A New Array System for Multiphysics (MT, LOTEM, and Microseismics) with Focus on Reservoir Monitoring

K. Strack[1, a)], S. Davydycheva[1, b)], T. Hanstein[1, c)] and M. Smirnov[1, d)]

[1)] *KMS Technologies (Thailand, USA & Germany)*

[a)] corresponding author's email : Kurt@kmstechnologies.com

Abstract. Over the last 6 years we developed an array system for electromagnetic acquisition (magnetotelluric & long offset transient electromagnetics [LOTEM]) that includes microseismic acquisition. While the system is being used in many countries for magnetotellurics, we focus here on the autonomous operation as reservoir monitoring system including a shallow borehole receiver and 100/150 KVA transmitter. Marine extension is also under development. For Enhanced Oil recovery, in addition to reservoir flood front movements, reservoir seal integrity has become an issue [1]. Seal integrity is best addressed with microseismics while the water flood front is best addressed with electromagnetics. Since the flooded reservoir is conductive and the hydrocarbon saturated part is resistive, you need both magnetic and electric fields. The fluid imaging is addressed 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 [2,3]. From the 3D modeling, we derived a key requirement that borehole and surface data needed to be integrated by measuring between surface to borehole and calibrated using conventional logs including anisotropy. This would significantly reduce the risk [4,5,6]. To overcome the volume-focus inherent to electromagnetics we added a new methodology to focus the sensitivity under the receiver. The same can be achieved using a shallow borehole system that includes microseismic, 3C magnetics and 3C electrical measurements. Field data and 3D modeling confirm this and as results this could increase the efficiency of applying LOTEM to exploration and reservoir monitoring problems.

INTRODUCTION & BACKGROUND

Standard applications for CSEM have been in exploration. Onshore, only limited applications have been done for geothermal/hydrocarbon applications in the past 20 years [7]. Only after the success in the marine industry has the interest in land electromagnetics increased. The biggest market is in the reservoir monitoring industry, which is a multi-billion $ market. Thus, we focus in this article on the implementation of CSEM for monitoring.

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 [1] 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 CSEM in the time domain as the most sensitive method [2,3]. 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 calibrated using conventional logs including anisotropy. This would significantly reduce the risk [4,5,6].

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 list of geophysical techniques available in the industry, 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. They can be used with different geometries: from the surface, downhole, in a surface-to-downhole 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 reservoir pressure creating potential problems to the integrity of the cap-rock. When the grain-to-grain contact breaks, resulting fractures produce small amounts of seismic energy measurable with micro-seismic sensors. At the same time, the pore space changes causing a decrease in resistivity.

The injection of steam into the reservoir will alter the rock properties including seismic velocity and resistivity. 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 (shallow) 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. For electromagnetics, 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 [8, 9] 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 [1].

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 [10, 11], 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. gives an overview of the hardware components. The system uses architecture like a seismic node [21] 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 capable to produce up to 250 A 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. The array acquisition system can

record from DC to 40 kHz with almost any geophysical receiver. The acquisition system and CSEM transmitter are autonomous and can operate various methods using a scheduler. All the system can acquire microseismic and EM data simultaneously.

