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Target Detectability and Reservoir Characterization Using 1D Marine Controlled Source Electromagnetics

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Summary

Controlled Source Electromagnetic-Marine (CSEM) Method is a very powerful technique in deciphering whether the reservoirs are hydrocarbon or water saturated. Hence, to reduce the risk in deep water areas CSEM is employed to detect the resistive hydrocarbon reservoirs. This paper discusses about the various 1D Marine CSEM responses due to the presence of subsurface resistive bodies since hydrocarbon saturated reservoirs are 10-100 times more resistive than the overlying sediments.

The effect of variable resistive target and presence of shallow resistors like Gas-Hydrates, Salt bodies, Evaporites on detectability window is also studied. For this purpose a representative layered earth model has been generated to study the feasibility of this method to detect the potential hydrocarbon bearing reservoirs. Among these shallow resistors, evaporites/salt bodies have the tendency to mask the target response depending on their thickness. Further, attempt has been made to characterize the reservoir by determining the water and hydrocarbon saturation.

Keywords: *Detectability Window, Hydrocarbon Reservoir, Marine CSEM, Resistivity, Hydrocarbon saturation*

Introduction

Deep ocean reservoirs exploration and mapping the sediment thickness below the trap are the main interests for Oil & gas industries. The Seismic reflection method has been used as a primary geophysical tool for exploring the marine hydrocarbon reservoirs as it provides the high resolution of sub-surface structure compared other marine geophysical methods. However, this Seismic method is not sufficient to define the fluid characteristics of the potential reservoirs e.g. whether the reservoir contains hydrocarbon or gas-charged water (Wright et al., 2002). Thirud (2002) approximated that about 90% of potential reservoirs detected by seismic technique are saline water saturated.

Measuring subsurface resistivity has always been one of the major challenges in marine hydrocarbon exploration. Previously, wire-line logging was the only method of precisely estimating the resistivity of the subsurface. But the increased cost of drilling reduced the overall economic viability of the method and the scientific community was on a lookout for a reliable and affordable alternative. Several Electromagnetic methods for mapping sub-seafloor resistivity variations have been developed (e.g. Sinha et al. 1990; Chave et al. 1991). The CSEM technique has been successfully applied to the study of oceanic lithosphere and active spreading centers (Young & Cox 1981; Evans et al. 1994; Constable & Cox 1996; MacGregor et al. 1998, 2001).

Stat-Oil invented in the late 1990s the use of CSEM method for remote identification of hydrocarbons in marine settings (Eidesmo et al., 2002). In 2000 the first CSEM survey was performed offshore Angola (Ellingsrud et al., 2002). Today, electromagnetic methods are attractive for the petroleum industries as complementary tools to seismic methods, or even stand alone tools, for remote sensing of the reservoir.

There exists a resistivity contrast of 10-100 between the hydrocarbon saturated reservoir and overlying sediments and thus electromagnetic method can be used to map the hydrocarbon saturated reservoirs. Here we demonstrate various 1D marine CSEM responses. The effect of variable resistive target and presence of shallow resistors like gas-hydrates, salt bodies, evaporites on detectability window is also studied. For this purpose a layered earth model has been generated to study the feasibility of this method to detect the potential hydrocarbon bearing reservoirs.

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Theory

The basis of the approach is the use of a mobile Horizontal Electric Dipole (HED) source and an array of seafloor electric field receivers (Fig.1). The transmitting dipole emits a low frequency (<1Hz) electromagnetic signal that diffuses outwards both into the overlying water column and downwards into the seabed. The ultra low frequency signal is helpful for detecting the deeper resistive target due to its less amplitude attenuation (Ward and Hohmann, 1998).The rate of decay in amplitude and the phase shift of the signal are controlled both by geometric and by skin depth effects. Both the amplitude and the phase of the received signal depend on the resistivity structure beneath the seabed.

The method relies on the large resistivity contrast between hydrocarbon-saturated reservoirs, and the surrounding sedimentary layers saturated with aqueous saline fluids. Hydrocarbon reservoirs typically have a resistivity of a few tens of Ωm or higher, whereas the resistivity of the over and underlying sediments is typically less than a few Ωm. In the following sections it will be demonstrated that this resistivity contrast has a detectable influence on CSEM data collected at the sea bed above the reservoir, even though the hydrocarbon bearing layers are thin compared to their depth of burial.

