Relaxed repeatability requirements for 4D marine CSEM: inversion study

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Summary

Repeatability of acquisition parameters for the base and monitor surveys is an important consideration for time-lapse studies of hydrocarbon reservoirs using controlled-source electromagnetics (CSEM). Variations in parameters such as source and receivers positions, conductivity and depth of seawater, etc lead to differences in the recorded EM fields that are often comparable to or exceed EM response due to production-induced changes in the reservoir resistivity. In that case, 4D CSEM is not feasible as long as 4D effects are analysed in the data domain. In the present study, we demonstrate the feasibility of 4D CSEM even for large differences in the acquisition parameters if the analysis is performed in the model domain. Using the "canonical" model considered by Orange *et al*. [Geophysics, 2009], we show that the repeatability requirements for water conductivity and receiver positions are relaxed approximately by an order of magnitude if the conventional sensitivity analysis is replaced by examination of inverted resistivity volumes.

Introduction

The time-lapse controlled-source electromagnetic (CSEM) method can be used to monitor changes in pore fluid during production of hydrocarbon reservoirs by imaging corresponding changes in electric resistivity. Despite numerous synthetic studies addressing feasibility of 4D CSEM (see e. g. Orange *et al*., 2009; Zach *et al*., 2009; Black *et al*., 2011; Andreis and MacGregor 2011, Patzer *et al*., 2017), there have been no marine CSEM surveys acquired so far that aim specifically at time-lapse applications. One of the main obstacles towards practical use of 4D CSEM is repeatability concerns, especially in a marine environment. Many acquisition parameters – position and orientation of source and receivers, conductivity and depth of seawater, source current and receiver calibration – will experience some variations between the base survey and a monitor survey a few years later.

Repeatability requirements for 4D CSEM have been analysed in several papers (Orange *et al*., 2009; Zach *et al*., 2009; Andreis & MacGregor 2011), but the analysis was restricted only to the data domain. Namely, it was postulated that differences in the recorded EM fields induced by non-repeatability of survey parameters must be smaller than the 4D response – differences in EM fields due to changes in the reservoir resistivity. That requirement might look logical, but can be misleading if the 4D effects are analysed in the model rather than in the data domain. Indeed, instead of comparing the two measured CSEM datasets, one can invert them and compare the resulting resistivity models. The inversion approach has already proven to be very efficient in analysing synthetic time-lapse CSEM data (Black *et al*., 2011; Andreis & MacGregor 2011, Patzer *et al*., 2017).

Unfortunately, no studies exist on how repeatable CSEM surveys should be for the inversion-based interpretation of 4D data to be successful in resolving small changes in reservoir resistivity. To answer this question we present a proof-of-concept study based on the "canonical" model considered by Orange *et al*. (2009). The repeatability issues are first addressed by the standard sensitivity analysis, and then by carrying out inversions of both synthetic datasets. It is demonstrated that the inversion approach allows one to relax the repeatability requirements for seawater conductivity and receiver positions approximately by one order of magnitude. The repeatability of survey parameters is thus a relatively minor issue as long as these parameters can be measured with acceptable accuracy. Similar findings have recently been reported for the 4D seismic problem (Qu & Verschuur, 2017).

Model

We used the 2.5D model introduced in the time-lapse study by Orange *et al*. (2009), see Fig. 1. A 5 km long hydrocarbon (HC) reservoir with resistivity of 100 Ωm is buried 1 km below the seabed. During production the

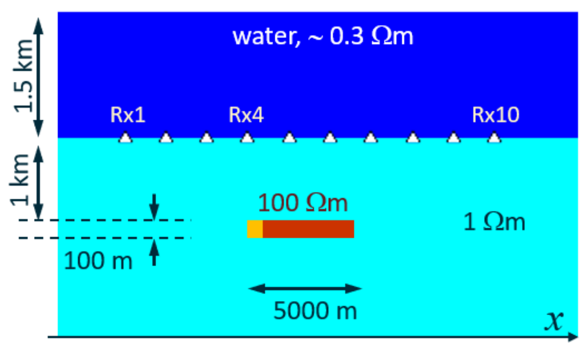

Figure 1: A 2.5D marine CSEM model used for the 4D study, as proposed by Orange *et al*., 2009. A 100 m thick oil reservoir with resistivity 100 Ωm is buried 1 km below the seabed. It is flooded from the left edge and reduction in its volume is picked up by CSEM response measured by 10 seabed receivers spaced by 2 km.

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reservoir is flooded from the left edge by 4, 8 or 12%, i.e. the reservoir length effectively reduces by 200, 400 or 600 m. Resistivity in the flooded part drops to 1 Ωm. A horizontal electric dipole source is towed 30 m above the seafloor, and seabed receivers are spaced 2 km apart.

