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Design and Implementation of a Scalable, Automated, Semi-Permanent Seismic Array for Detecting CO2 Extent during Geologic CO2 Injection

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Design and implementation of a scalable, automated, semi-permanent seismic array for detecting CO_2 extent during geologic CO_2 injection

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Abstract

A proof-of-concept demonstration using a scalable, automated, semipermanent, seismic array (SASSA) is being conducted to test a novel seismic method for detecting and tracking an injected CO_2 plume as it traverses discreet points within a reservoir in southeastern Montana at Bell Creek oil field which is undergoing commercial CO_2 enhanced oil recovery (EOR). This document serves to describe the technical design of the project infrastructure, the operational approach, corresponding data collection, and data-processing activities.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: monitoring; seismic; array; time-lapse; semipermanent

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1. Introduction

It is necessary to measure and predict the lateral and vertical movement of injected CO_2 volumes and their associated fluid saturation changes during operations at a geologic CO_2 storage facility. Monitoring technologies are needed that facilitate CO_2 storage accounting, that allow calculation of storage efficiencies and storage capacities of geologic systems, and that monitor containment in order to verify the goal of greater than 99% CO_2 storage permanence. To be commercially viable, implementations of CO_2 storage program monitoring, verification, and accounting (MVA) technologies need to be cost-effective, have minimal impact to operations, and provide a means to improve operational parameters.

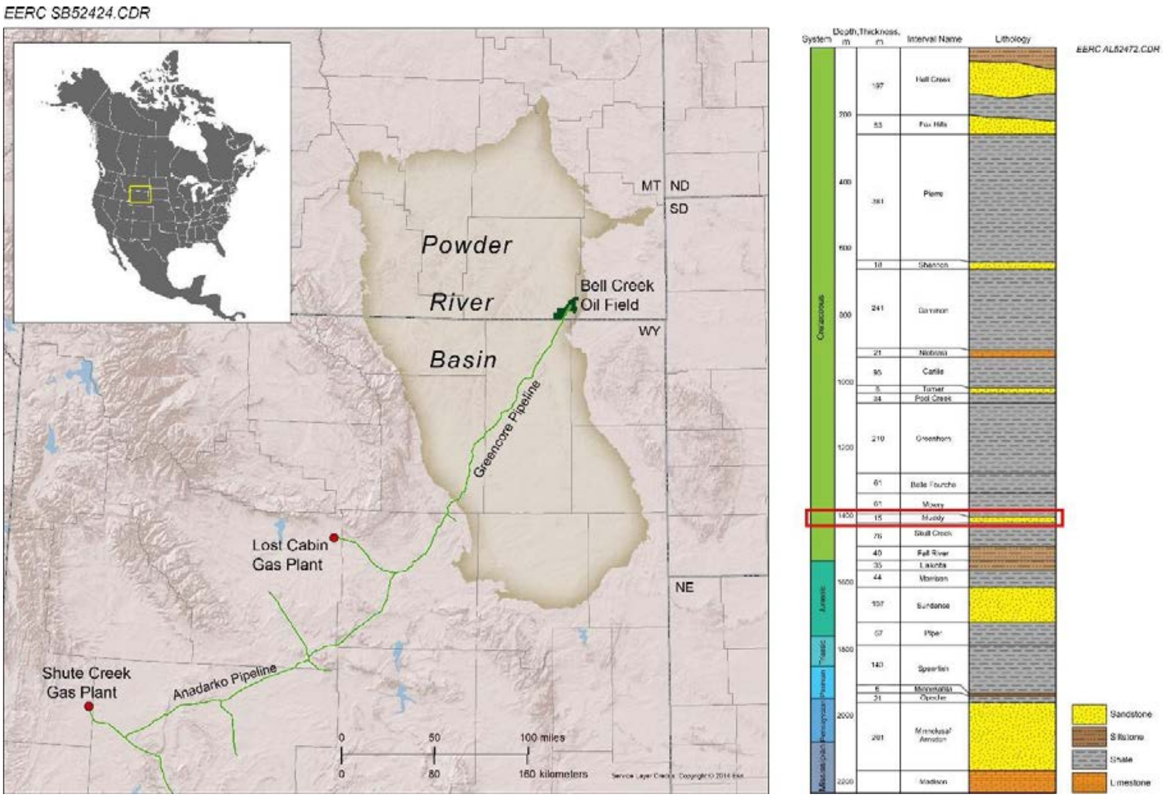
Time-lapse seismic monitoring has been demonstrated as a viable monitoring method capable of mapping lateral and vertical CO_2 saturation changes between and away from wells in the context of both CO_2 storage and CO_2 EOR. To achieve this result, large conventional time-lapse 3-D surveys (4-D seismic) often require thousands of receiver and shot point locations on the surface. 3-D vertical seismic profile (VSP) surveys with receivers in the wellbore also require hundreds or thousands of surface shotpoints. Both types of survey require sophisticated and specialized processing methods to produce 3-D images of the subsurface, which often provide excellent interpretive results with regard to where CO_2 saturation changes are located. However, their shortcomings include high cost, long time intervals between surveys, and disruptive implementations because of the heavy impact of site access needs.

