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Demonstration of novel monitoring techniques for a North Dakota carbon capture and storage project

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Abstract

We present an overview and initial results of the novel and sustainable monitoring techniques developed by the Energy & Environmental Research Center (EERC) and its commercial partners associated with the Red Trail Energy (RTE) carbon capture and storage (CCS) project. RTE is an investor-owned 64-million-gallon dry mill ethanol production plant in Richardton, North Dakota, USA. Currently in operation as of June 2022, the RTE facility will capture 180,000 tonnes of carbon dioxide (CO_2) annually (>99% CO_2) that is otherwise emitted during the ethanol production process and inject it into the Broom Creek Formation, a deep saline aquifer, for permanent on-site geologic storage.

A set of novel monitoring techniques were applied at the RTE CCS project site to track the migration of the injected CO_2 plume. The set of techniques include 1) fiber-optic systems equipped with distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) interrogators, 2) an actively sourced sparse seismic method (i.e., scalable, automated, semipermanent seismic array [SASSA]), and 3) ground deformation measurements via interferometric synthetic aperture radar (InSAR).

Through the Japanese Research Institute of Innovative Technology for the Earth (RITE), the EERC is collaborating with Class VI Solutions and the Lawrence Berkeley National Laboratory (LBNL) to integrate the recorded data from the fiber-optic system installed in the flowline, injection well, monitoring well, and each of the dedicated groundwater-monitoring wells at the RTE CCS site to monitor temperature, CO_2 saturation, and pressure. Fiber-optic sensing monitoring is a part of a project commissioned to RITE by the New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade, and Industry (METI) of Japan. RITE also installed four surface orbital vibrators (SOVs) at the storage site to provide an active sourcing method. The EERC is currently conducting a field test of its SASSA method through the Plains CO_2 Reduction (PCOR) Partnership Initiative, an EERC-led consortium with over 200 members focused on accelerating the deployment of CCS.

Deployment of fiber optics, SASSA, and InSAR at RTE will inform long-term monitoring efforts as well as demonstrate improved sustainability for monitoring commercial CCS projects.

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1. Introduction

Demonstrating more sustainable (i.e., safe, effective, compliant, adaptive, low-cost, and low-environmental-footprint) monitoring techniques for commercial-scale geologic carbon dioxide (CO_2) storage projects is essential for worldwide implementation of carbon capture and storage (CCS) technologies to reduce greenhouse gas emissions. The development of novel and more sustainable geophysical techniques (e.g., time-lapse seismic or electromagnetic surveying) is a priority, as such data sets can provide some of the most meaningful information for monitoring the migration of an injected CO_2 plume in a geologic (storage) reservoir.

The Energy & Environmental Research Center (EERC) and its commercial partners associated with the Red Trail Energy (RTE) CCS project in Richardton, North Dakota, USA, are currently testing a set of novel and more sustainable geophysical monitoring techniques as a supplemental research effort to support the project's overall monitoring, verification, and accounting (MVA) strategy. The set of techniques includes 1) fiber-optic systems equipped with distributed temperature-sensing (DTS), distributed acoustic-sensing (DAS), and distributed strain-sensing (DSS) interrogators; 2) an actively sourced sparse seismic method (i.e., scalable, automated, sparse seismic array [SASSA]) [1]; and 3) ground deformation measurements via interferometric synthetic aperture radar (InSAR).

The scope of this paper is to provide an overview of initial results of the novel monitoring techniques for the RTE CCS project for demonstrating advancements in sustainable geophysical MVA strategies that are ready for full-scale implementation in CCS.

The RTE CCS project is located in Richardton, North Dakota, USA (Fig. 1). RTE will capture 180,000 tonnes of CO_2 annually from its 64-million-gallon dry mill ethanol facility over a 20-year period. The captured CO_2 stream will be transported approximately 3.7 kilometers (2.3 miles) east of the capture facility and injected on-site into the Broom Creek Formation, a deep saline aquifer approximately 1945 meters (6380 feet) below ground surface. RTE began CCS operations in June 2022 after becoming the first commercial CCS project in North Dakota, as well as the first entity to receive approval for geologic CO_2 storage (Class VI well permit) by North Dakota's regulatory authority. North Dakota was granted Class VI primacy by the U.S. Environmental Protection Agency (EPA) in 2018.

The RTE site is bisected by a major highway and rail line. The area monitored around the injection well is a mixture of cropland and pasture used for livestock grazing. The northeast area at the site includes some elevation relief with limited access. There is minimal surface water at the site; however, some areas collect water during the spring, creating land access issues for conducting traditional 3D seismic surveys. RTE and the EERC are mindful of the concerns of

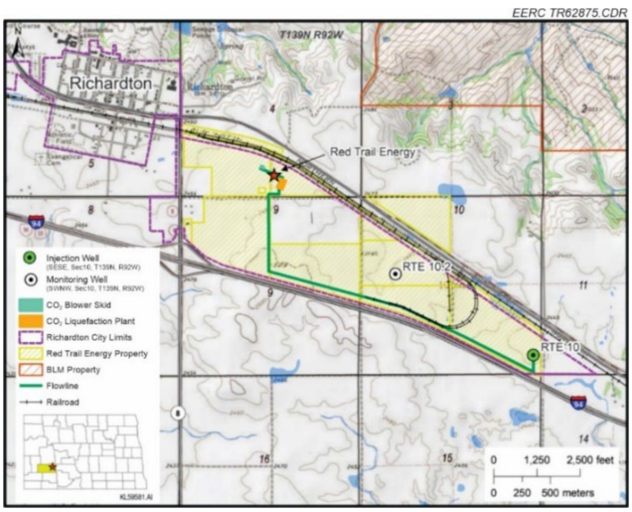

Fig. 1. RTE storage facility site map.

the local landowners and their assets, and the research into sustainable methods should lead to improved long-term relationships at this site and future CCS sites. These local site-specific accessibility concerns make the RTE site ideal for implementing and developing the SASSA method.

