3D CSEM for Hydrocarbon Exploration in the Barents Sea

P.T. Gabrielsen (EMGS), D.V. Shantsev* (EMGS) & S. Fanavoll (EMGS)

SUMMARY

Large multi-client 3D CSEM surveys have been acquired in the Barents Sea in 2008 and 2010. This data has been used by oil companies in Norwegian license application rounds to support their geological models and prospects. We show case examples where 3D resistivity models obtained by inverting CSEM data help locate areas of interest and update prospect risks. Despite the challenges often associated with the Barents Sea, such as a complex overburden and large resistivity anisotropy, the producing Snøhvit Field is imaged as a CSEM anomaly with the correct burial depth and lateral extension. This shows that CSEM data can be an important exploration tool in the Barents Sea.

Introduction

Marine controlled source electromagnetic (CSEM) surveying came into active use for hydrocarbon exploration during the last 10 years (Eidesmo et. al 2002, Ellingsrud et. al 2002, Constable 2010, Zhdanov 2010). In the conventional setup, low-frequency (0.1 – 10 Hz) electromagnetic fields are generated by a horizontal electric dipole source towed slightly above the seabed, and recorded by a line or grid of receivers deployed at the seafloor (Gabrielsen et. al 2009). The recorded fields carry information about the distribution of electrical resistivity in the subsurface. The CSEM measurements are especially efficient for detecting hydrocarbon prospects because (i) electrical resistivity of hydrocarbon-filled reservoirs is by orders of magnitude larger than that of brine-filled reservoirs, and (ii) thin and highly resistive hydrocarbon layers serve as a kind of waveguide for the propagating electromagnetic fields, leading to an anomalously strong response at large source – receiver offsets, see Figure 1.

Up to now, more than 500 CSEM surveys have been acquired around the globe in water depths ranging from ~40 to 5000 m. Applications of CSEM include lead generation in frontier regions, ranking and de-risking of prospects prior to drilling decisions, as well as locating bypassed reserves (Danielsen and Bekker 2011). A thorough statistical analysis of correlation between the magnitude of measured CSEM anomalies and the drilling success over a database of 86 wells (Hesthammer et al. 2010, Fanavoll et al. 2010) demonstrates that CSEM surveying can substantially reduce the drilling risks in oil and gas exploration. Recent announcements of large-scale multi-year CSEM acquisition programs in the Gulf of Mexico and offshore Brazil mark one more important milestone in the industrial adoption of the developing technology.

The Barents Sea was believed to be one of the most prospective areas for oil and gas exploration after the Snøhvit Field was discovered in the early eighties. However, since then the drilling success in the Norwegian sector has been low, see Figure 2. There have been only a handful of economic discoveries over the last three decades: Snøhvit and Goliat, along with the recent Skrugard and Norvarg. At the same time, we can see from the drilling statistics in Fig. 2 that the majority of wells in the area do have hydrocarbon shows. In fact, one of the largest geological risks in the region is the breach of the seal, which leaves seismic prospective areas with only traces of gas or oil. This implies that CSEM measurements, which are sensitive to the fluid content in the reservoir, can be an important supplement to seismic exploration in the Barents Sea. Indeed, all of the Snøhvit, Goliat, Skrugard and Norvarg discoveries show up as anomalies in CSEM data.
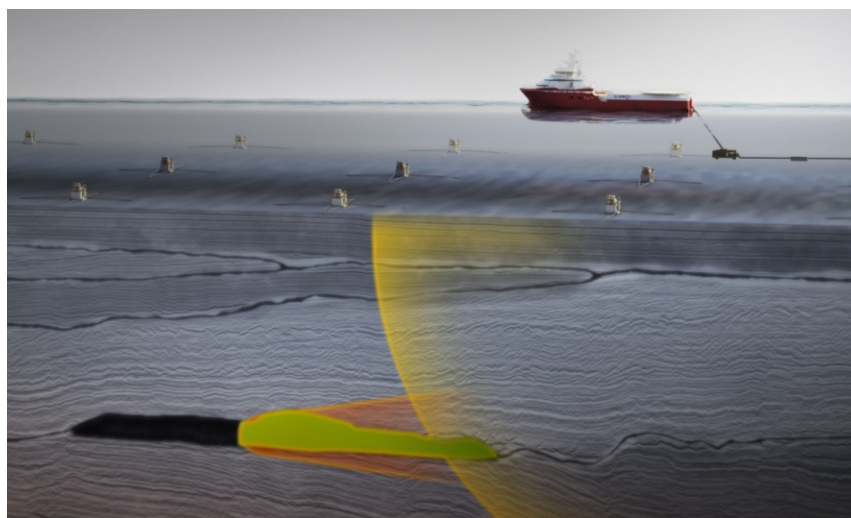

