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Sea Bed Logging– Direct Hydrocarbon Detection Technique in Offshore Exploration

Arun Kumar+1 and Jan Erik Lie+ 2
+1 Dept. of Geology and Geophysics, University of Utah, Salt Lake City, Utah , 84112-1183 , USA,
+2 ElectroMagnetic GeoServices (emgs), Americas, Houston, Texas, 77079-4023 , USA

Summary

Seabed logging, a special application of frequency domain controlled-source electromagnetic (CSEM) method, is classified as an ultra low frequency method. The basic principle which makes a potential tool in the offshore exploration is based on the electrical resistivity contrast between a hydrocarbon bearing reservoir and surrounding host rocks. Seabed logging (SBL) uses a horizontal electric dipole (HED) source towed near the seabed and an array of receivers on the seabed. In the offshore exploration, SBL is used to determine fluid contents before drilling: whether the potential reservoir detected by seismic imaging contains hydrocarbon or it contains water. This is done in order to reduce the risk of dry well and improve the exploration efficiency. In this paper we carried out plane layer modeling which is called one-dimensional (1-D) forward modeling in order to analyze the electromagnetic (EM) response at seabed receiver. The results of numerical study demonstrate that electric and magnetic field responses depends on sea water depth, thickness and resistivity of the overburden layer, target layer thickness and resistivity, seabed topography, and frequency and strength of the transmitted EM signal. Therefore, 1-D modeling analysis for SBL is critical for understanding the responses from a known geological resistive target and for optimizing the survey configuration.

Introduction

The seismic exploration is a major and powerful technique in hydrocarbon exploration, but not a ‘’Silver Bullet’’ in marine environment. Seismic data provide good information about the subsurface stratigraphy and structure. The formation characteristics, such as lithology and fluid content, can also be predicted from seismic data (Bhuiyan et al., 2006). However, a problem with conventional seismic method in offshore exploration is usually telling the difference that reservoir filled with water and hydrocarbon before drilling. For hydrocarbon detection and assessment, only the resistivity logs, recorded after drilling, have been the industry's benchmark to indicate the presence of hydrocarbon in the potential reservoir. However, offshore drilling is relatively very expensive and the success rate of the exploration well is only about 10-30 % (Johansen et al., 2005). Therefore, marine controlled-source electromagnetic (MCSEM) techniques have been used as complementary have tools in offshore hydrocarbon exploration to overcome the ambiguity of the seismic method (Hoversten et al., 1998). Over the past several years, MCSEM measurements become an essential and valuable tool in exploration of hydrocarbon reservoirs in the marine environment (Eidesmo et al., 2002, Ellingsrud et al., 2002). MCSEM method is a direct and remote hydrocarbon detection technique; detection of the hydrocarbon reservoir is based on the resistivity contrast of the resistive reservoir to its conductive host sea sediments. SBL, a frequency domain CSEM exploration method, is described by Eidesmo et al. (2002). The principle of the SBL method is very simple hydrocarbon saturated rocks that typically show higher resistivities than rocks saturated with water. A high resistivity of the hydrocarbon filled reservoir (30-500 _-m) compared with reservoirs filled with saline formation water (0.5 -2.0 _-m) makes SBL a potential and promising tool for detection and assessment of hydrocarbon. SBL provides good information about the reservoir content; indicating whether reservoir is filled with water or hydrocarbon. In addition, SBL is a strong tool for determining the edges of a hydrocarbon (HC) saturated reservoir, delineating the lateral extent of the HC reservoir. Such information provides valuable complementary constraints on reservoir geometry and on characteristics obtained by seismic surveying. SBL is a promising new tool to supplement seismic methods for marine HC exploration.

SBL Survey Procedure and Receiver Response

The SBL technique uses the horizontal electric dipole as a source and an array of the receiver located at the seabed (Young and Cox, 1981, Cox et al., 1986). During the SBL survey, EM energy is continuously generated by a horizontal electric dipole (HED) source. The transmitting dipole emits a low frequency EM signal both into the seawater layer and downward into the subsurface. The frequencies in the range of 0.01– 10 Hz are transmitted in a typical SBL survey. The EM receiver was dropped from the vessel and sinking freely to the seabed along the predetermined sail line–*acoustic ultra baseline (USBL)* communication system was used to establish exact receiver positions and EM energy is transmitted in all direction and recorded on seabed receiver. At the seabed the receivers were held in position by concrete anchors. The sail line starts at approximately 10 km before the first receivers on the line and ends at approximately 10 km after the last receiver (this is the standard sea bed logging data procedure of the major oil and gas exploration companies). The situation where the boat is approaching a given receiver is called "in-towing" in the following. When the boat is leaving the same receiver, it is called "out-towing" (Mittet et al., 2004). After the recording period, an acoustic signal from the vessel triggered a release mechanism, causing the receivers to release from their anchors and float back to the sea–surface.