This research is funded through the U.S. Department of Energy (DOE) Plains CO_2 Reduction (PCOR) Partnership Initiative. The PCOR Partnership Initiative, one of four Regional Carbon Sequestration Partnership (RCSP) programs operating under the DOE National Energy Technology Laboratory (NETL), is an EERC-led consortium with over 200 members focused on accelerating the commercial deployment of CCS. Leveraging the EERC's partnership with RTE and in collaboration with California-based ClassVI Solutions and the Lawrence Berkeley National Laboratory (LBNL) through the Japanese Research Institute of Innovative Technology for the Earth (RITE) with funding from the New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade, and Industry (METI) of Japan, this research supports the PCOR Partnership Initiative via demonstration of novel and sustainable MVA techniques.

2. Geophysical techniques at RTE

This research project, while focused on demonstrating novel and more sustainable geophysical techniques, complements the MVA strategy developed for RTE's Class VI permit, approved by North Dakota's regulatory authority (Table 1), by providing additional monitoring of surface infrastructure as well as the near-surface and deep subsurface environments.

Table 1. Summary of the Underground Injection Control (UIC) Class VI Permit MVA program and research overlays. Bold text indicates supplemental DOE-funded PCOR Partnership Initiative research activities. Figure modified from RTE's (2021) Class VI well permit.

Monitoring Type	**RTE Monitoring Program**	**Structure/Project Area**
Analysis of Injected CO_2	Compositional and isotopic analysis of the injected CO_2 stream	Wellhead
CO_2 Flowline	**DTS/DAS and DSS**	Capture facility to the wellsite
Continuous Recording of Injection Pressure, Rate, and Volume	Surface pressure/temperature gauges and a flowmeter installed at the wellhead with shutoff alarms	Surface to reservoir (injection well)
Well Annulus Pressure Between Tubing and Casing	Annular pressure gauge for continuous monitoring	Surface to reservoir (injection well)
Internal and External Mechanical Integrity	Tubing-casing annulus pressure testing (internal) **DTS/DAS fiber-optic cable**, ultrasonic imager tool (USIT) (external)	Well infrastructure
Corrosion Monitoring	Flow-through corrosion coupon test system for periodic corrosion monitoring	Well infrastructure
Near-Surface Monitoring	Groundwater wells in the area of review (AOR) dedicated to Fox Hills monitoring wells and soil gas sampling and analyses	Near-surface environment, USDWs
Direct Reservoir Monitoring	Wireline logging, external downhole pressure and temperature gauges, and **DTS/DAS fiber-optic cable**	Storage reservoir
Indirect Reservoir Monitoring	Time-lapse geophysical surveys, gravity surveys, **InSAR** and passive seismic measurements	Entire storage complex

2.1. Fiber-optic sensing

Fig. 2. illustrates the general design for the installation of permanent fiber for the RTE CCS project. DTS, DAS, and DSS fiber optics were buried with the CO_2 flowline (Fig. 3) and installed outside the casing of the CO_2 injection wellbore (RTE-10) (Fig. 4) and monitoring wellbore (RTE-10.2) from the surface to the storage reservoir. The same fiber-optic cable was also installed from the surface to the lowest underground source of drinking water (USDW) within the two dedicated groundwater-monitoring wellbores drilled adjacent to the RTE-10 and RTE-10.2 well pads.

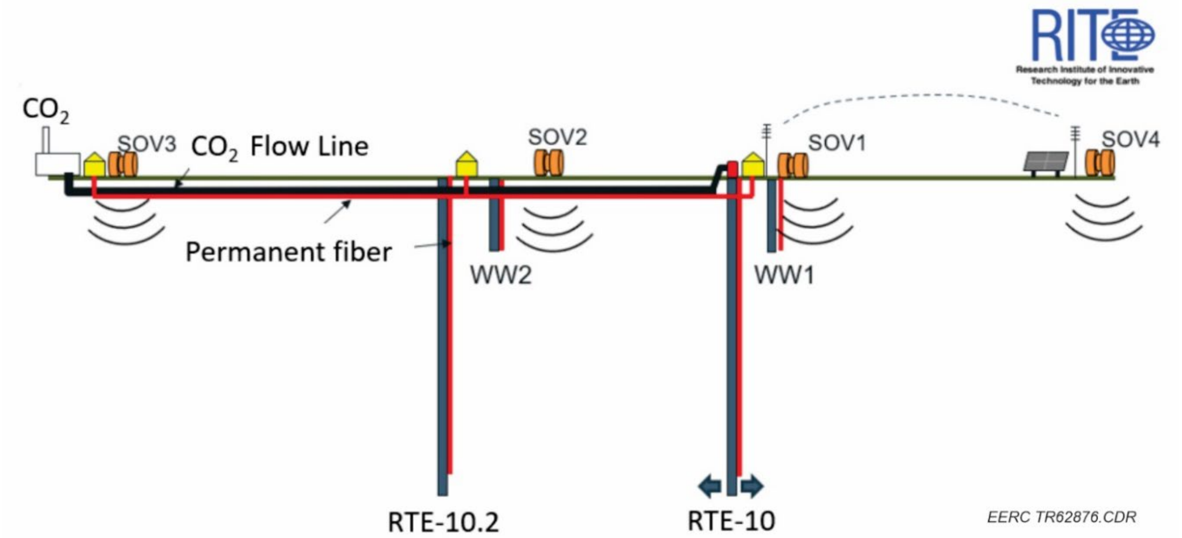

Fig. 2. Schematic showing permanent fiber (red) installed in the RTE-10 injection well, RTE-10.2 monitoring well, CO_2 flowline, and groundwater-monitoring wells (i.e., WW1 and WW2). Also shown are the relative positions of the surface orbital vibrators (SOVs)(orange) and data sheds (yellow). Figure from RITE.

