Vertical source, vertical receiver, electromagnetic technique for offshore hydrocarbon exploration

Terje Holten,1* Eirik Grude Flekkøy,1,2 Bension Singer,1 Erik Mårten Blixt,3 Alfred Hanssen3,4 and Knut Jørgen Måløy1,2 outline an electromagnetic method for detection of hydrocarbons offshore which differs in some notable respects from the currently established marine controlled source EM technology.

We present and discuss the properties of a time-domain CSEM (controlled source electromagnetic) technology that utilizes vertically oriented transmitters and receiver antennas. The data are recorded in transient mode, wherein voltage time-series are recorded after transmitter switch-off. A square pulse with an alternating polarity is followed by a silent period in which the response is measured. The response curves from many pulses are averaged in order to reduce noise, and then binned into time windows. From theory, the vertical electric field is sensitive to deep resistive layers. At late times the vertical electric field decays like \( E_z(t) \sim t^{-5/2} \) over a rock of uniform conductivity. Another model, with the same overburden resistivity but with a resistive layer gives rise to a faster temporal decay, with a maximum contrast occurring at typically at \( t=2-10 \) s depending on the depth of the resistivity layer (HCs). The method has been verified on the relatively challenging Luva field, where our observed data have been found to carry a signature of the gas column there. This gas column has a relatively low resistivity contrast and is located at a depth of 1700 meters below the sea floor.

Introduction

Various CSEM methods have been developed in the last two decades (Edwards, 2005). The seabed logging method (SBL) (Ellingsrud et al., 2002) has been used extensively for the last decade in HC exploration. It uses a horizontal dipole towed over a grid of horizontal receivers, each of them with two horizontal electrical lines perpendicular to each other. The signal has given frequencies and long offsets (distance between transmitter and receiver) are used. Vertical dipoles have already been used in the MOSES (Magnetometric Off-Shore Electrical Sounding) method (Edwards et al., 1985) with magnetic measurements in the frequency-domain. However, this method is not particularly sensitive to resistive layers. Using a vertical dipole and vertical receiver for marine borehole measurements has been suggested by Scholl and Edwards (2007).

An offshore, time domain EM method that uses vertical, stationary transmitters and receivers has been developed by the Norwegian geophysical company Petromarker (Barsukov et al., 2007). Short offsets in the range of 500–500 m are used to probe the electrical near-field that results from turning off a source current. The SBL technology, based on the horizontal transmitter-horizontal receiver setup, measures a large electromagnetic wave directly through the sea, and a smaller signal from the underlying rock. The vertical current resulting from a vertical transmitter is sensitive to horizontal resistive layers and therefore carries information about the deeper structures.

Technology overview

The Petromarker pulsing system technology consists of two pulse generators working in parallel with a total capacity of 5000 A, each transmitter dipole has a current capacity of 2500 A and consists of two electrodes attached to the vessel with cables. The lower pulse electrode, connected to the pulse cable, is positioned on the seabed. The position of the lower electrode is measured by averaging the positional data from an acoustic transponder attached to the lower pulse electrode. The vessel is moved to a position directly above the stationary lower electrode and the upper electrode is lowered 50 m below sea surface and placed so that verticality is achieved.

A square pulse with alternating polarity followed by a silent period (pause) is used in this time domain method. The transmitter signal changes sign in sequences of eight pulses (so-called P8 sequence), which is a Thue-Morse sequence (Allouche and Shallit, 1999). The corresponding time series are added or subtracted according to the sign of the transmitted signal. The sum of the responses corresponding to pulses of negative polarity is subtracted from the sum of the pulses of positive polarity. This averaging procedure, known as...
'stacking', removes any DC components of external noise. Linear- and quadratic-in-time trends in the data are also removed. In addition to the stacking, the data is averaged in bins of sizes that increase exponentially with time, so that the averaging is more extensive for the weak signal of late time when the noise becomes more significant (Nabighian and Macnae, 1991).

The challenge when measuring the vertical, rather than the horizontal field, is the small amplitude of the signal. At late times the horizontal response from a horizontal dipole is 2-3 orders of magnitude stronger than the vertical response from a vertical dipole (Chave and Cox, 1982). Therefore both transmitter and receiver tilt angles must be kept very small, a challenge that has motivated the design of a stable tripod where verticality is achieved through the action of gravity. The dependence of the measured data on transmitter and receiver positions can be used to control tilt effects.

Each receiver consists of a top unit with electrodes and a bottom unit with electronics (batteries, data storage, bottom electrodes, and recording unit) and a dead weight. The top electrodes are held vertically above the bottom unit by either a buoy with strong buoyancy or a rigid tripod system. Different receiver lengths have been used, ranging from 18 m for the rigid tripod to 30-60 m for the flexible cable receivers (Figure 1). A mobile transmitter antenna is then positioned at various positions, where it is stationary while pulsing. There is no physical connection to the sea surface, so data is downloaded after recovery of the receiver station on deck or subsea via a remotely operated vehicle (ROV) which connects to the receiver base. Each receiver has four pairs of Pb/PbCl electrodes. A sampling frequency of 1000 Hz with 24-bit resolution is used for measurements. The long receivers have a higher signal level than the tripod. Large sea current leads to oscillatory electrical noise and a small tilt. The tripod has low noise, less tilt, and low signal level compared to the long cable receiver. Electric field measurements, navigational data, source data, and sea state data are all recorded.

