Feasibility study of reservoir monitoring in an onshore oil field using SQUITEM system

Michael Zhdanov, Leif Cox, and Alex Gribenko, TechnoImaging and University of Utah;*
Hideaki Ban and Hiroshi Chiba, JOGMEC

Summary

The ability to understand and control the behavior of the hydrocarbon (HC) reservoir over the production allows for optimization of reservoir performance and production strategies. The use of seismic data for water flooding monitoring is very challenging because of the small variation of seismic velocities over time and because of the difficulty of survey repeatability. There is a growing interest in developing innovative geophysical methods for monitoring hydrocarbon reservoirs. This paper introduces a feasibility study of using the highly sensitive SQUID magnetometers for reservoir monitoring in an onshore oil field. The proposed approach is based on measuring the time domain electromagnetic response from a reservoir by a set of JOGMEC developed SQUID sensors, located on the ground. The EM field is generated by an electric bipole source, or a combination of electric bipoles sending the electric pulses in the ground. We identify this survey system as a SQUITEM.

This paper describes the results of the feasibility study conducted by JOGMEC and TechnoImaging to optimize the SQUITEM survey parameters. We have performed 3D modeling on a variety of survey configurations with the reservoir geometry to optimize future surveys and to develop a recommendation for an optimal SQUITEM survey for HC reservoir monitoring in an onshore oil field. The modeling shows that creating a vertical flow of current will couple better with the resistive reservoir than the typically used horizontal electric bipole source. This can be achieved by a vertical bipole source or by a ground source configuration which simulates the vertical dipole, such as a circular, star, or cross bipole configuration.

Introduction

JOGMEC (Japan Oil and Gas, Metals National Corporation), Metal Exploration Department developed SQUITEM system with SUSTERA (Superconducting Sensing Technology Research Association) and MINDECO (Mitsui Mineral Development Engineering Co. Ltd.). A general description of the developed SQUITEM system and the results of its field study conducted in 2017 at Mallee Bull prospect in NSW Australia were published by Motoori et al. (2018). The high sensitivity of the SQUID magnetic sensors, with a thin-film multilayer structure including multiple oxide high-temperature superconducting (HTS) thin films, allows the user measuring a relatively small response of the HC reservoir for a wide time interval. In addition, the SQUID sensors measure the magnetic B field, instead of its time derivative, dB/dt, which ensures the measurement of the EM response at later time corresponding to greater depth than by using the conventional induction coils.

The key objectives of this paper are as follows: 1) modeling the effect of environmental noise sources; 2) modeling the effect of reservoir in the observed data; and 3) optimization of the SQUITEM survey configuration.

Methods

Modeling the effect of environmental noise sources

The major sources of the environmental noise include the pipelines and the cased boreholes in the survey area as well as the near-transmitter conductivity variations. The effects of all these sources were modeled to test the EM response at the receivers.

The survey, as modeled, is shown in Figure 1. The conductive anomalies were placed under the transmitter. They were of variable thickness and covered an areal extent of 2 km x 4 km. The conductivity was varied to find the bounds of what caused a change in the observed data of less than 5%.

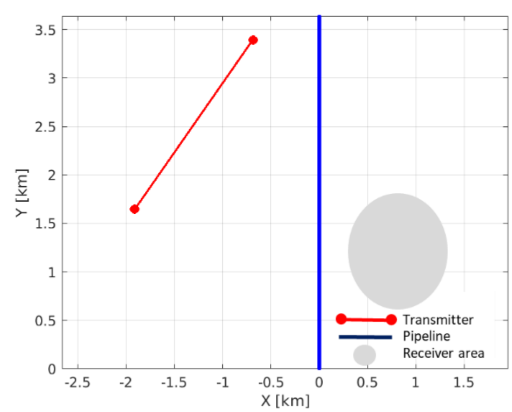

Figure 1: Map view of the model for the pipeline and near-transmitter conductivity modeling excercise. The electric bipole source is shown by a red line. Vertical blue line indicates the pipeline. The grey oval outlines an area with the SQUITEM receiver array.

The studies show that the effects of the transmitter conductivity variations are relatively minor. The observed data change by less than 5% when the conductivity of the near-surface anomaly is twice the conductivity of the half-space, or conductivity of the near-surface anomaly is 10 times smaller than half space conductivity. As an illustration,

Figure 2 compares responses of the 3 Ohm-m half-space (HS) with and without 1.5 Ohm-m conductive near surface anomaly. Figure 3 illustrates effect of 30 Ohm-m resistive near surface anomaly. It is recommended, but not required, to perform some type of conductivity measurement at the transmitter area for modeling and inversion purposes.

