SPE-184089-MS

Integrated Geophysical Reservoir Monitoring for Heavy Oil

H. Passalacqua, MEOFS, Kuwait
P. Boonyasaknanoon, Bangkok, PTTEP, Thailand
K. Strack, KMS Technologies, Houston, Texas

This paper was prepared for presentation at the SPE International Heavy Oil Conference and Exhibition held in Mangaf, Kuwait, 6–8 December 2016.

Abstract

Heavy oil (HO) is often produced with Enhanced Oil Recovery (EOR) methods such as steam or water flooding. In addition to flood front movements reservoir seal integrity has become an issue. Seal integrity is best addressed with microseismics and water flood front bets with electromagnetics. We address the fluid imaging problem using electromagnetics and after careful 3D feasibility and noise tests. We selected Controlled Source Electromagnetics (CSEM) in the time domain as the most sensitive method. From the 3D modeling we derived as key requirement that borehole and surface data needed to be integrated by measuring between surface to borehole and also calibrated using conventional logs.

Depending on the resistivity contrasts between the reservoir and the surrounding formation we need to measure electric AND magnetic fields as each of them have different sensitivity. The magnetic field senses more conductive strata, while the electric field will define fluid changes inside the HO reservoir. Furthermore, for shallow reservoir multi-frequency band sensors need to be deployed to get the optimum sensitivity.

Over the last decades we carried out 3D feasibilities for many oil fields and we are presently conducting the FIRST steam flood Pilot in an oil field in Asia. We also design custom data acquisition system for land, marine and borehole. Carrying out a Feasibility for each reservoir is key to control risk and cost. 3D modeling allows to integrate complex nature of the reservoir by constraining the model with existing seismic data. In all hydrocarbon cases it shows the need for full tensor CSEM, surface and borehole measurements to effectively determine the HO/steam flood front.

Introduction

Enhanced oil recovery is always challenged by the knowledge of the oil/water (or steam) front. Only limited geophysical techniques have been applied. Seal integrity is best addressed with microseismics (Carlson, 2013) and water flood front best with electromagnetics. Since the flooded reservoir is conductive and the hydrocarbon saturated part is resistive you need both magnetic and electric fields. After careful 3D feasibility and noise tests, we have selected Controlled Source Electromagnetics (CSEM) in the time domain as the most sensitive method (Strack and Aziz, 2013; Kumar and Hoversten, 2012). From the 3D modeling we derived as key requirement that borehole and surface data needed to be integrated by measuring between surface to borehole and also calibrated using conventional logs including anisotropy. This would significantly reduce the risk (He et al., 2006 and 2010; Tietze et al., 2015).

4D Geophysical datasets obtained at different times during the life of the reservoir are images of the evolution of the reservoir through the production history. These differences are explained by the changes in the physical characteristics of the reservoir during production, generally a result of collapsing of the open pores and the displacement or injection of fluids. Geophysics allows to obtain data away from the one-dimensional and restricted near-zone of the wellbores, improving the lateral continuity of the reservoir models, enabling the engineers and geoscientists to engage in a more comprehensive understanding of the reservoirs.

Among the quite extensive list of geophysical techniques available in the industry for this purpose, Electromagnetics (EM) and Passive Seismic are being tested for this purpose. The integration of these specific techniques with the appropriate engineering tools is the key for incrementing recovery factors. Most of these techniques can be used with different geometries: from the ground surface, downhole, in a surface-to-borehole array or in borehole-to-surface array. Feasibility studies must be conducted to establish the technique and the field layout that best applies in each case, considering the natural and induced noise levels. Field measurements and computing modeling are used for the design and planning of these surveys.

The injection of steam produces an increase in the original pressure of the reservoir creating potential problems to the integrity of the cap-rock. The production of fractures produces small amounts of seismic energy measurable with micro-seismic sensors.

The injection of steam into the reservoir will alter the rock properties. In particular, the seismic velocity field will change. Specific algorithms to monitor these changes and account for them in the interpretation should be used. This is critical to accurate monitoring for risk reduction.

The increase of temperature substantially decreases the resistivity of fluids in the reservoir. This means that the movement of steam within or outside the reservoir can be monitored with EM techniques.

The objective of EM survey is to obtain resistivity maps based on a measurement grid at the surface and in observation wells in order to cover the area under steam flooding. Energy sources will be located on the surface of the ground. The movement of fluids due to the injection of steam in the formation will change the electrical resistivity of the geological formation. Changes in electrical resistivity are detectable with EM technologies.

