

Permanent sparse monitoring design concepts for CO₂ plume monitoring

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Summary

Sparse reflection seismic monitoring is being investigated as a cost-effective monitoring solution for geological CO₂ storage (GCS) sites. Permanent seismic sources and receivers with automated acquisition cycles may provide an advantageous alternative to conventional 2D and 3D seismic covering extensive CO₂ plumes and acquired infrequently over decades. For an onshore GCS scenario similar to the Quest project in Alberta, we present a conceptual sparse acquisition design with the objective of minimizing the number of permanent monitoring nodes required while providing adequate delineation capability to evaluate conformance and containment of the CO₂ plume.

Method

This sparse acquisition design used a simple plume model based loosely on injection parameters and 4D seismic monitoring results from the Quest project (Harvey et al., 2022; Quest, 2023). An elliptical plume was used to approximate asymmetric spreading from gradual up-dip migration to the north-east. Table 1 summarizes the scale of the simple CO₂ plume model for a sandstone reservoir of 50 m thickness at 2000 m depth, with 10% porosity, a supercritical CO₂ density of 710 kg/m³, and a storage efficiency factor (SEF) of 0.07.

Table 1. Injected mass and plume size by year of operation used in this scenario.

Year	Injected mass (Mt CO ₂)	Semi-major axis (km)	Semi-minor axis (km)
1	0.3	0.93	0.41
2	0.6	1.32	0.58
3	0.9	1.61	0.72
4	1.2	1.86	0.83
5	1.5	2.08	0.92
10	3.0	2.94	1.31
20	6.0	4.16	1.85
30	9.0	5.09	2.26

For the monitoring array, we chose a hexagonal acquisition pattern on a triangular grid to minimize the number of permanent receivers and sources. Source and receiver nodes are offset from each other by 1.5 km, the approximate upper limit of the optimum offset window for seismic reflections (Hunter and Pullan, 1989) for a 2 km deep target in the Western Canada Sedimentary Basin.

Figure 1 illustrates the sparse array and reflection points over the first five years of injection at a single well. First, seven permanent receiver arrays are installed with one positioned near the well pad, with the other six at a distance of 2.6 km from the well. These permanent receiver arrays also form the backbone of a passive seismic monitoring network for induced seismicity monitoring,

enhancing the cost-effectiveness of the sparse approach. Six permanent source locations with good coupling are then installed at a distance of 1.5 km from the well pad, each hosting a semi-permanent seismic source that can be re-deployed to other locations at a later stage of the project. For example, our approach at Carbon Management Canada’s Newell County Field Research Station (Macquet et al., 2022), is to use small moveable semi-permanent seismic sources, mounted on steel helical piles that form the permanent source locations, paired with permanent buried receivers (Nyffenegger et al., 2025). Alternative designs could include sources mounted on concrete pads (e.g. Pevzner et al., 2022). In this scenario, each source location is also instrumented with seismic sensors, both to record the downgoing signal for deconvolution and act as additional permanent receivers for the sparse monitoring array. Crucially, the permanent source and associated power unit (e.g. solar and batteries) remain accessible at surface for servicing and removal.