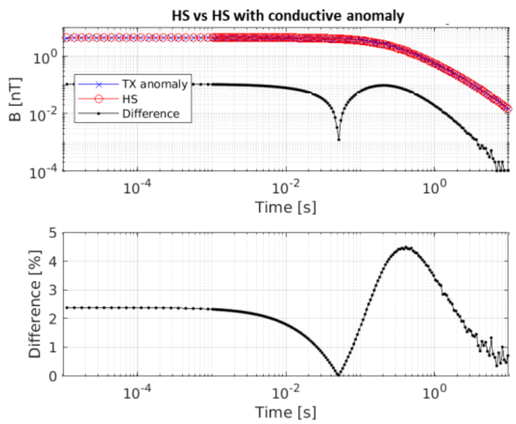

Figure 2: Variations in vertical magnetic field observed by SQUITEM receiver from the thin conductive overprint under the transmitter. The models are with and without the 1.5 Ohm-m conductive anomaly in the tranmitter location.

Figure 3 shows a comparison of the responses with and without pipeline. Differences between responses for models with and without pipelines is below 2%.

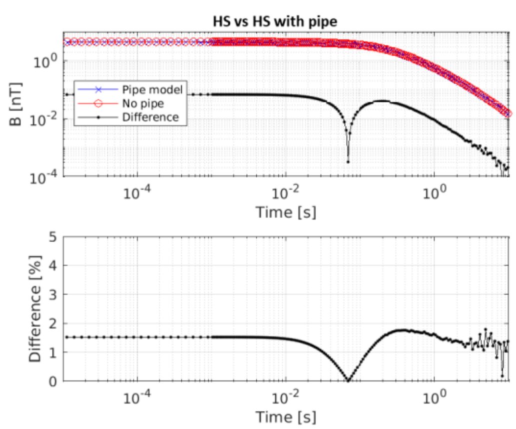

Figure 3: Variations in vertical magnetic field observed by SQUITEM receiver from the pipeline shown in Figure 1 and difference between responses for models with and without the pipeline.

We have also modeled the effect of the borehole casing. Figure 4 shows the relative positions or the transmitter, receivers, and the borehole in 3D view. Figure 5 compares responses of the 3 Ohm-m half space with and without borehole for the magnetic field SQUITEM receiver. The difference between two cases appears insignificant. This is likely due to the mostly vertical orientation of the borehole, which will not couple well to the primarily horizontal currents induced with the horizontal transmitter.

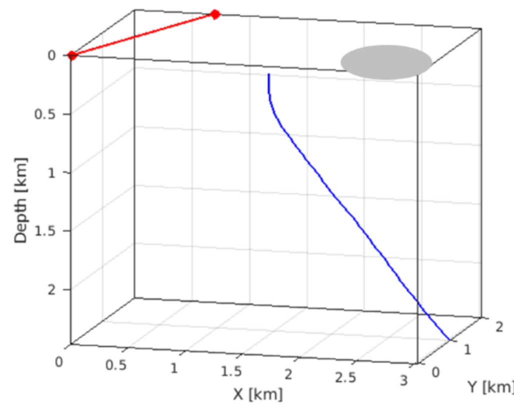

Figure 4: 3D view of the model for the cased borehole modeling excercise. The electric bipole source is shown by a red line. The blue line indicates the borehole. The grey oval outlines an area with the SQUITEM receiver array.

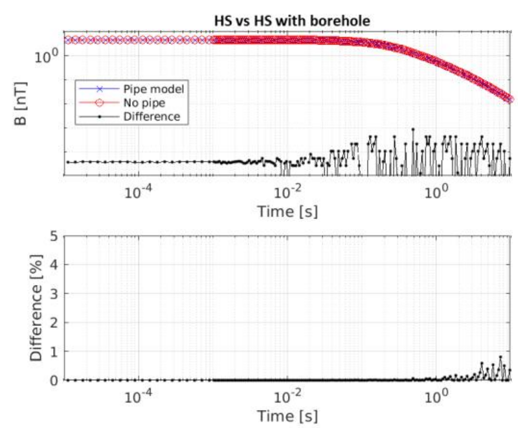

Figure 5: Variations in vertical magnetic field observed by SQUITEM receiver from the cased well shown in Figure and difference between well and no-well cases. The response of the well is insignificant.

