Integrated interpretation of a CSEM anomaly on the Nordland Ridge, Norwegian Continental Shelf

Stein Fanavoll, Pål T. Gabrielsen, EMGS ASA*

Summary

In 2011, a 3D CSEM survey was conducted in the Norwegian Sea, covering some discoveries and prospects. In this paper, an analysis of the results from this survey is presented. Through a thorough processing workflow, a distinct anomaly has been visualized from 3D anisotropic inversion. A number of possible explanations for this anomaly are evaluated, such as leaked gas, salt, anisotropic layers and hydrocarbon filled reservoir, and the likelihood of each explanation is assessed. In a drilling decision process, such assessments can aid the asset teams to increase the success rate in exploration drilling.

Introduction

Marine controlled-source electromagnetic (CSEM) surveying is mainly used for hydrocarbon exploration where an oil or gas reservoir has an anomalously high resistivity compared with its surroundings (Eidesmo et al. 2002, Ellingsrud et al. 2002).

It is well known that a resistive anomaly can be caused by different types of sources and not only a hydrocarbon reservoir. Lithologies such as salt, carbonates and shales can create resistive anomalies. Another factor is that CSEM surveying is a low-frequency method and therefore provides low-resolution results. Although EM inversion aims to place an anomaly at the correct depth, there are always uncertainties associated with depth estimates. Furthermore, inversion results are smeared vertically, even though the source for the anomaly might be a thin resistor, for example, a hydrocarbon reservoir. Therefore, if a resistive anomaly is confirmed by processing CSEM data, it is important to interpret the results alongside the other available geophysical data.

Throughout the fairly short history of CSEM as an exploration tool, there are numerous examples of EM results being ignored due to lack of understanding of how to interpret the results. This is mainly due to the fact that there are only few people with the sufficient understanding of EM combined with a sound petroleum geology background. The main objective of this paper is to demonstrate how the integration of EM with other geophysical data can be used to evaluate different geological models, which, in turn, could influence drilling decisions. It is important to mention that the final conclusion must be made by the asset teams and decision makers. In this paper, we do therefore not draw any firm conclusion as to which explanation is the most likely.

The 3D Data Acquisition (EDDA) consortium was established in 2010 to provide the industry with state-of-the-art 3D EM datasets. The EDDA consortium has acquired two 3D datasets: one covering a discovery and some prospects in the Norwegian Sea; the other over a producing field in the Barents Sea. In this paper, we interpret results from the Norwegian Sea CSEM data to give feasible qualitative explanations for the observed EM responses.

Data

In 2010, a 3D dataset was acquired over parts of PL559, which is operated by Rocksource (Figure 1). The survey comprised 137 receivers along eight source-towing lines. The receivers also recorded marine magneto-telluric (MMT) data while the controlled source was inactive. In addition, several well logs, two 3D seismic surveys and the outline of the Linerle and Falk discoveries were available (Figure 1). The position of a new well drilled by the license (Hesthammer et al., 2011) after acquisition of EM data is shown in Figure 1. The well was dry, but was drilled outside the main anomaly, and cannot be regarded as an EM-driven drilling decision. The analysis here was not part of the basis for the drilling decision.

Our interpretation is based on the results from an integrated processing workflow, which includes comparison of attributes (for example normalized magnitude), and 2.5D and 3D inversion results. A robust starting model for 3D CSEM inversion is established through analysis of the available information, including CSEM, MMT, well-log and seismic data. Further, 3D post-inversion modeling provides sensitivity with respect to target depth. At every stage of the data analysis, a strong and consistent anomaly is apparent and the observations support a thin resistor creating the anomaly.

To make an interpretation, the EM inversion results are loaded onto a workstation where they can be co-rendered with seismic and well data. Figure 2 shows 3D anisotropic inversion with depth-converted seismic data and interpreted horizons and faults. The anomaly seems to be located in the Triassic and is laterally limited by faults in the west and a Triassic horizon in the east. In Figure 2, the anomaly outline is drawn where the color goes from orange to yellow. The dip of the Triassic layers is approximately 10°.

