Integrating geophysical monitoring data into multiphase fluid flow reservoir simulation

Trevor P. Irons*, Brian J.O.L. McPhserson, Nathan Moodie
University of Utah
Department of Civil & Environmental Engineering
Energy & Geoscience Inst.
tirons@egi.utah.edu, b.j.mcpherson@utah.edu, nmoodie@utah.edu

Rich Krahenbuhl & Yaoguo Li
Colorado School of Mines
Department of Geophysics
Center for Gravity, Electrical, and Magnetic Studies
rkrahenb@mines.edu, ygli@mines.edu

**presenting author asterisked*

SUMMARY

Simulation of multiphase flow systems are of critical importance in managing hydrological systems. Flow simulations are affected by a number of factors including structure and flow properties including porosity and permeability as well as the anisotropy and heterogeneity of these properties. In many cases traditional hydrological and reservoir data are highly affected by these parameters, but are not directly sensitive to them. As such modellers often adjust these parameters in an ad hoc manner until solutions numerically converge. Simulation models are generally based on structural data from reflection seismics whose physical flow properties are then populated using geostatistical extrapolation techniques utilizing a sparse number of borehole logs and core analysis. In multiphase systems including enhanced oil recovery and carbon capture and sequestration uncertainties regarding phase-dependent physical properties confounds this challenge further. Geophysical methods provide a means by which to gain an improved understanding of phase distributions in the subsurface. In this paper we will look at applications from active carbon capture and sequestration and enhanced oil recovery applications, as well as synthetic examples. Geophysical data including electromagnetic and gravity are inverted using structural constraints from the reservoir model. Inversions are then mapped into flow properties using calibrated relations such as Archie's Equation. The coupled models can then be used to both verify and improve on the reservoir flow model which improves it's predictive power and utility as a management tool.

Key words: CCS, electromagnetic methods, multiphase flow

INTRODUCTION

Carbon capture and storage (CCS) has emerged as a promising technology for the abatement of anthropomorphic climate change. Adoption of CCS technology would allow for the transition from a "carbon economy" to a "post-carbon" economy to be more gradual and less disruptive. Carbon capture utilization and storage (CCUS) projects monetize the storage of CO_2 through activities such as enhanced oil recovery (EOR). CCS methods have matured into a viable trusted technology; however, concerns remain about the widespread adoption of CCS due to the need to guarantee long-term storage permanence. Leakages of CO_2 at best negate the efforts of sequestration, and also pose environmental risk to underground supplies of drinking water (USDW). As such, the need for cost-effective monitoring of CCS projects is clear, and integrated approaches have great promise.

The challenges faced in a CCS/CCUS project are due to a unique blend of environmental, economic, logistical, and technical requirements. The result is a mix of trade-offs in CCS monitoring choices. In an effort to ensure storage permanence and to maintain a supercritical phase, CO_2 is typically injected at depths of several kilometres; these depths, however, make monitoring much more difficult and expensive. The resolution of low-cost monitoring techniques such as electromagnetic methods are typically low at such depths. In many cases brownfield oil reservoirs are utilized as CCUS (CO_2-EOR) sites for economic reasons of existing infrastructure as well as the economic benefits of producing hydrocarbons simultaneously with CO_2 storage. In these instances, geologic seals are known to be of good integrity, and the most likely scenario for leakage is through a wellbore casing (Gasda et al., 2004; Carey et al., 2007), or fault.

State of the art monitoring of CCS projects relies upon a combination of technologies including active and passive seismic methods, reservoir modelling based on site characterization, tracers, and surface-based monitoring measurements. Incorporating these signals into a (reasonably-autonomous) dynamic intelligent monitoring system remains a noble goal for long term monitoring. However, many of the (surface-based) monitoring technologies are not responsive to changes in the reservoir, and are more suitable for detecting catastrophic leaks. Embedded sensors are responsive, but often provide information only in the immediate vicinity of the sensor. Furthermore, costs associated with the permanent installation of sensors at the depths of most CCS projects are prohibitive--a single drill hole can cost on the order of a million dollars in many instances. There is a pressing need for cost-effective, deeply responsive monitoring solutions.

