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A Broadband Marine CSEM Demonstration Survey to Map the Uranus Salt Structure

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SUMMARY

To apply a broad spectrum of signal frequencies for a marine electromagnetic survey (0.01 Hz to 500 Hz) is a unique way for detailed mapping of geology in conjunction to hydrocarbon exploration. We present results from a demonstration research survey over the Uranus salt structure (Nordkapp Basin, Barents Sea) involving purpose built broadband receiver systems containing electric and magnetic field sensors as well as four component seismometers. EM data interpretation in tight combination with seismic models indicates a deep salt body rather than the shallow diapir interpreted from seismic alone. The deep salt body was confirmed by an exploration well. The positive results of this proof of concept survey triggered numerous commercial surveys with similar configurations.

Introduction

For almost a decade, Marine Controlled Source Electromagnetic (CSEM) exploration has been offered as a prospect de-risking tool to the hydrocarbon exploration community (Eidesmo et al., 2002). The main focus has been to search for hydrocarbon indicators by tying local high resistivity target responses derived from CSEM surveys to prospects mapped from seismic. Conventional CSEM surveys would typically make use of rather low frequencies in order to penetrate the low resistivity overburden to reach the targets at depths. However, in the case where a high resistivity salt body lies close to the seabed, as is the case for many of the Nordkapp Basin salt structures (Nilsen et al., 1995), also higher frequencies may be added to the survey, to resolve the salt structure rather than finding an isolated resistor at depth. Generally, increasing the number of frequencies and covering a wider band, makes the data richer in subsurface information. It increases the resolution and precision and reduces the ambiguity in interpretation/inversion.

Here we present a broadband CSEM research (proof of concept) survey at the Uranus structure (Nordkapp Basin, Barents Sea) involving feasibility modelling, data acquisition with purpose built hardware and preliminary data 2D interpretation of measured data in a frequency range from 0.01 Hz to 500 Hz.

CSEM feasibility for salt mapping

As the overall aim of the broadband survey to map the structure (base) of a salt diapir was fundamentally different to the usual target (thin resistor at great depth), detailed feasibility modelling was needed to assess the CSEM sensitivity to the salt / sediment interfaces. As a first step we performed frequency / offset scans for representative 1D models to learn which parameters would potentially provide the best response and consequently most stable inversion result. Given the fairly shallow (top of salt some 200m below mud line) and very resistive (> 1.000 Ωm) target conventional low frequency CSEM data would only poorly resolve the parameters of interest (Figure 1). Frequencies of 1Hz to 100 Hz are needed to achieve a sufficient signal to noise level (A relative response of > 20 % is commonly regarded as achievable with real field data). Note the fundamental difference in response from top- and bottom of salt with respect to both frequency and offset.

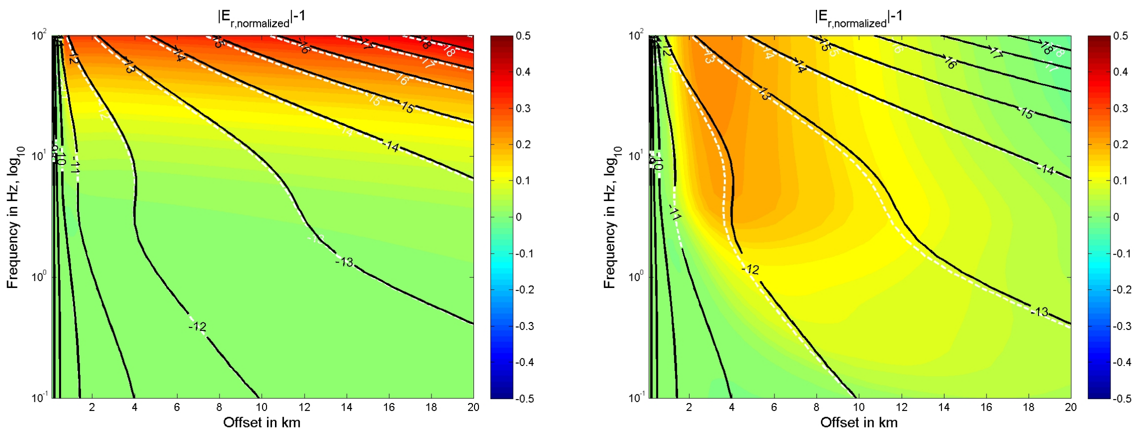

Figure 1 *CSEM sensitivity to salt layer thickness from a 1D sedimentary model with an embedded 1 km thick salt body (1.000 Ωm) extending from 180 m below the seafloor (210 m water depth, sediments 2 to 5 Ωm). Left and right panel show colour maps of normalized E-field amplitude sensitivity to 10% depth increase for top of salt and bottom of salt. E-field magnitude is indicated by the contour lines.*

For detailed survey planning and to assess the edge effects of the three dimensional salt body, 1D results have been followed up with exemplary 2D feasibility modelling. While these results are to complex to show here, we provide a cross section of electric field amplitudes created in a salt diapir by a CSEM transmitter (horizontal electric dipole) on the sea floor (Figure 2). The colour map clearly indicates how the high salt resistivity gives rise to strong electric field amplitudes and deflection of the current lines on the strong contrast between salt and surrounding sediment. A sea-floor to borehole CSEM tomography survey layout (Kong et al., 2009) would appear promising for detailed mapping of the salt diapir underside.

