CO_2 injection detection using light time-lapse seismic monitoring

Introduction

Carbon Dioxide (CO_2) injection has been used for Enhanced Oil Recovery (EOR) in the Weyburn field in southeast Saskatchewan in Canada for over 20 years. Since 2000, the Weyburn Unit has sequestered over 34 million tonnes of CO_2, with an ultimate storage capacity estimated at 55 million tonnes. Since 1997, time-lapse (4D) seismic has been an essential surveillance tool to ensure safe and optimized development throughout the field. Multiple 4D seismic surveys have been acquired to monitor the evolution of CO_2 flooding and identify sweeping inefficiencies and infill drilling opportunities. 4D seismic plays an integral role in understanding the Weyburn Unit's CO_2 flooding performance and helps in strategic planning and time-critical field optimization (Chen et al., 2021).

To maximize the value of information while controlling costs, a novel light seismic monitoring approach has been "blind-tested" on a CO_2 use case. The concept requires the use of only one source and one receiver location optimally placed in the field to monitor a spot in the subsurface, using time- lapse shots to detect 4D changes in the zones of interest (Brun et al., 2021). This technology has already shown successful results and is currently being used for several applications: steam monitoring in a heavy oil field, fracking and over a gas storage monitoring area.

The objective of this blind-test was to identify the zones that were affected by a CO_2 injection without knowing the injection scenario thanks to the ultra-light time-lapse seismic acquisition system designed. The results were then successfully matched to the 4D time-lapse CO_2 amplitude anomalies within the CO_2 flood, with the SpotLight technology successfully identifying CO_2 swept vs non-swept spots by calculating travel time delays.

Method

Weyburn Field in southeast Saskatchewan covers about 180 km^2. Oil reserves lie within a thin zone (< 30 m) of fractured carbonates in the Midale beds of the Mississippian Charles Formation at a depth of ~1450 m. The reservoir is comprised of vuggy limestone with overlying marly dolostone that are sealed above by anhydritical dolostones and anhydrites.
The estimated effects of a CO_2 injection on seismic properties within the reservoir intervals are large enough to produce an observable seismic response to CO_2 injection. Simulation of the pressure effects indicate that P-wave velocities are reduced by <4% due to reduced effective pressure associated with injection. However, it is recognized that there is increased uncertainty in these simulation results for low effective pressures due to the difficulty of making laboratory velocity measurements on core samples under these conditions (White, 2009).

The results discussed in this paper utilized the 4D design made of non-permanent 3C geophones that are buried at 12 meters below the surface, and 1kg of dynamite also buried at 12 meters depth. The survey was designed to give an azimuthal and offset distribution as uniform as possible.
The datasets used in this paper are a baseline acquired in November 2004 and a monitor acquired in November 2018. For this blind-test, 2 spot locations have been defined by the client for which the injection scenario was not disclosed to SpotLight. The goal was to see how this approach focused on spots could track a CO_2 swept area and match with 4D seismic amplitude anomalies which are mainly employed to map CO_2 plumes in the field. The 2 spots and the acquisition design are presented in Figure 1.

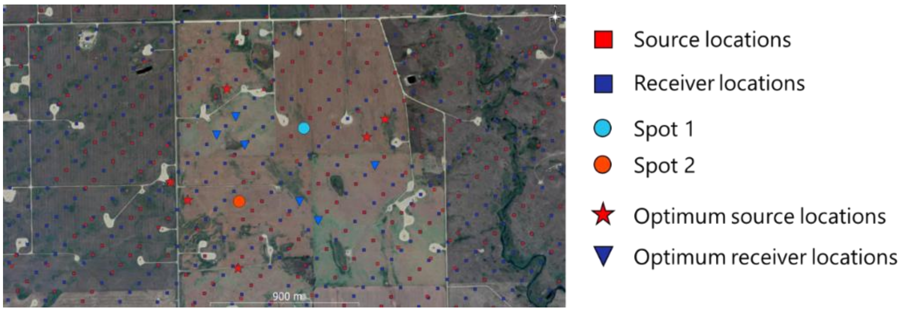

Figure 1 *Blind-test acquisition design on the Weyburn field. Spot locations and part of the 2004 acquisition design are indicated. Optimum source and receiver locations of each antenna used in Figure 2 are also displayed.*

A survey design step was completed to find the optimum source and receiver locations per spot using the migrated data of 2004. The objective of this phase is to retrieve the best source and receiver's locations out of the entire survey of 2004 (see Morgan et al., 2020 & Brun et al., 2021 for more details). 3 optimum traces have been selected for each spot per monitor and are displayed in Figure 2. The offset ranges from 730 to 1025 meters.

