Target Detectability of Marine Controlled Source Electromagnetic Method – Insights from 1-D Modeling*

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Abstract

The paper highlights a comparative study of detectability of a hydrocarbon reservoir in a marine environment, using controlled source Electromagnetic method (CSEM) on typical benchmark models. The target is a thin resistive body buried at a certain depth under the sea floor. Depth of the seawater, overburden sediment depth, thickness and resistivity of the reservoir are variable model parameters. Transmission frequency was also taken into account. For different sets of these parameters, a set of 1-D models has been generated using a frequency domain forward modeling code by Løseth and Ursin (2007) to show the effectiveness of CSEM in varying geological setup.

Introduction

Marine controlled-source electromagnetic surveying (CSEM) or Sea Bed Logging (SBL) is now an established technique for hydrocarbon exploration (Eidesmo et al., 2002; Ellingsrud et al., 2002; Srnka et al., 2006). Marine CSEM methods use an electric dipole to probe the subsurface. The technique has proven to be particularly useful for detecting thin highly resistive layers characteristic of the geometry of hydrocarbon reservoirs. The electric and magnetic receivers are placed on the seabed and the electric dipole transmitter is typically towed at an elevation of 30 m. The method was originally viewed as a deep-water technique because of the strong contribution to the electromagnetic field due to the air-water interface in shallow water depths. However, in the present scenario, there is a lot of advancement in the field of CSEM and hence it is used in shallow water. The paper highlights the detectability and resolution power of Marine CSEM for a 1-D hydrocarbon reservoir in a marine environment and under varying geological conditions.

Interpretation Methodology

An interpretation approach commonly used in hydrocarbon industry is based on examining Normalized in line magnitude versus offset plots (MVO) and Phase versus offset (PVO) plots. The normalized MVO equals the observed magnitude divided by the magnitude at a reference receiver. This approach is based on the following assumption. If a proper reference receiver is selected (for instance, in an area where hydrocarbon absence has proven), the normalized magnitude versus offset can indicate resistive layers, possibly associated with the presence of hydrocarbons. In other words the presence of a resistive hydrocarbon bearing layer reduces the attenuation of the electric field with distance so when the magnitude of the data measured in the unknown area is divided by the magnitude of the reference data at any given offset, this ratio (normalized magnitude should be greater than 1).

Modeling Methodology

The motivation for this study is to evaluate the CSEM responses generated by a relatively small reservoir in shallow, deep-water settings in varying geological condition. 1-D marine CSEM response is studied for a Standard Geological model consisting of a 50 m thick hydrocarbon bearing layer having resistivity of 100 ohm-m, buried at a depth of 1 km in 1,000 m seawater, with background sediments resistivity of 1 ohm-m. The HED height from the seabed is taken as 50 m and the receiver position is taken on the seafloor. Figure1 illustrates the XZ cross-section of the models used in this study. The 1D model Figure 1 presents an infinite reservoir propagated in the X and Y-directions in the presence of 1 km water depth. Seawater, background, and target resistivities are 0.3, 1.0, and 100 Ω·m, respectively. In this paper, a frequency domain forward modeling code by Løseth and Ursin (2007) has been used.

This scheme can model anisotropic electromagnetic data, but it is only isotropic results that are used in the following example. The paper preferentially highlights how 1-D CSEM response of a standard geological model can vary under variable model parameters, which include (i) depth of the seawater (ii) overburden sediment thickness (iii) thickness of the reservoir (iv) resistivity of the reservoir and (v) transmission frequency.

