

Application of 3D anisotropic CSEM inversion offshore west of Greenland

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Summary

CSEM can provide oil companies with information on rock resistivity before drilling a well. We present a CSEM interpretation workflow based on anisotropic 3D inversion applied to a dataset acquired offshore west of Greenland. We show how the method can give complementary information on the resistivity properties. Integrated with seismic and geological knowledge, this allows high-grading prospective leads, detection of resistivity features such as volcanics or shallow basement, and provides evidence of possible resistivity anisotropy.

Introduction

Although there have been many publications on theoretical aspects of marine CSEM, covering most elements from data processing through to inversion, there have been few on interpretation and practical use of these data. Amongst these, significant contributions have been made by: Carazzone et al. for subsalt exploration in Brazil (2008) and in Angola (2005), Buonora et al. (2008) in Brazil, Price et al. (2008) in Nigeria, and Darnet et al. (2007) in Malaysia. In this paper, we show how multi-dimensional inversion and interpretation contribute to the ranking of prospects in two blocks west of Greenland. In both, the geological targets are Cretaceous sandstones in elongate structures; known complicating factors include the presence of shallow resistive volcanics and the intermittent presence of crystalline basement at relatively shallow depths below some of the targets.

The west of Greenland survey

In the summer of 2008, after detailed survey design, WesternGeco Electromagnetics carried out a large survey offshore west of Greenland for the joint venture (JV) operated by EnCana with partners Cairn-Energy and Nunaoil. Acquiring CSEM, MT, gravity and magnetic data, the survey covered two different blocks for a total of more than 1000 km of tow lines and more than 200 EM receivers. On completion of the acquisition phase, WesternGeco EM with the JV produced an integrated CSEM and MMT interpretation workflow to increase the confidence in the geological model of the two areas and to aid in ranking the surveyed prospects.

Survey Design

Before the survey, extensive use was made of all *a priori* information (seismic horizons and well logs) to assess the

sensitivity of the CSEM method for the expected targets in order to optimize the survey design in terms of transmitter and receiver layout and acquisition parameters.

The first step consisted of building preliminary 1D scenarios and using the synthetic model responses to verify the sensitivity by means of a normalized amplitude/phase difference approach over a wide range of frequencies. The analysis was extended to 3D modeling only for targets that showed 1D sensitivity, i.e., the ones with anomalous responses that exceeded 20% and were clearly above the system noise threshold (conservatively set to 10^{-15} V/Am² for the electric field measurements).

3D modeling is essential in survey design (Bornatici et al., 2007) to properly evaluate the target responses: 1D modeling where any layer has an infinite extension in both X and Y directions grossly overestimates possible responses and fails to take into consideration variably bathymetry and geology.

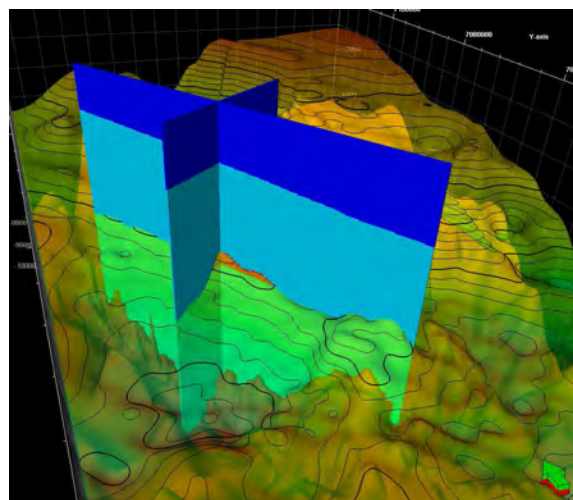


Figure 1: Seismic surfaces were utilized to build the three-dimensional resistivity model. Target scenario model is shown here in two perpendicular sections.

WesternGeco EM's finite-difference code was used for 3D modeling and inversion (Mackie et al. 2007; Rodi and Mackie 2001). The resistivity volumes were built using the seismic horizons as resistivity boundaries (Figure 1) with resistivity values chosen from neighboring well logs. For each investigated prospect, with- and without-target scenarios were used to compute synthetic CSEM responses. Normalized amplitude and phase difference sensitivity maps and pseudosections were utilized to analyze the 1D

Application of 3D anisotropic CSEM inversion offshore west of Greenland

modeling detectability and to define optimal frequency/offset parameters for each prospect area.

In designing the receiver and tow line positions, the above considerations were used as guidelines together with bathymetric considerations to optimize the cost/benefit ratio of the survey. The waveform was designed to maximize the energy at the frequency that showed the best trade-off between earth penetration and target response magnitude. At the high latitude of the survey, strong magnetotelluric signal (due to proximity to the polar electro jet) was expected, and because it could significantly affect the CSEM signal, the waveform base period was selected to give the best signal-to-noise ratio (SNR).