Fig. 3. Images showing the installation of the fiber-optic cable along the CO_2 flowline (left) and the buried flowline and flowline riser at the RTE-10 injection well pad (right).

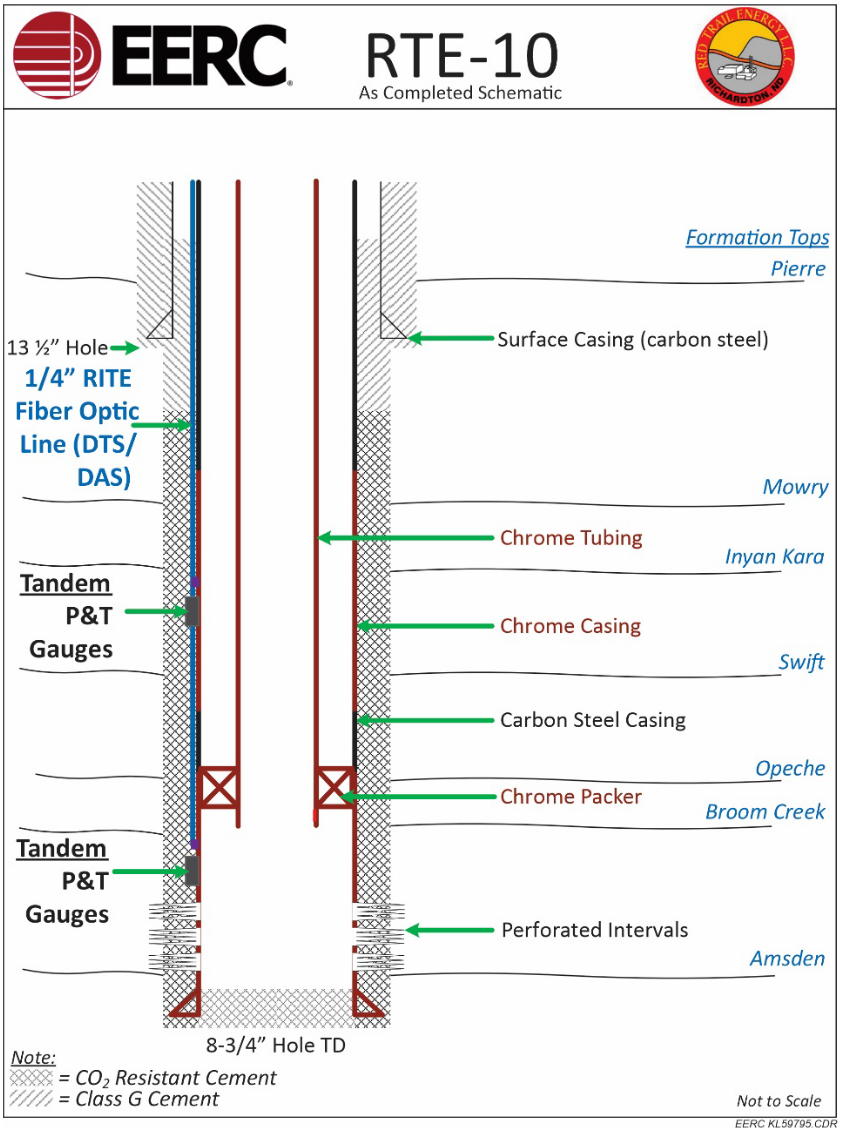

Fig. 4. RTE-10 wellbore schematic modified from RTE [2] showing the placement of the permanent fiber.

The DTS fiber will monitor for signs of potential leakage in the CO_2 flowline and wellbores by continuously measuring changes in temperature for real-time monitoring of the CO_2 flowline and wellbores. Fig. 5 shows initial DTS results along the CO_2 flowline and down the RTE-10 injection well. In the deeper part of the well, there is a drop in temperature associated with CO_2 flowing into the open perforations in the Broom Creek interval. The temperature profiles along the flowline and within the RTE-10 injection well show constant temperature for the two days until injection testing begins, as expected when the CO_2 fills the flowline. In contrast, the RTE-10.2 monitoring well shows no initial change in temperature approximately 1.6 kilometers (1 mile) to the northwest.

The fiber also provides DAS and DSS data for monitoring the CO_2 saturation and pressure in the storage reservoir. The DAS method will continuously monitor injection operations allowing for near-real-time monitoring of acoustic events. The DSS method allows for continuous monitoring of far-field strain related to injection operations. The fiber is connected to a supervisory control and data acquisition (SCADA) system with alarms that will alert RTE if events are detected in the fiber, allowing RTE to quickly identify significant DAS/DSS events for processing and interpretation in near-real time.

