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Magnetotelluric and Controlled-Source Electromagnetic Study of Aquistore CO_2 Sequestration Site, near Estevan, Saskatchewan

Joe, B, McLeod[1], Ian, J, Ferguson[1], Jim Craven[2], Brian Roberts[2], Eric Roots[2,3], Bernard Giroux[4]

1: University of Manitoba, 2: Natural Resources Canada, 3: Simon Fraser University, 4: Institut Nationale de la Recherche Scientifique

Summary

Pre-injection magnetotelluric (MT) and controlled-source electromagnetic (CSEM) surveys at the Aquistore carbon sequestration site, Estevan, Saskatchewan are being used to determine the capability of surface electromagnetic (EM) methods for monitoring an injected CO_2 plume. MT is being used to characterize the background resistivity structure of the Williston Basin and local EM noise conditions, and CSEM is being tested for its ability to delineate the target and the overlying resistivity structure. There are a number of challenges in imaging the CO_2 plume with surface EM techniques, including the > 3 km depth of the storage complex, conductive Mesozoic rocks above the target, and the high EM noise environment. Analysis of pre-injection MT data from surveys conducted in 2013 and 2014 demonstrates the ability to measure accurate MT responses across the site, defines a dominantly 1-D resistivity structure, and delineates a period band (0.125 to 6.667 s) of strong EM noise. Theoretical modeling shows that for a colinear electric-dipole transmitter and receiver configuration, and offsets of < 10 km, the CSEM response is sensitive to shallow (<1 km) resistivity but provides limited resolution of a resistive plume at the injection depth. Analysis of CSEM data collected at the site in 2013 using frequency-domain and time-domain methods shows that the signal from a 0.5 Hz, 29400 A.m bipole source can be accurately detected to offsets of at least 4 km.

Introduction

The Aquistore project is a large-scale carbon dioxide (CO_2) capture and sequestration (CCS) initiative, taking place southwest of Estevan, Saskatchewan. Emissions of CO_2 generated from SaskPower's nearby Boundary Dam Power Station are to be captured and injected, in liquid form, deep into sedimentary packages of the Williston Basin for long-term storage (Aquistore, 2013). The units targeted for geological storage are the Winnipeg and Deadwood formations, located at the base of the Williston Basin, at a depth of ~3100 m. Impermeable layers of rock, both above and below this storage complex, seal the reservoir from potential leakage. The overall aim of the project is to reduce greenhouse gas emissions coming from a fixed source of CO_2 discharge, while demonstrating the effectiveness of using geological formations as a sequestration reservoir (Whittaker and Worth, 2011).

A crucial part of the project is monitoring of the distribution of the injected fluid as the continued injection of CO_2 will be dependent on the integrity of the sealing units and on the subsurface distribution of the fluid. A suite of monitoring techniques is being utilized at the Aquistore site to ensure that these requirements are being satisfied at multiple stages of the injection (Aquistore, 2013). Although seismic monitoring predominates, alternative geophysical techniques are being tested to establish greater financial flexibility and more robust monitoring for future CCS projects.

Electromagnetic (EM) monitoring has potential in this CCS application as the CO_2 plume is expected to form an electrically resistive target contrasting with the conductive deep saline aquifers of the Williston Basin. In this study, two magnetotelluric (MT) datasets, collected 14 months apart in 2013 and 2014, are used to define the pre-injection geoelectric conditions at the site. The MT method is a deep-penetrating geophysical technique well-suited for regional-scale studies. Audiofrequency MT (AMT) soundings can be used to image at smaller (< 3km) scales (Ogaya et al. 2013). The 2013 dataset also includes controlled source EM (CSEM) data collected by the MT receivers during transmission of a signal from a dipole transmitter. CSEM soundings using co-linear electric dipole receivers and transmitters allow effective imaging of sub-surface resistivity (e.g., Streich et al. 2011). The CSEM data collection for the present study was done in conjunction with a larger-scale CSEM survey at the Aquistore site by GroundMetrics Inc. (GMI). The GMI survey used a borehole to surface electromagnetic (BSEM) configuration: results are currently under analysis and will be reported elsewhere (Hibbs 2014).

