Geophysical Surveys for Oil Sands Development

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ABSTRACT
Airborne and ground based geophysics programs are increasingly being used to address geotechnical issues related to resource extraction such as presence and continuity of cap rock, presence and quality of water, location of aggregates and clays, and mapping of muskeg thickness. Examples of applications will be presented along with some of the limitations and challenges in interpretation of these types of geophysical data.

RÉSUMÉ
Les etudes geophysiques aeroportes et sur terre sont utilisees de plus en plus pour repondre a des questions geotechniques. De telles questions sont par exemple : l'extraction de resource, l'existence de la roche couverture, la presence et la qualite de l'eau, la localisation des aggregats et de l'argile, ou cartographier l'epaisseur de tourbieres. Des exemples d'applications vont etre presente avec les limitatations et defis d'interpretation de ces types des donnes geophysiques.

1 INTRODUCTION

Geophysics has the potential for use not only in the exploration for oil, which is the most traditional application, but also in the development phase of oil sands exploitation. As with all geophysical applications, the most critical factor in the success of such a survey is the presence of a measurable contrast in physical properties.

For electromagnetic methods this most commonly means a contrast in electrical conductivity. The key to interpreting the geophysical results is an understanding of how the electrical properties measured in the survey relate to the geologic units of interest to the project engineer/geologist.

Some general statements can be made to aid in this interpretation. An increase in electrical conductivity indicates the presence of very fine grained sediments (typically clays and shales). Likewise an increase in resistivity generally corresponds to a coarsening of grain sizes. However, these general "rules of thumb" must be applied with a full understanding of their limitations in order to avoid misinterpretation of the geophysical results.

2 AIRBORNE GEOPHYSICS

The main types of geophysical methods used in airborne surveys associated with oil sands are magnetic or electromagnetic. Magnetic surveys tend to be used to map basement structures while electromagnetic surveys are used to map shallower electrical structures.

There are two distinct types of electromagnetic surveys: time domain (TEM) and frequency domain (FEM).

2.1 Airborne Time Domain Electromagnetics (TEM)

The time domain system resolves the resistivity of the earth's subsurface at pre-determined time (depth) increments. This method provides data to a depth of approximately 200 m. Instrumentation consists of a transmitter to impart current to a loop of wire which is slung below a helicopter, or attached to a fixed wing airplane. A multi-component (X, Y and Z) receiver coil is used to measure and record the resulting magnetic field.

The transmitter loop is energised by successive current pulses. While the current is constant, the primary magnetic field generated is invariant. The process of abruptly reducing the transmitter current to zero induces currents within the subsurface, in accordance with Faraday's law. Ground resistivity is such that the amplitude of the resulting current decays with time, thereby inducing a secondary magnetic field at an increasing depth from the source current. The secondary magnetic field, as measured at incremental time gates, is dependent upon the electrical properties of the subsurface. Decaying secondary magnetic fields are sampled in both the 'on-time', i.e. in the presence of the primary electromagnetic field, and in the 'off-time', in the absence of the primary field. As the survey line is traversed, both vertical and lateral variations in electrical properties may be resolved.

2.2 Airborne Frequency Domain Electromagnetics (FEM)

The frequency system also resolves the resistivity of the earth's subsurface, but cycles through a number of specific frequencies, rather than sampling the response over time. The frequency domain method generally images to shallower depths than the time domain system. It is particularly sensitive to electrical conductors, but may not be able to differentiate between two resistors. In general a higher frequency results in increased resolution at the cost of decreased depth of penetration. For this reason a series of frequencies are used to obtain a depth sounding of the sub-surface.

Instrumentation for the frequency domain technique includes transmitter coils which energize conductors at pre-determined frequencies. The secondary electromagnetic fields are sensed simultaneously by means of receiver coils that are maximally coupled to their respective transmitter coils.

2.3 Interpretation of Survey Results

The success of both the TEM and FEM methods in delineating subsurface strata is dependent on the degree of contrast in the electrical properties of successive lithologies, target thickness and depth of occurrence. Table 1 illustrates typical *in-situ* resistivity ranges of various formations present within the Athabasca - McMurray oil sand deposit.

