Electromagnetic monitoring of CO2 sequestration in deep reservoirs

Michael S. Zhdanov,[1,2*] Masashi Endo,[1] Noel Black,[1] Lee Spangler,[3] Stacey Fairweather,[3] Andrew Hibbs,[4] George A. Eiskamp[4] and Robert Will[5] **present a feasibility study of permanent electromagnetic (EM) monitoring of CO_2 sequestration in deep reservoir using a novel borehole-to-surface EM (BSEM) method.**

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 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.

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 programmes 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 government sponsors Aquistore Programme, and industry is funding and managing the CO_2 Capture Project (CCP). These programmes are intended to advance technologies that will underpin the deployment of industrial-scale CCS. Part of the long-term intentions for CCS is sequestrating 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 $37 billion Gorgon project in $_2$009, 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.

The majority of approaches currently proposed for CCS rely on storing CO_2 in a supercritical state in deep saline reservoirs where buoyancy forces drive the injected CO_2 upward in the aquifer until a seal is reached. The CO_2 is stratigraphically and structurally trapped below an impermeable rock layer. Secondary mechanisms include the residual trapping of small amounts of CO_2 in pore spaces as the supercritical fluid moves through the formation and solubility trapping whereby CO_2 dissolves in existing formation fluids, becoming more dense and sinking in the formation over time. Maximum storage security occurs through mineral trapping. CO_2 dissolves in the brine, forming a weak carbonic acid. Over time, this compound interacts with the minerals in the surrounding rock or with the minerals in the formation fluid to form solid carbonate minerals.

Figure 1 shows the concept of the mechanism of CO_2 trapping. The permanence of this type of sequestration depends entirely on the long-term geological integrity of the seal. There is a strong correlation between the change in CO_2 saturation and the change in water saturation in a saline reservoir. Dissolved salts react with the CO_2 to precipitate out as carbonates thereby decreasing the electrical resistivity. As a result, there is a direct correspondence between the change in saturation and the measured electric field at the ground surface, which makes electromagnetic (EM) methods well suited for monitoring CO_2 sequestration.

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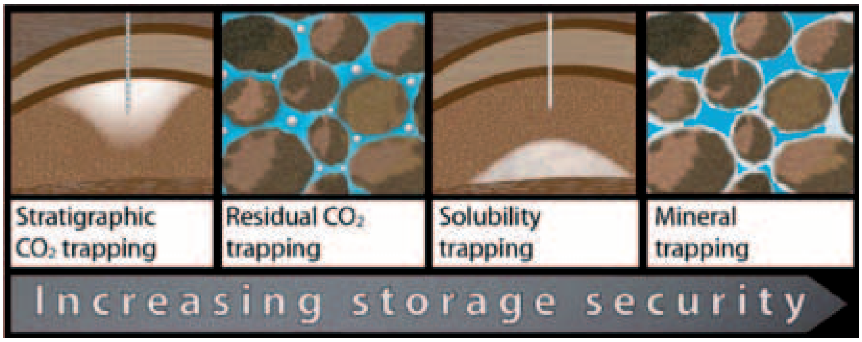

***Figure 1** Conceptual sketch of the different mechanisms of CO2 trapping.*

In order to analyze and image the injection of CO_2 in saline reservoirs, 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. The 3D inversion requires full-field 3D Earth modelling that is inclusive of overburden, reservoir, and infrastructure such as well casing and pipelines. The 3D Earth model is constructed from a priori seismic and resistivity well logs, as well as dynamic reservoir simulations. For a reservoir to be considered for CO_2 sequestration, considerable ancillary data, such as well logs, seismic surfaces, and rock and fluid properties are generally known prior to when an EM survey would be conducted. Moreover, a suite of dynamic reservoir simulations that test subsurface uncertainty are often completed. 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 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 for overcoming this limitation of surface data acquisition systems 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). Figure 2 shows a schematic model of a reservoir target embedded in a host geological formation. In the BSEM method, the horizontal (*Ex* and *Ey*) and/or the radial components, *Er*, 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 from 0.1 Hz up to 100 Hz.