Pre-injection 2013 and 2014 MT-CSEM Surveys

The 2013 EM survey was conducted between August 23 and 28, 2013 at a total of 12 recording sites (Figure 1). MT soundings were made at sites in a 4 km by 4 km area surrounding the injection well and at a remote-reference site 10 km to the southwest. CSEM data were collected at additional sites located along a profile parallel to the NE-SW oriented dipole source, to the northeast of the injection well. The most distant CSEM site is ~9.5 km away from the transmitter. The 2014 survey was conducted between November 6 and 12, 2014. MT soundings were made at all of the 2013 sites and an additional remote site was established to the northeast, near the town of Bienfait, Saskatchewan.

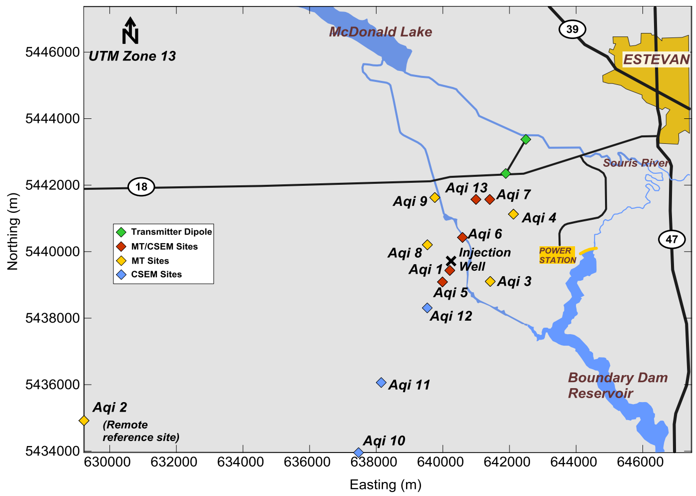

Figure 1: Location map of 2013 MT-CSEM survey. Note the proximity of the survey sites to the Boundary Dam Power Station.

MT data were recorded using Phoenix Geophysics MTU instrumentation. Telluric fields were recorded with 25 to 50 m dipole lines and porous pot electrodes and magnetic fields with MT and AMT induction coil sensors. The MT recording duration at each site was typically 14.5 to 20 hours. In order to expedite data collection, a deployment scheme was used in which the telluric field was measured at every site and the more spatially-uniform magnetic field measured at a smaller number of representative sites. Ideally AMT frequency magnetic data were imported from sites less than 1 km from the main site and MT frequency data from sites less than 4 km away. Careful selection of recording parameters allowed determination of a full MT-AMT response using a single telluric recording by importing of both AMT and MT magnetic data. In order to define the tipper response and more fully define the spatial distribution of EM noise, the 2014 survey included vertical magnetic field recordings at some sites.

CSEM data were recorded for short durations (2 to 4 hours) during the 2013 survey. At the MT sites the transmitted signal was recorded using the four telluric and magnetic channels and at the CSEM-only sites it was recorded by a single 25 m long electric dipole aligned parallel to the transmitter. The transmitter bipole was 1188.6 m in length and carried a 24.75 A, 0.5 Hz rectangular wave.

MT and CSEM Analysis

MT and AMT data processing has been done for the 2013 and 2014 data sets, but the 2013 CSEM data has yet to be fully processed. MT processing was done using Phoenix Geophysics software and transformed the recoded time series into frequency-dependent MT impedances, apparent resistivities, and phases using the robust Jones-Jödicke weighted cascade decimation approach (method 6 in Jones et al. 1989). Fourier transforms were computed at 4 frequencies per octave. For robust processing, the time series were divided into 20 equal length segments for which crosspowers were calculated at the selected frequencies. Crosspowers were rejected from the MT response determination if the coherency between the local and remote data was below a threshold of 0.35, or if the coherency between the telluric and magnetic data was below 0.25. Data were inversely weighted by their uncertainties.