Several innovative seismic monitoring approaches are being evaluated for feasibility to provide accurate MVA data in a more cost-effective and timely manner than conventional seismic monitoring methods. These methods typically utilize some form of permanent seismic acquisition system to produce an image of the subsurface. The acquisition systems have included ocean bottom seismometer arrays [1], distributed acoustic sensing cables [2,3], buried or downhole geophone arrays [4,5], buried hydrophone arrays [6] and, in some cases, a combination of several of the aforementioned [7] in addition to utilizing a variety of seismic sources. Many studies are currently under way to continue to assess these methods and develop new ones.

The Energy & Environmental Research Center (EERC) is conducting a proof-of-concept study using a scalable, automated, semipermanent, seismic array (SASSA) to test a novel seismic method for detecting and tracking injected CO_2 plume miscible fronts as they traverse discreet points within a reservoir. This new method may provide an economical means of continuously monitoring the CO_2 plume edges and the CO_2 reservoir boundaries and/or to interpret vertical or lateral out-of-reservoir CO_2 migration. With SASSA, the seismic method is used not to create a subsurface image but to provide an indication of physical changes occurring at monitored locations within the reservoir due to the passing of a carbon dioxide (CO_2) plume. A source at a fixed location is periodically fired into a sparse array of autonomous surface receivers. The surface array is designed so that a set of reflection points within the reservoir/storage formation are monitored at carefully chosen locations that are expected to encounter the CO_2 plume during the course of the project. As the CO_2 plume moves through the formation, detectable character changes should occur on the recorded reflections from the reservoir, becoming visible on simply processed time-lapse traces and providing a means of determining when the CO_2 front has moved past monitored reflection points. This test is being funded by the U.S. Department of Energy with partnership from Denbury Onshore LLC (Denbury) and the Computer Modelling Group (CMG). The test is being conducted in southeastern Montana at the Bell Creek oil field which is undergoing commercial CO_2 enhanced oil recovery (EOR). This document serves to describe the technical design of the project infrastructure and the operational approach and corresponding data collection and data-processing activities.

2. Study Area

Located in southeastern Montana, the study area for this project is in the Bell Creek oil field (Fig. 1a), which is operated by Denbury. The Bell Creek oil field lies near the northeastern corner of the Powder River Basin. Since oil and gas discovery in the 1960s, oil and gas production through primary and secondary recovery has resulted in production decline and has led to the implementation of a CO_2 injection-based tertiary oil recovery project. CO_2 is being injected into the oil-bearing sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately1372 meters (Fig. 1b).



(a) (b)

Fig. 1. (a) The Bell Creek oil field in southeastern Montana lies near the northeastern corner of the Powder River Basin. CO_2 is delivered to the site via pipeline from the Lost Cabin gas plant. (b) Stratigraphic column for the Bell Creek area with lithology. The red box highlights the Muddy [8].

At the Bell Creek oil field, the Muddy Formation is dominated by high-porosity (15%–35%), high-permeability (150–1175-mD) sandstones. Thickness of the clean reservoir sands in the project area varies from approximately 6 to 11 meters. The seismic reflection interval of the Muddy tends to be thicker at about 17 meters and includes the bounding nonreservoir silty sands [9]. The oil field is located structurally on a shallow monocline with a 1°–2° dip to the northwest and with an axis trending southwest to northeast for a distance of approximately 32 kilometers. Stratigraphically, the Muddy Formation in the Bell Creek oil field features an updip facies change from sand to shale that serves as a trap. The overlying Upper Cretaceous Mowry Formation shale is the primary seal, preventing vertical fluid migration. Overlying the Mowry Formation is over 1000 m of low-permeability shale formations, including the Belle Fourche, Greenhorn, Niobrara, and Pierre shales (Fig. 1b), which offer several key seismic marker reflections that will be useful in this study for correlating with SASSA data.