Synthetic Examples: Effect of Ocean Water Depth

Here a simple 1D model composed of a seawater column of 1km thick followed by an infinite uniform earth of 1Ohm-m resistivity has been considered. Figure 2 shows the amplitude and phase of the corresponding horizontal electric field for various water depths using a representative frequency of 0.25Hz. When the water depth is increased we can see the amplitude (with a logarithmic scale) and phase (with a linear scale), have a close to linear behavior especially at large offsets. This is characteristic of the electric field propagation in the simple uniform earth considered here. As we decrease the water depth, the amplitude of the measured electric field increases. There is an abrupt change in the slope of the amplitude curve occurring at shorter and shorter offset as the water depth is reduced (at an offset of 1-2 km approximately). Similarly, in the phase response the effect of reducing the water depth is to decrease the slope of the phase at progressively shorter offsets.

At face value, these signatures can be explained by a simple coupling with the atmosphere via a refracted wave at the sea surface propagating in the air (Constable and Weiss, 2006). As the air is infinitively resistive, the skin depth tends to infinity corresponding to a decay factor of 1: no attenuation, and low slope (~ flat) phase symbolizing an infinite phase velocity. The decay after the abrupt change in the slope of the amplitude could be explained by the spherical divergence term, as the waves are not plane waves. Nevertheless, a closer look at the curves shows that the effect of signal interaction with the air can be seen at all ranges and even beyond the onset of the airwave signature, the measured signals depend on seafloor structure. Decrease in ocean water depth increases the airwave effect (Figure 2c).

Hence, shallow water condition is not promisible for target detection due to masking of signal by airwaves, but better processing and interpretation tools may give good results. However, the application or target delectability of Marine CSEM is appreciable at greater water depth. It is evident that with increasing seawater depth the response of CSEM increases along with the width of the delectability window. In all the above-mentioned scenarios, the intermediate offset area (4-11 km) provides valuable information about the hydrocarbon reservoir (Figure 2c).

Effects of Transmission Frequency

In Figure 3, we can see how inline electric field magnitude can vary as a function of source receiver range for transmission frequencies of 0.1 Hz, 0.25 Hz and 1 Hz for the reservoir model shown in Figure1. The Electric field magnitude depends on frequency and is larger for lower frequencies. However, at higher frequency the magnitude of the fields falls below the instrument noise threshold.

Spatial resolution of CSEM measurements at very low frequencies (near-DC case) is primarily determined by offsets and at high frequencies by the EM field wavelength (λ). At the CSEM - low frequency range, λ is related to the plane-wave skin-depth, δ: $\lambda = 2\pi\cdot\delta$, $\delta = (\rho/ (\mu0\pi f))$ 1/2, where ρ, f, and $\mu0$ are resistivity, frequency, magnetic permeability of free space, respectively. The table below shows δ and λ for three frequencies and $\rho = 1\ \Omega\cdot$m:

f (Hz)	δ (m)	λ (m)
0.05	2251	14143
0.25	1007	6327
1.00	503	3160

In shallow water (Figure 3a), the anomalous reservoir response is weak at high frequencies, but it is stronger at near-DC frequencies (e.g., <0.05 Hz), at which the airwave effect is weak. In deep water (Figure 3b); the anomalous response is stronger at higher frequencies. However, the signal attenuates at higher frequencies, and its level at longer offsets becomes closer to the noise floor, which makes these data difficult to interpret/invert.

Effect of Overburden Sediment Thickness

The overburden sediment thickness of the reservoir is another important variable. The inline horizontal electrical amplitude for different sediment thickness (i.e. 1,000 m, 1,500 m and 2,500 m) has been compared for the reservoir model shown in Figure 1. We can see from Figure 4b with increasing sediment thickness above the reservoir the amplitude of the electric field decreases. This feature is marked at larger offset whereas at shorter offset this difference is negligible.

The effect of increasing sediment thickness over the reservoir is also marked in case of Normalized Magnitude. With decreasing sediment thickness, the normalized magnitude increases. This can be explained by the simple phenomena of spherical divergence.

Effect of Varying Resistivity and Target Thickness

One possible application of the marine CSEM method is mapping the size (lateral extent and thickness) of hydrocarbon reservoirs. Electromagnetically, there are two contributions to size in the 1D sense — thickness and resistivity which are correlated inevitably to some extent. Generally the galvanic component of current flow and that the inductive component of field attenuation is sensitive to the resistivity of the target and, to some extent, be independent of thickness.