Source Receiver Geometry

An array of electric dipole receivers kept on the seafloor to record the horizontal components of the electric field, coming from the different geological interfaces. If the receiver is placed along the axis of the dipole it is known as in-line Survey (Purely Radial) and if the axis of the dipole is placed orthogonal to the axis (ϴ=900), it is known as Broadside-survey (Purely azimuthal) (Fig.2).But in practice both the Radial and Azimuthal components of electric field are recorded for an azimuth 'ϴ', which helps in interpretation (Eidesmo et al., 2002). The variation of magnitude with offset is known as MVO and the variation of phase with offset is known as PVO. Both the Electric field magnitude and phase is plotted with respect to different source-receiver offset, for the Marine CSEM interpretation.

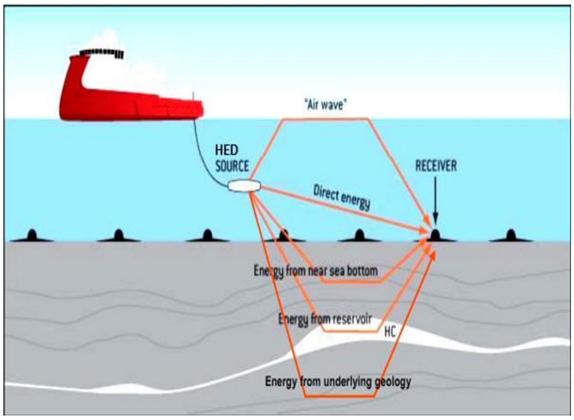

Figure 1: A Sketch of a basic marine CSEM survey layout. The Source antenna is towed behind the vessel, and the receivers are situated on the sea-bed. The signal propagation is indicated assuming that a hydrocarbon reservoir is present.

Description of galvanic effect and Inductive effect

The relationships between the electric currents flowing in two adjacent regions of space are determined by both galvanic and inductive effects. Since charge is conserved, the current leaving one volume of the subsurface and that arriving in an adjacent volume along the direction of current flow are related to each other by a galvanic mechanism. For the galvanic case the magnetic field will be polarized transverse to the resistive hydrocarbon layer and we denote this as a transverse magnetic mode(TM mode). If the electric field enters the resistive hydrocarbon layer under a critical angle and propagates along the layer. The detection of the guided energy is the basis of Marine CSEM (Ellingsrud et al. 2001).

On the other hand, if two volumes are close together but separated from each other along a direction orthogonal to current flow, then the coupling between the currents flowing in the two volumes will be primarily inductive. In this case E-fields will only be reflected from the layer, and the reflected energy will die off as a function of offset.

For conducting media, Ohms Law yields the conduction current density J (Stratton 1941) given as:

$$J=\sigma E \quad (1)$$

where σ is the conductivity and E is the electric field. The current is proportional to the E-field (equation 1). Applying this to our model of a sub-seafloor structure containing a thin but resistive hydrocarbon reservoir, we can infer that the effect of the reservoir on the survey results will strongly depend on the direction of flow of the currents generated by the transmitter or the direction of the E-fields.

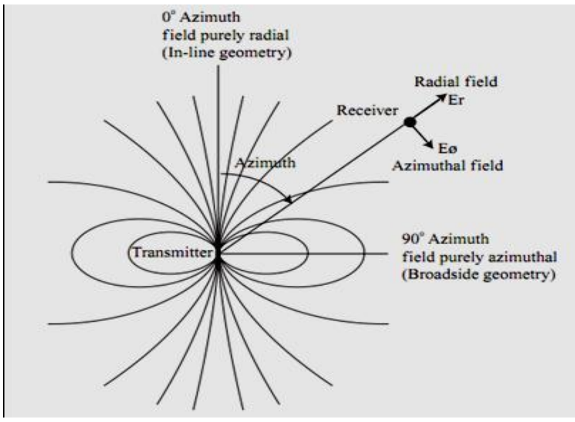

Figure 2: The geometry of CSEM dipole fields. Along the polar axis of the dipole transmitter, the field is purely radial. Along the equatorial axis, the field is purely azimuthal. At other azimuths the received fields are a trigonometric mix of both modes.

Signals from the transmitter that follows the propagation path through the intermediate offset area (4-10km) is our area of interest, where the detector records the signals coming from the resistive target (Fig.2) and this particular area is known as **"Detectability Window"**. Both reflected and guided energy is measured by the detector but it is found that with increasing source receiver offset distance the reflected signals get attenuated.

