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Toward CO_2 multimeasurement geophysical monitoring in the North Dakota CarbonSAFE project

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Abstract

Seismic surveys have been the standard geophysical method for the monitoring of carbon dioxide (CO_2) injection into subsurface reservoirs and cap rock integrity from the earth's surface. Since electromagnetic (EM) and gravity methods are also sensitive to CO_2 saturation and volume changes within the reservoir, those methods were explored as alternative or complementary CO_2 monitoring methods in the North Dakota CarbonSAFE (Carbon Storage Assurance Facility Enterprise) project. North Dakota CarbonSAFE is assessing safe, permanent, commercial-scale geologic storage of CO_2 generated by the Milton R. Young (MRY) coal-fired power plant. This project is part of the U.S. Department of Energy initiative to develop geologic storage sites to store 50+ million tonnes of CO_2 from industrial sources. Feasibility studies for seismic, controlled-source EM (CSEM), and gravity methods were conducted to determine the effectiveness of these methods in monitoring CO_2 in the Broom Creek Formation (Fm) and Deadwood Fm, which are at depths of approximately 1450 and 2835 m, respectively, beneath the MRY power plant. While all three methods can be used to monitor CO_2 injected into the Broom Creek Fm, only the seismic and CSEM methods proved applicable to monitoring CO_2 injected into the Deadwood Fm. Based on the positive results of those studies, baseline seismic, CSEM, magnetotelluric (MT), and microgravity data were acquired around the MRY power plant and associated coal mine. Overcoming data acquisition challenges associated with a lake in the study area, electrical infrastructure around the plant, noise from mine activities, complex near-surface conditions associated with reclaimed mine land, high wind speed, and extremely cold temperatures, data processing, modeling, and inversion of the baseline geophysical data demonstrated the importance of high-quality data for a CO_2 geophysical monitoring program. Implementing more advanced data acquisition and processing techniques in future monitoring surveys can further improve confidence in interpretations of geophysical survey data.

Keywords: CO_2 monitoring; multimeasurements; geophysical methods; seismic method; electromagnetic method; gravity method

1. Introduction

Geophysical methods are well-suited to monitoring geologic reservoir rock and fluid property changes due to carbon dioxide (CO_2) injection since these changes produce elasticity, density, and resistivity geophysical anomalies. These changes can be quantified when geophysical methods are applied before and after CO_2 injection. Current

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alternatives for monitoring CO_2 injection into subsurface reservoirs and cap rock integrity from the earth's surface include seismic, gravity, and electromagnetic (EM) methods. The sensitivity of these methods to CO_2 saturation and volume changes within the reservoir and economic factors can play a crucial role in selecting the optimal geophysical characterization and monitoring method for carbon capture, utilization, and storage (CCUS) projects.

Technology advances in data acquisition, processing, and interpretation/inversion from extensive research and development (R&D) activities over many decades in the oil industry have made seismic the standard geophysical method used in CCUS projects, primarily because of its high horizontal resolution. However, its limited sensitivity to a wide range of CO_2 saturation can contribute to uncertainty in seismic imaging of CO_2 plume boundaries and the estimation of reservoir parameters. Furthermore, seismic data acquisition costs have a high impact on the budget for CO_2-monitoring activities. The turnaround time from seismic data acquisition to data interpretation/inversion constitutes a determining factor in planning geomodel building for reservoir characterization and updating the geomodel during monitoring activities.

Although the R&D efforts dedicated to gravity and EM methods have been less than the seismic method, developments associated with these methods have resulted in advances in robust data acquisition, processing, and modeling/inversion. Moreover, their sensitivity to a broad range of CO_2 saturation and the lower data acquisition costs than the seismic method represent fundamental considerations for their use (individually or combined with the seismic method) in CCUS projects to reduce the uncertainty in CO_2 monitoring and reservoir parameter estimation.

A CO_2 multimeasurement geophysical baseline acquisition has been conducted under the North Dakota CarbonSAFE (Carbon Storage Assurance Facility Enterprise) project, which is part of the U.S. Department of Energy (DOE) initiative to develop geologic storage sites to store 50+ million tonnes (Mt) of CO_2 from industrial sources. North Dakota CarbonSAFE is assessing safe, permanent, commercial-scale geologic storage of CO_2 generated by the Milton R. Young (MRY) coal-fired power plant. The Energy & Environmental Research Center leads the project in partnership with DOE's National Energy Technology Laboratory (NETL) and Minnkota Power Cooperative.

As part of an integrated multimeasurement geophysical approach, the study explored the possibility of using a combination of surface-based geophysical methods—comprising 2D seismic, controlled-source EM (CSEM), magnetotelluric (MT), and microgravity—to monitor CO_2 plume location and conformance as an alternative to 3D seismic. This paper presents the feasibility of using 3D seismic, CSEM, and microgravity methods for CO_2 monitoring in the study area and baseline data acquisition and processing results of those methods.

2. Geologic background

The study area is located near Center, North Dakota, USA, with storage of approximately 4 Mt of CO_2 per year expected in the Broom Creek Fm (primary target) and Deadwood Fm (second target) at depths of approximately 1450 and 2835 m and average thicknesses of 70 and 85 m, respectively.