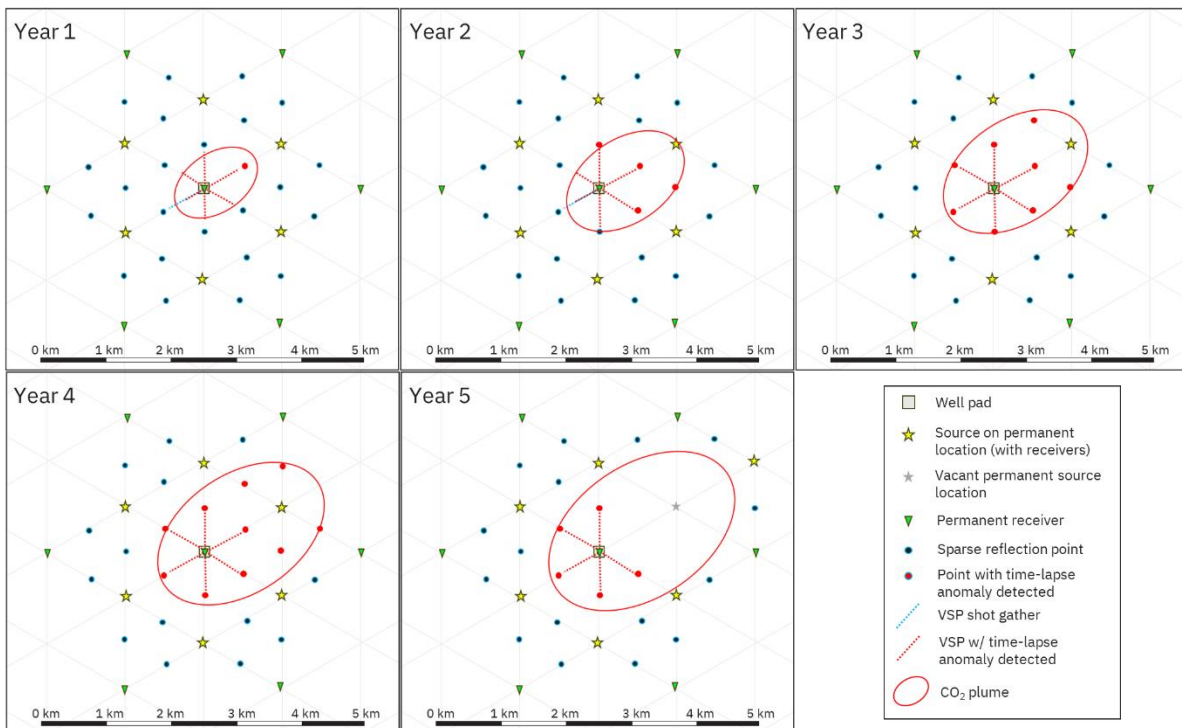


Figure 1. Plan view schematic showing the sparse acquisition design. Detection and coarse delineation of the CO₂ plume (red ellipse) occurs at reflection midpoints over five years of injection. Each panel is approximately one quarter-township (5 km x 5 km). A legend is provided in the bottom right.

Six high-repeatability far-offset vertical seismic profile (VSP) shot gathers are also depicted in Figure 1, provided that borehole sensors (e.g. distributed acousting sensing fiber) are included in the well design. As demonstrated by Pevzner et al. (2022), automated VSP acquisition can provide rapid time-lapse imaging during the first weeks, months, and years of the injection to verify conformance and containment and provide early warning of anomalies. Farther afield, the plume’s arrival is detected and delineated at twenty-four sparse reflection points. Although the reflection points are sparsely distributed and unmigrated, the frequent (e.g. weekly) sampling would provide time-series to confidently identify traveltimes and reflectivity changes at each location and provide

reservoir model updates. Figure 1 shows that after five years of injection, the north-east front of the CO₂ plume extends past the original reflection points. A new permanent source location is then installed farther to the north-east at the optimum 1.5 km offset. One source, along with its power and control system, is then moved to the new location to expand the spatial coverage. The original, now-vacant source location remains in place for future use.

Figure 2 depicts the growing and adapting sparse seismic network until and beyond closure. The original receiver arrays are used for active and passive monitoring throughout the thirty-year injection program. However, in order to extend the spatial coverage and establish a final perimeter around the plume, it becomes necessary to install two to four additional receiver arrays and to increase the number of source locations to between fourteen and twenty. The number of seismic sources remains at six throughout the project.