Figure 1. shows a representative heavy oil reservoir where multi-physics methods must be applied. Above the reservoir is clastic material which is water saturated., the bottom of which is salt saturated. The underlying reservoir potentially leaks into the top layer. Below the heavy oil is the free water zone and it may also encroach in the reservoir. This means we are trying to map reservoir boundaries at top and bottom as well as the heavy oil zone. From electromagnetics viewpoint this means we need to use high frequency and low frequency sensors for the conductive water saturated zones and electric sensor for the resistive oil zone (Eadie (1980) and Passalacqua (1983) show that resistive hydrocarbon bearing layers

are mapped with controlled source electromagnetics and electric field measurements). Since reservoir leakage in the upper layer is possible, we should use also microseismic sensors. (Carlson, 2013)

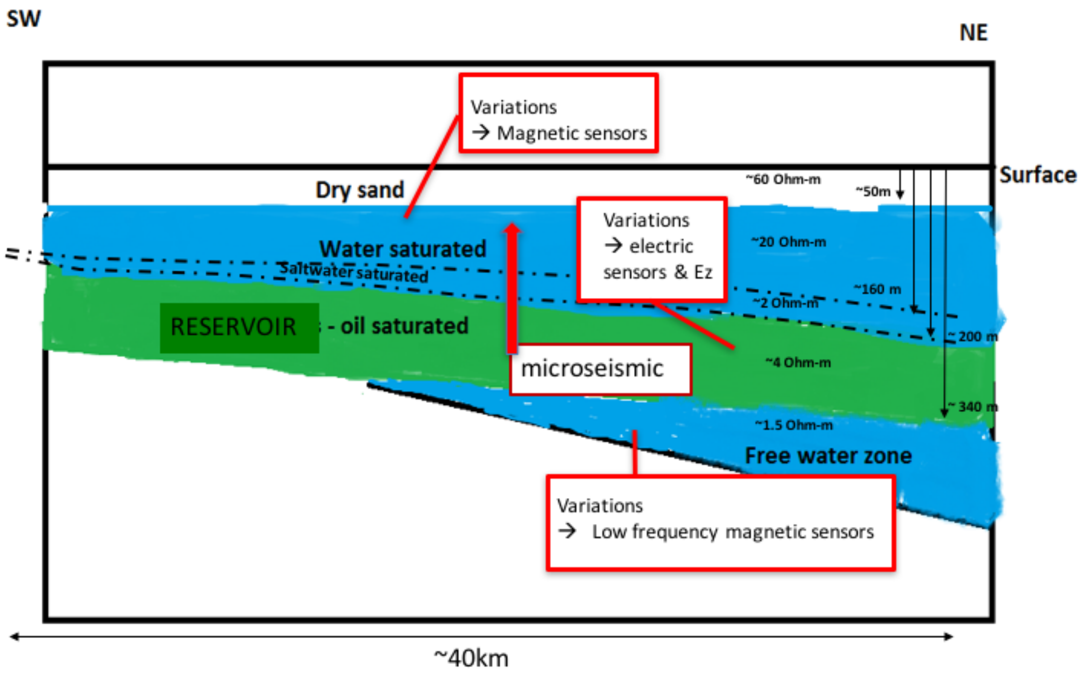


Figure 1: Geologic section of a representative heavy oil reservoir. Annotaed are the fluid variations and which type of electromagnetic sensor must be used. Microseismic data would give indication about seal integrity.

EM Methods offer several advantages over other geophysical techniques:

- Allows the tracking of the steam injection away from the injection wells.
- Very sensitive to temperature changes. For a temperature change of 100 °C resistive changes of 150% and P-wave velocity of 33%.
- Several times less expensive than seismic techniques.
- Faster data acquisition and processing.
- Shallow occurrence allows higher frequency content.
- Possibility of tailoring the techniques to the target by choosing the right method.
- Fast field deployment.

After the commercial success of marine electromagnetics (Eidesmo et al., 2002; Constaple, 2010), the interest in land electromagnetics was revived. Over the past 15 years, we develop a complete new generation of electromagnetic hardware that can be used for land and marine and borehole applications. Key in making surface measurements successful is the integration and calibration with the borehole. Figure 2 give an overview of the hardware components. The system uses an architecture similar to a seismic node (Jiang et al., 2015) and a complete EM node is displayed on the upper left side. To its right is the marine equivalent and at the bottom right the controlled source transmitter. Recently, also 150 KVA version of this have been deployed. On the lower left side is a picture of a laboratory prototype for a deep borehole tool that utilizes the infrastructure of a commercial borehole tool. In the center is the setup diagram of our recent shallow borehole tool. All system can measure seismic and EM signal in in one unit at the same time.