The major Broom Creek lithofacies are eolian sandstone, nearshore marine sandstone, marine carbonate, and anhydrite. The Broom Creek Fm in the study area can be divided into upper, middle, and lower sandstone-dominated intervals, with an average porosity of 23% and median permeability of 100 mD. Mudstones, siltstones, and interbedded evaporites of the undifferentiated Opeche Fm and Spearfish Fm unconformably overlie the Broom Creek Fm. Mudstones and siltstones of the lower Piper Fm (Picard Member and lower) overlie the Opeche Fm/Spearfish Fm. The lower Piper Fm and Opeche Fm/Spearfish Fm serve as the primary confining zone for the CO_2 storage reservoir, with an average thickness of 47 m. The Amsden Fm (dolostone, limestone, and anhydrite) unconformably underlies the Broom Creek Fm and serves as the lower confining zone, with an average thickness of 82 m [1]. The base of the Broom Creek Fm is approximately 1500 m above the Precambrian basement.

The Deadwood Fm unconformably overlies the Precambrian of the Williston Basin and consists of siliciclastics, carbonates, and evaporites. The Deadwood Fm can be divided into six members, A–F [2]. The earliest A member is Cambrian, composed of alluvially deposited conglomerates and sandstones. The B member consists of glauconitic shallow marine sandstones and siltstones. The C–F members consist of an Ordovician succession of three regressive–transgressive sequences containing sandstones, siltstones, mudstones, and carbonates. The A–E members are present in the study area. The Winnipeg Group unconformably overlies the Deadwood and consists of three formations: Black Island, Icebox, and Roughlock. The Black Island Fm consists of a mixture of sandstone and shale deposited in a fluvial–deltaic to shallow marine environment [3]. The Icebox Fm conformably overlies the Black Island Fm and is a marine shale that serves as the primary upper confining zone, with an average thickness of 36 m. The Roughlock Fm is a calcareous shale to argillaceous limestone. The continuous shales of the Deadwood Fm B member serve as the lower confining zone, with an average thickness of 10 m. In addition to the Icebox Fm, there are 174 m of impermeable rock formations between the Black Island Fm and the next overlying porous zone, the Red River Fm [1].

3. Seismic and rock physics

The BNI 1, Flemmer 1, J-LOC 1, and J-ROC 1 wells were drilled during different North Dakota CarbonSAFE project phases to assess the CO_2 storage feasibility of the Broom Creek Fm and Deadwood Fm. After penetrating the Broom Creek Fm, the BNI 1 and Flemmer 1 wells reach total depth (TD) in the Amsden Fm. The J-LOC 1 and J-ROC 1 wells reach TD in the Precambrian after penetrating the Broom Creek Fm and Deadwood Fm. Core data and a comprehensive set of well logs were acquired.

Several seismic data sets have been acquired in this project, including an 8-km-long seismic source test and 17-km^2 3D seismic survey (Center 3D) in 2019 and a 31-km^2 3D seismic survey (Minnkota 3D) and 34 km of 2D seismic lines in 2020 (Fig. 1). 2D Line 1 connects the two 3D seismic data sets and ensures consistent interpretation across the entire study area. 2D Lines 2, 3, 4, and 5 intersect at the J-ROC 1 well. Seismic data have been used to assess geologic structure, interpret interwell heterogeneity, and inform well placement.

Seismic data acquisition was affected by no-permit areas, Nelson Lake, the power plant, electrical utility infrastructure, mine noise, and the challenging near-surface conditions associated with reclaimed mine land. Data were processed with an amplitude variation with offset (AVO) amplitude-preserving workflow through prestack time and depth migration. This workflow included reliable and consistent static solutions across the surveys, AVO-compliant noise attenuation tools, surface-consistent amplitude corrections, consistent survey wavelets, and imaging supported by the available wells. Data-processing products included migrated cubes and 2D lines and AVO-compliant gathers for rock physics and inversion.

3.1. Rock physics

Rock physics analysis provides the means to connect rock properties and fluid saturation determined from geology or petrophysics with measurements from geophysics. Once the relationships are established, the process can be reversed so that rock properties and fluid saturations can be predicted in the subsurface, away from outcrops and well

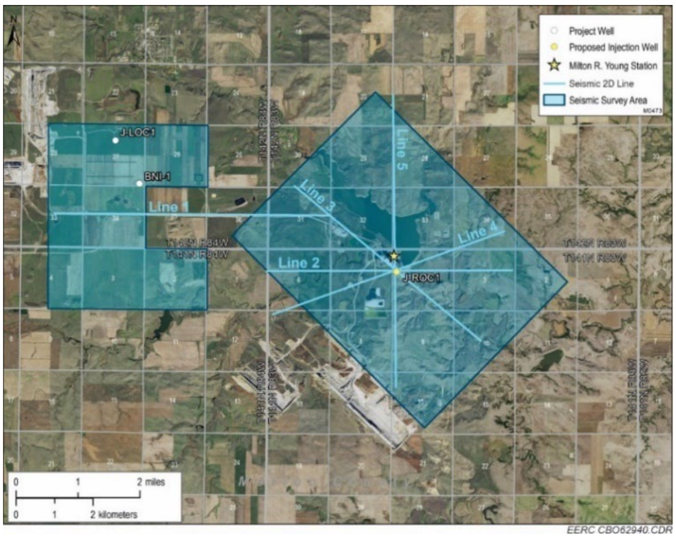

Fig. 1. Map showing study area 2D and 3D seismic surveys. Left: Center 3D data set and BNI 1 and J-LOC 1 wells. Right: Minnkota 3D data set and 2D Lines 1, 2, 3, 4, and 5 intersecting at J-ROC 1 well (yellow point) located near MRY power plant (yellow star).

control. Additionally, rock physics can be used to predict how changes to rock properties and fluid saturation will affect geophysical measurements and thus the feasibility of using geophysics to monitor sequestration and storage of CO_2.

