Multi-measurement integration – a case study from the Barents Sea

Ivan Guerra1*, Federico Ceci1, Fabio Miotti1, Andrea Lovatini1, Graham Milne2, Mehdi Paydayesh2, Margaret Leathard2 and Ajai Sharma2 describe the processing, modeling and integration of 3D CSEM data with high resolution 3D seismic data and inversion, to provide a better understanding of geological structures that may represent prospective targets for hydrocarbon exploration and development in the Barents Sea.

Oil exploration in the Barents Sea began in the 1970s, but exploration and production in the region has increased significantly since 2002. This was when Statoil obtained approval from the Norwegian government for its plans to develop the Snohvit gas field, which produces from Lower to Middle Jurassic sandstones. Several other oil and gas fields have been discovered in the area, stimulating further exploration and development.

Numerous geophysical and geologic studies have been performed in the Barents Sea to improve the understanding of play potential and economic viability of hydrocarbon production in the area. Further work is needed, particularly to evaluate prospects in clastic sediments above the Base Cretaceous Unconformity (BCU) that are currently less well known but are potentially as productive as the proven Jurassic and Triassic reservoirs. Since 2008, WesternGeco has acquired and processed – including depth imaging – high resolution 3D seismic data in the Barents Sea on a multi-client basis. Meanwhile, EMGS has acquired an extensive programme of 3D controlled source electromagnetic (CSEM) data in the area, also on a multi-client basis. Within the framework of a collaborative joint agreement between the two companies, 3D seismic data and 3D CSEM data from part of the West Loppa area (Figure 1) have been integrated with the objective of identifying and reducing uncertainty about potential prospects.

Seismic investigations give clear indication of at least two active petroleum systems in the study area, while resistive anomalies concentrated in certain portions of the sedimentary sequences could indicate the presence of hydrocarbon fluids, which normally increase the bulk resistivity of a rock. These two aspects have been analyzed in an integrated way on a high resistivity and seismic anomaly located in the Cretaceous to Oligocene sedimentary sequence. In 2012, parts of the 3D CSEM data were processed and inverted independently by the two companies. The resulting models, which were very similar, confirmed the presence of strong resistive features of interest both in the Triassic-Jurassic sequence and in the Cretaceous sediments. In parallel, seismic inversion was performed to derive 3D acoustic impedance (AI), Poisson’s ratio, and density models. These were subsequently input, together with the resistivity models produced from the CSEM inversion, to a petrophysical joint inversion to derive saturation and porosity distribution. This article focuses on the anomaly observed in the Cretaceous sequence.

Figure 1 Location of the West Loppa study area within the WesternGeco seismic survey. The green polygon represents the area covered by the EMGS CSEM survey.

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documented by Fanavoll et al. (2012) and Gabrielsen et al. (2013). Hydrocarbon occurrence in Cretaceous sequences is documented on the top of many Jurassic plays (e.g. Seldal, 2005) but the volumes of oil and gas in place has, to date, been considered too low and exploitation has been judged uneconomical.

Method

The analysis carried out in this project exploits two different hydrocarbon exploration technologies, namely CSEM and seismic inversion. These techniques belong to the electromagnetic and elastic domain respectively, and their integration allows recovering valuable complementary information to assess the nature of the seismic and resistivity anomalies. This integrated approach reduces uncertainty in the results and consequently provides a more reliable final model.

CSEM data acquisition

For this study, the marine CSEM data were acquired by deploying a series of receivers on the seafloor that measured both the horizontal electric and magnetic field components. An electromagnetic (EM) transmitter was towed by a vessel 30 m above the mud line to illuminate the receivers. Three lines of receivers were recording for each transmitter tow-line, resulting in inline and azimuth data. The azimuth data has a maximum broadside offset of 3 km. The transmitter was a horizontal electric dipole that transmitted a square wave-like signal with energy in the frequency range 0.1–10 Hz. EM fields measured by the receivers are typically dominated by a signal that has followed a path of diffusion into the seafloor and then through the subsurface. The signal therefore carries information about the resistivity of structures at depth. The recorded fields were processed into the frequency domain to obtain amplitude-versus-offset and phase-versus-offset data. The frequency domain data was then inverted to obtain an anisotropic 3D resistivity model of the subsurface.