Figure 5 shows the effect of varying resistivity for the reservoir model shown in Figure 1. We can see that with increasing resistivity of the reservoir the electric magnitude increases at an offset of 1-2 km, whereas the difference becomes very negligible at larger offset. The Normalized Magnitude is also high for highly resistive reservoirs whereas low for low resistive reservoirs.

As one would expect, the electric-field response varies monotonically with thickness. The radial mode response varies almost linearly with thickness, which bodes well for using the method to map reservoir geometry. Figure 6 shows effect of varying thickness of target for the reservoir model shown in Figure 1. The marine CSEM signature is high for thick target rather than thinner. Not only that, the width of the detectability window also increases with increasing reservoir thickness.

Conclusions

The paper highlighted how 1-D CSEM Modeling response can vary with variable model parameters i.e. ocean water depth, transmission frequency, overburden sediment thickness, thickness and resistivity of the reservoir for a standard geological model. It also facilitate at what optimum value of a model parameters the reservoir can be detected very easily. All the parameter should be considered carefully while interpreting CSEM data.

Acknowledgements

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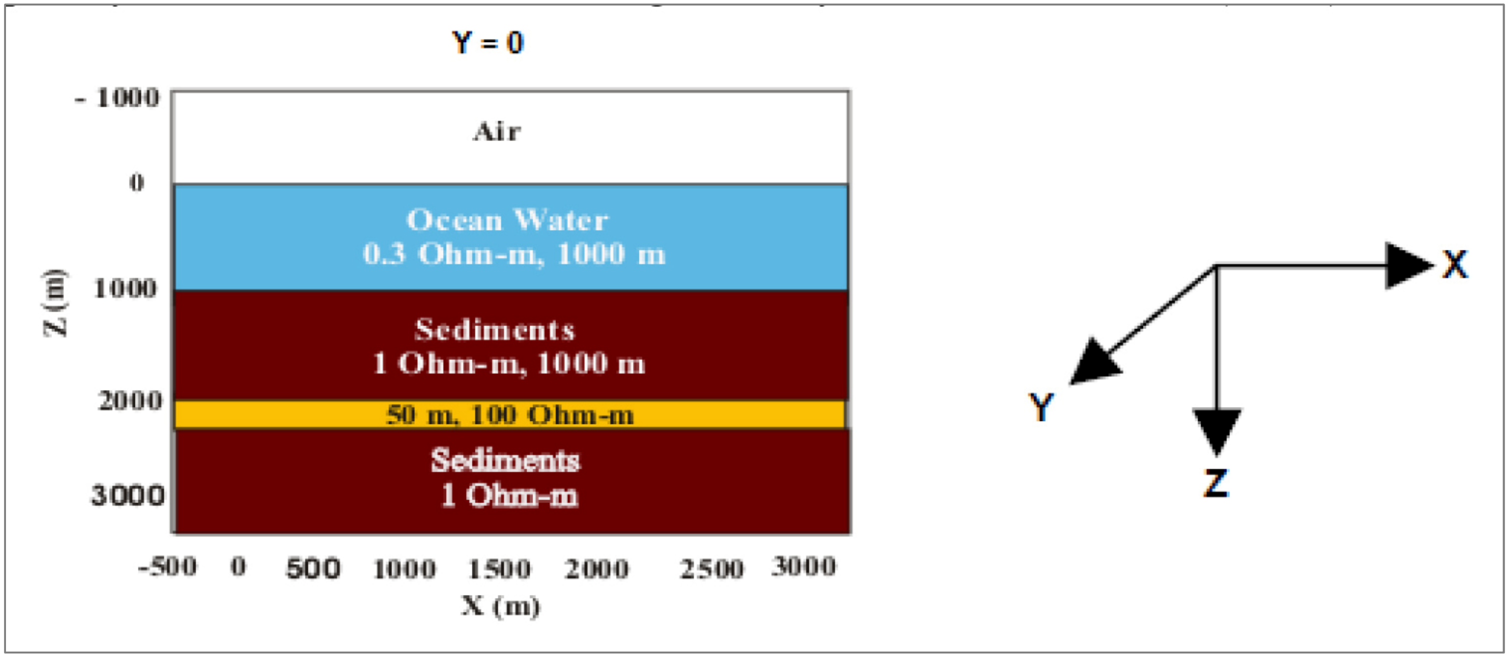