Electrical properties of porous rocks are known to be sensitive to the fluid composition in the interstitial space in a CCS environment (Börner et al., 2013, Figure 1). Geophysical methods for probing electrical conductivity at depth include electrical resistance

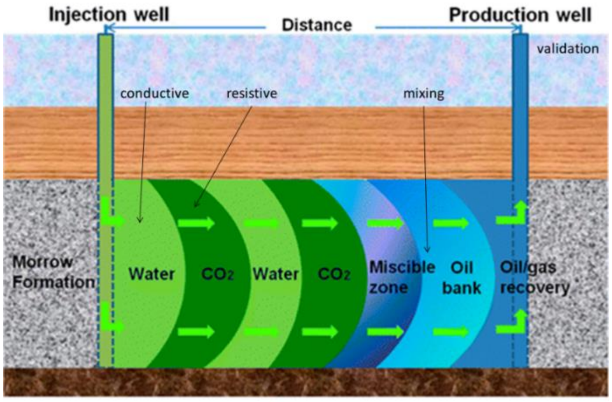

Figure 1 – An illustration of a CCS/EOR site utilizing water alternating gas injections to produce hydrocarbons (figure adapted from Dai et al., 2014).

tomography (ERT), Gravity (Krahenbuhl et al., 2011), induction EM, controlled source electromagnetics CSEM and magnetotellurics (MT). While ERT methods can be done from the surface, in order to obtain a sharp image at depth, it is usually necessary to utilize cross-well measurements. To complicate matters, electrodes must be electrically insulated from casing, or resistive casing must be used (Kiessling et al., 2010). In the case of monitoring deep storage, these requirements pose a significant economic hurdle. Surface based MT and audio-MT methods have the ability to image deep structures--and are therefore valuable exploration tools--but lack the resolution to discern subtle changes of interest in continuous monitoring. Induction EM is generally incapable of imaging the depths necessary for CCS monitoring, and is mostly sensitive to the presence of conductors.

In marine exploration, CSEM methods represent a mature technology that is relied upon to image resistors at depth. On land CSEM is a less common technique, but one which is increasingly being adopted (Streich, 2015). Typically, in CSEM galvanically coupled bi-pole transmitters inject current into the ground. The transmitters may operate either in the frequency or time domain. In the frequency domain, peak signal is expected in the 0.5-5 Hz range, above which it falls of quickly (Wiranto et al., 2010). The resulting electrical and magnetic fields are then measured on the surface. The electric field (**E**) measurements have been shown to be more sensitive to the presence of resisters at depth than the magnetic field (**H**) measurements, which are more sensitive to conductors. For these reasons land based CSEM utilizing **E** field measurements is a promising and emerging techniques for monitoring CCS projects.

Grayver et al. (2014) demonstrate the utility of CSEM for a CCS project using surface based sources and electric-field receivers. Wirianto et al. (2010) demonstrate the benefits of using vertical sources with surface based electric field measurements, although they propose the equivalent/reciprocal case of a single receiver in a borehole and moving sources on the surface. Vilamajó et al. (2015) perform borehole to surface CSEM at a CCS site in Spain and achieve good quality data for a modest target. Their dipole transmitter was strongly influenced by the conductive casing even though it was insulated from it. Tang et al. (2015) present an analysis of the use of a charged wellbore casing (CWC) as a long galvanically coupled electrode (Figure 2). Groundmetrics recently commercially developed similar technology in their TCS-30 CSEM transmitter and capacitively-coupled E field receivers (www.groundmetrics.com/technology/tcs-30).