We denote by $Er1$ and Er_2 the radial components of the field generated by vertical electric bipole sources *A0A1* and *A0A2*, respectively (Figure 3). We can then calculate a difference signal, $\Delta E = Er2 - Er1$, which represents the response of the target reservoir. Note that one of the major 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

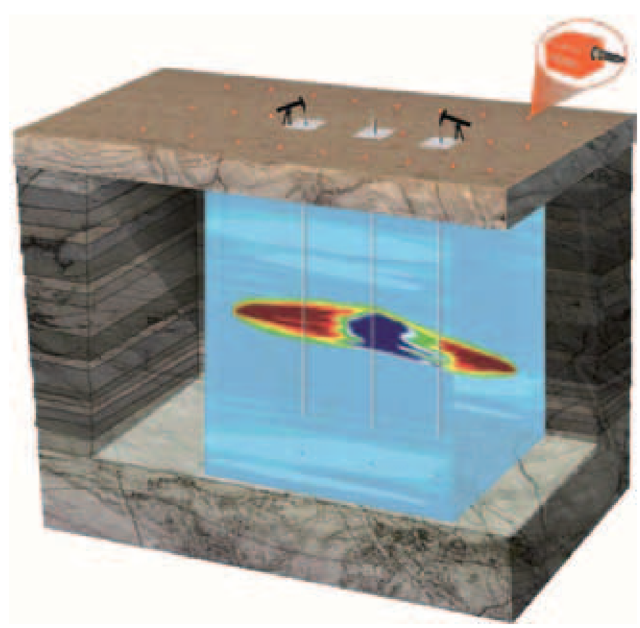

***Figure 2** Schematic model of a reservoir target embedded in a host geological formation.*

casing, near-surface infrastructure, 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.

Recently, Saudi Aramco has conducted a trial BSEM survey over a known oilfield 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

An important question is what kind of sensors should be used in EM monitoring of CO_2 sequestration in deep reservoirs, magnetic B-fields, or electric E-fields. Compared to B-field measurements, E-field measurements have superior sensitivity to variations in formation resistivity as would be encountered with CO_2 sequestration. However, this has historically meant using galvanic electrodes. which rely on electrochemical coupling to their local environment. It is unfeasible to permanently deploy such electrodes owing to their continual electrochemical degradation, and the effects of changing groundwater content and temperatures in the near surface, which act to produce measurement artifacts. In addition, by their very nature, galvanic electrodes require continual ionic exchange with the local ground material. This means that the ground must be relatively moist, or water must be added (often mixed with a specialty mud) to the ground where the sensors are emplaced. Essentially, either the ground is adequately wet, or water/mud is added, in which case the sensors will operate but degrade unacceptably over time, or the ground is too dry for conventional sensors to work at all. Moreover, such sensors are very difficult to deploy in harsh environments such as ice/snow, sand, gravel, and caliche.

In 2011 GroundMetrics 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.

Big Sky Carbon Sequestration Partnership

The experimental work to test an integrated EM acquisition, processing, and imaging system for the permanent

