3D inversion of transient EM data: A case study from the Alvheim field, North Sea

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We present a case study leading to the 3D inversion of transient electromagnetic (EM) data for delineating reservoir extent at the Alvheim field in the Norwegian sector of the North Sea. The survey was conducted in July and August 2008 using one method of marine EM surveying, namely a two ship operation and ocean bottom cables. One ship laid a receiver cable with 30 receivers on the sea floor, and the second ship placed a source cable on the sea floor which was used to generate a coded transient signal. 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 20 km, resulting in measurements of 1270 source-receiver locations. The measured electric field for each source-receiver pair was deconvolved for the measured 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 and this is the property determined in 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 then measure the resulting electric fields using a multi-channel ocean bottom receiver cable. 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.

This 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 field. The target reservoirs lie some 2 km beneath the sea floor where the water depth is approximately 120 m. The complete survey included a feasibility study, data acquisition, data processing, 1D inversion and, what we believe is the first for marine transient EM data, full 3D inversion.

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 in Figure 1. Current may be injected at the sea floor between two source electrodes (the source) and the potential difference then measured between two distant electrodes (a receiver), also 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.

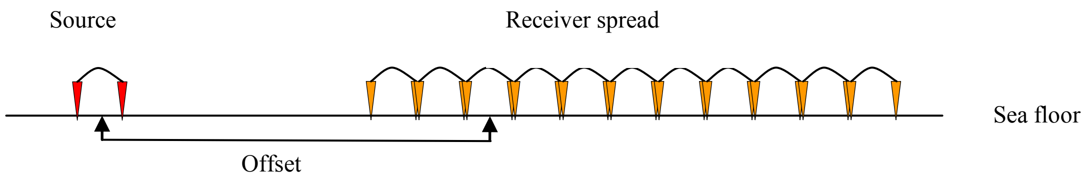


Figure 1 *Acquisition geometry for OBC transient EM surveying.*

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. The measured voltage at the receiver is the convolution of the source current with the impulse response of the Earth, plus noise. Thus the impulse response can be determined by deconvolving the recorded signal at the receiver for the measured input source waveform.

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 20 km and was positioned as shown in Figure 2. 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 3. The extent of the data coverage is represented in the common midpoint (CMP) versus offset plot shown in Figure 4.

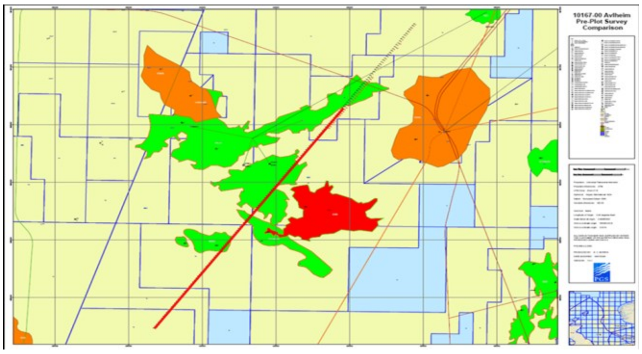
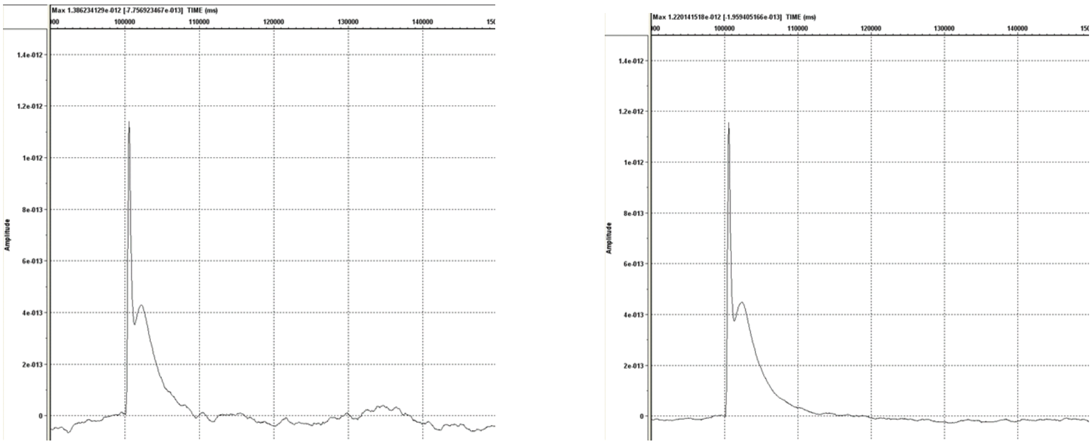


Figure 2 *Transient EM survey profile line (red) across the Alvheim field.*



(a) (b)