The data set used in the rock physics analysis consists of all available well logs and core data from the four wells and both 3D seismic data sets. The geologic data set used for rock physics analysis consists of regional geology, core descriptions from whole core and thin sections, and core plug analysis results, including x-ray diffraction, x-ray fluorescence, and measurements of porosity, permeability, and grain density.

Rock physics crossplot analysis and diagnostic modeling results showed that average porosity and dominant lithology might be detectable from seismic prestack inversion in the Broom Creek Fm. Fluid property modeling demonstrates that a reduction in Vp, density of the fluid mixture, and increased resistivity are caused when CO_2 is injected into the reservoir. Furthermore, permeable, clean sand with a small volume of cement like the middle Broom Creek sand at the J-LOC 1 well will be sensitive to changing saturation. The Broom Creek at the J-LOC 1 well is divided into three sandy intervals separated by anhydrites and dolomites.

Synthetic seismic 1D and 2D models show that time-lapse seismic is likely to detect saturation changes indicated by an amplitude increase (~0.09 normalized) in the middle sand. The upper sand is thin, with porosity like the middle sand. The lower sand consists of several thin sands that have lower porosity and permeability and a greater volume of dolomite/anhydrite cement. Seismic 1D models reveal that both sands will likely produce a small amplitude decrease (~-0.04 normalized) when the reservoir is CO_2-saturated. This change in seismic amplitude is likely to be challenging to detect and will require diligence in seismic acquisition and processing.

The sands in the Deadwood Fm are well-cemented and intermediate to low porosity. Most variation in the Vp/Vs vs. acoustic impedance (AI) space is observed in AI and is produced by changes in porosity and lithology. Furthermore, changing lithology produces a small Vp/Vs ratio variation that may be challenging to detect, requiring careful data conditioning before prestack inversion. Fluid property modeling indicates that CO_2 injected into the reservoir will cause a reduction in Vp and density of the fluid mixture and increased resistivity.

Seismic 1D modeling shows that time-lapse seismic may detect a weak amplitude (~0.04 normalized) increase associated with CO_2 saturation. Moreover, diagnostic modeling suggests that effective pore shapes are flat, indicating potential sensitivity to changes in pore pressure. Pressure modeling indicates that a 5-MPa increase in pore pressure will create an additional increase (~0.05 normalized) in seismic amplitude. Detecting these small amplitude increases will require diligence in seismic acquisition and processing.

A detailed description of Broom Creek and Deadwood rock physics analysis for CO_2 monitoring in the study area is reported in Adams et al. and Barajas-Olalde et al. [4, 5].

3.2. Prestack seismic inversion

Time-lapse seismic is an effective and proven technology for getting snapshot images in time of CO_2 distribution in a subsurface reservoir [6–9]. When injected, CO_2 displaces other reservoir fluids and seismic impedance changes, causing seismic amplitude differences in the injection zones. This is due, in part, to the high sensitivity of the seismic signal to changing pore pressure and fluid properties.

Incorporating seismic inversion and rock physics into seismic interpretation can considerably improve modeling and monitoring to detect stored CO_2 and assess the location of the CO_2 plume over time [10, 11]. Seismic inversion transforms seismic reflection data into models of rock elastic property distributions (i.e., velocity, density) that produced the reflections. When seismic inversion is integrated with rock physics, elastic properties can be quantitatively transformed into geologic properties (e.g., porosity, lithology) for reservoir characterization.

Wave equation-based (WEB)-AVO inversion [12, 13] was applied to the baseline 2D and 3D data sets targeting the Broom Creek reservoir. WEB-AVO is a target-oriented inversion based on an iterative solution of the elastic wave equation that accounts for multiple scattering, mode conversion, and transmission effects. Target-oriented refers to the application of the inversion algorithm to an interval consisting of a reservoir sequence and a top and bottom seal. The reservoir can be defined by strata with initial elastic parameters. The boundaries of the target interval are defined relative to a marker horizon. The seismic data are redatumed to the target interval upper boundary as if they had been acquired at the depth of the target interval. A target interval reduces the computational cost of the elastic wave equation while still accounting for all internal scattering effects and true travel times over the interval. As only the seismic data corresponding to the reservoir and its surroundings are inverted, overburden- and surface-related multiples are considered noise, as they do not obey the target-oriented wave equation. This makes the technology robust, even with older seismic data sets or in other situations where signal-to-noise ratios are low.

The first step of the WEB-AVO algorithm consists of an initial estimate of the reservoir model obtained from the incident field in a smooth background, assuming a linear relationship (primary reflections only) between elastic subsurface properties and seismic amplitudes. In the next step, the wave equation is deployed to include second-order scattering based on the first estimate of the reservoir properties. The whole scheme comprises an iterative procedure consisting of AVO inversions, using the best estimate of the wave field in the reservoir, followed by updating the wave field based on the latest reservoir model. The procedure is repeated until neither the reservoir model nor the wave field changes and convergence is reached. In general, only a few iterations are required. A more elaborate discussion of the technique is provided by Gisolf et al. [12].

The WEB-AVO method directly inverts for compressibility and shear compliance (inverses of bulk and shear moduli, respectively). This feature makes the technology highly suitable for time-lapse monitoring, as compressibility is the most sensitive elastic parameter to fluid changes [13]. At the same time, the shear compliance is only sensitive to lithology. As shear compliance is insensitive to changes in pore fluid, it can be used as an additional constraint when inverting several monitor data sets simultaneously. WEB-AVO technology has been successfully applied to monitoring a mature oil field undergoing CO_2 enhanced oil recovery to improve understanding of CO_2 distribution in the reservoir [14].

