcasing the advancements of inversions made in recent years.

REGIONAL EXPLORATION

Airborne EM data can be used in conjunction with seismic and drilling data to characterize the regional geology. EM surveys have the advantage that the data can be acquired, processed, and inverted relatively quickly. In addition, data collection is significantly less expensive than seismic surveys.

Data were collected over an oil sands property using the VTEM system, which uses a helicopter-towed transmitter and receiver loop. The system collected time-domain EM data over approximately 430,000 locations in a region that spans 9 by 12 km. The vertical component of the time-derivative of the magnetic field was measured at 44 off-time time channels, ranging from 20 μs to 9 ms after transmitter shut-off.

Because the geology is fairly uniformly layered, we downsample and invert the data set using a laterally-constrained 1D approach (Farquharson and Oldenburg, 1993; Fournier et al., 2014). This means the data are inverted in 1D but the inversion allows information from neighbouring locations to influence the model. Devriese (2016) provides more details about the inversion process, which uses a regional mesh with 200 m cells

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in the horizontal direction. The result is a large-scale regional resistivity model for the uppermost layers.

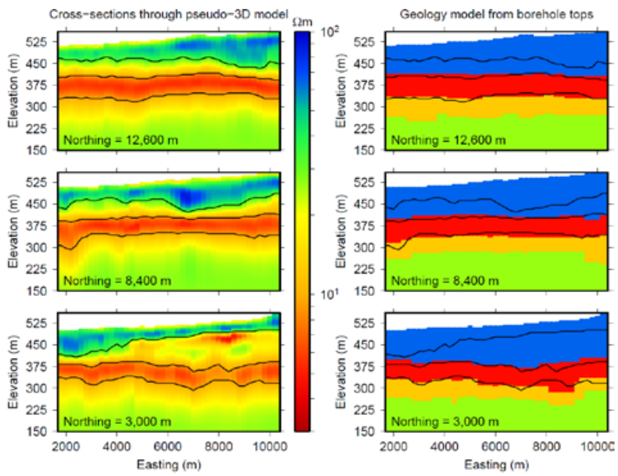

Figure 1: (left) Cross-sections through the pseudo-model from inverting airborne EM data with an interpretation of the geologic layers; (right) Interpretation from EM data overlayed onto geologic model from borehole data. Note that the figures are vertically exaggerated to show variation in the resistivity with depth.

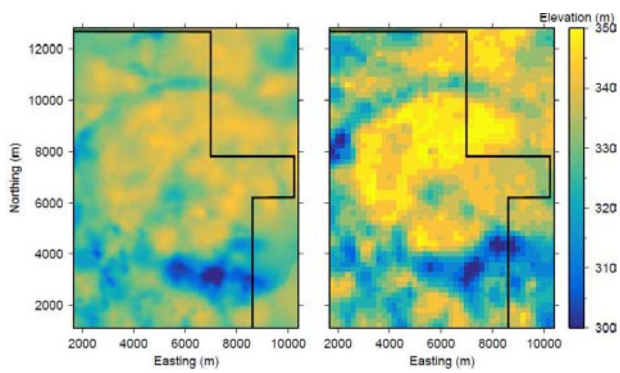

Figure 2: Top of the McMurray Formation based on (left) seismic data and well logging and (right) the inversion of airborne EM data.

Cross-sections through the pseudo-3D model are shown in Figure 1. The model indicates a resistive layer at the surface, with a channel-like feature cutting into the underlying more conductive layer from the northeast to the southwest part of the data region. This is interpreted as a paleo-channel incising into the Grand Rapids Formation. Below the Grand Rapids Formation lies a highly conductive layer with relatively uniform thickness. This layer does not follow the topography and is instead flat-lying. We interpret this layer, which has a recovered uniform resistivity of approximately of 6 Ωm, as the Clearwater Formation.