Figure 1 Illustration of the marine 3D CSEM method. Electromagnetic energy is emitted by a towed dipole source, propagates into the subsurface, interacts with highly resistive hydrocarbon plays, and is measured by a grid of seabed receivers.
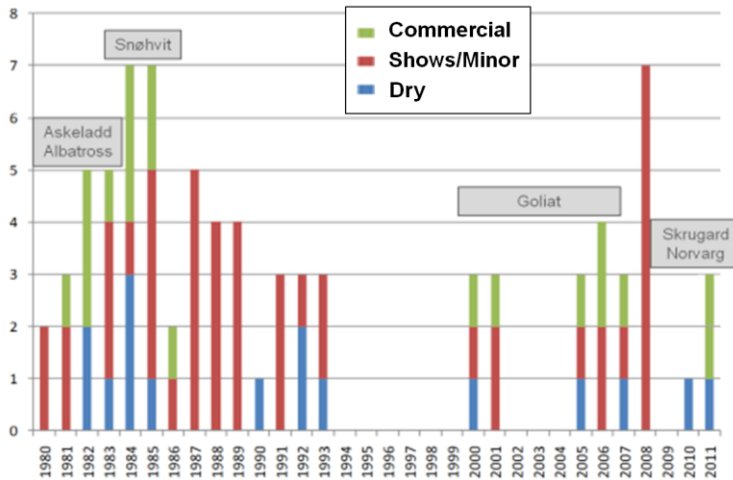
Figure 2
Drilling statistics in the Barents Sea prepared from NPD public data (npd.no). Since the first discovery in 1981 there have been few commercial discoveries despite the large number of wells with hydrocarbon shows. After the Skrugard and Norvarg discoveries in 2011, the interest in the area is growing again.

Barents Sea CSEM database

Today, there exists an extensive CSEM database over the Barents Sea as a result of EMGS multi-client campaigns in 2008 and 2010 (Figure 3). In total, 16 000 km^2 were covered during the two campaigns. All the data went through a thorough attribute analysis, allowing one to highlight the areas with high subsurface resistivity. In addition, data acquired in 2010 were 3D inverted to obtain 3D resistivity depth models. For Norwegian licensing rounds, oil companies used the CSEM data in their applications to support their geological models and to upgrade or downgrade their seismic prospects (Fanavoll et. al 2009). In the present paper we show examples from 3D multi-client surveys in the Barents Sea acquired in 2010.

All surveys in the Barents Sea CSEM campaigns were acquired with 3D geometry, i.e. the receivers were deployed in a grid, and the source was towed along multiple lines. It implies a significant increase in the amount of collected data as compared to 2D geometry, and in addition gives access to azimuth data. The advantage of having azimuth data available is that it provides good sensitivity to both thickness and resistivity of hydrocarbon layers (Constable and Weiss 2006). Furthermore, with azimuth data one is sensitive to both vertical and horizontal resistivity (Morten et al. 2010), which makes 3D acquisition especially important in regions with high electrical anisotropy, such as the Barents Sea.
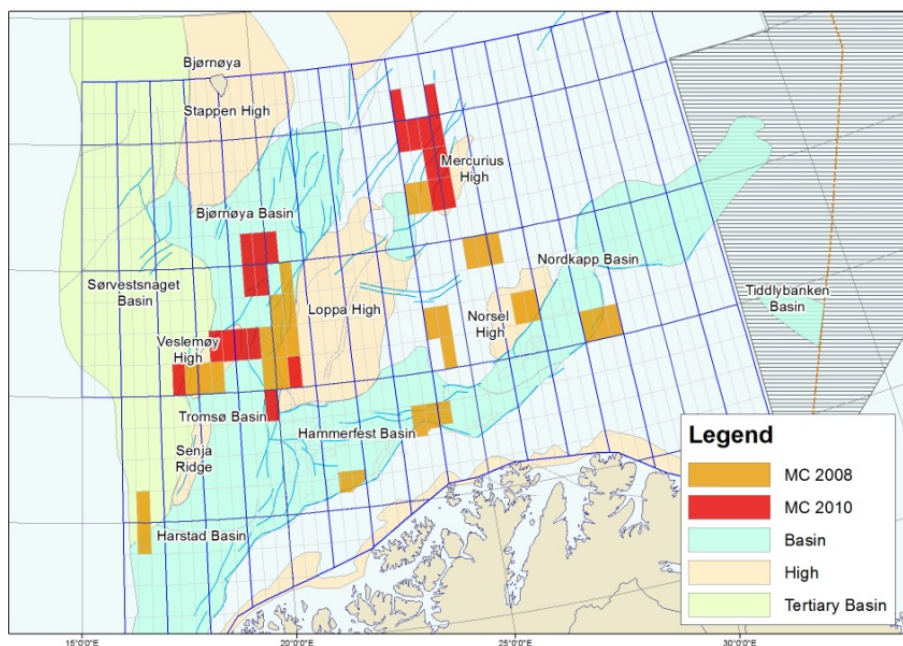

Figure 3
3D CSEM data in the western Barents Sea acquired within EMGS multi-client campaigns in 2008 and 2010.