3. Array Design

The main project goal is to detect and track CO_2 as it moves through the reservoir and passes discrete monitored reflection points. In the study area, CO_2 injection is implemented in a five-spot pattern: each injector has neighboring producing wells in each cardinal direction at approximately 0.4-km distance, and the pattern repeats systematically. Monitor locations were strategically chosen within and around four injector–producer patterns covering approximately 2.6 square kilometers (Fig. 2). Some injectors are closely monitored with several reflection points around them. This is to provide higher-resolution monitoring and redundancy over areas of the reservoir with the highest probability of experiencing a CO_2 saturation change over the time frame of the project.

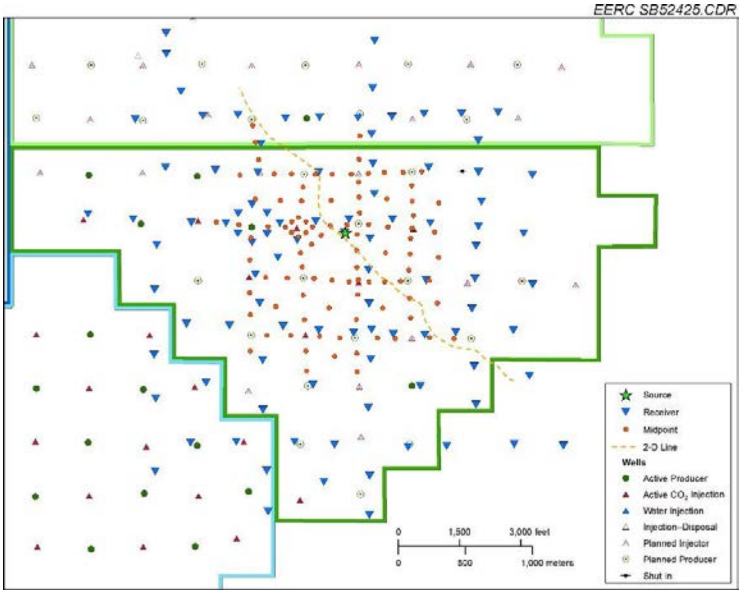


Fig. 2. Map of the SASSA field layout including source and receiver geometry and associated midpoint locations.

As a rule of thumb, given the generally flat geology (dip is only one to two degrees), the surface location of the node will be twice as far from the source as the monitored point. The actual location is determined by modeling which takes the dip and three-dimensional velocity variations of the subsurface into account. The 3-D velocity model was created by extracting a subset of the migration interval velocity volume from the Bell Creek baseline 3-D seismic survey acquired in 2012. Nine geologic layers were defined using the depth-converted inline seismic cross section that passed through a well near the source location (Fig. 3a). Layers were interpolated along the strike to create a 3-D layered volume. The velocities were assigned to the layers from the migration velocity file and velocity gradients computed between layers. Topography from a lidar survey was incorporated with a near-surface velocity. Estimated node locations for the preplanned layout were entered and ray tracing was computed for reflections off of the reservoir reflector (Fig. 3b). Reflection points computed by ray tracing were compared to the preferred monitoring locations, and adjustments to the node layout were made in an iterative process.