An array of seabed receivers measures the amplitude and phase of the transmitted signal. The variation in amplitude and phase of the received signal as a function of source receiver separation, of survey geometry, and also of the frequency of the signal, can be interpreted in terms of resistivity structure of the subsurface. The signal, which is recorded by an array of receivers on the seabed, consists of the following energy contribution shown in Figure 1.1.

[1] - Direct energy travels from the source to the receiver without subsurface interaction. This contribution is referred to as "direct wave". [2] - A second contribution without subsurface interaction is the refracted energy from the sea air interface, referred to as "air wave". [3]- The last contribution contains all the wanted information and is represented by the reflected and refracted energy from the subsurface.

The three above mentioned types of energy will dominate the recorded signal to a variable extent—depending on source-receiver distance, subsurface structure and water depth. The "direct wave" will dominate recorded signals at short source-receiver offsets. Energy refracted along the sea-air interface will generally dominate the recorded signal at relatively large source–receiver offsets. The "air wave" is the offset dependence strongly influenced by the water depth, subsurface resistivity and the used frequency spectrum. In a case where the water depth is large (more than about 1500m) only a minor contribution of the air wave to the recorded signal is seen for offsets less than 10 km. This contribution increases as the water depth decreases. The energy which is reflected and refracted from the subsurface will affect the recorded signals most strongly at intermediate offsets, usually between 3 and 8 km. This depends on the burial depth of the refracting (anomalous) interface.

SBL data were acquired as a time series at a receiver. Through the Fourier transform, the recorded time series is converted into magnitude and phase. This magnitude and phase data which are presented as magnitude versus offset (MVO) and phase versus offset (PVO) plots.

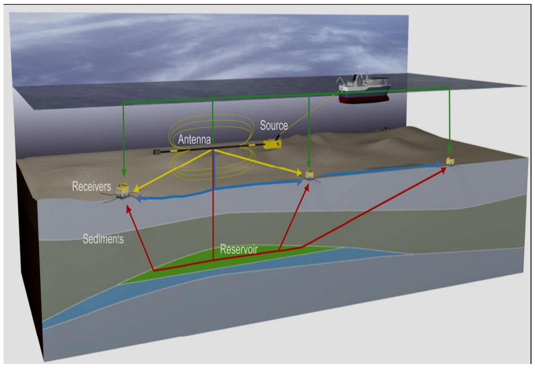

Figure 1.1 schematic diagram of a controlled –source electromagnetic survey. The horizontal electric dipole (HED) source is towed close to the seafloor. EM receivers which measure electric and magnetic fields

This magnitude and phase data which are presented as magnitude versus offset (MVO) and phase versus offset (PVO) plots. The common interpretation approach of SBLdata is based on examining the behavior and shape of normalized inline MVO and PVO. The normalized MVO equals the observed magnitude divided by the magnitude at a reference receiver. The normalized PVO equals the observed phase minus the reference phase (Dell' Aversana,2007). This approach is based on the following assumption: if a proper reference receiver is selected (for instance in an area where the HC absence has been proven), the normalized MVO and PVO can indicate the resistive layer referred to which will most likely be associated with the presence of HC.

Forward Modelling of SBL Data

Forward modeling of EM data provides good understanding of the physics of the EM method and optimizes the surveying parameters. Such parameters include transmitter location, receiver geometry, receiver's spacing, and frequency of the transmitted signal, etc. It is a method of predicting the SBL observed data for a given source within a given model. The reconstruction of subsurface conductivity (inverse of resistivity) distribution from the EM data requires thorough knowledge of the field's behavior in the presence of typical geological structures. Forward modeling is the most powerful tool to assist such reconstruction. The effective approach to the interpretation of marine EM data is based on forward and inverse modeling. A straightforward and practical starting point in interpreting the SBL data is based on the 1-D forward modeling of layered earth structures.

Synthetic Marine SBL Data

In the process of 1-D forward modeling, a synthetic SBL survey was conducted. The SBL survey was carried out by the HED antenna, which consisted of two electrodes separated approximately 266 m from each other. The peak to peak current between the electrodes varied from zero to almost 1241 Amperes.