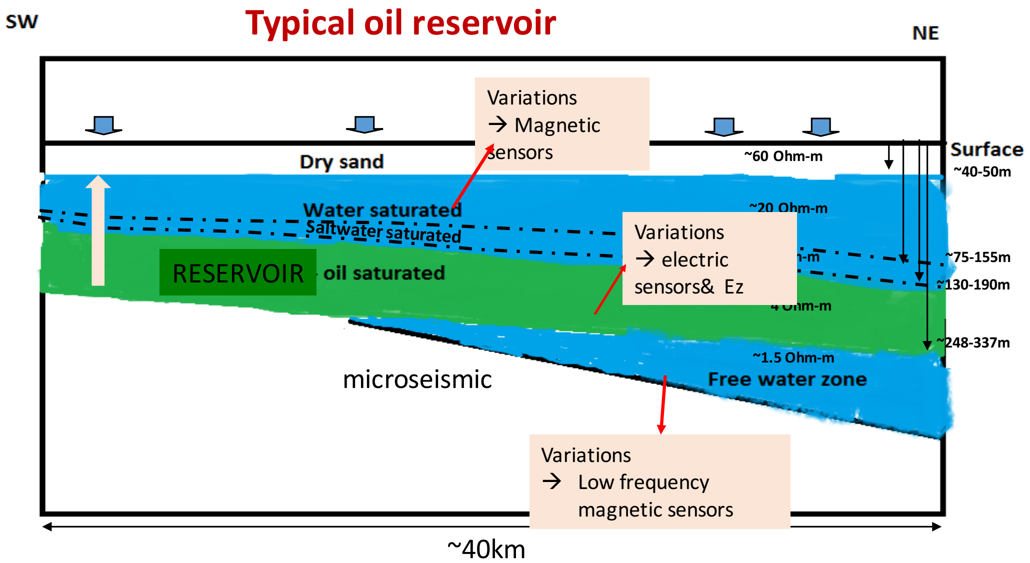


FIGURE 1. Sample geologic cross section of a representative heavy oil reservoir. Annotated are the fluid variations and which type of electromagnetic sensor must be used. Microseismic data would give indication about seal integrity between the reservoir and the overlying layer.

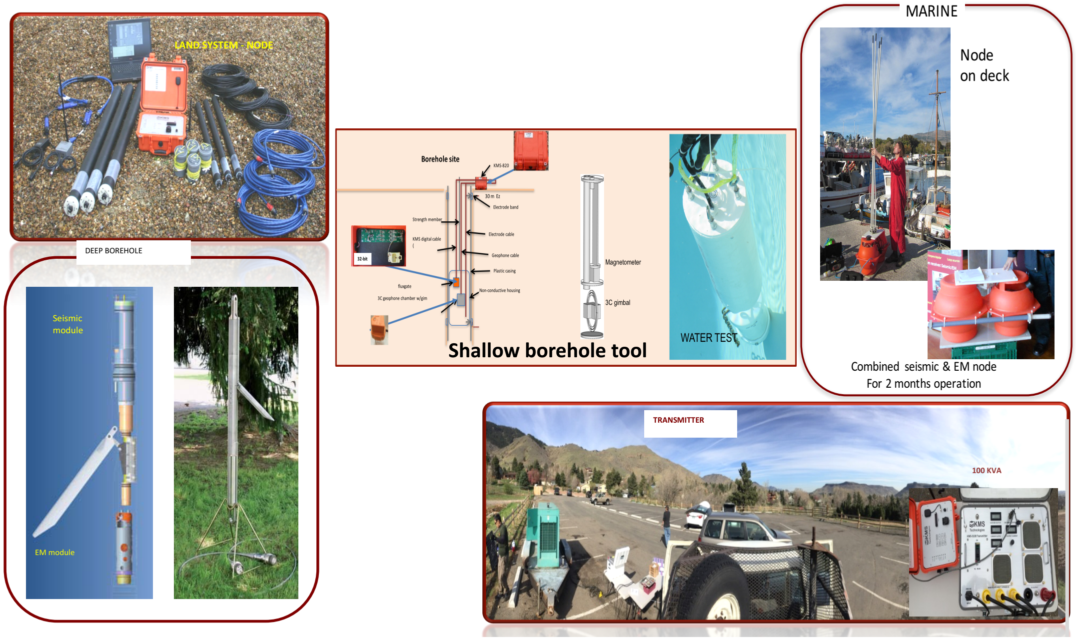
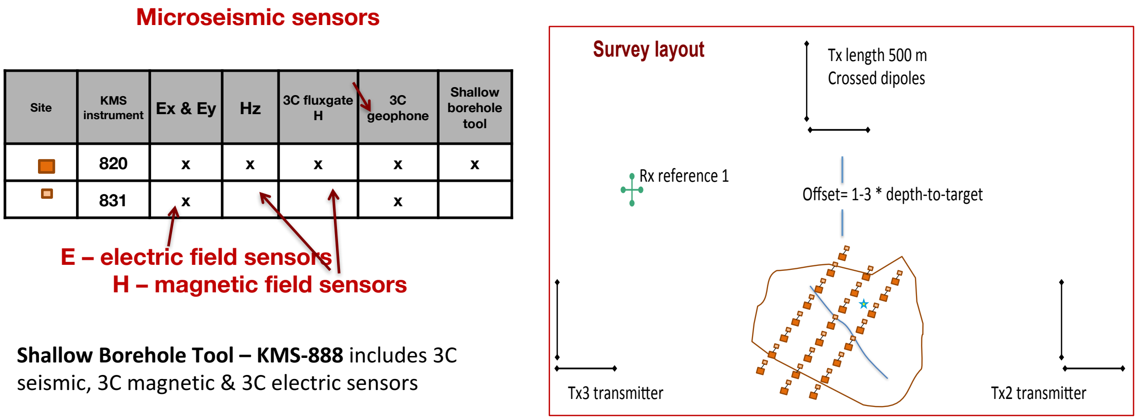


