The first practical 3D inversion of towed streamer EM data from the Troll field trial

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Summary

During 2010, PGS conducted one of the first field trials of their towed streamer electromagnetic (EM) system at the Troll field in the Norwegian North Sea. Obviating the need for ocean bottom receivers, the towed-streamer EM system enables CSEM data to be acquired simultaneously with seismic over very large areas in frontier and mature basins for higher production rates and relatively lower cost than conventional CSEM. The towed streamer EM data are currently processed and delivered as a spectrum of frequency-domain responses. In this paper, we review the large-scale 3D inversion of towed streamer EM data using a moving sensitivity domain. We present a case study for the 3D inversion of towed streamer EM data from the Troll field, and demonstrate our ability to image the Troll West Gas Province and Troll East Gas Province.

Introduction

The premise of the various marine CSEM methods is sensitivity to the lateral extents and thicknesses of resistive bodies embedded in conductive hosts. Over the past decade, CSEM surveys have been characterized by arrays of fixed ocean-bottom receivers and towed transmitters, and applied to de-risking exploration and appraisal projects with direct hydrocarbon indication. The most successful applications of CSEM to date have been in complement to those seismic interpretations where lithological or fluid variations cannot be adequately discriminated by seismic methods alone (e.g., Hesthammer et al., 2010). However, relatively high acquisition costs have represented a significant obstacle to widespread adoption of conventional CSEM technology, particularly in frontier basins and infrastructure-led exploration. To this end, a towed streamer system capable of simultaneous seismic and EM data acquisition has recently been developed and tested in the North Sea (Anderson and Mattsson, 2010; Mattsson et al., 2010; Linfoot et al., 2011; McKay et al., 2011). This moving platform geometry (Figure 1) enables EM data to be acquired over very large areas for higher production rates and lower costs compared to conventional CSEM methods.

In exploration, hydrocarbon reserves and resources are estimated with varying confidence from volumetrics that are predicted from different 3D earth models and scenarios. Quantitative interpretation of EM data is inherently reliant upon 3D earth models derived from inversion since EM data cannot simply be separated or transformed with linear operators as per seismic methods. However, methods for inverting CSEM data are complicated by the very small, non-unique and nonlinear responses of hydrocarbon-bearing reservoir units when compared to the measured total fields. Moreover, 3D inversion of towed streamer EM data poses a significant challenge because of the increased scale of the surveys, the requirement for high resolution models, and the significantly increased number of transmitter-receiver pairs.

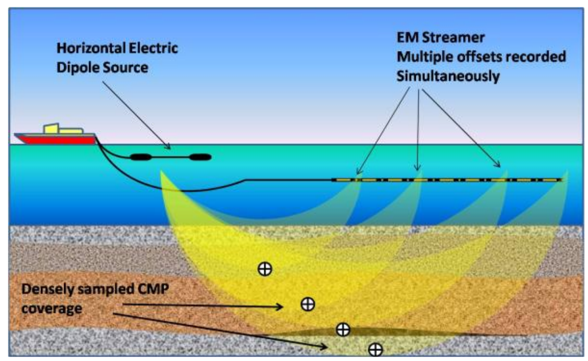

Figure 1. *Typical in-line towing configuration of sources and receivers for the towed streamer EM system.*

Large-scale 3D inversion of towed streamer EM data

Large-scale conventional CSEM surveys may have in the order of hundreds of fixed receivers, and in the order of thousands of transmitter positions. Reciprocity is routinely exploited in 3D conventional CSEM modeling and inversion to minimize the number of source terms that need to be solved (e.g., Zhdanov et al., 2011a). Towed streamer EM surveys may have thousands of transmitter positions, and thousands of receiver positions. Reciprocity cannot be exploited for any computational efficiency. In this respect, towed streamer EM surveys are analogous to airborne EM (AEM) surveys, in that they consist of moving transmitter-receiver pairs. As per our recent developments culminating in the first practical, large-scale 3D AEM inversion methodology (e.g., Cox et al., 2010), we can exploit the fact that the volume of the towed streamer EM system's sensitivity is significantly less than the size of the survey area, and we introduce the concept of a moving sensitivity domain (Zhdanov et al., 2011b).

