SAM (Sub-Audio Magnetics) Detection and Delineation of Bitumen Deposits

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Summary

SAM (Sub-Audio Magnetics) is a proprietary electric/electromagnetic technique which uses a high-sensitivity Cesium vapour magnetometer to measure the electromagnetic fields due to electric current flow in the ground. The system allows very fast and highly detailed data acquisition from the ground or from a helicopter towed bird. The system has been in operation for 2 decades in Australia and has had considerable success mapping resistivity variations beneath highly conductive cover such as salt pans. This forward modelling study has indicated that the SAM system is capable of mapping important geological features in the athabasca oil sands to SAGD operators including quaternary channels and some types of lithofacies variation within the McMurray formation.

Introduction

Electrical and electromagnetic techniques have been used in oil sands exploration in northern Alberta since the 90's as an alternative and adjunct to seismic. These techniques rely upon the marked difference between the electrical resistivity of the bitumen saturated sand within the fluvial channel sands of the McMurray Formation, and the electrical resistivity of the surrounding and overlying sediments and sedimentary rocks, particularly the overlying marine shales and sands of the Clearwater Formation and the Quaternary glacial overburden. Ground electrical resistivity techniques, such as ERT (electrical resistivity tomography), and airborne electromagnetics systems, such as helicopter-borne TEM (transient electromagnetics), have been used in recent years with considerable success in detecting and delineating oil sands deposits.

However, these methods have their limitations. They have a limited ability to detect high resistivity formations beneath conductive cover, and they have a limited ability to resolve detail. These limitations are inherent in electrical and electromagnetic techniques because electric currents preferentially flow in the most conductive formations. Therefore, the electrical resistivity response is dominated by the response of the conductive cover with less detectability of the underlying resistive formations. Similarly, EM fields are strongly attenuated by conductive cover and less signal is generated from the underlying resistive formations. This results in reduced depth of investigation and reduced resolution capability.

SAM (Sub-Audio Magnetics) is a proprietary electric/electromagnetic technique which uses a high-sensitivity Cesium vapour magnetometer to measure the electromagnetic fields due to electric current flow in the ground (Cattach et al, 1991).

The technique uses a high powered transmitter to induce current flow either electromagnetically using an EM loop or galvanically, using a grounded dipole. For galvanic applications such as MMR, the dipole separation is typically up to ten km and may extend by one or two kilometres on either side of the survey area. Acquisition for both modes of operation may be conducted at ground level or from a low flying helicopter using a towed bird.

The transmitted current waveform is a bipolar, 50% duty cycle, square wave. The total magnetic field response is measured continuously across the survey area with a rapid sampling, high precision magnetometer. Since the magnetic readings are total field, they can be made with the sensor in motion. This allows very fast, very detailed and low cost surveying. As this is a magnetic measurement, the signal is not attenuated by the overlying conductive cover. These two advantages allow SAM to map resistive structures to greater depths under conductive cover sequences than is possible using ERT or heli-TEM.

Forward Modeling

We have carried out forward modelling of the magnetometric resistivity (MMR) response from a SAM survey over two types of geological resistivity models of relevance to a Steam Assisted Gravity Drainage (SAGD) operation. The geological models were developed using public data available on the Alberta Energy Regulator's (AER) website.

Table 1: Estimated unit resistivity

Unit	Estimated Resistivity
All units above Clearwater (including Quaternary)	50 Ohm m
Clearwater	5 Ohm m
Wabiskaw	3 Ohm m
McMurray Oil saturated	2000 Ohm m
McMurray Water saturated	200 Ohm m
Devonian Limestone	5000 Ohm m

The first example is a Quaternary channel which is incised through the Clearwater shales, the McMurray formation and into the underlying basement limestones. Locating these channels accurately has considerable economic value since, for a number of reasons; they must be avoided in the development of SAGD fields. The shape of the Quaternary channel used for forward modelling is based on a known channel existing at Nexen's Long Lake SAGD operation (AER report, 2012, Long Lake SAGD Annual D-54 Performance Presentation). While

the channel shape remains consistent with the report, the channel's extents have been rescaled for the purposes of modelling.