CSEM data processing

The CSEM dataset went through a workflow that included data masking and pre-conditioning, qualitative data imaging, 1D, 2.5D, and 3D anisotropic modelling (Alumbough et al., 2006; Mackie and Watts, 2007; Lovatini et al. 2009; and De Stefano et al., 2011). The workflow, which focused on the horizontal electric field, was applied both to inline and broadside data. All available transmitter–receiver combinations (soundings) were analyzed to identify possible outliers and assess the overall quality of the dataset. The frequency content, which was in the range 0.2–3.2 Hz, underwent comprehensive quality control procedures.

The fields were rotated to the transmission direction, whereby Ex is the electric field in the direction of transmission and Ey is the field in the perpendicular direction. The dataset

Geologic setting

The Barents Sea is an intracratonic basin bounded by two young passive margins to the west and north developed in response to the Cenozoic opening of the Norwegian-Greenland Sea and Eurasian basin respectively (e.g. Faleide et al., 1993). Its southwestern part contains some of the deepest sedimentary basins on Earth, reaching depths of several kilometres and formed as a consequence of several deformation events involving the North Atlantic and Arctic region. The present-day regional tectonic setting is shown in Figure 2.

The main deformation event was the Early Tertiary crustal breakup that allowed the separation of Eurasia and Greenland and accretion of oceanic crust. At that time, two mega-lineaments were present in the southwestern Barents Sea: the North Atlantic rift and the De Geer shear zone (e.g. Faleide et al., 1993), the latter possibly continuing into the Arctic Ocean along the Greenland and Canadian continental margin. Late Mesozoic-Cenozoic evolution of the study area in a tectonic rift-shear sense is well documented in many papers (e.g. Brekke and Riis, 1987), while late tectonic evolution of the southwestern Barents Sea is less well known or documented. Cenozoic compressional structures along the northeastern Atlantic margin have been documented in Doré and Lundin (1996) while their impact on hydrocarbon exploration after Late Cenozoic uplift and erosion is the subject of a study by Doré and Jensen (1996). The major discoveries of the Skrugard, Norvarg and Havis fields in the past two years, and the application and potential benefits of CSEM technology on these discoveries, has been...
was checked by analysis of pseudo-sections and common offset maps extracted at selected frequencies and offsets. The maps and sections, although affected by bathymetric effects, regional trends, and limitations of the qualitative assessment methods, consistently indicated a negative anomaly at the western border of the survey area and a strong positive anomaly located roughly at centre of the area with a W–E trend. This anomaly showed good correspondence with trends in the interpreted Base Tertiary horizon (Figure 3).

Anisotropic 1D modelling was performed for further quality control of the data, checking inconsistencies among the different models obtained for the various soundings. Information about horizontal resistivity values was taken from public-domain well data available in the area. Seawater resistivity was modelled using a layered resistivity distribution based on available regional information from the Barents Sea as well as water resistivity measurements made during the acquisition.

**CSEM modelling and inversion**

The input model was obtained incorporating a priori geologic information in the form of seismic horizons and resistivity from 1D CSEM inversion results. Specifically, the seismic horizons were used to build a gridded structural model consisting of five zones corresponding to Neogene, Tertiary, Cretaceous, Jurassic, and pre-Jurassic formations. Each zone was populated using the values obtained by the 1D models, allowing for lateral resistivity variations inside each zone. The resistivity models had previously been checked for outliers and filtered, keeping only resistivity values within the range ($\mu - \sigma$) and ($\mu + \sigma$), where $\mu$ is the mean value of the logarithmic distribution of resistivities and $\sigma$ is its variance.

The reliability of the anisotropic starting model was tested via 2.5D and 3D anisotropic forward modelling, investigating misfits between the synthetic and observed data. Several separate 3D inversions were run using varying model parameters to achieve a stable result whilst aiming to minimize the RMS misfit. All available frequencies were inverted and inline and broadside soundings were inverted together, increasing data control to include the direction perpendicular to transmission.

The results of the 3D anisotropic modelling were consistent with the qualitative imaging performed in advance. The 3D inversion algorithm proceeded to further minimize the data misfit by changing the starting model with the insertion of a series of resistivity anomalies. Among these anomalies were a conductive zone inserted at the western border of the area and a resistive body at Tertiary level, confined by the Base Tertiary horizon. These resistive features are in agreement with the common offset maps extracted directly from the processed data (Figure 4). A series of other features were indicated by the inversion, showing a good level of agreement with the seismic image (Figure 5).
Some of the resistive features were tested through forward modelling, generating synthetic responses from anti-models without the resistive and conductive features. Sensitivity to the presence or absence of the features was assessed by normalizing the responses of the models and their anti-models. A detectable difference in the data (i.e., >15% in normalized amplitude and >5° in phase) was considered as showing the possibility for the CSEM data to discriminate between the two scenarios (Figure 6).