The use of legacy wellbore casings as electrodes achieves an extraordinary reduction in costs compared to installation of dedicated vertical electrodes or monitoring wells capable of use in a CSEM survey. Any CCS project will contain at the very minimum the injection well, so the technique will be broadly applicable. Additionally, many CCS projects utilize brownfield oil fields due to the fact that such locations are well characterized, have validated and trusted geologic traps, and existing infrastructure. Additionally, injection of CO2 is an effective method for enhanced oil recovery (EOR), and as such external economic factors also can influence site selection.

Utilizing CSEM for monitoring CCS projects is therefore an emerging and promising technique, but not without its limitations. The benefit of either vertical electric field receivers or transmitters has been demonstrated numerous times. However, installing this capability is usually prohibitively expensive as it is not (currently) possible to retrofit existing boreholes. The resolution of CSEM is not stellar due to the diffusive nature of electric field propagation. Integration with reservoir and constrained interpretation are promising approaches to maximizing the available information (Liang et al., 2011), but more work is required to establish the relationship between change of electrical conductivity with CO2 distribution and migration. For these reasons CSEM monitoring of CCS projects has not yet been widely adopted.

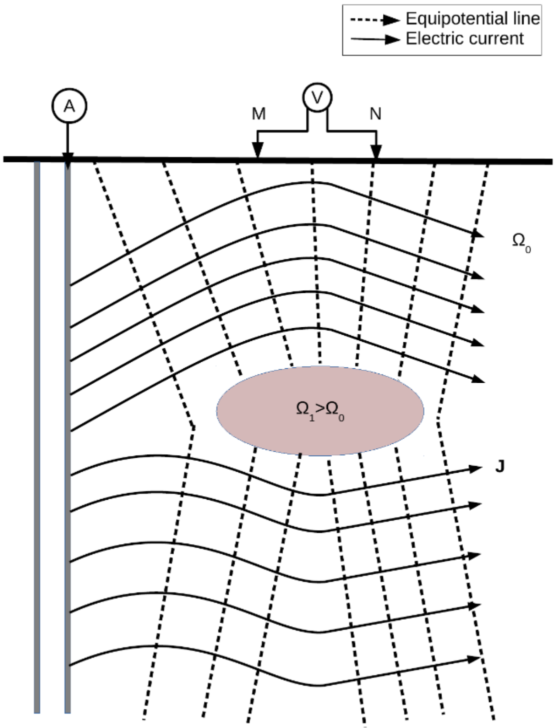

Figure 2- Borehole casings can be used as long deep electrodes for electrical current injection. Measurements of electrical potential at the surface are sensitive to the subsurface resistivity structure.

METHOD AND RESULTS

We are investigating the use of legacy wellbore casings as long vertical current injection electrodes in CSEM monitoring at an active CO_2-EOR project (Bell Creek, MT, operated by Denbury Resources, INC) in order to demonstrate the responsiveness of the method to changes in subsurface fluid distribution. The sensitivity of such surveys has been established, but the technology has not yet been validated in an extended monitoring application. Our first field survey is planned for the middle of October 2017 and will utilize the two well configuration shown in Figure 4.

Surveys will utilize state of the art commercially available CSEM instrumentation. High power transmitters and 32-bit digitizers with a broad dynamic range will provide for high fidelity data to be acquired. Trade-offs between capacitive- and galvanically coupled sensors are numerous. Capacitive sensors can be easier to install, especially in rugged terrain, and have a small footprint. Galvanic sensors have lower noise characteristics and tend to be better calibrated, with less repeatability errors (more stable). Proper calibration is critical for inversion (Minsley et al., 2014). For the proposed field site, installation of galvanic sensors in loose soil will not be problematic, and considering the need for stable time-lapse data, we elect to use galvanically coupled **E** field receiver sensors. Two and three component magnetic field measurements will be made as well to compliment the electrical field data.

