

Active seismic monitoring at a carbon test storage facility from a sparse SADAR array network

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Abstract

In November 2021, a sparse seismic network of four permanent compact volumetric phased SADAR arrays was installed at Carbon Management Canada's Newell County Field Research Station (FRS) outside Brooks, AB. These continuously recording passive microseismic monitoring arrays have also recorded active 2D seismic monitor lines shot at the site, two or three surveys per year. The active shot data can be extracted from the continuous passive record and processed through a conventional surface seismic reflection processing sequence with an additional step of beamforming for the volumetric arrays. The resulting image is a processed receiver gather where each array is considered as a single station. The net effect of beamforming increases the signal-to-noise ratio (SNR), improves reflector continuity and vertical resolution, and extends the optimum offset window with respect to coherent noise from shallow refractions and surface and air waves. The permanent emplaced receivers and repeat shot station locations make this active survey data suitable for timelapse analysis. A strong 4D signature has not yet been observed in the data for the volume of CO₂ injected to date.

Introduction

The Newell County FRS is a test facility for carbon capture and storage measurement, monitoring, and verification (MMV) technologies (Lawton *et al.*, 2019; Macquet *et al.*, 2022). Since 2017, controlled volumes of CO₂ have been injected into the 7m thick Basal Belly River Sandstone (BBRS) formation reservoir at approximately 300m depth at rates generally less than 20 metric tons annually.

The SADAR arrays at the FRS site are configured as variants of nested cylindrical shells with GS-ONE vertical geophones as array elements grouted into shallow boreholes below the weathering layer between 9-19m below the surface. Passive microseismic monitoring has been performed at the FRS with the SADAR network since 2021 (Nyffenegger *et al.*, 2023; Zhang *et al.*, 2023; Hutchenson *et al.*, 2025). Over this time, repeat 2D seismic monitor survey lines have also been shot at the FRS site two to three times per year. The monitor surveys do not always repeat the same full suite of 2D shot lines, but the surveys rotate among a set of common 2D lines. Figure 1 shows the FRS layout with shot lines 13 and 15 and their midpoint locations for the four SADAR arrays. Shot spacing along these lines is 10m resulting in a 5m midpoint spacing for the subsurface lines. Line 15 was lengthened in 2024 to take advantage of the SADAR sparse network coverage.

Most repeat surveys were shot with an EnviroVibe source unit owned by the University of Calgary. Other controlled frequency source units have been tested at the site. Several survey vintages are available for timelapse analysis.

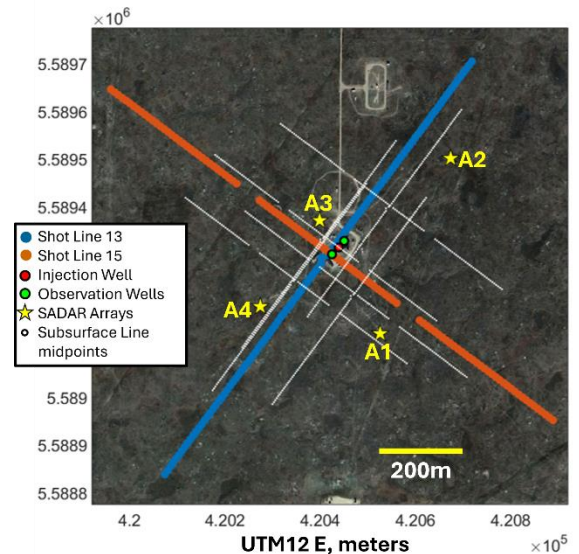


Figure 1: Layout of the shot lines, SADAR stations, and midpoints at the Carbon Management Canada Field Research Station.

Method

Data segments extracted from the passive SADAR network at survey shot times are used in a conventional surface seismic reflection processing sequence with the additional step of beamforming the data acquired using the volumetric arrays. The beamforming is essentially a delay-and-sum operation analogous to statics application to align array elements for a preferential arrival direction for a beam's main response axis (MRA), in this case vertical. Even with the permanent arrays installed below the weathering layer, care must be taken that the processing sequence does not introduce timelapse differences between the different survey vintages.

The processing sequence for the active 2D survey lines (Quigley *et al.*, 2025) includes:

- 1) Cut shot segments from continuous record data
- 2) Cross-correlate shot segments with sweep
- 3) Sum common shot stations for a single survey

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- 4) Conventional array beamforming
- 5) Sort to common receiver gathers
- 6) Normal moveout (NMO) correction
- 7) Cross-equalization data scaling

Results

The BBRS reservoir target has the most potential interest for timelapse differences given that CO₂ has been injected into this reservoir since 2017. Over 100 metric tons of CO₂ have been injected to date. Seismic subsurface line cross sections for Line 15, Array 4 and Line 13, Array 3 are shown in Figures 2 and 3 for a monitor survey from October 2024. Because far surface offsets are dominated by noise from refracted wave energy in the shallow section and near offsets are dominated by strong coherent surface wave noise, the focus is on an optimum offset window of good signal quality (Hunter and Pullan, 1989) between about 100m to 400m offset from the SADAR arrays for the BBRS target horizon at 300m depth (light blue box, Figure 2). The optimum offset window is of course time (depth) variant and can also vary for the different array locations.

