Subsurface hydrocarbons detected by electromagnetic sounding

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Seismic imaging techniques can readily detect potential hydrocarbon (HC) traps but discriminating between the presence of water or hydrocarbons in such traps has remained a challenge. Detection of subsurface hydrocarbons by an active source electromagnetic (EM) sounding application, termed seabed logging (SBL), has recently shown very promising results, but has until now not been fully demonstrated. Here, we present SBL data from the Troll West Gas Province (TWGP), offshore Norway, providing irrefutable evidence for direct detection of a deeply buried hydrocarbon accumulation by electromagnetic sounding. A powerful horizontal electric dipole (HED) source induced up to 170 % increased subsurface returned signals above the gas accumulation. This result opens a new frontier in hydrocarbon exploration.

Introduction

Remote sensing techniques record variations in petrophysical parameters such as acoustic or electric properties. Seismic sounding is by far the most common of such tools and typically uses acoustic waves to map boundaries between layers with contrasting acoustic properties. Seismic data can provide detailed information about layering but is not very well suited for direct detection of pore fluid composition. Given detection of a structural geometry that may have allowed accumulation of HC within porous sedimentary rocks, the main remaining uncertainty is therefore whether the pore space is filled with saline water or HC. For this reason only 10-30% of exploration wells penetrate commercial oil or gas reserves in many areas.

Electromagnetic sounding uses EM energy transmitted by an HED source to detect contrasts in subsurface resistivity. Resistivity variations in rocks are generally controlled by the interplay between highly resistive minerals ($10^{11}$-$10^{14}$ Ωm) and pore fluids including low resistive saline water (0.04-0.19 Ωm) and/or infinitely resistive hydrocarbons (Rider, 1996). Tight crystalline rocks such as oceanic crust typically show high resistivities (100-1000 Ωm) with variations mainly controlled by saline fluids in fracture networks. Sedimentary rocks can exhibit a wide range of resistivities (0.2-1000 Ωm) mainly controlled by variations in porosity, permeability and pore connectivity geometries in addition to pore fluid properties and temperature (Rider, 1996; Schlumberger, 1987).

The high resistivity of hydrocarbon filled reservoir rocks (30-500 Ωm) compared with reservoirs filled with saline formation water (0.5-2 Ωm) makes EM sounding a potential tool for detection of subsurface HC. Although EM techniques have been used for many years, EM sounding has until recently not been applied in offshore HC exploration. A full scale EM sounding test offshore Angola in 2000 indicated that a new application of EM sounding, SBL, had a promising potential for direct detection of deeply buried hydrocarbons (Ellingsrud et al., 2002; Eidesmo et al., 2002). Until now the interpretation of SBL data has been hampered by the lack of statistically significant calibration data demonstrating that deeply buried HC accumulations were detectable by the SBL method. However, recent development of a new powerful HED source has opened the way for improved acquisition, processing and interpretation of SBL data.

In this study we present SBL data across the TWGP, offshore Norway. Increased EM return signals over TWGP are caused by reflection and refraction of EM energy from a high resistivity HC accumulation situated ca 1100 m below the seabed. These data are in accordance with modelling results and provide the first evidence for direct detection of a deeply buried hydrocarbon accumulation by subsea EM sounding.

SBL method

In controlled source EM sounding (CSEM) a horizontal electrical dipole (Young and Cox, 1981, Cox et al., 1986) is towed close to the seabed emitting an ultra low frequency EM signal which is recorded by stationary seabed receivers. This is also the case for SBL which is a special application of CSEM. As illustrated in Figure 1, seabed receivers record the EM responses as a combination of energy pathways including signal transmission directly through seawater, reflection and refraction via the seawater-air interface, refraction and reflection along the seabed, and reflection and refraction via possible high resistivity subsurface layers.

Low frequency EM signals decay exponentially with distance $z$ (m) by $e^{-z}$ where $\delta = (2\pi/f)/(8\cdot10^{-7}\cdot\rho\cdot\mu)$ and $\rho$ and

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f denote resistivity (Ωm) and signal frequency (Hz) respectively. The distance required to attenuate an EM signal by the factor $e^{-1}$ (0.37) is defined as the skin depth and is about $551$ m in seawater ($0.3$ Ωm), $1424$ m in $2$ Ωm sediment and $10^7$ m in air ($10^{10}$ Ωm) for a $0.25$ Hz signal.

EM signals are rapidly attenuated in seawater and seafloor sediments saturated with saline water, and these signal pathways will dominate at near source-to-receiver offsets (~ 3 km). In high resistivity and relatively thin (20-200 m) subsurface media, such as hydrocarbon filled reservoirs (30-500 Ωm), the energy is guided along the layers and attenuated less depending on the critical angle of incidence (Kong et al., 2002). Guided EM energy is constantly refracted back to the seafloor and is recorded by the EM receivers. Energy is also reflected and refracted via the air-water interface. This energy is commonly termed the air-wave and dominates at far offsets (~ 6 km) depending on water depth. The refracted energy from high resistivity subsurface layers will dominate over directly transmitted energy when the source-receiver distance is comparable to or greater than the depth to this layer. The detection of this guided and refracted energy is the basis of SBL (Ellingsrud et al., 2002).