For the modelling effort we use the following simplified stratigraphy and associated estimated resistivities provided in Table 1. An image of the quaternary channel model is shown in Figure 1. The depth of the top of the McMurray formation is 200m, its thickness is 60m and in this case and the McMurray formation contains both oil saturated (above) and water saturated components (below).
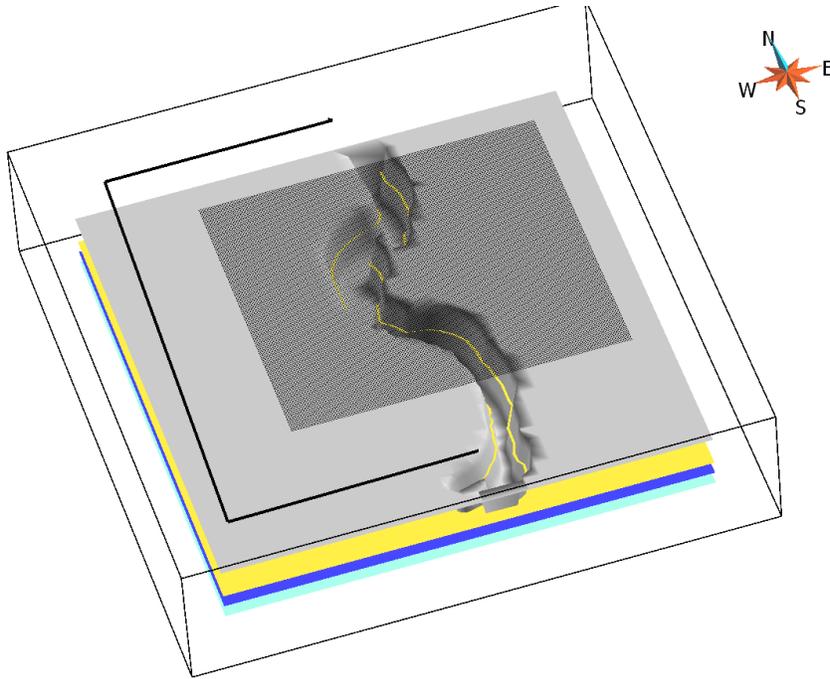
Figure 1: Perspective view of quaternary channel geological model with topography removed. The quaternary channel is incised through the Clearwater shale, the McMurray Formation and slightly into the Devonian limestone basement. The shaded region is the 2km by 2km area where magnetic data will be sampled. The thick black line denotes the location of the transmitter responses. A vertical exaggeration of three has been applied.

The survey area is a 2km by 2km and the transmitter dipole's electrodes are separated by 3km in a North-South orientation (roughly along the axis of the channel). Note that the current carrying wire goes around the survey area, not through it.

The magnetic data were then forward modelled in the frequency domain usign the UBC-GIF program EH3D (Haber et al. 2006). The SAM technique is a time domain method which uses a 50 percent duty cycle square wave operating at 4-8Hz. For the purpose of proof of concept we simplify the modelling effort by only using the fundamental frequecy of the SAM system and scale responses by the amplitude of the fundamental frequecy. This will mean that the modelled response amplitudes will be somewhat underestimated when comared to the true square wave case.

SAM data are processed by removing the primary field using the known position of the transmitter poles and the wire connecting them. This leaves the secondary magnetic response in the direction of the earth's ambient magnetic field which, at the magnetic latitude of northern Alberta, is typically a "crossover" above anomalous object. For the purposes of interpretation further processing is done to perform a MagnetoMetric Conductivity (MMC) transform, which locates electromagnetic highs above conductors and electromagnetic lows above resistors (Boggs 1991).

The results of the MMC transform applied to the quaternary channel model is shown in Figure 2. The channel appears as a low due to the high resistivity of the qauternary sediments as compared to the low resistivity clearwater shales. The amplitude of the anomalous response is more than 1500 pT for this example, assuming 6 Amp transmitter current while a typical system noise floor for the SAM system is estimated at 15 pT.
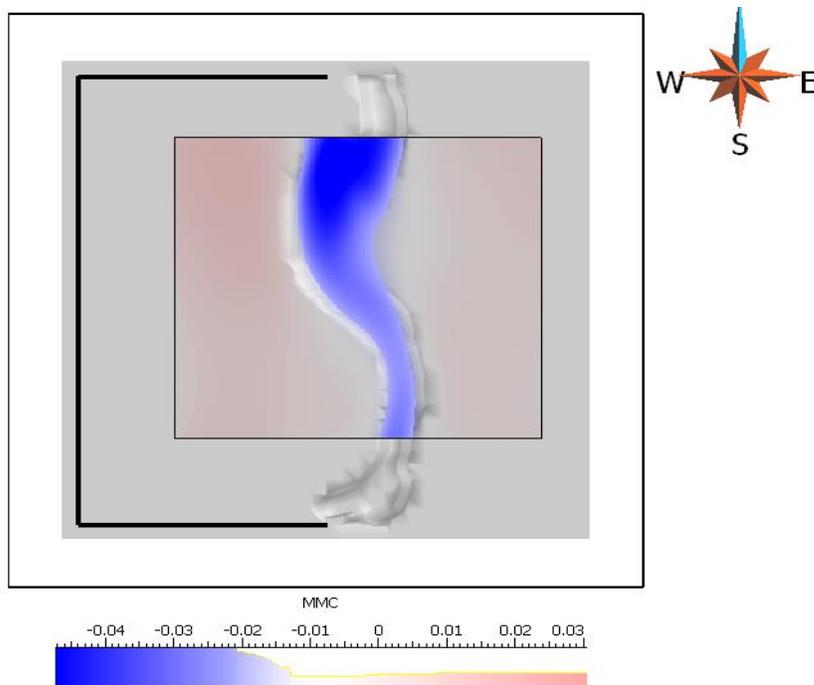
Figure 2: MMC transformed data from the Quaternary channel geological model.