Input data for the North Dakota CarbonSAFE application of WEB-AVO consisted of prestack time-migrated (PSTM) seismic offset gathers of the Minnkota 3D and 2D lines; sonic; shear sonic; density well logs from the BNI 1, J-LOC 1, and J-ROC 1 wells; and the velocity model as used for PSTM.

The WEB-AVO workflow included rock physics analysis and evaluation of expected time-lapse effects in the well log and seismic domains; seismic data preconditioning (multidimensional dip-filter, amplitude balancing along offset, lateral scaling); conversion of seismic image gathers from offset to angle/slowness domain; extraction of angle/slowness-dependent wavelets by tying seismic to well synthetics; building a low-frequency background model using low-pass-filtered well logs and horizons; and 2D and 3D inversions. Interbed multiple analysis was conducted at the BNI 1 well to assess any linear and elastic responses at the top of the Broom Creek that could affect the AVO of the data.

Fig. 2 shows WEB-AVO results at the Broom Creek Fm using the Minnkota 3D data set. A time slice (1216 ms) of PSTM data (seismic amplitude) is depicted as a reference at the top of the figure. The excellent resolution of compressibility (Fig. 2b) and shear compliance (Fig. 2c) should be noted. Facies estimated based on WEB-AVO and rock physics (Fig. 2d) include anhydrite (blue), carbonates (gray), sands (red), and shales (yellow). This estimation is compatible with previous seismic interpretation results (not shown here) that considered eolian dunes in the reservoir and interdune carbonate beds (internal communication). Similar results were obtained using 2D seismic data (not shown here).

These results using the seismic baseline data are encouraging for applying WEB-AVO to future monitoring data sets. The compressibility and shear compliance estimated by WEB-AVO might facilitate development of a workflow for the differentiation between pressure and saturation effects reported in Barajas-Olalde et al. [14].

4. EM

As CO_2 is electrically resistive, EM methods such as CSEM are well-suited for monitoring CO_2 injected into a reservoir because of the strong conductivity contrast created from CO_2 replacing brine [15]. When CO_2 replaces brine, resistivity of the reservoir increases.

A feasibility study was performed to determine the effectiveness of CSEM monitoring CO_2 injected into the Broom Creek Fm and Deadwood Fm. This study consisted of 3D modeling of the CSEM response and a field noise test. The goal of 3D modeling was to define the expected surface EM field response level caused by an increase in CO_2 saturation and determine whether signals of that magnitude could be detected in the field in the presence of observed noise levels. Additionally, the feasibility study helped refine CSEM survey field parameters, such as optimizing station spacing along survey lines to maximize signal from the target formations and indicating any locations that should be avoided because of high EM noise levels.

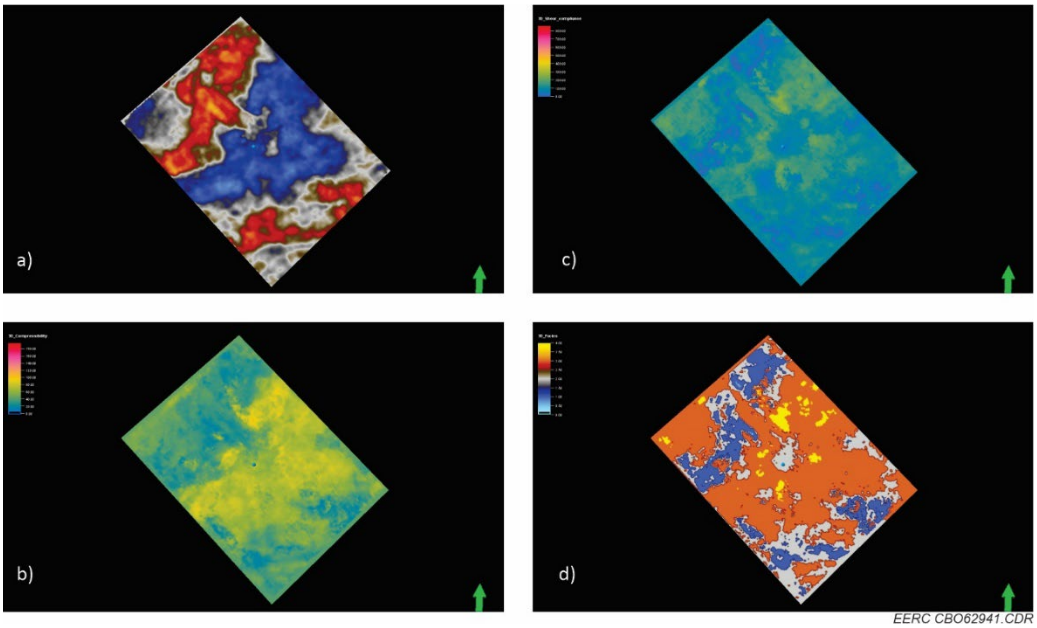

Fig. 2. Time slices: a) PSTM, b) WEB-AVO compressibility, c) WEB-AVO shear compliance, and d) estimated facies (1: anhydrite [blue], 2: carbonates [gray], 3: sands [red], and 4: shales [yellow]) at the Broom Creek reservoir. Compressibility and shear compliance values were scaled by 1E+12 to simplify color scale labels. The blue dot in the middle of the rectangle represents the location of the J-ROC 1 well.

