3D focusing regularized inversion of marine transient electromagnetic data: A case study from the Alvheim field, North Sea

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Summary

We present a case study leading to the 3D inversion of transient electromagnetic (EM) data for delineating a reservoir's extent at the Alvheim field in the Norwegian sector of the North Sea. The survey was conducted in July and August 2008 using a two ship operation and ocean bottom cables. One ship laid a receiver cable with 30 receiver nodes on the sea floor. The second ship placed a source cable used to generate a coded transient signal on the sea floor. The configuration of the source and receiver spread was analogous to 2D seismic acquisition, as the system was rolled along to obtain multi-fold coverage of the subsurface. The survey spanned 21 km, resulting in measurements of 1270 source-receiver locations. The electric fields for each source-receiver pair were measured and deconvolved with the source current to determine the impulse response function. Preliminary inversions were made for each source-receiver pair using a 1D model, and the results were stitched to a 2D image. Having defined a background model, all data were then simultaneously inverted in 3D with focusing regularization. This revealed high resistivity volumes corresponding to the known hydrocarbon-bearing reservoirs of the Alvheim field.

Introduction

Oil and gas impregnation of a porous rock causes a substantial increase in resistivity. This is the property determined by electromagnetic (EM) surveying. Mapping high resistivity volumes in the subsurface may thus serve to delineate the extent of a reservoir. One way to conduct marine EM surveys is to inject a large transient electric current at the sea floor and measure the resulting electric fields using a multi-channel ocean bottom cable (OBC). The source and receiver spread are moved along the ocean floor in a manner similar to roll-along 2D seismic surveying. Processing techniques determine the impulse responses and inversion of that data enables the subsurface resistivity to be assessed. The OBC method of marine transient EM surveying was employed over the Alvheim field in the Norwegian sector of the North Sea in order to delineate the extent of a known reservoir (Figure 1). The targets lied some 2 km beneath the sea floor where the water depth was approximately 120 m. The complete survey included a feasibility study, data acquisition, data processing, 1D inversion and, what we believe is the first full 3D inversion for marine transient EM data.

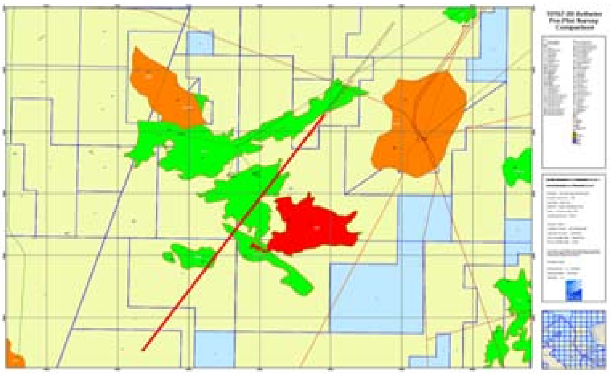


Figure 1. *Transient EM survey profile line (red) across the Alvheim field. The prospects are shown in green.*

Methodology

The multi-transient EM (MTEM) method (Wright et al., 2002; Ziolkowski et al., 2007) uses a current bipole source and a line of bipole receivers as depicted schematically in Figure 2.

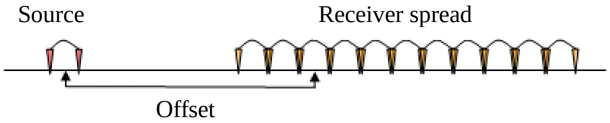


Figure 2. *Acquisition geometry for OBC transient EM surveying.*

Current may be injected at the sea floor between two source electrodes (the source) and the potential difference is measured between two distant electrodes (a receiver), also located on the sea floor. These four electrodes are generally collinear and the distance between the mid-point of the source electrodes and the mid-point of the receiver electrodes is termed the offset. Transient current injection at the source may take the form of a step change in current, such as a reversal in polarity of a DC current, or a coded, finite-length sequence such as a pseudo-random binary sequence (PRBS). The latter was employed exclusively in this survey and for the most part a PRBS of order 13 was used at a bit sampling rate of 25 Hz. This gave 8191 points describing the coded source waveform and each transient took around 5.5 minutes to generate. The measured voltage at the receiver is the convolution of the source term and the impulse response of the Earth plus noise. The impulse response can be determined by deconvolving the recorded signal at the receiver by the measured input source waveform. The deconvolution effectively compresses the 8191 points into a single spike and greatly increases the signal-to-noise ratio.