All receivers will be surface located in order to ensure no disruption in field operations at the active site. As a result, the proposed work will not require access to any borehole internals. Electrically coupling casings will be minimally disruptive to field operations, and due to the high power transmitter, we will have flexibility in which casings are needed for use as transmitters. Additionally, we prefer surface based receivers as measurements in multiple locations can be made simultaneously and do not require access to the wellbore interior. The downside of this approach is near surface sensitivity and noise. The use of 32 bit A:D converters along with noise mitigation algorithms, reference station noise cancellation (Oettinger et al., 2001), filtering, despiking, and digital processing can be employed. Rapidly acquired central loop sounding transient electromagnetic data will be collected in order to apply static corrections (Sternberg et al., 1988).

Preliminary modelling has been carried out prior to field operations utilizing finite element modelling codes developed at the Colorado School of Mines and the University of Utah (Figure 3). For these simulations, relatively simple resistivity structure used: a 20 Ω·m halfspace and a 200 Ω·m CO_2 plume. Results of the secondary field simulation are shown in Figure 5.

Once field work commences, effort will be expend developing coupled multiphase flow simulations which will be used to develop electrical resistivity to fluid phase saturation relations. Additionally, inversions will be constrained based on the known geometry and injection schedule of the CO_2-EOR operations. Time-lapse surveys will be performed to verify and develop the monitoring methodology. Joint history matching of the production and CWC-CSEM data will provide further opportunity to integrate the monitoring data into reservoir models (Glegola et al, 2012), and will build upon the previous coupled modelling efforts.

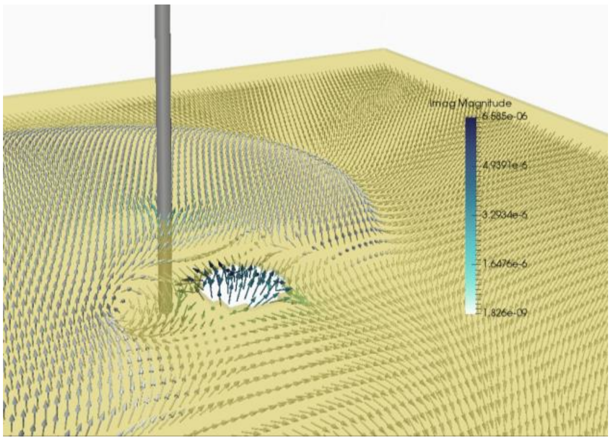

Figure 3- Vector glyph plot of imaginary component of the electrical field in a CWC-CSEM survey.

CONCLUSIONS

Monitoring CCS/CCUS projects is of critical importance in order to verify plume migration and sweep for hydrocarbon production as well as meet regulatory monitoring requirements. Geophysical imaging methods could greatly enhance well based point observations. However, geophysical monitoring of CCS projects is often challenging due to the depths involved and relatively modest change in fluid densities. Additionally, many imaging techniques are not sensitive to fluid phase, which is of primary importance in a CCUS monitoring project. Electrical and electromagnetic methods are promising techniques as the CO_2 phase will present as a large resistive body within a depleted reservoir of conductive saline water. Additionally, dissolved CO_2 in the oil phase will also be resistive. The depths involved place a high cost on drilling and traditional electrical resistance tomography methods can easily become cost-prohibitive in a CCUS project. However, many CCUS projects contain a large number of legacy boreholes which have been used for production, injection, or monitoring over the life of the field. We propose using these legacy borehole casings as long deep electrodes in a controlled source electromagnetics survey which penetrate the reservoir of interest, as well as the overburden. Measurements of the electrical and magnetic fields on the surface can be used to reconstruct the electrical conductivity of the subsurface; which, when combined with reservoir simulations, can be used to monitor changes in fluid phase within a CCUS project.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding for this work through DOE/NETL award number FE-0028320. Collaborative partnership with Denbury Resources Inc. and the University of North Dakota Energy & Environmental Research Center are further acknowledged.