1D Forward Modeling

Chave and Cox, (1982), and Løseth and Ursin, (2007) determined the radial and azimuthal electric fields components for a HED over the 1D model (Fig.3) as:

The Radial E-Field is:

$$E_{\rho} = -\frac{I\ell}{4\Pi} Cos\theta \left(X_0^{TM} + \frac{1}{\rho}\left(X_1^{TE} - X_1^{TM} \right) \right) \qquad (2a)$$

And the Azimuthal E-field is:

$$E_{\theta} = -\frac{I\ell}{4\Pi} Sin\theta \left(-X_0^{TE} + \frac{1}{\rho}\left(X_1^{TE} - X_1^{TM} \right) \right) \qquad (2b)$$

To illustrate the geometric effect, we consider a 1D structure consisting of 100m thick hydrocarbon bearing layer having resistivity of 100Ωm, buried at a depth of 1000m below the sediments in 1000m seawater, with background sediment resistivity of 1Ωm (Fig.3).The HED height from the seabed is taken as 50m and the receiver position is taken on the seafloor. The transmission signal frequency is taken as 0.3 Hz for computation. The Microsoft Developer Studio (FORTRAN) software has position is taken on the seafloor. The transmission signal frequency is taken as 0.3 Hz for computation. The Microsoft Developer Studio (FORTRAN) software has been used for evaluating the integrals as described in Eq. (3) to compute radial and azimuthal 1D marine CSEM responses.

Air	∞ Ωm
Seawater, 1000m	0.31 Ωm
Sediments, 1000m	1.0 Ωm
Resistive Target, 100m	100 Ωm
Sediments	1.0 Ωm

Figure 3: Canonical 1D Model setup.

Where the product of current times length (Iℓ) is the electric dipole current moment, ρ is the radial distance in the horizontal plane from the HED source, and Θ is the azimuthal angle (angle between the transmitter and receiver). Here for the sake of convenience unit dipole current moment has been taken for the electric field equations. The superscript TM and TE denote the transverse magnetic and transverse electric modes $X_0^{TE}, X_1^{TE}, X_0^{TM}, X_1^{TM}$ are the TE and TM contributions for the radial and azimuthal electric fields and these are given by

$$X_0^{TE} = \int_0^{\infty} \lambda K^{TE}(\lambda) J_0(\lambda\rho)\, d\lambda$$

$$X_1^{TE} = \int_0^{\infty} \lambda K^{TE}(\lambda) J_1(\lambda\rho)\, d\lambda$$

$$X_0^{TM} = \int_0^{\infty} \lambda K^{TM}(\lambda) J_0(\lambda\rho)\, d\lambda$$

$$X_1^{TM} = \int_0^{\infty} \lambda K^{TM}(\lambda) J_1(\lambda\rho)\, d\lambda$$

……… (3)

where λ is the horizontal wave number, and J_0 and J_1 are the Bessel functions of order zero and one, respectively. K, the reflection response, is a function of λ which contains the direct field (the contribution in a homogeneous medium), h is the vertical distance between the source and the receiver, and the second terms are the reflection responses from layered earth model.

$$K^{TE}(\lambda) = \frac{\omega\mu}{\gamma}\left(e^{i\lambda h} + R^{TE}(\lambda)\right) \qquad \ldots\ldots \quad (3a)$$

$$K^{TM}(\lambda) = \frac{\gamma}{\omega(\varepsilon + i\sigma/\omega)}\left(e^{i\gamma h} + R^{TM}(\lambda)\right) \qquad \ldots. \ (3b)$$

Equation (3a &3b) are made of two terms, the first corresponding to the response of direct field whereas the second contains the information about the layered earth, ω is the source frequency, μ is the magnetic permeability, h is the vertical height between source and receiver, and ε and σ are the electric permittivity & the conductivity of the medium respectively. The vertical wave number is denoted by $\gamma = \sqrt{k^2 - \lambda^2}$ and total wave number is $k = \sqrt{\omega^2 \mu\varepsilon + i\omega\mu\sigma}$. The reflection responses R^{TE} & R^{TM} are calculated from the later parameters (Løseth and Ursin, 2007).

Results

1D CSEM responses

Figure 4 shows the MVO (Magnitude Vs Offset) plot of radial and azimuthal electric fields respectively by considering the canonical model (Fig.3).This shows a strong magnitude response of Normalized E-Field in both the mode. Also it is observed that the detectability window in radial mode response is wider than the azimuthal mode.

