The impact of CSEM on exploration decisions and seismic: two case studies from the Barents Sea

Stein Fanavoll^{1*}, Pål T. Gabrielsen¹ and Svein Ellingsrud¹ provide an update on CSEM activity in the Barents Sea and argue that CSEM data can support seismic and help the industry make better decisions at different stages of exploration.

he past few years have seen heightened interest in hydrocarbon exploration in the Barents Sea, due to several recent discoveries and the opening up of 39,000 km² in the southeastern Barents Sea prior to the 23rd licensing round.

Skrugard and Havis (now referred to as 'Johan Castberg') on the Polheim sub-platform are both substantial oil discoveries as is the Norvarg gas discovery on the Bjarmeland platform in the northeastern Barents Sea and verified by well 7225/3-1.

Furthermore, the recent Wisting discovery and the significant quantities of light oil discovered have raised expectations not only for the surrounding areas but also for the entire Barents Sea. The other recent discoveries in Skrugard, Norvarg and Havis have also verified the existence of a large working petroleum system.

Yet, up until now, more than 100 exploration wells have been drilled on the Norwegian side with most of these classified as dry or as non-commercial discoveries. To date, only one field is in production (Snohvit) and one undergoing development



Figure 1 An overview of EM acquisition in the Barents Sea. The case study examples are shown 1-2; red rectangles indicate blocks where CSEM was acquired.

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Marine Seismic

(Goliat). The last few months have also seen a number of disappointments with Statoil unable to find commercial quantities during its drilling campaign in the Hoop area.

Historically, exploration wells in the Barents Sea have been drilled on the basis of seismic data and geologic structures. Since 2008, however, EMGS has begun acquiring 3D controlled-source electromagnetic (CSEM) data. Over 40,000 km² of multi-client data has been acquired to date and is being used as an interpretation tool alongside seismic.

In recent discoveries, the resistivity responses inverted from the CSEM data have also provided a close match to the resource volumes announced by the operators (Gabrielsen et al., 2013). CSEM has also been acquired over several other wells both before and after drilling with the results in accordance with the well data.

Using this data and two case studies, this article will demonstrate how CSEM data can help oil companies to improve their decisions throughout the exploration workflow in regard to licence applications, prospect ranking, drill-drop decisions and farm-in-farm-out decisions.

Using CSEM in the Barents Sea

CSEM – method, survey design and inversion methodology 3D Controlled Source Electromagnetic (CSEM) data maps resistive anomalies in the subsurface, where the larger the resistive body, the greater the response. This is due to the electrical resistivity of the sub-surface being a physical property that strongly correlates with the fluid content and saturation of hydrocarbon reservoirs.

The resistivity contrast between the background geology and hydrocarbon reservoirs is often of one or more orders of magnitude, making resistivity very suitable as a hydrocarbon indicator when measured from the seafloor (Eidesmo et al., 2002; Ellingsrud et al., 2002).

All multi-client CSEM data acquired in the Barents Sea was 3D wide-azimuth data. Staggered grids of receivers (all with multi-component electric and magnetic sensors: Hx, Hy, Ex, and Ey) along with a 3 km receiver and line distance, were acquired. With an average block size in the Barents Sea of 300 km², a typical receiver grid of approximately 120 receivers will cover three blocks at a time.

In the case examples, the CSEM data was inverted into 3D earth resistivity models. The inversion used a 3D finite-difference time-domain modelling code and a Broyden-Fletcher-Goldfarb-Shanno algorithm for the model update (Maaø, 2007; Zach et al., 2008; Mittet, 2010).

The end results from the 3D inversion are earth model cubes of horizontal and vertical resistivity, displayed by using a colour scale where red represents high resistivity and blue/ purple low resistivity.

The extensive coverage with CSEM data not only gives a regional overview of the resistivity distribution but also maps

out resistivity anomalies or thin resistors that could identify hydrocarbon-filled traps. CSEM is also sensitive to all kinds of thin resistors as well as charged stratigraphic traps and lithologies with higher resistivity than the surrounding geology.

CSEM in the Barents Sea

Most of the wells in the Barents Sea are concentrated in the southwest, in the Hammerfest Basin, the Loppa High, and the Polheim subplatform. Here, the geology is variable, ranging from Tertiary Basins in the west, Jurassic Basins (e.g., Hammerfest Basin) in the middle part, and Triassic and Permian platforms (e.g., Bjarmeland platform and Finnmark platform, respectively) in the east.