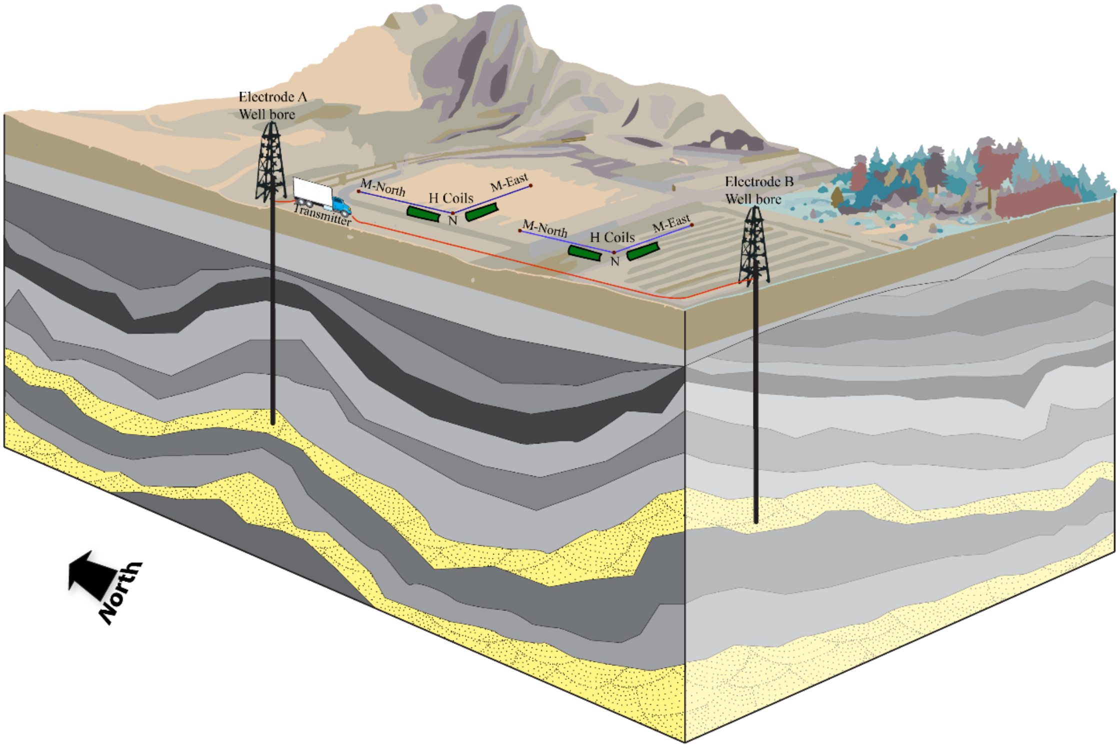

Figure 4 – Configuration of the CWC-CSEM survey utilizing two legacy borehole casings as current injection electrodes. Surface measurements of electrical potential and magnetic fields are responsive to changes in the subsurface resistivity. (*Modified from Young (2007)*).