Figure 1. XZ cross section of the 1-D Standard Geological model at Y= 0; The model consists of air (White), Sea water (ice blue), earth below the seafloor i.e. sediments (brown).

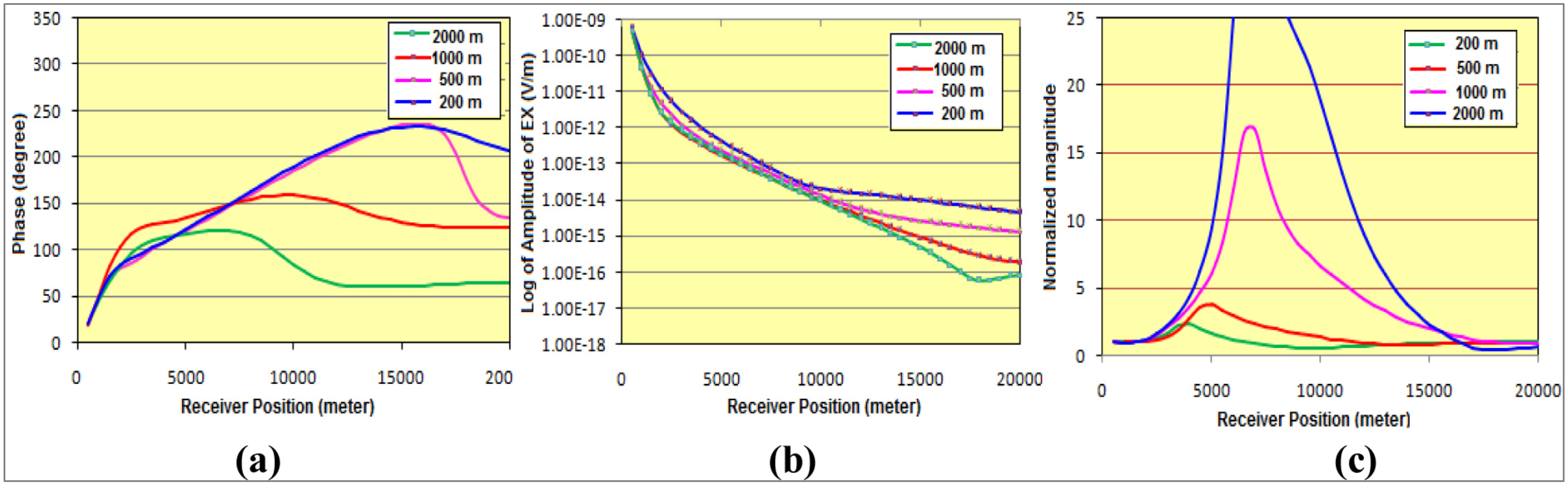

Figure 2. Responses for inline horizontal electric field at sea water depths of 200 m, 500 m, 1,000 m and 2,000 m. (a) phase versus offset plot at different water depths; (b) electric magnitude; (c) normalized response at different water depths.