Major uncertainties remain, however, in regard to the prospectivity of some areas. This is related to models for reservoir rocks, especially in the Cretaceous and Triassic, where several possible play models are not confirmed by earlier drilling. New ideas and technologies are therefore needed to increase future success rates.

Between 2008 and 2013, EMGS built up a substantial EM multi-client library, as shown in Figure 1. Here, the red rectangles illustrate acquired blocks and the case study examples are shown -1 and 2.

As part of the multi-client campaign, approximately 20 well locations were covered by 3D CSEM with some drilled prior to acquisition and others after. Out of these locations, in only three were the results from CSEM inconclusive, mainly due to a lack of sensitivity to the target or due to a full 3D inversion not being carried out.

The apparent anisotropy map in Figure 1 also shows numerous resistive anomalies that have not yet been drilled with the key question being what these undrilled anomalies represent.

There are a number of different variables at play here. Stratigraphic setting plays a role in assessing a CSEM anomaly with settings varying from Triassic to Tertiary and from 1 to 100 Ω m (Fanavoll et al., 2012). These factors must be carefully assessed in an integrated interpretation procedure with it unlikely that all anomalies represent hydrocarbon accumulations yet at the same time it being equally unlikely that none of them represent hydrocarbons.

Case study 1: The Hoop area and different play models

The first case study from the Hoop area illustrates how CSEM supports play models and generates valuable information for licence applications.

In the past three licensing rounds in the Barents Sea, a total of 15 blocks were awarded in an area known as the Hoop Fault Complex, a dominating structural element on the Bjarmeland platform. Substantial volumes of 3D seismic



Figure 2 A 3D CSEM inversion with vertical resistivity on the Wisting discovery as displayed on a seismic line. The black line indicates the well location. CSEM results indicate hydrocarbons in two fault blocks in the North Eastern part of the structure. Seismic data is courtesy of TGS.

and 3D CSEM were acquired in this area during 2013 as can be seen in Figure 1.

While there was no gas discovery in this area until the Norvarg announcement in 2011, the majority of exploration wells exhibited minor amounts of hydrocarbons, indicating that there is a working hydrocarbon system in the area.

One of the targets south of Hoop has been in the Triassic succession, yet there has been a lack of high-quality reservoir sands and sufficient volumes. In this example, we illustrate how a new play model can be upgraded based on the integration of CSEM and seismic.

One key prospect in the Hoop is the Wisting prospect in Lower- to Middle Jurassic reservoir rocks. In September 2013 the Austrian oil company OMV announced an oil discovery in licence PL537 on the Wisting prospect with an oil column of 50-60 m and potentially recoverable reserves of 60-130 MMboe.

The discovery was associated with a significant EM anomaly as can be see in Figure 2 where the CSEM results indicate the presence of hydrocarbons in two fault blocks in the northeastern part of the larger structure, whereas the southwestern part seems to be dry. There is also a high correlation between the seismic and CSEM results with the CSEM anomaly conforming to structure and matching the well in depth and lateral extent with the seismic amplitude anomaly.

The Wisting discovery – where light oil was discovered – also demonstrates that even with a highly resistive background, oil can be seen. Once background resistivity is viewed as less of a hindrance, explorationists can look to new plays on the Bjarmeland platform and elsewhere.

In the same licence, a second well targeting a deeper stratigraphic level was subsequently drilled, deliberately avoiding any shallow CSEM anomaly. However, this well was dry, matching the CSEM results when taking into account the reduced sensitivity to the deeper target.

The Wisting discovery also opens up additional oil discoveries in the area with the CSEM data revealing large anomalies that should be further investigated.

Recently, for example, some have argued the case for an increased focus on a different depositional environment in the upper Triassic that may give rise to larger volumes and better reservoir development (Kjølhamar, 2012). This idea is supported by the inversion results from the CSEM data, where CSEM anomalies are present in the area where these Triassic reservoirs are assumed to be present (Fanavoll et al., 2013). This also raises fundamental questions as to which play models should be pursued: the resistive Triassic target or the relatively conductive Jurassic target?

