# Sea Bed Logging (SBL), a remote resistivity sensing technique for in hydrocarbon exploration

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This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.



### Abstract

Remote resistivity sensing of buried resistive layers within conductive sediments, a concept called Sea Bed Logging (SBL), has been proven successfully by several surveys. A survey carried out offshore Angola proved to be ideal for the SBL technique due to large water depths, short distances from the sea floor to the reservoirs and high resistivity contrasts between the overburden and the hydrocarbon bearing zones. Another survey over the Ormen Lange gas field, offshore Norway, demonstrated that the technique has high potential also in more adverse areas with rough sea floor topography, rather large distance from the seafloor down to the reservoir and relatively low hydrocarbon saturation (low resistivity).

### Introduction

The concept of Sea Bed Logging (SBL), has been demonstrated both theoretically by Kong et al. (2002) and Eidesmo et al. (2002) and in practice by a survey over a known oil field offshore Angola in November 2000 (Ellingsrud et al., 2002). The Angola survey was run over an area which is ideal for the SBL technique mainly due to large water depth and shallow reservoirs. In November 2002, ElectroMagnetic GeoServices (emgs) established by Statoil in February 2002, ran another survey over the Ormen Lange gas field offshore Norway. The Ormen Lange field is the main hydrocarbon discovery in deep water areas offshore Norway (only one other discovery). The survey was run to calibrate the SBL technique, with focus on improved source and receiver modules (Røsten et al., 2003). Ormen Lange is a challenging area for SBL, with rough seafloor topography, highly varying water depths, relatively large and varying distances from the sea floor down to the reservoir and varying low resistivities in the gas zone.

### Method and equipment

The SBL technique is well described by Eidesmo et al. (2002) and Ellingsrud et al. (2002). SBL is a special application of controlled source electromagnetic sounding (CSEM). It uses a horizontal electrical dipole (HED; Young and Cox 1981, Sinha et al. 1990) that emits a low frequency electromagnetic (EM) signal into the underlying seabed and downwards into the underlying sediments. Electromagnetic (EM) energy is rapidly attenuated in the conductive seafloor sediments due to water-filled pores. In high resistive layers such as hydrocarbon-filled sandstones and at a critical angle of incidence the energy is guided along the layers and less attenuated (Kong et al. 2002). Energy constantly refracts back to the seafloor and is detected by sea floor EM receivers. When the source-receiver distance (offset) is comparable to or greater than the depth of reservoir burial, the refracted energy from the resistive layer will dominate over directly transmitted energy. The detection of this guided and refracted energy is the basis of SBL (Ellingsrud et al. 2001).

Each EM receiver is dropped from the vessel and freely sinks to the seabed. Acoustic ultra-short baseline (USBL) communication is used to establish exact receiver positions. At the seabed the receivers are held in position by concrete anchors. After the recording period an acoustic signal from the vessel trigger a release mechanism, causing the receivers to float back to the sea surface. The horizontal electrical dipole (HED) antenna consists of two electrodes separated approximately 230 m apart with electrical contact to the seawater. The electrodes are positioned on a streamer section providing neutral buoyancy at depth. The streamer is towed behind an instrumented tow fish. Each electrode is connected electrically to a signal source located on the tow fish. The output signal to the electrodes is monitored at the tail of the tow fish. The source transmits a continuous periodic signal with any curve shape and frequency ranging from 0.05 to 10 Hz. The peak-to-peak current varies from zero to several hundreds Ampere.

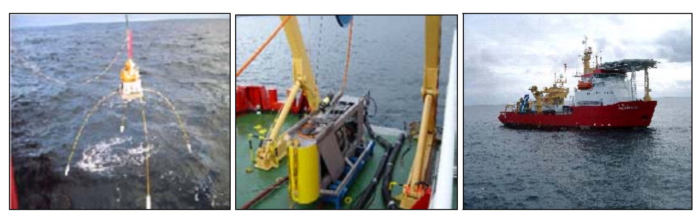


**Figure 1 -** The left picture shows the first receiver dropped over Ormen Lange. All instruments have electrodes mounted at the end of each electrode antennae arm, with lengths around 8 m, giving two orthogonal electrical channels. The electric field measured at each channel is amplified and converted from analog to digital format before being recorded on an internal storage device. The EM source tow fish is displayed in the middle. The Polar Bjørn shown to the right was used as survey vessel.