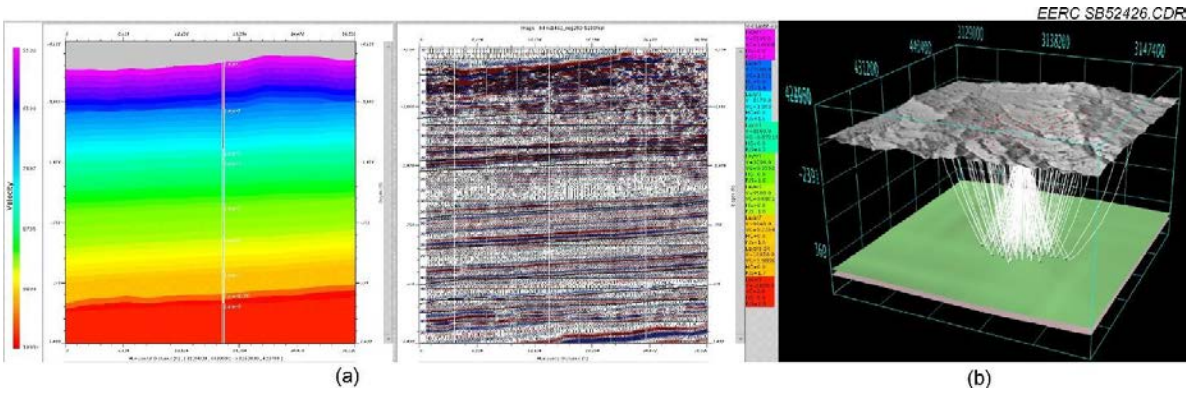


Fig. 3. (a) A 3-D layer model is created with structural layers transferred from depth-converted 3-D seismic data and well log and migration velocities. Layer velocities are converted to gradient functions. (b) Ray tracing shows reflections off of the reservoir layer through the 3-D velocity model to determine a preliminary layout of the nodes [10].

3.1. Source

The seismic source is a GISCO ESS850 "Turbo" Electronic Seismic Source (ESS850) 385-kilogram elastomer accelerated weight drop (Fig. 4a, 4b). The source has sufficient energy to monitor a wide range of offsets at the 1372-meter reservoir depth at distances up to three well spacings, or 1.2 km, and accommodates surface receiver node placements up to 3.2 km from the source (Fig. 5a). A partially processed shot record from a baseline 2-D line in the project area reveals significant reflection energy even from deep geologic layers (Fig. 5b).

Fig. 4. (a) Completed shed wired for power showing the installed and anchored ESS850 source, remote control computer system (back left corner), and space heater (mounted on rear wall). (b) Engineered footing shown during assembly and before burial. The footing is dug in to place the top plate at grade. The coupling plate on the ESS850 is removed so that the hammer directly strikes the footing [10].

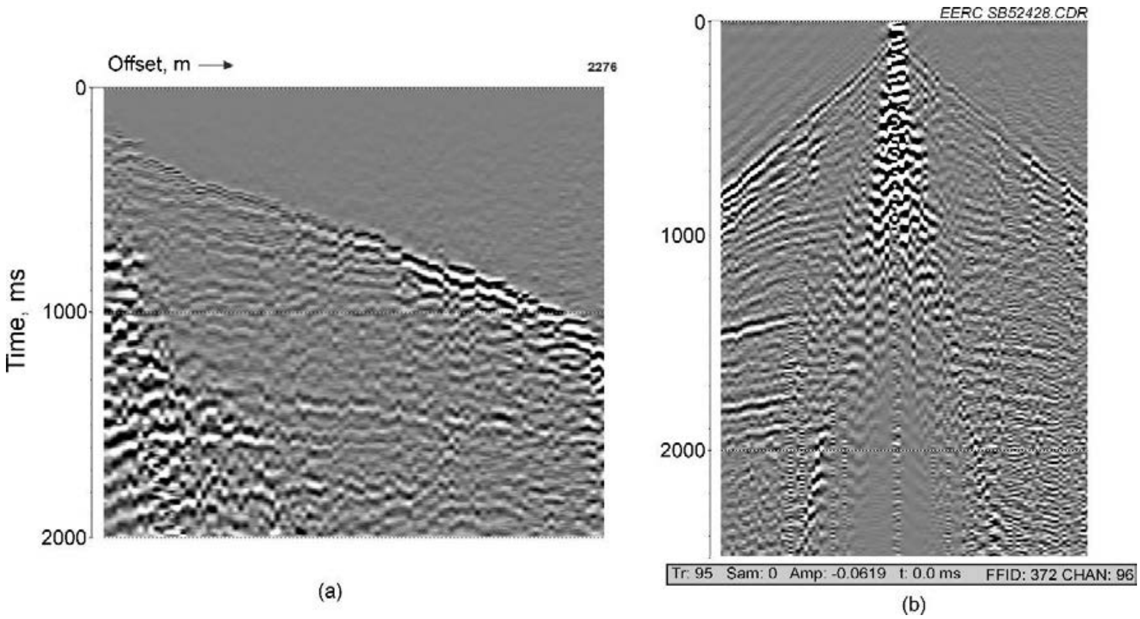


Fig. 5. (a) SASSA shot record ordered by offset showing easily visible reflections down to 1.8 seconds. (b) Reflections from geologic layers as deep as the Minnelusa at more than 1800 m are easily visible at 1.8 seconds on this partially processed shot record from the 2-D line acquired October 4, 2015, at Bell Creek using the ESS850 source (processed using RadExPro) [10].