Twenty-one months of CO_2 injection in the Broom Creek Fm was simulated using a 60% average CO_2 saturation and an injection radius of 500 m. The simulation showed that 15–18 months of injection produced a strong anomaly. Next, an injection radius of 150 m was used, and the required receiver spacing was estimated. The 3D modeling results for the Broom Creek Fm for Ex, Ey, and dBz/dt showed acceptable results to reconstruct the CO_2 anomaly for 100-, 200-, and 300-m receiver spacings.

As the Deadwood Fm has lower porosity and is significantly deeper than the Broom Creek Fm, a conservative 30% CO_2 saturation after injection (representing a 150-m flood zone radius) was considered. Ex, Ey, and dBz/dt responses and differences corresponding to reservoir conditions before and after CO_2 injection are between 1% and 5% for a 1D model and below 1% for 3D models. Based on these results, monitoring injected CO_2 in the Deadwood Fm under the assumed field and survey parameters will be challenging, and novel anomaly-enhancing methods will be needed.

Based on these feasibility study results, a time-lapse CSEM monitoring project was designed. The survey layout and design are shown in Figure 3a. The baseline survey was taken before the injection of CO_2 into the formations. Furthermore, a magnetotelluric (MT) survey was performed in conjunction with the baseline CSEM survey to measure field site background resistivity. The survey was carefully designed, and special attention was paid to noise levels in the field to ensure that any time-lapse differences observed would be solely due to changes in CO_2 concentration within the reservoir.

4.1. CSEM and MT data acquisition

Initial EM surveying lines were designed to overlap 2D seismic lines. Protected areas were avoided when setting out the lines, and most stations were located at least 100 m away from power lines to avoid disturbance from EM noise. The survey layout consists of three lines of receivers and two separate CSEM transmitter sources to the north and south of these lines, each having two dipoles. Given the optimal 200-m station spacing as determined from the feasibility study, 125 CSEM receiver locations were used. The receivers consisted of 100-m-long dipoles oriented north–south (Ex) and east–west (Ey). Orthogonal dipoles were used partially for data redundancy and to observe the difference between the dipoles for anomaly enhancement. An air loop or buried induction coil was laid out on the northwest quadrant of each receiver site to measure the vertical magnetic field (Hz). Contact resistance was logged at each site for quality assurance (QA) during acquisition, processing, and interpretation.

Each source consisted of buried electrodes connected by a 1-km-long cable to the transmitter. The source dipoles were oriented in north–south and east–west directions. The transmitter was set to transmit between 160 to 250 amperes of current. The actual current was monitored and recorded during transmission to normalize data. The recording times for each receiver station were between 3 and 4 hours. Extended long recording times (total of 7 hours per transmitter) were done at overlapping sites for use as reference locations should they be required for later time-lapse processing.

Forty-two MT site locations were deployed, as depicted by large green dots in Fig. 3a. A total of three survey lines were laid, with a spacing of 600 m between each MT recording site. Three planned stations located near the power plant were skipped during the survey because of accessibility issues. Six additional sites were located close to a noise source; the recorded data were reviewed in these cases, and the measurements were repeated because of unsatisfactory quality. A primary remote reference site was in Grand Forks, North Dakota, USA, and a backup site was operated in Austin, Texas, USA, during the first part of the survey. MT data quality was greatly improved by using the remote reference during data processing.

QA/quality control procedures were carried out in the field during collection (real time) and after data processing. High-EM noise areas near some receiver sites required additional measures, including carefully selecting the length of the lines when laying out the site, extending data acquisition time, and conducting necessary repetitions based on close monitoring of daily operations. Data were uploaded to the cloud to conduct quality assessments during 24-hour field operations. If a receiver station showed poor data quality, the station was investigated, and the measurements were repeated until the quality improved. This workflow maintained high data quality while monitoring acquisition equipment moved along the survey line (leapfrogging).

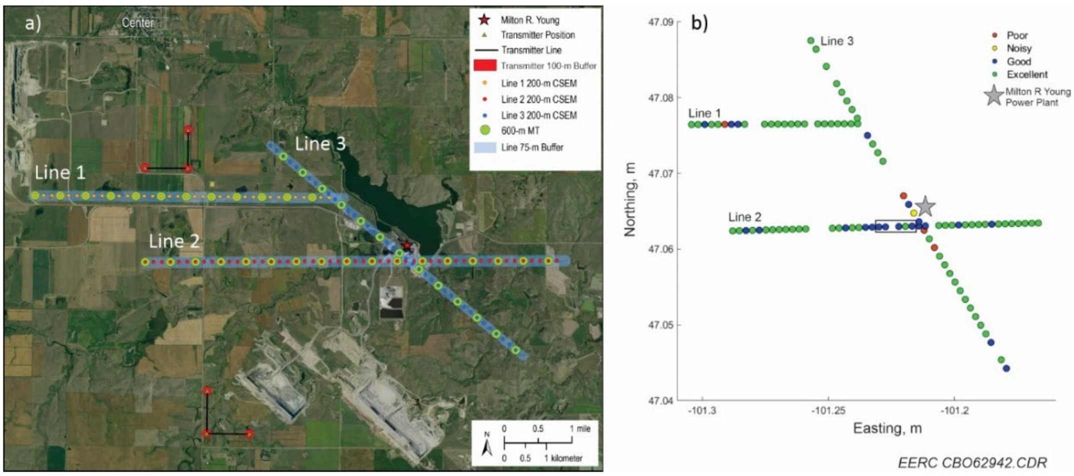

Fig. 3. a) CSEM and MT North Dakota CarbonSAFE baseline survey layout. CSEM receivers were placed at 200-m intervals along the three shaded lines, and source electrodes were placed at two transmitter sites. MT sites were deployed at 600-m intervals along the receiver lines, indicated by the large green dots. b) Geographical representation of data quality for a specific component and transmitter–orientation pair. The box indicates the location of the profile shown in Fig. 4. Poor and noisy data points can be singled out for future survey design consideration.