For the non-repeatability study let us consider seawater conductivity σ_{water}: it will always vary between the base and monitor surveys due to high sensitivity to temperature and salinity. Orange and co-workers (2009) considered variation of σ_{water} from 3.03 to 3.175 S/m (i.e. by 4.5%), and we stick to the same numbers. Figure 2 illustrates that the EM response due to such a variation of σ_{water} (right panel) is comparable to the EM response from a 4% flooding (left panel). It is thus tempting to conclude that the given variation of water conductivity makes it impossible for the CSEM method to resolve depletions of 4% or less. This conclusion is however proven wrong by the inversion study introduced in the next section. The data uncertainty used for normalization in Fig. 2 (and for data weighting in inversion) assumes 2% multiplicative noise and a noise floor of 10^{-15} V/Am^2 for *E* and 10^{-12} 1/m^2 for *H*.

Inversion results

Synthetic data for reservoir before and after production are inverted using our in-house 2.5D Gauss-Newton inversion (Hansen & Mittet, 2009). The inverted data include Ex and Hy field components at frequencies 0.1, 0.4, 0.8 and 1.2 Hz, cut at the noise floor or at 10 km offset. The resistivity is assumed isotropic. The start model is a half-space with background resistivity of 1 Ωm. In 4D studies, the geometry of the reservoir is usually known, thus high resistivities were allowed only within or nearby the actual location of the reservoir. Elsewhere the resistivity was kept within ±20% of the true background value: from 0.8 to 1.25 Ωm. Smoothness regularization was relaxed around the reservoir edges and 800 m inside the reservoir to allow for a sharp resistivity contrast at the flooding front.

Fig. 3 (left) shows resistivity images obtained by inverting synthetic datasets for the fully saturated reservoir and three depletion stages of 4, 8 and 12%. For simplicity, the reservoir was represented as one cell thick, though a finer vertical resolution can be used when needed e.g. to discriminate between left and bottom flooding scenarios. Inversion recovered the correct resistivity close to 100 Ωm for the largest part of the reservoir with some deviations at the edges where regularization prevented an abrupt resistivity jump. Effect of flooding from the left edge is evident on the inversion images, where the flooding front is seen to move inside the reservoir during depletion.

Two synthetic datasets for depleted reservoirs were created: for water conductivity σ_{water} = 3.03 S/m and 3.175 S/m. Data for the fully saturated reservoir were computed with σ_{water} = 3.03 S/m. All datasets were inverted assuming perfect knowledge of water conductivity: start models had the correct value of σ_{water}. Resistivity difference images with respect to the full-reservoir case are shown in Fig. 3 (right). It is remarkable that one can hardly notice any effect of non-repeatability of the water conductivity: difference images for σ_{water} = 3.175 S/m look essentially as good as those for 3.03 S/m. Both show that the resistivity changes are localized to the left edge of reservoir, where they are supposed to be. Next, we averaged the inverted resistivities over the anomalous region and plotted its relative reduction versus the actual depletion, see Fig. 4 (left). Depletion detected from the resistivity images is very close to the actual depletion, only slightly underestimated. Moreover, variation of water conductivity

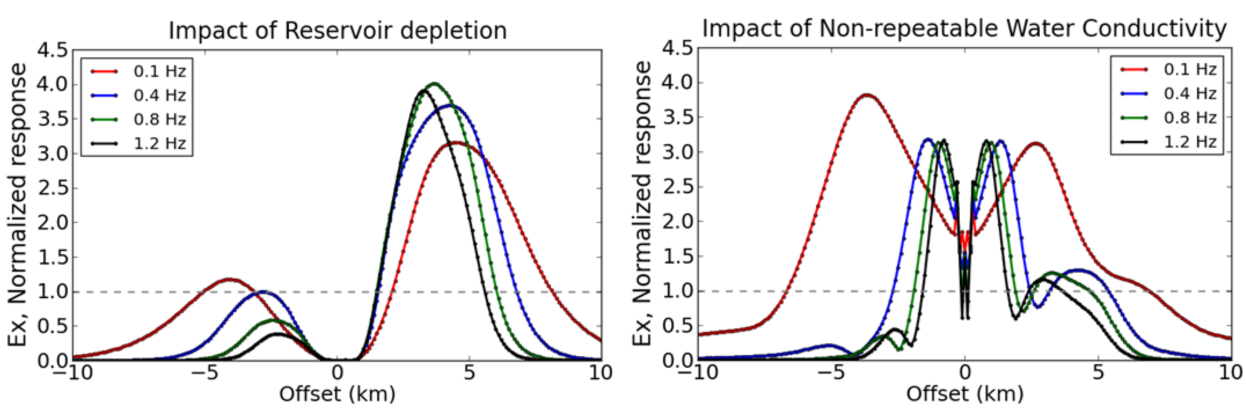

Figure 2: CSEM response resulting from a 4% depletion of the reservoir (left) and from a 4.5% variation of seawater conductivity (right). The response is recorded for receiver Rx4 placed above the depletion region (see Fig.1) and normalized to data uncertainty (dashed line shows the noise level). Variation of water conductivity strongly affects CSEM data and can mask the time-lapse response.