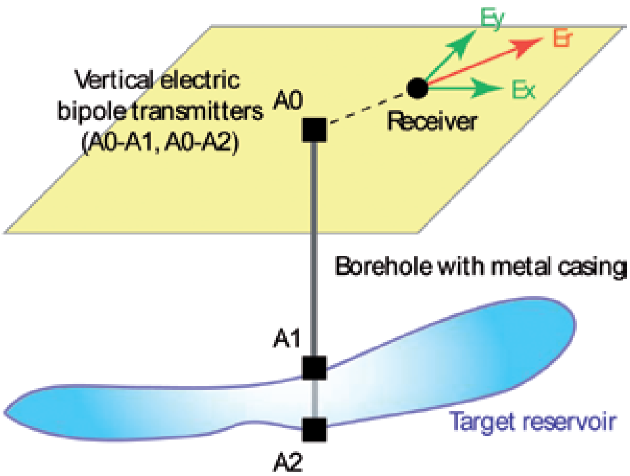

Figure 3 *Sketch of typical BSEM survey configuration.*

Figure 4 *Location map of the Kevin Dome project site.*

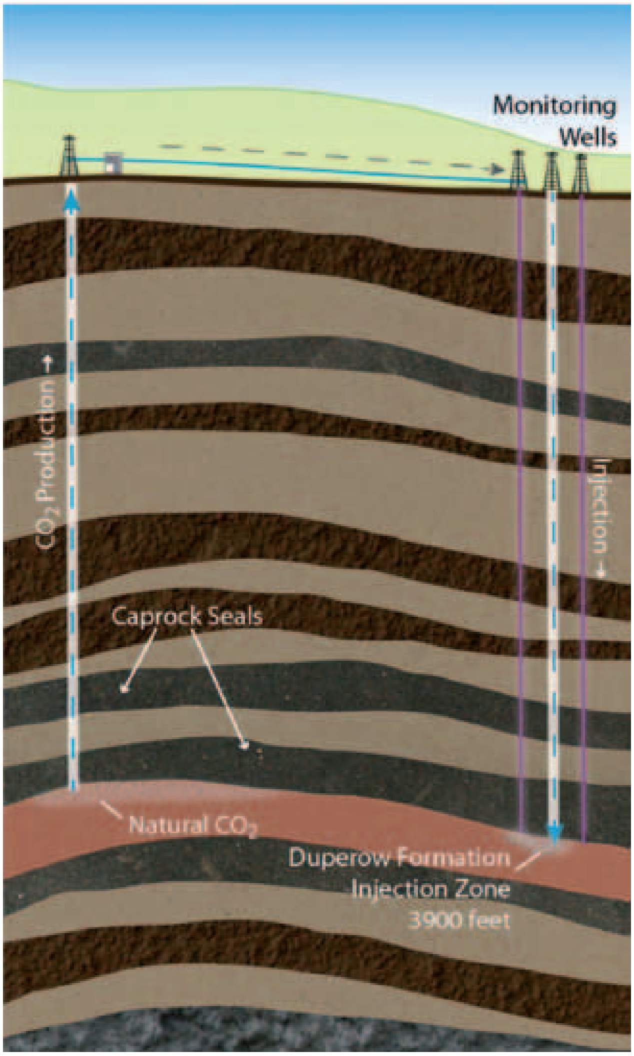

Figure 5 *Schematic view of the Kevin Dome project.*

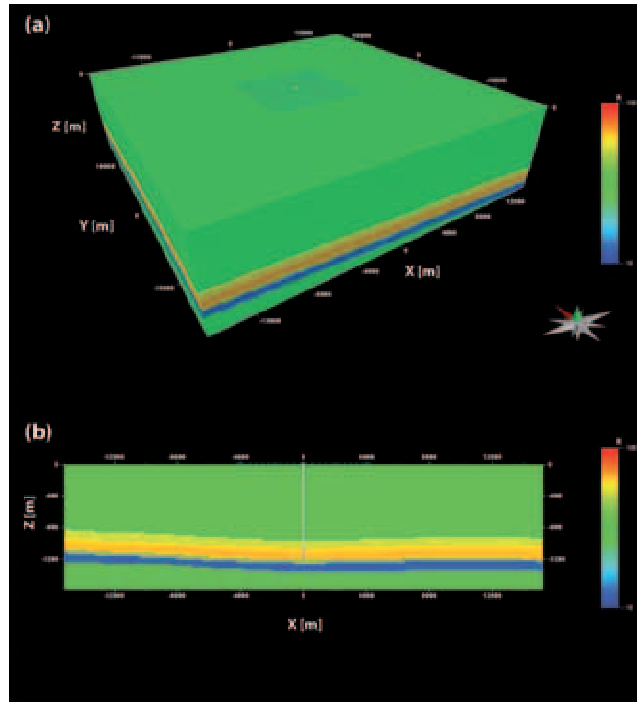

Figure 6 *3D resistivity model of the Kevin Dome.*

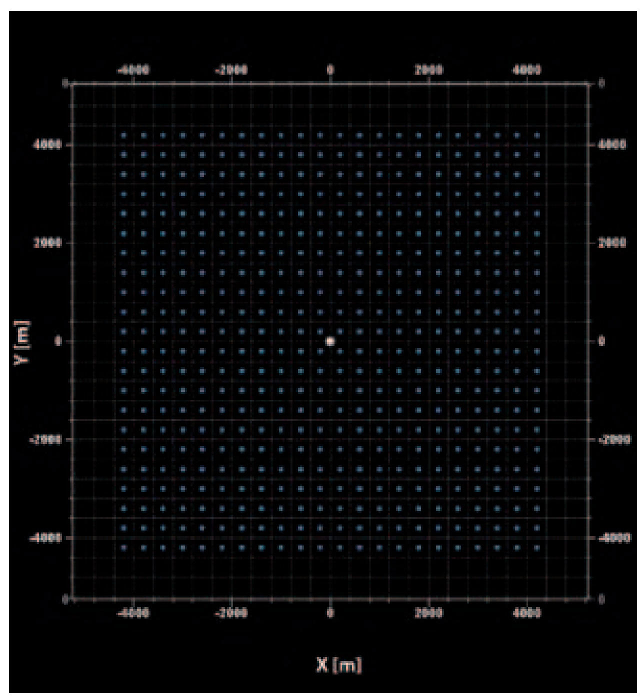

Figure 7 *Plan view of the receiver locations for the BSEM survey.*

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 the part of Montana State University's Energy Research Institute. The partnership is supported by the US 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. The BSCSP relies on existing technologies from the fields of engineering, geology, chemistry, biology, geographic information systems (GIS), and economics to develop novel approaches for both geologic and terrestrial carbon storage in the region, which encompasses Montana, Wyoming, Idaho, South Dakota, eastern Washington, and Oregon. The BSCSP is currently working on a large scale carbon storage research project in northern Montana. Through the project, the BSCSP aims to show that a subsurface geologic structure in Toole County called 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-in 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

Kevin Dome is a large underground geologic feature that covers roughly 700 square miles in Toole County, Montana (Figure 4). This area 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. This short distance helps keep costs low and reduces environmental impacts. 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 5 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 in the site (Figure 5). The model consists of 12 layers with the approximate resistivity range between 30 to 150 ohm-m. We assume