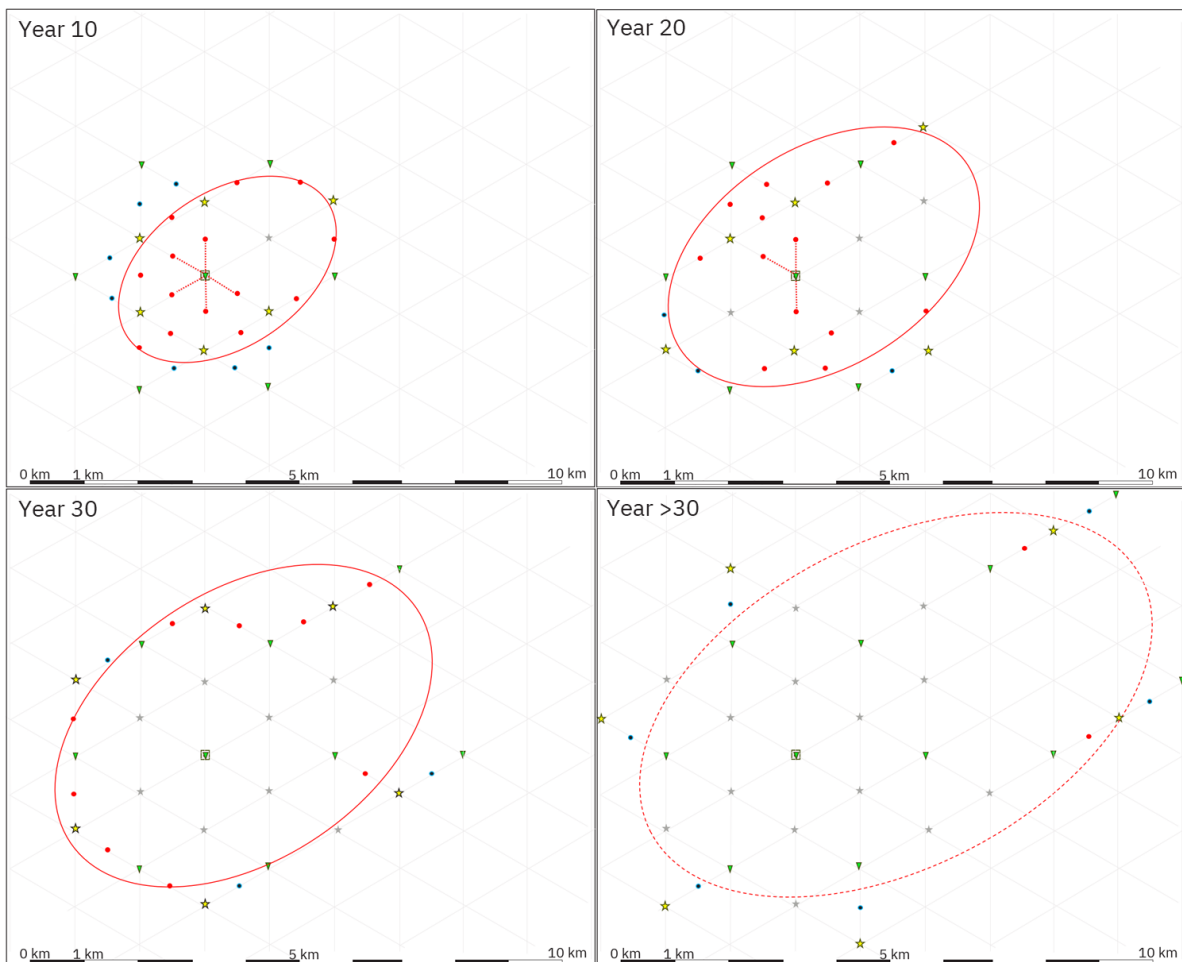


Figure 2. Starting at ten years of injection, the extent of the CO₂ plume and the growth and adaptation of the sparse monitoring network is depicted up to and beyond the thirty-year injection period of the well. Each panel is approximately 10 km x 10 km, roughly equivalent to one township in Alberta. See Figure 1 for legend.

Vacated source locations remain in place so that they can be re-occupied periodically. Although minimal time-lapse change would be expected within the known plume extent, acquisition from the old source locations would provide proof-of-absence of anomalies above the reservoir at each reflection point, verifying containment. Following thirty years of injection, a probable final configuration of the monitoring array is depicted in the bottom right panel of Figure 2, with a perimeter of six reflection points around the plume to detect lateral or vertical migration due to buoyancy. Some or all of the permanent receivers and source locations can either be removed or left in place for post-closure monitoring.

The acquisition design depicted in Figures 1 and 2 was intended to maximize the use of the least costly components (permanent source locations, e.g. steel piles or concrete pads) while minimizing the more costly receiver arrays and seismic sources with associated mobile power and control units. A summary of the major monitoring components required for this scenario is provided in Table 2.

Table 2. Summary of the hardware requirements for the sparse seismic monitoring array.

Year of injection	Source & power unit	Permanent receiver arrays	Permanent instrumented source locations
0	6	7	6
5	6	7	7
10	6	7	9
20	6	7	14
30	6	11	20

Conclusion

The design of the monitoring array for the onshore Quest-like scenario required six seismic sources, up to eleven permanent receiver arrays, and up to twenty permanent instrumented source locations. Preliminary estimates for this sparse monitoring scenario indicate substantial cost reductions compared to a conventional seismic monitoring program for a similar GCS scenario using 2D and 3D surface acquisition (e.g. estimates by Hunt et al., 2024), while providing more timely monitoring data. This scenario was for a single injection well, but cost efficiencies may be enhanced further by sharing seismic sources between neighbouring wells as the lateral growth rate of the plume decreases over time, requiring less frequent sampling. Where conventional seismic acquisition is impractical due to surface restrictions, a sparse nodal approach with a minimal footprint could achieve conformance and containment verification that would not otherwise be possible. At sites with baseline 3D seismic, sparse monitoring can reduce the need for costly conventional monitor surveys and provide more timely detection of conformance and containment anomalies, triggering targeted 3D surveys if needed.

Novel/Additive Information

An evaluation of the permanent infrastructure needed for a sparse monitoring network for a commercial scale injection scenario.

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