Detecting Skrugard by CSEM — Prewell prediction and postwell evaluation

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Abstract

The discovery of Skrugard in 2011 was a significant milestone for hydrocarbon exploration in the Barents Sea. The result was a positive confirmation of the play model, prospect evaluation, and the seismic hydrocarbon indicators in the area. In addition, the well result was encouraging for the CSEM interpretation and analysis that had been performed. Prior to drilling the 7220/8-1 well, EM resistivity images of the subsurface across the prospect had been obtained along with estimates of hydrocarbon saturation at the well position. The resistivity distribution was derived from extensive analysis of the multiclient CSEM data from 2008. The analysis was based on joint interpretation of seismic structures and optimal resistivity models from the CSEM data. The seismic structure was furthermore used to constrain the resistivity anomaly to the Skrugard reservoir. Scenario testing was then done to assess potential alternative models that could explain the CSEM data in addition to extract the most likely reservoir resistivity. Estimates of hydrocarbon saturation followed from using petrophysical parameters from nearby wells and knowledge of the area, combined with the most likely resistivity model from CSEM. Our results from the prewell study were compared to the postwell resistivity logs, for horizontal and vertical resistivity. We found a very good match between the estimated CSEM resistivities at the well location and the corresponding well resistivities. Thus, our results confirmed the ability of CSEM to predict hydrocarbon saturation. In addition, the work demonstrated limitations in the CSEM data analysis tools as well as sensitivity to acquisition parameters and measurement accuracy. The work has led to more CSEM data acquisition in the area and continued effort in development of our tools for data acquisition and analysis.

Introduction

The first commercial application of the controlled source electromagnetic (CSEM) method for hydrocarbon exploration was performed by Statoil in 2002 (Elingsrud et al., 2002; Røsten et al., 2003), and spurred a period with extensive data acquisition and technology development. The optimistic early days of CSEM turned into a period of contemplation due to various inconclusive and disappointing results after some years of experience. As described in Buland et al. (2011), the evaluation of Statoil’s CSEM database in 2009 showed that newer data in general had a stronger impact on chance of success for finding hydrocarbons, whereas old surveys in many cases were weak or inconclusive. The database analysis showed a positive trend with time for CSEM application due to improvements of data quality and analysis.

However, the database also had newer data that were difficult to analyze. The multiclient data acquired over the Johan Castberg area in 2008 for the 20th licencing round application were seen as very challenging to analyze at that time due to quite challenging geologic settings. A small deviation from the background trend was observed over the Skrugard prospect, but the conclusion was that more advanced analysis and a better understanding of local and regional properties were needed.

The Johan Castberg area is located in the Barents Sea in the PL532 license as shown in Figure 1. The Skrugard prospect is located within the Bjørnsøyrenna Fault Complex on the crest of a north–south-trending rotated fault block partly modified by erosion, see Figure 2. A geologic section through the prospect, as interpreted prewell, is presented in Figure 3. A combination of structural tilting of the Realgrunnen Subgroup reservoirs

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Manuscript received by the Editor 1 October 2013; revised manuscript received 6 December 2013; published online 22 May 2014. This paper appears in Interpretation, Vol. 2, No. 3 (August 2014); p. SH67–SH78, 18 FIGS.

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Figure 1. Overview of the Johan Castberg area in the Barents Sea.

Figure 2. Top reservoir structure map showing the locations of the 7219/9-1 well from 1988, the Skrugard well 7220/8-1 from 2011, and the Havis well 7220/7-1 from 2012.
containing the Stø, Nordmela and Tubåen formations, and truncation of the intraCretaceous unconformities at the crest of the fault block, has formed the Skrugard trap. The structural apex is at 1204 m MSL, and the elongated four-way closure covers an area of 14 km². The reservoir zone containing hydrocarbons was predrill expected to be thicker than 100 m in most of the structure. The water depth in the area is 370 m.

In 2010, before the first exploration well were to be drilled at the Skrugard prospect, the CSEM data were revisited among a variety of other extensive data analysis and preparation work. The ambition was to apply newly developed data analysis and workflows to estimate probability for discovery, and moreover predict prewell reservoir resistivity and hydrocarbon saturation from the CSEM data.