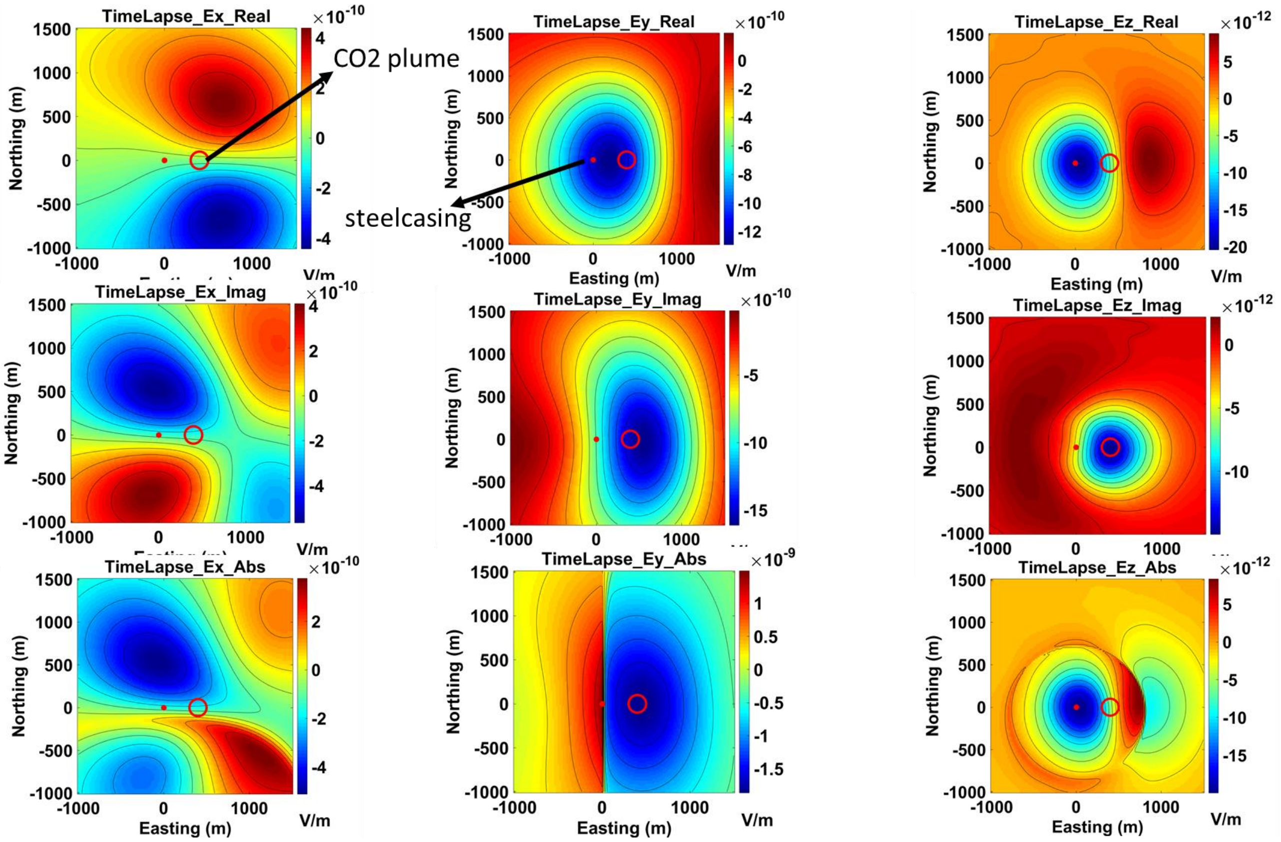

Figure 5 – Secondary field simulations of a CWC-CSEM survey assuming a simple CO_2 plume model.

REFERENCES

Börner, J. H., Herdegen, V., Repke, J.-U. and Spitzer, K. (2013), The impact of CO2 on the electrical properties of water bearing porous media – laboratory experiments with respect to carbon capture and storage. Geophysical Prospecting, 61: 446–460. doi: 10.1111/j.1365-2478.2012.01129.x

Carey, William J., Marcus Wigand, Steve J. Chipera, Giday WoldeGabriel, Rajesh Pawar, Peter C. Lichtner, Scott C. Wehner, Michael A. Raines, George D. Guthrie Jr. (2007), Analysis and performance of oil well cement with 30 years of CO2 exposure from the SACROC Unit, West Texas, USA, International Journal of Greenhouse Gas Control, Volume 1, Issue 1, April 2007, Pages 75-85, ISSN 1750-5836, http://dx.doi.org/10.1016/S1750-5836(06)00004-1.