FIGURE 2: System hardware examples for the multi-physics array electromagnetic system.

These system components are combined to make up a reservoir monitoring system and a layout is shown in Fig. 3. Here, we see the layout with 3 cross dipole transmitters to get tensor measurements and determine the electrical anisotropy of the reservoir and the layers above and below. We laid out 3 lines with multiple receivers, nodes and wired sub-acquisition units. The mix of the components is shown in the table in the figure. A shallow (30 m) borehole tool is deployed at every node locations. It measures 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 electromagnetics and seismic is not new. It was proposed by Strack and Vozoff [12] and Thomsen [13]. What has changed since then is the capability of hardware and software.



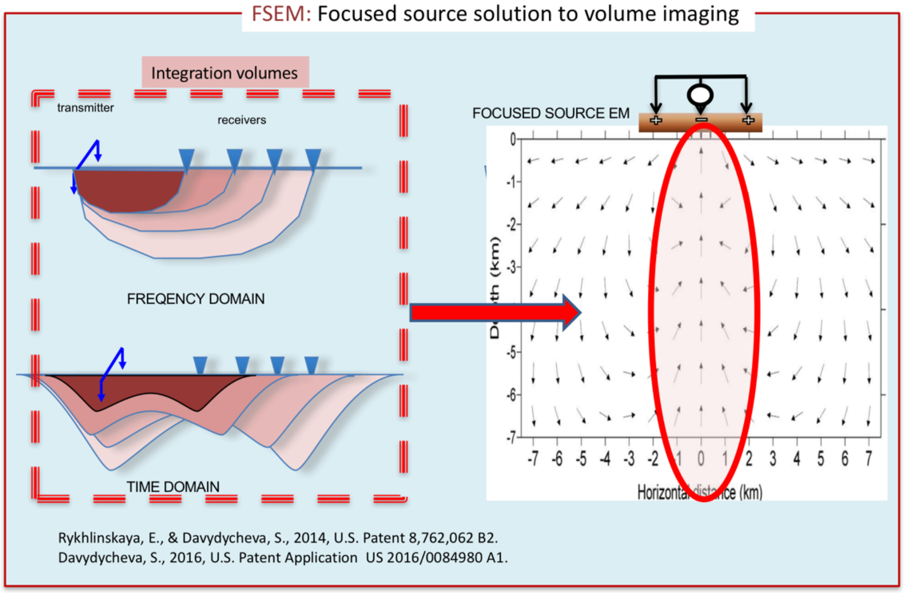
Site	KMS instrument	Ex & Ey	Hz	3C fluxgate H	3C geophone	Shallow borehole tool
■	820	x	x	x	x	x
▪	831	x			x	

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

FIGURE 3. Generic survey layout for monitoring applications for a flood front using multi-physics geophysical sensors.

Challenges to EM methods are the information focus and noise. We are addressing this by using differential focusing methods known as Focused Source EM (FSEM) [14, 15, 16, and 17] and adding shallow/deep boreholes to the system [18, 19]. 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 like focused borehole laterologs. The differences between adjacent receivers is subtracted and appropriately normalized to only produce a sensitivity to the vertical electric field.

Figure 4. shows on the left the sensitivity (2D) for different receiver offsets for frequency and time domain. In the frequency 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 either frequency or time domain the FSEM technique, we obtain mostly sensitivity below the receiver as depicted on the right of the Fig. 4.



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. Both the Controlled Source EM methods only give an anomaly of 10-40%. Another benefit of applying FSEM is that it removes near surface effects.