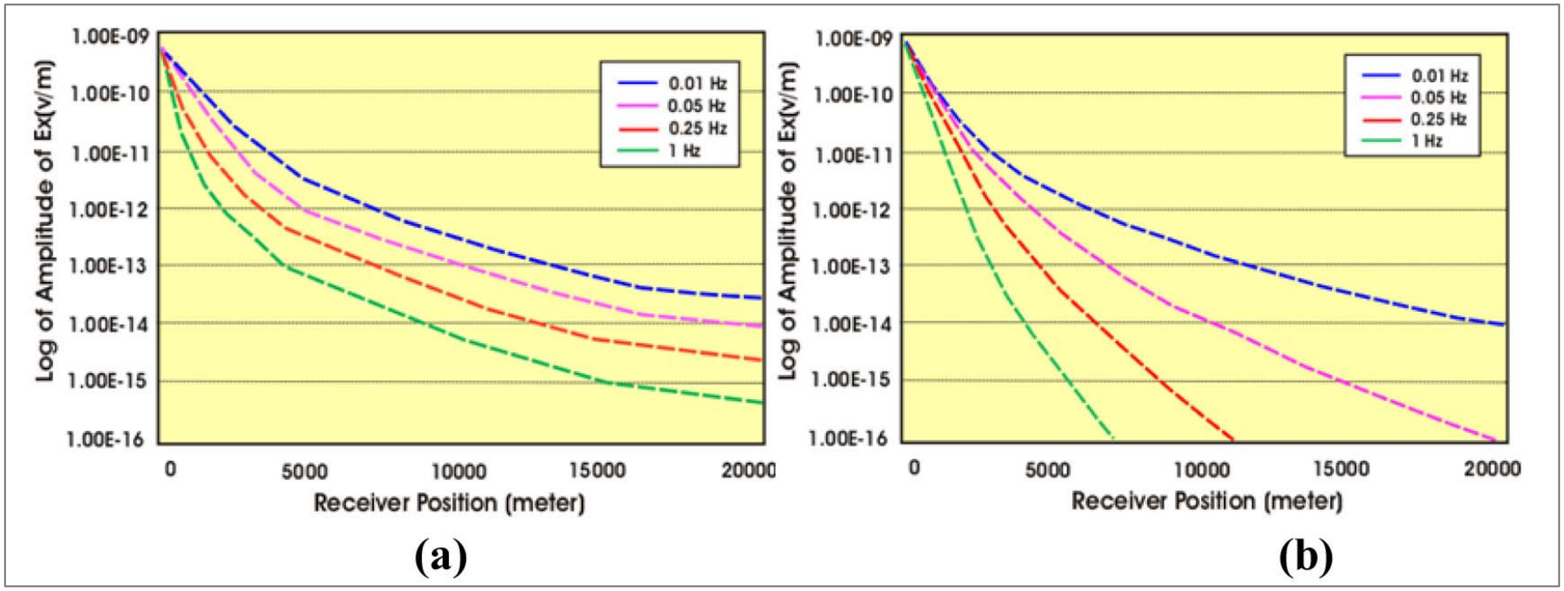

Figure 3. Electric magnitude of the reservoir model shown in Figure 1 at transmission frequencies of 0.01 Hz, 0.05 Hz, 0.25 Hz and 1 Hz for the reservoir model shown in Figure 1. (a) Effect of transmission frequencies at shallow water; (b) effect of transmission frequencies at deepwater.

