ERT and Crosswell EM Imaging of CO_2: Examples from a Shallow Injection Experiment at the Carbon Management Canada CaMI FRS in Southeast Alberta, Canada

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Summary

Electromagnetic (EM) geophysical techniques offer the possibility of monitoring subsurface CO_2 in saline reservoirs due to the fact that CO_2 has high electrical resistivity compared to the surrounding geologic materials. In this paper we first discuss the underlying physics of two different borehole-based EM monitoring techniques; electrical resistivity tomography (ERT) and crosswell EM. This discussion is followed by the description of an experiment at the Carbon Management Canada CaMI FRS test site where time-lapse single well ERT and crosswell EM data have been acquired to image CO_2 injection into a shallow aquifer. Resistivity imaging results from inversion of the two data types separately and jointly will be compared and contrasted, and interpretation of the extent of the injected CO_2 provided.

Introduction

Electrical and electromagnetic (EM) geophysical techniques offer much promise in terms of monitoring the injection and storage of CO_2 in saline reservoirs due to the fact that CO_2 has very high electrical resistivity compared to the saline-water and brines that it is replacing. That is, the injection of CO_2 into a reservoir will cause a region of high resistivity to develop which correlates to the location of the CO_2 plume. Two geophysical data acquisition technologies that can be applied within or outside of boreholes for monitoring time lapse changes in subsurface electrical properties are electrical resistivity tomography (ERT) (e.g. Schmidt-Hattenberger et al., 2011; Carrigan et al., 2013; Macquet et al., 2021) and crosswell electromagnetics (EM) (e.g. Wilt and Alumbaugh,1998; Um et al, 2020). The ease of deployment of these two methods in boreholes is very different as are the physics of anomaly detection and sensitivity to concentrations of liquid and gaseous accumulations of CO_2.

Methods

For monitoring wells that are not cased with standard steel casing, ERT data acquisition employs metal electrodes mounted on the outside of casing with wires running from each of the electrodes up to the surface data acquisition system (e.g. Binley and Kemna, 2005). Low frequency electric currents are injected between successive pairs of electrodes and voltages measured between other pairs of non-current transmitting electrodes. The resulting data are inverted to produce images of resistivity around and between the wells. Note that the casing on which the electrodes are mounted must be electrically resistive to avoid short circuits between electrodes and thus PVC or fiberglass casing is often used. Because of this requirement, the number of well pairs that crosswell data can be collected between will depend on the number of fiberglass/PVC cased wells that have been instrumented with the electrode arrays prior to well completion. If only one fiberglass well is available then only single well data can be collected.

From a physics perspective, the sensitivity of the ERT method comes from the continuity of normal current boundary condition across interfaces of contrasting resistivities. This boundary condition results in charge build up along the interface, which in turn produces anomalous voltages in the region around the boundary therefore providing sensitivity to the anomalous distribution of CO_2. ERT tends to be equally sensitive to resistive and conductive anomalies, and in electrically micro-and macro anisotropic media is primarily sensitive to the vertical resistivity of the formation when measurements are made using vertical wells.

Crosswell EM data acquisition does not require installation of any instrumentation during the well construction stage, and rather, the acquisition system is deployed using traditional wireline logging methods either prior to or after well completion (Wilt et al, 1995; Wilt and Alumbaugh, 1998). The method does require at least one of the two wells between which data acquisition occurs to be cased with non-conductive fiberglass or PVC casing while the second well can be completed with standard steel casing (Wilt et al., 1996; Wilt, 2018). Data acquisition involves deploying a magnetic solenoid source in the non-steel cased well and energizing it with a time varying current. This produces a time varying magnetic field that induces electric currents in electrically conductive materials. The anomalous currents generate secondary magnetic fields which are detected along with the 'primary' magnetic source field by magnetic field sensors in the second well. The magnetic field data are then inverted to produce images of resistivity between the wells.

Because the physics of the method involves inducing currents in electrical conductors, the method tends to be more sensitive to conductors than resistors. In addition, the higher the frequency, the greater the degree of scattering currents that are induced in the conductors, and therefore higher frequency generally results in better image resolution. However, collecting data in steel casing limits the highest frequency that can be obtained due to inductive losses in the casing(Wu and Habashy, 1994). In addition, a frequency dependent complex-valued casing attenuation coefficient must be determined for each receiver position when the data are measured in a steel cased well(Liu et al, 2008). This is

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usually included as an inversion parameter within the imaging scheme. Because 1) steel casing requires lower frequencies of acquisition, and 2) additional inversion parameters are including during inversion, resolution will be limited when steel casings are involved in the acquisition scenario (Gao et al., 2008). As a last note, in electrically anisotropic media where vertical wells are used to acquire the data, crosswell EM is primarily sensitive to the horizontal resistivity of the formation.

Field Experiment

In order to investigate the physics of gaseous CO_2 accumulations that might leak from a deeper reservoir, Carbon Management Canada (CMC) in collaboration with the University of Calgary is injecting CO_2 at the Containment and Monitoring Institute (CaMI) Field Research Station (FRS) near Brooks, Alberta, Canada (Lawton et al., 2019; Macquet et al., 2019). The simulation involves CO_2 being injected into an aquifer at approximately 300 m depth. As shown in Figure 1 the site has two monitoring wells straddling the injection well and spaced approximately 50 m apart. Monitoring well OBS #1 was primarily designed for geochemical sampling and is cased with standard carbon steel casing. Monitoring well OBS #2 was designed for geophysical monitoring including ERT and cross-well EM, and is thus cased with fiberglass. Among other permanently installed sensors, the well has an array of electrodes spaced at 5 m intervals mounted outside of casing from 245 to 330 m depth.