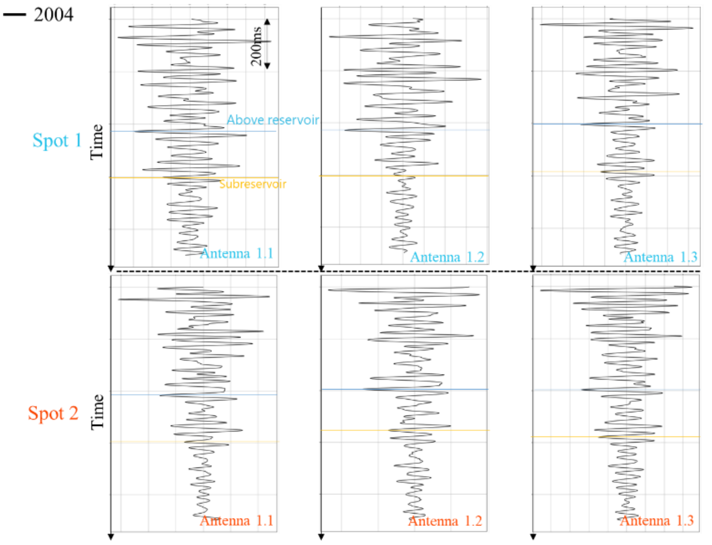

Figure 2 *Optimum antennas chosen for both spots on the 2004 survey. 2 horizons above and below the reservoir are indicated as an information for the detection.*

Before computing detection attributes, an in-house processing sequence has been applied to enhance the signal to noise ratio and achieve a better repeatability. These steps essentially include a phase and amplitude matching operator and adapted frequency bandwidths to obtain a stable signal in the overburden area. A Normalized Root Mean Square (NRMS) value was computed (Table 1) in the overburden area after the processing sequence was applied on each of the antennas.

		NRMS in the overburden area
Spot 1	Antenna 1.1	15%
	Antenna 1.2	11%
	Antenna 1.3	18%
Spot 2	Antenna 2.1	21%
	Antenna 2.2	24%
	Antenna 2.3	33%

Table 1 *NRMS values in the overburden area.*

Regarding Spot 1, each of the antennas have an NRMS value under 20%, which shows an excellent repeatability. Regarding Spot 2, 2 antennas out of 3 have an NRMS value around or below 20%. However, the antenna 3 shows an NRMS value of 33% which is too high compared to the other antennas. This antenna was disqualified from the study, the repeatability being too low in the overburden area which is not adequate with a detection at reservoir level. It was noticed that the source position was moved from one side of a road to the other between the two surveys, which explains such a difference of repeatability compared to the other antennas.
Jervis et al (2012) showed that small source changes (< 2m) may seriously degrade survey repeatability. In a regular SpotLight acquisition, the position of the source should not move to avoid this problem. In that case the processing sequence may not be enough to correct non-reservoir-related 4D effect in the overburden area. The final processed seismic traces are shown in Figure 3.

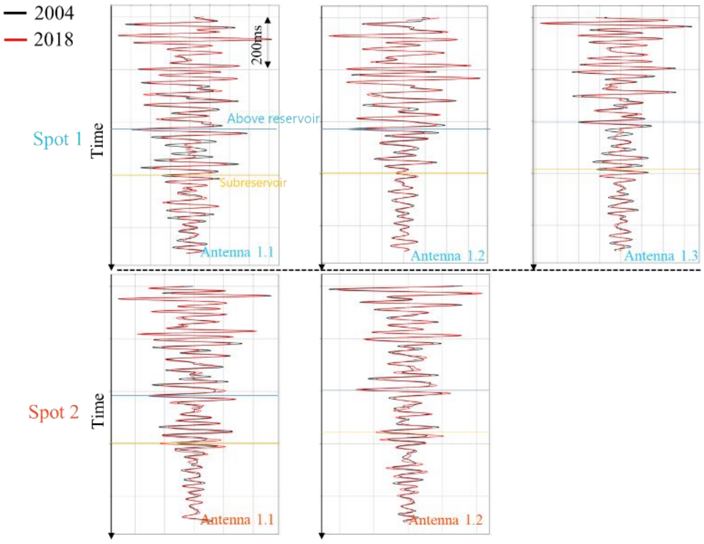

Figure 3 *Processed seismic traces for each spot from the 2004 and 2018 acquisition. The third antenna of Spot 2 was disqualified for the detection due to a mispositioning of the source between the two monitors.*