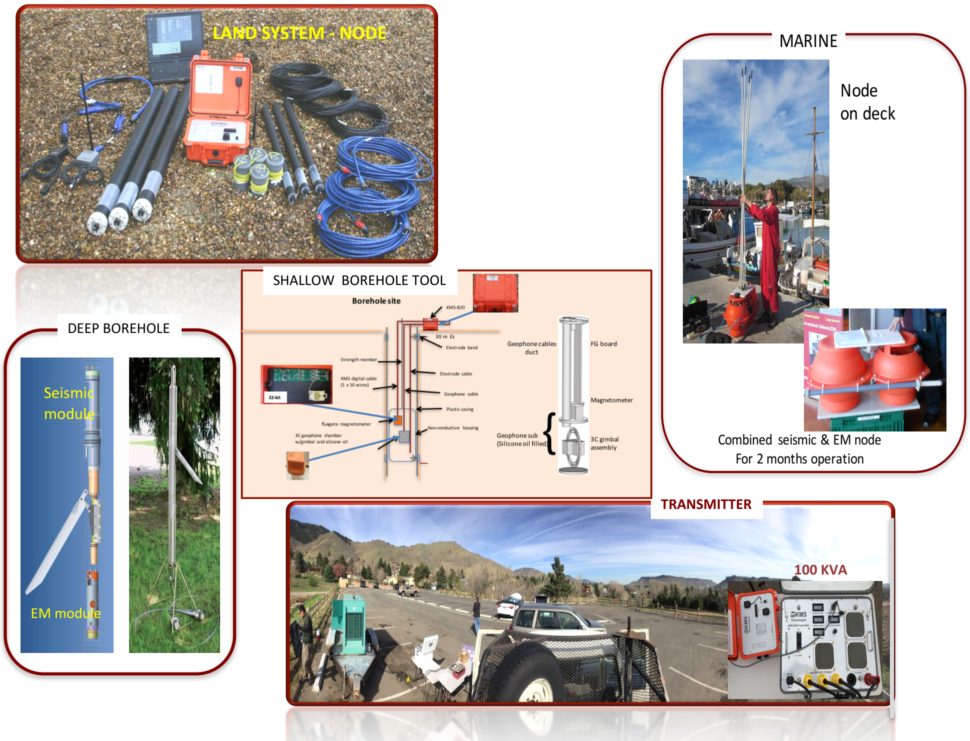
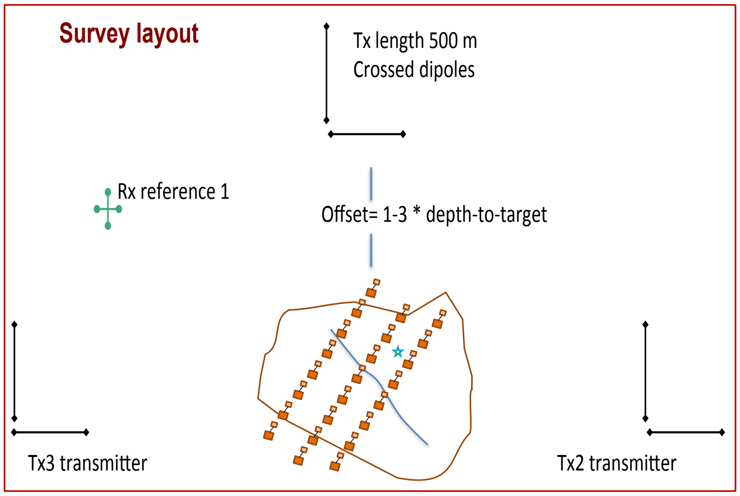


Figure 2: **Overview picture of the hardware components.**

These system components are the combined to make up a rservoir monitoring system and a layout is shown in Figure 3. Here, we see the layout with 3 cross dipole transmitter to get tensor measurements and determine the electrical anisotropy of the reservoir and the layers above and below. We layed out 3 lines with muktiple receivers nodes and wired satelites. The mnix of the componets is shown in the table in the figure. A shallow (30 m) borehole tool is deployed at every node locations. It measure 3-component (3C) magnetic and 3C electric fields as well as the 3C microseismic signal. A reference receiver is used for noise rejection. The combinations of electromagnetcis and seismic is not new. It was proposed by Strack and Vozoff (1996) and Thomsen (2014). What has changes since then is the capability of hardware and software.