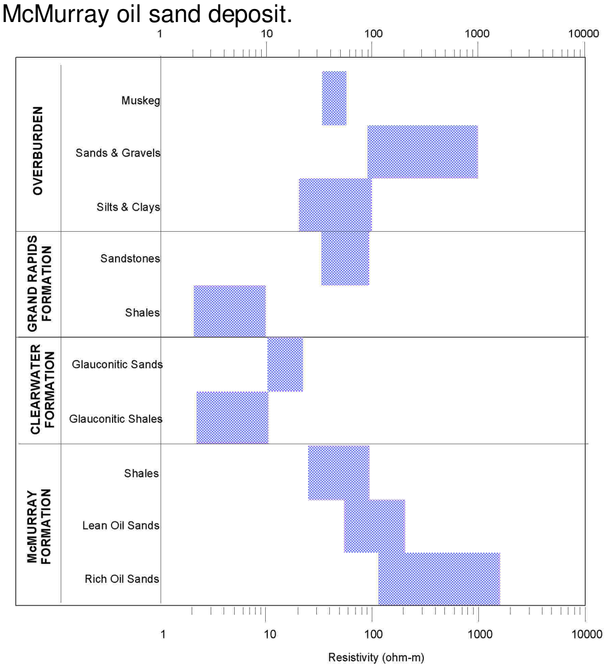

Table 1: Resistivity Ranges for Various Athabasca Basin Formations. (Henderson et al., 2004)

The resistivity values summarised in Table 1 provide a guide for the interpretation of electromagnetic data. Emphasis should be placed on the relative resistivity values of the various formations rather than the absolute values which do not necessarily reflect those measured by airborne methods.

In order to properly convert the results obtained from the receiver coils into a map of resistivity with depth, a process called inverse modelling is used. Through this process, a geo-electric model may be derived that best fits measured data in a least squares sense. Note that the Principle of Equivalency states that it is impossible to distinguish between two layers of differing thickness and conductivity (inverse of resistivity) if their thickness-conductivity product is equal. That is, the presence of a thick resistive layer overlying a thin conductive layer cannot be resolved if the products of their thickness and conductivity are equal. Thus, many different geo-electric models may satisfy a given data set. In order to minimise the possible number of equivalent models, the starting models are based on induction logs from existing drill holes whenever these data are available.

Most inversion programs permit the user to invert on one or more layers and on resistivity and thickness independently. Alternatively, it can be assumed that all the layer resistivity values are known and invert only on thickness for all layers. The best approach is often to run the inversion program using inversions iterated on both layer thickness and resistivity to determine if the process would find a reasonable layering scenario over a variable geological section.

Inversion methods can be sensitive to the starting model so it is common to construct a starting model based on drill information. It is understood that the small interval resistivity variations seen on the electric logs cannot be resolved by the airborne EM survey. The EM method tends to "average" the subsurface resistivity variation.

Interpretation of the results of both a frequency domain and time domain survey can be challenging. Electromagnetic surveys, when properly processed, provide a map of the distribution of electrical properties in the subsurface. What are generally required however, are not electrical properties, but rather geologic formation boundaries, or hydrologic characteristics or some other property which must then be related to the electrical properties. A thorough examination of drill data, geologic maps and geologic model of the area can be critical in relating the electrical properties obtained from the geophysical surveys to the geologic and hydro-geologic boundaries and properties required by the geologist.

3 APPLICATIONS

3.1 Mapping Cap Rock

The location and thickness of cap rock is critical in designing the most efficient resource extraction plan for in-situ oil sands projects. While drilling provides very accurate information, it has numerous drawbacks including permit requirements, seasonal nature of drilling, point source information and access issues.

Geophysics, particularly airborne geophysics, allows the possibility of greater areal coverage for decreased cost. This is assuming of course the existence of a measurable contrast in physical properties Fortuitously cap rock, by its very definition, tends to be very fine grained and therefore electrically conductive rock such as the shale of the Clearwater Formation. As the resource beneath is often hosted in a coarse grained sedimentary rock it is therefore most commonly electrically resistive.