The second geological model is an attempt to show that SAM MMR is capable of mapping lithofacies variation within the McMurray formation itself. In this example, shown in Figure 3, a more complicated channel shape was selected based on maps from Statoil's Leismer project (AER report, 2013, Leismer SAGD Annual D-54 Performance Presentation). While the exact situation at Leismer's project in not known to the authors, we propose that some of zero pay areas with a channel-like shape are the result of later, mud-filled channels incised into the broad McMurray sands. We find some evidence for this in the discusssion and Leismer sections shown in Shackleton et al., 2010. The channel in the McMurray is modelled as filled with conductive Wabiskaw shale material presenting a lateral resistivity contrast contact within

the McMurray. In this case the depth to the top of the McMurray formation was modelled as 200m.
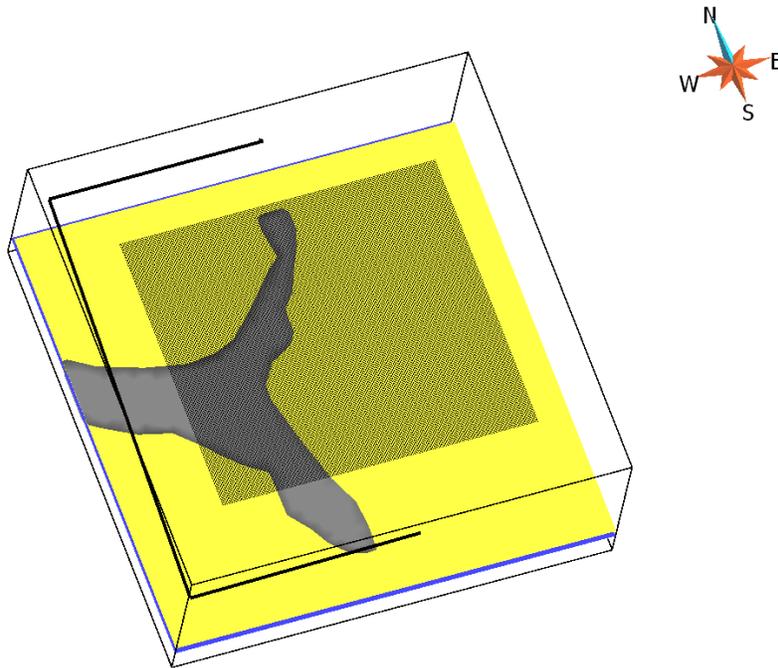
Figure 3: Perspective view of lithofacies geological model with topography, Clearwater and top of Wabiskaw removed. The mud filled channel (grey) is incised in to an oil saturated McMurray sand (yellow). The shaded region is the 2km by 2km area where magnetic data will be sampled. The thick black line denotes the location of the transmitter wire (grounded electric dipole) used to generate the magnetic responses. A vertical exageration of three has been applied.