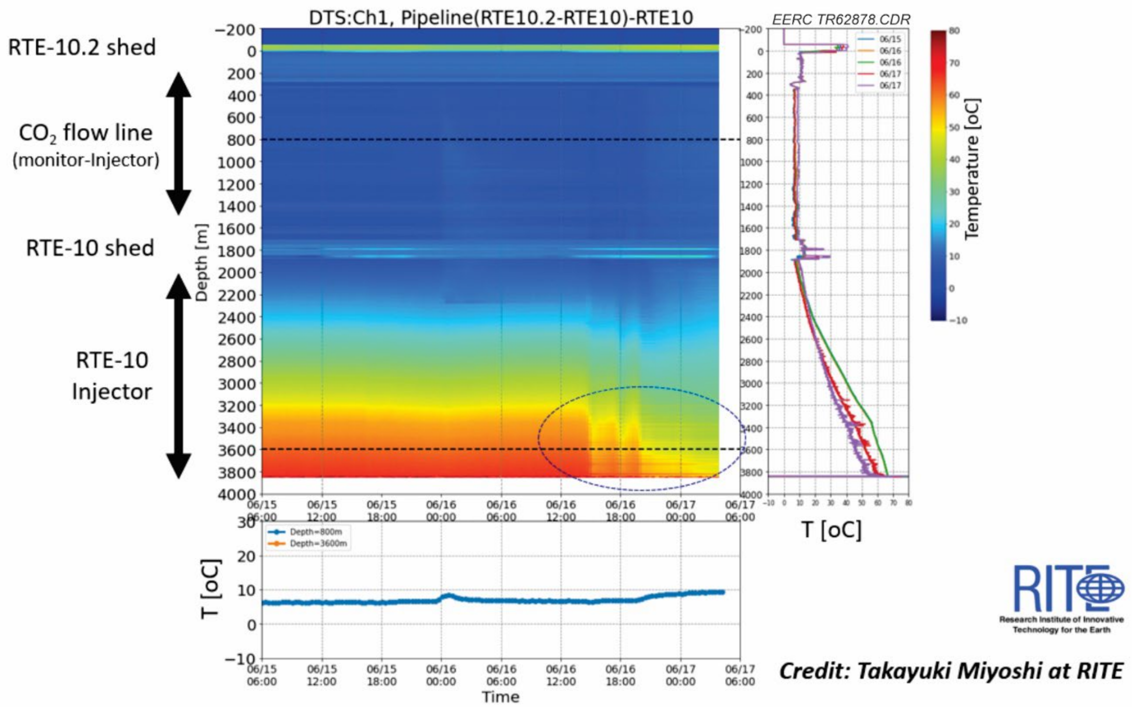

Fig. 5. Initial DTS profile in RTE-10 and CO_2 flowline.

The DAS measurements record actively and passively sourced acoustic energy in the storage facility area. RITE installed four SOVs at the storage site to provide an active sourcing method. The SOVs shown in Fig. 6 are installed on reinforced cement foundations and inside sheds to protect from inclement weather. Each SOV coupled with its cement foundation provides approximately 147,000 Newtons or 33,000 pounds of ground force, which is equivalent to a small vibroseis truck. Each SOV location includes an installed 3C geophone buried beneath the foundation to capture the source signature of the sweeps. These static SOVs allow for frequent monitoring recorded with the DAS fiber.

The SOVs are currently operating periodically each day. Parameter testing to determine the proper duration and frequency of running the SOVs based on the site-specific subsurface and surface layout is ongoing. Testing to optimize baseline sourcing parameters were performed. This testing ensures sufficient down-going energy and recording time for sparse seismic reflection acquisition.

Active seismic recording can be acquired for monitoring time-lapse changes related to CO_2 saturation and pressure. Active sourcing includes installed static sources (i.e., SOVs) and conventional seismic sources (i.e., dynamite, vibroseis, and weight drop). SOV sources provide a static and more repeatable transmission signal as well as the opportunity for frequent on-demand data acquisition. The combination of small and large motors provides a range in frequency similar to conventional vibroseis equipment. Sweeps are repeated and stacked to enhance the signal-to-noise ratio.

The fiber can also be monitored passively for local microseismicity events and strain resulting from normal injection operations. Injection operations may cause small seismic events in the near-wellbore area related to fluid flow or small fractures within the storage reservoir. These fiber-based measurements can be calibrated with direct measurement of surface and downhole pressure gauges.

The multiple, permanently installed, continuously recording DAS capable fiber arrays allow for on-demand vertical seismic profiles (VSPs). As shown in Fig. 7, RITE and the EERC collected a 3D VSP on RTE property, providing a baseline for future VSP recording as another low-impact, low-cost monitoring option compared with acquiring a more traditional 3D seismic survey.