This provides an electrical contrast which, if not located deeper than the range of the geophysical technique employed, provides an excellent target for a geophysical survey.

As an example of cap rock mapping, a cross-section over the Clearwater edge is shown in Figure 1. The dark blue corresponds with Clearwater shales. In this case, the Clearwater is eroded through by a channel, indicated in

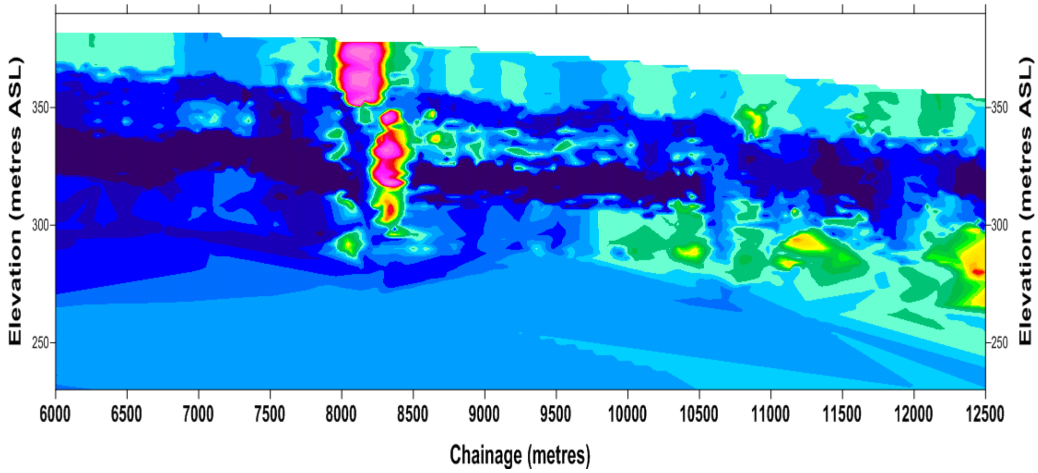

Figure 1: Geo-electric cross-section at Clearwater boundary produced from airborne time domain survey. Dark blue corresponds to Clearwater formation; pink/red corresponds to coarse grained channel cutting through the Clearwater ;

pink/red, at a chainage of approximately 8250 m. Also of interest is the Clearwater outlier seen at chainage 11500m and again at the eastern edge of the survey line, chainage 12500.

Parallel flight lines can produce a detailed areal map of the Clearwater edge with better detail and at lower cost than a drilling program. The anticipated depth to the cap rock must, of course be within the range of the instrument chosen for the survey. Standard Time Domain electromagnetic (TEM) Airborne surveys can nominally map to a depth of about 300m. However a very conductive overburden such as clay till, may limit signal penetration somewhat.

3.2 Hunt for Water

A resource cannot be extracted without an appropriate water supply nearby. In addition regulators often request that a lease owner show a good understanding of hydrogeology and a reliable source water for the project

Airborne geophysics has the potential to supply maps of potential aquifers and paleo-channels which may control hydraulic flow. An example of a paleo-channel identified in an airborne survey is shown in Figure 2. The coarse grained materials of the channel show up in red and green and stand out clearly against the more clay-rich surrounding unit shown in blue.

Although one can say with some confidence that a paleo-channel exists, the survey in Figure 2 cannot be used to determine whether there is water within the channel or not. This can only be determined through drilling but the optimal drill locations can be selected on the basis of the airborne geophysical data

A number of factors affect the overall resistivity: the rock matrix, thickness of each layer, depth of occurrence and the fluid in the pore space. There is considerable variation in the overall resistivity of the unit depending on whether the matrix is fine or coarse grained, and the pore fluid is air, fresh water, oil or saline water. In order to differentiate among them, some ground truthing must be used.