For this model, due to the more complex channel shape it was found that the North-South oriented dipole did not image the entire channel shape. An additional East-West oriented dipole was modelled and by superposing the MMC responses from the two perpendicular dipoles we obtain the MMC response shown in Figure 4. As expected the channel appears as distict high in the MMC data due to the presense of the conductive mud channel incised in the McMurray The peak amplitude of the anomalous response is more than 500 pT for this example, assuming 6 Amp transmitter current while a typical system noise floor for the SAM system is estimated at 15 pT.
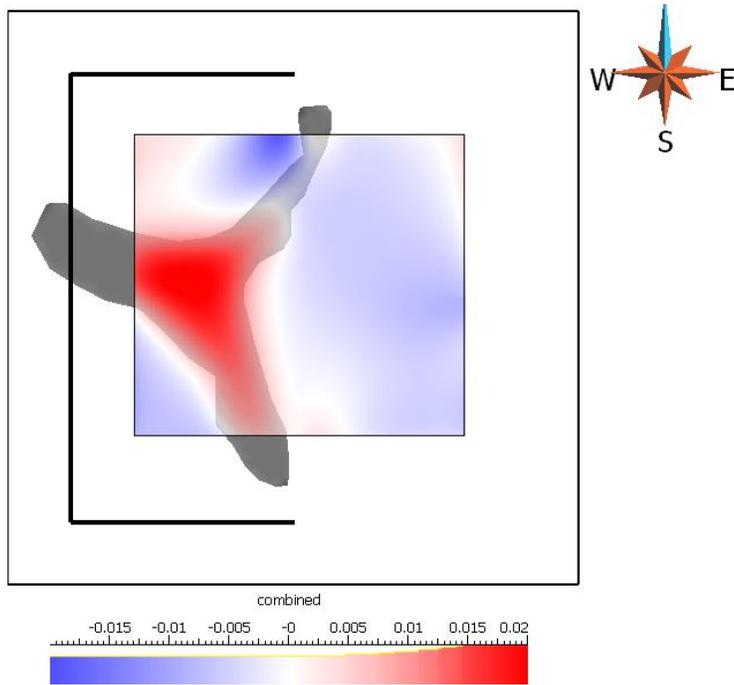
Figure 4: Superposition of MMC transformed data from the lithofacies model for a North-South (shown) and East-West dipole (not shown) transmiiters.

Both models were run with the McMuray formation at 200m depth, however the very strong responses that were observed in the modelling, relative to the typical system noise floor, indicate that these types of geological features will be detectable at much greater depth. The response the SAM system recovers for elongated features, where current channeling can take place, is expected to drop off propotionaly with depth of the source which is a singificant advantage over heli-AEM systems where responses drop-off proportional to the sqaure of the depth to the source.

The forward modelling process is ongoing and we anticipate positive results from the same models with the McMurray formation located at 300m and 400m depth.

Survey Data Example

Figure 5 and 6 display survey data from a gold exploration project in Western Australia. Figure 5 shows the Total Magnetic Intensity (TMI) response obtained automatically from a SAM survey, while Figure 6 shows the MMR response from the same survey. Ten grids were appended to create the final dataset which spans approximately 20km from north to south. The MMR data clearly shows the gold-bearing fault structure. Note that the MMR response is unaffected by near surface magnetic anomalies and that there is still significant response despite the highly conductive salt lakes scattered over the survey area.
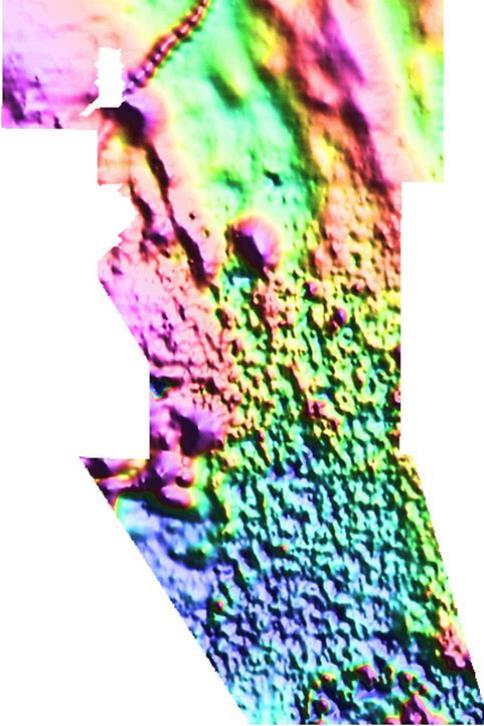
Figure 5: TMI over fault system in Western Australia. Area is approximately 20km from North to South. Red indicates magnetic hights and blue indicates magnetic lows.

Figure 6: MMR over fault system in Western Australia. Red indicates conductivity highs and blue indicates conductivity lows. Note the numerous branches along the fault system which connect to the cental pit in the bottom centre of the map. These branches have gold-bearing potential.

Conclusions

Electromagnetic methods have been used in the Athabasca oil sands for several decades, however with the move toward the exploitation of deeper resources in SAGD operations, previous techniques such as ERT and heli-TEM have had difficulty to image resistivity variation beneath the conductive cover sequences.

The SAM system has existed and been in commercial operation for many years in Australia and has been shown to be consistently effective at mapping resistivity variation below highly conductive cover, such as salt pans, in mineral exploration examples.

In this paper we have demonstrated, through forward modelling, that the SAM system is capable of mapping important geological features in the Athabasca oil sands including quaternary channels and some types of lithofacies variations within the McMurray formation at 200m depth. The forward modelling process is ongoing and based on physical arguments we anticipate positive results with the McMurray formation located at 300m and 400m depth.

References

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