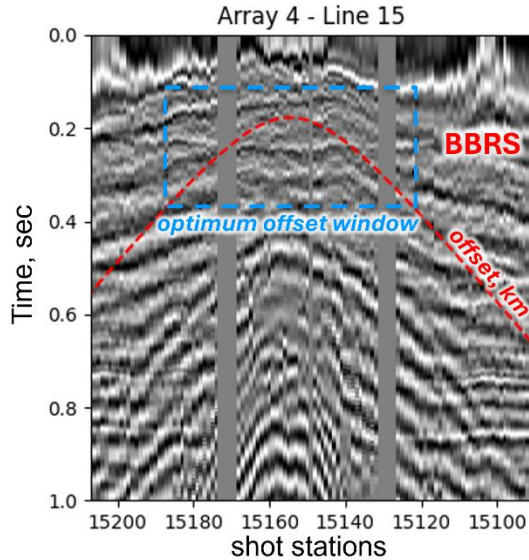


Figure 2: Line 15, Array 4 subsurface line cross section, shot stations decrease from northwest to southeast. Light blue box highlights approximate 100m-400m optimum offset range to image the BBRS target horizon. Red dashed line is offset in km.

The subsurface line with the closest approach within about 35m of the injection well is Line 13, acquired using Array 3, shown in Figure 3. In this figure, the BBRS horizon is clearly visible southwest of the injection well but hard to identify to the northeast. This shows how local effects at different array locations can complicate a simple selection of an “optimum” offset window.

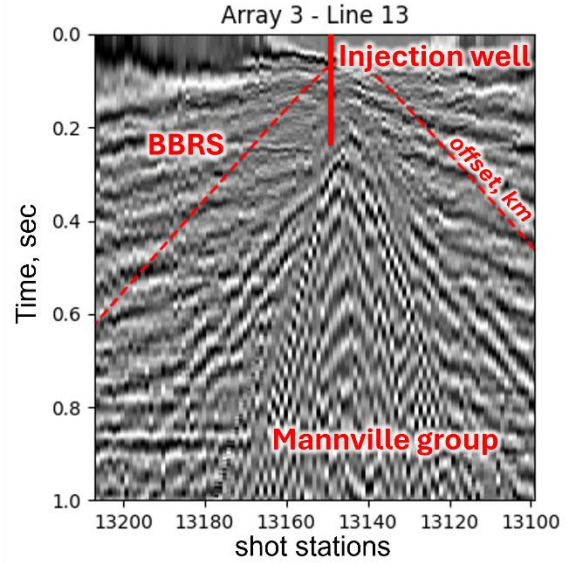


Figure 3: Line 13, Array 3 subsurface line cross section, shot stations decrease from southwest to northeast. Note BBRS target horizon is in approximate 100m-300m optimum offset range west of the injection well, but is less apparent east of the injection well.

The difference between the October 2024 Line 13, Array 3 monitor line from Figure 3 and a baseline survey from July 2022 is shown in Figure 4. The difference is overlain on the normalized RMS attribute (Kragh and Christie, 2012).

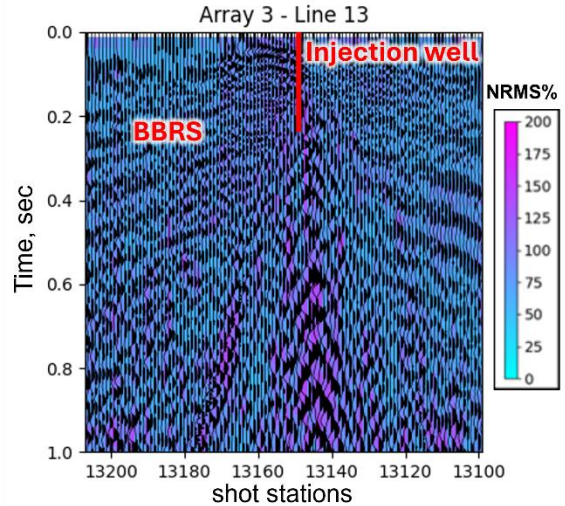


Figure 4: Line 13, Array 3 subsurface line cross section difference between October 2024 monitor and July 2022 baseline surveys overlain on NRMS attribute. Note the strong noise contributions to a high level of nonrepeatability.

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Despite the permanent array stations installed below the weathering layer, strong nonrepeatable noise from shallow refractions and coherent surface wave energy dominates the difference in Figure 4. Given the high levels of noise, it is difficult to observe a timelapse signal in the data from the BBRS reservoir. Increasing concentrations of dissolved CO₂ have been observed in Observation well #1 (northeast of Injection well in Figure 1) at the FRS site since injection began but without an observed increase in pressure.

Conclusions

Permanently emplaced array sensor elements of a passive microseismic monitoring network have less noise than surface sensors and provide highly repeatable locations for timelapse analysis from repeat active seismic monitoring surveys such as those described at the Carbon Management Canada FRS. Although permanent arrays are beneficial for signal repeatability, strong coherent surface wave noise and shallow refractions at this site are highly non-repeatable and complicate the timelapse analysis. Therefore, the analysis focuses on an optimum offset range outside the surface wave noise cone and below shallow refractions.

Applying conventional beamforming to the volumetric array data improves the SNR which enhances reflector continuity and extends the optimum offset window over what single sensor elements can provide. Nevertheless, this was not adequate on its own to attenuate the highly non-repeatable noise. Given the high levels of nonrepeatable noise, no timelapse signal is currently observable for the illuminated area from the sparse SADAR network, at least for the period from July 2022 to October 2024. More advanced beamforming approaches and signal processing techniques may provide a greater total uplift and benefit the timelapse analysis.

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