Determination of accurate MT responses requires that the telluric and magnetic recordings for the main site have no correlated noise, and that magnetic data from the main and remote sites have no correlated noise. Aquistore data processing was complicated by EM noise, particularly for the 2013 survey, for which the spatial distribution of noise had not been established. For some sites and recording times, there is no low-noise magnetic data available for import. When available, data from the remote-reference site were imported as the local magnetic field precluding remote-reference processing. These limitations restricted the period-range and/or quality of the MT response at some sites. However, the overall quality of the MT responses at most sites for the 10^{-3} to 10^{3} s period range is very high (e.g., Figure 2) especially considering the proximity of the sites to the power station and additional infrastructure including powerlines, pipelines, and electric fences.

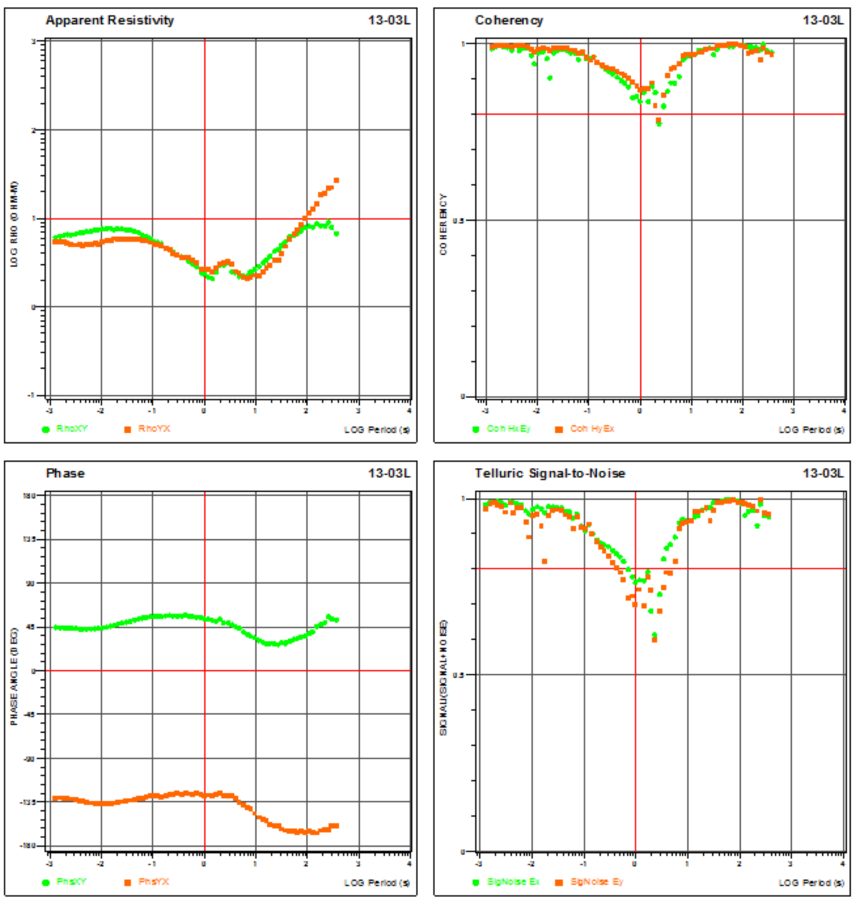

Figure 2: MT responses for aqi 05 for 2013 survey. Left panels show apparent resistivity and phase responses. Green curve is the xy-component (north-south electric current) and orange curve is the yx-component (east-west current). Right panels show measures of EM noise: local Ex-Hy and Ey-Hx coherences and telluric signal-to-noise ratio.