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Following Zhdanov (2002), the volume of the subsurface where a specific transmitter-receiver combination in a towed-streamer EM system has a measurable sensitivity can be determined from the integrated sensitivity of the system, allowing the interpreter to evaluate a cumulative response of the observed data due to the physical properties of the subsurface. The dimensions of the sensitivity domain are dependent on the transmitter and/or receiver locations, geometries and components of the observed data, spectral content of the data, and subsurface physical properties. The volume of the sensitivity domain is usually much smaller than the volume of the entire earth model used to describe the subsurface. For a given transmitter-receiver pair, the responses and Fréchet derivatives are computed from a 3D earth model that encapsulates the towed streamer EM system's sensitivity domain. The sparse (rather than full) Fréchet matrix for the entire 3D earth model is then constructed as the superposition of Fréchet derivatives for all sensitivity domains. It follows that memory and computational requirements can be reduced by several orders of magnitude. For example, the number of non-zero elements in each row of the Fréchet matrix is just the number of cells within each sensitivity domain (in the order of thousands to tens of thousands) rather than the total number of cells in the 3D earth model (in the order of millions).

We use a reweighted regularized conjugate gradient method for minimizing our Tikhonov parametric functional that incorporates focusing regularization (Zhdanov, 2002). We base our frequency-domain modeling on the 3D contraction integral equation (IE) method (Zhdanov, 2009). In practice, there are several distinct advantages to using an IE method in a moving sensitivity domain inversion, rather than any of the finite-difference, finite-volume, or finite-element methods. First, the Green's tensors and background electric fields beyond the towed streamer EM system's footprint needn't be calculated, and all boundary conditions on the footprint domain are perfectly matched. Second, the body-to-body Green's tensors can be pre-computed for a single footprint domain and translated across the entire 3D earth model. Third, the integral equation can be written to directly solve for the total electric field in the 3D earth model while preserving the distributed source term. Fourth, the integral equation can be expressed as a convolution, enabling FFT matrix-vector multiplications to reduce computational complexity in Krylov subspace methods from $O(n^2)$ to $O(n\log n)$. Fifth, the Fréchet derivatives can be accurately calculated for negligible expense using the quasi-analytical method. Sixth, the transmitter-receiver pairs and their sensitivity domains need not correspond with grid positions, edges or centers. Finally, in practice, sensitivity domain-related indexing can be generalized to include frequency-dependent model discretization and sensitivity domain size.

Case study – Troll field, North Sea

The Troll field, operated by Statoil, is located in the Norwegian sector of the North Sea (Figure 2) within blocks 31/2, -3, 5, and -6. The field is separated into three parts; the Troll West Oil Province (TWOP), the Troll West Gas Province (TWGP), and the Troll East Gas Province (TEGP). The reservoir intervals are Jurassic (Songefjord Formation) sandstones. Gas-filled reservoir intervals have resistivities of approximately 70 Ωm, while the water-saturated sands and overburden have resistivities in the range of 0.5 Ωm to 2 Ωm. The TWGP is an ideal CSEM target, and has been previously surveyed for various CSEM field trials (e.g., Admundsen et al., 2004). A field trial of the towed streamer EM system was undertaken over the Troll field during 2010. The aim of the survey was to demonstrate that the towed streamer EM system was capable of acquiring EM data suitable for delineating the Troll reservoir structures, and for extracting subsurface information about them via 3D inversion.