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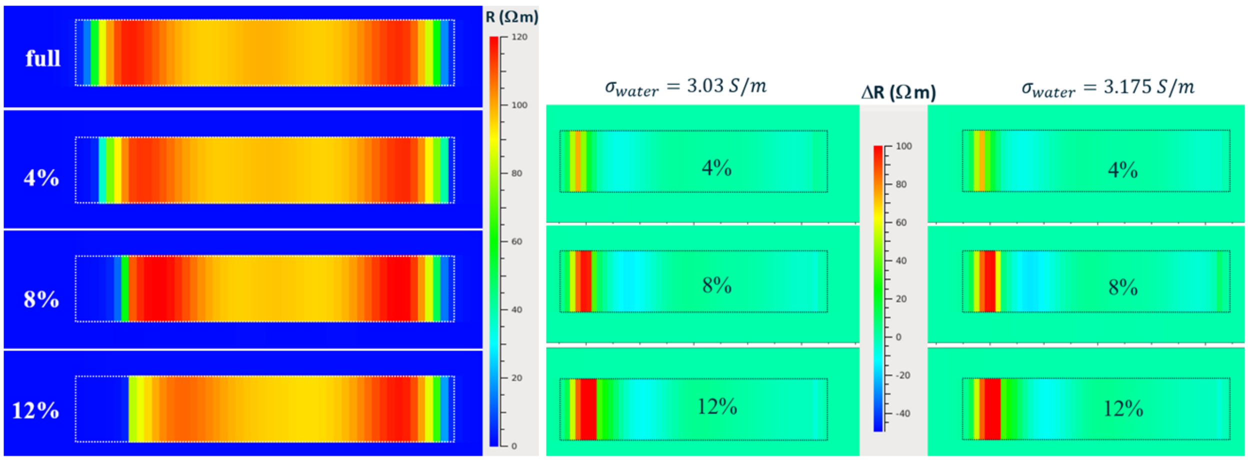

Figure 3: Inversion results: resistivity within the reservoir (left), and its changes (right) at different stages of depletion. The resistivity reduction at the left edge is equally well resolved for both cases of constant or varying water conductivity σ_{water} between the base and monitor surveys

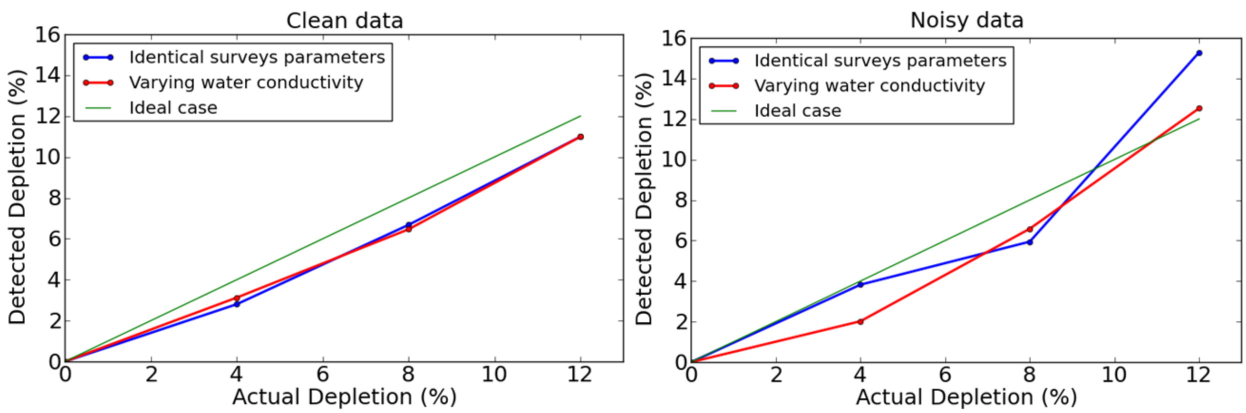

Figure 4: Depletion of HC reservoir determined by inverting CSEM data vs the actual depletion. Blue lines (fully repeatable surveys) and red lines (non-repeatable water conductivity) closely follow the "ideal behaviour" (green line). Non-repeatability in water conductivity does not make the detected depletion less accurate. This holds whether the inverted data were clean (left), or noisy (right).

between the two surveys has almost no effect on the inverted resistivity, though it had a strong effect on the CSEM data in Fig. 2.