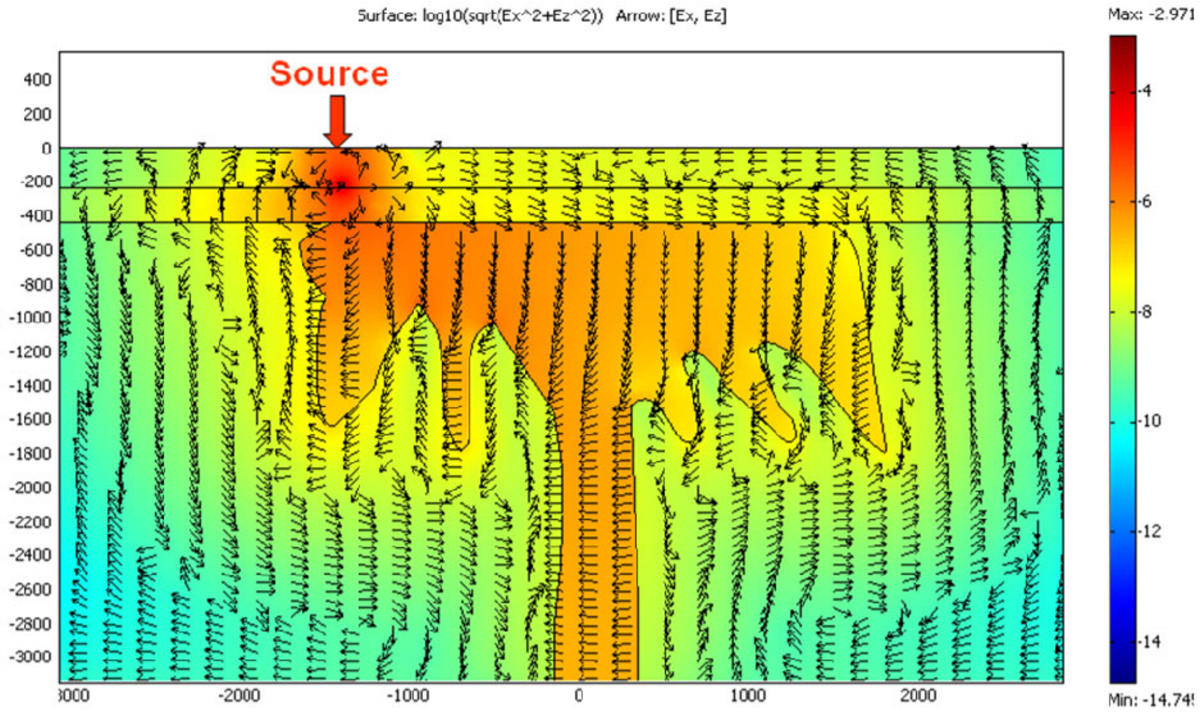

Figure 2 *Cross section showing electric field amplitude (colour map) and trajectory (arrows) derived synthetically using a 2D finite element CSEM model of a representative salt diapir structure (100 Ωm).*

The Uranus salt diapir

The study area lays over the Uranus structure (Nordkapp Basin, Barents Sea, PL 202), a salt dome with uncertain base of salt (Figure 3). The existing seismic data over Uranus, indicates that the sediment thickness between the seabed and salt is in the order of 100 to 200m mostly Quaternary sediments. The water depth is about 230m, and occasional pockmarks can be seen on the seabed. Current seismic data leaves large uncertainties in the interpretation of the shape and size of the salt body. Amongst other reasons high-velocity sediments surrounding the salt structure, multiples and internal salt structure diffractions make it difficult to define base of salt (Haugen et al., 2008).