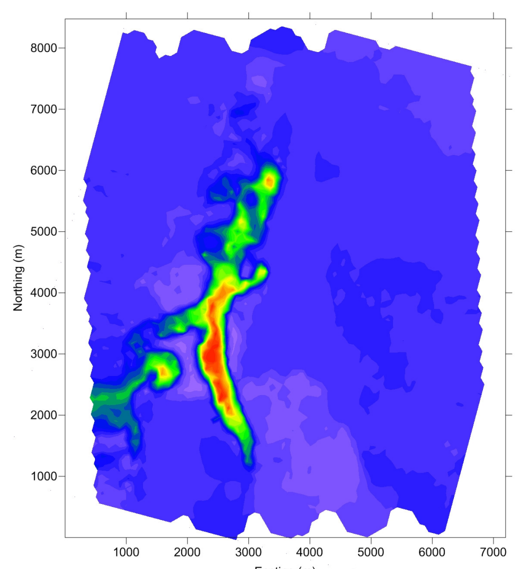

Figure 2: Paleo-channel at a depth of approximately 30m.

An example of an airborne TEM survey over surface mineable oil sands is shown in Figure 3. The surface resistor (in pink) occurring between chainage 7000 m and 9500 m reflects the presence of sands and gravels. The other resistors in the section represent rich McMurray Formation. In this survey the electrically conductive unit in dark blue is indicative of saline water when it occurs at depth. There is a conductive layer at a shallower depth between chainage 7000 m and 7500 m that represents an outlier of Clearwater Formation. Once the airborne TEM data have been inverted into a section such as this a few representative drill holes can provide a significant amount of information.

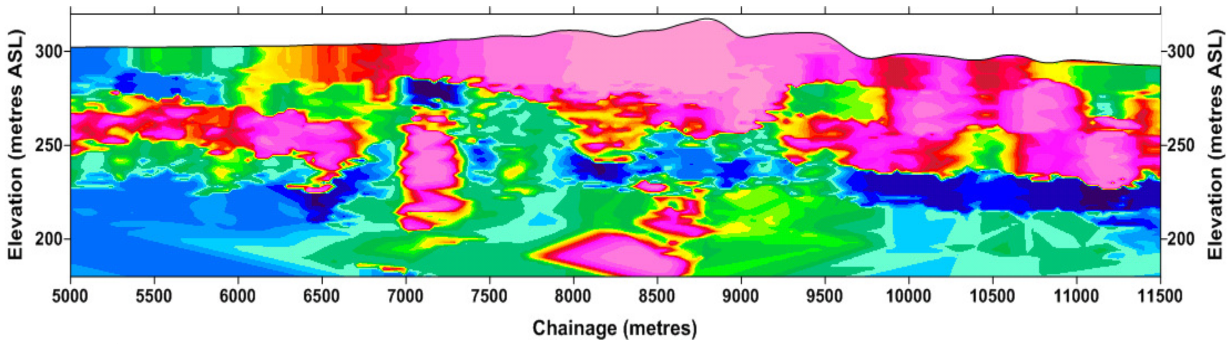

Figure 3: Cross-section from TEM airborne survey showing saline water in dark blue.

3.3 Aggregates and Clays

The development of roads, plants, tailings ponds, and other infrastructure requires a good and preferably local, supply of aggregates and/or clay. Airborne frequency domain (FEM) provides a relatively inexpensive way of identifying potential targets.

An example of a typical survey is shown in Figure 4. The high potential gravel areas are in red; the high potential clay areas are in blue.

There will always be some ambiguity in interpretation of these surveys. For example, sands and gravels have identical resistivity ranges and cannot be differentiated using a resistivity survey.

As with the interpretation of water sources, ground truthing is important. In some settings, the highest potential for gravel may not correspond to the highest resistivities. For example a particular gravel unit may be associated with a higher percentage of clays thereby decreasing the overall resistivity of the unit. Interpretation in this case may be an iterative process, correlating mid range resistivities with other factors to produce a high-gravel-potential map.