The direct electrical drive system of the ESS850 eliminates the need for hydraulics, hoses, fluid tanks, and the associated leaks, eliminating concern for leaking fluids while the system is operated remotely. Trickle chargers are connected to the power grid and the source batteries to keep the batteries charged. As the unit is entirely electrically powered, with fully automatic cycling, a single button push (a simple contact closure) will initiate a complete firing sequence. The automatic cycling on electrical contact closure can be easily exploited to control the source remotely.

The source is housed in a secured 3 m by 4.3 m by 3 m tall insulated steel building framed with 5-cm steel tubing. The building is in an elevated fenced area with a cattle grate. Prior to the building's construction, the grading contractor bladed the area to expose a hard surface to build and operate the source on. The building has a dirt floor and is anchored in place by rebar stakes on each side. Power to the building is brought from a nearby drop from an overhead line. Outdoor cabling was trenched to the shed to bring two lines of 110-volt power to operate lights, computer equipment, Internet modem, and battery chargers. One 220-volt circuit was provided to power a space heater to maintain internal temperatures above 0°C.

The source acquisition system includes a mounted trigger switch (hammer switch) and an onboard source signature recorder (SSR). The SSR captures and records auxiliary traces from two mounted accelerometers and the shot GPS time stamp and source location information when the source is fired. The remote control system for the GISCO ESS850 was developed to provide complete control and monitoring of the seismic source and its enclosed environment with options for expandability if required. The system comprises three major subsystems: the seismic source monitoring and control system, the ESS850 with installed SSR, and the computer and electronics rack [10]. The components used for seismic source monitoring and control provide all of the support necessary to safely fire the seismic source. This subsystem comprises a seismic control box, remote lighting, and a wireless IP camera (Internet protocol camera). The seismic control box contains an Ethernet-based relay that is used to provide fire and jog signals to the ESS850, control a warning strobe light and overhead lighting in the source shed, count the number of ESS850 firing events, and monitor the temperature in the source shed. The IP camera is used to allow the operator of the source at the EERC to view the source, supporting hardware, and monitor for safe conditions and proper operation. The camera, with tilting and panning capabilities, is positioned to be able to view the doors, LED indicators on the SSR, and battery chargers as well as view the hammer under the trailer to verify it is free from obstructions, as well as aligned and operating properly. The remote-controlled system requires an Internet connection. The service offers 20 GB per month of data bandwidth, which is sufficient for the project needs. The system includes an external permanently mounted satellite dish and modem electronics within the source shed powered by a 110-volt outlet on the UPS (uninterruptible power supply).

A 680 kg engineered footing with the top set at grade level was designed to help ensure consistent source signature over the life of the project. The footing pyramids up from a 3.5-cm thick 91.4-cm × 91.4-cm base to a 3.8-cm thick 71.1-cm × 71.1-cm middle and a 12.7-cm thick 50.8-cm × 50.8-cm column (Fig. 4b). To prevent the source from moving off center, it is held in place by straps pulled tightly against rods that are commonly used to anchor trailer houses.

3.2. Seismic Recording System

The seismic recording system is the Fairfield Nodal Zland Recorder System. The system comprises 96 three-component recording nodes, two handheld terminals for deploying the nodes in the field, and a seismic management system consisting of a data server with specialized software and two networked harvester–charger racks (Fig. 6). The recording nodes are self-contained within a sturdy package; each is a recording system containing three orthogonally mounted 5-Hz geophones, a Li-ion battery pack powers a GPS module, GPS antenna, and 32 GB of flash memory. Programmable, they can record continuously or incrementally over a range of days. Battery life can be as long as 60 days before recharge is needed.