Microseismic sensors

Site	KMS instrument	Ex & Ey	Hz	3C fluxgate H	3C geophone	Shallow borehole tool
🟧	820	x	x	x	x	x
□	831	x			x	

E – electric field sensors
H – magnetic field sensors

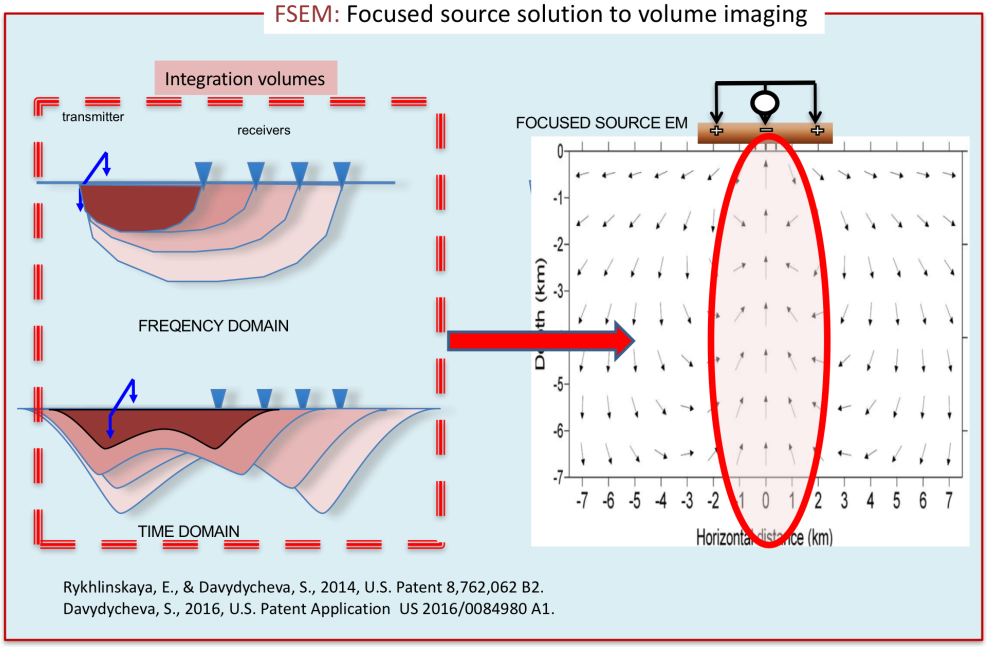
Shallow Borehole Tool – KMS-888 includes 3C seismic, 3C magnetic & 3C electric sensors

Figure 3: Generic survey layout for a heavy oil applications inclduing mixed components.

Challenges to EM methods are the information focus and noise. We are addressing this be using a differential focusing methods known as Focused Source EM (FSEM)(Davydycheva and Rykhlinski, 2009 & 2011; Rykhlinskaya and Davydycheva, 2014; Davydycheva, 2016) and adding shallow/deep boreholes to the system (Strack, 2003 & 2004). In addition, we use array data processing methods to optimize the noise rejection. This methodology is described in the following two figures (Figure 4. and Figure 5.).

The FSEM configuration works similar to focused borehole laterologs. The differences between adjacent receivers is subtracted and approriated normalized to only produce a sensitivity to the the vertical electric field.