4.2. CSEM and MT data processing

After passing initial QA during acquisition, transmitter and receiver data were merged into sequential files. This process also included time alignment between transmitter signal and receiver data and a correction for time shifts. Once all input parameters were verified (including onset time, transmitter current used for normalization, waveform period, and type of waveform), a prestack low-pass filter with a 15-Hz cutoff was applied to the data. This frequency was chosen based on the feasibility analysis of response time of electric and magnetic fields concerning the target Broom Creek Fm and Deadwood Fm. The choice of this simple filter also represents the philosophy of preserving data integrity since only as much processing as necessary should be performed.

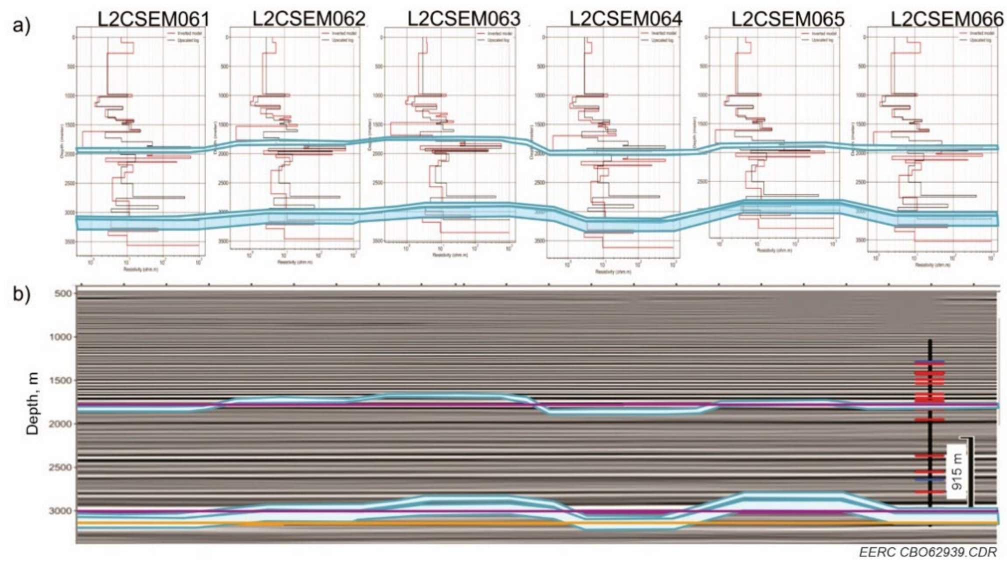

Fig. 4. a) Profile of 1D inversion results (red) and the anisotropic borehole model (black) along data acquisition Line 2. Shaded areas interpolate the reservoirs of the Broom Creek Fm (top) and Deadwood Fm (bottom). b) Plot of the seismic data over this profile, with the Broom Creek Fm and Deadwood Fm tops denoted by magenta lines. Blue areas show estimated formation depths from CSEM data.

Current normalization was required to get highly accurate and repeatable signals, as repeat surveys are expected to have slightly different transmitters and receivers. After normalization, the current trace in the processing workflow serves as a reference channel. Sporadic noise caused by natural sources is not recognized and cannot be removed using filters. However, this noise can be eliminated using robust stacking techniques. Here, selective stacking was chosen. This technique sorts data amplitudes in ascending order for each time sample for all transients. Amplitude frequency distributions are calculated from sliding overlapping windows over sorted amplitude curves for each time sample of all transients. Data within the area under the symmetric distribution curve are kept, and a percentage of that area about the maximum is calculated [16].

MT data were processed to produce an apparent resistivity and phase curve for each location that was of acceptable quality. Further analysis was performed to calculate the spectra of the data and coherency plots. Data from each line were inverted in 2D to generate a resistivity model along the profile. These models were combined to generate a starting 3D resistivity model used as a reference model for CSEM inversion.

4.3. CSEM data quality analysis

In postprocessing, the time series data are plotted and evaluated for data quality. The data are categorized as excellent, good, noisy (acceptable), or poor, depending on the pattern and rate of both magnetic and electric transient decay. All categories of data may additionally show transient reversals (zero crossovers), suggesting the possible presence of signal channeling and/or 3D structures. These categories can be evaluated and plotted to visually represent the data quality for each pair of field components and transmitter orientation as a function of field location, as in Fig. 3b. While data marked as poor and noisy are not used for further interpretation, knowing where these data occur can be vital for future time-lapse CSEM surveys. Special attention can be paid to the data collection process at these sites. Data from such sites may also indicate the effect of a noise source, such as an anthropogenic feature that cannot be addressed or attenuated, suggesting that an alternate site should be considered for future data collection.

Because of the careful field data collection process, approximately 85% of collected data were classified as either good or excellent. Another 6% could be further processed to reach that level of quality. For a field CSEM data set, this is a high level of data retention and nicely sets up future time-lapse surveys for success. An unconstrained 1D inversion was performed for each receiver site. The results were compared to an anisotropic borehole resistivity model to validate the data further.

Fig. 4a shows the 1D inversion results (in red) and the borehole model (in black) of six sites adjacent to each other along survey Line 2. Generally, inversion results align well with borehole data, indicating high confidence levels in data collection and processing. Blue outlines indicate the interpreted Broom Creek Fm and Deadwood Fm from the inversion results. Results were further validated by comparing the inverted resistivity models with 3D seismic data, as shown in Fig. 4b, with the Broom Creek and Deadwood seismic horizons indicated by magenta lines. For most stations, CSEM inversion accurately matches the seismic model. Inversion results that deviate from the seismic could indicate lower data quality or denote areas of 3D structure unaccounted for in 1D inversion.