The depth of the source above the seabed (target depths are 50-100 m) is continuously monitored by an echo sounder. The target depths were easily obtained in Angola, but the very rugged seabed topography at Ormen Lange caused larger variations locally (up to ca. 200 m). The depth of the tow fish and the HED are controlled by the length of the umbilical running from the survey vessel. The umbilical cable also provides power and signal transmission between the vessel and the tow fish. The antenna position and its depth below the vessel are monitored by two acoustic USBL transponders, one at the tow fish and one located behind the tail electrode.

**The Angola oil field**

The petroleum prospects offshore Angola are in a deep Tertiary basin consisting of a thick (10-20 km) sequence of prograding sands and shale. Well logs show sediment resistivities typically around 0.7 Ωm that rises to around 100 Ωm in petroleum reservoirs. The survey site was on the continental slope in water depths of about 1200 m, with the upper channel sand at approximately 1100 m and the lower channel sand 900 m below the seafloor. A shallow salt diapir occurs in the northeast corner of the area.

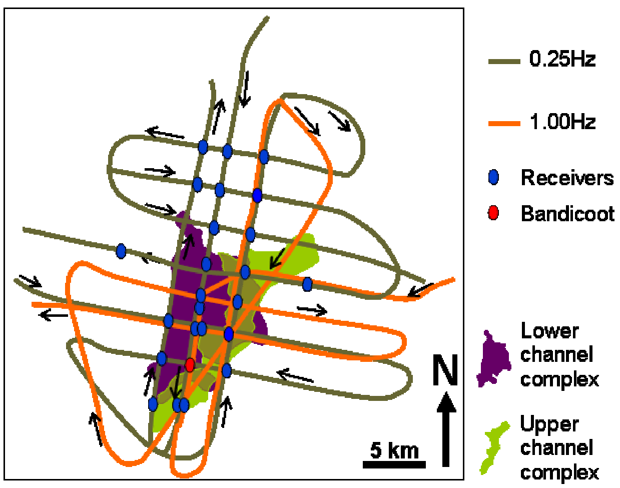



**Figure 2 -** The study area comprises a lower channel complex and an upper channel complex, located offshore Angola. The survey deployed 26 seafloor receivers. The primary part of the survey used a 0.25 Hz transmitting frequency. This was followed by a survey along a subset of the tow lines using a 1 Hz transmitting frequency.

**The Ormen Lange gas field**

The Ormen Lange field (Figure 3) is a large gas accumulation with an estimated GIIP of 570 x $10^9$ $Sm^3$ located offshore 160 km west of Kristiansund lying in the western part of mid-Norway. The gas accumulation covers an area of approximately 350 $km^2$, and is mainly defined by seismic DHI observations. Water depths over the gas field range between 700 and 1100 m, with highly variable seabed topography resulting from the Storegga submarine landslide. The Ormen Lange reservoir interval comprises the Jorsalfare and Egga Formations, and represents deep marine turbidite deposits of upper Cretaceous to Lower Tertiary age. Reservoir overburden in the SBL study area is around 1600m. Gas-filled reservoir intervals have resistivities around 30-50 Ωm, while water-bearing sands and overburden generally show resistivities in the 0.5–2 Ωm range.

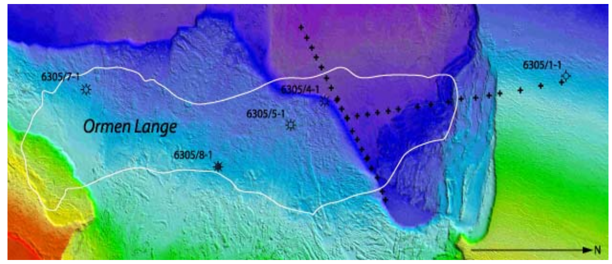



**Figure 3 -** Bathymetry and wells in the Ormen Lange area. Crosses denote SBL receiver layout along N-S and SW-NE towlines. The gas-water contact is outlined by the white curve.