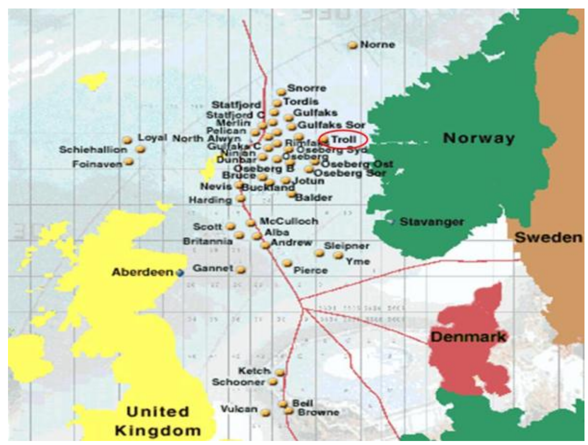

Figure 2. *A map of the Troll Field location.*

The Troll survey comprised of 12 lines of data (Figure 3) acquired above benign bathymetry at an acquisition speed of 4 knots. During the survey, the weather was uniformly poor, with sea states of 5. Nine of the lines crossed the TWOP, TWGP, and TEGP from west to east. One of the lines crossed the TWOP from north to south. Two of the lines replicated previous CSEM surveys (Admundsen et al., 2004). The rate of production is typical for seismic acquisition, and is several times faster than conventional marine CSEM acquisition.

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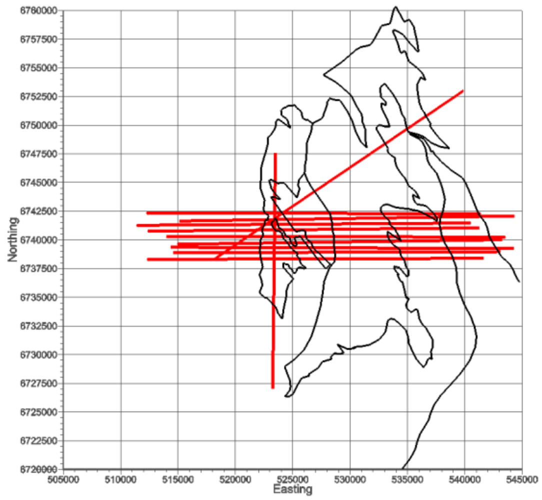

Figure 3. *A map of the towed-streamer EM Troll survey. Line 6 crosses the TWOP, TWGP, and TEGP.*

The data was acquired in water depths of approximately 320 m, with the main reservoir at a depth of 1420 m. A range of reservoir thicknesses occur between 40 m and 100 m, with the TWGP being the thickest and TWOP the thinnest (e.g., Figure 4). For this survey, 6500 m of streamer was deployed with receiver offsets between 2400 m to 5400 m. The source operated at 800 A with 800 m electrode spacing. The transmitter waveform consisted of an optimized repeated sequence designed to produce two decades of useable frequency content most sensitive to targets in the Troll field.

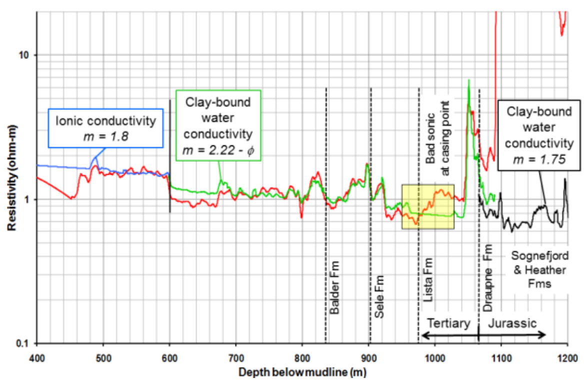

Figure 4. *Interpretation of resistivity logs for TWGP well 31-21.*

Qualitative interpretation of the towed streamer EM data shows clear responses from the TWOP, TWGP, and TEGP (Figure 5). We have applied our 3D inversion to all of the towed streamer EM data. The sediments were assigned a 2 Ωm isotropic resistivity. Note that, only in-line electric field data were measured by the towed receivers. The regularized conjugate gradient inversion was run for 23 iterations until the L2 norm of the residuals between the observed and predicted towed streamer EM data, normalized by the L2 norm of the observed data, decreased to about 10%. Figure 6 shows the convergence plot of the iterative inversion.