Below the Clearwater Formation, the model returns to the reference resistivity model of 20 Ωm. Thus, the results indicate limited to no information about the McMurray Formation. We interpret boundaries for each geologic formation by picking transitional resistivities. Our interpretation is plotted on the cross-sections in Figure 1. The right panel in Figure 1 shows a geologic model created from borehole data indicating the elevation of each geologic layer. This shows very good correlation between the ground truth and the interpretation from the inversion for the top of the Clearwater Formation, and surprisingly, the top of the McMurray Formation. The geologic data did not provide the contact between the quaternary deposits and the Grand Rapids Formation.

The top of the McMurray Formation is plotted as a topographical map in Figure 2 and compared to a map constructed from seismic and well logging data (Imperial Oil Resources Ventures Limited, 2013). While the elevations differ slightly, the two maps show very similar structures, indicating that airborne EM can provide detailed information about the geologic layers in the Athabasca oil sands. The EM result can be further improved by including more soundings and using a finer mesh.

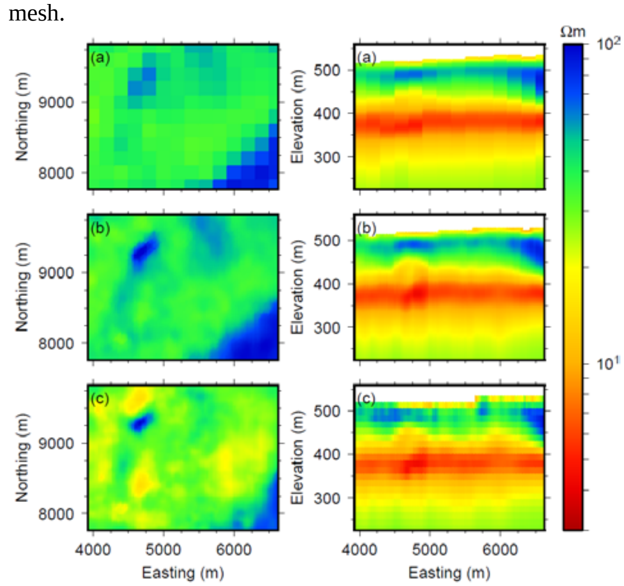

Figure 3: Comparison of (left) plan-view and (right) cross sections for the (a) coarse and (b) fine psuedo-3D models, and (c) the 3D recovered model. The left-hand figures are at an elevation of 465 m. The right-hand figures, at a northing of 8400 m, are vertically exaggerated to show variations in the resistivity with depth.

The main limitation of the airborne method is that due to the depth of the reservoir and the high conductivities of the overlying layers, it does not provide information below the top of the McMurray Formation. For this, we require more localized surveys that penetrate deeper into the subsurface.

LOCAL EXPLORATION

We choose a smaller, local region from the VTEM data set and invert a denser set of the airborne data in 3D. The area is approximately 2.7 km by 2 km and lies in the middle of the VTEM survey region. The mesh now consists of cells that are 30 m in the northing and easting directions. The laterally-constrained inversion is first repeated on the local mesh and recovers a more detailed resistivity model. Figure 3 compares the fine pseudo-3D model (Figure 3b) with the portion of the coarse mode in the same area (Figure 3a). The finer mesh and greater data density model allow for significantly more detail to be recovered.

By forward modelling the pseudo-3D model in 3D, we determined that the model provides an accurate representation in some regions but not others (Devriese, 2016). This suggests that there are 3D structures that cannot be explained using the laterally-constrained 1D method. The pseudo-3D model fits the data from the middle and later time channels but does not always agree with data from the earlier channels. This indicates that 3D structures exist closer to the surface, likely in the Quaternary layer, whereas the Clearwater and McMurray Formations are more one-dimensional. These conclusions are supported by what is known about the local geology (Imperial Oil Resources Ventures Limited, 2013).

In an attempt to better resolve these near-surface structures, the data subset is inverted in 3D using parallelization and local meshes (Yang et al, 2014). The fine pseudo-3D model is used as the starting model for the inversion. Plan-view and cross sections of the recovered model are compared to the coarse and fine pseudo-3D models in Figure 3, showing small differences in the top layers, while the Clearwater Formation remains relatively unchanged.