5. Gravity

Microgravity is a geophysical tool sensitive to minute changes in density. As there exists a density contrast between CO_2 and existing pore fluids, either hydrocarbon or brine, a microgravity survey has the potential to identify and map time-lapse density changes reflective of reservoir saturation change due to injected CO_2 [17, 18]. Moreover, microgravity measurements could detect the resulting change in density if CO_2 were to leak from the reservoir and travel up to the near-surface. Gravity measurements can also be combined with seismic data to help understand geologic structure, particularly at basement depths, and may assist in delineating geologic features at a depth that might affect a CO_2 storage project. Since microgravity data acquisition and processing are relatively inexpensive, the overall cost of a CO_2-monitoring program would not increase significantly by incorporating microgravity alongside conventional time-lapse seismic surveys. Their use can increase the frequency of reservoir-monitoring efforts.

A baseline microgravity survey was conducted targeting the Broom Creek Fm. The initial step consisted of a feasibility study based on Young's vertical cylinder method [19] to determine the magnitude of the expected microgravity signal given estimated injection rates and reservoir properties. The gravity anomaly measured is thus a function of the ratio of cylinder radius to cylinder depth, and a range of reservoir settings and dimensions can thus easily be modeled for a given amount of CO_2.

Multiple scenarios were tested for various volumes of injected CO_2 and expected plume height and radius for Broom Creek porosity and saturation values. Using the most likely reservoir simulation scenarios, Young's model predicts that after 8 years of CO_2 injection, the gravity anomaly is on the order of 10 μGal, while after 25 years of CO_2 injection, the anomaly is on the order of 22 μGal. This prediction suggests that the time-lapse effect from surface gravity measurements alone will be challenging to detect and require careful field data collection techniques and consistent attention to detail.

The scale of the anomalies expected from a time-lapse microgravity survey at this site tests the limits of accuracy and precision of relative gravity meters. Based on the expected anomaly level, the Scintrex CG-5 meter was chosen, which has a reading precision of 1 μGal, repeatability of ±5 μGal and a residual long-term drift of <20 μGal/day and records data at 6 Hz [20]. Teleseisms, elastic hysteresis, wind, traffic, and other cultural noise affect microgravity surveys. This noise makes survey precision close to instrument precision challenging to achieve. Microgravity surveys attempt to reduce noise by acquiring data over long observation times and with multiple observations at each station. The study used an observation time at each station of 20 minutes with three occupations or 30 minutes with two occupations, which allowed the completion of up to 19 station occupations per day. Typically, base stations were measured at every sixth station occupation. The CG-5 meter records and applies some basic processing to the data, returning an average and standard deviation for each record. Typical record durations are 30–60 s, but it is crucial to select a recording time that is long enough to suppress random noise in the records optimally. Boddice et al. [21] discuss selecting a record length that suppresses short-period noise without creating drift caused by the partial cancellation of longer-period noise by measuring the Allan deviation of raw gravity measurements. The Allan deviation estimates the standard deviation of the data group averages as the size of the groups is changed. An acquisition time of 150 s was selected, which is close to the minimum Allan deviation and allows eight records during each station occupation.

5.1. Gravity data acquisition

Microgravity data were collected along 2D Lines 1 and 3 across the project site, connecting the proposed locations of two potential CO_2 injection wells. The profile consisted of 52 stations, spaced 225 m apart, for a total line length of 11.5 km. Data acquisition entailed a land survey for establishing station locations and a gravity survey. A differential global positioning system (GPS) was used for the land survey, achieving an elevation error of less than 0.34 cm. The gravity survey followed the land survey.

The gravity survey consisted of three parts: 1) establishment of a new gravity base station at the Oliver County Courthouse (OCC) in Center, North Dakota, referenced to the William L. Guy Federal Building base station in Bismarck, North Dakota (the tie consisted of six loops between Bismarck and Center); 2) use of the OCC station to establish six temporary base stations at Stations 6, 16, 26, 33, 34, and 44 along the 2D line to be used during the survey (the tie consisted of three loops with the OCC station); and 3) a survey of the remaining 46 stations (each station was loop-tied to a local base station).

Gravity data acquisition at an active coal mine on the prairie in North Dakota in autumn results in several challenges. Low overnight temperature results in frozen soil in the morning and thawing later in the day, which creates challenges with meter leveling and tilt. Wood blocks under the tripod legs reduced tilting by distributing the meter's weight over a larger area. Part of the survey was located 50 m from an active haul road. Passing loaded coal trucks can weigh 227,000 kg; their vibrations are sensed by the gravity meter and observed in the raw data. Wind on the prairie can be strong. During the survey, wind gusts up to 56 km/h were experienced. On most days, wind gusts were around 32 km/h. A bottomless tub placed around the meter was the best solution for noise reduction. Meter leveling and vibration during transport were also challenging. Short periods of off-level transport between stations caused elastic hysteresis in the meter response.

5.2. Corrections and data selection

The data were processed to remove noise and the effects of terrain and elevation, resulting in free air and complete Bouguer anomaly data sets. The Scintrex CG-5 conditions the data records and outputs the average value and standard deviation to a file. The meter includes corrections for tilt, linear drift, and spike rejection. Postacquisition processing includes editing records based on observer notes and noise spikes; corrections for earth tides, instrument height, residual drift, and local barometric pressure; and conversion to absolute gravity. The review and editing of data consisted of removing any records noted for removal in observer notes, followed by a review of occupation record sets to remove exceptionally noisy records with standard deviations greater than three times the average record standard deviation for the day.