Broadband CSEM data acquisition

In the pursuit for additional information especially regarding the base of salt, the PL 202 license partners a the time (Statoil and Hydro) gave NGI the opportunity to carry out a "Wide Band Controlled Source EM test" over the Uranus structure, using custom built equipment. The intention was to improve the definition of base of salt with a survey covering frequencies in the band from 0.01 Hz to 500 Hz. The wide band CSEM test was conducted along the seismic well line where also a multi-offset and walk-away VSP survey had been conducted. Three CSEM receiver stations, each containing two E-field spreads (20m dipoles separated by 180m), 4 component seismometers and 3 component fluxgate magnetometers, were placed on the seabed over the top of the structure (Figure 4). A 150m long horizontal electrical dipole source was laid out on the seafloor and transmitted both discrete sinusoidal and square waves, and stepped frequency sweeps at amplitudes up to 100 A. Source stations where separated 150m to 300m. Additional to CSEM signals, also a small airgun was used to image top of salt with the 4C ocean bottom stations.

CSEM results

For the majority of frequencies E-field data quality was satisfying (0.1Hz and 250Hz), while the magnetometers only provided data up to medium offsets due to the comparably low sensitivity of fluxgates used at the time (2006). Seismic data was of poor quality due to the small source but top of salt could generally be identified and corresponded well with 1D CSEM inversion on parts of the data with transmitter positions within the salt outline (fulfilling the 1D approximation). Additionally to the seismic depths, also resistivities from a then existing well (7227/11-1) where matched with CSEM inversion deriving salt resistivities of over 1.000 Ωm. Even with base of salt being the main target, proper modelling of the overburden is crucial due to the diffusive nature of CSEM fields. These consistent results confirmed good data quality and encouraged further interpretation.

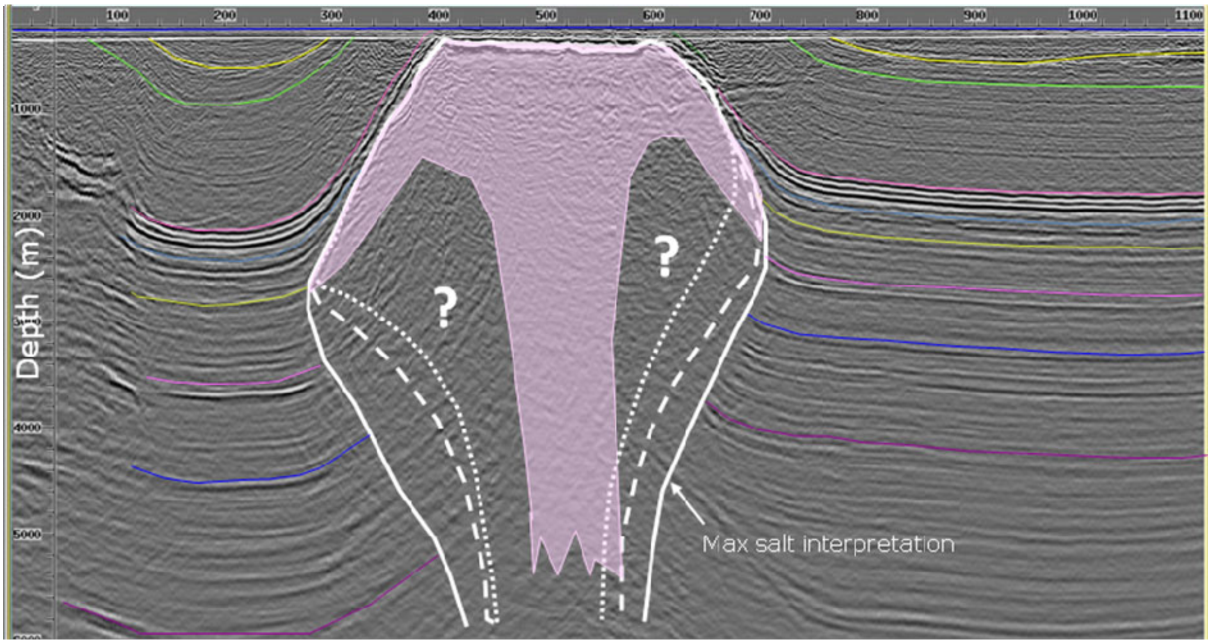

Figure 3 *Seismic section of the Uranus structure with possible minimum and maximum base of salt interpretations (pre well).*

Further 2D CSEM data analysis was carried out with NGI's structural inversion approach using an in-house, purpose developed 2.5D finite element code. Our strategy is to use horizons from depth migrated seismic data as constraints for distinct geological units. Subsequently the inversion algorithm finds resistivities for these bodies and optionally also updates the geometry within certain boundaries. This approach leads the ill posed EM inversion problem to a regularized, geologically meaningful solution. The Uranus well (green lines in Figure 4) was terminated in salt much deeper than expected (3 km true vertical depth) and thus proved the assumed diapir structure wrong (pink in Figure 3). CSEM models with deep and shallow salt bodies were in agreement with this finding with deep salt giving better fits (Figure 4). Electrical anisotropy in the basin sediments (up to a factor of 4 for the Triassic) needed to be taken into account to achieve satisfying data fits

Conclusions

The research survey discussed here was very successful in the sense that it proved the concept of multi frequency CSEM to map salt structures. This was achieved by thorough survey planning and feasibility studies in tight cooperation with the end user of the data, a crucial aspect of successful CSEM campaigns. Extensive processing and inversion (also Statoil in-house) proofed the value of broadband CSEM data for better model resolution and confidence.