Next, the inversions were repeated after contaminating data with 2% random Gaussian noise, and using the same noise floors for E and H as defined above. The 2% noise was uncorrelated for different receivers, offsets and frequencies, but correlated for E_x and H_y. The results are presented in Fig. 4 (right) and show that the detected depletion has also become more noisy and there is an additional random error. Nevertheless, our main conclusion still holds: non-repeatability in water conductivity did not degrade the ability of inversion to detect time-lapse changes in the reservoir.

Variation in Receiver Positions

During the monitor survey, the receivers may end up at slightly different positions than those at the base survey. Orange *et al*. (2009) argued that moving a receiver by 25 or 50 m may mask the observation of 4D effects if one directly compares the EM fields. In this study we analysed 4D effects in the model domain and observed that the

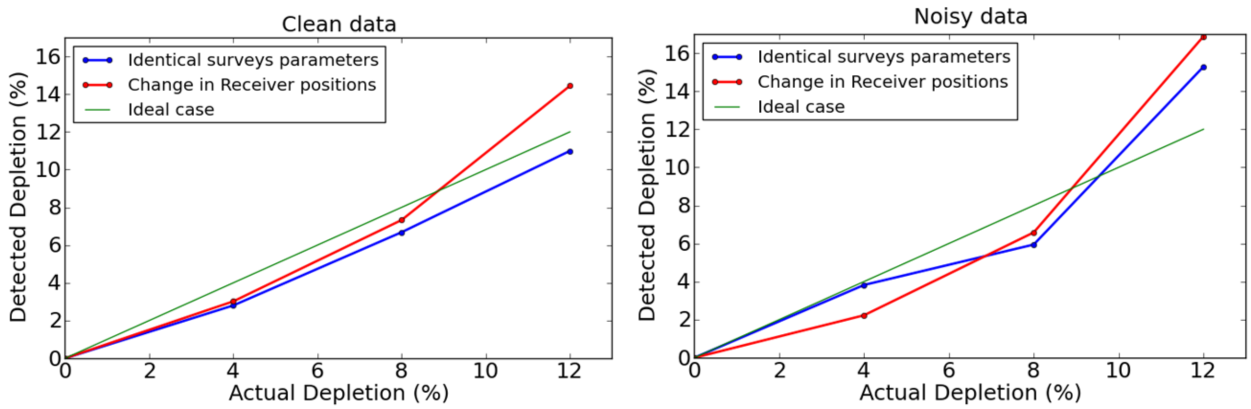

Figure 5: Depletion of HC reservoir determined by inverting CSEM data vs the actual depletion. The case of receivers randomly shifted by up to 500 m (red line) looks as good as the case of fully repeatable surveys (blue line). The green line indicates the ideal case. Left: inversion uses clean data; Right: the data are contaminated with noise, leading to larger errors in the detected depletion.

impact of shifted receivers is dramatically reduced. We shifted each receiver along the towline direction by a random distance between -500 and +500 m. The realistic non-repeatability in receiver position is much smaller than 500 m, but even in this extreme case, inverting the 4D CSEM data allowed one to accurately resolve early stages of the reservoir depletion as shown in Fig. 5 (left). Though receivers have been moved, we assume here that their positions were precisely known. If we add random noise to data (Fig. 5, right), errors in the detected depletion become larger, but remain equally large for repeatable and non-repeatable cases. Noise in data is directly related to measurements errors, thus Fig.5 essentially indicates that errors in the measured receiver positions is a bigger problem than their non-repeatability.

Discussion and Conclusions

It has been demonstrated that the repeatability of survey parameters in time-lapse CSEM studies is not a critical requirement if 4D effects are analysed in the model domain, i.e. employing the inverted resistivity images. It is however critical that these parameters are accurately measured. Repeatability requirements obtained by sensitivity studies can therefore be overly pessimistic and misleading.

A similar study (Babakhani, 2015) showed that the same conclusions hold even if the background resistivity in the start model is 10% wrong. Sensitivity to small changes in the reservoir resistivity can be further improved by “cascaded” inversions that utilize the fact that production-induced changes are localized only within the reservoir (Babakhani, 2015; Patzer *et al*., 2017). Denser receiver and towline spacing, e.g. 1.0 or 0.5 km used in appraisal CSEM surveys (Granli *et al*, 2017), as well as full-azimuth 3D coverage, should also boost resolution compared to the case considered in this work.

Acknowledgments

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