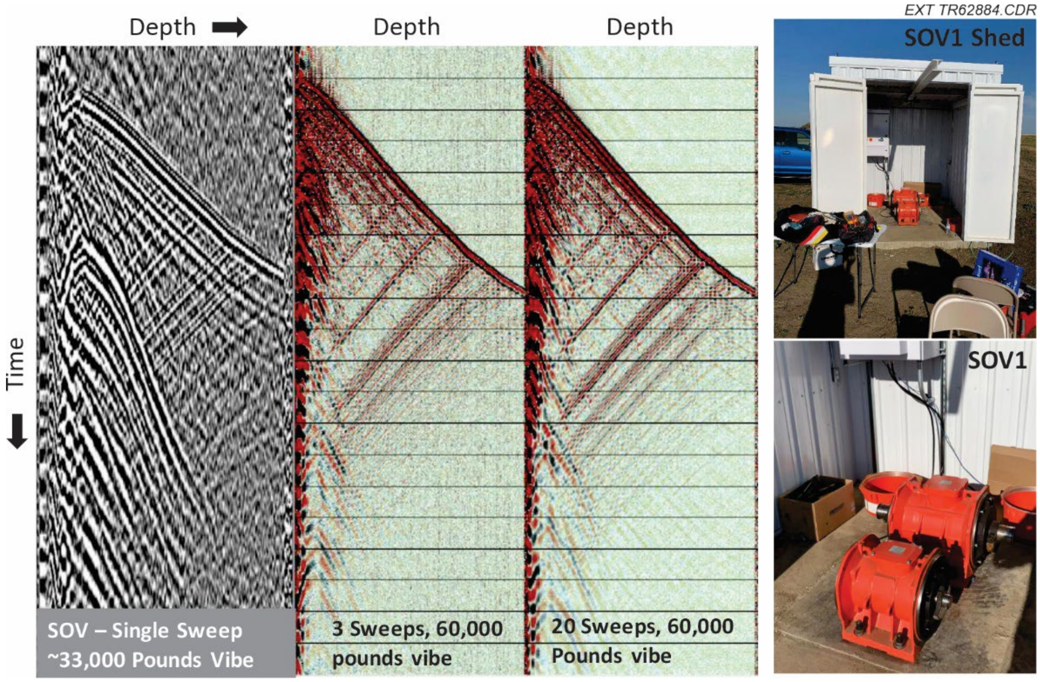

Fig. 6. Comparison of SOV with a conventional large vibroseis truck shows great data quality with both source types. The SOV installation is shown on the right, secured to its foundation inside a shed to reduce cultural noise and for protection from weather.

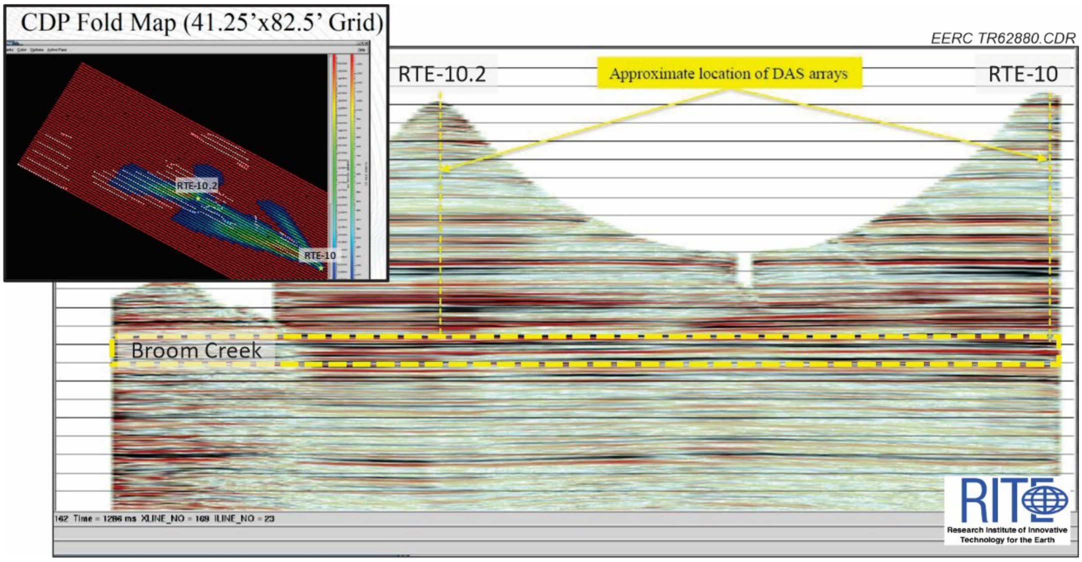

Fig. 7. 3D VSP data collected at the RTE-10 wellsite.

2.2. CO_2 monitoring with SASSA

SASSA is a cost-effective and low-environmental-footprint seismic monitoring method. The subsurface sampling, with midpoints in areas away from or between wells, where changes in the reservoir due to CO_2 injection are expected, is a key consideration of the SASSA method (Fig. 8) [3]. Since only time-lapse amplitude changes are considered to

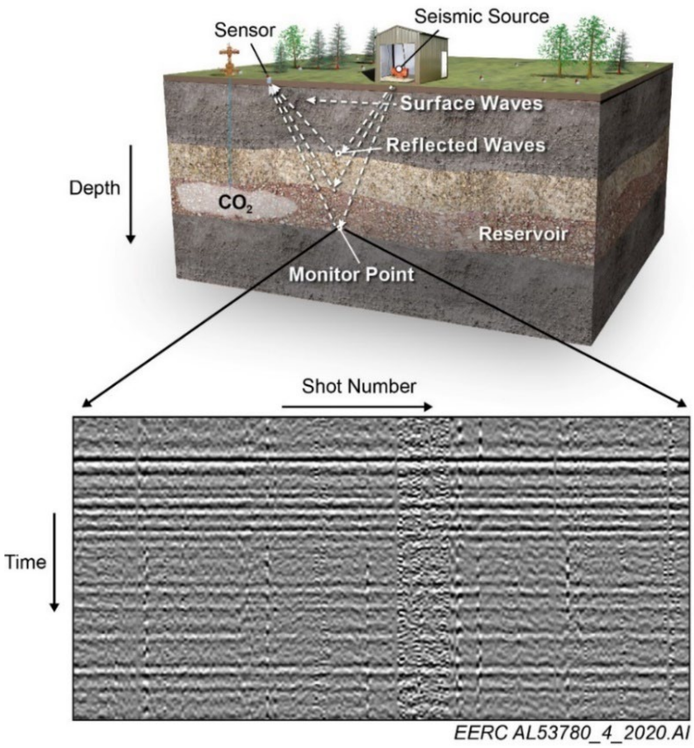

Fig. 8. Generalized SASSA surface design from Bell Creek oil field, Montana, USA.

estimate whether the CO_2 has reached a sampled point at the reservoir, data acquisition can be accomplished by an irregular and sparse distribution of sources and receivers on the earth's surface. The SASSA data acquisition can be conducted with tens of receivers instead of the hundreds or thousands of receivers used in small, conventional 3D surveys.