The difference between a response from non-hydrocarbon (HC) and a reservoir containing HC in one dimension is fairly constant within a radius of about 2 km, if the reservoir is deeper than 1 km. At very short offsets (under 300 m) slight movements of the upper electrode lead to uncertainties, and polarization effects may dominate the measurements in some cases, while at larger offsets (over 1 km) 3D effects and tilt effects become more significant. In between these boundaries, the optimal offset can be found, which is usually in the range from 500 m to 1500 m. The response from the underground is recorded while the transmitter is off, so that the uncertainties of the location of the pulse electrodes do not lead to a time dependent noise. Verticality eliminates the air-wave components from the received signal.

**Modelling**

The vertical component of the current density decays in a way similar to a temperature field in a layered medium of variable thermal conductivity; that is, it is governed by the diffusion equation, and it is continuous across horizontal boundaries. The electrical diffusion constant is given by $D=1/(\mu \sigma)$, where $\mu$ is the magnetic permeability and $\sigma$ is the conductivity. So, in this analogy, the electric conductivity corresponds to the inverse thermal conductivity and the boundary condition at the sea surface where no current passes into the atmosphere, which corresponds to a zero temperature at the surface. At late times $t$ the electric field, or the temperature, decays as $E_z(t) \sim t^{-5/2}$ (Ward and Hohmann, 1987) in a homogeneous medium. Just as a temperature field will equilibrate more quickly due to the presence of a more conductive layer, the vertical current density will decay more quickly when a layer of smaller electric conductivity is present (Figure 2). The scaling between the characteristic time $T$, at which the corrections to the $E_z(t) \sim t^{-5/2}$ behaviour sets in, and the depth $d$ of the HC layer is simply $d^2 = 2DT$. In practice, the maximum contrast occurs at $t=2-10s$. The diffusion equation governing the electric current density in a model with horizontal layers of different conductivities is readily solved to give the forward prediction for the electric field. Conversely, standard inversion techniques are applicable to obtain the conductivities of different layers that best fit the measurements. The model based on the idea of a one-dimensional horizontally
layered earth also assumes the absence of induced polarization effects (Cole and Cole, 1941; Veeken et al., 2009) and magnetizable materials. While these are restrictive assumptions, complementary seismic and geological surveys may nevertheless justify the use of such a model.

Luva discovery
The Luva gas discovery is proven in a tilted fault block on the Nyk High in the Voring Basin of the Norwegian Sea. The HC column is about 180 m at its maximum height and is enclosed in an area of about 7 km by 3.5 km. This happens at a depth of about 2960 m from mean sea level, with a water depth of around 1270 m. The licence, PL218, is currently operated by StatoilHydro with ConocoPhillips and ExxonMobil as partners. The Luva gas accumulation was discovered by BP in 1997 by well 6707/10-1. The Luva structure consists of an eastwards tilted fault block with bounding faults running in a north-south direction. The reservoir consists of sandstones of the Nise Formation of Late Cretaceous age, and is a part of a 1200 m thick section dominated by sheet sandstones, of high reservoir quality, deposited in a basin floor fan complex. The sandstone intervals are separated by shale layers.

The reservoir containing the HC accumulation exhibits a strong laminar structure, with the resistivity peaking up to 200 Ω·m between intervals of resistivity lower than 10 Ω·m where the sandstone is interbedded with shale layers. This yields a fairly low average resistivity of about 20−25 Ω·m. Combined with the resistivity of the surrounding shales (1−7 Ω·m), the Luva discovery becomes a target of relatively low resistivity contrast, making it difficult to identify using CSEM (Carstens, 2007).

Modelling 3D effects on the Luva discovery
The curves shown in Figure 2 represent responses of two different 1D cross sections, one of which includes a layer containing HC and another one which does not. The layer with HC is an infinite horizontal layer. In practice, one may expect such a layer to be restricted in all its dimensions and heterogeneous. This necessitates evaluation of the response of realistic 3D structures containing HC. It is well known that smaller or larger 3D effects are present in all electromagnetic methods, especially those relying on acquisition of the electric field (Commer and Newman, 2004).

To evaluate 3D effects for the area of Luva discussed in the previous section, a 3D model was composed using all available geologic and geo-electric data. The model also accounted for the variable bathymetry of the area. A numerical simulation was carried out using the 3D integral equation code by Singer (2008). The simulation addressed the particular positions of the transmitter dipole used in the survey. An example of responses calculated for the first position of the transmitter in the area 101 of Luva (named Tx1 in Figure 3) is shown in Figure 4.
The blue curve in Figure 4 depicts the response of the ‘normal’ model of Luva, which is a 1D model that does not contain a resistive (HC) layer. The red curve represents another 1D response, which can be called ‘local’. Unlike the normal model of the area, the local model includes a horizontally infinite resistive layer with parameters that characterize the HC layer immediately under the transmitter dipole. From Figure 4, the 1D local response is noticeably different from the normal response.

