Detection threshold of a shallow CO_2 plume with VSP data from the CaMI Field Research Station

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Summary

Reliable geophysical monitoring is needed for effective Measurement, Monitoring and Verification (MMV) of geological CO_2 sequestration. The Containment and Monitoring Institute's Field Research Station (CaMI.FRS) provides unique field data relevant to shallow injection and shallow leak detection for Carbon Capture and Storage (CCS) and Enhanced Oil Recovery (EOR) operations in sedimentary basins. CO_2 injection at the FRS simulates a shallow leak from a deeper reservoir. VSP data were collected between 2017 and 2021 using geophones and Distributed Acoustic Sensing (DAS). Monitor surveys provided snapshots of the reservoir after injection of 7 t, 15 t, and 33 t of CO_2. Permanently installed seismic sensors and repeated shot locations allowed for highly repeatable time-lapse surveys. Dissimilarity between baseline and monitor data was principally caused by seasonal variations in surface conditions and in near-surface filtering. A time-lapse compliant processing workflow was developed to detect the subtle amplitude effects of a small amount of CO_2. The 10 Hz – 150 Hz field data required cautious processing, relying on deterministic deconvolution to properly scale and balance amplitudes across most of the 10 Hz – 150 Hz frequency bandwidth. Remaining spectral differences caused by near-surface filtering were removed with high-cut filters. The CO_2 plume was confidently detected with geophone VSP data after 33 t of injection. Equivalent DAS VSP data was collected with different interrogator units for baseline and monitor surveys. This led to greater dissimilarity between datasets and ambiguous time-lapse results. Establishing a detection threshold of 33 t of CO_2 approaches the limit of detectability in the geological setting at CaMI.FRS. These results provide insight into the challenges and capabilities of shallow reservoir monitoring and shallow leak detection for CO_2 sequestration operations.

Introduction

At the Field Research Station in Newell County, Alberta, CO_2 is injected at 300 m depth into the Basal Belly River Sandstone, a saline aquifer of 6 m thickness and 10% porosity at the base of the Foremost Fm (Dongas, 2016, Macquet and Lawton, 2017). A geophysics observation well (Obs 2) is offset from the injection well by 20 m to the south-west (Figure 1). Walk-away VSP monitoring lines extend from the Obs 2 well, with the SW-NE oriented Line 13 running parallel to the injection well (Inj) and geochemistry well (Obs 1). Fluid substitution modeling performed by Macquet et al. (2019) indicated that between 0% and 40% saturation, gas-phase CO_2 in the 10% porosity reservoir causes a gradual non-linear decrease in P-wave velocity. The corresponding decrease in reflectivity produces a trough-peak time-lapse residual from the top and bottom interfaces of the BBRS reservoir.

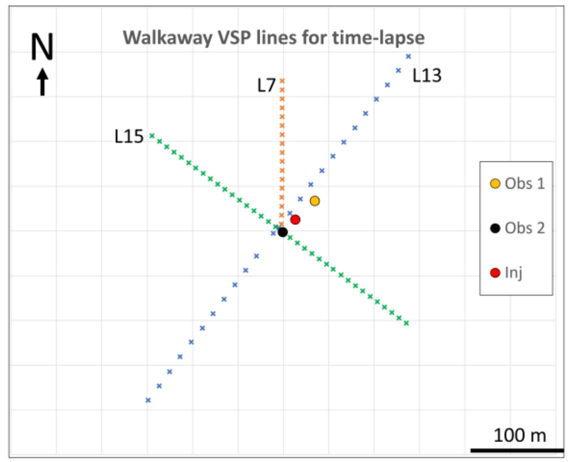

Figure 1: Map of the walk-away VSP lines and well locations at the CaMI Field Research Station.

Method

With highly repeatable acquisition, seasonal variations in surface conditions and near-surface filtering were the principal source of dissimilarity between baseline and monitor data. Resolving these differences while preserving the subtle amplitude effects of a small CO_2 plume motivated the development of a time-lapse compliant VSP processing workflow. A detailed explanation of this process is given by Kolkman-Quinn (2022). Of note, error-prone trace scaling steps were avoided during processing and cross-equalization. Deterministic deconvolution properly scaled trace amplitudes across most of the available frequency bandwidth. Independently processed reflection amplitudes were directly comparable, except in the higher frequency bands where seasonal variations in near-surface filtering caused significant differences in attenuation. Figure 2 shows frequency spectra of two processed shot gathers, using a 400 ms window which included the BBRS injection interval. Shot 13145 shows similar levels of near-surface filtering, with similar bandwidth and amplitudes after deconvolution. The reflection amplitude decrease in shot 13145 is caused by the presence of CO_2. Shot 13155 suffered significantly different levels of attenuation in the baseline survey, which were not entirely reversed during deconvolution. For cross-equalization, shaping filters designed from both the downgoing direct arrivals and the upgoing reflected arrivals were tested. Shaping filters were unable to adequately match the higher frequency bands, while also risking alterations to the amplitude effects of the CO_2 plume (Figure 2). To preserve amplitudes while eliminating spectral differences, high-cut filters were designed for each pair of baseline and monitor shot gathers. This shot-by-shot filtering matched bandwidths and eliminated high frequency residuals from the time-lapse difference (Figure 2). Without need of further cross-equalization, stacked baseline reflection amplitudes could be directly subtracted from the monitor data to produce a time-lapse difference.

