3D inversion of time-lapse CSEM data based on dynamic reservoir simulations of the Harding field, North Sea

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Summary

Recent studies have inferred the feasibility of time-lapse controlled-source electromagnetic (CSEM) methods for the monitoring of offshore oil and gas fields. The time-lapse CSEM inverse problem is highly constrained though inherently 3D since the geometry of the reservoir is established prior to production from high-resolution seismic surveys, rock and fluid properties are measured from well logs, and multiple history-matched production scenarios are contained in dynamic reservoir models. Using Archie's Law, rock and fluid properties from dynamic reservoir simulations of the Harding field in the North Sea were converted to resistivity, from preproduction in 1996 to decommissioning in 2016. CSEM data were simulated for each state. We demonstrate how 3D inversion can be used for monitoring the oil-water contact from preproduction to the end of oil production in 2011, and for monitoring of the gas-water contact from 2011 to 2016 during gas production. In particular, we show that focusing regularization is able to recover sharp resistivity contrasts across the oil-water and gas-water boundaries, whereas smooth regularization fails to recover an adequate resistivity contrast.

Introduction

Decisions pertaining to reservoir management are made on the basis of dynamic reservoir simulations which characterize production and subsurface uncertainty from a suite of probabilistic reservoir models populated with rock and fluid properties. These reservoir models are usually upscaled from detailed geological models, themselves built from the geostatistical population of well data within structural models inferred from seismic interpretation. During production, the confidence in a particular suite of reservoir models is garnered as the dynamic reservoir simulations are history-matched with known volumetrics.

During production, changes in reservoir rock and fluid properties manifest themselves as changes in acoustic impedance which, if measureable, can be interpreted from time-lapsed seismic surveys. In reservoir engineering workflows, these interpretations can provide additional reservoir characterization so as to reduce subsurface uncertainty (e.g., Walker et al., 2006). However, the sensitivity of seismic data to variations in fluid saturation is subtle, and it may only be after several years of production that a measurable change in acoustic impedance can be effectively interpreted. Should production veer towards the more unfavourable scenarios beforehand, the intervention strategies can be based only upon those reservoir models interpreted from baseline seismic data.

The premise of various controlled-source electromagnetic (CSEM) methods is that their responses are sensitive to the lateral extents and thicknesses of resistive bodies embedded in conductive hosts. Hence, the initial applications have been for de-risking exploration and appraisal projects with direct hydrocarbon indication (Hesthammer et al., 2010). Reservoir surveillance is a logical extension of the CSEM method on the basis of fluid discrimination, in particular tracking the position of the oil-gas and oil-water contacts. Recent model studies have implied the feasibility of time-lapse CSEM via 1D (Constable and Weiss, 2006), 2.5D (Orange et al., 2009) and 3D (Lien and Mannseth, 2008; Black and Zhdanov, 2009; Ziolkowski et al., 2010; Andreis and MacGregor, 2010) modeling. Black et al. (2010) demonstrated via a model study how 3D inversion of time-lapse CSEM data could recover the position of the oil-water and gas-water contacts.

In this paper, we present results of a model study from the Harding field in the UK sector of the North Sea. Using Archie's law, rock and fluid properties from the Harding Central dynamic reservoir models were converted to resistivity models, starting from pre-production in 1996 to decommissioning in 2016. CSEM data were then simulated for each of these models and then subjected to multiple 3D inversion scenarios. We demonstrate how 3D inversion can be used for monitoring the oil-water contact from preproduction to 2011, and can be used for monitoring of the gas-water contact from 2011 to 2016 during the gas blowdown phase. In particular, we show that focusing regularization is able to recover sharp resistivity contrasts across the oil-water and gas-water boundaries, whereas smooth regularization fails to recover an adequate resistivity contrast.