The CSEM interpretation workflow included a series of unconstrained and constrained 2.5D inversion and 3D inversion runs, on inversion codes developed by Statoil and EMGS. Most importantly, a thorough scenario testing was performed. This study was essential to establish reliable quantitative estimates for the Skrugard prospect, and to assess the strength and robustness of the estimates. In addition, a new stochastic tool for saturation estimation, described in Wiik et al. (2012), was developed and implemented.

The Skrugard exploration well, 7220/8-1, was drilled early in 2011, and a broad logging program was performed for the well, among other things to validate the results of the prewell CSEM predictions. The resistivity logs in the Skrugard well contain vertical and horizontal resistivities from the seabed to the total depth and are thus quite unique in terms of benchmarking remote resistivity measurements.

In this paper, we present the CSEM predictions prewell and the postwell comparison to the resistivity well logs. Through the various steps of the workflow, we show how the most likely resistivity images of the subsurface were obtained from extensive CSEM data analysis. The significant effort on scenario testing is described; that is, we show how synthetic modeling and inversion studies based on the results from field data can be used to interpret data acquired over a prospect to assess the chance of success in a qualitative and quantitative manner. Furthermore, we outline how the CSEM data were used together with limited petrophysical knowledge in the area to estimate hydrocarbon saturation in the reservoir. Finally, the prewell predictions are compared to the well results. A short version of this work is presented in Løseth et al. (2013). An independent data analysis performed by the contractor is presented by Gabrielsen et al. (2013).

Prewell data analysis

Subsurface resistivity from inversion of CSEM data

The 2008 multiclient data were acquired as a so-called scanning grid along north/south striking lines as shown in Figure 4. The frequencies with sufficiently good signal-to-noise ratio (S/N) were in the range 0.2–1.2 Hz. The data set consists of a southern part (Area R) and a northern part (Area S) and these two areas were well.
acquired with two separate vessels. Being acquired in 2008, the data are, in CSEM terms, rather old data, meaning that they suffer from measurement inaccuracies (e.g., receiver calibration with inherent challenges on clock drift and electrode impedance variation) that have improved since then. In addition, the northern area has poorer data quality than the southern area.

As can be seen from Figure 4, the receiver coverage was suboptimal for the prospectivity in the area. The line covering Skrugard is positioned along the edge rather than on the top of the reservoir. This will reduce the detectability. Moreover, Skrugard lies in the overlapping area between Area S and Area R, implying that we only have partial data coverage with sufficient quality over the southern part. Thus, the effect of suboptimal coverage and insufficient data quality in the northern area needed to be addressed in the data analysis. In addition, the acquired frequency spectrum is not optimal for the rather shallow target depth due to lack of higher frequencies with strong S/N. The data coverage and quality is, however, sufficient for appropriate analysis of a large part of the area.

One of the important initial tasks was to perform unconstrained 2.5D anisotropic inversion with smoothing regularization along all the lines, using all available frequencies. Anisotropy here refers to transverse isotropy with a vertical symmetry axis. The inversion result for the line closest to Skrugard is shown in Figure 5. The data misfit was 4.2%, approximately at the noise level of the input data. Here, misfit is a root-mean-square value describing the sum of relative differences between measured data and data forward modeled from the obtained model. The start model was the sea water layer over a half space. As seen from Figure 5, there is a clear anomaly at the approximate lateral position and approximate depth of the prospect location. Due to the smoothing regularization and limited data coverage, the image is smeared out to the north. Our analysis of the inversion results showed that high resistivity at the prospect location was needed to obtain low data misfit. However, the effect of the 2.5D assumption and suboptimal location of receiver line, with respect to the reservoir, called for further investigation.

In obtaining our 2.5D inversion results, we found it essential to ensure plausible and consistent background resistivity values across the area using seismic data and regional understanding to guide the iterative analysis. As part of validating the inversion results, we compared the results to seismic structural interpretation and the resistivity log from the well 7219/9-1 located to the southwest of the Skrugard well, see Figure 2. A comparison between the resistivity measured in the 7219/9-1 well and the CSEM resistivity at the well position is shown in Figure 6. Only horizontal resistivities were measured in the 7219/9-1 well. Thus, we had no calibration of the obtained vertical CSEM resistivity. As can be seen from Figure 6, the match between horizontal CSEM resistivity and resistivity trend in well log is quite good. The vertical CSEM resistivity increase correlates with well-log resistivity “spikes.” The observations confirmed that the inverted background model for horizontal resistivity was quite realistic, and indicated a significant degree of electrical anisotropy.