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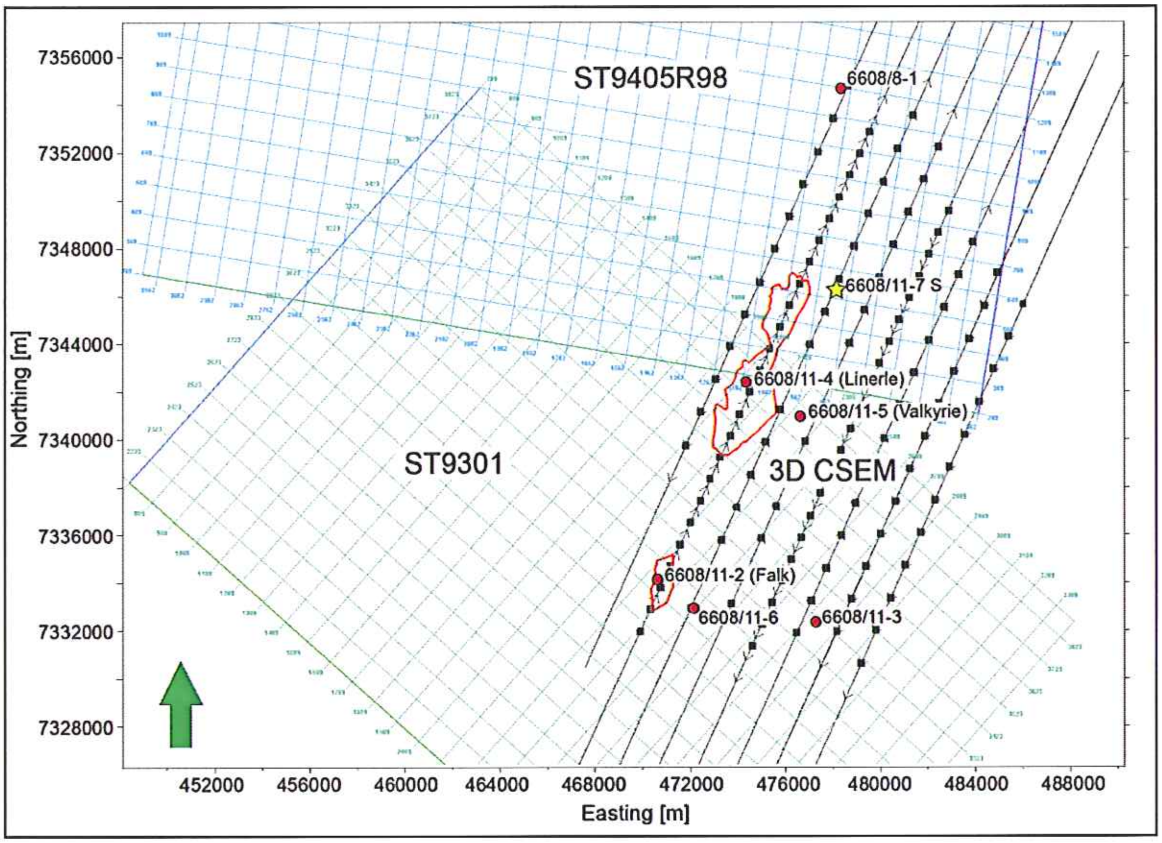

Figure 1: Coverage of the EM survey and the 3D seismic (ST9405R98 and ST9301) data, and selected wells (red dots). The yellow star shows the well drilled in 2011.

Interpretation

As we were confident during the processing phase that the anomaly is a consequence of a local increase in resistivity that is significant in relation to the surrounding sediments, the next step was to evaluate possible explanations for the anomaly.
The interpretation study offers some possible explanations for the CSEM anomaly:

a) Above the base Cretaceous unconformity, a Paleocene horizon (the Tare formation) exhibits increased seismic amplitudes over the area of anomaly, which could be caused by gas content. These seismic amplitudes do not map to the measured anomaly (Figure 3a). Although the seismic feature might be caused by gas leakage, this is unlikely to be the major source of the EM anomaly. However, amplitude versus offset analysis, which would normally be part of the workflow, was not carried out in this work.