Time-lapse CSEM modeling and inversion

Survey repeatability for time-lapse CSEM is recognized as a significant technical challenge and remains subject to on-going research (e.g., Chuprin et al., 2008; Orange et al., 2009). Assuming that changes occur only in the reservoir, then the background conductivity model is constant. If we assume that CSEM surveys can be repeated, then the background electric fields are also constant. This means that time-lapse CSEM responses are due entirely to the differences in anomalous fields, and these are nonlinear to the anomalous conductivity models at both times. Moreover, inversion on the time-lapse CSEM response requires inversion for the anomalous conductivity distribution at both times! Hence, inversion of the time-lapse CSEM response is unlike inversion of time-lapse gravity responses, which are linear with respect to the change in model properties between both times. As such, we have found it is better practice to invert each CSEM survey independently, and preferable to use the baseline inversion results or reservoir models a priori for subsequent inversions. Such a strategy has the advantage that it obviates the need for precise survey repeatability and 4D interpretation workflows can be based on existing 3D interpretation workflows (e.g., Zhdanov et al., 2010).

Model study – Harding field, North Sea

Harding is a medium-sized oil and gas field covering approximately 20 km^2 that is located in block 9/23B in the UK sector of the North Sea, about 320 km northeast of Aberdeen (Figure 3). The field has a high net-to-gross, high quality, Eocene Balder sandstone reservoir about 1700 m below the seafloor in a 110 m water column. With 300 Mboe initially in place, production commenced in 1996 from the Harding Central and South reservoirs. Since then, two further reservoirs have been developed: Harding South East, and by extended reach drilling, Harding North. The reservoirs contain gas, and this has been injected back into a gas cap for later production. Oil production is now in decline, with current production of approximately 10,000 bpd with increasing water cut. The remaining hydrocarbon column consists of a gas cap about 100 m thick, and a thin oil rim about 20 m thick (Ziolkowski et al., 2010).

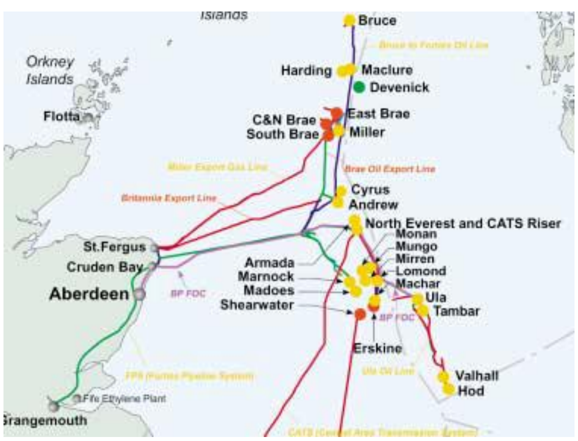

Figure 1. *Location of Harding field (courtesy of BP).*

The Harding Central dynamic reservoir models are populated by porosity and fluid saturations. Core analysis shows the Balder sands at Harding to be clean, so Archie's law is appropriate to relate the petrophysical properties to resistivity. Resistivity logs from well 9/23b-7 showed resistivities greater than 1200 Ωm through the dry gas intervals. In actuality, some intervals may exceed resistivities of 1200 Ωm, but resistive limits of CSEM responses mean that their values are indiscernible from CSEM data. The 3D model consisted of a 110 m 0.3 Ωm water column overlying an otherwise homogeneous half-space of 1.0 Ωm in which the Harding reservoir model was embedded (Ziolkowski et al., 2010).

CSEM data were simulated with the 3D integral equation method (Zhdanov, 2009). The CSEM survey consisted of six survey lines: three oriented north-south, and three oriented east-west (Figure 1). The line spacing was 1 km. Each line contained 11 receivers spaced 500 m apart, giving a total of 66 receivers. Data were simulated to offsets of 5500 m for inline and vertical electric fields and transverse magnetic fields at frequencies of 0.10, 0.25, 0.50 and 0.75 Hz. For inversion, data were threshold above the respective noise floors.