Response over varying target resistivity

Figure 5 demonstrates the CSEM response of the model with varying resistivity value (20 Ωm, 50 Ωm, 70 Ωm &100 Ωm) of the target and it is gradually becomes weaker as the resistivity contrast i.e. the value of target resistivity is decreasing. The PVO response indicates that there will be a phase advancement as the resistivity of the target is increasing.

Response in the presence of Gas-Hydrates at 130m

To demonstrate the effect of gas-hydrates on marine CSEM response, we choose a gas-hydrate bearing zone of resistivity 3Ωm at 130m from the seafloor & keeping other parameters same as in the canonical model (Fig.6).

Response in the presence of Evaporite or Salt at 1km

To study the behavior of marine CSEM response, in the presence of Salt or evaporite, we have generated responses by considering Salt/evaporite of resistivity same as that of the target (100Ωm) and thickness of 20m & 200m at a depth of 1000m from the seafloor & keeping other parameters same as in the canonical model (Fig.7).The purpose of doing this is to ensure whether the presence of salt or evaporite obscuring the detectability window or not.

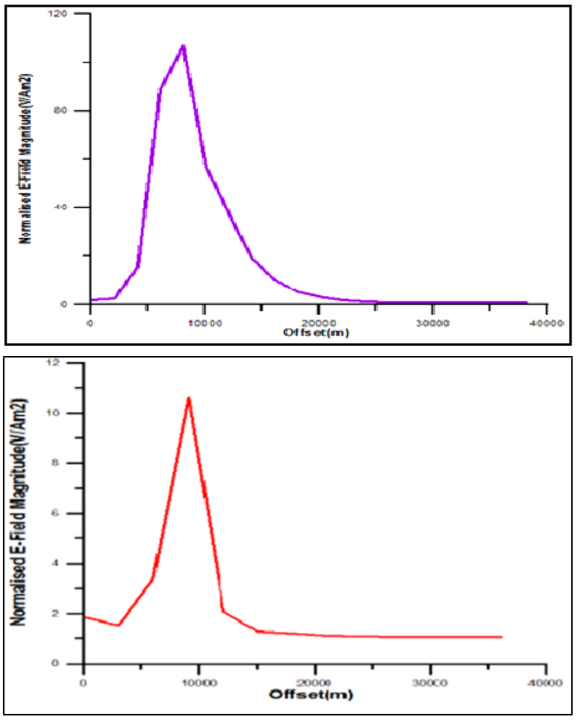

Figure 4: Radial and Azimuthal mode marine CSEM normalized E-field response, computed for the canonical model with resistive target.

Estimation of hydrocarbon saturation

Archie's law (Archie, 1942) is used to relate measured bulk resistivities to porosity estimates for a simple two-phase system that consists of the resistive grain matrix and the conductive pore fluid. In a general form, it is given by

$$R_t = aR_w\phi^{-m} \qquad (4a)$$

Where R_t is the measured formation resistivity (measured by calculating relative error, Fig.8), R_w is the resistivity of the formation water (equivalent to seawater =0.31 Ωm), ϕ is the sediment porosity, 'a' is a constant and m the cementation factor. The latter two parameters can be derived from laboratory measurements and vary between 0.5<a<2.5 and 1.5<m<3.

To calculate the resistivity of a similar rock containing in addition resistive petroleum, gas or gas hydrate, we have to modify the above formula. The modified formula is given by

$$R_t = aR_w\phi^{-m}S^{-n} \qquad (4b)$$

the parameter 'S' is now the pore water saturation factor, 'n' is the saturation coefficient and it is generally taken as n=2.

Hence the hydrocarbon saturation is given by

$$S_h=(1-S) \qquad (4c)$$

Using (4b) we can calculate the hydrocarbon saturation as 68.35% and water saturation as 31.65%.

