Feasibility study of electromagnetic monitoring of CO_2 sequestration in deep reservoirs

Michael S. Zhdanov, University of Utah and TechnoImaging; Masashi Endo and Noel Black[*]*, TechnoImaging; Lee Spangler and Stacey Fairweather, Big Sky Carbon Sequestration Partnership; Andrew Hibbs and George A. Eiskamp, GroundMetrics; Robert Will, Schlumberger Carbon Services*

Summary

Geophysical monitoring of carbon dioxide (CO_2) injections in a deep reservoir has become an important component of carbon capture and storage (CCS) projects. Until recently, the seismic method was the dominant technique used for reservoir monitoring. In this paper we present a feasibility study of permanent electromagnetic (EM) monitoring of CO_2 sequestration in a deep reservoir using a novel borehole-to-surface EM (BSEM) method. The advantage of this method is that the sources of the EM field are located within the borehole close to the target reservoir, which increases the sensitivity and resolution of the method. Another innovation is the use of capacitive electric field sensors with an operational lifetime of tens of years. We illustrate the effectiveness of the BSEM method by computer simulating CO_2 injection monitoring in the Kevin Dome sequestration site in Montana, USA.

Introduction

A growing consensus that global climate is changing has generated significant efforts in developing effective methods for carbon capture and storage (CCS). Many international research programs have been established in order to address this problem, e.g., the Australian government sponsors the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), the Canadian and Saskatchewan governments sponsor the Aquistore Program, and industry is funding and managing the CO_2 Capture Project (CCP). These programs are intended to advance technologies that will underpin the deployment of industrial-scale CCS. Part of the long-term intentions for CCS is sequestering CO_2 during enhanced oil recovery (EOR). To date, this has only been achieved at a few sites, such as the Statoil-operated Sleipner field in the Norwegian sector of the North Sea; the BP, Sonatrach, and Statoil operated In Salah field in Algeria; and the Chevron operated Gorgon field in Australia. One of the significant reasons for delays in CCS deployment has been the lack of a regulatory framework, especially for long-term liability. Indeed, as part of a decision by the Chevron, ExxonMobil, and Royal Dutch Shell joint venture to commit to the US$ 37 billion Gorgon project in 2009, the Australian government set a worldwide precedent by assuming liability for potential damages for hundreds of years should the geological integrity of the field fail. This aspect of geological integrity implies that the monitoring, verification, and accounting for CO_2 is absolutely critical for the widespread application of CO_2 sequestration.

In order to analyze and image the injection of CO_2 in a saline reservoir, it is necessary to produce a 3D resistivity model from the observed EM data. This 3D resistivity model can subsequently be interpreted for fluid saturations using effective medium models. Ultimately, the aim of 3D inversion is to update the dynamic reservoir models for the verification and accounting of CO_2.

In recent years, a number of feasibility studies have demonstrated that marine CSEM methods are able to monitor changes in resistivity from producing oil and gas reservoirs (e.g., Black et al., 2010, 2011). However, fewer model studies have been presented for CO_2 sequestration, though it is known that some IOCs have commissioned such studies. Good examples are given in Gasperikova and Hoversten (2006).

In this paper we present the results of a numerical feasibility study for a new method of electromagnetic (EM) monitoring of CO_2 sequestration in deep reservoirs using the borehole-to surface EM (BSEM) survey.

Borehole-to-surface EM Surveys for Reservoir Monitoring

One of the main challenges in application of the EM method for reservoir monitoring is related to the fact that the target reservoir is relatively thin and deep. Considering the diffusive nature of EM fields, it is difficult to accurately resolve movement of fluids at depth based on surface observations only. One possibility to overcome this limitation of the surface data acquisition system is to place the source of the EM field in the borehole close to the reservoir, while keeping the receivers on the ground. This approach is implemented in the borehole-to-surface EM (BSEM) method that consists of a borehole-deployed transmitter, and a surface-based array of receivers (e.g., He et al., 2005, 2010). In the BSEM method, the horizontal (E_x and E_y) and/or the radial components, E_r, of the electric field are measured on the surface of the Earth excited by two vertical electric bipole transmitters (one electrode for each transmitter is located on the surface, while others are located above and below the target layer) with some specific frequencies in the range of 0.1 Hz up to 100 Hz. We denote by E_{r1} and E_{r2} the radial components of the field generated by the vertical electric bipole sources A0A1 and A0A2, respectively (Figure 1). We can then calculate a difference signal, $\Delta E = E_{r2} - E_{r1}$, which represents the response of the target reservoir. Note that one of the major

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problems with the permanent EM monitoring of CO_2 sequestration is the effect of the near-surface inhomogeneities caused by many artificial structures, such as boreholes with metal casings, near-surface infrastructures, pipelines, etc. (cultural EM noise). The advantage of using a difference field, ΔE, for analysis and inversion of the BSEM data is based on the fact that in this field the effect of near-surface geoelectrical inhomogeneities is significantly reduced.