The handheld terminal (HHT) is a GPS unit with special software for deploying and stopping the nodes. On deployment, a serial data connection tether is connected to the node from the HHT. Specifications for the field acquisition are loaded, and the node is turned on to seek its location and set its GPS timing before going to sleep to await its preplanned acquisition wake time. The HHT is synchronized with the seismic management system, and the node as-laid coordinates and deployment times are transferred to the management system. The seismic management system with the data harvester–charger racks has been installed in an office trailer on-site.

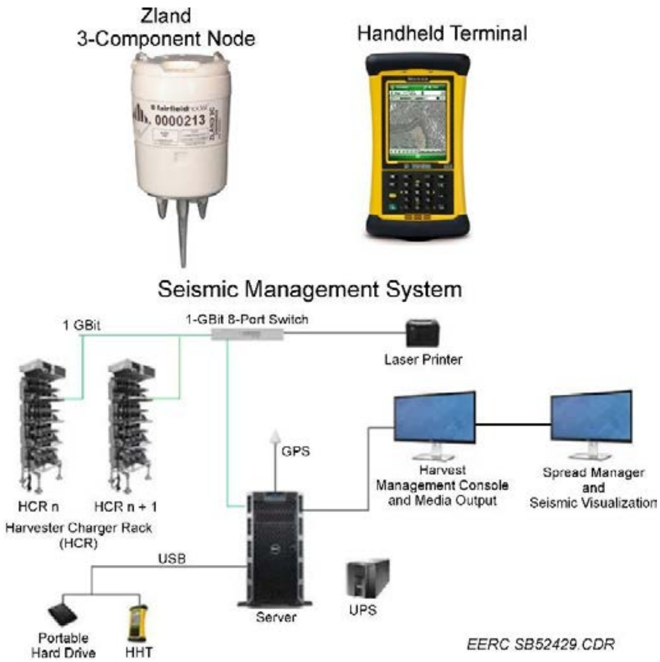


Fig. 6. Components of the seismic recording system (modified from Fairfieldnodal ZSystems Zland Gen 2 1C and 3C Node User Manual (2014) [11].

When deployed, the recording nodes are planted in a 18-cm PVC sleeve with a cap that is dug in level with grade. The node is installed in the sleeve, firmly coupled to the soil at the bottom. This dug-in container approach is to address concerns that nodes placed at grade without the sleeve and cover will be frozen in place during the winter, making monthly retrieval problematic. It also protects the nodes from wildlife and livestock.

4. Data Acquisition

The array was installed in October 2015 and remained in the field through October 2016. The autonomous recording nodes were programmed to wake up and collect data for 8 hours on Saturday and Sunday and 5 hours on Monday. These time periods were chosen to minimize the amount of noise present while firing and allow the operator the flexibility to abstain from shooting during adverse weather conditions and provide enough time to troubleshoot Internet connection difficulties. Six baseline data sets were collected before the start of injection in January 2016. After injection started, 50 shots were remotely fired weekly. Every 6–8 weeks, the nodes were picked up, the batteries were charged, and data were harvested in the field prior to redeployment of the nodes.

5. Processing Flow Development

Since the SASSA concept is not to use the seismic method to create a subsurface image but to provide an indication of physical changes occurring at monitored locations within the reservoir, an individual trace-based analysis of time-lapse data from each receiver is required. This provides the unique platform to create individualized processing flows for each receiver and allows for individual attention with processes and parameter choices.

SASSA processing occurs in two domains: shot and receiver. Receiver domain processing exploits the unusual situation where, with a single-source location, each trace on a common receiver gather should be exactly the same, with any differences due to noise, reservoir changes, or seasonal factors. A robust processing flow with relatively simple trace-based processing is currently being developed. Common receiver gathers show improved signal-to-noise after a preliminary processing flow is applied (Fig. 7). The main components of this processing flow include spreading correction, various noise reduction methods, deconvolution and filtering, and applicable time-lapse calibration processes. Current processing flow development includes an in-depth analysis of noise to aid in process and parameter selection. Passive data collected by the receivers is being used to characterize the unique noise signature for each node. Additionally, weather history matching is being done to address noise and understand seasonal changes.