On-board processing and data QC

The data continuously recorded at the receiver locations are processed together with the transmitter current time series and the stream of navigation data describing the dipole instantaneous geometry and positions along the tow line. The three different streams are synchronized and subsequently segmented to be merged and transformed into the frequency domain. The processing stage is critical to produce reliable data to be used in the interpretation workflow. QC and processing flow software was used that was capable of processing three-dimensional receiver spreads and several tow lines while considering the instantaneous variations in both the data and acquisition geometry and estimating the instantaneous noise component associated. The introduction of the SNR estimation allowed discrimination of usable and non-usable data and assignment of a SNR-driven confidence value to each data sample. Displays such as normalized pseudosections and common offset maps were used for QC purposes; as interpretational devices they were seriously misleading due to the influence of shallow irregular volcanic resistors.

Integrated interpretation: The method

1D inversion can be less sensitive to targets of finite lateral extension, but in reality, they have two practical advantages: the benefit of accurately recovering the background resistivity distribution and a sharp sensitivity to shallow targets. The background resistivity distribution matched quite accurately the resistivity distribution determined from distant (~100 km) wells. The major variance was a multiplicative factor of approximately 2.0 that is explained by the primary sensitivity of inline CSEM data to the vertical component of resistivity rather than the horizontal resistivity that measured by most logging tools. The resistivity distributions derived from well logs and revised with the 1D inversions, together with horizons from seismic interpretation, were used to build the 3D resistivity models used as the starting point for inversion. The 3D

inversion code allows exploiting fully the tridimensional nature of both source and geology, including the possible anisotropic distribution of each resistivity cell in the unknowns.

Integrated interpretation: synthetic and observed data examples

In the example below, we demonstrate the inversion technique correctly recovers the starting model from synthetic data and that artifacts, in particular, potentially interesting resistors, are not introduced. We also verify the 3D inversion sensitivity to the expected target.

Synthetic 3D responses using the actual survey acquisition parameters (frequencies), coverage (inline and broadside), and instantaneous source geometry were generated using forward modeling from two different 3D models. In one case, the target was included; in the other, it was not inserted in the model. Both synthetic datasets were 3D inverted, and in both cases, the inversion succeeded in reconstructing a model close to the *a priori* one. In a third test, the most critical, the synthetic dataset with target included was inverted starting from a model close to the area geology excluding the target. The inversion result was positive and showed that a resistivity feature was needed to fit the data, depth, and lateral extensions of this feature, matching the ones of target included in the model that originated the data (Figure 2).

The same inversion settings and *a priori* model were then used to invert the observed data (Figure 3). The resulting resistivity volume confirmed shallower resistive features as indicated by 1D inversion, but inserted a resistivity feature in the model (> 10 Ohm.m) that conformed to the expected depth and lateral extent of the target. The synthetic responses obtained from the inversion model fit the observed data well for both the inline and broadside cases (Figure 4). A similar workflow was then followed also for other prospects, giving geologically reasonable results that confirmed its validity (Figure 5 and Figure 6).

Integrated interpretation: anisotropic behavior

Several investigated prospects in the two Greenland blocks were illuminated by tri-dimensional source-receiver layout. This allowed measuring responses to the both vertical and horizontal induced currents and, through 3D CSEM inversion, the determination of anisotropic resistivity response.

3D inversions using both inline and broadside data yielded results where anisotropic behavior was evident in two as anomalous ratios indicated by deviation from the isotropic value of one. V/H anisotropy was seen between vertical and horizontal resistivities and X/Y anisotropy between the inline and broadside direction horizontal resistivity. These anisotropic responses were completely data driven, i.e. the

Application of 3D anisotropic CSEM inversion offshore west of Greenland

starting model was isotropic and no resistivity contrasts were input in the starting model where the inversion showed stronger anisotropy. It is remarkable how this anisotropic response conformed well to the depth interval delimited by two horizons (top Paleocene and intra-Paleocene) likely to be associated with volcanic strata (Figure 7 and Figure 8). This anisotropy observed on the CSEM inversion results are believed to be a geologic effect that could offer new and useful geologic information for exploration drilling and further validates the utility of CSEM.

Conclusions

The workflow applied in the west of Greenland CSEM survey allowed prospects to be high-graded. The CSEM method provided complementary resistivity property information to be used with the usual seismic and geologic data. Continuing integration of conventional geophysical and geological interpretation with the CSEM results is expected to contribute towards the further understanding and ranking and drilling prognosis of the hydrocarbon prospects.