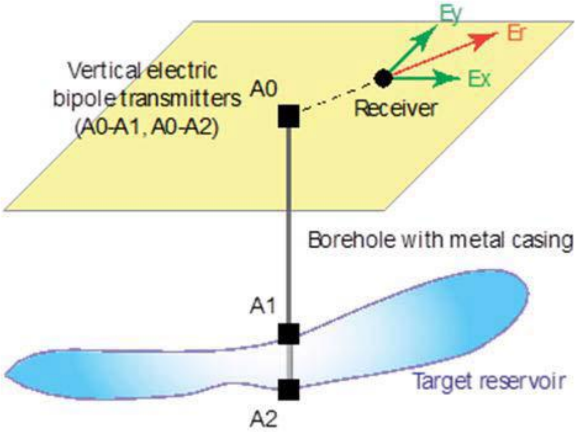

Figure 1: Sketch of a typical BSEM survey configuration.

Recently, Saudi Aramco has conducted a trial BSEM survey over a known oil field to determine the oil-water contact (Marsala et al., 2011a, b). This BSEM survey and other activities for EOR can be considered as a partial proof-of-concept of EM technology for CCS. EOR will also provide development synergy and economies of scales that will help support the technology for CCS. In particular, borehole electric field sources have been developed for BSEM that can be applied to CCS. In addition, groups such as those at Lawrence Berkeley National Laboratory are developing borehole-deployed EM sources specifically for use in CCS projects.

Development of Permanent Electric Field Sensors

In 2011 GroundMetrics, Inc. developed and introduced a new type of E-field sensor that employs chemically inert electrodes that couple capacitively to electric potentials in the Earth (Hibbs and Nielsen, 2007). This coupling is a purely electromagnetic phenomenon, which, to the first order, has no temperature, ionic concentration or corrosion effects, providing unprecedented measurement fidelity. The sensor contacts the ground via an insulated metal surface which, under normal atmospheric conditions, forms a protective and self-healing oxide. This can potentially provide an operational lifetime of tens of years, even when exposed to extreme environmental conditions.

The Big Sky Carbon Sequestration Partnership

The experimental test of an integrated EM acquisition, processing and imaging system for the permanent monitoring, verification, and accounting of CO_2 in deep reservoirs will be conducted in the Kevin Dome sequestration site located in northern Montana in collaboration with the Big Sky Carbon Sequestration Partnership (BSCSP), which is part of Montana State University's Energy Research Institute. The partnership is supported by the U.S. Department of Energy as one of seven regional carbon sequestration partnerships. The goal of the BSCSP is to help identify the best approaches for permanently storing regional carbon dioxide (CO_2) emissions. Through the project, the BSCSP aims to show that Kevin Dome is a safe and viable site to store CO_2. This project will produce 1 million tonnes of CO_2 from a natural source within the dome. The CO_2 will then be transported in a 2" diameter pipeline approximately 6 miles to the injection site. From there, the CO_2 will be injected deep underground into the Duperow formation located on the edge of the Kevin Dome. Throughout the project, scientists will closely monitor the geology, geochemistry, water quality, air quality, and CO_2 behavior.

Computer simulation of the BSEM survey over Kevin Dome, Montana

Kevin Dome is a large underground geologic feature covering roughly 700 square miles in Toole County, Montana, and is an excellent study site for several reasons. First, there is an abundance of naturally occurring CO_2 that has been trapped in place for millions of years indicating strong cap rock formations. Second, CO_2 can be extracted from the top portion of the dome and piped a relatively short distance (six miles) down the dome's flank and outside the natural CO_2 accumulation to the injection site. Kevin Dome's geology allows for the comparison of rocks that have been previously exposed to CO_2 to rocks freshly exposed through CO_2 injection. Lastly, this area has an active oil and gas industry that may be able to provide practical and economical applications of the study's findings. Figure 2 shows a schematic model of Kevin Dome.

We have constructed a 3D resistivity model of the Kevin Dome from a lithologically-constrained geostatistical inter/extrapolation from all resistivity logs available on the site (Figure 3). The model consists of 12 layers with an approximate resistivity range between 30 to 150 Ohm-m. We assume CO_2 to be injected in the Devonian Duperow (dolomite) Formation (target layer, approximately from 1110 m to 1140 m depth), where CO_2 is naturally trapped,

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with a resistivity of 20 Ohm-m without CO_2 and of 100 Ohm-m when CO_2 is present.