b) In a few wells on the Nordland ridge, two Triassic anhydrite intervals have been penetrated. These can be interpreted on seismic images over the entire Trondelag Platform (~40,000 km2). However, in the wells, the resistivity and the thickness of these intervals are insufficient to explain the measured anomaly (approximately 30 m, with an average resistivity less than 10 Ωm). A local development of thicker, pure salt layers has to be inferred to explain the anomaly. The seismic expression of the anhydrite layers in the study area can be followed up-dip from the location of the anomaly to a truncation point further east (Figure 3b). Selecting the salt model as the most likely explanation requires evidence for a much more resistive salt interval at the location of the anomaly. No clear evidence of this is seen in the seismic data available to the project.

c) Anisotropic layers are known to create increased background responses, and sensitivity modeling shows that the anomaly itself could be created by a strongly anisotropic interval. There can be many reasons for electrical anisotropy (Ellis et al., 2010),

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but discussing this is beyond the scope of this paper. Looking at a seismic line across the anomaly and another north of the anomaly shows they have the same stratigraphic and structural expression (Figure 3c). The crucial question in order for anisotropy to be a plausible explanation for the observed anomaly is how anisotropy can change rapidly between such similar areas. As of today, no such changes have been scientifically documented.

d) The key issues for a hydrocarbon model in the area are the presence of a reservoir and a migration route for hydrocarbons. Possible reservoirs associated with the anomaly could be either Triassic grey/red beds or Upper Jurassic/Lower Cretaceous basal sands. Neither of these reservoir models is sufficiently proven by wells in the area. The depth uncertainty of the resistor is analyzed through post-inversion modeling. Comparing two different models, one at 1500 m (the hydrocarbon model), the other at 2000 m (the salt model, discussed above), the misfit between synthetic and real data is lowest for the shallower model with a resistor just below the base Cretaceous unconformity. This gives preference to the hydrocarbon model. Migration is the other factor crucial to the presence of hydrocarbons. It has been hard to understand how hydrocarbons could migrate into the prospect without leaving traces in the drilled prospect (Figure 2). However, hydrocarbon migration is one of the least understood subsurface processes, and we have seen no conclusive evidence ruling out migration into the area in question.