Data acquisition and processing

Data were acquired using a two-ship operation – one vessel operated the 700 A source whilst another controlled the OBC receiver cable. The profile line spanned 21 km and was positioned as shown in Figure 1. Data actually acquired are represented in the common midpoint (CMP) versus offset plot shown in Figure 3.

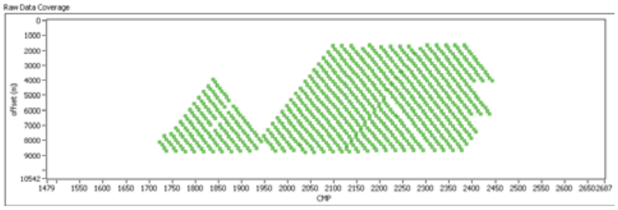
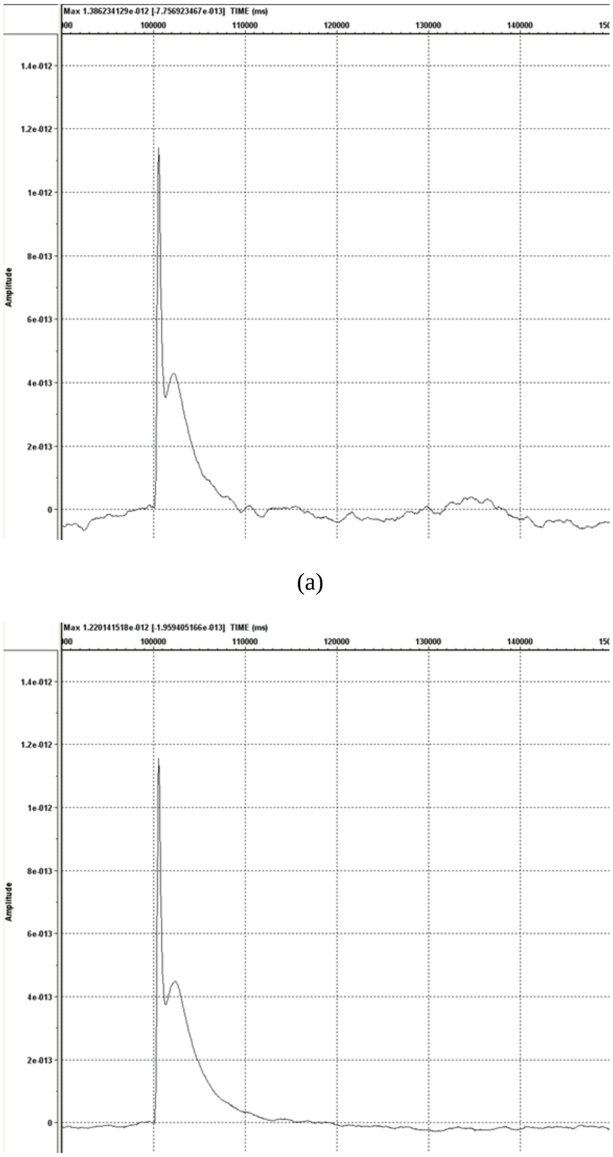


Figure 3. *Common midpoint (CMP) versus offset plot. The Earth's impulse response has been determined for each point over a lateral range of 15 km and an offset range of 2 km to 9 km.*

The source current was measured and relayed to the receiver vessel enabling deconvolution to impulse responses and real-time quality control. Further processing included magnetotelluric (MT) noise removal using the technique invented by Ziolkowski and Wright (2008) and demonstrated by Ziolkowski et al. (2009). An example of the effect of this process is given in Figure 4.