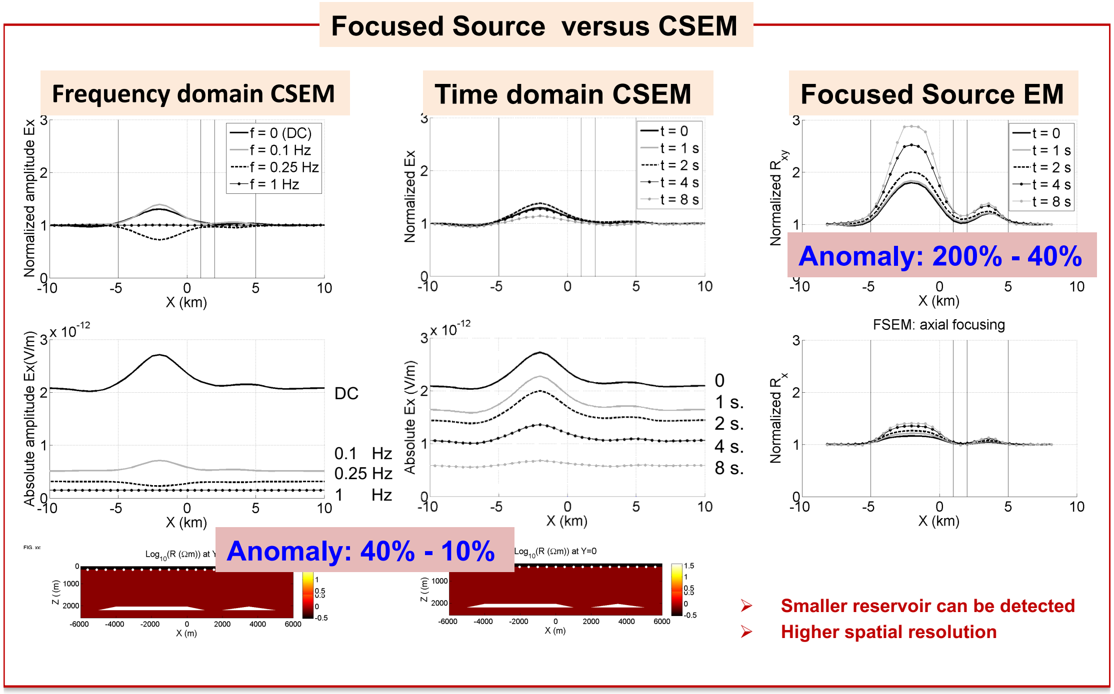
In Figure 4. We show on the left sensitivity (2D) function for different receiver offsets for frequency and time domain. In the freqiency domain we sample the entire volume between transmitter and receiver and in the time domain we are sensitive to a volume below the receiver AND a volume below the transmitter. If we apply to either frequency or time domain the FSEM technique, we obtain mostly sensitivity below the reciver as depicted on the right of the figure.


FSEM: Focused source solution to volume imaging

Rykhlinskaya, E., & Davydycheva, S., 2014, U.S. Patent 8,762,062 B2.
Davydycheva, S., 2016, U.S. Patent Application US 2016/0084980 A1.

Figure 4: Summary sensitivity plots for time and frequency domain on the left and on the right Focused Source EM.

Figure 5. shows the response for the methods for a 3D reservoir target at 3 km depth. Bothe Controlled Source EM methods only give an anomaly of 10-40%. When applying FSEM we can see this anomalous response being greatly improved.


Focused Source versus CSEM

- Smaller reservoir can be detected
- Higher spatial resolution

Figure 5: 3D modeling results for a 2 km depth reservoirmodel for time and frequency domain on the left and on the right Focused Source EM.

We have run field tests with the FSEM methods over a salt dome and could verify these results similar to Davydycheva (2016).

Proposed Methodology

Operating such a geophysical array is easy, but measuring the right components and using the right operations parameters requires a careful approach. We use 3D Feasibility studies and design the survey parameters. Over the past 30+ years we have used this approach in many surveys around the world and looking back we always achieved consistency between Feasibility modeling and survey. However, it should also be said that in more than 50% of the case, we determine that the anomaly is too small to apply EM. This is why we review the Feasibility approach here in detail.

Key element in the design of steam flood monitoring is a careful strategy combining 3D modeling, geologic and petrophysical model, flooding operations and acquisition parameters.

First, we select several candidate reservoirs. Based on the resistivity signature derived from logs we select one for 3D Feasibility. Figure 6. shows the workflow from selection of a reservoir to final permanent installation.