A small number of receivers contributes to the reduction of the turnaround time for delivering data-processing results after data acquisition. The logistics of the SASSA monitoring activities are simplified with receivers (nodes) planted semipermanently and one or more permanent seismic sources operated remotely. The autonomous recording equipment used in the SASSA method allows for months of continuous recording. To optimize the nodes' battery performance, the frequency of data acquisition, and data harvesting, the nodes are programmed for weekly acquisition. Data are harvested at intervals of 8–12 weeks.

Data processing depends on the distribution of SASSA sources and receivers. Data processing of SASSA gathers includes fewer steps than the processing workflows of conventional 3D surveys. The basic data-processing steps are noise attenuation, stacking, and time-lapse cross-equalization.

The SASSA method has been previously applied to the monitoring of mature oil fields undergoing CO_2 EOR in Montana, USA (Fig. 9) [1, 4]. The SASSA method is further developed in this project using more powerful SOVs than in a previous project and combining Fairfield Nodal Zland receivers and Stryde sensors for acquiring baseline (preinjection) information for future comparison with injection operations data.

As part of the SASSA survey design, a noise test was conducted. The deployment plan is shown on the map in Fig. 10. The sensors were installed in strategic locations for monitoring a variety of noise levels in the vicinity of cultural noise. 96 Fairfield Nodal Zland three-component nodes were deployed to characterize multicomponent, multimode coherent, and random noise. 20 Geospace GSX-C nodes were deployed for demonstration of on-demand data harvesting, and 750 Stryde nodes were deployed with varying levels and geometries of high-density arrays for noise characterization and baseline monitoring. This noise analysis informed the deployment of the baseline data collection and monitoring phase. Fig. 11 shows the modified location of the deployed sensors for SASSA monitoring at the RTE site. The locations were adjusted based on landowner access and agricultural operations.

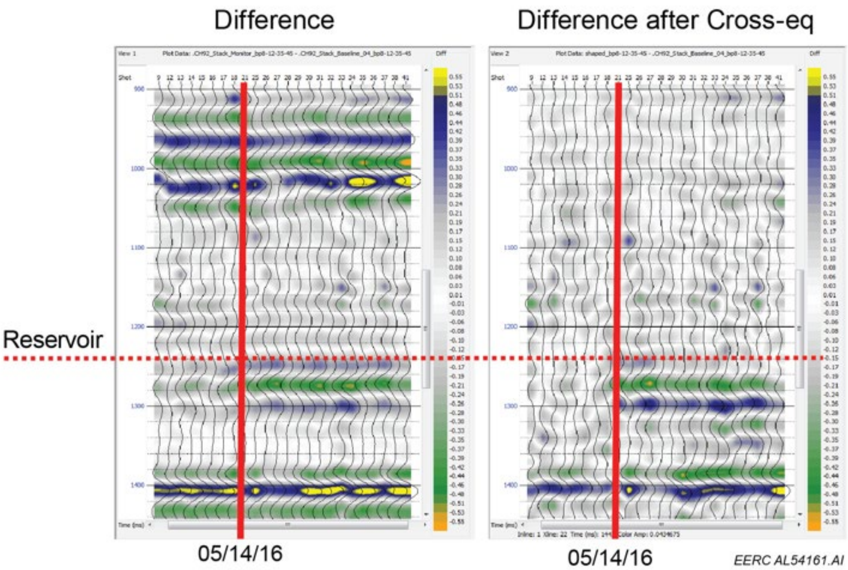

Fig. 9. Monitoring of strategically located discrete subsurface locations for seismic reflection changes indicating change in CO_2 saturation. Example from Bell Creek, Montana, USA.

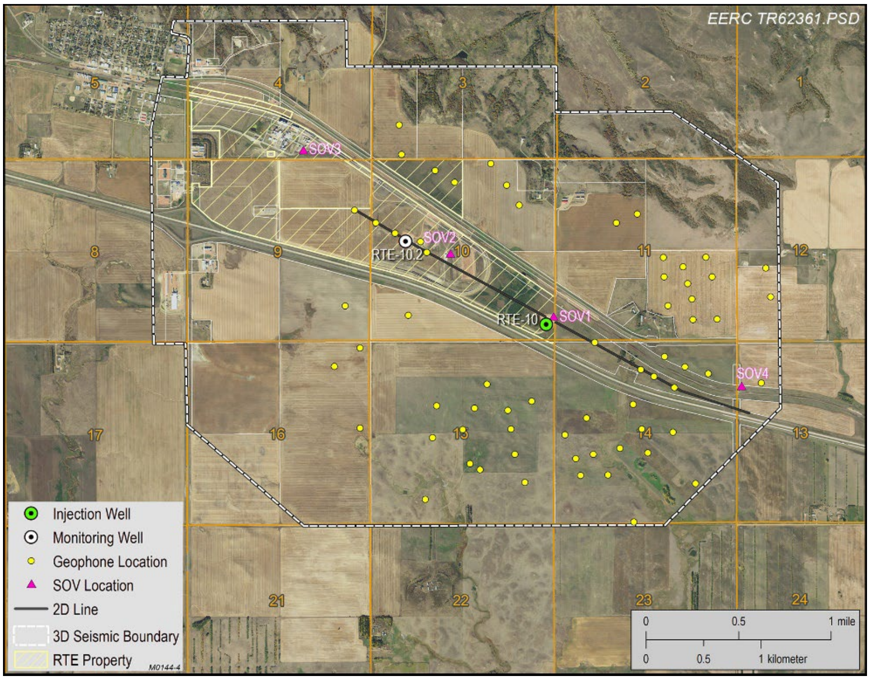

Fig. 10. Planned SASSA deployment for performing noise test.