6. Method Validation

The SASSA results will be compared to a traditional time-lapse difference display from a baseline and repeat 2-D surface seismic line running through the center of the study area and to predictions of CO_2 migration from dynamic reservoir simulations of injection and production. By shooting a 2-D line across the study area both before and after injection and processing it as a time-lapse survey to get a difference display, the presence and location of CO_2 visible on the display can be used to confirm the SASSA project results. A 2-D line was acquired in October 2015 prior to injection and in October 2016 after injection along a field road that traversed the study area diagonally from southeast to northwest (Fig. 2). The 96 nodes were deployed every 33.5 meters along the road to form a mildly crooked 3.2-km line. The ESS850 was fired 16 times between every other node in a geometry that mimics a previous 2-D test line used to produce a time-lapse difference display in another area of the field.

Predictive reservoir simulations and production history matching will also be used to corroborate and validate SASSA project results by modeling the plume location, movement, and CO_2 concentrations. Where results differ, SASSA results may provide information to calibrate the predictive simulations. These comparisons will allow for a cost–benefit analysis and validation of the concept and will advance the science of seismic monitoring techniques for CO_2 storage projects.

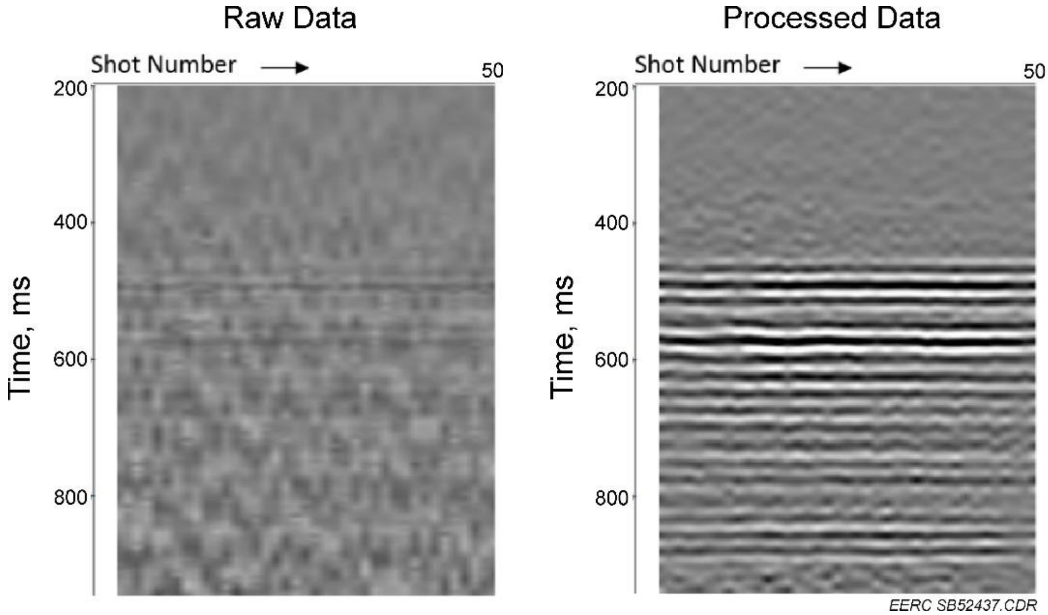


Fig. 7. A common receiver gather with one trace for every one of the 50 shots recorded at a single receiver location for a day of shooting. Processing applied includes spherical divergence correction, burst noise removal, time and frequency domain filtering, gap and spiking deconvolution (65-ms gap), f-x deconvolution, and a bandpass filter (10-15-55-60).

7. Conclusion

The EERC is conducting a proof-of-concept demonstration using SASSA to test a novel seismic method for detecting and tracking an injected CO_2 plume as it traverses discreet points within a reservoir. Located in southeastern Montana, the test was conducted at the Denbury-operated Bell Creek oil field, which is undergoing commercial CO_2 EOR. SASSA, a 96-station seismic array with a single stationary source, was deployed in October 2015 to detect and track CO_2 plume migration not by imaging but by monitoring discrete source–receiver midpoints. Midpoints were strategically located within and around four injector–producer patterns covering approximately 2.6 square kilometers. Receivers used were Fairfield Nodal Zland three-component, autonomous, battery-powered nodes. A GISCO ESS850 accelerated weight drop source located in a secure structure was remotely fired on a weekly basis for one calendar year, including a 2-month period prior to initiation of CO_2 injection to establish a baseline. Fifty shots were fired 1 day each week to facilitate increased signal-to-noise through novel receiver domain processing and vertical stacking. Currently, a robust processing flow is being developed. To validate the success of the methodology results will be compared to conventional time-lapse difference results from a 2-D baseline and monitor survey collected in the project area as well as dynamic reservoir simulations.

