Monitoring of hydrocarbon reservoirs using marine CSEM method

Noel Black and Michael S Zhdanov, University of Utah*

SUMMARY

Marine controlled-source electromagnetic (MCSEM) technology has been successfully established as an effective tool for offshore hydrocarbon (HC) exploration. In this paper we consider another application of the MCSEM method for HC reservoir monitoring. We demonstrate that EM methods can also be used for the monitoring of producing wells in connection with the enhanced recovery of hydrocarbons. We have developed a powerful new EM modeling technique based on the integral equation method with an inhomogeneous background conductivity (IE IBC). This new method and the corresponding computer software make it possible to model the EM response over a realistic complex model of a sea-bottom HC reservoir. The numerical modeling results demonstrate that the MCSEM method has the ability to map changes in resistivity caused by the production of hydrocarbons over time. In addition, the EM data help to visualize changes in the location of the oil-water contact within the reservoir. This result opens the possibility for practical application of the EM method in HC reservoir monitoring.

INTRODUCTION

During recent years marine controlled-source electromagnetic (MCSEM) surveys have become intensively used for offshore petroleum exploration (Eidesmo et al., 2002; Ellingsrud et al., 2002; Carazzone et al., 2005). The importance of MCSEM as an exploration tool is now widely accepted. As the technology advances and the method becomes more affordable, applications other then exploration may find MCSEM data useful. In this paper we study the use of MCSEM methods for reservoir production monitoring.

Effective reservoir management requires time lapse reservoir information throughout the interwell volume. The ability to understand and control reservoir behavior over the course of production allows for optimization of reservoir performance and production strategies. Good monitoring information makes it possible to improve the timing and location of new drilling (both production and injection wells), to recognize flow paths, and to map oil that has been bypassed. The use of seismic data for monitoring is very challenging because of the small variation of seismic velocities over time and of the difficulty of survey repeatability.

Here, we perform a numerical experiment of reservoir monitoring using MCSEM. We compute EM fields for a model of a partially depleted sea-bottom reservoir with different positions of the oil-water contact over time. For a more realistic representation of the sea-bottom environment we include a salt dome and a rough sea-bottom bathymetry. As an EM modeling tool we use the integral equation (IE) based code (Hursán and Zhdanov, 2002). We use the multiple-domain (MD) IE method (Endo et al., 2009) to efficiently model extensive anomalous regions of bathymetry, salt structures, and the reservoir itself. Maps of the EM field components clearly reflect the position of the oil-water contact. The principal advantage of the multiple domain technique is that we are able to isolate the effect of the reservoir. This is especially important in the case where bathymetry must be considered. The oil-water interface is clearly resolved in several field components by extracting only the induction from the reservoir. Our study demonstrates that MCSEM data can accurately provide the position of the oil-water contact inside the reservoir over time.

PRINCIPLES OF RESERVOIR PRODUCTION MONITORING USING MARINE EM METHODS

EM methods are potentially useful as a means to monitor reservoir production because they can distinguish between hydrocarbons and saline water based on their differing resistivities. The range of resistivity variation is much greater than the range of variation for seismic velocities. Seismic data is useful primarily for estimating lithography and porosity, both of which remain essentially constant over the lifetime of a producing reservoir. Seismic velocities are different enough to discriminate fluid type (oil vs. water) only for high porosities, greater than about 30%. Since the velocity differences are small, seismic methods rely on fixing survey parameters so that differences between surveys at different points in time can be seen. The potential of seismic methods for monitoring is thus limited by the repeatability of the seismic surveys.

Enhanced oil recovery (EOR) is a prime scenario for investigating the potential use of EM for monitoring. For water injection recovery, there will be a flooding front that advances over time as the reservoir is produced. The ability to locate the position of this oil-water contact is an important test of the method. The main question with EM is resolution. It remains to be seen whether the low frequencies of these methods, which are needed to avoid attenuation to the depths of interest, can resolve the smaller length scales associated with monitoring compared with those needed for exploration. Since the process is diffusive, there is no applicable Raleigh criterion limiting expected resolution, and hence a numerical experiment needs to be performed.