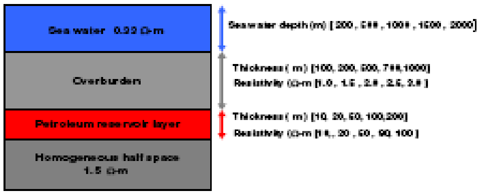

Figure 1.2 shows the vertical section of 1-D geo-electrical model. The model consists of the seawater layer with a constant resistivity 0.33 Ohm-m, an overburden-sediment layer, and a hydrocarbon layer underlain by a homogeneous half-space.

The distance from the HED source to the seabed was maintained at approximately 30m and was continuously monitored by an *echo-sounde.*The source transmitted a continuous square-shaped signal at a fundamental frequency of 0.25 Hz. The survey set-up consists of an array of seabed EM receivers. The background 1-D geoelectrical model shown in Figure 1.2 consists of a seawater column having a constant resistivity of 0.33 Ohm-m, an overburden homogeneous sediment layer, and a hydrocarbon layer underlain by a homogeneous half-space.

In the next section, 1-D forward modeling was carried out in order to better understand the EM response from variable seawater depth, as well as from the thickness and resistivity of the overburden layer, and target layer's thickness and resistivity. 1-D forward responses were computed using the plane layer modeling code (Loseth 2006). The Plane layer modeling code used in this work was developed by ElectroMagnetic GeoServices (emgs). 1-D modeling responses give a good indication of the expected response from the target at a particular depth as well as how the results are influenced by the airwave and the subsurface layer distribution. The modeling results show an estimate of the air wave effect on the easured data as well as an estimate of the maximum expected response from a reservoir.

[1] Water Depth

The shallow water exploration is an extremely difficult environment for SBL application. In particular, due to the airwave effect, the seawater depth has strong influence on the measured electric signal. The airwave is generated at the sea-air interface, where the total electric field produced by the dipole source is scattered downward. This strong signal reaches the receivers located on the sea floor masking the earth response and misleading the interpretation of SBL data. The air wave effect starts from an offset that depends on water depth. The greater the water depth is, the longer the offset where the airwave starts to be dominated.

We computed the forward responses at water depths 200m, 500m, 1000m, 1500m, and 2000m. The forward modeling results clearly indicate that seawater depth affects the response at all offsets. We plotted MVO and PVO plots at the above mentioned seawater depth. The magnitudes are increasing at large offsets due to a decrease in water depth shown in Figure 1.3. We can clearly see that a decrease in water depth influences the electric magnitude response differently than the magnetic response. Therefore, the magnitude of the electric component and the magnetic component are not equal at the shallow water depths

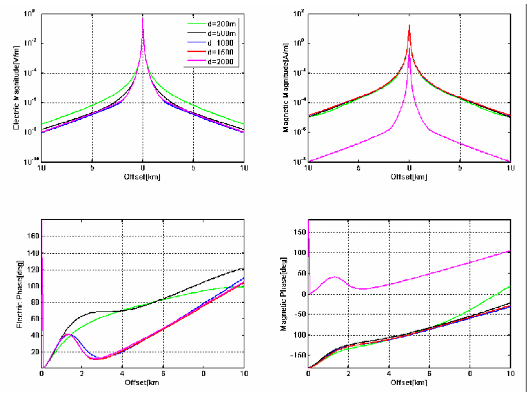

Figure 1.3: shows the magnitude vs. offset (MVO) and phase vs. offset (PVO) plots for electric and magnetic components at different seawater depths

The electric and magnetic fields are measured in [V/m] and [A/m] respectively, and phase is measured in [deg] for both components. When the water depth is greater than 1500m, the airwave effect on the recorded signal is insignificant

To highlight the effect of the hydrocarbon layer, the response from the hydrocarbon model normalized by the response from the reference model (non-hydrocarbon model) is calculated. The normalized inline MVO and PVO can indicate resistive layers that are most likely associated with the presence of HC. In other words, the presence of a resistive hydrocarbon-bearing layer reduces the attenuation of the electric field with distance. Therefore, 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 (called normalized magnitude) should be greater than 1.

Generally, normalized curves depend on the selection of the reference-receiver data. Thus, an additional open question concerns the choice of the reference receiver raised. It is clear that different reference data can produce different normalized curves, and these curves caused an additional ambiguity into the interpretation process and made the problem non-unique and unstable. However, this is the first-hand common interpretation approach of the SBL data. It is not difficult to show that, especially in shallow water (200-400), this normalization-based interpretation can be misleading. In shallow water (about 200 m in this case) the normalized MVO is lower than the 1 (instead of greater than 1). The interpretations of the SBL data based on the normalized magnitude and phase indicate that this simplistic approach has a limitation in shallow water as well as in complex geological settings.