Barents Sea case examples

Initial analysis of CSEM data can be performed on attribute maps, allowing one to highlight areas of interest. However, experience has shown that the Barents Sea is a challenging area when it comes to resistivity properties. In particular, high anisotropy and strong lateral changes in the shallow overburden have proven to be important issues to solve. If not handled properly, this can lead to misinterpretation of the results. 3D inversion of CSEM data, solving for both vertical and horizontal resistivity models, will account for anisotropy factors as well as lateral resistive changes in the earth.

Figure 4 shows an example depth slice of vertical resistivity obtained by 3D inversion over an area of approximately 850 km^2. The red areas indicate the lateral extent of the highly resistive subsurface. Such maps can guide the focus of the interpreter to the most prospective areas. The exploration history in the Barents Sea shows that seismic data alone cannot reveal the economic presence of hydrocarbons. Therefore, the additional information provided by resistivity maps, which are very sensitive to hydrocarbon saturation, can lower the associated risks.

3D inversion also makes it possible to directly integrate CSEM results with seismic depth sections as illustrated in Figure 5. This example shows a resistive anomaly close to a major fault. The resistivity information should be integrated with existing geological knowledge in order to get the best possible interpretation of the observed anomalies.
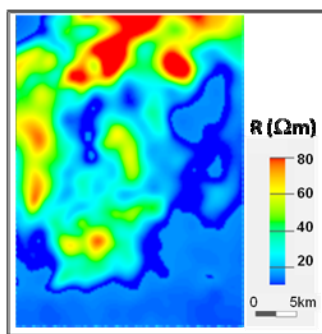

Figure 4
Results from 3D CSEM inversion showing a constant-depth slice covering one of the survey areas in the Barents Sea. The red color corresponds to anomalously high resistivity, which may indicate a hydrocarbon accumulation.
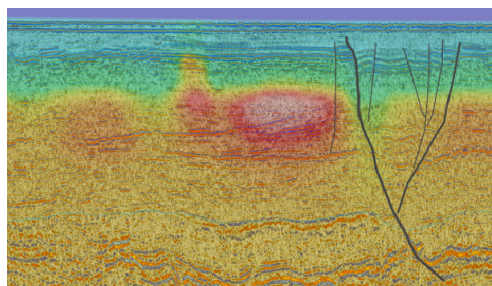

Figure 5
Vertical resistivity slice obtained from 3D CSEM inversion. The corresponding seismic section has been added on top. A resistive anomaly is seen close to a major fault. This example demonstrates the value of joint interpretation.

Using CSEM data from a number of surveys in the area together with seismic and well log data allows one to build a global resistivity geo-model for the western Barents Sea. This systematic approach makes it easier to separate regional trends from local anomalies. Application of this approach by Rocksource allowed them to perform detailed prospect ranking in a portfolio setting (Stefatos et al. 2011).

In 2010, a CSEM dataset was acquired over the Snøhvit Field for the EDDA consortium (3D Data Acquisition). This dataset is of special interest as the Snøhvit Field is a proven gas discovery now under production. It therefore serves as a valuable calibration point for the processing and interpretation of data from less explored acreage. The Snøhvit area shows the same challenges discussed earlier for the Barents Sea, i.e. strong anisotropy and lateral resistivity variations. The latter are mainly caused by shallow gas and fluid migration paths, but could also be due to variable thickness and resistivity of highly resistive layers in the Tertiary. In fact, initial analysis of the CSEM attributes was not consistent with the location of the Snøhvit Field, as these were significantly

influenced by variations in the overburden. In order to obtain a trustworthy distribution of the subsurface resistivity, one needs to 3D invert the CSEM data. Figure 6 shows a vertical resistivity depth slice at 2.4 km obtained with unconstrained anisotropic 3D inversion. It displays a pronounced resistivity anomaly (red) which based on available well logs relates to the area with the thickest gas column of the Snøhvit Field.
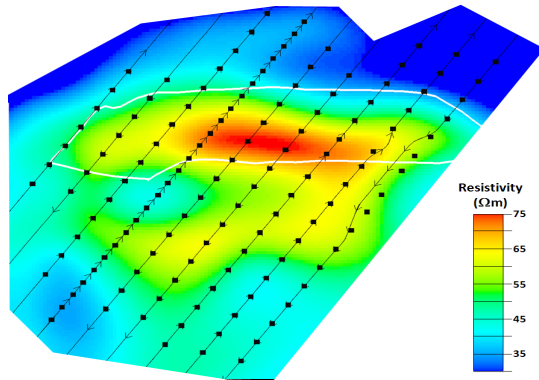

Figure 6
Depth slice of vertical resistivity distribution obtained by 3D inversion of CSEM data. The white polygon is the outline of Snøhvit gas field. The black lines and squares respectively represent tow-lines and receiver positions.

Acknowledgment

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