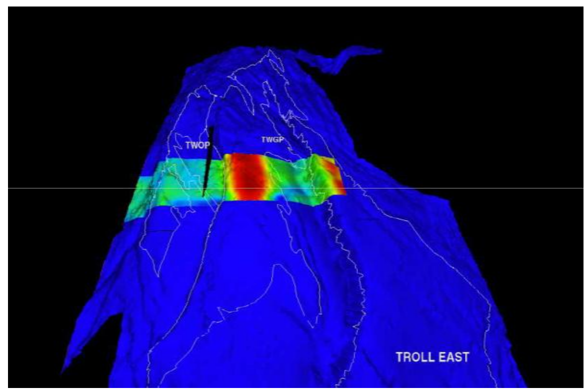

Figure 5. *Quantitative interpretation via the target response for the 5120 m offset data superimposed on the top of reservoir horizon. Note that the Troll West Oil Province (TWOP), Troll West Gas Province (TWGP), and Troll East Gas Province (TEGP) are apparent in the observed data.*

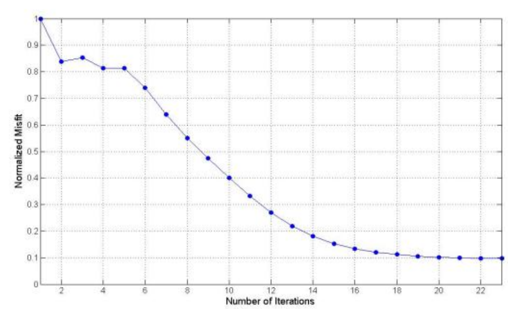

Figure 6. *Convergence plot of the iterative inversion of the towed streamer EM data from Troll.*

Figure 7 presents an example of the vertical cross section of the 3D resistivity model along line 6 as recovered from inversion. Line 6 is is oriented east-west and crosses TWOP, TWGP, and TEGP, respectively. The results in Figure 7 are shown for the inversion with minimum norm

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regularization. We should note, however, that, for the current example, no a priori information was used. Nevertheless, this figure shows a very promising initial result. The resistive zones are shown by dark blue color in this image, and represent the TWGP and TEGP. Line 6 only crosses a very thin part of the TWOP, and thus isn't readily apparent in the results. Given the poor weather conditions during the survey, the robustness of the towed streamer EM system with respect to noise from large wave heights have been demonstrated, and shown not to be a factor when inverting the processed EM data. In fact, the inversion was able to converge to about 10% misfit (Figure 6), implying that the towed streamer EM data are of relatively high quality. We anticipate that adding some a priori seismic information and focusing regularization will help us to produce an improved resistivity image, which is the subject of ongoing activity.

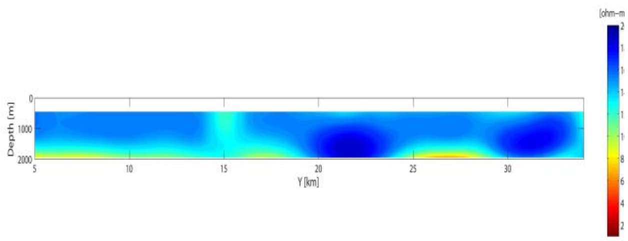

Figure 7. *An example of vertical cross section of the inverse resistivity model along line 6, which is oriented east-west along TWGP (~22 km) and TEGP (~32 km). The resistive zones (~20 Ωm, shown by dark blue) correspond to the TWGP and TEGP.*

Conclusions

Obviating the need for ocean bottom receivers, the recently developed towed streamer EM system enables CSEM data to be acquired simultaneously with seismic over very large areas in frontier and mature basins for higher production rates and relatively lower cost than conventional CSEM methods. The increased volume of CSEM data represents a challenge to existing 3D CSEM inversion methods. To that end, we have demonstrated a practical methodology for the large-scale 3D inversion of towed streamer EM data that is based on a moving sensitivity domain. We have presented a case study for the 3D inversion of towed streamer EM data from a 2010 field trial over the Troll field in the Norwegian North Sea. We have demonstrated our ability to image the TWGP and TEGP reservoirs from the towed streamer EM survey. Given the poor weather conditions during the survey, the robustness of the towed streamer EM system with respect to noise from large wave heights have been demonstrated, and shown not to be a factor when inverting the processed EM data. Indeed, the data were very high quality and the inversion was able to converge successfully.

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