Figure 5. Unconstrained 2.5D inversion result corendered with seismic data. The white squares denote receivers, whereas the white polygon illustrates the identified reservoir container down to the deepest flat spot. The section is taken along the receiver line across Skrugard (cf., Figure 4).

Figure 6. Comparison of the horizontal resistivity in the dry well 7219/9-1 (red curve) and the extracted profiles from the CSEM unconstrained inversion result. Black curve represents horizontal resistivity and dashed black curve represents vertical resistivity. The resistivity log is upscaled to 15 m intervals.
Several 3D inversions were run on the data set. A variety of start models were tested, including a smoothed model based on the 2.5D inversion results. The lateral extension of the main resistive anomalies observed in 2.5D and 3D inversion is shown in Figure 7. Some resistive anomalies are present with both methods. However, although the 3D inversion results indicated an anomaly at the Skrugard reservoir location, the results showed a substantially weaker resistivity increase than the 2.5D inversion results across the prospect. We interpreted this as an effect of the suboptimal receiver coverage and weaker optimization algorithm in the 3D inversion (gradient-based optimization scheme, L-BFGS) compared to 2.5D (Gauss-Newton), cf., Nocedal and Wright (2006). In addition, we were not quite satisfied with the final data misfit we were able to achieve with the 3D inversion, although it was just slightly above the input-data noise level. We suspected that higher accuracy in the data used, and better preprocessing, would be needed to improve the 3D inversion results.

Although the 3D inversion was not able to reproduce the same convincing resistivity anomaly for the Skrugard reservoir as the 2.5D inversion, the 3D result was important to gain confidence in the 2.5D inverted anomaly by reducing the probability that a large resistive feature nearby the reservoir could mislead our 2.5D interpretation.

Of the several possible alternative models, referred to as anti models, that potentially could explain the CSEM data across Skrugard, high resistivity in the lower Cretaceous was considered likely, but with difficulties in explaining the excellent lateral match to the Skrugard reservoir geometry in the 2.5D inversion results.

**Scenario testing**

Based on the encouraging inversion results, an extensive synthetic scenario testing was performed. The workflow is illustrated in Figure 8. As reference models, we used 3D resistivity models derived from 3D and 2.5D inversion. In the latter case, we extrapolated the 2D resistivity distribution to 3D. In the reference models, the resistivity anomaly we believe could be attributed to Skrugard was removed. The models thus described the assumed background resistivity. Next, we performed 3D forward modeling of different scenarios for survey geometry, reservoir width and reservoir resistivity profiles using prospect geometry derived from seismic data. The resulting synthetic data were inverted in 2.5D using the same inversion parameters as had been used for the measured data. This enables us to compare inversion results of various scenarios to the actual results for the measured data. The work was important to evaluate the effects of suboptimal survey geometry and the 2.5D assumption in the inversion.

Figure 9a shows the interpreted outline of Skrugard, indicating a 2 km wide reservoir to the south, and an offset of 1 km between the towline (same as the receiver line) and the center of the reservoir. Figure 9b shows the baseline reservoir resistivity profile used in the scenario testing. In this model, we have a 100 ohmm gas cap on top of a 50 ohmm oil-leg, which is considered as a high resistive model. The fluid contacts were inferred from flat spots observed in the 3D seismic data. Three different investigations were performed. First, we looked at the effect of the 2.5D assumption by varying the reservoir width indicated in Figure 9c. Second, we considered the effect of suboptimal towline location
by varying its offset to the center of the reservoir as sketched in Figure 9d. Finally, we evaluated the effect of varying the resistivities in the reservoir using the profiles sketched in Figure 9b, but with different scaling factors in each case.

To evaluate the effect of the 2.5D assumption, we investigated the amount of resistivity anomaly that is recovered through 2.5D inversion when the true reservoir width is not infinite. A box model was populated with resistivity according to the profile shown in Figure 9b, and CSEM data responses for different widths were modeled with an optimally located towline centered over the box. The vertical resistivities recovered from the subsequent 2.5D inversions with different reservoir widths were shown in Figure 10. Based on the results, a guideline for the recovered transverse resistance (resistivity-thickness product) from inversion as a function of reservoir width was produced as shown in Figure 11.