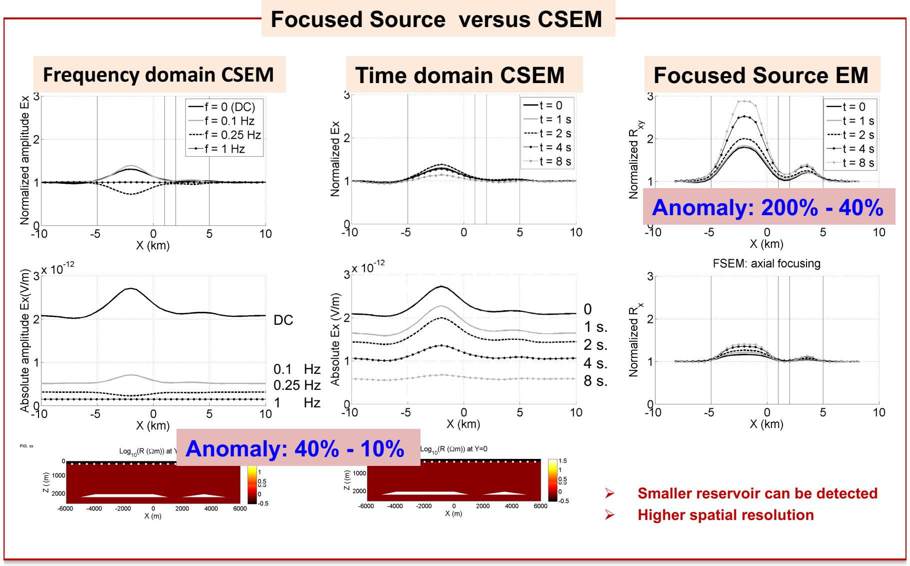


FIGURE 5. (a) 3D modeling results for a 2 km depth reservoir model for time and frequency domain and (b) Focused Source EM.

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 optimum 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 cases, we determine that the anomaly is too small to apply EM. Therefore, 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.

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 measurements 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 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 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 cases (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) [8, 9]. 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 [20].

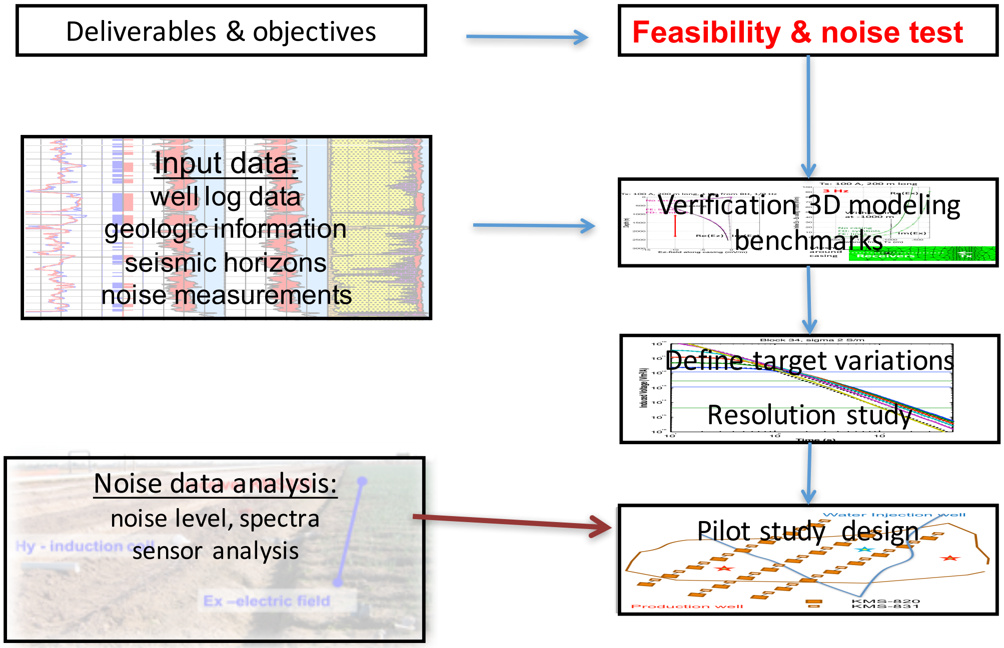


FIGURE 6. Workflow showing the selection of a reservoir through Feasibility, and eventually Pilot.