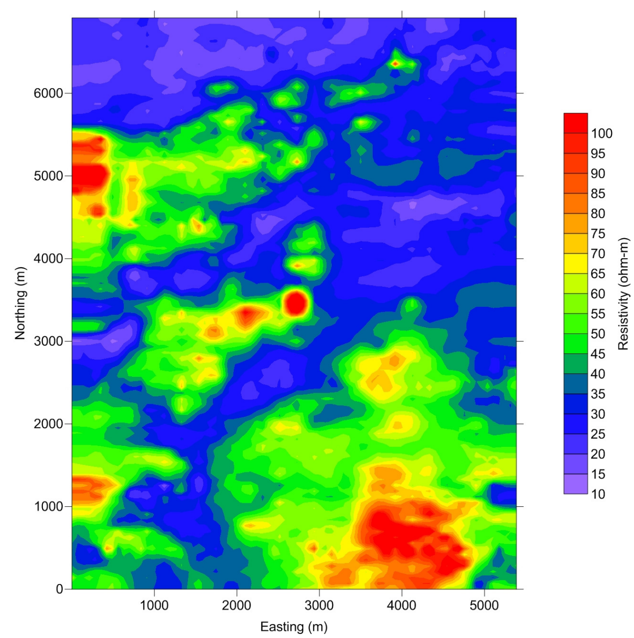

Figure 4: Plan map of resistivity showing areas of high potential gravel (red) and high potential clay (purple).

3.4 Muskeg Mapping

A non-airborne technique which has seen more use lately is ground penetrating radar used to map the location and depth of muskeg. Both for road and pipeline construction, this information can be critical to a solid design and construction plan.

Muskeg is composed for the most part of water, which has a very high dielectric constant. As GPR is most sensitive to dielectric constant, a reflection occurs at boundaries marking a change in water content.

The GPR unit can be towed behind a skidoo and therefore provide continuous data along a cut line in a relatively short time. This method can provide important information for planning pipelines, roads or other infrastructure associated with oil sands development. An important consideration in the selection of the appropriate acquisition parameters for GPR surveys is the required depth of exploration and accuracy.

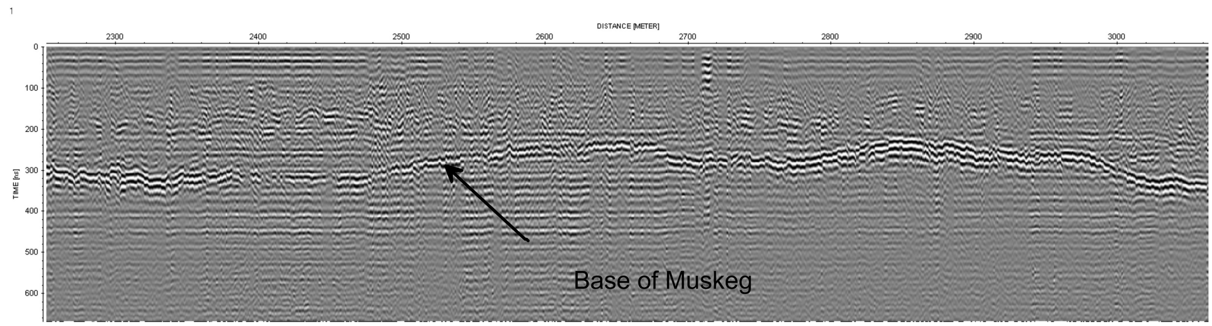

Figure 5: Example of a GPR section collected over muskeg.

Figure 5 shows an example of a GPR section collected over muskeg. The base of muskeg is marked by a very clear reflector. If a good velocity can be determined either through drill control or a CMP (central mid-point) survey analysis, the depth to the base of muskeg can be calculated.

4 CONCLUSIONS

Geophysics can be used to provide useful information for oil sands develpment in a cost effective manner. Care must always be taken, however, to interpret the results using ground truth information and knowledge of the overall geology of the survey area.

The prime objective of geophysical surveys should be to target drill hole locations and to subsequently interpolate subsurface conditions between drill holes. Airborne geophysical survey results can be used to target areas requiring additional ground geophysical surveying may be required.

REFERENCES

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