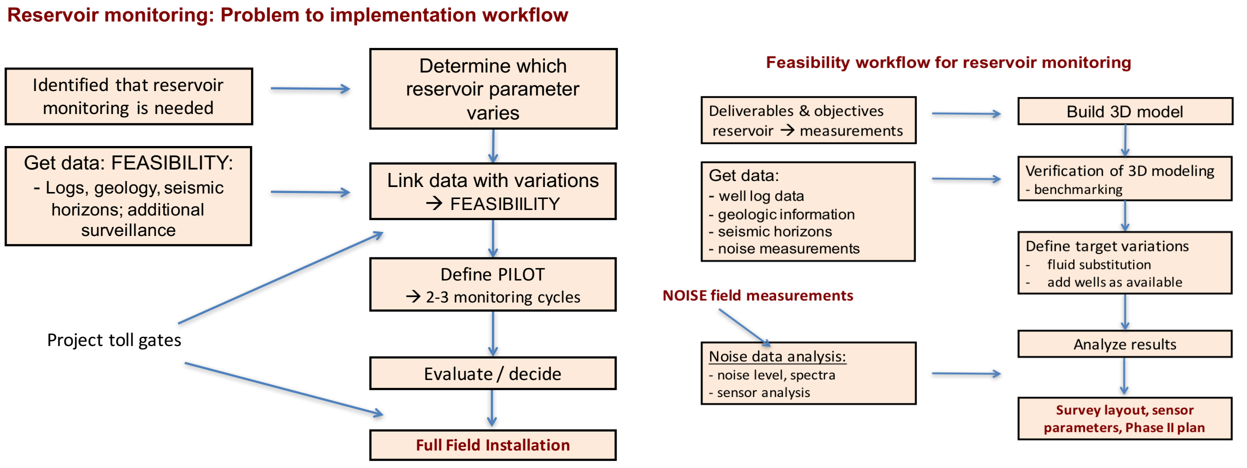


Figure 6: **Workflow staring with the selection of a reservoir through Feasibility, Pilot and eventually permanent installation (RIGHT). On the lefts is the Feasibility workflow.**

Then, we collect the required geoscientific information and derive the models required for the 3D modeling. We also will constrain the model with all available data such as seismic section and logs. We then establish target parameter variations, the details of this is shown in the workflow on the right of the figure. Next, we add noise measurements over the reservoir. The purpose is to establish measurement that represent the survey area, define the right sensors, combine field noise with the 3D modeling results from Phase 1 and to establish if we can actually measure the variation modeled. Resulting is the design of a set of sensors optimized for the specific reservoir.

Since most hydrocarbon reservoirs are electrically anisotropic and consist of resistive (oil) and conductive (brine) targets, every monitoring project with a 3D modeling feasibility that uses well logs to derive the resistivity models and seismic horizons for the reservoir boundaries in an anisotropic fashion. After fluid substitution we can estimate the expected anomaly. We concluded in several case (US, Middle East and Asia) that magnetic and electrical tensor measurements are required. Normally, we assume hydrocarbon reservoirs are mostly resistive and give an anomalous EM response known as Direct Hydrocarbon Indicator (DHI) (Passalacqua, 1983; Eadie, 1980). When you add steam flood to such a reservoir, one gets a more conductive anomaly which requires 3-component magnetic data. Using modern logging tools that measure electrical anisotropy, surface tensor EM measurements are calibrated and tie better to seismic images. When modern anisotropy logs are absent, the anisotropy is estimated using equivalence principle first suggested by Keller and Frischknecht (1967).

Following is a 3D model shown for one of the 3D Feasibilities we carried out (USA) following the above workflow (Figure 8.) The different colored curves are for different offsets and show a ± 10% anomaly. The models were constrained by 3D seismic by matching the reservoir depth to the seismic layers. Subsequent to the modeling we carried out a noise test over the reservoir using different sensors. The results are shown in Figure 9. The 3D modeling results are converted to realistic voltages using the transmitter and receiver parameters. Then different recording times and sampling rates are acquired for the different sensors (some sampling frequencies have better noise rejection than others). Getting the very best signal-to-noise ratio is paramount to ensure reliable data. In Figure 9. We see the voltages for the layout shown on the left of the figure.