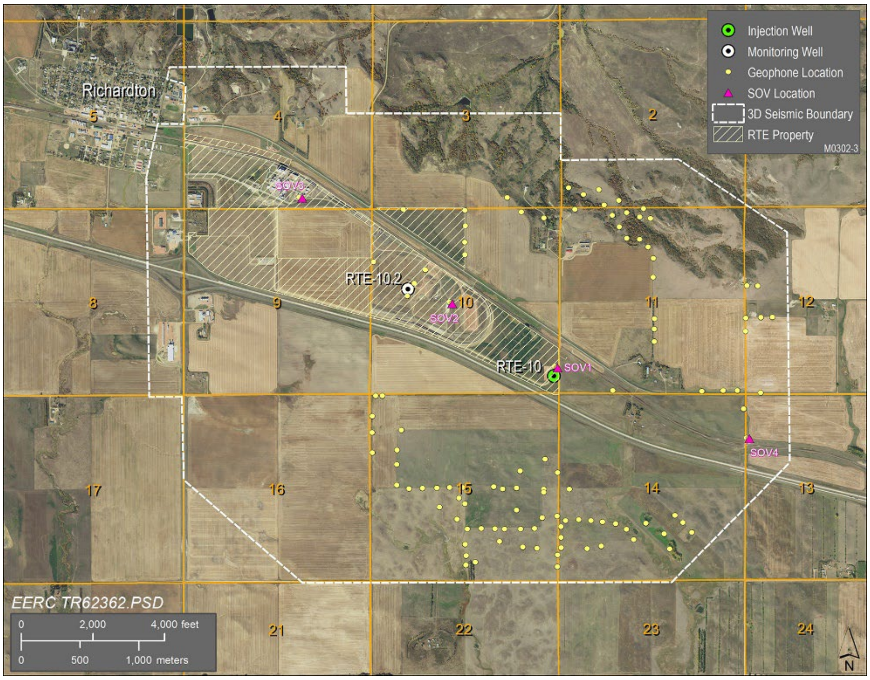

Fig. 11. Actual SASSA deployment with simulated CO_2 plume overlays. Also shown on this map are eight potential locations for seismometer stations (numbered orange stars).

2.3. InSAR monitoring

During CO_2 injection into storage reservoirs, pore pressure increases while reservoir temperature decreases. These pore pressure and temperature changes induce localized stress variations that could cause vertical ground displacement (or surface elevation changes) during CO_2 injection and storage. Surface deformation data from satellite-based SAR imagery is being used to understand pressure changes away from the wellbore. By comparing two time-delayed SAR images (interferograms), an InSAR image is produced, which is then converted into vertical ground displacement. SAR data are collected via satellite at 1- to 2-week intervals, with varying spatial resolutions and wavelengths. Spatial resolution can be as little as 10–20 centimeters with vertical resolutions of a few millimeters, providing extremely dense coverage where there is sufficient natural reflectivity. Wavelength is an important consideration with varying surface conditions such as snow cover, vegetation, and erosional and agricultural land use. Low-frequency (long wavelength) radar can penetrate through some vegetation but is inherently lower vertical resolution, while relatively higher frequency radar will not reach the surface to sense the elevation changes at the detection limit required for the RTE CCS project.

When surface conditions are not optimal, InSAR may require installing artificial reflectivity monuments. However, even very sparse InSAR surface coverage related to variable surface conditions can be very informative of pressure changes related to the migration of injected fluid volumes. In the same way, time-lapse seismic methods may require sparse acquisition because of surface owner assets and infrastructure, culturally and biologically sensitive areas, and areas that are inaccessible to conventional seismic sources.

To properly predict the vertical ground displacement due to long-term CO_2 injection, 3D mechanical earth models (MEMs) are necessary because the injected CO_2 plume propagates not only near injection wells but also spatially along permeable pathways, including injection layers and permeable geological conduits connected to the injection layers. Therefore, the storage reservoir has been characterized for its subsurface storage capacity and geomechanical properties. This geomechanical interpretation is conducted by building a MEM. MEMs have been used to identify in situ and dynamic stresses as well as pore pressure in the subsurface in response to CO_2 injection. 1D MEMs are created along wellbores based on data from well logs (i.e., gamma ray log, bulk density log, and compressional and shear sonic logs), direct pressure measurements, elastic core measurements of the reservoir and overlying confining zones, and drilling data to estimate surface elevation changes near the injection wells (i.e., at early injection time). Correlation of CO_2 injection parameters (pressure and fluid injection quantity) to the vertical ground displacement at an oil field with CO_2-enhanced oil recovery (EOR) activities in Montana, USA, measured with InSAR early in the injection period by using a 1D MEM has been reported in the literature [4].