We have simulated the synthetic BSEM data over this model by using a 3D EM modeling algorithm based on the integral equation (IE) method (Zhdanov, 2009). The EM sources were deployed in a metal-cased borehole (two vertical electric bipoles, one electrode for both transmitters is located on the surface while others are located above and below the target layer), and the radial component of the electric field were computed on a regular grid across the Earth's surface. The electric field difference signal varies from 1 μV/m near the center, to approximately 100 nV/m at a distance of 4 km. For comparison, a capacitive electric field sensor can reliably achieve a sensitivity of 1 nV/m in a 1 second measurement at a frequency of 1 Hz, and a factor of two better at 10 Hz. We should note that inversion accuracy depends on the signal-to-noise ratio, which is expected to be on the order of ten, at least.

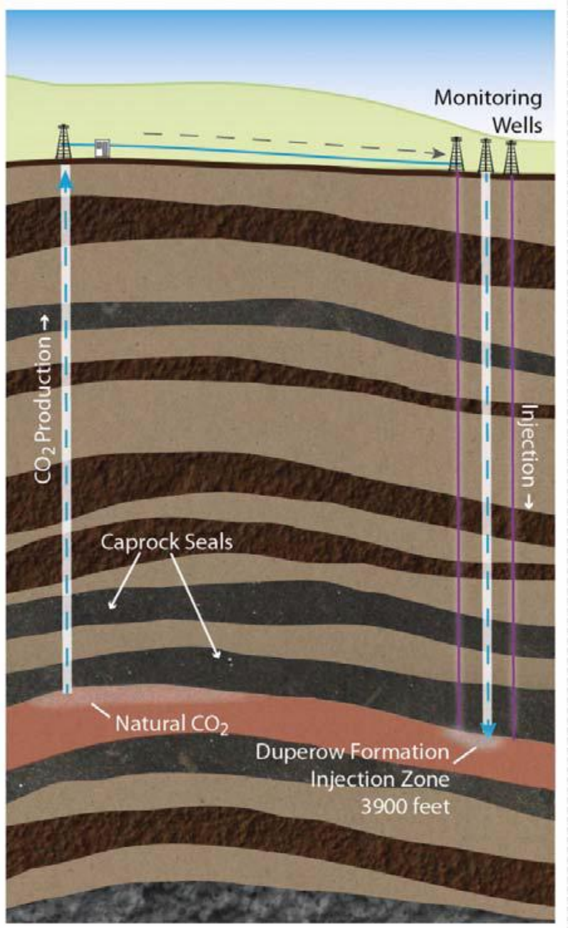

Figure 2: Schematic view of the Kevin Dome project.

We have performed a 3D inversion of this BSEM data. The inversion algorithm is based on the iterative regularized conjugate gradient method, which ensures rapid and robust convergence of the iterative process (Zhdanov, 2002). The forward modeling, required for the inversion algorithm, is done by the contraction integral equation method with inhomogeneous background conductivity (IBC), which allows for different discretizations within the different parts of the Kevin Dome model. This is important because accurate modeling of the cased-borehole and near-surface geoelectrical inhomogeneities requires fine discretization in those areas, while larger cell size can be used elsewhere.

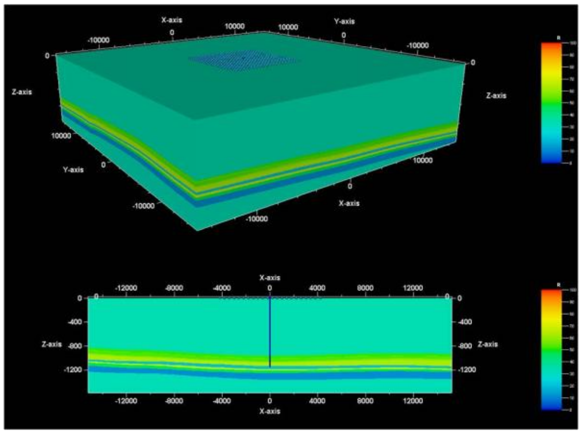

Figure 3: 3D resistivity model of the Kevin Dome. bipoles, one electrode for both transmitters is located on the surface

The details of our IBC IE modeling method can be found in Zhdanov, 2009. In our forward modeling simulation of the BSEM survey data, we have assumed that the geometry of the target reservoir is known from available well-log and geophysics data; however, the resistivity distribution within the target reservoir, which reflects the CO_2 propagation, is unknown. The results of 3D inversion are shown in Figures 4 through 7. We present in Figures 4 and 5 3D perspective views of the true model of the CO_2 plume and the image recovered from the 3D inversion of BSEM data for plume radius equal to 1000 m, 1500 m, 2000 m, and 2500 m, respectively. Figures 6 and 7 show a comparison between the true resistivity model and the inverse model at the same depth of 1125 meters for different stages of CO_2 sequestration. The left panels in these figures show the horizontal slices of the true models, while the right panels present similar sections of the corresponding inverse models. In these figures, the areas of CO_2 propagation are manifested by increased resistivity in the inverse images. As one can see, the CO_2 plume can be recovered well from these images, so that the 3D inversion of the BSEM data

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can effectively be used for EM monitoring of CO_2 sequestration in deep reservoirs.