Modeling the effect of reservoir in the observed data

The 3D numerical modeling for this project is based on the integral equation method (e. g, Zhdanov 2002, 2018; Gribenko and Zhdanov, 2007). The code has been extensively tested for this project, comparing fully analytical, 1D, and 3D solutions to confirm the validity.

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To test the response of the reservoir, a simple 3D conductivity model shown in Figure 6 was built. Both 2 Ohm-m conductive and 20 Ohm-m resistive anomalies were considered.

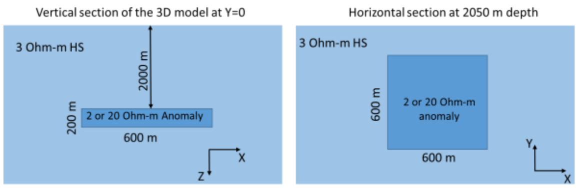

Figure 6: Vertical (left) and horizontal (right) sections of the simplified 3D model used in the study of the response of the reservoir located at 2 km depth.

The horizontal Y-dipole configuration for this simple model is most similar to the conventional field survey setup. Figure 7 shows the anomalous field, which largely circulates around the reservoir, causing a null in the vertical component and a maximum in the horizontal component over the reservoir. With this transmitter configuration, it would be advantageous to measure the horizontal component over the reservoir or the vertical component some distance away.

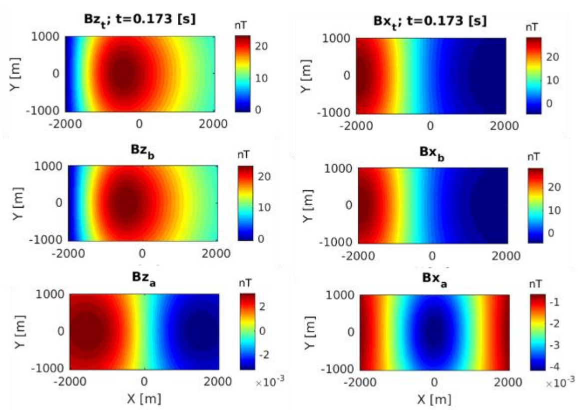

Figure 7: Maps of the vertical B_z (left) and horizontal B_x (right) responses. The oil reservoir responses are shown in the top panels, water filled reservoir responses are shown in the middle panels, and their differences are shown in the bottom panels.

Optimization of the SQUITEM survey configuration

To improve the signal from the reservoir, several survey configurations were tested on this simple reservoir model. These included the configurations shown in Figure 8. A variety of source-reservoir offsets and transmitter lengths were used. Transmitter dipole lengths varied between 1 and 3 km. 1000 A current was assumed in the transmitter. Variable distance between transmitter dipole and the center of the anomalous body was used, from 0 to 3 km.

The three components of magnetic field and the two horizontal components of the electric field were synthesized and compared. The simple reservoir model was a 600 m x 600 m x 200 m 20 Ohm-m block buried 2000 m below the surface in a 3 Ohm-m background.

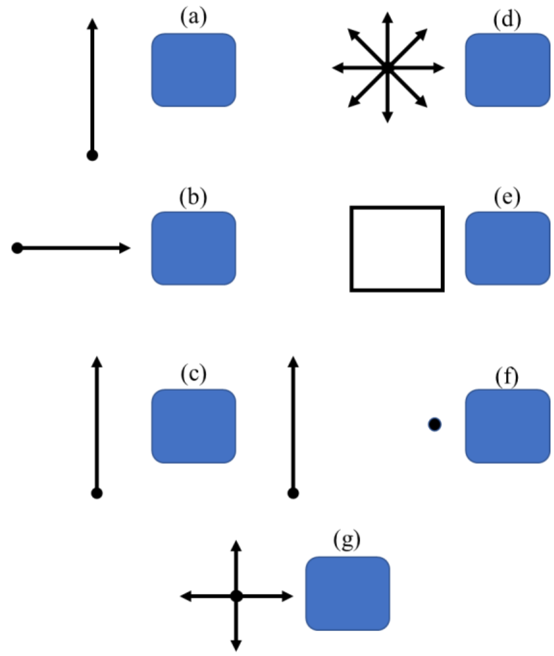

Figure 8: Survey configurations, the blue square is the reservoiur location and the black line indicates an electric dipole. Survey configurations tested: (a) y-dipole (broadside); (b) x-dipole (inline); (c) double y-dipole; (d) star; (e) loop; (f) z-dipole (downhole); (g) cross.