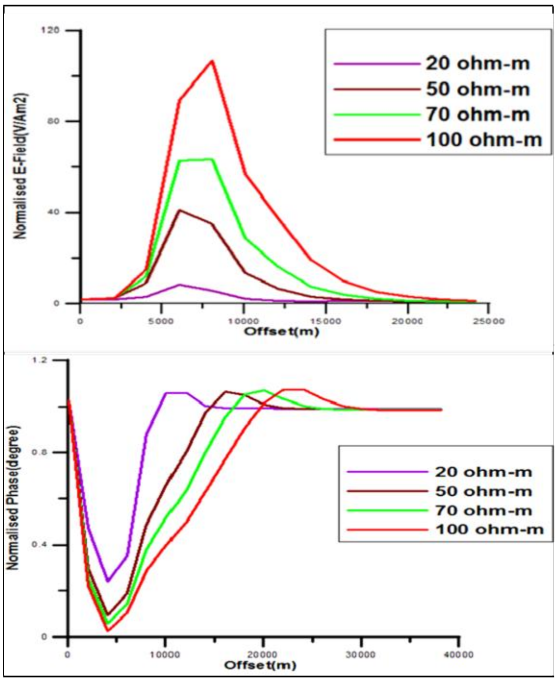

Figure 5: Radial mode marine CSEM normalized E-field and phase response computed for the canonical model with varying target resistivity.

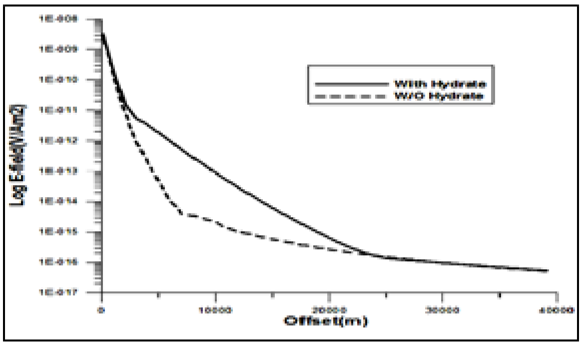

Figure 6: Radial mode marine CSEM logarithmic E-field response computed for the canonical model in the presence of gas-hydrates at 130m from seafloor.

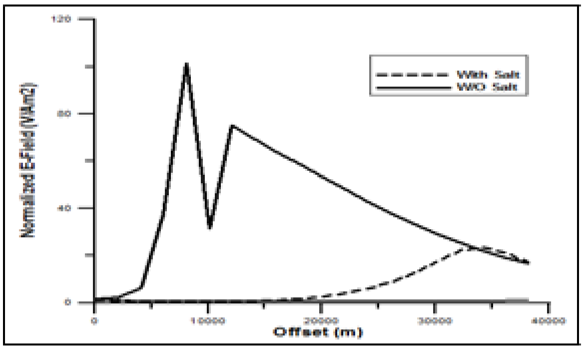

Figure 7: Radial mode marine CSEM normalized E-field response as a function of offset, computed for presence of salt at 1000m from seafloor.

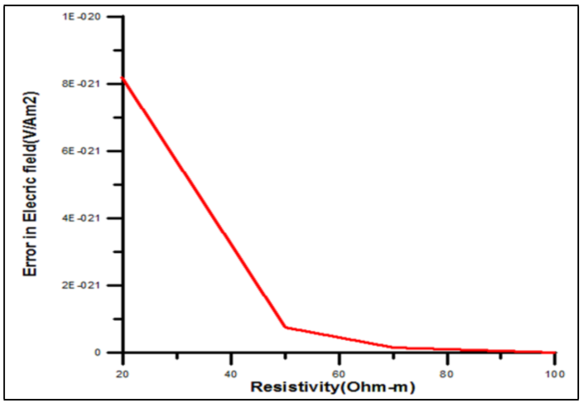

Figure 8: Error in E-field response of radial mode marine CSEM as a function of resistivity, computed to estimate the formation resistivity (Rt).

Conclusions

This paper presents a method to characterize the reservoir by estimating the hydrocarbon saturation. The various CSEM responses show that the effect of shallow resistors on target resistivity over the detectability window is within acceptable limit. Also it is seen that the radial mode E-field response is weaker than the azimuthal mode in the absence of resistive target. Because radial mode response is more sensitive to the presence of resistive target. In radial mode, the detectability window is found to be wider than the azimuthal mode to delineate the resistive target more prominently.

With the variation in resistivity of the target, the marine CSEM responses are found to be different. It is seen that the response gradually fades with the resistivity contrast. The PVO response indicates that there will be a phase advancement as the resistivity of the target is increasing.

The effect of shallow resistors like gas-hydrates, evaporite does not obscure the detectability window. We observe the evidence that presence of Salt obscures the signal coming from the target i.e. Salt or evaporite depending upon the thickness has the tendency to mask the detectability window.

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