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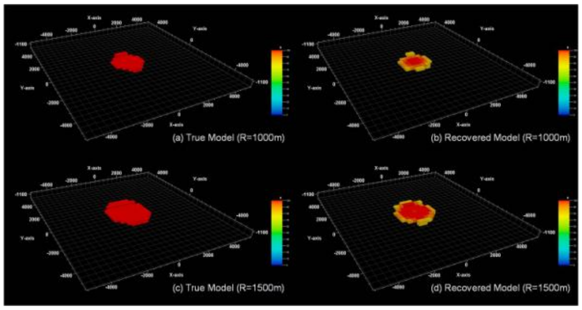

Figure 4: 3D perspective view of the true model of CO_2 plume and the image recovered from 3D inversion of BSEM data (R = 1000 and 1500 m).

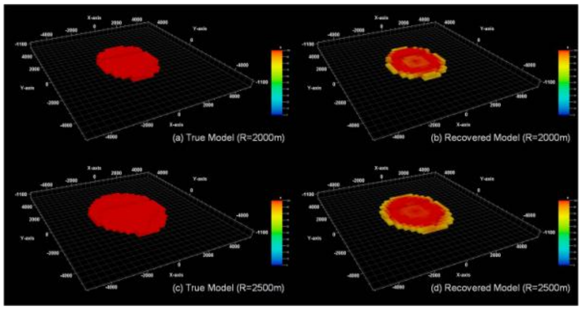

Figure 5: 3D perspective view of the true model of CO_2 plume and the image recovered from 3D inversion of BSEM data (R = 2000 and 2500 m).

Conclusions

The most widely considered approach to carbon capture and storage is the one based on storing CO_2 in deep, natural saline reservoirs. An important problem arising in this case is monitoring and verification of the injection process and long-term geological integrity of the reservoir seal. Thus, geophysical methods of reservoir monitoring should play a critical role in the CCS process

We have demonstrated in this paper that EM methods, especially borehole-to-surface (BSEM) surveys, may represent effective techniques for monitoring CO_2 injection in deep reservoirs. Computer simulation has shown that BSEM data provide a clear indication of the location of the CO_2 plume in the underground formation. However, a practical field test is necessary for optimizing and practical evaluation of this technique. We plan to conduct a field experiment on the BSEM survey technique in the Kevin Dome sequestration site in near future.

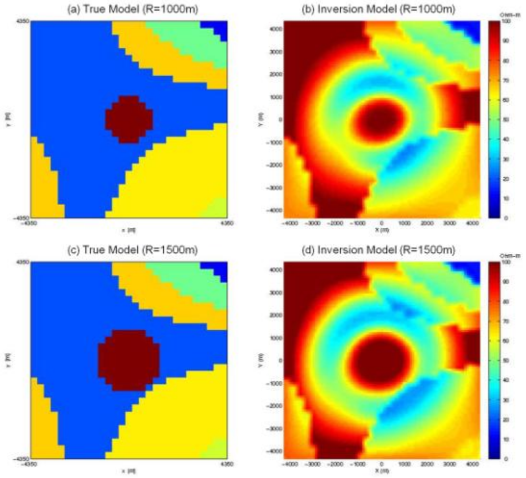

Figure 6: Comparison between the true resistivity model and the inverse model at the same depth of 1125 meters for different stages of CO_2 sequestration (R = 1000 and 1500 m).

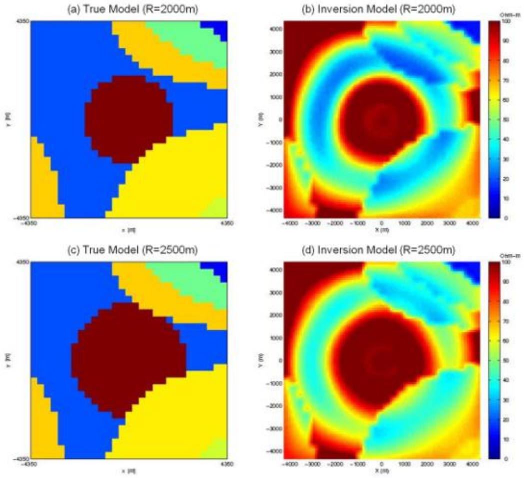

Figure 7: Comparison between the true resistivity model and the inverse model at the same depth of 1125 meters for different stages of CO_2 sequestration (R = 2000 and 2500 m).

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