[2] Frequency of EM signal

EM energy attenuation generally depends on the conductivity of the subsurface, the source–receiver separation, as well as the frequency of the transmitted EM signal. EM energy propagation satisfied the skin-depth phenomenon, which depend on the resistivity of the layer and frequency of the transmitted signal.

We computed the EM response at different transmitted frequencies. The magnitude responses of the EM signals, which decrease as the frequencies increase, are shown in figure 1.4. On the other hand, the phase response increases as the frequency increases. The responses of normalized magnitude and of phase difference are increasing as the frequency increases.

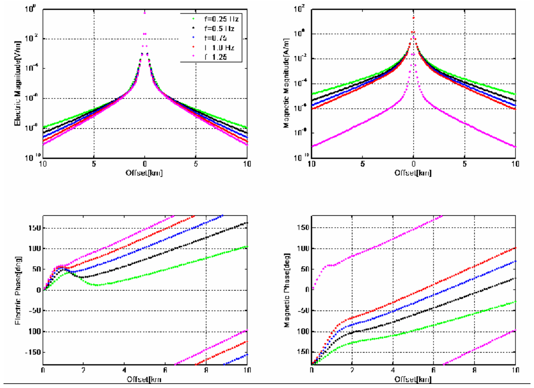

Figure 1.4: The electromagnetic (EM) response is computed at each of the different frequencies of this signal.

[3] Overburden resistivity and thickness effect

In next numerical experiment, we analyze the effect of resistivity and thickness of the overburden layer. An increase in overburden resistivity or high resistive layer increase the resistivity profile of the subsurface .The magnitude response is increasing with increasing resistivity profile of the overburden and phase response is decreasing with increasing resistivity profile. On the other hand, as Overburden thickness increasing magnitude decreasing and phase response is increasing with increasing overburden thickness. The modeling results are shown in Figure 1.5 [A] and 1.5[B]

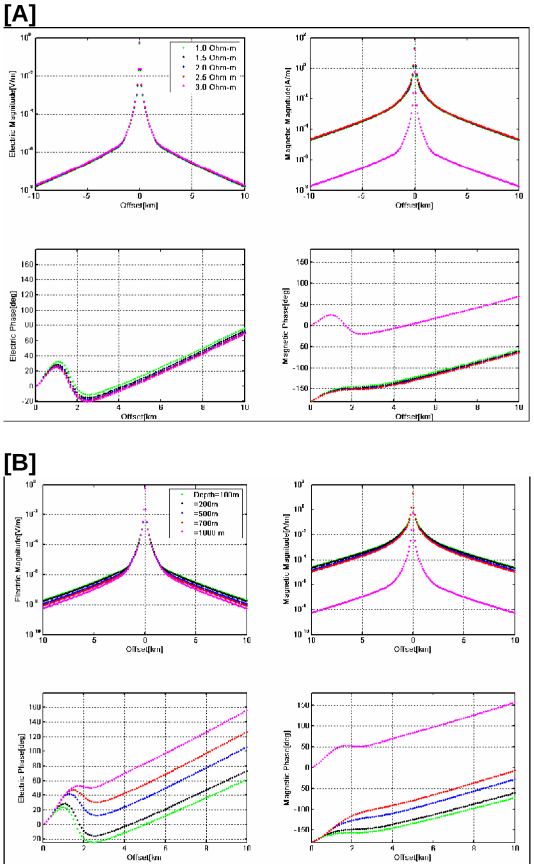

Figure 1.5 [A] and [B]show the MVO and PVO variation at different thickness and resistivity of the overburden

[4] Target thickness and resistivity effect

In the last numerical experiment, we also analyzed the effect of target (petroleum reservoir) thickness and resistivity. The plane-layer modeling responses give a good indication of the expected responses from the target body and show how the EM responses are influenced by variation in thickness as well as by the resistivity of the target.

The magnitude increases as the thickness of the target increases, and the phase responses decrease as the thickness of the target increases. This is shown in Figure 1.6 [A]. Second, magnitude responses increase and the phase responses decrease as the resistivity of the target increases. The computed forward modeling responses are shown in Figure 1.6 [B]

Finally, the above modeling result shows an estimate of the air wav effect on the measured data, an estimate of the maximum expected response from a reservoir at the respective depths. Finally, three dimensional (3-D) modeling was applied to investigate the effect of the limited width and extension of the prospect structure