Figure 9 presents, as an example, locations of transmitter and receivers for star-type configuration. The Star transmitter configuration was introduced to create more vertical current across the HC reservoir. Because the target is resistive, electric fields perpendicular to the reservoir (vertically) will be perturbed more than the current flowing horizontally around the reservoir. Indeed, this is the best array to detect the reservoir with a surface configuration. Figure 10 shows the decay curves for the horizontal component $\mathbf{B_y}$ of the total, background, and anomalous fields for a receiver close to the center of the reservoir. The anomalous fields are of the same magnitude as the primary fields, and in many cases greater.

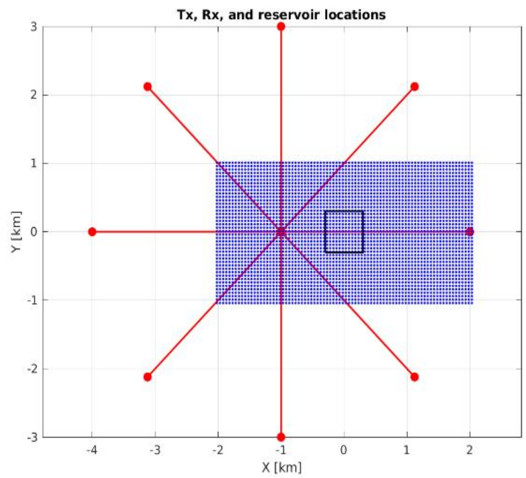

Figure 9: Transmitter and receiver locations for the Star configuration. The electric bipole sources are shown by the red lines. The black rectangle outlines the location of the reservoir. The blue grid shows an area with the SQUITEM receiver array.

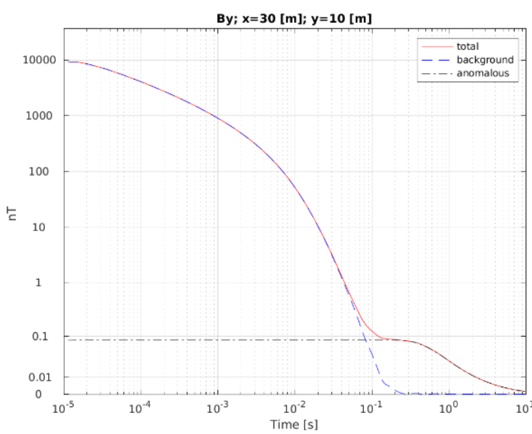

Figure 10: Decay curves of the total (redline), background (dashed blue line), and anomalous (dashed black line) $\mathbf{B}_y$ fields for a receiver close to the center of the reservoir for the Star transmitter. After 0.1 s, the fields become almost entirely due to the reservoir.

The results of our modeling study show that the dipole configurations (Figure 8b, c) and the loop (Figure 8e) show a similar or nominal increase in response compared to the horizontal bipole configuration (Figure 8a). However, the circular (star and cross) and vertical current configurations greatly increase current flow across the thin resistor (reservoir) and show a very large increase in reservoir response, both in terms of absolute magnetic field and as a percentage of background. The star and cross configurations approximate the circular electrical dipole configuration (Helwig, et al, 2010).

The downhole configuration is well known to couple well to a reservoir (Marsala et al, 2011). However, the logistics of this requires utilizing an existing production well, which is challenging to do in the producing field.

Conclusions

The results of the conducted research demonstrate that optimizing the survey configuration is where most of the improvements in reservoir detection and monitoring can be made. The Cross, Star, or Z-dipole configurations all show much improved anomalous responses from the reservoir. These configurations are listed in order of improved sensitivity, but also in order of more complex field logistics. If detection of the reservoir is the main goal, then the SQUITEM survey should be designed to create a large anomalous field in the presence of a relatively small primary field. However, if monitoring is the goal (repeated measuring to monitor changes in the reservoir), then a large primary field is acceptable along with the desirable large anomalous field. This is because the primary fields from the two surveys can be subtracted to find the difference fields, which will leave only the anomalous fields.

Another important conclusion, based on the modeling results, is that measuring all three components of the magnetic field is very important, because in some cases the anomalies of the horizontal components of magnetic field over the reservoir could be much stronger than those of the vertical component.

In summary, we conclude that, the SQUITEM sensors represent a unique geophysical instrument for accurate recording a signature of the hydrocarbon and/or water filled reservoir in the electromagnetic response on the ground. By using the optimal survey configuration introduced in this paper, the SQUITEM technology can be effectively utilized for reservoir management and HC production monitoring in the oil and gas field.

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