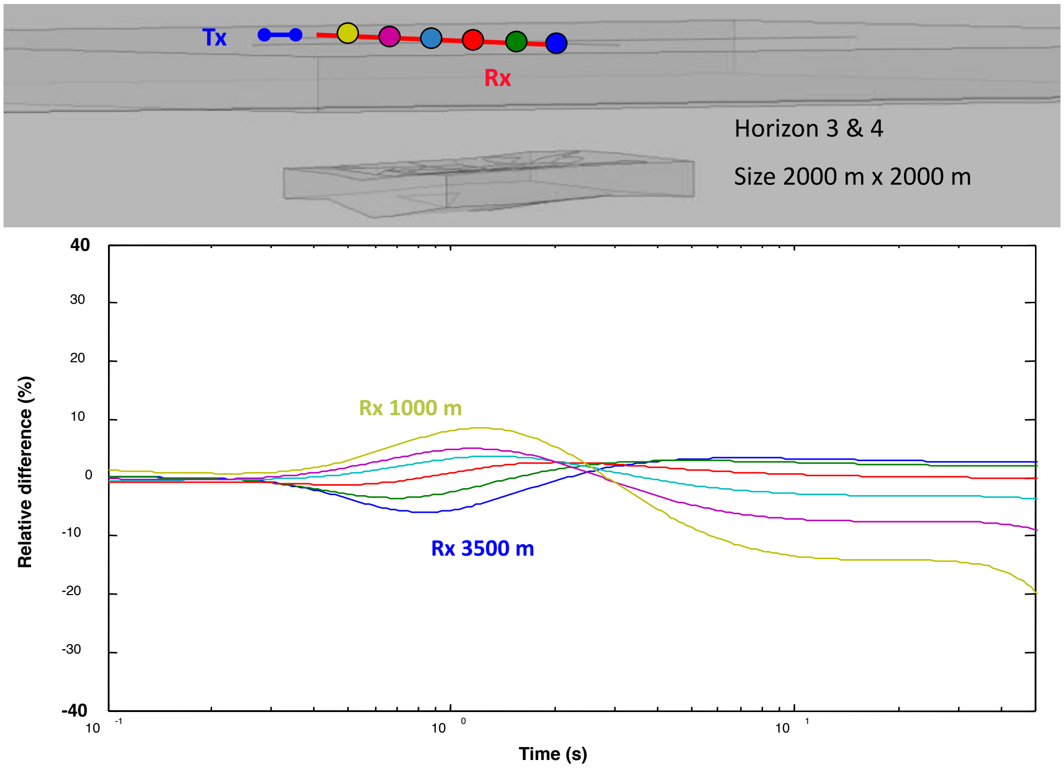


Figure 8: **Example 3D model and 3D modeling response of a 3D Feasibility.**

From the noise measurements, we have the noise thresholds superimposed for the different sensors. In this case, clearly our air coil gave best results.

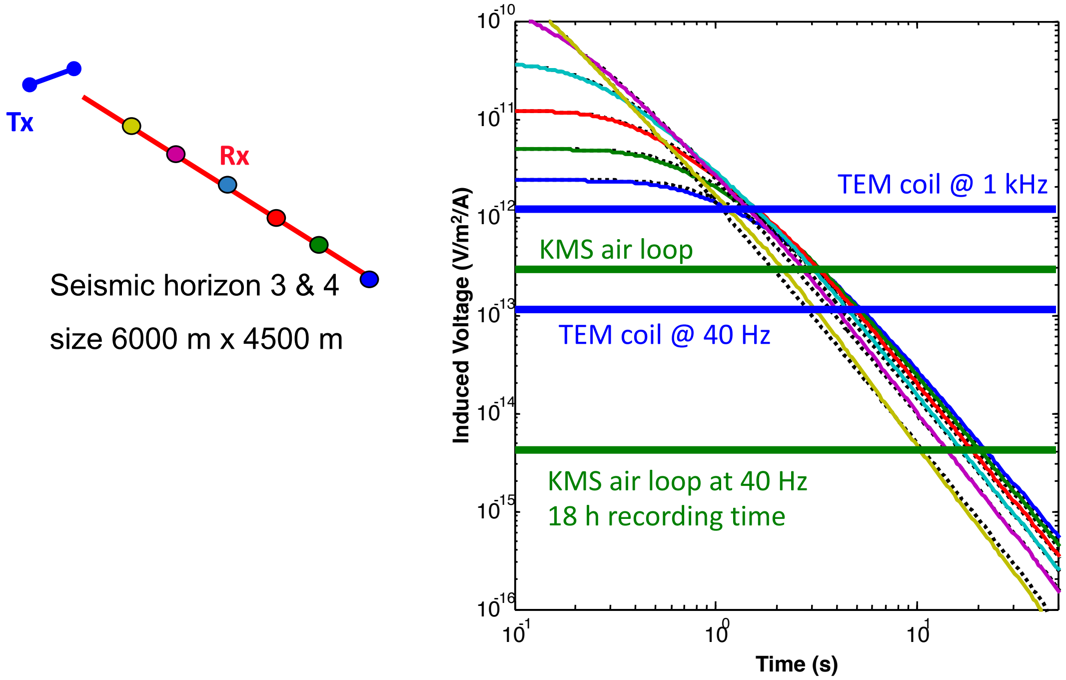


Figure 9: **Noise test results superimposed on the 3D modeling results (converted to voltages).**

We have carried out many feasibility studies for a variety of reservoir. Heavy oil reservoir appears to be one of the more promising applications. We have also started a pilot field installation which is ongoing.