**Data acquisition and quality**

The Angola survey was designed as a 3D survey. As this was the first scientific SBL survey ever run, the 26 university EM receivers where dropped in the positions shown in Figure 2. The university source was towed through the receiver array along several towlines, and in total 314 km of source lines were towed. Two square wave signals of fundamental frequencies of 0.25 Hz and 1.0 Hz were used in this experiment. Four receivers were lost or failed to give data. The data quality varied, but the best receivers gave valuable data up to an offset of approximately 6 km.

The Ormen Lange survey was designed with two 2D lines at the northern part of Ormen Lange (Figure 3) and was ran with commercially developed source and receivers. 34 EM instruments were dropped and 80 km of source lines were towed with a sine wave signal of 0.25 Hz. The data quality was high with reliable information to an offset of more than 8 km. This is both due to a high power source and high quality receivers.

**Processing and interpretation**

The SBL data are acquired as time series, and then processed by a windowed Fourier series analysis at the transmitted frequency. After processing, the data can be displayed as magnitude versus offset (MVO) or phase versus offset (PVO) curves followed by interpretation.

**Results for the Angola survey**

The uppermost part of Figure 4 shows N-S changes in the electric field magnitudes for the Bandicoot receiver from the Angola survey (see Figure 2). The lowermost part of the figure displays a seismic section spatially oriented to allow for direct comparison with the electric field magnitude data.

By plotting the most likely propagation direction of the energy that will reach the receiver at a certain source-receiver offset, it is possible to obtain an understanding of the resulting changes in electric field magnitude and how these relate to the subsurface geology. The seismic section shows the presence of a lower channel complex, as well as a smaller upper complex. The southernmost limit of the upper channel complex fits well with a drop in the electric field when using a wave propagation angle of around 11 degrees (2.3 degrees in the figure as the scale is exaggerated vertically), which is the approximate critical angle for refraction. This may suggest that the channel complex is filled with hydrocarbons all the way to point where the electric field magnitudes drop to lower values. Uncertainties are related to the exact pick in the resulting electric field strength amplitude plot, and the true propagation of the electric field, which will, to some extent, depend on resistivity contrasts between layers in the subsurface.

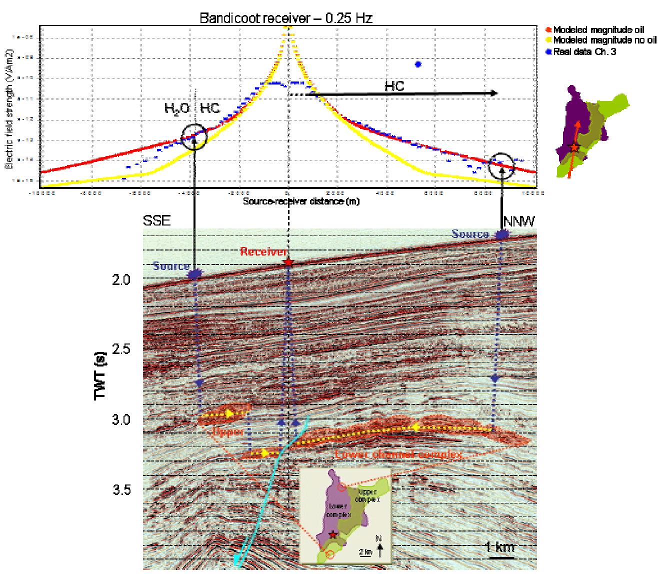



**Figure 4 -** Electric field measurements from the Bandicoot receiver compared with a seismic line for the same area. The extent of the channel complexes are shown with purple and green shaded areas. The sudden drop in electric field magnitude to the SSE at a source-receiver distance of 3.8 km (leftmost part of the section) corresponds to the limits of the upper channel complex. Since the channel complex extends beyond the measurements to the NNW, it is not possible to define the extents of possible hydrocarbon-filled layers in this direction.