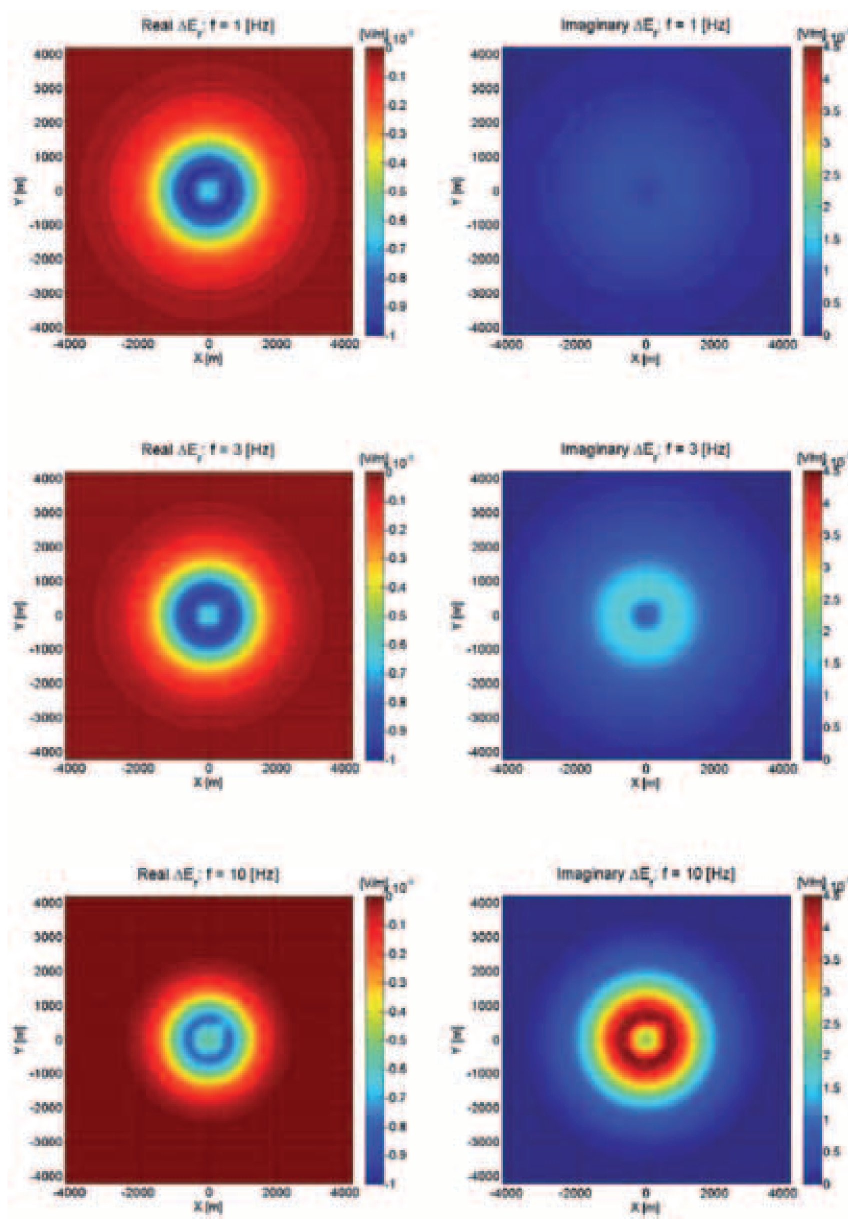

Figure 8 Maps of the BSEM data on the surface of the Earth.

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, with a resistivity of 66 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 (Figure 7). Figure 8 shows an example of the measured electric fields (the differences of the electric fields due to two transmitters) on the surface of the Earth. The electric field difference signal varies from1 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 measurements 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 10, at least.

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 modelling, 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 modelling of the cased-borehole and near-surface geoelectrical inhomogeneities requires fine discretization in those areas, while larger cell size can be used elsewhere. The details of our IBC IE modeling method can be found in Zhdanov, 2009.

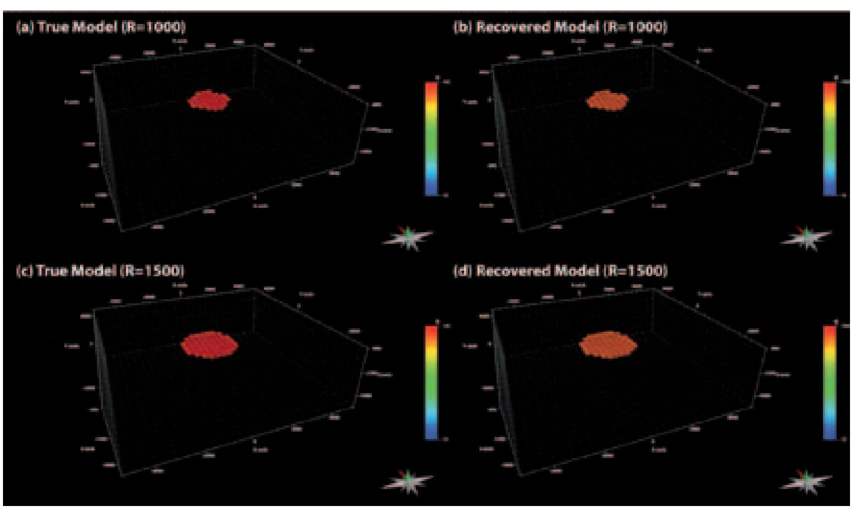

Figure 9 *3D perspective view of the true model of CO2 plume and the image recovered from 3D inversion of BSEM data (R = 1000 and 1500 m).*