Based on the promising results from this survey, Statoil did later (in 2007) acquire another 20 EM lines (both CSEM and marine magnetotelluric) to map another 10+ salt structures in the Nordkapp Basin (Hokstad et al, submitted to SEG monograph, editor Leon Thomsen)

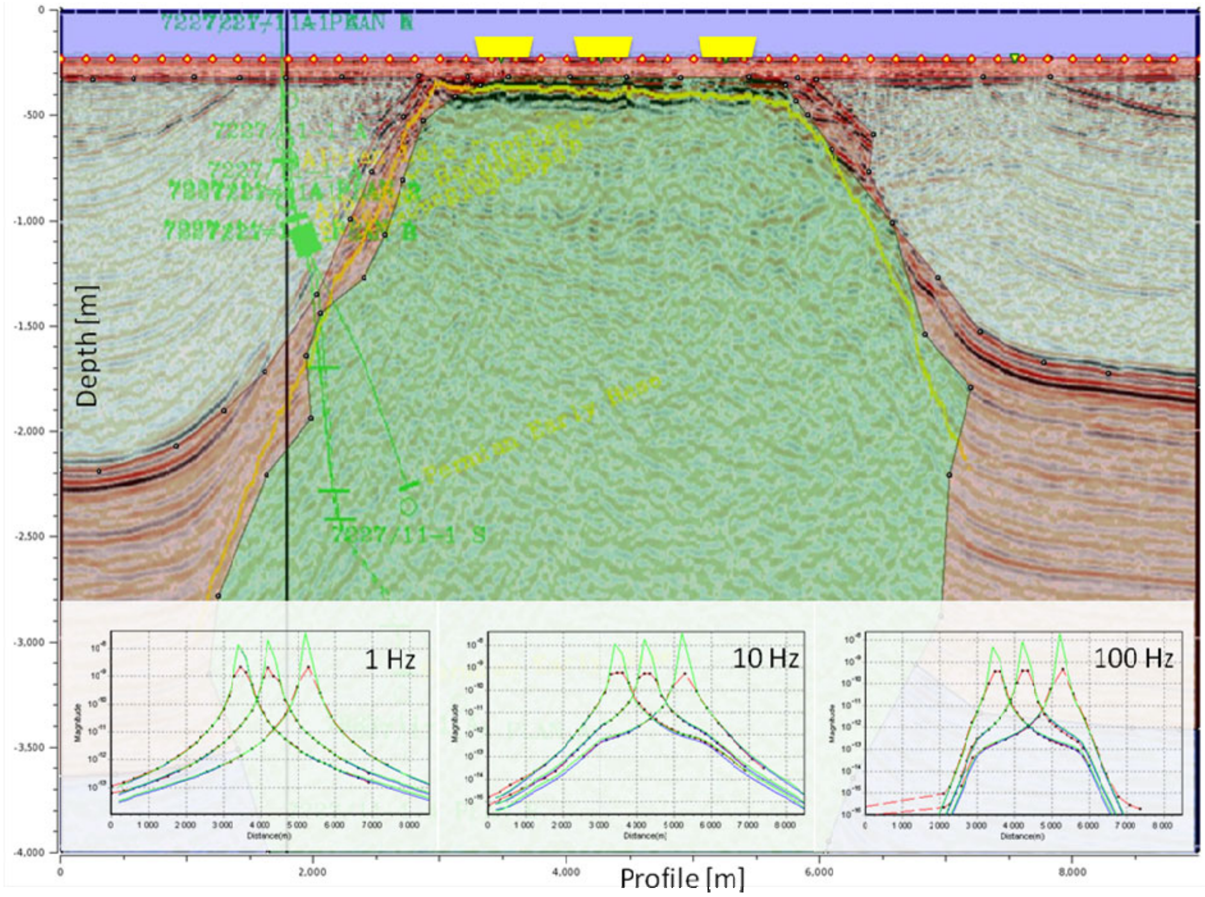

Figure 4 *2.5D CSEM structural interpretation model with seismic section in the background including receiver positions (yellow trapezoids. Graph insets show E-field amplitude curves for modelled and measured data for some selected frequencies for the shown deep salt model. Note the excellent data fit and the poor sensitivity of the low frequency data to the salt edges.*

Acknowledgments

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