**Troll West Gas Province**

The Troll Field complex is the largest gas discovery on the Norwegian Continental Shelf located in relatively shallow water (300-360 m) in the northeastern part of the North Sea (Gray, 1987). The field is subdivided into three separate compartments. Troll East is by far the largest and contains two thirds of the HC reserves. For the SBL verification test the much smaller TWGP was selected (Figure 2). The reservoir interval is Jurassic sandstones (Sognefjord Fm.) with up to $160$ m gas column. HC filled sands show high average resistivities around $200-500$ Ωm and occur at a burial depth of about $1400$ m below sea level. Water bearing Sognefjord Fm. sands and overburden sediments show resistivities in the $0.5-2$ Ωm range. Due to the high reservoir resistivities, well defined field edges, the low and relatively constant resistivities in the geological layers above the reservoir (overburden), constant water depth, smooth sea floor, and the moderate distribution of the HC filled reservoir, the TWGP is well suited for testing of the SBL method.

**Forward SBL modelling**

When interpreting SBL data it is important to compare the EM response over the HC accumulation with the EM response in a reference area immediately outside the accumulation. It is also critical to understand SBL responses from high resistivity bodies other than the HC reservoir itself which can potentially generate significant responses. In addition to addressing these questions, forward SBL modelling can also answer critical questions related to practical survey planning required for carrying out an optimal verification survey.

![Figure 1](image-url) (Top) Schematic sketch of air-water-sediment geometry and receiver (Rx) layout on seabed during towing of electromagnetic source. Typical resistivities of air, water, sediments and hydrocarbon reservoirs are shown for reference. Black arrows denote refracted transmission of electromagnetic signals via the air-water interface. Blue arrows denote direct transmission of electromagnetic signals through water and by refraction along the seabed. Red arrows denote refracted transmission of electromagnetic signals via a buried high-resistivity layer (hydrocarbon reservoir). (Bottom) Electric magnitudes measured at a single receiver as a function of source-receiver distance. Red curve show the expected response from a model including a high-resistivity hydrocarbon reservoir. Blue curve is the significantly weaker response from a model without a hydrocarbon reservoir. (Top) To better visualize theoretical differences in amplitudes between the two cases the reservoir curve (red) was divided (normalized) by the no-reservoir curve (blue).
To simulate EM responses we used plane layer FK-modelling (Chave and Cox, 1982) and 3D finite difference time domain forward modelling (Berenger, 1994; Chew and Weedon, 1994; Macnae, 1984; Rappaport, 1995). The 3D modelling software used in this project was developed by Electromagnetic Geoservices (emgs). Plane layer modelling gives a good indication of the expected response from the target at the actual depth and how the results are influenced by the airwave. When the target is relatively large, as in the TWGP case, it also gives a good indication of changes in response over and outside the HC accumulation. 3D modelling shows how the EM response is affected by the geometry of the reservoir and the effect of varying receiver layout geometries. The version of the 3D modelling tool used here does not include the airwave in the simulations. With the ultra low frequencies (0.25 Hz) used in SBL, it is the resistivity variations in the illuminated media that dominate the response measured at the seafloor. All measured and modelled EM responses are normalized to the response from a 2D model with no subsurface HC accumulation. For response B, the simulated SBL line crosses TWGP at an angle as indicated in Figure 2. E and F are results from plane layer modelling. E is the response from the ‘on-reservoir’ model normalized by itself without reservoir, while F is the response from model ‘on-reservoir’ normalized by model ‘off-reservoir’ (Figure 3).

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There is a strong increase in simulated SBL response above TWGP along the selected SBL survey line. The modelled SBL response also increases with increasing reservoir width and, for 5 km width, the simulated response is more than three times stronger than the response from a non-reservoir case. For survey design it was important to avoid Troll West Oil Province west of TWGP to obtain a good reference area without hydrocarbons (Figure 2).
fore, had to be run in a SW-NE direction. The modelling indicates that crossing TWGP at this angle should not reduce the response from the reservoir significantly. The reduction from response A to B is a combined effect also reducing the reservoir width from 5 to 3.5 km.

In the simulations described above, the sea-air interface is not included in the model. The EM energy trapped at the sea-air interface will refract back and influence the modelled EM response, particularly at far offsets. To understand this effect, plane layer modelling with the air layer included is useful. Plane layer modelling is also useful for understanding changing SBL responses from above the hydrocarbon accumulation compared to the reference area outside the HC accumulation. The general patterns and normalized maximum strength of the plane layer modelling results are comparable to 3D modelling results (case E and F in Figure 3). The effect of the airwave is seen at large offset where the normalized response is significantly weakened. The disagreement between the two modelling approaches can be explained by the simplified geological input models in the case of plane layer modelling and by differences in calculation approach for the two methods. Based on the very promising modelling results, the SBL verification survey at TWGP was recommended.

**Data acquisition**

The survey was designed with 24 EM receivers across TWGP as illustrated in Figures 2 and 4. Each EM receiver was dropped from the vessel freely sinking to the seafloor. Acoustic ultra short baseline (USBL) communication was used to establish exact receiver positions. At the seabed the receivers were kept in position by concrete anchors. 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.