OVERVIEW OF THE NUMERICAL MODELING TECHNIQUE

In this section we will present a short overview of the IE method with multiple domains following Endo et al. (2009). In the framework of the IE method, the conductivity distribution is divided into two parts: 1) the background conductivity, σ_b, which is used for the Green's functions calculation, and 2) the anomalous conductivity, σ_a, within the domain of integration, *D*. One principal advantage of the IE method over the other numerical techniques is that the IE method requires discretization of the anomalous domain *D* only.

The inhomogeneous background conductivity (IBC) IE method (Zhdanov et al., 2006) overcomes the limitation of the conventional IE method of restriction to layered backgrounds only and allows inclusion of important geoelectrical stuctures like bathymetry and salt domes in the background model. Endo et al. (2009) developed the iterative inhomogeneous IE method for modeling with multiple inhomogeneous domains. By using this method we can evaluate the individual response from every domain, which includes the possible EM coupling effects between the different domains. A rigorous separate calculation of the EM fields produced by different anomalous domains representing different geological structures (e.g., bathymetry, salt structures, reservoirs) represents an important practical problem of EM exploration.

COMPUTER SIMULATION OF HC RESERVOIR MONITORING USING EM METHODS

We have performed a numerical experiment of forward modeling for several stages in the production of a reservoir by water injection. We consider a realistic geoelectric model of a HC reservoir and accompanying salt dome, with a sea-bottom bathymetry. The reservoir is filled from one end with injected saline water. For simplicity we model the oil-water contact as a sharp vertical interface. The EM field is generated by horizontal electric bipoles near the sea floor and detected by a line of receivers at the sea floor. The model is described in more detail in the following section.

Geoelectrical model: HC reservoir and a salt dome structure, with a sea-bottom bathymetry

A vertical section of the geoelectric structure of the model is shown in Figure 1 . This figure shows a resistive HC reservoir with a resistivity of 100 Ohm-m and a salt dome with a resistivity of 30 Ohm-m located within conductive sea-bottom sediments whose resistivity is 1 Ohm-m. The resistivity of the seawater layer is 0.33 Ohm-m, and the depth of the seafloor is 1350 m below sea level. We have also included a rough sea-bottom bathymetry, with the same resistivity as the sea bottom. This is very important from a practical standpoint because the effect of the bathymetry can significantly distort the EM response from a HC reservoir, and therefore also of the oil-water interface position in production monitoring. As a prototype of the bathymetry structure we use a simplified model of the known bathymetry of the Sabah area, Malaysia (provided by Shell International Exploration and Production, acquired in 2004). The reservoir is flooded from the right (positive *x* direction) by 0.5 Ohm-m water. We model four positions (x_0 = 14.0, 12.8, 11.6, and 10.4 km) of the (vertical) oil-water interface to simulate production.

The EM field in this model is excited by an *x* directed horizontal electric bipole of length 1 m and current 1000 A, which is located at the points with horizontal coordinates from 0 to 20 km (every 200 m) in the *x* direction and from -3 km to 3 km (every 200 m) in the *y* direction. The elevation of the transmitter bipole is 50 m above the sea bottom. The transmitter generates the frequency-domain EM field at frequencies of 0.3 and 0.01 Hz (we studied a range of frequencies between 0.01 and 10.0 Hz, and present results for these two). We modeled 9 electric field receivers, equally spaced (2.5 km spacing) along the *y* axis between 0 and 20 km. To narrow the scope we confine our analysis in this paper to the first receiver (#1) at the far left of Figure 1 ($x = 0$).

Following the main principles of the MD IE method for multiple inhomogeneous domains, the modeling area is divided into three modeling domains D_1, D_2 and D_3, corresponding to the locations of the bathymetry, salt dome and HC reservoir, respectively. Domain D_1 for the bathymetry area is discretized into 200 x 60 x 10 = 120000 cells, domain D_2 for the salt dome area is discretized into 35 x 60 x10 = 36960 cells, and domain D_3 for the HC reservoir area is discretized into 40 x 40 x 8 = 12800 cells. All three domains have the same cell size, 100 x 100 x 25 m3, although in principle the cell size can be different in each domain.