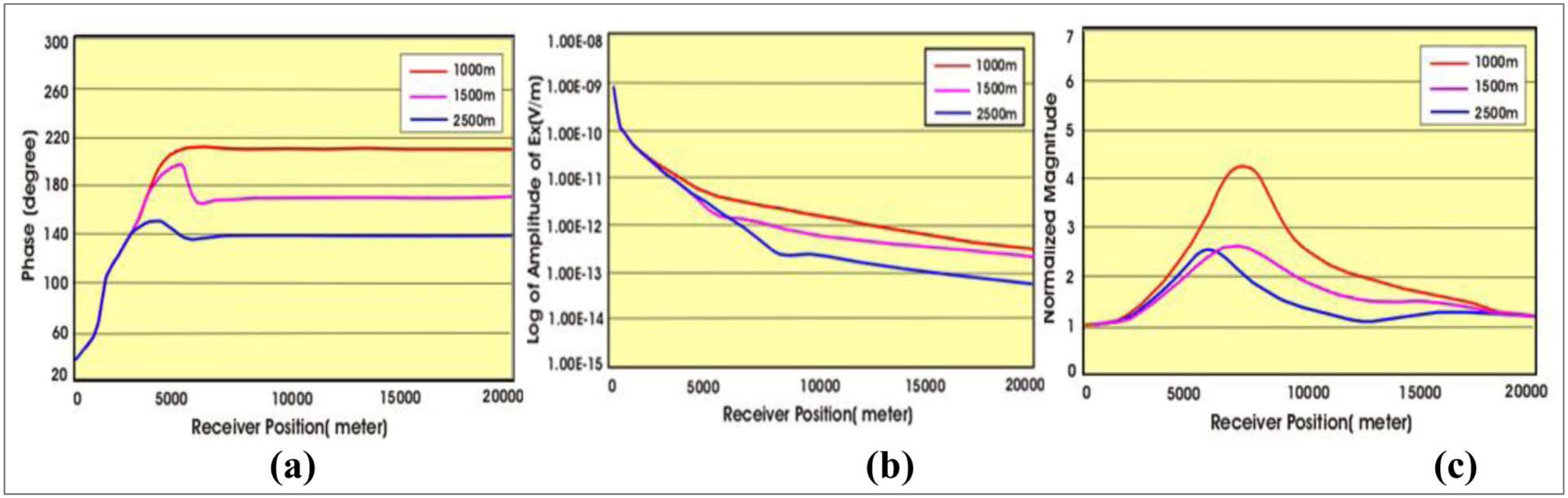

Figure 4. The inline horizontal electric field response at different sediment depth (i.e. 1,000 m, 1,500 m and 2,500 m) for the reservoir model shown in Figure 1. (a) Phase versus offset plot; (b) electric magnitude versus offset plot; (c) normalized magnitude.