Conclusions

Heavy oil reservoirs are often steam flooded. Knowledge of the steam front is often sketchy and monitoring technology is required as it will allow the mapping of the steam front thus improving the recovery factor. Knowledge of the steam movement and subsequent flooding optimization will also reduce cost.

Among the geophysical methods, electromagnetic methods are the most suitable methods for this task as they allow fluid imaging. Over the past 10 years after the success of the marine industry, the interest in land electromagnetic applications has increased to appoint that a complete new generation of technology exist including new array acquisition hardware, transmitter, shallow borehole sensors and processing and 3D interpretation methods. Using these tool for Feasibility study we can reduce the risk to carry out Pilot for steam flooding and greatly contribute to the production effort.

Acknowledgments

We appreciate the support of T. Hanstein and S. Davydycheva by carrying the noise tests and 3D modeling. Over the years we have received support from many companies. They included: Aramco, BP, DeepLook consortium (BP, Chevron, ConocoPhillips, Shell), ENI, Ormat, PTTEP, Shell, WellDynamics. We also thanks our organizations for permitting too publish this paper.

REFERENCES

Carlson, M, 2013, Caprock failure at Joslyn, Journal of Canadian Heavy Oil Ass.,

Constable, S., 2010, Ten years of marine CSEM for hydrocarbon exploration: Geophysics, 75, 75A67.

Davydycheva, S., and N. Rykhlinski, 2009, Focused Source EM survey versus time-domain and frequency-domain CSEM: The Leading Edge, no.8, 944-949.

Davydycheva, S., and N. Rykhlinski, 2011, Focused Source electromagnetic survey versus standard CSEM: 3D modeling in complex geometries, Geophysics, 76, 1, F27-F41.

Eadie, T., 1980, Detection of hydrocarbon accumulations by surface electrical methods - feasibility study: M. S. Thesis, University of Toronto.

Eidesmo. T., S. Ellingsrud, L. M. MacGregor, S. Constable, M. C. Sinha, S. Johansen, F. N. Kong, and H. Westerdahl, 2002, Sea Bed Logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deep water areas: First Break, 20, 144-152.

He, Z., X. Liu, W. Weiting, and H. Zhou, H., 2006, Mapping reservoir boundary by borehole-surface TFEM: Two case studies: The Leading Edge, 24, 896-900.

He, Z., W. Hu, W. Dong, 2010, Petroleum Electromagnetic Prospecting Advances and Case Studies in China, Surveys in Geophysics, 31, 207-224.

Jiang, J., Aziz, A.A., Liu, Y., and Strack. K.M., 2015, Geophysical acquisition system, US 9,057,801.

Keller, G.V., and F. C. Frischknecht, 1967, Electrical methods in geophysical prospecting: Pergamon Press.

Kumar, D., and G.M. Hoversten, 2012, Geophysical model response in a shale gas GEOHORIZONS Journal of Society of Petroleum Geophysicists, India, 16, 31-37.

Neese, J.W. and L. Thomsen, 2014, Seismic processing of numerical EM data, SEG

Passalacqua, H., 1983, Electromagnetic fields due to a thin resistive layer: Geophysical Prospecting, 31, 945-976.

Rykhlinskaya, E., and Davydycheva, S., 2014, Method for marine geoelectrical exploration with electrical current focusing, U.S. Patent 8,762,062 B2.

Davydycheva, S., 2016, Method and apparatus for detecting and mapping subsurface anomalies, U.S. Patent Application US2016/0084980 A1.

Strack, K.M., and A.A. Aziz, 2013, Advances in electromagnetics for reservoir monitoring: Geohorizons, 32-44. (Special shale issue)

Strack, K. -M., 2003, Integrated borehole system for reservoir detection and monitoring, US 06541975 & US 06670813.

Strack, K. -M., 2004, Surface and borehole integrated electromagnetic apparatus to determine reservoir fluid properties, US 06739165.

Strack, K.M., and K. Vozoff, 1996, integrating long-offset transient electromagnetics (LOTEM) with seismics in an exploration environment: Geophysical Prospecting, 44, 99-101.

Thomsen, L., 2014, Electromagnetics and seismics: The deep connection, SEG Technical Program Expanded Abstracts, 855-859.

Tietze, K., O. Ritter, and P. Veeken, 2015, Controlled-source electromagnetic monitoring for reservoir oil saturation using a novel borehole-to-surface configuration, Geophysical prospecting, 63, 1-23.