Figure 3 *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).*

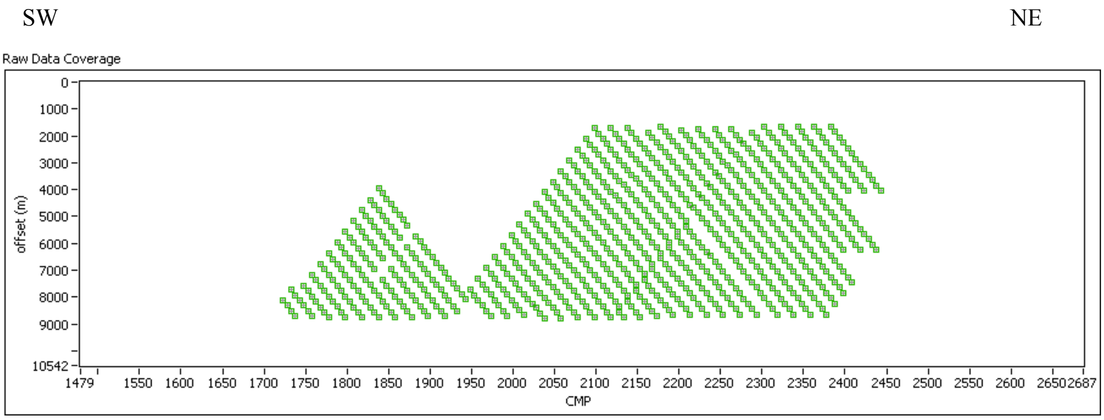


Figure 4 *Common midpoint (CMP) versus offset plot. The Earth's impulse response has been determined for each point over a lateral range of 15 km and an offset range of 2 km to 9 km. Distance along the profile is related to the CMP number through distance = (CMP/10-101)* x *200 m.*

1D inversion

As a first step towards interpretation, the impulse responses represented in Figure 4 were each independently inverted using a 1D model with a maximum smoothness stabilizer; the so-called "Occam" approach (Hobbs et al., 2006). The starting model for each inversion was a uniform half-space underlying a water column of prescribed depth (119 m) and resistivity (0.3125 Ωm). A simple inversion scheme was used to determine the resistivity value of the underlying half-space whose impulse responses best fitted the data. The 1D inversion results were then collated to produce the resistivity image shown in Figure 5. 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.

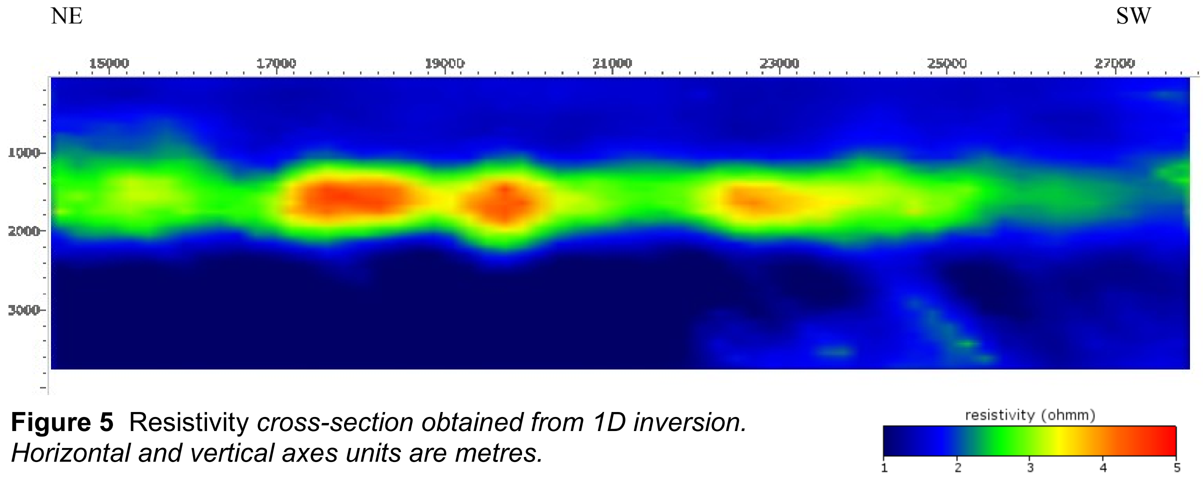


Figure 5 Resistivity *cross-section obtained from 1D inversion. Horizontal and vertical axes units are metres.*