Following is a 3D model shown for one of the 3D Feasibilities we carried out (USA) following the above workflow (Figure 7). 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. After the modeling, we carried out a noise test over the reservoir using different sensors. The results are shown in Fig. 8. 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 8, we see the voltages for the layout shown on the left of the figure.

To judge if we can measure the target response, we superimposed for the different sensors their noise levels with the 3D modeling results. Figure 8. shows the results for this survey. The different sensors are marked in the figure. In this case, clearly our air coil gave best results. We also varied sampling rate to estimate acquisition times and survey layout. Once this is done we propose a field layout as in Fig. 3. and survey specifications. These are translated into survey parameters and, depending upon applications, reservoir parameters are then again included.

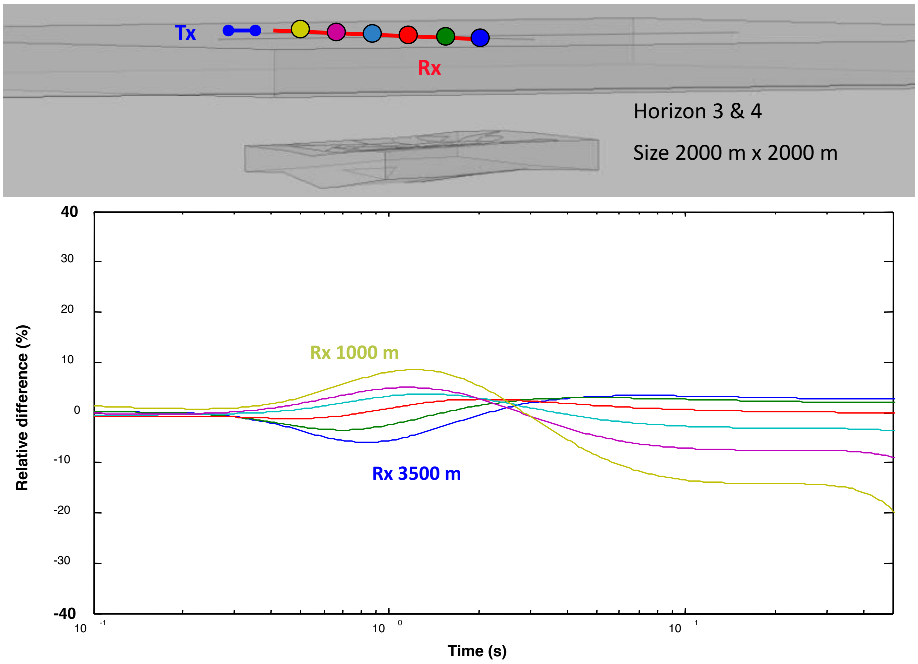


FIGURE 7. Example 3D model and 3D modeling response of a 3D Feasibility where the receivers are located at the surface along a profile.

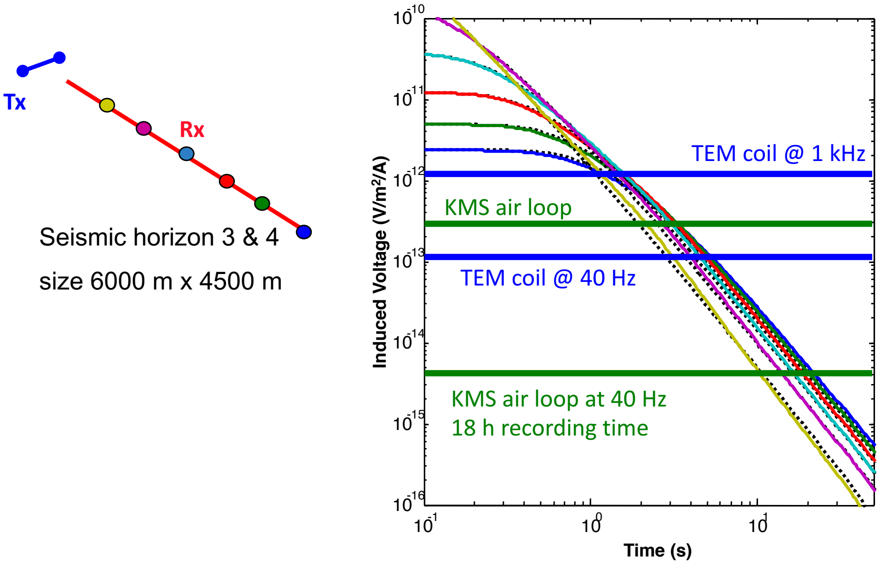


FIGURE 8. Noise test results superimposed on the 3D modeling results (converted to voltages).