(a)

(b)

Figure 4. *An example earth impulse response (a) obtained from deconvolution of the received signal by the source current measurement and (b) after MT noise removal following Ziolkowski et al. (2009).*

1D inversion

As a first step towards interpretation, the impulse responses represented in Figure 3 were independently inverted using a 1D model with a maximum smoothness stabilizer; the so-called “Occam” approach (Hobbs et al., 2006). No a priori model was used so as to not bias the interpretation. The 1D inversion results were then stitched together to produce the resistivity image shown in Figure 6. This image shows a band of resistive material within which there are enhanced resistivity values between 17 km and 20 km along the profile, and at approximately 23 km along the profile. These coincide with the known aspects of the Alvheim complex.

3D inversion

Following the 1D inversion, a full 3D inversion was applied. The 3D inversion domain covered the profile from 12 km to 31 km, and extended from the seafloor down to 4 km depth. The regularized inversion scheme used the 3D integral equation method for modeling of the electric fields, and was iterated using the regularized re-weighted conjugate gradient (RRCG) method with focusing stabilizers (Zhdanov, 2002, 2009). In order to use the RRCG method for the minimization of the Tikhonov parametric functional, it is necessary to calculate the sensitivities of the data with respect to the model parameters. These calculations are based on the expressions for the Fréchet derivative matrix given by the quasi-analytical approximation with variable background. The details of these derivations can be found in Gribenko and Zhdanov (2007).

Traditional inversion algorithms providing smooth solutions for geological structures have difficulties in describing the sharp boundaries between different geological formations. We applied 3D regularized inversion algorithm with focusing stabilizers. Focusing regularization makes it possible to recover subsurface models with sharper geoelectric contrasts and boundaries than can be obtained with smooth stabilizers, such as the maximum smoothness one used in the 1D inversion. As per 1D inversion, no a priori model was used so as to not bias the 3D interpretation.

Multiple inversion scenarios were run for different inversion parameters. The resistivity image along the profile obtained from 3D inversion with the minimum vertical support stabilizer (Zhdanov, 2009) is shown in Figure 7. The image of the 1D inversion results from Figure 6 superimposed on the 3D inversion results is shown in Figure 8. The 1D inversion result is in general agreement with those obtained by 3D inversion; particularly the resistive feature between 17 km and 21 km. The lateral placement correlates well with the known location of the Alvheim complex. At the 20 km mark, the reservoir is known to have its top at around 2 km depth. The 3D inversion result places the resistive feature at the correct depth, and distinguishes it from the smaller and shallower resistivity anomaly circa 24 km. Moreover, the 1D inversion underestimates the resistivity relative to 3D inversion, and the maximum smoothness stabilizer of the 1D inversion blurs the model unlike the focusing stabilizer in the 3D inversion.

Conclusions

We have shown that transient electromagnetic surveying can produce high quality data in the form of impulse responses and that these may be inverted in 3D to successfully obtain subsurface resistivities of hydrocarbon-bearing structures over the Alvheim field. Stitched 1D inversion produces a useful preliminary resistivity image with accurate lateral positioning of resistivity anomalies, but with poor vertical control. On the other hand, 3D inversion produces an image correct in both depth and lateral position, and does not underestimate the resistivity. We expect that combination of the transient EM methodology which determines impulse responses and 3D inversion will make transient EM a most useful tool for hydrocarbon exploration, appraisal, and monitoring.

Acknowledgements

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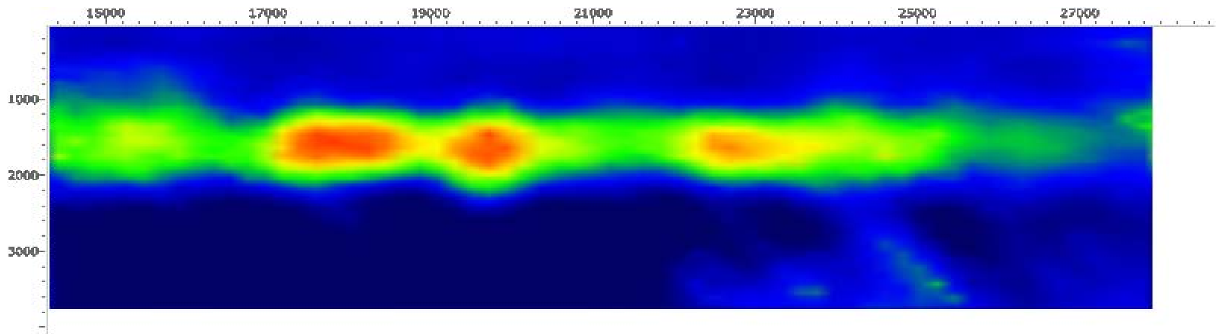