The solid black and the dotted grey curves show 3D responses that can be expected at the third and sixth receivers at offsets of 1000 and 1065 m, respectively. As could be expected, limited dimensions of the target body reduce the response of the HC reservoir, which still can be detected if the noise level is below 10%. Similar results have been obtained for other transmitter locations. Interpretation of such a 3D response using a 1D inversion algorithm will most probably underestimate the resistivity of the HC layer.

Another 3D effect may also be noticed in Figure 4. Indeed, the 1D local curve has a clear tendency to approach the normal curves at large delays after switching off the source. By contrast, the 3D curve tends to become parallel to the normal curve. This is a trait of the one of the most well-known distortions caused by 3D heterogeneities, i.e. the so-called ‘static shift’. This effect is present in SBL-measurements as well as in time domain acquisition, which underlies the Petromarker technology (Singer et al. 2007).

Survey design and results

Between 27 July and 7 August 2008, Discover Petroleum acquired, in collaboration with StatoilHydro and Shell, a CSEM survey of the Luva gas discovery in the Norwegian Sea. Instead of using a more conventional line-survey strategy, data from three different locations were collected (Figure 3), location 101 over the centre of the hydrocarbon (HC) accumulation, and location 102 and 103 in the area where the reservoir is water filled. In location 101 and 103 a total of seven receivers were placed on the sea floor in a simple pattern of two parallel lines, and the transmitter was placed in three positions on different sides of the pattern, this gave rise to data with offsets between 500–1250 m. On location 103 two receivers were located next to each other at an offset of 750 m from the single transmitter position used on that location. On each transmitter position the pulsing lasted from four to 12 hours. Each pulse was 8 s long, with a 20 s listening period between each pulse. Two pulse generators with total current of 3900 A and transmitter length of 1240 m were used.

A selected ensemble of P8-averaged response curves were averaged to produce a high-confidence low noise overall response curve. Our rejection criteria were based on: (i) rejection of response curves with a large fluctuation level in the far tail, and (ii) rejection of response curves sampled during non-vertical transmitter periods. Typically, about 1/2–1/3 of the P8-cycles were rejected. Figure 5 shows the comparison of ensemble averaged response curves from above the HC accumulation in area 101 (red curves), and from the water-filled reservoir in area 102 (blue curves). Each curve shown is an average over several receivers, which are at similar (within tens of a metre) offsets from the transmitter. Dashed lines indicate the estimated errors.

Figure 4 Vertical-to-vertical 1D normal, 1D local, and 3D responses at 1000 and 1065 m offsets, respectively for transmitter position Tx1 and receivers Rx3 and Rx6 located in acquisition area 101 of Luva (see Figure 3). The electric field is evaluated for a 1Am source dipole.

Figure 5 A comparison of ensemble averaged response curves from above the HC accumulation in area 101 (red curves), and from the water-filled reservoir in area 102 (blue curves). Each curve shown is an average over several receivers, which are at similar (within tens of a metre) offsets from the transmitter. Dashed lines indicate the estimated errors.
accumulation lies only 500–1000 m away from location 102. The resistivity of this HC body might influence the results at the water reference location 102 due to its proximity, as one-dimensional inversion of these data indicates an apparently higher resistivity in the water-filled reservoir than in the overlying sediments.

Conclusion

A time domain EM method with vertical transmitters and receivers has been developed. The vertical electric field is sensitive to deep resistive layers, and the modelling shows a significant difference between HC-filled and a water-filled reservoirs.

The key component of our computational method is the solver that gives the electromagnetic response over a layered model. This solver is fast and therefore easily employed in any standard inversion scheme. Moreover, we have demonstrated the ability to perform more challenging and realistic 3D simulations. This technique will be central in future developments.

While the present verification of the technique for a layered earth shows the ability to recognize a rather weakly defined gas reservoir, it has not yet been employed to make a definite identification/discovery of such a field. However, in conjunction with existing seismic data on any given field, our technique may be used to strongly reduce the uncertainty in HC prediction. Also, our technique holds the potential to monitor the evolution of reservoirs already under production, as well as to locate the perimeter of a discovered reservoir when an array of observation sites is employed.

The HC signature is apparent in the ensemble averaged data. This is an important finding as our test case, the Luva discovery is a fairly weak target (low resistivity contrast between overlying shales and the HC accumulation: 1-7 $\Omega\text{m}$ versus $\sim 20 \Omega\text{m}$, and a relatively deep target: $\sim 1700$ m overburden). A contrast between data from the HC zone and water reference of around 30–50 % shows the HC signature in the averaged data. It is evident that our time domain, vertical-vertical CSEM method is sensitive enough to identify the low-resistivity contrast Luva target.

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References