Because the Skrugard reservoir is approximately 2 km wide toward the south where we have data coverage, we conservatively estimated that our 2.5D inversion would only reconstruct at most 25% of the true resistivity anomaly of Skrugard. These findings were necessary to make quantitative prewell estimates of true reservoir resistivity and saturation.

The effect of suboptimal survey geometry was evaluated using the box model with 2 km reservoir width. For the reference model, we used a centered towline. We then shifted the towline toward the west, and compared the resulting inversion models from the inverted synthetic data (see schematics in Figure 9d). From Fig-

![Figure 9](https://example.com/figure9.png)

**Figure 9.** (a) Skrugard outline and closest CSEM towline. (b) Assumed base case resistivity profile through the reservoir depth section. (c) Model example of varying reservoir widths with perfectly centered CSEM towline. (d) Model example of fixed reservoir width and varying towline locations.

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Effect of reservoir width on recovered anomaly from 2.5D inversion. Slices show vertical resistivity. The vertical depth and horizontal distance is the same as in Figure 5.
Figure 12, we observe that a 2 km wide anomaly with tow-line geometry as on Skrugard and resistivity profile as described in Figure 9b gives a smaller anomaly than the inverted measured data. This indicates that a maximum resistivity of 100 ohmm in the assumed profile in Figure 9b is not enough to explain the measured data.

**Figure 11.** Recovered transverse resistance (resistivity-thickness product) anomaly by 2.5D inversion as a function of actual reservoir width. The relation is derived from a simple box model example with centered CSEM towline as illustrated in Figure 9c.

**Figure 12.** Effect of recovered anomaly by an offset towline, as illustrated in Figure 9d. A reservoir width of 2 km is used. Thus, (a) is the same as Figure 10d. The towline offsets in (b) and (c) are 1 and 2 km, respectively. Slices show vertical resistivity. The vertical depth and horizontal distance is the same as in Figure 5.

**Figure 13.** Inverted measured data compared to inverted synthetic data using the resistivity profile in Figure 9b, but using different scaling of the curves. In (e), the resistivity anomaly only extends down to the shallowest flat spot. Slices show vertical resistivity. The vertical depth and horizontal distance is the same as in Figure 5.
These observations prompted a study of different resistivities in the reservoir, using the true survey geometry and reservoir outline. In the test, the same relative resistivity profile was used, varying the maximum resistivity in each case, except for the last test where only a gas cap down to the shallowest flat spot was assumed. The results are shown in Figure 13. We observe that the 400 ohmm maximum resistivity case is the closest to the measured data inversion model, whereas the case with only a highly resistive gas cap down to the shallowest flat spot does not match the measured data, see Figure 13e. From this, we concluded that high resistivity down to the deepest flat spot is needed to explain the CSEM observations.

Finally, we performed a constrained 2.5D inversion on the line across Skrugard, inferring the reservoir geometry from seismic interpretation. We used the interpreted top reservoir horizon and the deepest flat spot (assumed oil-water contact) to construct a zone of lowered regularization strength, thus allowing for more variation of the resistivity in the reservoir region. This was done to investigate whether the entire Skrugard anomaly could be attributed to the reservoir, while still obtaining a reasonable data misfit. The result is shown in Figure 14, and the data misfit was 4.9%. The transverse resistance across the anomaly is the same as for the results shown in Figure 5. This result supported that the CSEM anomaly is accounted for by high resistivity located within the reservoir container.

**Estimating saturation from CSEM data**

Having established an estimate of the resistivity in the reservoir and gained confidence that the anomaly could be attributed to hydrocarbons, we went on to make an assessment of the expected saturation based on the CSEM results. The large scale resistivity estimates from CSEM is not unconditionally appropriate for saturation estimation via common resistivity-saturation relations as Archie’s equation (Olsen, 2011). As shown in Figure 5, only the vertical CSEM resistivity identified the reservoir. Due to limitations of the CSEM methodology and inversion results, the vertical resistivity anomaly was distributed over a larger interval than the reservoir, even in the constrained inversion case (see Figure 14). However, estimating the transverse resistance across the anomaly is more robust and this parameter can also be related to petrophysical parameters. In an exploration setting, these petrophysical parameters are not exactly known, but based on seismic information and regional experience, expected values and variation of parameters as reservoir thickness, porosity, brine salinity, temperature, cementation, and saturation index are formulated as probability density functions. The resulting stochastic method is described in Wiik et al. (2012), and makes use of Monte Carlo simulations to connect petrophysical parameters to the observed CSEM transverse resistance.