The effect of broadband EM noise is seen in all MT responses, particularly in the period range 0.125 to 6.667 s where there is a decrease in signal coherence centered on ~3 s. The noise exists across the whole survey area, and affects coherences for both locally and remotely processed data. An exception is coherence between local H_Y and remote H_Y channels, which is usually significantly stronger. For some sites, the noise was sufficiently large to require removal of large parts of the response. At other sites, there were sufficient segments with unaffected crosspowers to allow definition of a smooth response at all frequencies. Additional noise is evident at the longest and shortest periods, and there is a consistent drop in coherence at ~0.001 s. The CSEM transmitter signal is visible in the MT time series and spectra derived from them. With careful processing, its effect can be removed from the MT responses.

The MT responses (e.g., Figure 2) are very similar for the xy- and yx-modes and for different sites indicating the sub-surface resistivity is dominantly one-dimensional. At shortest periods, the apparent resistivity of ~6-10 Ω.m indicates moderately conductive near-surface rocks. Between ~0.05 s and 4 s the response becomes more conductive (lower apparent resistivity and higher phase) reflecting very conductive Mesozoic rocks. At ~10 s, the xy and yx curves diverge, indicating multidimensional structures in the underlying Precambrian rocks. Visual examination shows that the 2013 and 2014 MT responses are very similar indicating minimal variation in the near-surface and deeper resistivity structures. The noise characteristics are also consistent despite addition of new infrastructure at the site between surveys. Future analyses will include statistical-based comparison of the 2013 and 2014 responses to define the effective limits of resolution of temporal changes in the MT response.

Initial analysis of the 2013 CSEM data has included frequency-domain-based examination of signal spectra and time-domain-based stacking of the repeated waveform. The transmitter response can be defined accurately up to 5 km from the source (aqi 05) with the harmonics of the signal exceeding the noise level to periods as short as 0.0167 s. Preliminary examination of stacked data from the CSEM sites shows that the signal can still be detected, although less accurately, at sites up to 9 km from the source.

Theoretical CSEM Modeling

Theoretical modelling using EMIGMA software (e.g., Figure 3) has demonstrated the co-linear electric dipole CSEM survey configuration used at the Aquistore site provides limited resolution of a resistive plume at 3 km depth. Although scattered EM fields associated with the plume have distinct spatial forms, they are up to 4 orders of magnitude smaller than fields associated with the background geological structure and the primary field travelling through the atmosphere. The CSEM configuration provides better resolution of shallow plumes (200-600 m depth) suggesting that the method will be optimally used, along with AMT responses, to define the shallow (< 1 km) resistivity across the survey area. The method therefore also has some potential in the monitoring for leakage of CO_2 into the shallow strata overlying the injection reservoir.

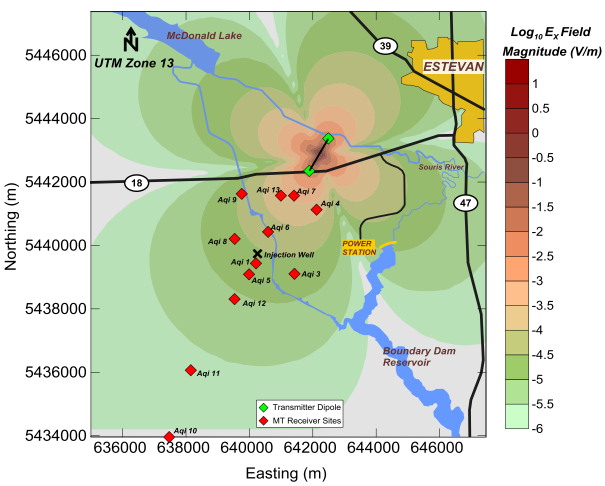

Figure 3. Signal pattern produced by an electric dipole source at the Aquistore site. Contours show the component of total electric field parallel to the source.

Conclusions

Repeat MT surveys in 2013 and 2014 at the Aquistore carbon sequestration site have defined the local MT response. The results confirm that the resistivity structure is dominantly one-dimensional and define the spatial distribution of EM noise. They will also allow statistical examination of the ability to resolve temporal changes in the MT response. Theoretical modelling indicates that CSEM data collected in 2013 will be optimally used, along with the AMT responses, to define the shallow (<1 km) resistivity structure at the site.

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