We now have a highly detailed background resistivity model but it does not contain information about the McMurray Formation and Devonian limestone. Using borehole data, a semi-synthetic reservoir is added to the recovered 3D model, shown in Figure 4a. To recover these units, we propose using a local survey. Ground-based loops can be larger than airborne loops, generating greater currents in the subsurface. Receivers at the surface can measure 3-component electric and magnetic fields to detect deeper layers and recover them using 3D inversion. Here, a 1 km by 1 km surface loop with 657 receivers is used to measure EM data at 10, 25, 40, and 75 Hz (Devriese, 2016). The airborne result is used as a starting model to invert the surface data in 3D. Figure 4b compares the result to the semi-synthetic true model. The reservoir is recovered while preserving the information about the upper layers. On the downside, the transition between the Clearwater and McMurray Formations is smoother in the recovered model. This shows a limitation of the inversion but could be alleviated by imposing more constraints.

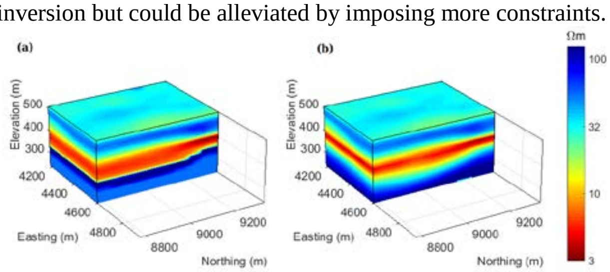

Figure 4: a) A semi-synthetic McMurray Formation and Devonian basement are added to the 3D recovered model using borehole data. b) Inversion of surface EM data recovers the McMurray Formation.

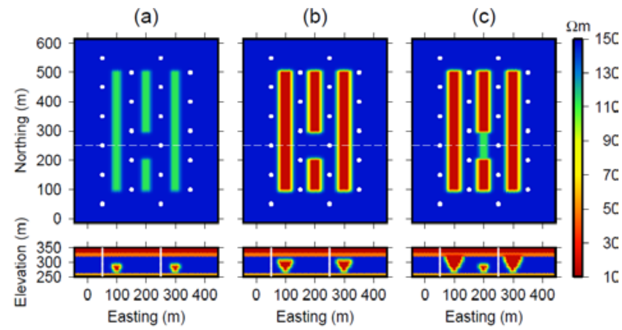

Figure 5: True resistivity model showing three steam chambers at different time steps.

MONITORING

We now have a complete background resistivity model that can be used to monitor changes in resistivity due to SAGD steaming processes. A synthetic model is considered where three chambers are added to the McMurray Formation at three time steps (Figure 5). The three time-steps represent early, middle, and late stages in the steaming process and show growth in the vertical and horizontal directions. In addition, the centre chamber contains a region where no steam is penetrating due to a blockage. Such details are important to monitor as oil production in this region will be lower than expected. At the late stage, we have allowed a small amount of steam growth in the blocked region to determine the resolution capabilities of the EM survey.

Devriese and Oldenburg (2016) investigated EM monitoring surveys, including those with inductive source transmitters and grounded current electrodes. The work showed that a combination of large transmitter loops with borehole receivers detect steam chambers for this region while limiting survey costs associated with fully borehole surveys. The receivers, using electrodes, measure only the vertical component of the electrical field. The electrodes can withstand the high-heat environment and collect multi-year data (Tøndel et al., 2014). Existing observation wells are used to minimize additional drilling costs. The use of two (or more) transmitters at the surface excite the chambers in orthogonal directions, providing different information. Such a configuration allows for better recovery of the chambers through inversion than a single transmitter alone (Devriese and Oldenburg, 2016).

For this example, we use two surface transmitters, each 1 km by 1 km, at the surface. The transmitter loops lie to the east and north of the SAGD well pad, as shown in Figure 6. Receivers are placed in boreholes that surround the three horizontal well pairs. Each borehole has 33 receivers, spaced every 20 m, except within the heavy oil reservoir, where receivers are placed every 5 m. For each transmitter and time step, we forward model the z-component of the electric field at 10, 50 and 100 Hz and add 2% Gaussian noise to the synthetic data.