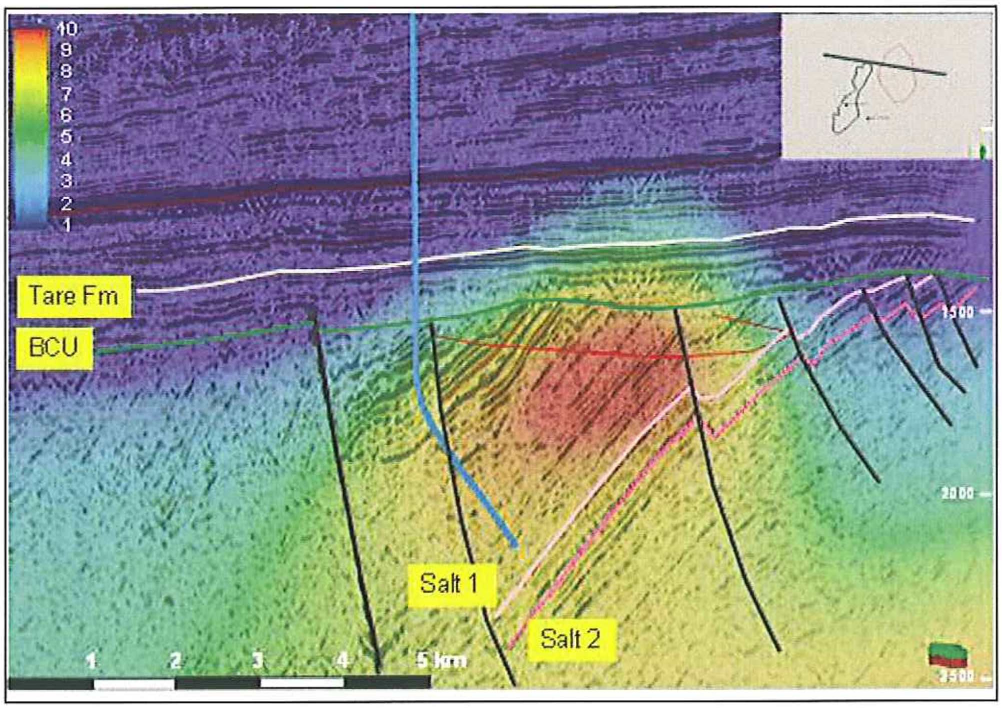

Figure 2: Results of the 3D inversion, vertical resistivity co-rendered with seismic data. Faults (black lines), inferred salt layers, key horizons (the Tare formation and the base Cretaceous unconformity) and trace of the new well (blue line) are indicated. The positions of the section (black solid line), the anomaly outline (red circle) and the Linerle discovery (black polygon) are given in upper right map.

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Discussion

Several interpretations have been suggested to explain the observed resistive anomaly. However, none of these models fully explains the anomaly unless some unknown effects are assumed. It is important to note that our analysis does not completely rule out any of the suggested explanations. Deciding which model to choose as the basis for a potential drilling decision must be the result of extensive analysis of the CSEM data and the geologic setting in the area. For instance entering the CSEM results into a formal risking and evaluation scheme will prove to be a useful tool in this assessment. By doing so, one can evaluate the expected value (EV) of the prospect in light of the EM results.
A drilling decision should be based on a thorough assessment of the different models. If the hydrocarbon model was evaluated as being sufficiently probable compared with other models, this would favor the decision to drill at the location of the CSEM anomaly.

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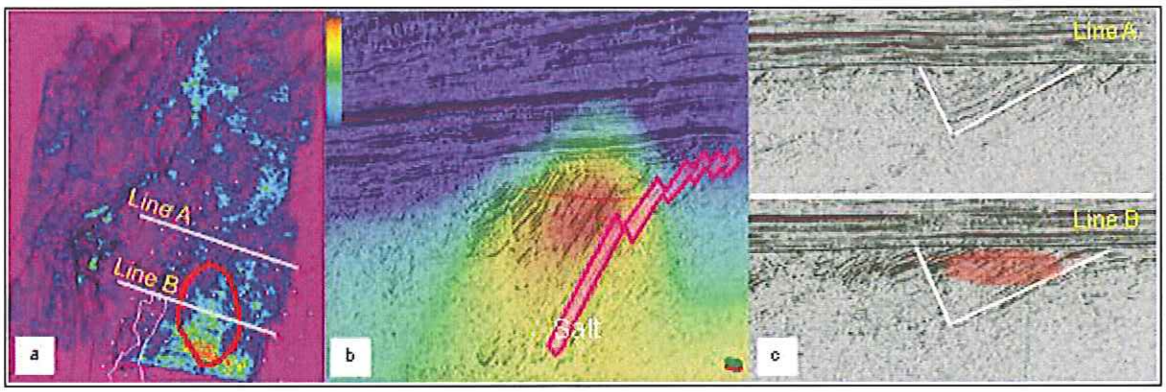

Figure 3: Possible models to explain the observed anomaly. a) The seismic amplitude anomaly of the Tare formation is seen to not coincide with the EM anomaly (red outline). b) The salt layer extends outside the anomaly. c) Two similar structural and stratigraphic elements must show different anisotropies to explain the anomaly. The location of the two lines is shown on Figure 3a.

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REFERENCES

Eidesmo, T., S. Ellingsrud, L. M. MacGregor, S. Constable, M. C. Sinha, S. Johansen, F. N. Kong, and H. Westerdahl, 2002, Sea bed logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas: First Break, **20**, 144–152.

Ellingsrud, S., T. Eidesmo, S. Johansen, M. C. Sinha, L. M. MacGregor, and S. Constable, 2002, Remote sensing of hydrocarbon layers by seabed logging — SBL: Results from a cruise offshore Angola: The Leading Edge, **21**, 972–982.

Ellis, M., M. Sinha, and R. Parr, 2010, Role of fine-scale layering and grain alignment in the electrical anisotropy of marine sediments: First Break, **28,** no. 10, 49–57.

Hesthammer, J., J. I. Rykkelid, S. Sperrevik, and D. Cumming, 2011, Use of CSEM data to aid a revised interpretation from the Norwegian Sea: First Break, **29**, no. 9, 57–66.