Results

A sliding time-shift (using a 100ms window) detection has been computed over the two monitors (corresponding to the base of 2004 minus the monitor of 2018) for each of the antenna. The results are shown in Figure 4.

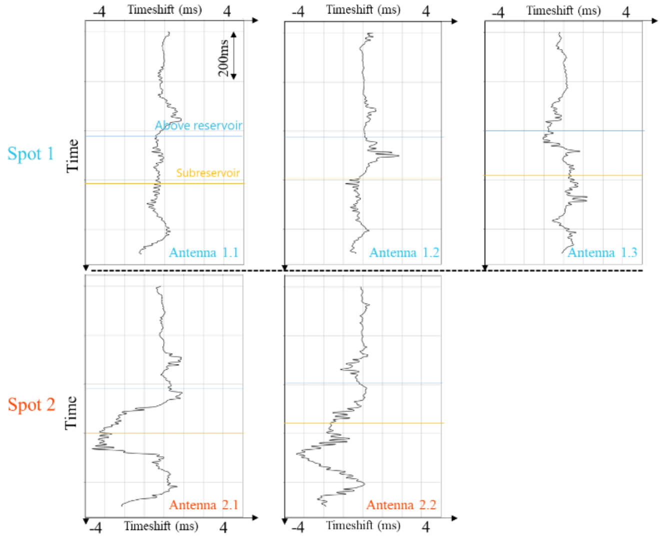

Figure 4 *Sliding time shifts for each of the antenna. 2 horizons above and below the reservoir are indicated as an information for the detection.*

For Spot 1, the 3 antennas are showing a stable time shift that varies between 0.002 and 0.08ms in the overburden area which means that all the effects above the reservoir have been corrected thanks to the processing sequence. When looking in and under the reservoir (on a 200ms window), the time shift values are fluctuating on average between -0.30 and 0.35ms, with no effect being built inside and under the reservoir layer. It was stated that this spot has not seen any CO_2 effect.

For Spot 2, the 2 remaining antennas are showing a stable time shift which varies between -0.03 and -0.1ms in the overburden area. In and below the reservoir (on a 200ms window), for both antennas, time shift values vary between -1.75 and -2.43ms with an effect being built inside and under the reservoir layer. It was stated that a CO_2 injection was detected in this area.

These negative time-shifts are coherent with a CO_2 injection, as the density of the reservoir will be reduced and thus a decrease in term of velocities is observed.

After presenting these results to the operator, we were able to correlate the travel time delay results from the light and focused seismic monitoring system with 4D seismic amplitude anomalies from the operator’s data. The two methods successfully distinguish CO_2 swept area versus non-swept area.

Conclusion

In this paper, a light and focused seismic detection approach has been successfully tested to detect a CO_2 injection over the Weyburn field.

2 spots were indicated by the operator to blind test the approach on a CO_2 use case. After a survey design, 3 antennas were chosen for each spot, being among the most contributory seismic traces to each spot’s illumination. Due to small travel time delays expected, it would be recommended to use a small receiver-antenna to make sure to avoid any random noise or operational issue. Due to the deviation of source & receiver positions in between surveys, it was decided to compute time-shift values on a 200ms window. The results were plotted and successfully identified CO_2 swept/non-swept spots by showing travel time delays where the presence of CO_2 in the reservoir causes longer travel time reaching the formations beneath the reservoir zone.

This blind test has proven two new points: it is possible to detect a CO_2 injection using only one source and one receiver optimally located per spot and thanks to a stable operational model on the field it was possible to detect an injection with 2 seismic surveys 14 years apart.

A CO_2 monitoring project using this light and focused seismic monitoring approach will be performed offshore this year on the Project Greensand.

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