When studying the map for two of the blocks in the area (see Figure 3), for example, it can be seen that there is little correlation between the shallow Jurassic structure and CSEM anomalies. This suggests that if the anomalies are caused by hydrocarbons, the traps will partly need stratigraphic closure and/or fault seal. In addition, these resistive anomalies seem to represent a deeper source for resistivity than the Wisting discovery.

Furthermore, the structural closure in the south is likely to be higher risk because there is no resistive anomaly associated with the structure. If one believes it contains hydrocarbons, the reservoir resistivity has to be much lower than for Wisting given the structure's low-resistivity measurements.

Making the right decisions between Triassic and Jurassic targets will be of enormous value to the industry, especially as the same question applies for many of the other Hoop area licences.

An integrated approach that includes CSEM, seismic AVO and inversion, well results, and other geologic information will be crucial in achieving this.





Figure 3 A structure map and CSEM results on two blocks Northwest of the Wisting discovery. The depth structure map (left) indicates a large, shallow structural closure (contour interval 50 m), whereas the CSEM anisotropy anomaly map (right) shows resistive anomalies in the northern part.





Case study 2: The Polheim sub-platform and Bjørnøyrenna Fault Complex – looking for analogs

The second case study shows how drilled targets are correctly predicted by CSEM data and how CSEM provides crucial input to prospect ranking and drill-or-drop decisions. Here, several new leads are identified based on combined CSEM and seismic interpretation.

The Polheim sub-platform and the Bjørnøyrenna Fault Complex separate the Loppa High to the east from the Bjørnøya Basin to the west. Skrugard and Havis were discovered on the Polheim sub-platform in 2011 and 2012.

The Skrugard discovery is reported to have a double flat spot on the seismic data (gas-oil and oil-water contacts) and the Havis discovery one flat spot (published in presentations by Statoil). The two oil and gas discoveries have boosted interest in the Barents Sea because they proved oil in the Middle to Lower Jurassic play.

It has previously been demonstrated (Gabrielsen et al., 2013; Nguyen et al., 2013) that Skrugard and Havis are identified with CSEM data due to resistive anomalies.

Figure 4 shows six wells in the area where CSEM provided a correct prediction for the Lower to Middle Jurassic and Lower Cretaceous plays along the Bjørnøyrenna Fault Complex.

Three of the wells are significant discoveries (Havis 7220/7-1, Skrugard 7220/8-1, and 7220/5-1) and three wells

are non-commercial or dry (7219/9-1, Salina 7220/10-1, and Nunatak 7220/5-2), demonstrating CSEM's ability to distinguish between commercial and non-commercial hydrocarbon-bearing reservoirs.

The last well drilled (Skavl) also revealed oil and gas gas predicted by CSEM, and although it was a rather small discovery, it will provide valuable additional reserves to the development of Johan Castberg. Although Johan Castberg has confirmed an oil play in this part of the Barents Sea, there is still considerable risk in basing drilling decisions on seismic defined structures and AVO responses alone.

The main play risk is associated with Cenozoic uplift and erosion. This can cause expansion of gas resulting in the spilling of earlier trapped oil and reduced overburden and leading to reactivation of faults and breaching of seals. Perfect looking reservoirs on seismic with structural closure and AVO responses can in fact be blown traps with only low hydrocarbon saturation.

The Upper Jurassic-Lower Cretaceous play is also high risk with respect to reservoir presence and quality. Combining seismic data with CSEM data therefore considerably reduces risk as a resistive anomaly associated with a seismic-defined structure or AVO response can separate high hydrocarbon-saturated reservoirs from low-hydrocarbon-saturated reservoirs.

The main pitfall with a resistive anomaly in this area is probably mature source rock in the Upper Jurassic and possibly the Cretaceous that show high resistivity (20–40 Ω m) from other wells (e.g., well 7219/8-1). In addition, a well farther north in the Fingerdjupet area (7321/7-1) penetrates what we interpret to be cemented sandstone with high resistivity (60 Ω m). However, these resistive anomalies are much lower than what is shown from the Skrugard well that has a peak value above 1000 Ω m (Løseth et al., 2013).