Dai, Zhenxue, Richard Middleton, Hari Viswanathan, Julianna Fessenden-Rahn, Jacob Bauman, Rajesh Pawar, Si-Yong Lee, and Brian McPherson (2014), An Integrated Framework for Optimizing CO2 Sequestration and Enhanced Oil Recovery. Environmental Science & Technology Letters, 1 (1), 49-54, doi: 10.1021/ez4001033

Gasda, S. E, S. Bachu, M.A. Celia (2004), The potential for CO2 leakage from storage sites in geological media: analysis of well distribution in mature sedimentary basins. Environmental Geology, 46 (6-7), 707-720

Glegola, M., P. Ditmar, R. Hanea, O. Eiken, F. Vossepoel, R. Arts, and R. Klees, 2012, History matching time-lapse surface-gravity and well-pressure data with ensemble smoother for estimating gasfield aquifer support — A 3D numerical study: SPE Journal, 17, 966–980

Grayver, A. V., Rita Streich, and Oliver Ritter (2014). 3D inversion and resolution analysis of land-based CSEM data from the Ketzin CO2 storage formation. GEOPHYSICS, 79(2), E101-E114. doi: 10.1190/geo2013-0184.1

Kiessling, D. C. Schmidt-Hattenbergera, H. Schuett, F. Schilling, K. Kruegera, B. Schoebel, et al.(2010). Geoelectrical methods for monitoring geological CO2 storage: first results from cross-hole and surface–downhole measurements from the CO2SINK test site at Ketzin (Germany) Int. J Greenh. Gas Control, 4, pp. 816–826

Krahenbuhl, R., Y. Li, and T. Davis, 2011 The Leading Edge, Special Issue (Time-Lapse measurements). Understanding the applications and limitations of time-lapse gravity for reservoir monitoring. The Leading Edge, 30, Issue 9, 1060 - 1068.

Liang, L., Abubakar, A., & Habashy, T. M. (2011). Production Monitoring Using Joint Inversion of Marine Controlled-source Electromagnetic Data And Production Data. Society of Exploration Geophysicists.

Minsley, Burke, M. Andy Kass, Greg Hodges, and Bruce D. Smith (2014). Multielevation calibration of frequency-domain electromagnetic data. GEOPHYSICS, 79(5), E201-E216. doi: 10.1190/geo2013-0320.1

Oettinger, G., V. Haak, J.C. Larsen (2001). Noise reduction in magnetotelluric time-series with a new signal–noise separation method and its application to a field experiment in the Saxonian Granulite Massif. Geophysical Journal International, 146(3), 659-669. doi:10.1046/j.1365-246X.2001.00473.x

Sternberg, B. K., Washburne, J. C., & Pellerin, L. (1988). Correction for the static shift in magnetotellurics using transient electromagnetic soundings. Geophysics, 53(11), 1459-1468.

Streich, Rita (2015), Controlled-Source Electromagnetic Approaches for Hydrocarbon Exploration and Monitoring on Land. Surveys in Geophysics, 37(1), 47-80. doi: 10.1007/s10712-015-9336-0"

Tang, W., Li, Y., Swidinsky, A. and Liu, J. (2015), Three-dimensional controlled-source electromagnetic modelling with a well casing as a grounded source: a hybrid method of moments and finite element scheme. Geophysical Prospecting, 63: 1491–1507. doi: 10.1111/1365-2478.12330

Vilamajó, E., Rondeleux, B., Queralt, P., Marcuello, A. and Ledo, J. (2015), A land controlled-source electromagnetic experiment using a deep vertical electric dipole: experimental settings, processing, and first data interpretation. Geophysical Prospecting, 63: 1527–1540. doi: 10.1111/1365-2478.12331

Wirianto, M., Mulder, W. A. and Slob, E. C. (2010), A feasibility study of land CSEM reservoir monitoring in a complex 3-D model. Geophysical Journal International, 181: 741–755. doi: 10.1111/j.1365-246X.2010.04544.x

Young, G.B.C., Lintz, V.A, Widmann, B.L., Bird, D.A., and Cappa, J.A., 2007, CO2 sequestration potential of Colorado: Colorado Geological Survey Resource Series 45.