The electric field data follows the modeled data for oil-filled reservoir towards the north. The seismic section shows the presence of the western channel complex beyond the limits of interpretable electric field data (around 5 kilometers north of the Bandicoot receiver). The data may thus indicate that the channel complex is hydrocarbon-filled within the limits of the electric field data for the Bandicoot receiver towards the north. The overall impression is consistent with the existing interpretation of distribution of upper and lower channel complexes as shown in the lower part of Figure 4.

Figure 5 shows the electric field data for the same Bandicoot receiver, but this time, the towing direction of the transmitting antenna was towards the west. Also here, the drop in the electric field amplitudes to the west of the receiver location fits well with the westernmost limits of the lower channel complex as interpreted from seismic data. Similarly, the drop in electric field magnitude data corresponds well to the easternmost limit of the channel complexes. Any uncertainties are related to the exact pick on the electric field magnitude diagram and potential erroneous interpretation of the distribution of channel sands.

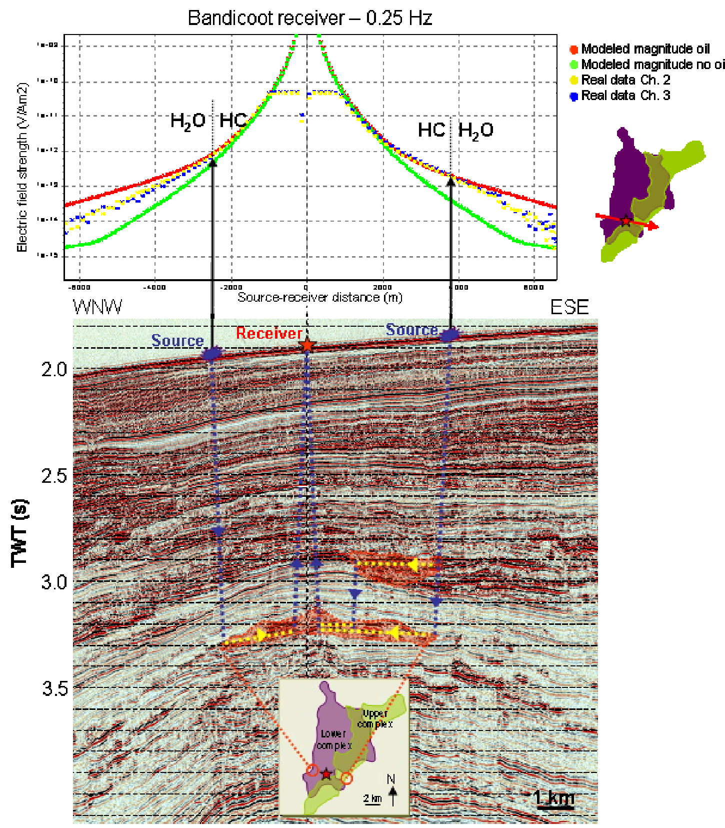
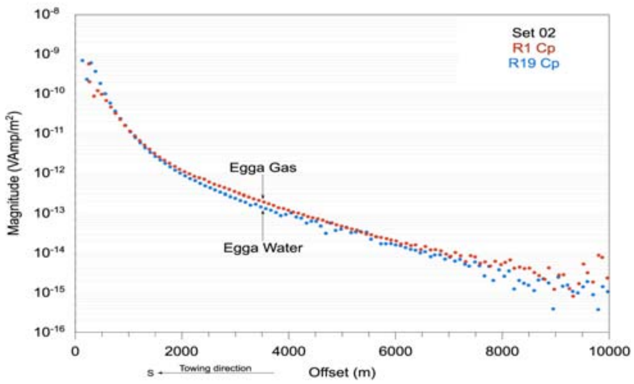



**Figure 5 -** Same as Figure 4, but in E-W direction.

### Results for the Ormen Lange survey

To identify possible MVO signatures related to gas from the Ormen Lange reservoir we have here chosen to compare MVO data from the two receivers that are most likely to record water and gas scenarios. Receiver R19 located adjacent to the dry well 6305/1-1 (Figure 3) is inferred to record water or "dry well" scenario, while the southernmost receiver (R1) on the N-S towline should record additional return signal from gas.