The predicted reservoir thickness from seismic data, with uncertainties, was discretized into piecewise homogeneous layers, and reservoir parameters such as brine conductivity and porosity were assigned to each of these layers. The parameters for each layer were determined by drawing them from probability distributions describing the expected reservoir properties and their variability. Archie’s equation (Archie, 1943) was then applied to estimate resistivity. Next, the corresponding transverse resistance for the entire reservoir model was calculated. A Monte Carlo approach, implying that many realizations of the reservoir are pro-

**Figure 14.** Constrained 2.5D inversion result corendered with seismic data. The white squares denote receivers, whereas the white polygon illustrates the identified reservoir container down to the deepest flat spot. The section is taken along the receiver line across Skrugard, cf. Figure 4.

**Figure 15.** Probability distribution of average reservoir water saturation versus logarithm of reservoir transverse resistance. The black line denotes the most likely combination. Brighter colors denote higher probability. The white rectangle illustrates the range of predicted transverse resistance derived from inversion of CSEM data. The red dotted line represents the most likely transverse resistance and corresponding water saturation based on the 2.5D inversion result.
duced, resulted in the distribution shown in Figure 15. The figure visualizes the joint probability density function for average water saturation in the reservoir and the logarithm of the transverse resistance.

Furthermore, Figure 15 sketches how the realized distribution for transverse resistance compares to the transverse resistance derived from the CSEM inversion results shown in Figure 14. The upper bound was determined from the constrained 2.5D inversion compensating for the suboptimal positioned receiver line and the fact that 2.5D inversion recovers less than 25% of the actual transverse resistance across Skrugard due to the finite width (cf. the synthetic study related to Figure 11). The lower bound was set based on the small anomaly recovered by 3D inversion.

By using this methodology, we predicted, with conservative parameters, the average hydrocarbon saturation in the reservoir to be in the range 75%–95%. The most likely resistivity models from the 2.5D inversion indicated a result in the very upper part of this range.

Prewell summary

From the CSEM data analysis described above, we concluded prior to drilling the Skrugard well that a hydrocarbon-filled reservoir with high resistivity was likely. The scenario testing increased the confidence that high hydrocarbon saturation is needed to explain the CSEM data. In fact, we were a bit confused about the seemingly very high resistivities needed to compare with the inversion result of measured data, exceeding 400 ohmm. Potential antimodels were a concern, and the main one was attributed to resistivity variations in the Cretaceous. In addition, the suboptimal survey geometry and data quality in 2008 slightly reduced our confidence in the data. However, none of these factors were able to overturn our main conclusion.

Postwell results

Advanced well logging program

The Skrugard exploration well, 7220/8-1, drilled early 2011, had a very advanced logging program. In particular, the horizontal and vertical resistivity was logged from the seabed down to total well depth with a triaxial induction tool. The reservoir section exceeded the operational limit of induction tools and was logged with an array-laterolog. Among other things, logging of horizontal and vertical resistivity was essential to properly verify the CSEM resistivity prediction. The log is shown in Figure 16, with horizontal resistivity in red and ver-

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**Figure 16.** Results from well logging in 7220/8-1 (Skrugard). (a) Volumetric relative fractions of shale (dark green), sand (yellow), gas (red), oil (green), and water (blue) in the reservoir section to the left. Sketch of well design overlaid a seismic cross section to the right. (b) Results from resistivity logging along the well with horizontal resistivity (red curve) and vertical resistivity (blue curve). Resistivity logs are upscaled to 15 m intervals.
tical resistivity in blue. This allowed us to calibrate our CSEM inversion results properly.

**Comparison of CSEM and well log data**

Figure 17 contains the resistivities measured in the well and the resistivities predicted by 2.5D inversion of CSEM data. The black lines in Figure 17a represent the results from unconstrained 2.5D inversion. In the resistivity track, the graph with red shade is the difference between the vertical resistivity recovered just outside and inside the reservoir. Figure 17b represents the corresponding results from constrained 2.5D inversion. The additional red area represents the scaling that incorporates the suboptimal receiver locations and 2.5D assumption.