To monitor and image the gaseous CO_2 plume, single well ERT data have been acquired using an electrode array installed outside of well OBS2 since 2017; currently data are acquired on a daily basis. Results from the inversion of the ERT data alone can be found in Macquet et al. (2021). As part of joint seismic and EM monitoring program, the US Department of Energy has funded Lawrence Berkeley National Laboratory (LBNL) to acquire crosswell EM data with the magnetic source in OBS2 and a two induction-coil receiver string in OBS1(Um et al., 2020). Baseline crosswell EM data were successfully acquired at 200Hz in 2017 with plans to return for a time-lapse survey sometime in the spring of 2020. Unfortunately, due to COVID related travel restrictions, repeat data at 319Hz and 600 Hz were not acquired until December of 2021.

The two different data types have been inverted separately using the MARE2DEM inversion code produced by Key (2014) to produce 2D images of resistivity as well as time-lapse changes in resistivity due to the introduction of the CO_2. More recently, the data have been jointly inverted. Due to ERT primarily being sensitive to the vertical resistivity while crosswell EM is mostly sensitive to the horizontal component, an anisotropic model must be employed during the joint inversion process. This presentation will discuss the pros and cons of these two different resistivity imaging techniques both from acquisition and physics point of view, show results of inverting the two different data types collected at the CaMI FRS separately, and then demonstrate the results of jointly inverting the data with the hope of providing higher resolution of the CO_2 than either of the methods can provide separately.

Conclusions

In this presentation we will discuss the physics and acquisition logistics of two different borehole geophysics techniques for monitoring changes in subsurface electrical resistivity caused by the injection of CO_2. The ERT method requires direct contact of electrodes with the formation or formation fluids which normally entails installation of electrodes on the outside of fiberglass or PVC casing. The method operates by directly injecting electric currents between successive pairs of electrodes and measuring voltages between other electrode pairs. Crosswell EM is deployed in two wells via normal wireline logging trucks and one of the two wells can be cased with normal steel casing. Data acquisition operates by producing a time varying magnetic field via an AC current introduced into a solenoidal coil which serves as the source, and which produces secondary or scattering currents in electrically conductive subsurface formations. Measurements of the primary and associated scattered magnetic field provide sensitivity to the subsurface resistivity. Resistivity images are produced for both data types via non-linear inversion of the data. Examples of these two methods for CO_2 monitoring purposes will be provided via data collected at a research site in South-Eastern Alberta Canada where gaseous CO_2 is being injected into an aquifer at 300m depth.

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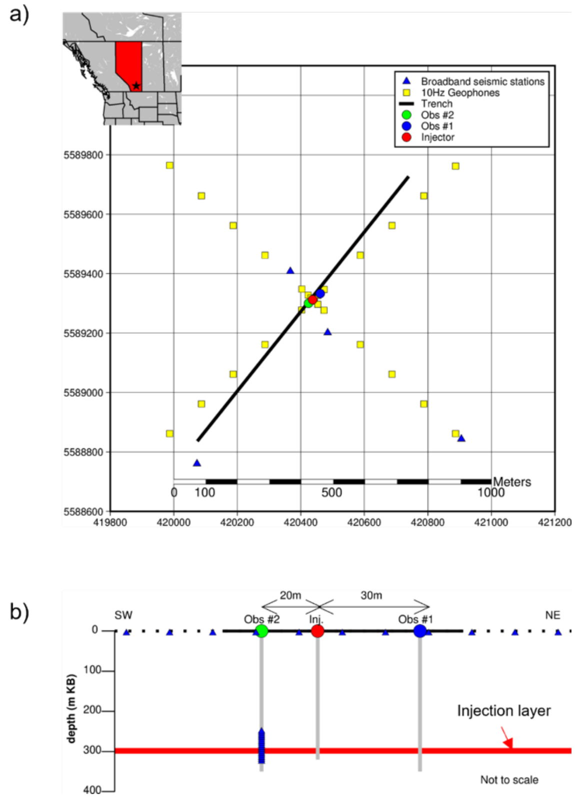

Figure 1: a) Permanent layout of the CaMI Field Research Station. Observation well #1 – or Geochemical well - (blue dot) hosts the geochemical equipment for gas and fluid sampling, as well as straight fiber optic cable for distributed acoustic sensing (DAS) surveys. It is located 30 m northeast of the injection well. Observation well #2 – or Geophysical well - (green dot) hosts 16 electrodes and 24 3C geophones, as well as helical and straight fiber optic cables for DAS surveys. It is located 20 m southwest of the injection well. The 1.1 km long trench hosts 112 electrodes, and helical and straight fiber at a depth of 1.5 m. At the surface, broadband stations and 3C geophones (blue triangles and yellow squares) are recording continuously for microseismicity analysis. Fiber for distributed temperature sensing (DTS) measurements are deployed in each of the three wells. b) Schematic cross-section of the CaMI.FRS installation. Blue triangles are the permanently installed electrodes (16 in the observation well #2, 112 along the surface trench). Only the borehole electrodes are used in this study.

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