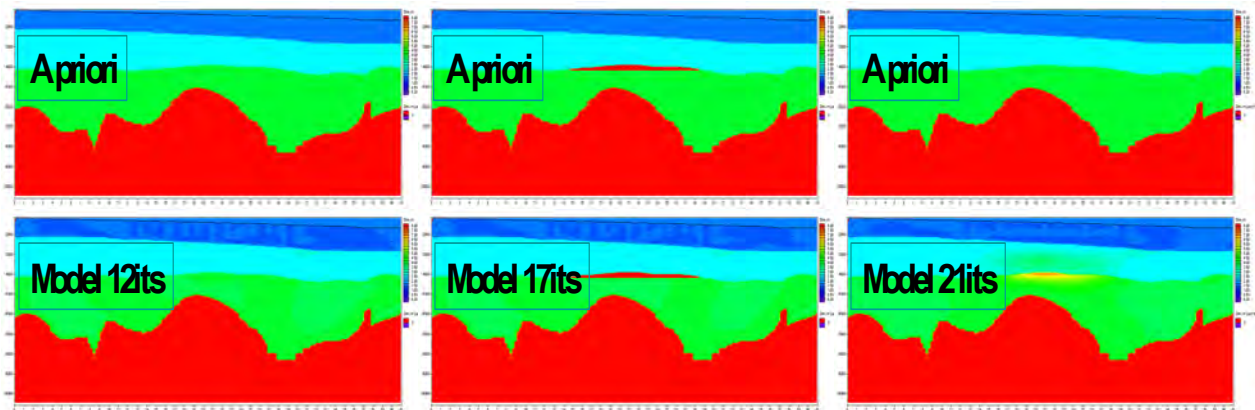


Figure 2: Synthetic data study: from the left, the *a priori* model and 3D inversion resistivity output of three different tests are shown. In the first two examples, the synthetic data used in the inversion were generated from the *a priori* model itself, in the third, the synthetic data were generated by the second *a priori* model.

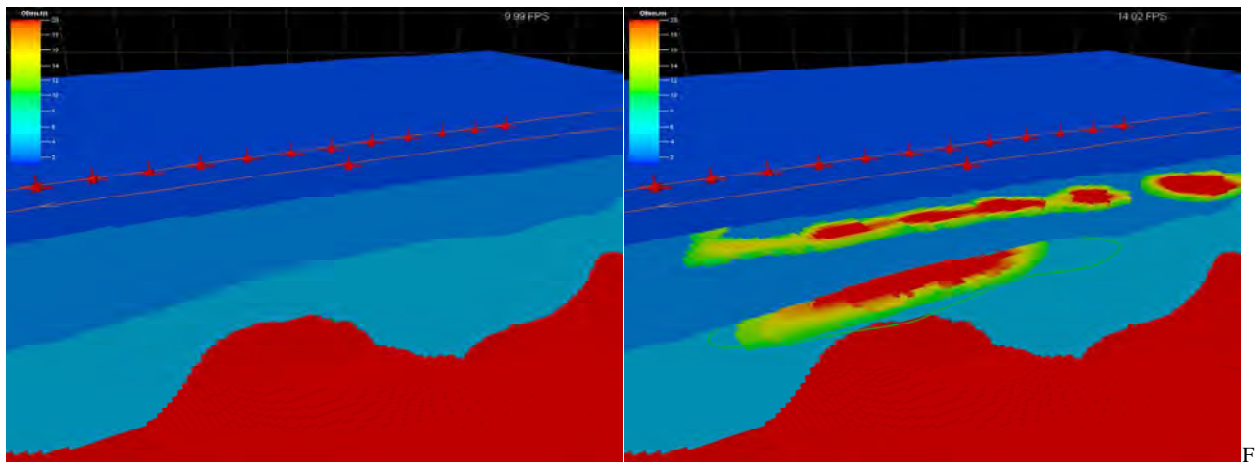


Figure 3: On the left, resistivity volume used as *a priori* model in the inversion of observed data; on the right, same model plus superimposed the inversion output model resistivity above 10 Ohm.m