Figure 5 shows three leads on the Polheim sub-platform along the Bjørnøyrenna Fault Complex where multi-client 3D CSEM and 2D seismic data are integrated. Two of the leads are interpreted to be analogs with the Lower to Middle Jurassic reservoirs penetrated by the wells (Figure 5a and 5b).

The third lead is located east of well 7219/9-1 (Figures 4 and 5c) and is interpreted to be associated with the Lower Cretaceous–Upper Jurassic section.

Through the integration of geophysical, seismic and CSEM data (see Figure 5a), an interpretation of the deltaic Lower to Middle Jurassic sand is shown in yellow and Lower Cretaceous fans are shown in green.

Structural closure is identified for the deltaic sand whereas the Lower Cretaceous fans need a combined structural-stratigraphic trap. CSEM data (anomalous vertical resistivity) overlays the seismic data to the right in Figure 5a. This CSEM attribute emphasizes anomalous resistivity values and is calculated by subtracting a background resistivity model from the vertical resistivity model obtained from inversion (Gabrielsen et al., 2013).

A value close to zero is interpreted to be part of the background resistivity trend, whereas higher values indicate thin resistors. Two anomalous resistors are observed (lead Eivind and Eivind2 U.), which can be linked to the Lower to Middle Jurassic and Lower Cretaceous reservoirs, respectively.

In Figure 5b, a possible flat spot is identified on 2D seismic data in a rotated fault block. The flat spot is interpreted



Figure 5 Three leads on the Polheim subplatform along the Bjørnøyrenna Fault Complex where multi-client 3D CSEM and 2D seismic data are integrated.

Marine Seismic

to be in the Middle Jurassic. The CSEM attribute apparent anisotropy overlays the seismic data to the right. Apparent anisotropy is calculated by dividing the inverted vertical resistivity model by the horizontal resistivity model.

This attribute emphasizes thin resistors because thin resistors are only imaged in the vertical resistivity model and not in the horizontal resistivity model in an unconstrained inversion (Alcocer et al., 2013; Gabrielsen et al., 2013). The apparent anisotropy shows an anomaly located in the same position as the flat spot on the seismic.

The last example is within Upper Jurassic to Lower Cretaceous syn-rift sediments southeast of the dry well 7219/9-1 (Figures 4 and 5c). Sand is predicted to be present in the syn-rift sediments by seismic inversion (Carstens, 2009; Gabrielsen, 1994) and a vertical resistivity anomaly is identified to be located in these syn-rift sediments (Figures 4 and 5c right). The depth of this resistive anomaly is uncertain.

The two first leads in Figure 5 also show resistive anomalies in Lower to Middle Jurassic sands located in a rotated fault block. One of them also shows indications of a flat spot on the 2D seismic data. These leads are interesting because they can be regarded as analogs to the Havis and Skrugard discoveries.

The result of combining CSEM with marine seismic is the identification of a number of new leads and vital information for prospect ranking and drill-or-drop decisions.

Conclusion

While exploration history in the Barents Sea cannot be considered successful to date, the emergence of CSEM data as a complementary tool to seismic acquisition raises reasons for optimism, especially as there are large unexplored areas (in the range of 100,000 km²).

With the coverage of 3D multi-client CSEM data allowing for the calibration of more than 20 wells – some drilled before and some after CSEM acquisition – we argue that for all these wells CSEM accurately predicted the outcome of drilling. This knowledge can in turn be used to better de-risk new prospects.

For screening purposes, the use of a CSEM anomaly map can also make exploration more efficient by limiting the area of interest and focusing interpretation within the anomalous area. In a licence application phase, this will aid the explorationist in making better decisions.

Based on this convincing track record to date in the Barents Sea, CSEM data – when interpreted alongside other geophysical and geologic information – can have a crucial influence on exploration decisions – where to and where not to drill, licence applications, prospect ranking, drill-drop decisions, and farm-in-farm-out decisions.

Acknowledgments

The authors would like to thank the Society of Exploration Geophysicists and Interpretation for permission to republish some of the material in this article (found in Interpretation, 'CSEM as A Tool for Better Exploration Decisions', August 2014).

Some examples are also taken from the joint project between EMGS and Multi-Client Geophysical ASA for seismic and CSEM integration.

We would also like to thank our colleague V. Furuholt for creating some of the maps used in the article and TGS for illustrations and data from the Wisting discovery.

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