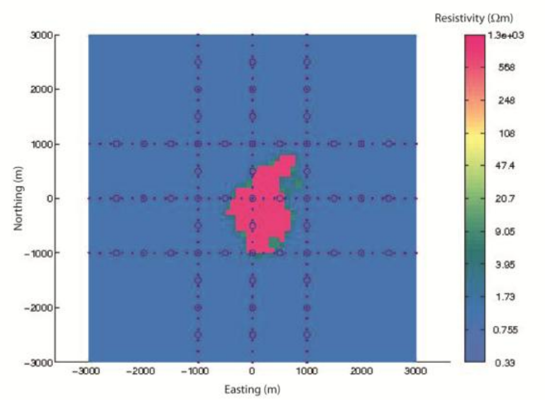

Figure 2. *Plan view of the Harding Central CSEM survey. The resistivity is shown for a cross section at 1662 m depth below the seafloor. Receiver positions are shown as circles, and transmitter positions are shown as dots.*

The inversion was iterated using the regularized re-weighted conjugate gradient (RRCG) method with focusing stabilizers (Zhdanov, 2002). Traditional regularized inversions provide smooth solutions and thus have difficulties describing sharp boundaries between different geological formations. Focusing regularization makes it possible to recover subsurface models with sharper resistivity contrasts and boundaries than can be obtained with smooth stabilizers (Zhdanov et al., 2010).

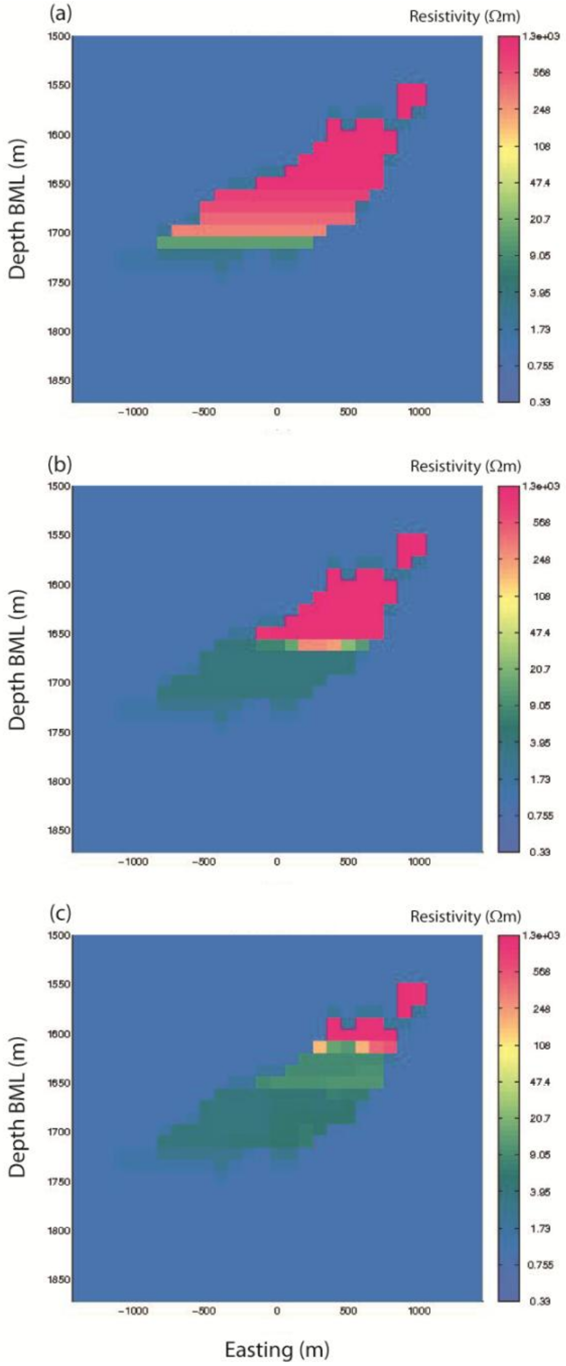

Figure 3. *Vertical cross sections of resistivity along 0 m northing from dynamic reservoir models for the (a) 1996 (pre-production) interval, (b) 2011 (end of oil production) interval, and (c) 2016 (gas blowdown) interval.*