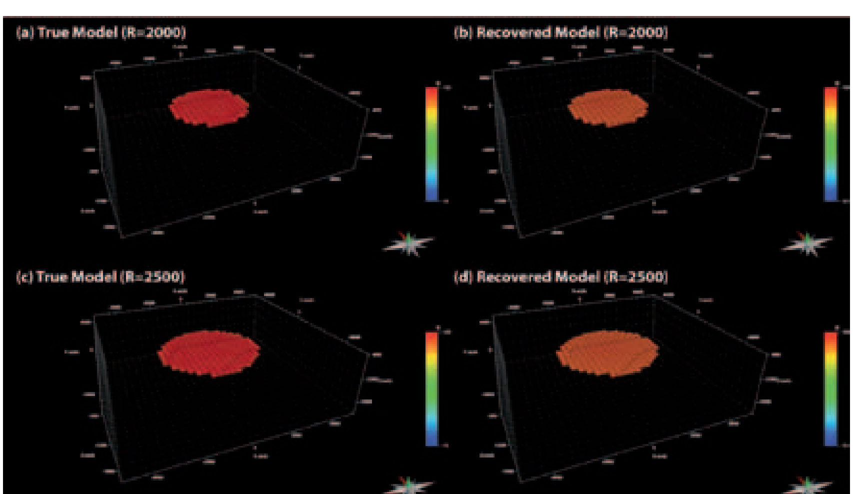

Figure 10 *3D perspective view of the true model of CO2 plume and the image recovered from 3D inversion of BSEM data (R = 2000 and 2500 m).*