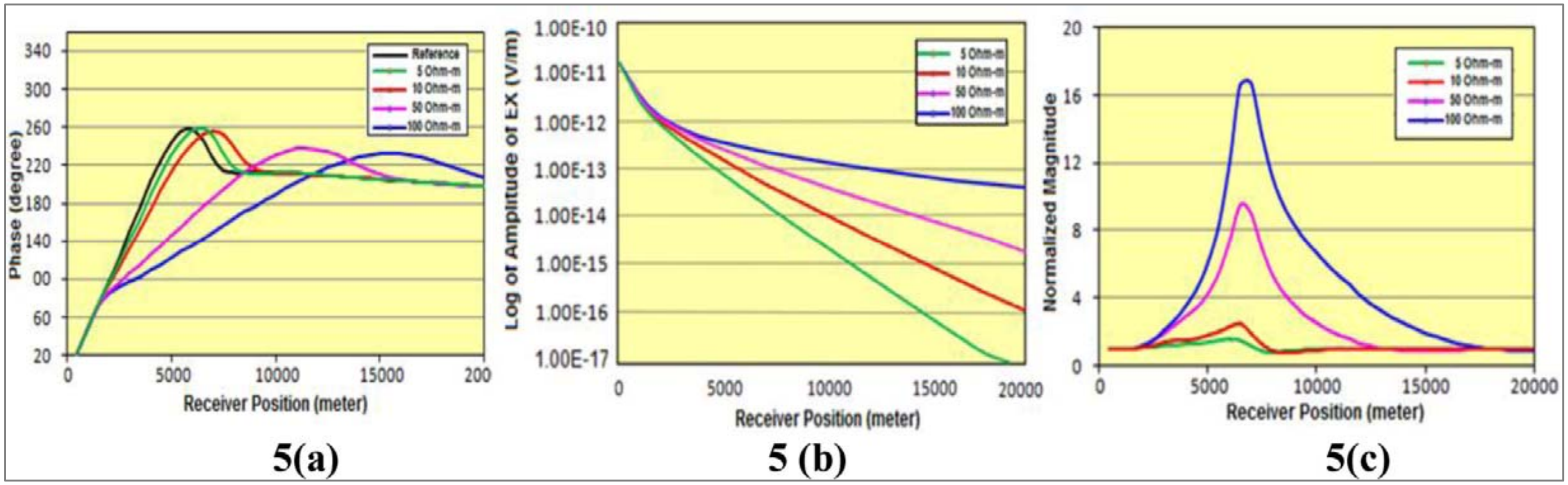

Figure 5. Inline electric field responses for the reservoir model in shown in Figure 1 at target resistivities of 5 Ohm-m, 10 Ohm-m, 50 Ohm-m and 100 Ohm-m. (a) Phase versus offset plot at different resistivities; (b) electric magnitude; (c) normalized magnitude.

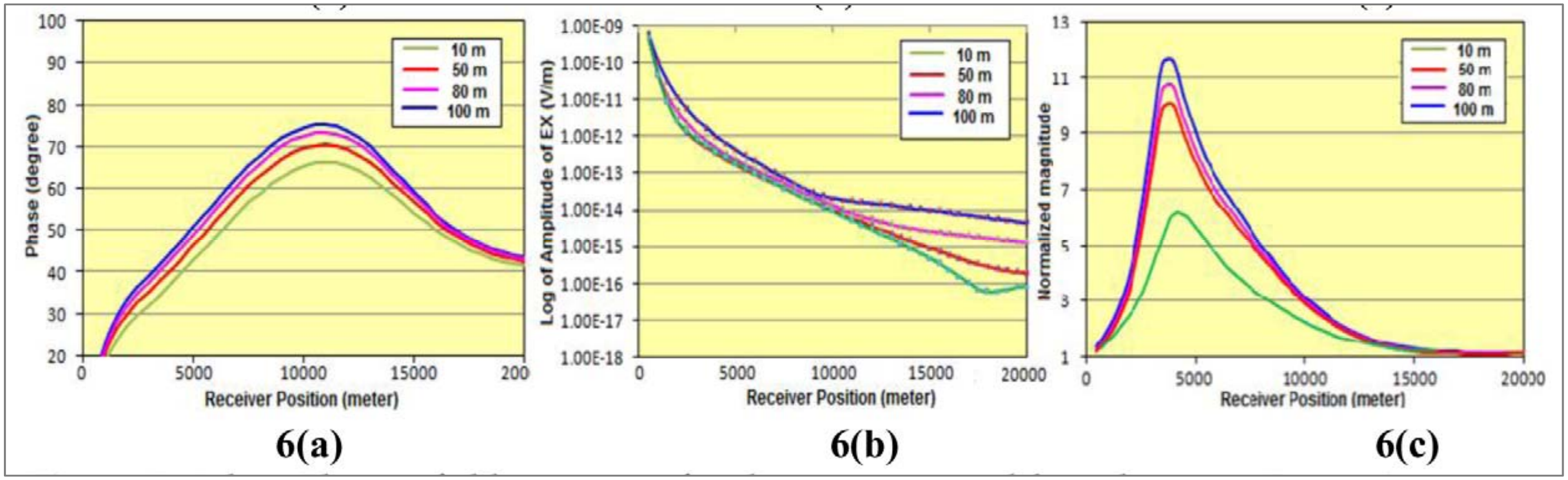

Figure 6. Inline electric field responses at target thickness of 10 m, 50 m, 80 m and 100 m for the reservoir model shown in Figure 1. (a) Phase versus offset (PVO) plot; (b) electric magnitude versus offset plot (MVO); (c) normalized magnitude.