In addition, the modeled vertical ground displacement measurements can be coupled with historical (preinjection) InSAR to understand the signal-to-noise levels associated with uncertainties of surface deformation measurements (Fig. 12). The EERC technical team will review these results to inform the decision to install artificial reflectors to improve signal-to-noise of InSAR collection. Also, InSAR measurements and time-lapse seismic methods can be used for calibrating a 3D MEM during the CO_2 injection period.

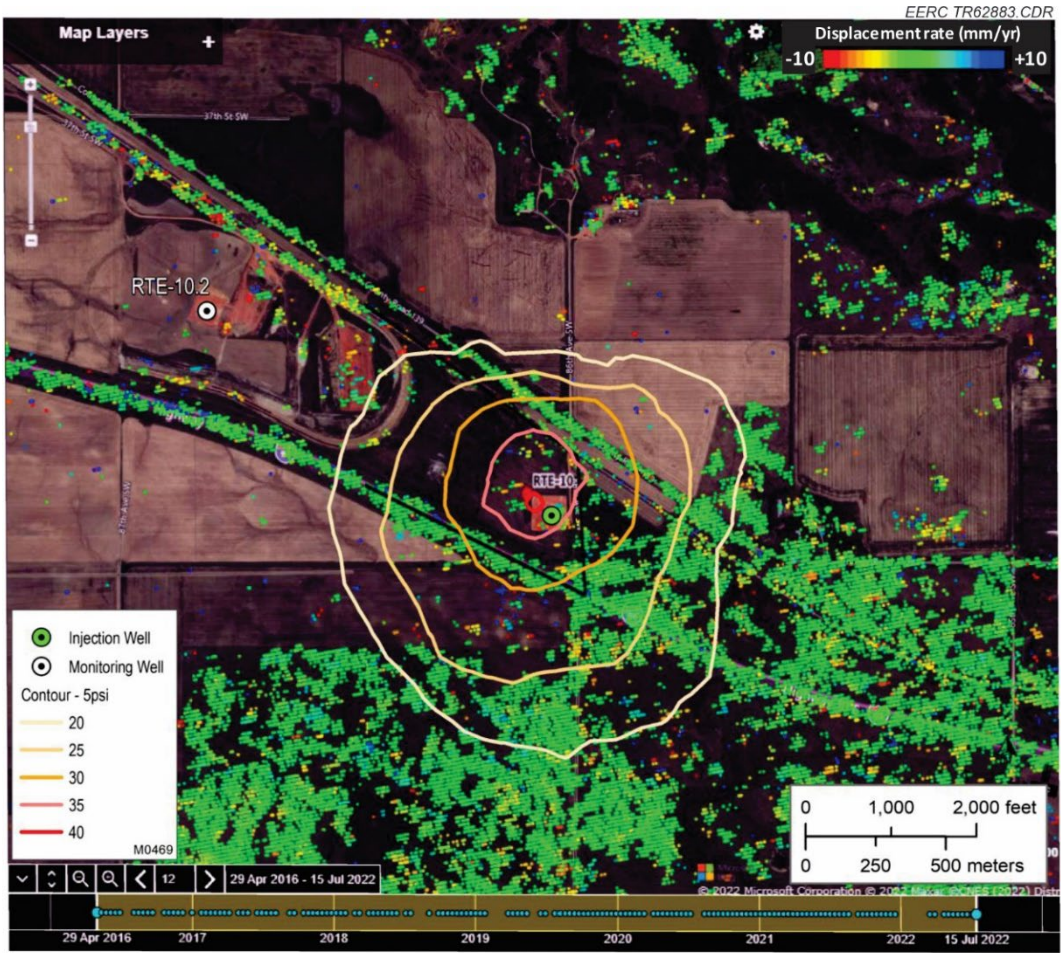

Fig. 12. Image from a historical analysis of SAR data from the Sentinel 1 satellite showing the calculated displacement rate. Image provided by SkyGeo. Green points indicate areas of zero ground displacement. Also shown is the predicted change in reservoir pressure at the end of the 20-year CO_2 injection period [1].

3. Conclusion

Operators of CCS projects must ensure safe storage and demonstrate compliance with regulatory and incentive programs, which requires robust, risk-based, and sustainable (i.e., safe, effective, compliant, adaptive, low-cost, and low-environmental-footprint) monitoring plans to meet storage goals. Monitoring plans should be adaptable to site-specific conditions, including flexibility to variable surface access and potential deviations from predicted subsurface fluid migrations. These sustainable methods should address the requirement for tracking the movement of CO_2 and provide measurements of downhole and reservoir conditions for on-demand and real-time decision making and process optimization, thus giving the operator and regulatory community assurance of storage permanence. Deployment of fiber-optics, SASSA, and InSAR at the RTE CCS site will inform long-term monitoring efforts as well as demonstrating improved sustainability for monitoring commercial CCS projects.

A set of novel monitoring techniques have been applied at the RTE CCS project site to track the migration of the injected CO_2 plume. The following conclusions are drawn from the initial results presented in this paper:

- Continuous DTS measurements show cooling in the storage reservoir due to CO_2 injection.
- The baseline 3D VSP collected with permanently installed DAS fiber-optic cable allows for an opportunity to repeat the survey within the injection time frame.
- The EERC has finalized deployment of SASSA sensor arrays for monitoring the CO_2 plume extent.
- Natural InSAR reflectivity will provide monitoring along railroads and roadways around the injection site.

Deployment of fiber-optics, SASSA, and InSAR at the RTE CCS site will inform long-term monitoring efforts as well as demonstrating improved sustainability for monitoring commercial CCS projects.

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