This new method may provide an economical means of continuously monitoring the CO_2 plume edge and the CO_2 reservoir boundaries and/or to interpret vertical or lateral out-of-reservoir CO_2 migration. The demonstrated ability to near-continuously detect changing interwell CO_2 saturations to guide larger monitoring programs and optimize injection/production parameters will significantly advance current monitoring practices being deployed in the CCS industry. Monitoring systems that are scalable and can be automated can be utilized to optimize the timing and location of MVA data acquisition which, in turn, provides a potential significant increase in the accuracy of CO_2 accounting practices through timely identification of potential deviations to the injection strategy and a means of optimizing the value of the overall monitoring program. Because each node is autonomous and independent, deployment is flexible and scalable with a minimal environmental footprint. The nodes are commercially available, allowing for scalable arrays to fit a specific design package. Simple processing allows for fast turnaround of the results, expediting the process of making strategic decisions regarding timing and location of other MVA activities and allowing for more efficient and cost-effective means to manage the evolving performance profile of injection operations. Finalized processing procedures being developed are expected to be applied routinely to newly acquired periodic data, providing the ability to recognize and act on changes observed to be occurring in the reservoir over modest time intervals.

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Disclaimer

References

[1] Tanaka Y, Abe M, Sawada Y, Tanase D, Ito T, Kasukawa T. Tomakomai CCS demonstration project in Japan, 2014 Update. Energy Procedia, 2014;63:6111–6119.

[2] Daley TM, Freifeld B M, Ajo-Franklin J, Dou S, Pevzner R, Shulakova V, Lueth S. Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring. The Leading Edge, 2013;32(6):699–706.

[3] Mestayer J, Cox B, Wills P, Kiyashchenko D, Lopez J, Costello M, Hill D. Field trials of distributed acoustic sensing for geophysical monitoring. In 2011 SEG Annual Meeting. Society of Exploration Geophysicists 2011, January.

[4] Pevzner R, Tertyshnikov K, Shulakova V, Urosevic M, Kepic A, Gurevich B, Singh R. Design and deployment of a buried geophone array for CO_2 geosequestration monitoring: CO_2CRC Otway Project, Stage 2C. In 2015 SEG Annual Meeting. Society of Exploration Geophysicists, 2015, December.

[5] White DJ, Roach LA, Roberts B. Time-lapse seismic performance of a sparse permanent array: experience from the aquistore CO_2 storage site. Geophysics, 2015;80(2):WA35–WA48.

[6] Hornman JC, Mateeva A, Potters JH, Lopez JL. New concepts for lowering the cost of frequent seismic reservoir monitoring onshore. In SEG Technical Program Expanded Abstracts, 2015, August.

[7] Meunier J, Huguet F, Meynier P. Reservoir monitoring using permanent sources and vertical receiver antennae: The Céré-la-Ronde case study. The Leading Edge, 2001;20(6):622–629.

[8] Braunberger JR, Hamling JA, Gorecki CD, Miller H, Rawson J, Walsh F, Pasternack E, Rowe W, Butsch R, Steadman EN, Harju JA. Characterization and time-lapse monitoring utilizing pulsed-neutron well logging—associated CO_2 storage at a commercial CO_2 EOR project: Energy Procedia 2014;63:3935–3944.

[9] Burnison SA, Burton-Kelly ME, Zhang X, Gorecki CD, Steadman EN, Harju JA. Bell Creek test site—3-D seismic and characterization report: Plains CO_2 Reduction (PCOR) Partnership Phase III, Task 4 – Deliverable D96, Technical Report to U.S. Department of Energy National Technology Laboratory, March 2014.

[10] Burnison SA, Beddoe CJ, Glazewski KA, Salako O, Hamling JA, Ayash SC, Gorecki CD. Technical design of a scalable, automated, semipermanent seismic array (SASSA) method for detecting CO_2 extent during geologic CO_2 injection: Deliverable D2 Interim Report on Completion of Technical Design (Oct 1, 2013 – Oct 31, 2015) for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FE0012665, Grand Forks, North Dakota, Energy & Environmental Research Center, October 2015.

[11] Fairfieldnodal ZSystems ZLand Gen 2 1C and 3C Node User Manual, 2014.