Variation of local atmospheric pressure can be a significant source of microgravity noise. Barometric pressure was measured at each station during every occupation. Local pressure correction was calculated using an algorithm described by Gabalda et al. [22]. During the survey, the atmospheric correction ranged over ±6 μGal.

An unexpected challenge to data selection is the presence of elastic hysteresis and microtears in the occupation records and their variability from set to set. Microtears, caused by jarring during handling and transport, create nonlinear drift that can spread over several occupations. Elastic hysteresis is created by changes in main spring tension when the CG-5 meter is tilted beyond a critical angle of 5.2–6.4 degrees. If the meter is tilted for as little as 3 min, it can require 15 min or more to recover [23]. Tilt beyond the critical angle for 10 min or more can require 81 min or more to recover. The only correction for elastic hysteresis is extended rest or recording time.

This survey assumed that the hysteresis curve was long-tailed and spent considerable time close to the actual value. Any measurements within ±5 μGal of the final low-noise measurement were accepted for potential use in the final estimate. Postacquisition analysis suggests that some occupations may not have been long enough to reach the asymptotic part of the curve.

The conversion from relative to absolute gravity requires three passes. Pass 1 establishes absolute gravity at the OCC base station, Pass 2 establishes absolute gravity at the survey base stations, and Pass 3 establishes absolute gravity at the remaining stations. This process is followed by calculating the standard deviation of corrected absolute gravity by station. Any station with a standard deviation of >15 μGal is reviewed, and any outliers are removed. In most cases, these data have strong elastic hysteresis effects or microtears. The remaining observations are averaged by station, and standard deviations are calculated. In the final data, 80% of the stations have a standard deviation of <10 μGal, and none of the stations have a standard deviation of >30 μGal. These results are consistent with the accuracy of 5–15 μGal reported by Bonvalot et al. [24] for their Scintrex CG-3M meter tests. The final accepted records are then averaged by station and reduced to produce free air and complete Bouguer anomalies. The complete Bouguer anomaly and elevation profiles are shown in Fig. 5.

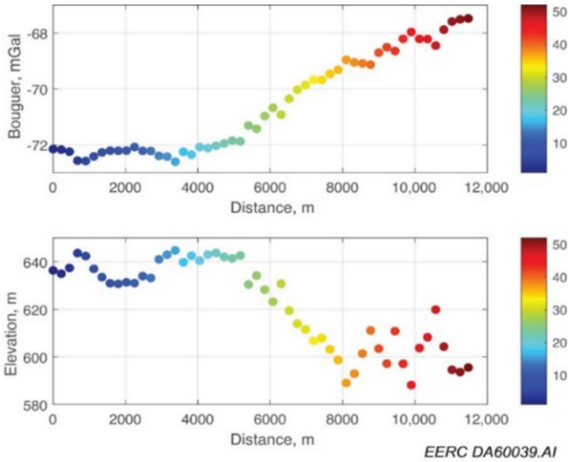

Fig. 5. Complete Bouguer gravity anomaly and station elevation. The color scale represents the station number.

5.3. Modeling and inversion

The processed data were used for 2D modeling of subsurface density structure, incorporating horizons from existing 3D seismic interpretation. Finally, the data were combined with publicly available gravity data with a larger footprint but much wider spacing to carry out a 3D inversion of the density in the project area. These modeling exercises help establish a baseline model for comparison to future data collected after the injection of CO_2 has begun.

The success of 2D density modeling in fitting the gravity data (not shown here) provides a good starting point for the time-lapse modeling effort. As the feasibility modeling indicated that changes in gravity due to injection of CO_2 into the Broom Creek reservoirs would be on the order of tens of μGal, a good initial density model will be crucial to observing changes in CO_2 concentration over time.

6. Conclusions

The viability of the seismic, CSEM, and microgravity methods for CO_2 monitoring in the target reservoirs of the North Dakota CarbonSAFE project was examined through multiple feasibility studies. Based on the results, all three methods can be used to monitor CO_2 injection within the Broom Creek Fm at this site. However, only the seismic and CSEM showed a strong enough response to be used to monitor CO_2 injection within the Deadwood Fm.

The gravity feasibility study estimated that a gravity anomaly of at most 22 μGal would exist after 25 years of CO_2 injection. Although the period for detecting the time-lapse gravity anomaly is more extensive than other geophysical methods considered for this project, the interpretation of the time-lapse gravity surveys provided a valuable constraint on joint geophysical analysis with seismic and EM data sets.

The CSEM feasibility study indicated that this method provides sufficient sensitivity to monitor CO_2 in the Broom Creek Fm after 2.7 Mt of cumulative injection, given approximately 60% CO_2 saturation. The time-lapse imaging of the Deadwood Fm is more challenging and requires additional feasibility data and probably improvements in data acquisition to enhance the signal-to-noise ratio.

The successful multimeasurement geophysical approach used in this project corroborates the need for high-quality data and the importance of meticulous selection of advanced data acquisition and processing technologies for future monitoring surveys in the study area. CO_2 monitoring of the Deadwood Fm can be improved, for instance, by using broadband seismic sources, increasing the EM transmitter moment, CSEM recording times, measuring the vertical current using shallow borehole receivers, or using the focused-source EM method [25]. Joint inversion methods will be beneficial if the seismic and CSEM methods are applied concurrently.

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