The horizontal electric dipole antenna consisted of two electrodes separated approximately 230 m from each other with electrical contact to the seawater. Electrodes were positioned on a streamer section providing neutral buoyancy at depth and towed behind an instrumented tow fish, and each electrode was connected electrically to a signal source located on the tow fish. The source transmitted a continuous square shaped signal at a fundamental frequency of 0.25 Hz. The peak-to-peak current varied from zero to almost 1000 Ampere. The distance from the source to the seabed was kept at approximately 40 m and was continuously monitored by an echo sounder. Tow fish and HED depths were controlled by the length of the umbilical running from the survey vessel. The umbilical cable also provided power and

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**Figure 3** Modelled SBL responses from simplified TWGP geological models. Columns to the right show plane layer geological models representing ON and OFF reservoir situations. The differences in overburden resistivity between ON and OFF reservoir are most likely due to lateral lithological changes. The cross section is a modification of the east-west cross section in Figure 2. Results from both 3D modelling (solid lines) and plane layer modelling (dashed lines) are included. Models A, C and D are responses from varying reservoir widths (in ‘cross line’ direction, 3 km, 2.5 km and 1.25 km respectively). In model B the width increases from 3.5 km (left) to 5 km (right), represent an oblique crossing of TWGP. Models E and F are responses from plane layer modelling. See text for explanation.
signal transmission between the vessel and the tow fish. Antenna position and depth below the vessel were monitored by two acoustic USBL transponders, one at the tow fish and one located behind the tail electrode.

Data were acquired as time series and then processed by a windowed Fourier series analysis and displayed as magnitude of the electric field normalized by the displacement, i.e., dimension (V/Am²) vs. offset (MVO) at the transmitted fundamental frequency. Data quality was high with reliable information to an offset ~ 8 km.

Results and discussion

Normalized values of electric magnitudes vs. offset measured by two representative receivers, one above (ON) the HC accumulation and one outside (OFF) the HC accumulation are shown in Figure 4. The selected ON and OFF receivers record near identical magnitudes out to 3.5 km but between 3.5 and 9.0 km offset the ON receiver shows systematically higher magnitudes compared to the OFF receiver. The corresponding normalized MVO predicted from forward modelling is also shown in the figure and there is good agreement between the forward simulations and the measured MVO values. The modelling results compared with the measured data are the plane layer simulation results. Likely reasons for the match between modelled and measured EM response include the large lateral extent of the reservoir and the fact that both the airwave and lateral changes in overburden are included in the modelling.

Normalised MVO data for the OFF receiver are close to 1.0 which is in accord with subsurface sediments comprising only water wet lithologies along this line segment. Normalised MVO data for the ON-receiver are close to 1.0 out to ca 3.5 km but increase gradually to levels above 3.0 at 7.5 km offset before gradually decreasing with higher offset. Magnitudes measured by the ON-receiver are reasonably similar to the modelled response for TWGP and in accordance with the position of this line segment over the main gas accumulation (Figure 4).

In order to display EM sounding systematics along the entire SBL survey line, we have calculated median normalised magnitudes at 6.5 ± 0.5 km offset for all receivers. This intermediate offset interval records close to maximum difference in measured magnitudes ON and OFF TWGP, and the data is not affected by noise. Median normalised magnitudes at 6.5 ± 0.5 km offset for all receivers are illustrated in Figure 4, with data plotted at 3.25 km offset halfway between source and receivers. Median normalised magnitudes are around 1.0 SW of TWGP (OFF), increase gradually up to 2.7 over the apex of the HC accumulation (ON), and decrease gradually down to 1.2 over the NW fringes of the field. The gradual increase is caused by the fact that both source and receiver must be above the target to record maximum returned energy from the HC accumulation. For TWGP this is the case only for a narrow zone above the middle part of the HC accumulation. We also see that the west-
ern slope of the anomaly is steeper than the eastern. A likely explanation for this is the asymmetric shape of the accumulation with a fault termination at the western extension and a more gradual eastward thinning as shown in Figure 4.

There are no observations of high resistive strata or structures that we know of, other than the TWGP, which can explain the high resistivity values measured by the SBL survey. Due to extensive seismic surveying and drilling in this part of the North Sea, the geology of the area is very well known.

Conclusions
Seismic imaging techniques easily detect reservoir structures where hydrocarbons can be trapped, but to determine the fluid content of the reservoirs is still very challenging.

Recent attempts at direct detection of hydrocarbon filled reservoirs by SBL have shown very promising results. But due to lack of statistically significant calibration data, the SBL technique has not yet been fully demonstrated. However, the SBL data across the TWGP provides to our knowledge the first published evidence for direct detection of a deeply buried hydrocarbon accumulation by subsea EM sounding. A powerful dipole source induced up to 170% increased subsurface return signals over TWGP. The increased return signal is due to reflection and refraction of EM energy by the high resistivity gas accumulation 1100 m below the seabed. Remote detection of TWGP is in accordance with modelling results and opens a new frontier in hydrocarbon exploration.

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