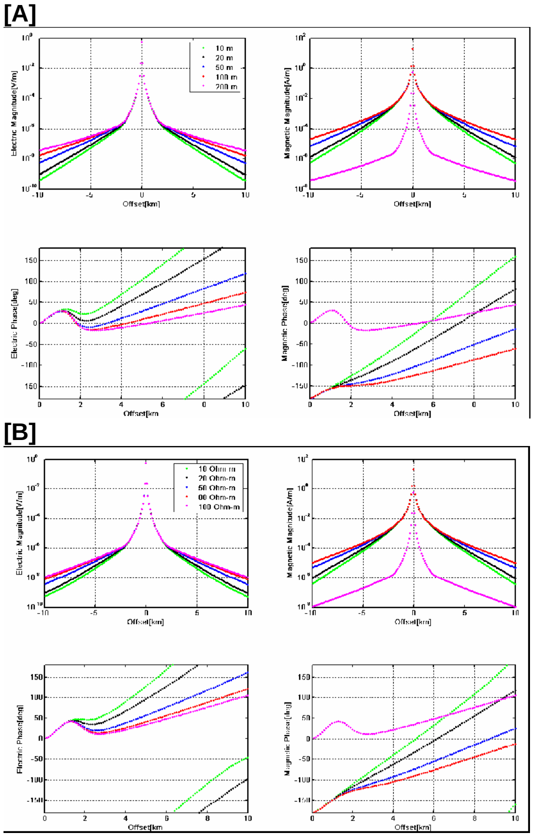

Figure 1.6: Forward response is computed at different reservoir thickness and resistivity. [A] Shows the MVO and PVO response at different reservoir thickness and [B] indicate the response variation at different target's resistivity.

Conclusion

In this research paper, we have exposed the 1-D forward modeling results of SBL and have discussed the factors that influence the electric and magnetic response. We can reach the following conclusions from this numerical study:

[1]- The modeling results show an estimate of the air wave effects on the measured data and demonstrate how the shallow water depth can cause a major problem in the SBL survey. The contribution of the air wave seen on the measured data in deep marine environment is insignificant (seawater depth >1000 m).

[2]- As target thickness and resistivity increase, the normalized MVO and PVO plots show a clear image of the presence of hydrocarbon. As a consequence, the amplitude trend vs. the offset can be indicative of the presence of hydrocarbon–filled sediments.

[3]-The thickness and resistivity of the overburden layer diminish the responses at the receiver.

In summary, 1-D modeling analysis for SBL data is essential in interpreting the responses from a known geological resistive target as well as in optimizing the survey parameters. Therefore, this ability to determine the resistivity of the deep drilling targets from the seafloor makes the SBL method a most important geophysical technique in the offshore exploration.

References

[1] Bhuiyan, A., T. Wicklund and S. Johansen [2006] Highresistivity anomalies at Modgunn arch in the Norwegian Sea: First Break, 24, 39-44.

[2] Cox, C.S., S.Constable, A.D. Chave, and S.C. Webb [1986] Controlled source electromagnetic sounding of the oceanic lithosphere, Nature, 320, 52-54

[3] Dell’ Aversana, Paolo [2007] Marine CSEM interpretation: Pitfalls and possible solutions, The Leading Edge, 26, 686 - 691.

[4] Dell’ Aversana, Paolo [2007] Improving interpretation of CSEM in shallow water, The Leading Edge, 26, 686 - 691.

[5] Eidesmo, T., 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 deepwater areas: First Break, 20, 144-152.

[6] Ellingsrud, S., T. Eidesmo, S. Johansen [2002] Remote sensing of hydrocarbon layers by sea-bed logging (SBL): Results from a cruise Angola: The Leading Edge, 21, 972- 982.

[7] Hoversten, G.L., H.F. Morrison and S. Constable [1998] Marine magnetotelluric method for petroleum exploration, Part II: Numerical analysis of sub salt resolution: Geophysics, 63, 826-840.

[8] Loseth, L.O., H.M. Pedersen, B.Ursen, L. Amundsen, and S. Ellingsrud [2007] Low frequency electromagnetic field in applied geophysics : Waves or diffusion: Geophysics, 71 , W29-W40.

[9] Mittet, R., L. Loseth and S. Ellingsrud [2004] Inversion of the SBL data acquired in shallow water: 66th EAGE Conference and Exhibition

[10] Johansen, S.E., H.E.F. Amundsen, T. Rosten, S. Ellingsrud, T.Eidesmo and A. Bhuyain [2005] Subsurface hydrocarbon detected by electromagnetic sounding: First Break, 23, 31-36.

[11] Young, P.D and C.S. Cox [1981] Electromagnetic active source sounding near the East Pacific Rise.Geophysical Research Letter, 8, 1043-1046.

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