One way to determine if the survey detects the growing steam chambers is by calculating the relative difference between each time step. The relative difference is computed as (F2 – F1)/F1, where F1 and F2 are the data from an early and later time step, respectively. If we compare the background model and the middle time step, the relative median differences are 78% using the eastern transmitter and 51% using the northern transmitter. This indicates that the survey is sensitive to the resistivity change, and hence detects the steam chambers. These values also suggest that the eastern transmitter has a greater sensitivity to the steam chambers than the northern transmitter. This difference stems from how the transmitters couple differently with the target and emphasizes the importance of using multiple transmitters if possible.

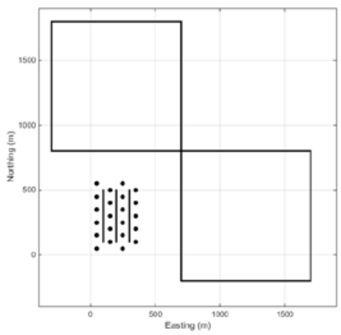

Figure 6: Monitoring survey using two large inductive transmitters at the surface and borehole receivers near the SAGD well pad.

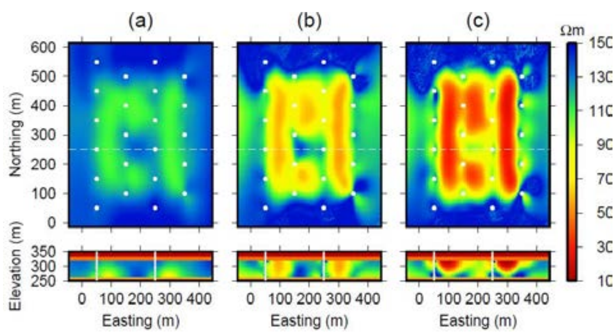

Figure 7: Recovered resistivity models from inverting EM data at different time steps.

We invert each time step in 3D using a cascading inversion approach, meaning that the recovered model from an earlier time step was used as the initial model for the inversion of a later time step. This significantly reduces the computation time by providing the inversion with an initial model that is assumed to better fit the data compared to the layered background model.

In addition, resistivity changes are limited to the reservoir between elevations of 263 and 318 m. Because the steam is expected to decrease the resistivity, the resistivity in the recovered model is limited to be less than 147 Ωm, which was the resistivity of the McMurray Formation. We also impose increased model smoothness along the horizontal wells, as their orientation is well known.

The recovered models for each time step are shown in Figure 7. The first major observation is that the horizontal locations of the steam chambers are well-imaged at each time step. The vertical resolution is less desirable but still shows that the steam chambers grow vertically and expand into the reservoir over time. If necessary, the vertical resolution could be improved by increasing the number of receivers within the reservoir.

In addition, the recovered models show the gap in the middle steam chamber, where steam is being blocked, possibly due to heterogeneity within the reservoir. This result can provide critical information to production engineers since the gap in the middle conductor indicates that no steam is penetrating and thus no oil is being produced.

Finally, at the last step, some growth occurs in the centre of the middle chamber and this decrease in resistivity is reflected in the recovered model. This again shows that the survey can detect small resistivity changes within the reservoir and has enough resolution to recover those changes using 3D inversion.

CONCLUSION

The impact of using EM methods to characterize the Athabasca oil sands is tri-fold. First, airborne data collection over a regional area provides high resolution information about the near-surface layers, including identifying channels that incise into lower geologic units and delineating the uniformity of the Clearwater Formation. However, the airborne data has minimal sensitivity to the oil-rich McMurray Formation. To image structures within the reservoir, we recommend ground-based local EM methods. This provided us with a complete background resistivity model which was used to understand how EM can be used for SAGD monitoring. Second, the EM monitoring survey was shown to be sensitive even to small steam chambers, thus allowing the survey to be useful from the moment SAGD steaming starts. Finally, the survey clearly detects relatively small changes in steam chamber growth, as shown by the recovery of the middle chamber at the latest time step. This research indicates that the combination of surface transmitters and borehole receivers can provide updates regarding steam chamber growth over time and that 3D inversion of the data can readily recover changes in the chambers.

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