Application of 3D anisotropic CSEM inversion offshore west of Greenland

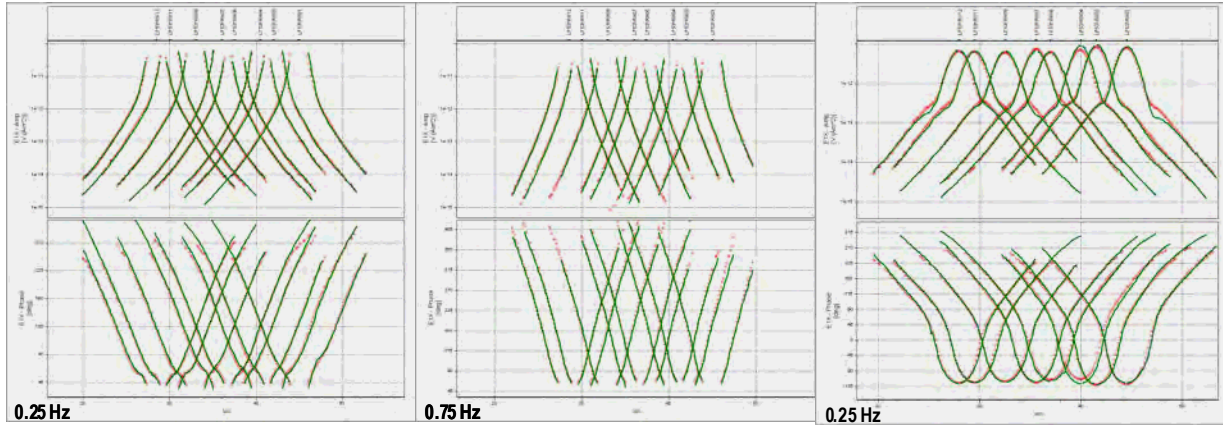


Figure 4: Data misfit between observed data (red dots) and 3D inversion results (green line). On the left, inline data at two different frequencies; on the right, broadside illumination case.

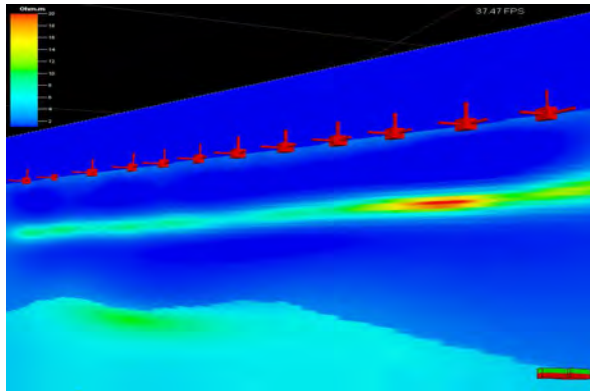


Figure 5: 3D inversion result: vertical resistivity section below a towline illuminated by a collinear and two parallel broadside towlines

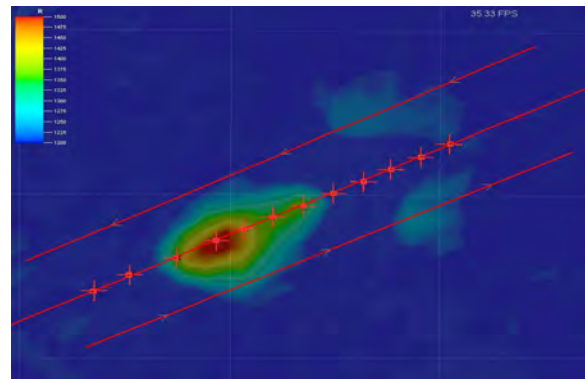


Figure 6: 3D inversion result: transverse resistance between seafloor horizon and 300m below it.

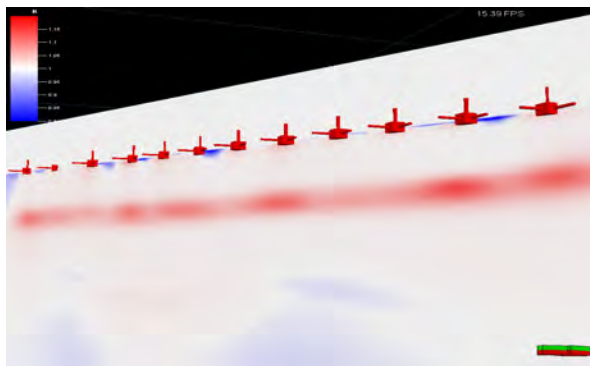


Figure 7: 3D inversion result: vertical vs. horizontal resistivity ratio, an isotropic behavior is shown in white, whereas anisotropy $(V/H) > 1$ is shown in red.

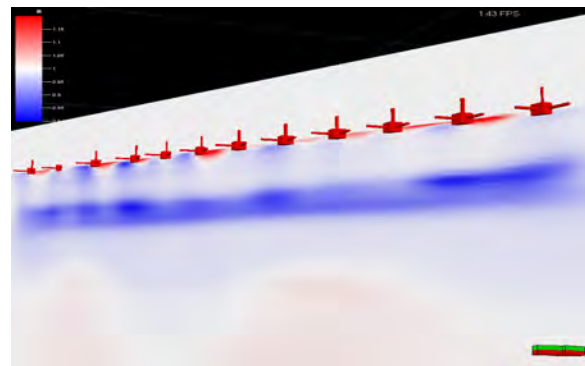


Figure 8: 3D inversion result: horizontal X (inline) vs. horizontal Y (broadside) resistivity ratio; color scale as in Figure 7

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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