**Seismic Inversion**

Fluid discrimination is a crucial task in seismic exploration and reservoir description. In this framework, AVO inversion yields elastic rock properties volumes that are useful for...
estimating lithology and fluid content. For this study, prestack AVO simultaneous inversion was performed to obtain AI, Vp/Vs, Poisson’s ratio, and density cubes. Poisson’s ratio and Vp/Vs are seismic attributes that are sensitive to gas content, (e.g., Hilterman, 2001; Barclay et al., 2008). According to this theoretical trend, low values of Poisson’s ratio support the presence of gas. More generally, the contribution of the seismic attributes supports the likely presence of hydrocarbons indicated by resistive anomalies in the CSEM inversion.

Results
Seismic processing generated a 3D seismic cube that showed two features of interest: (1) several flat spots distributed at variable depths but all within the older Triassic-Jurassic sedimentary sequence, and (2) a bright amplitude anomaly in the younger Cretaceous turbiditic sedimentary sequence (Figure 7). In addition, direct hydrocarbon indicators (DHIs) are present both in the Cretaceous and the shallower near-surface sedimentary sequence, an example of which is shown in Figure 8. These features indicate that at least two petroleum systems could be in place in the area, one predating the BCU charging the older reservoirs (i.e., the flat spots), and one after, possibly affecting the Cretaceous sedimentary system and indicated by the amplitude anomaly.

CSEM inversions performed by WesternGeco and EMGS gave very similar results. Both the flat spots in the Mesozoic sequence and the amplitude anomaly in the Cretaceous sediments are characterized by a resistivity anomaly that indicates a change from the normal conductive behaviour to an anomalous resistive behaviour. Co-rendering of CSEM inversion results with the equivalent section from the seismic cube highlighting RMS values on Cretaceous sediments gives additional information about the nature of that resistive anomaly, and conversely about the nature of the seismic RMS amplitude anomaly (Figure 7).

The amplitude anomaly highlighted by the seismic processing corresponds with the resistive anomaly found with CSEM modelling and inversion. Different interpretations are possible. The high RMS amplitudes and concurrently resistive anomaly in the Cretaceous sequence indicate that these layers could be charged with hydrocarbons. The multi-measurement approach enables recovery of valuable information on the consistency of the single domain results and on the consequent geological interpretation (Figure 9). The absolute value of resistivity in the Cretaceous anomaly is high, which could be an indication that the hydrocarbon is most likely to be gas; however, the lack of a clear structural trap could indicate that it is only a layer of highly compacted and cemented sediments.

Conclusions
Integration of different types of geophysical measurements in a portion of the West Loppa area in the Barents Sea has enabled definition of geologic features that, when considered separately within each different dataset, have a higher level of uncertainty. The multi-measurement methodology can deliver particular value in frontier exploration areas such as the Barents Sea where reducing uncertainty is fundamental for planning new wells and infrastructure that will deliver maximum economic benefit over the life of the field. The combination of 3D seismic and 3D CSEM data has the advantage of providing multi-property models – including AI, Poisson’s ratio, density, and resistivity – that truly describe the three-dimensional geological structures that may provide prospective targets for hydrocarbon exploration and development.

Figure 7 CSEM inversion results (WesternGeco version) on the younger Cretaceous anomaly co-rendered with seismic in 3D view (A), with depth iso-lines in map view (B), with RMS amplitude in section view (C) and RMS amplitude co-rendered with depth iso-lines in map view (D). The high resistive anomaly confined in the Cretaceous amplitude anomaly is evident in A and B. Correspondence between the resistive anomaly and the RMS amplitude anomaly in the same sedimentary layer is evident in C. Red dots are EM receivers. Seismic and resistivity images courtesy of WesternGeco; CSEM input data courtesy of EMGS.
Figure 9 Seismic data co-rendered with Poisson’s ratio and vertical resistivity (contour lines). Both models show evidence that supports the presence of gas. This result highlights the added value provided by the integration of different geophysical techniques such as AVO and CSEM.

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References