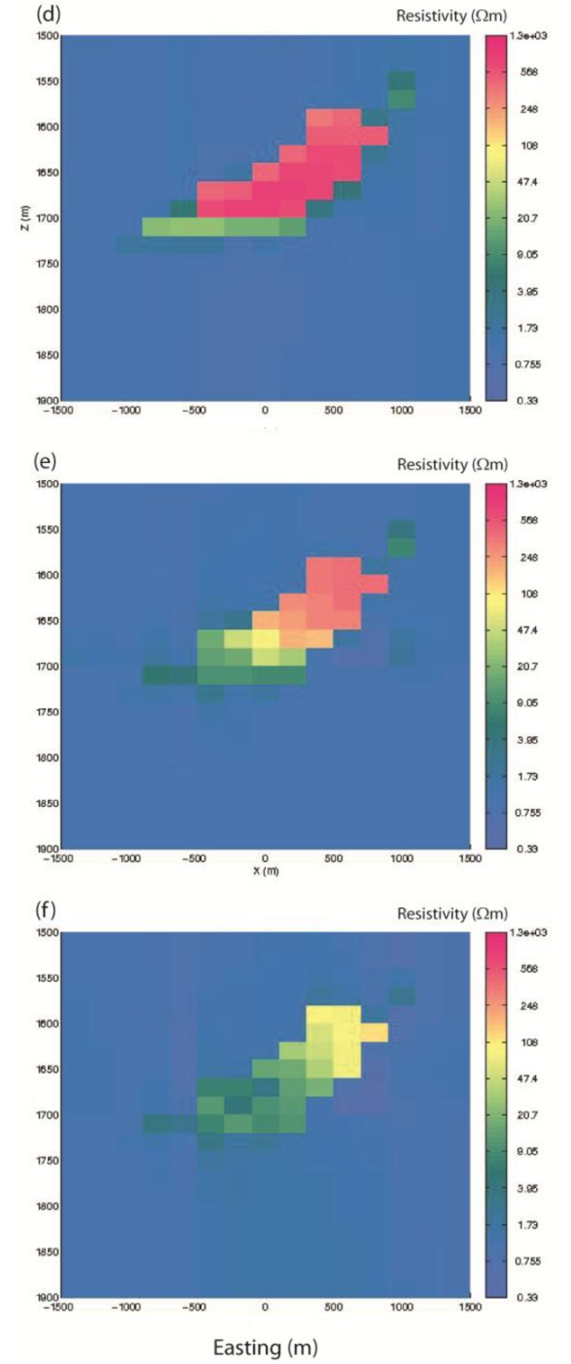

Figure 4. *Vertical cross sections of resistivity along 0 m northing from 3D inversion with minimum vertical support regularization for the (d) 1996 (pre-production) interval, (e) 2011 (end of oil production) interval, and (f) 2016 (gas blowdown) interval.*

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The a priori model for each 3D inversion was constructed by reducing the anomalous conductivity of the 1996 reservoir model by two-thirds. Results for 3D inversion with minimum vertical support regularization are shown in Figure 4. Note that we are able to recover sharp resistivity contrasts that can be related to the oil-water and then gas-water contacts. For the 2016 model, we do not recover the very high resistivities of the actual model, which we infer as the resistive limit of the CSEM method. Given the limited space of this expanded abstract, we cannot include a similar figure of the smooth inversion results for comparison. Suffice it to say that sharp resistivity contrasts are not recovered from smooth inversion.

Conclusions

Time-lapse CSEM inversion is highly constrained though inherently 3D since the geometry of the reservoir is established prior to production from high-resolution seismic surveys, rock and fluid properties are measured from well logs, and multiple history-matched production scenarios are contained in dynamic reservoir models. In this paper, we have used Archie's Law to transform rock and fluid properties from dynamic reservoir simulations of the Harding field to resistivity models. CSEM data were then simulated for each state. We have demonstrated how 3D inversion can be used for monitoring the oil-water contact from preproduction to 2011, and can be used for monitoring of the gas-water contact from 2011 to 2016 during the gas blowdown phase. Issues pertaining to survey repeatability can be minimized by 3D inversion of each survey independently, rather than attempting 3D inversion upon the difference of each model. Moreover, we have shown that focusing regularization is able to recover the sharp resistivity contrasts across the oil-water and gas-water boundaries, whereas smooth regularization fails to recover an adequate resistivity contrast.

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