Comparison of MVO data from these two receivers (Figure 6) shows systematically higher magnitudes at offsets higher than 2 km for the receiver situated above Ormen Lange gas. Receiver R1 shows a marked increase in magnitudes starting around 1.5 km offset, with a maximum increase of ca. 40% relative to R19 at ca. 3-5 km offset. A 40% increase in magnitude is in accordance with 1D modelling results for gas relative to water scenarios, although the modelling results predict that

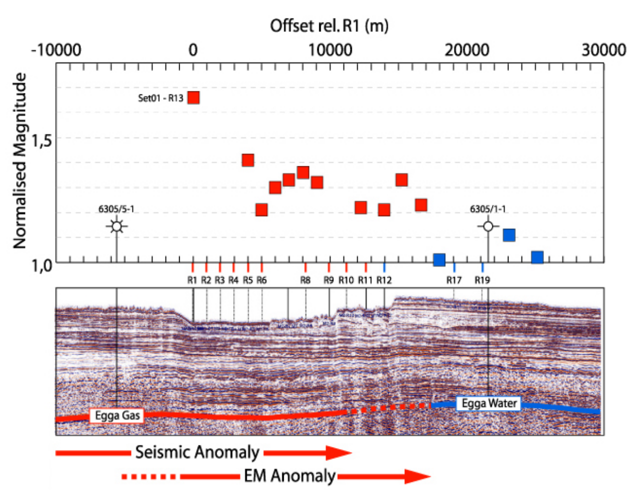



maximum magnitudes should occur at larger offsets.

**Figure 6 -** Comparison of MVO data for R1 and R19, located above gas and water, respectively. The electric fields are normalized by the source dipole moment, and the maximum polarization ellipse is calculated from the two orthogonal electrical channels.

To quantify differences in MVO signatures recorded along the two towlines we have normalised all MVO signatures by the MVO of the receiver situated above proven water (R19). Median filtered values of normalised magnitudes between 3.3 and 4.4 km offset for the N-S towline are shown in Figure 7, and display a step-wise variation in MVO signatures. Receivers located more than 4 km south of well 6305/1-1 show systematically 20 to 40% higher magnitudes. Remark that this shift is opposite to potential contributions from water depth variations. Similar MVO responses are also evident along the NE-SW towline. We interpret the observed variation in EM response recorded along the two towlines to reflect changing underground resistivity parameters. The approximate location of the change in EM response is close to the estimated boundaries of the Ormen Lange field as defined by seismic amplitude anomalies.

**Figure 7 -** Normalized MVO responses at 3.3 to 4.4km after median filtering and seismic amplitude anomalies




along the N-S towline (Figure 2). The normalized MVO responses are located at positions approximately 4km from the receivers.

## Conclusions

The analyses of EM data from the Angola survey show a clear correlation between high electric field measurements and hydrocarbon-bearing channel sands as interpreted from seismic data. The interpretation of electric field magnitude data from single receivers is also supported by pseudo-imaging the resistivity data using normalized radial electric fields at the seafloor for a given source-receiver range.

SBL over the Ormen Lange gas field reveals higher MVO for EM receivers above proven gas compared to EM receivers above proven water. The observed EM anomaly partially correlates with inferred seismic boundaries for Ormen Lange, although a direct link between the gas reservoir as interpreted from seismic data and the resistive layer responsible for the EM anomaly has not been established at present.

Final remark: emgs has patent applications in Brazil: PI 9913259.1, PI 0108016.4 and PI0113208.3.

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