The Feasibility Study for Optimum Marine CSEM Survey Design for Oil Exploration

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The controlled source electromagnetic (CSEM) method may be the most significant new technology for oil and gas exploration since the development of 3-D seismic 20 years ago. The promise for the technology lies in its ability to differentiate resistive, potentially oil-bearing intervals from surrounding, more conductive water-bearing units. The principal is the same as that used in well logging devices to identify hydrocarbon zones in well bores. The technique is not new but the capability to resolve relatively thin resistive intervals in the depth domain offers new promise to lower risk through direct hydrocarbon indicators in conjunction with modern seismic methods

We evaluated the sensing capability of the marine CSEM method to detect a thin hydrocarbon reservoir in deep, intermediate and shallow marine environments by analyzing the synthetic responses and the related physics using numerical modeling techniques. We would like to investigate the physics of marine CSEM using 1-D modeling program. The scope of investigation involved, all possible source-receiver configurations, advantages and disadvantages of frequency- versus time-domain systems, advantages and disadvantages of electric versus magnetic field measurements, a range of source-receiver separations including the coincident situation, and finally the air wave effect.

1. INTRODUCTION

The marine CSEM is characterized by its specific environment. Sea water is very conductive with its conductivity on the order of 3 to 4 mhos/m, and the survey instrument is submerged in it at the depth of tens of meters to a few kilometers. The mud below ocean bottom is less conductive, so more electric current can flow through sea water than through the mud. On the other hand, since the electromagnetic energy will decay faster through sea water than through the marine sediment, we might be able to pick up signals that went through the marine sediment which in turn may contain some information from the thin resistive layer in the depth. For this to happen, it is thought, there has to be a minimum horizontal separation between the transmitter and the receiver. However, there is another factor that makes the situation a little more complicated; the air wave. When the survey is conducted at shallow water environment, there is good chance that the EM field will easily propagate up to the surface, propagate horizontally, and then propagate back down to the receiver site. This is called the air wave, and it can easily overpower the anomaly from the resistive thin layer.

The foregoing statement is more or less superficial, although most scientists familiar to this subject would agree in principle. Here, we would

like to investigate the physics of the marine CSEM using simple 1-D program EM1D (programmed by Dr. Ki Ha Lee). The scope of investigation here involved, possible source-receiver configurations, advantages and disadvantages of frequency-domain versus time-domain survey systems, advantages and disadvantages of electric field versus magnetic field measurements, a range of source-receiver separations including the coincident situation, and finally the air wave effect under shallow water.

2. NUMERICAL STUDIES

To begin, a preliminary study was carried out using EM1D to see if there is any advantage in magnetic field over electric field. The model used is shown in Figure 1. This reservoir model consists of a 10m thick, 100 ohm-m layer representing a hydrocarbon reservoir, embedded at a depth of 1km below a 1.0 ohm-m seafloor sediment. As the background model, the same seafloor model was employed without the reservoir. The marine CSEM method employed 10,000A-m² (equivalently 1,000A with 100m dipole cable), x-directed HED (horizontal electric dipole, J_x). Transmitter-receiver separation was fixed at 5km, and the sea water thickness was a variable; 20m, 500m, and 1,000m. The source used was horizontal electric dipole (J_x), and the results are shown in Figure 2 and 3, for

electric field (E_x) and Magnetic field (H_y), respectively. Modeling results are shown in solid line for homogeneous model (non-oil bearing model), and in dash line for oil bearing model.

Figure 1. A test model where Tx-Rx separation is fixed at 5km.

The measurement sensitivities assumed in this model study, based on combined source-receiver moment and instrument noise, was $1.0E-6 \mu V\cdot m$ for the electric field, and $0.1 \mu \gamma\cdot m$ for the magnetic field. The anomaly in the electric field (the difference between non-hydrocarbon and hydrocarbon results) is barely detectable in case the sea water depth is 20 m. The anomaly is not detectable in case of deeper water. The magnetic field at shallow water appears to be strong, but there is no anomaly. When the sea water depth is increased to 500m and 1km, the anomaly becomes much larger than the assumed measurement sensitivity. The conclusion from this very limited study is that at large Tx-Rx separation, 1) electric field measurement is not appropriate, and 2) measurement of orthogonal component ($J_x\text{-}H_y$) of magnetic field may be useful, especially in deep water case.

In order to compare the marine time domain CSEM (TDCSEM) method to the marine frequency domain CSEM (FDCSEM) described before, the time domain HED source, and any other modeling parameters were kept identical to those used in FDCSEM modeling. The only difference is that the step-off synthetic response for non-hydrocarbon and hydrocarbon models were computed. The $J_x\text{-}E_x$ response is shown in Figure 4. TDCSEM senses the presence of 1-D reservoir. The observed difference in E_x response between non-hydrocarbon and hydrocarbon models are relatively small, in particular, under deep water environment, and most of the differences are a DC response in early time

rather than transient response within the decay.

This type of EM signal might help the TDCSEM method to overcome the ‘air-wave’ problem associated with the FDCSEM in shallow water environments. The FDCSEM method doesn’t work effectively at shallow water because the air-wave contaminates the seafloor EM responses.

The horizontal magnetic field (H_y) measurement on the seafloor also senses the presence of 1-D hydrocarbon reservoir (Figure 5). This is possible because the transient vertical currents are not canceled out at the seawater-marine sediment interface, and hence both horizontal and vertical transient currents contribute to the measured horizontal magnetic field on the seafloor.

3. DISCUSSION

Here, $J_x\text{-}E_x$ and $J_x\text{-}H_y$ configurations are selected for the frequency domain and the time domain in terms of signal strength and sensitivity to the resistive thin layer. These configuration is valid for the model to be considered here with Tx-Rx offset of 5km. In shallow water environment, $J_x\text{-}E_x$ configuration is obviously appropriate. Furthermore, TDCSEM is preferred, because i) the effect of the air is minimized since data is acquired after the induced current is turned off, all response is due to the collapsing DC current distributed in the entire region, ii) the TDCSEM data is approximately by 3 times more sensitive to the thin resistive layer.

On the contrary the best choice is the $J_x\text{-}H_y$ configuration. Both the FDCSEM and TDCSEM show similar degree of sensitivity, so one can go either way. Data acquisition time can be greatly reduced to on the order of 1 second, as opposed to approximately 100 second (0.01Hz) required for the FDCSEM system.

4. CONCLUSION

The study in this paper shows that TDCSEM might be better suited for the model to be considered here. J_x source is preferred considering field operation. For the survey under shallow sea water, the E_x component indicates better sensitivity to the thin resistive layer, whereas the H_y component seems to be preferred for the survey under deep water.

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Figure 2. Electric field (E_x) from electric source (J_x) for different sea water depth. Top panel is with 20m, middle one with 500m, and bottom one with 1,000m depth. Notice that detection limit is set to be $1.0 \times 10^{-6} \mu\text{V-m}$.

Figure 3. Magnetic field (H_y) from electric source (J_x) for different sea water depth. Top panel is with 20m, middle one with 500m, and bottom one with 1,000m depth. Notice that detection limit is set to be $0.1 \mu\text{Gamma-m}$.

Figure 4. Time domain response of Electric field (E_x) from electric source (J_x) for different sea water depths. (early-time response is based on galvanic due to initial current, but late-time is based on inductive due to

Figure 5. Time domain response of Magnetic field (H_y) from electric source (J_x) for different sea water depths.