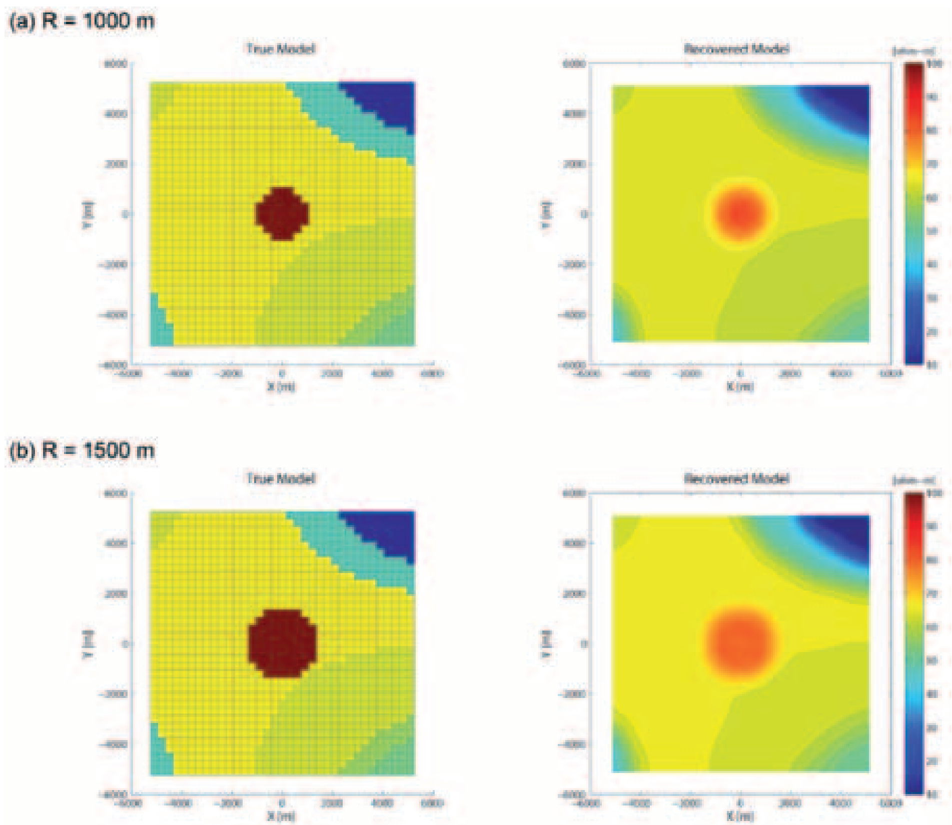

***Figure 11** Comparison between the true resistivity model and the inverse model at the same depth of 1125 m for different stages of CO2 sequestration (R = 1000 and 1500 m).*

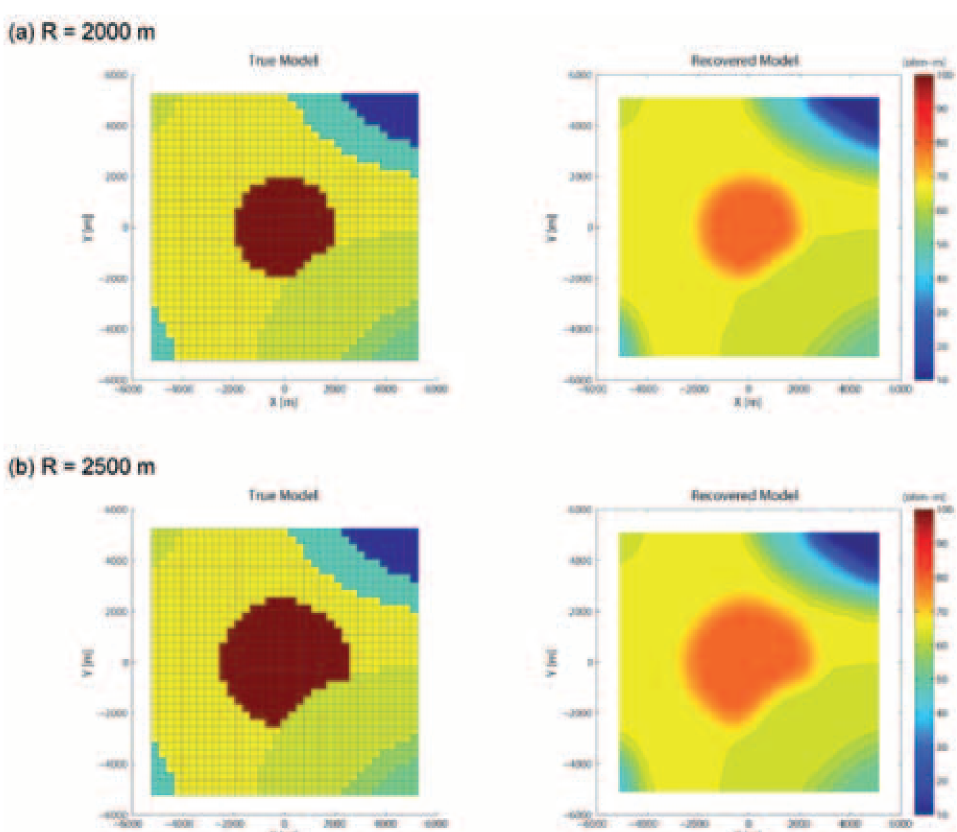

***Figure 12** Comparison between the true resistivity model and the inverse model at the same depth of 1125 m for different stages of CO2 sequestration (R = 2000 and 2500 m).a*

In our forward modelling 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 9 through 12. We present in Figures 9 and 10 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 11 and 12 show a comparison between the true resistivity model and the inverse model at the same depth of 1125 m 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 can effectively be used for EM monitoring of CO_2 sequestration in deep reservoirs.

Conclusions

The most widely considered approach to carbon capture and storage is the one based on storing CO_2 in natural deep 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 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 the near future.

Acknowledgements

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