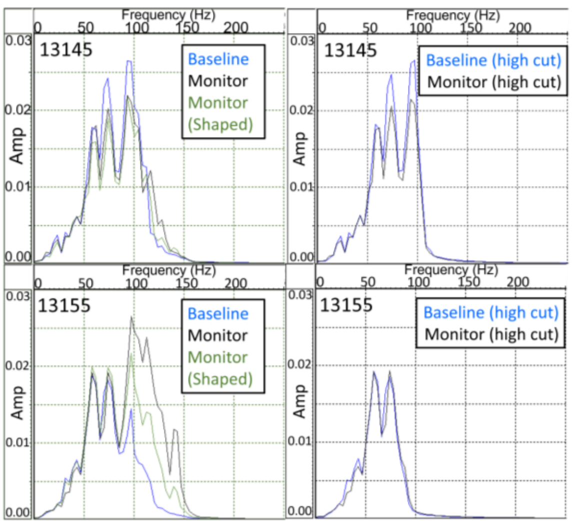

Figure 2: Baseline and monitor spectra from processed shot gathers. Shaping filters did not adequately address the variable near-surface filtering effects (left panels). After the application of high-cut filters (right panels), the baseline amplitudes could be directly subtracted from the monitor data.

Examples

Figure 3 shows field data examples of the time-lapse differences from two of the three main monitoring lines at CaMI.FRS. On the SW-NE monitoring line, Figure 3a shows no obvious CO_2 anomaly after 15 t of injection. After 33 t of injection, the amplitude effects of the CO_2 anomaly are clearly visible (Figure 3b). Note that the monitoring data for Figure 3a had fewer far-offset shots available, reducing its coverage compared to Figure 3b. Similarly, Figure 3c and 3d show the detection of the 33 t CO_2 plume on a north-oriented walk-away VSP line. The appearance of the time-lapse anomaly matched expectations set by a finite difference VSP forward model. Though an interpretation was made for the 15 t CO_2 plume in Figure 3a, it was not clearly above the detection threshold. In the context of detecting an unexpected leak, it is unlikely that 15 t of CO_2 could have been identified without prior knowledge of its existence. The 33 t CO_2 plume had achieved both sufficient saturation and lateral extent in the BBRS reservoir to produce an identifiable anomaly, above the level of the background time-lapse residuals. Characterizing the detection threshold in terms of CO_2 saturation and pore pressure will require inversion of the baseline and monitor data to be performed in the future.

The 1-C time-lapse VSP processing workflow was directly applicable to straight-fiber DAS data from the same observation well. However, additional processing steps were required due to the use of different DAS interrogator units for the baseline and monitor data. These additional steps

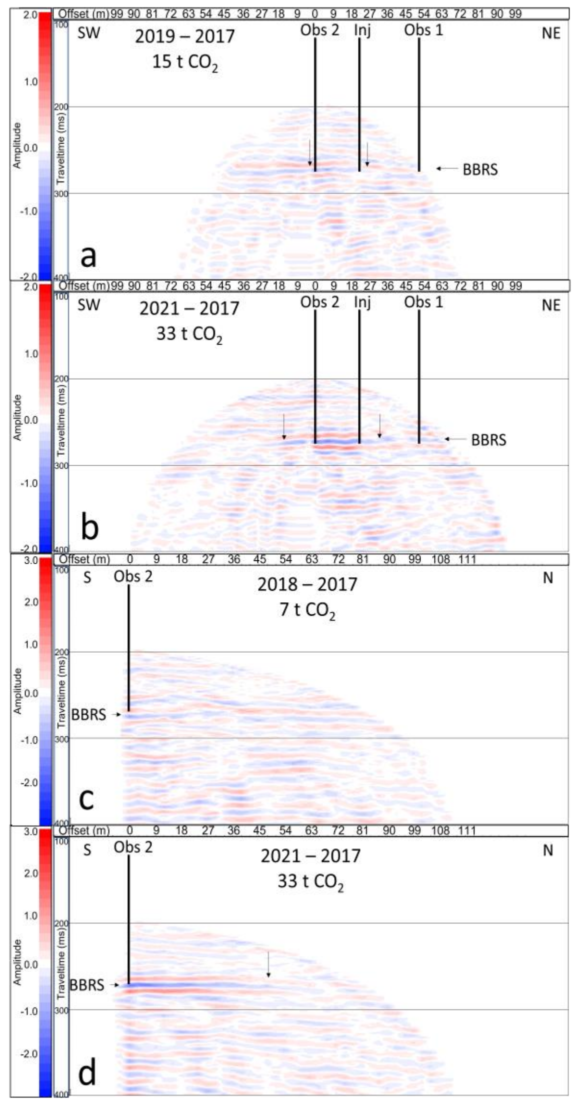

Figure 3: Time lapse results from Line 13 (a & b) and Line 7 (c & d) showing detection of the CO_2 plume after 33 t of injection.