Figure 6. *Resistivity cross-section across the Alvheim field obtained from 1D inversion.*

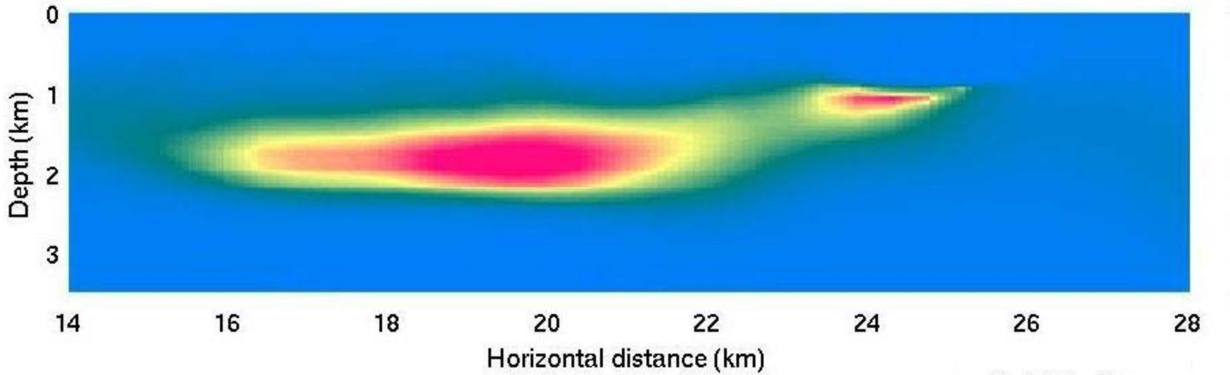

Figure 7. *Resistivity cross-section from the Alvheim field obtained from 3D inversion.*

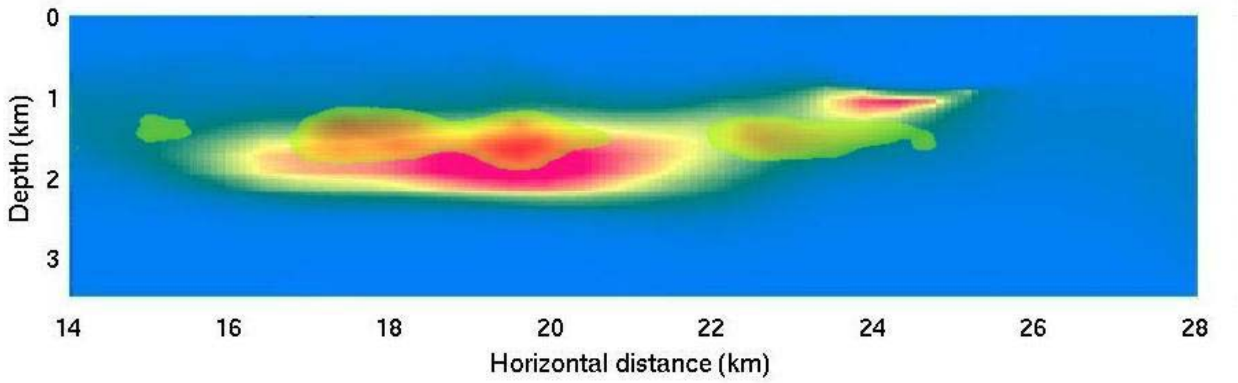

Figure 8. *Resistivity cross-section from the Alvheim field obtained from 3D inversion, with the* > 3 Ωm *features from the stitched 1D resistivity image superimposed upon it.*

EDITED REFERENCES

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