We have carried out many feasibility studies for a variety of reservoirs from various continents. Enhanced oil recovery applications and heavy oil reservoir appears to be among the more promising applications. We have also carried out a pilot field installation and partially confirmed the prediction from 3D modeling.

CONCLUSIONS

Controlled Source Electromagnetic methods are routinely applied for geothermal exploration and only to a more limited extend for land hydrocarbon exploration. Offshore they are becoming part of the routine workflow. 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.

The real potential for CSEM methods lies is reservoir monitoring and its various applications. Among the geophysical methods, electromagnetic methods are the most suitable methods for this task as they allow fluid imaging. To find the sweat spot in applications careful Feasibility study can reduce the risk to carry out Pilot for steam flooding and greatly contribute to the production effort.

ACKNOWLEDGMENTS

We appreciate the support of Herminio Passalacqua in discussing the material. 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.

REFERENCES

1. M.R. Carlson, 2012, An Analysis of the Caprock Failure at Joslyn, presented at the SPE Heavy Oil Conference held in Calgary, Alberta, Canada 12-14th June 2012. SPE-156962-PP.
2. K.M. Strack, and A.A. Aziz, 2013, Advances in electromagnetics for reservoir monitoring, Geohorizons, 32-44, (Special shale issue).
3. D. Kumar, and G.M. Hoversten, 2012, Geophysical model response in a shale gas, Geohorizons, Journal of Society of Petroleum Geophysicists, India, 16, 31-37.
4. Z. He, 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.
5. He, W. Hu, and W. Dong, 2010, Petroleum Electromagnetic Prospecting Advances and Case Studies in China, Surveys in Geophysics, 31, 207-224.
6. K. Tietze, 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.
7. K.M. Strack, 2014. Future directions of Electromagnetic Methods for Hydrocarbon Applications. Surveys in Geophysics 35, 157-177.
8. T. Eadie,1980, Detection of hydrocarbon accumulations by surface electrical methods - feasibility study: M. S. Thesis, University of Toronto.
9. H. Passalacqua, 1983, Electromagnetic fields due to a thin resistive layer, Geophysical Prospecting, 31, 945-976.
10. T. Eidesmo. 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.
11. C. Constable, 2010, Ten years of marine CSEM for hydrocarbon exploration: Geophysics, 75, 75A67.
12. K.M. Strack, and K. Vozoff, 1996, Integrating long-offset transient electromagnetics (LOTEM) with seismics in an exploration environment, Geophysical Prospecting, 44, 99-101.
13. L. Thomsen, 2014, Electromagnetics and seismics: The deep connection, SEG Technical Program Expanded Abstracts, 855-859.
14. S. Davydycheva, and N. Rykhlinski, 2009, Focused Source EM survey versus time-domain and frequency-domain CSEM, The Leading Edge, no.8, 944-949.
15. S. Davydycheva, and N. Rykhlinski, 2011, Focused Source electromagnetic survey versus standard CSEM: 3D modeling in complex geometries, Geophysics, 76, 1, F27-F41
16. E. Rykhlinskaya, and Davydycheva, S., 2014, Method for marine geoelectrical exploration with electrical current focusing, U.S. Patent 8,762,062 B2.
17. S. Davydycheva, 2016, Method and apparatus for detecting and mapping subsurface anomalies, U.S. Patent Application US2016/0084980 A1.

18. K.M. Strack, 2003, Integrated borehole system for reservoir detection and monitoring, US 06541975 & US 06670813.
19. K.M. Strack, 2004, Surface and borehole integrated electromagnetic apparatus to determine reservoir fluid properties, US 06739165.
20. G.V. Keller, and F. C. Frischknecht, 1967, Electrical methods in Geophysical Prospecting, Pergamon Press.
21. J. Jiang, Aziz, A.A., Liu, Y., and Strack. K.M., 2015, Geophysical acquisition system, US 9,057,801.