A good fit between the CSEM resistivities and well log resistivities can be observed in Figure 17, in particular throughout the overburden above the reservoir zone. As expected, the high horizontal resistivity in the reservoir is not visible in the CSEM data, because the electric field is almost purely vertical in a thin resistive layer (e.g., Løseth, 2007). Below the reservoir zone, the horizontal CSEM resistivity picks up the general trend quite well because this region is mainly sensed by the transverse electric mode. The match between the vertical resistivities below the high resistive reservoir is worse because the transverse magnetic mode is not very sensitive to the medium below the high resistor in this case.

From the well log, reservoir resistivities in the 1000 ohm-m range can be observed. This explains the results from the scenario testing inferring that very high vertical resistivities are needed to account for the CSEM anomaly. The transverse resistance extracted from CSEM inversion matches the logged transverse resistance well. The hydrocarbon saturation estimated from the well logs is approximately 95%.

Thus, the well confirmed very high hydrocarbon saturation, and corresponded nicely to the prewell estimates from CSEM data. This confirms the CSEM

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**Figure 17.** Comparison of well logs and unconstrained inversion in (a) constrained 2.5D inversion in (b). Black lines represent resistivity extracted from CSEM inversion. The red curve is the logged horizontal resistivity and the blue curve is the logged vertical resistivity. The red color emphasizes the difference between CSEM resistivities outside and inside the reservoir geometry, whereas the light red color in the right panel includes the required upscaling of the 2.5D inversion result.
data sensitivity to high saturation hydrocarbon reservoirs, and the ability to predict average reservoir saturation from thorough data analysis.

To this end, it should be noted that a new CSEM survey conducted in 2011 on behalf of Statoil, with a denser receiver grid and more optimal frequency spectrum, supported the prewell CSEM conclusions. The more optimal layout and frequency spectrum, in addition to improved data quality since 2008, made the data more suitable for inversion. In the new CSEM data, a clear anomaly at Skrugard was achieved by 3D inversion as illustrated in Figure 18 (see e.g., Nguyen et al., 2013). In addition, Figure 18 shows some high resistive features in the Cretaceous which were also evident in the 2008 CSEM data.

Conclusions

Our CSEM data analysis in the Skrugard area predicted a significant EM anomaly associated with the Skrugard reservoir. The results were based on an integrated approach using regional knowledge, quality seismic data, and availability of flexible CSEM inversion tools to achieve the best possible interpretation.

Both constrained and unconstrained 2.5D inversion imaged the resistive reservoir well. Confidence in the CSEM results was gained using a workflow that required thorough scenario testing of the inversion results of the measured CSEM data. Scenarios to quantify the effect of suboptimal survey geometry and limitations of the 2.5D modeling capabilities were tested, and the results were applied to make quantitative predictions of very high hydrocarbon saturation in the reservoir prewell.

The extensive well logging program in the Skrugard exploration well, including logging vertical and horizontal resistivity components from the seabed and far below the reservoir, serves as an excellent calibration for further CSEM analysis in the Barents Sea, and enabled us to evaluate the CSEM results properly. The transverse resistance derived from CSEM had an excellent match to the corresponding logged values. A stochastic estimation predicted high saturations from CSEM data prewell, demonstrating the value of CSEM for derisking prospects. The postwell saturation estimates are in the upper range of our prewell estimate, and confirmed our results and methodology.

In addition, the study revealed shortcomings in data acquisition and data analysis tools. Improvements of these shortcomings have been and will be essential in developing the CSEM methodology further. In particular, we think development of the 3D inversion tools and data accuracy, including hardware and data processing, are key elements to increase the potential of making reliable prewell predictions based on integrated CSEM and seismic data analysis.

Acknowledgments

We thank Statoil ASA for permission to publish this work and the Johan Castberg exploration team in Statoil for valuable discussions and assistance. In particular, we would like to thank Andreas Becht, Malgven Roudot, Janniche Nordskag, and Merete Jaarvik for valuable help on different parts of this work. In addition, we would like to thank the reviewers for constructive comments that helped to improve the text. We are grateful to WesternGeco and EMGS for permission to publish the multiclient seismic and CSEM data, respectively.

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Biographies and photographs of other authors are not available.