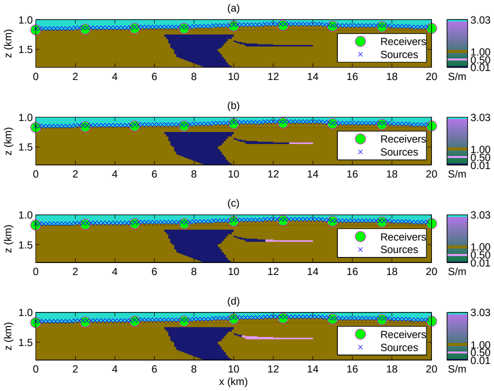

Figure 1: A vertical geoelectrical section of the model, containing a salt dome and a reservoir in an area with a rough sea-bottom bathymetry.

Forward modeling results

As an example, Figure 2 shows the *x* (in-line) component of the total electric field normalized by the fields induced in the layered background, the sea-bottom bathymetry, and the salt dome, $|E_x^{tot}|/(|E_x^b| + |E_x^{bath}| + |E_x^{sd}|)$, for the sea-bottom receiver #1 (located at $x = 0$) and for transmitter frequency 0.3 Hz. The solid white box indicates the horizontal position of the reservoir and the dashed white line indicates the horizontal position x_0 of the oil-water interface, for four different positions (i.e. stages of production). Water is filling from the right (positive *x* direction), forcing oil to the left (negative *x* direction). The interface is clearly seen for all four positions as an enhancement of the normalized field component.

Figures 3 (frequency=0.3 Hz) and 4 (frequency=0.01 Hz) show the *z* (vertical) component of the total electric field normalized by the fields induced in the layered background, the bathymetry, and the salt dome, $|E_z^{tot}|/(|E_z^b| + |E_z^{bath}| + |E_z^{sd}|)$, for the sea-bottom receiver #1. The unproduced portion of the reservoir is nicley outlined by a positive anomalous field along its boundary. We can clearly see not only the oil-water contact but also the location of the remaining hydrocarbon.

The magnitude of the source-moment-normalized anomalous reservoir electric field x and z components is in the range $10^{-14}-10^{-15}$ V/m. This is slightly above, or approximately at, the noise level of 10^{-15} V/m set by Um and Alumbaugh (2007). This noise estimate is slightly higher than that given by Constable and Weiss (2006). The magnitude of the source-moment-normalized anomalous reservoir magnetic field x and y components is in the range $10^{-8}-10^{-11}$ nT/m. The noise level quoted by Um and Alumbaugh (2007) is 10^{-10} nT/m. We therefore expect that at least some of these components will be detectable for the survey parameters modeled here.

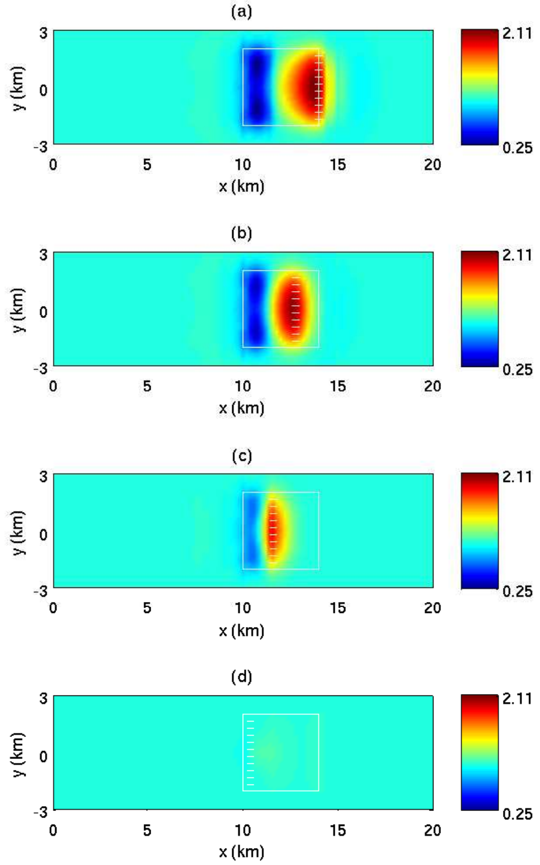

Figure 2: $|E_x^{tot}|$ normalized by background, bathymetry, and salt dome fields for frequency = 0.3 Hz.