included: spatial re-sampling, depth-registration, and de-noising of the raw DAS data. De-noising involved the use of an f-k filter, median filter, and RMS trace amplitude normalization. Figure 4 shows the best quality time-lapse result from the DAS data. For comparison purposes, the DAS data has been truncated to the same 190 m - 305 m depth range as the geophone array. Panels a and b show the baseline and monitor VSP CDP stacked sections with a high degree of similarity. Panel c shows the difference, and Panel d show the equivalent geophone result. In the case of the DAS data, the range of shot offsets was more limited, resulting in reduced coverage. A trough-peak time-lapse residual is visible at the BBRS interval in Figure 4c, however it is lower amplitude and less coherent than in the geophone result in Figure 4d. Despite aggressively de-noising the raw DAS data, some interrogator-related noise persisted through

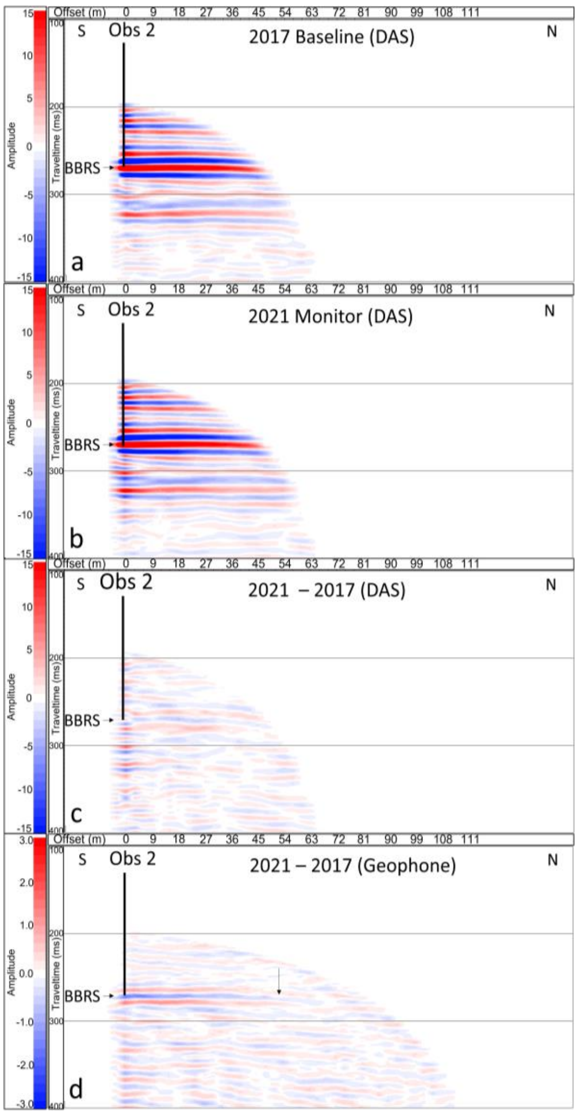

Figure 4: Baseline (a) and monitor (b) VSP CDP stacks of Line 7 DAS data. The time-lapse difference (c) does not clearly detect the CO_2 plume, as in the geophone result (d).

processing and stacking. In this context, DAS noise encompasses the lower SNR of the DAS data as well as the differences introduced by sampling the DAS fiber with single and dual pulse interrogators (Hartog, 2017) using different gauge lengths and output trace spacings. These factors specific to DAS acquisition prevented the CO_2 anomaly from clearly showing through in the difference between stacked baseline and monitor data. Increased CO_2 saturation and reservoir pressure is expected to allow detection of the CO_2 plume, but with a higher detection threshold than with the geophone data.

Conclusions

A detection threshold of 33 t was established for a simulated shallow CO_2 leak at the CaMI Field Research Station using geophone time-lapse VSPs. Achieved with high-quality, high-repeatability field data and cautious processing, this approaches the limit of detectability in this 6 m thick, 10% porosity reservoir at 300 m depth. The time-lapse compliant processing workflow relied on deterministic deconvolution to produce directly comparable baseline and monitor amplitudes. Cross-equalization was achieved without the use of shaping filters. The application of high-cut filters matched baseline and monitor frequency bandwidths, effectively removing seasonally variable near-surface filtering effects while preserving CO_2-related amplitude effects. The 33 t detection threshold and time-lapse compliant processing workflow help inform MMV capabilities for both shallow leak detection and shallow reservoir monitoring of CO_2 sequestration operations.

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