3D inversion results

Following the 1D inversion, a full 3D inversion was applied. The regularized inversion scheme used the 3D integral equation method for modelling the electric fields and their sensitivities, and was iterated using the regularized re-weighted conjugate gradient method with focusing stabilizers (Zhdanov, 2002, 2009). The use of focusing stabilizers makes it possible to recover subsurface models with sharper geoelectric contrasts and boundaries than can be obtained with smooth stabilizers such as maximum smoothness used in the 1D inversion. We performed the inversion using the minimum vertical support stabilizer which minimizes the thickness of resistive structures which is typical of hydrocarbon-bearing reservoirs. The 3D inversion domain covered the profile from 12 km to 31 km, was 3 km wide and extended from the seafloor down to 4 km depth. The inversion domain was discretized into cells of 100 m x 300 m x 30 m size in the *x*, *y* and *z* directions, respectively. The starting model for inversion consisted of a water column of prescribed depth (119 m) and resistivity (0.3125 Ωm) above an otherwise homogeneous half-space (1 Ωm). Though the inversion scheme can include a priori geoelectric models of arbitrary complexity, no such a priori was used in this inversion. 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 is shown in Figure 6a. This inversion result reached a global misfit of the time-domain data less than 5%. The image of the 1D inversion results from Figure 5 superimposed on the 3D inversion results is shown in Figure 6b.

The 3D inversion result is in general agreement with that obtained by 1D 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 be around 2 km depth and the 1D inversion is seen to place the associated resistivity anomaly too shallow. 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. With the inclusion of structural information in a more detailed a priori geoelectric model, we believe the high quality of the data as shown in Figure 3 will enable elucidation of the subsurface in more detail.

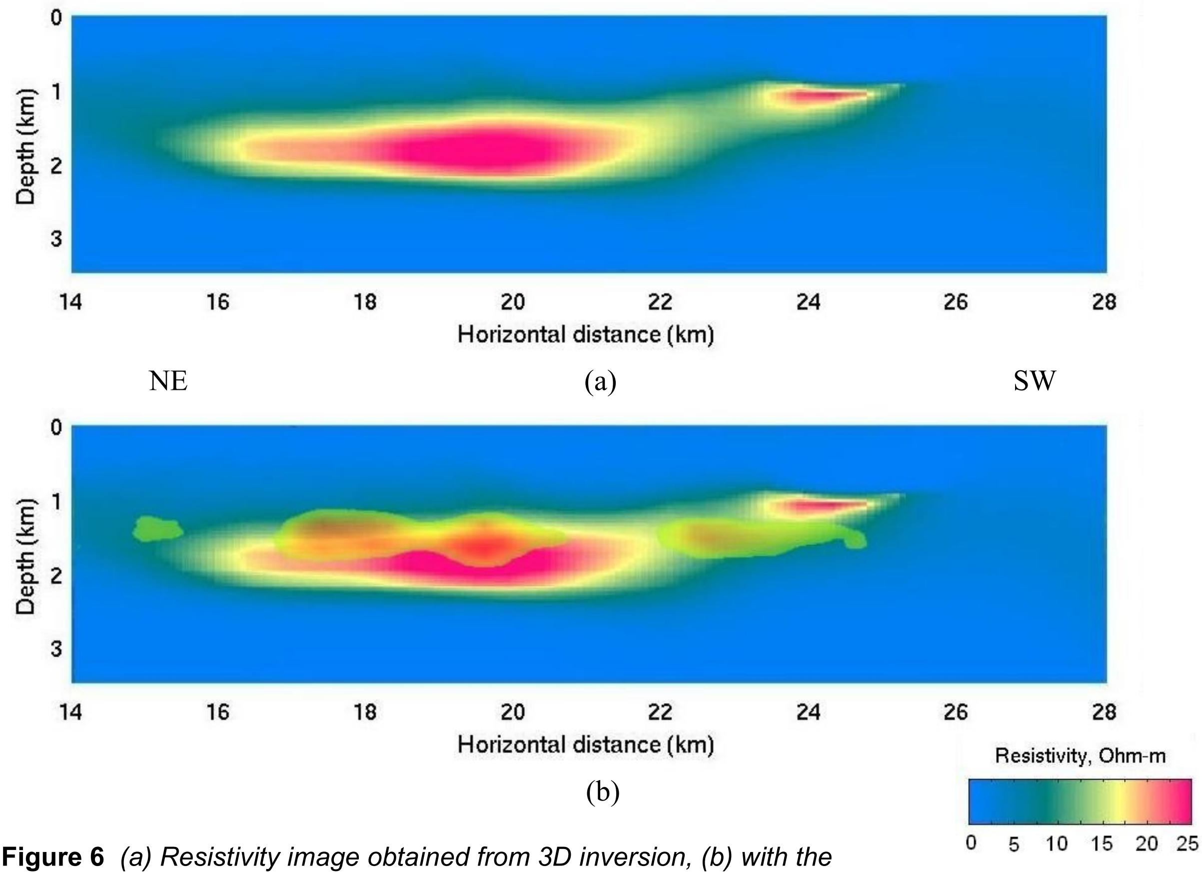


Figure 6 *(a) Resistivity image obtained from 3D inversion, (b) with the* > 3 Ωm *features from the collated 1D resistivity image superimposed upon it.*

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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