CONCLUSIONS

The difference in the resistivities of oil and the water filling the reservoir during production allows the possibility to monitor the flooding front by EM methods. The oil-water interface can be clearly seen in several field components even with a

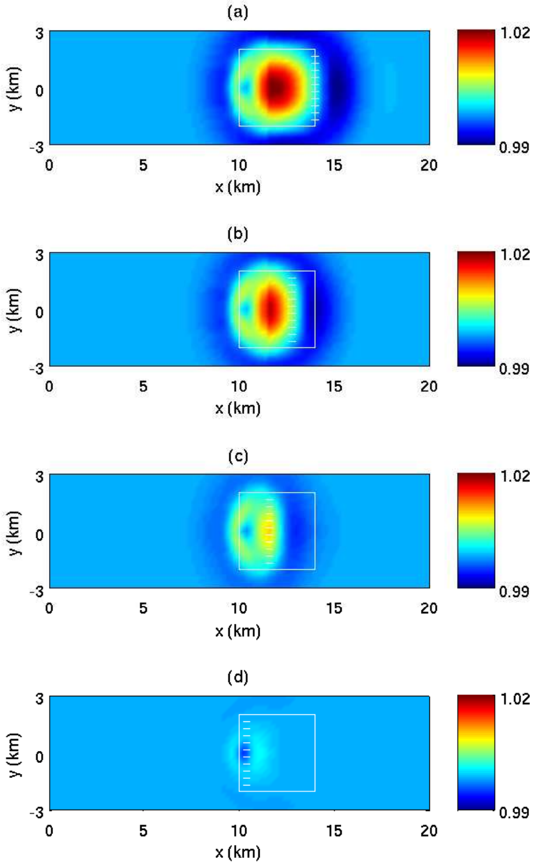

Figure 3: $|E_z^{tot}|$ normalized by background, bathymetry, and salt dome fields for frequency = 0.3 Hz.

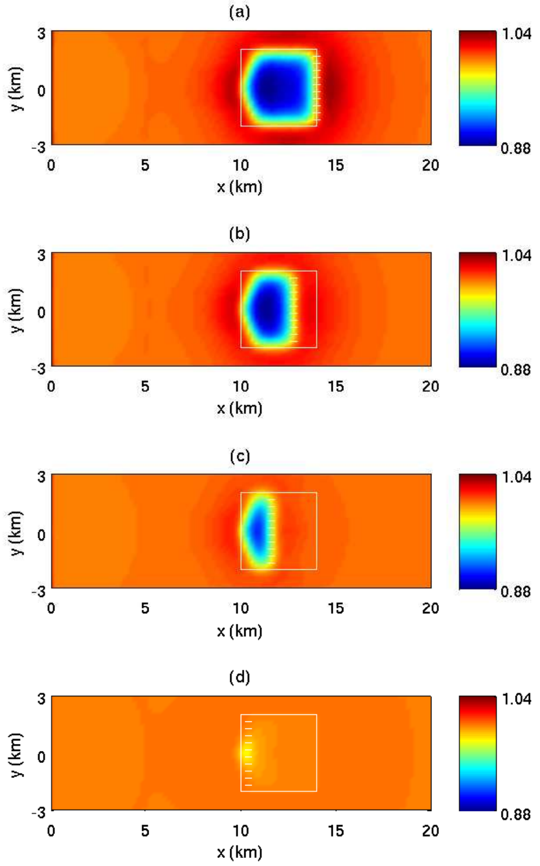

Figure 4: $|E_z^{tot}|$ normalized by background, bathymetry, and salt dome fields for frequency = 0.01 Hz.

sea-bottom bathymetry. Induction due to the different anomalous domains can be extracted separately with the IBC method, allowing for different normalizations of the total field. The reservoir, and therefore the oil-water contact, can be seen most clearly when normalized by the background, bathymetry, and salt dome fields. Our study demonstrates that measurable MCSEM data can provide an accurate position of the oil-water contact inside the reservoir over time. Future work should study more realistic models of the flooding front in the water injection recovery method. The oil-water interface can be nonvertical (angled), it can be nonsharp (occurring as a transition zone of up to tens of meters thick), and we should consider flooding from the bottom. Injection water of a range of resistivities should also be studied. The positive results of our experiment here with a simplified flooding scheme (but a realistic geological model) warrant these further investigations into the use of EM methods for reservoir monitoring during production.

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EDITED REFERENCES

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