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Initial Results of Time-Lapse Processing of VSP Geophone and DAS Fiber-Optic Cable at Aquistore CO2 Injection Site, Sask

S. Cheraghi* (Natural Resources Canada), D. White (Natural Resources Canada), K. Harris (Natural Resources Canada), B. Roberts (Natural Resources Canada)

Summary

The Aquistore CO2 storage site is located near the town of Estevan, Saskatchewan, Canada. The CO2 reservoir is located at a depth of about 3300 m, and injection and observation wells are drilled down to that depth. A coal-fired power plant east of the wells supplies the CO2 and a pipeline transfers the CO2 to the injection well. Prior to injection, vertical seismic profiles (VSPs) were acquired in November 2013 with two receiver types: a 60-level geophone tool deployed at a depth range of 1650-2650 m, and a fiber-optic cable used for distributed acoustic sensing (DAS) installed from the surface to a depth of 2766 m. CO2 injection started in April 2015 with a planned injection rate of 500-600 ton/day. In February 2016 about 36 kilotonnes of CO2 was injected when the first monitor VSP geophone and DAS data were acquired. The second DAS monitor survey was acquired in November 2016 when about 102 kilotonnes of CO2 was injected. We have applied a similar processing flow to all vintages of both geophone and DAS data to evaluate how repeatable VSPs can image the CO2 plume.

Introduction

The Aquistore CO_2 injection site is located near the town of Estevan, Saskatchewan Canada (Figure 1). The CO_2 reservoir is a permeable sandstone formation at a depth of about 3300 m. The CO_2 supply is a coal fired power plant located 3 km east of the study area, and a pipeline transports the CO_2 to the injection well (see Figure 1). A permanent array of receivers buried at a depth of 20 m are used for 4D seismic monitoring of the reservoir (Figure 1). Prior to CO_2 injection, two 3D surface seismic surveys were acquired in March 2012 and May 2013. White et al. (2015) and Roach et al. (2015) evaluated the repeatability of these surveys and showed that acquiring shots with a location accuracy of 1-2 m between the two surveys over the permanent array and applying similar prestack processing flow and postmigration cross-equalization sequence reduces the global Nrms to 0.07, which is promising for time-lapse studies. CO_2 injection started in April 2015 at a rate of 500-600 ton/day. The first post-injection surface data was acquired in February 2016, after about 36 kilotonnes of CO_2 was injected to the reservoir. Roach et al. (2017) imaged the seismic amplitude changes related to that volume.

Besides 3D surface seismic data, vertical seismic profiling (VSP) data is also acquired via two methods. The first method employs a 60-level 3C geophone tool in the observation well (see Figure 1 for the location) at a depth range of 1650-2650 m. Receiver spacing along this array is about 15 m. In the second method a fibre-optic cable deployed in the observation well is used for distributed acoustic sensing (DAS). The cable extends from the surface to a depth of 2766 m. DAS is able to measure backscattering of light in the fibre caused by acoustic energy and provides an almost continuous array of sensors along the fibre. Since sensitivity in DAS is limited only to axial strain, the fibre could be considered an array of vertical component receivers. At the Aquistore study site, a Silixa iDAS system with a channel spacing of 2 m is used to monitor the reservoir. DAS VSP data from Aquistore consists of 3 vintages that were acquired in November 2013 before injection (baseline), February 2016 (monitor 1) after injecting 36 kilotonnes of CO_2, and November 2016 (monitor 2) after injecting about 102 kilotonnes of CO_2. The geophone data is available for the baseline and monitor 1 surveys (monitor 2 is not acquired by the geophone tool). 1 kg dynamite charges buried at a depth of 15 m were used as sources for all VSP vintages (Figure 1). The shot locations were resurveyed for both monitor 1 and 2.

Harris et al. (2017) developed a processing flow to investigate DAS data for time-lapse analysis. They were able to process the baseline and monitor 1 data in a parallel manner such that identical processing steps were applied to shots of both vintages, and used a depth-migration algorithm to generate stacked volumes of both vintages (baseline and monitor 1). They applied a post-stack cross-equalization sequence to highlight the effect of injected CO_2. This analysis revealed amplitude changes in the cross-equalised sections in the area between the injection and observation wells at the reservoir depth (3200-3300 m). In this study we apply a similar processing flow as in Harris et al. (2017) for time-lapse processing of the DAS data (baseline, monitor 1 and 2) and geophone data (baseline and monitor 1).

Time-Lapse processing Flow

Ideally, the processing flow is designed to apply identical steps to each vintage and produce repeatable images. Time-lapse amplitude differences at the reservoir depth should reflect the effects of injection. However, small shifts in shot locations between surveys can produce time-lapse noise. Our processing flow is designed to reduce the effects of non-repeatable noise, and is identical for both geophone and DAS data.

First, shot locations in each survey are investigated to quantify shot shifts from one vintage to the other. Harris et al. (2017) determined the maximum acceptable shot shift to be ~5 m. We employed the same rejection criterion, and used the normalised root-mean-squares (Nrms) of the first arrivals in a 100 ms window to evaluate the repeatability of shots between vintages. The major processing steps are shown in Table 1.

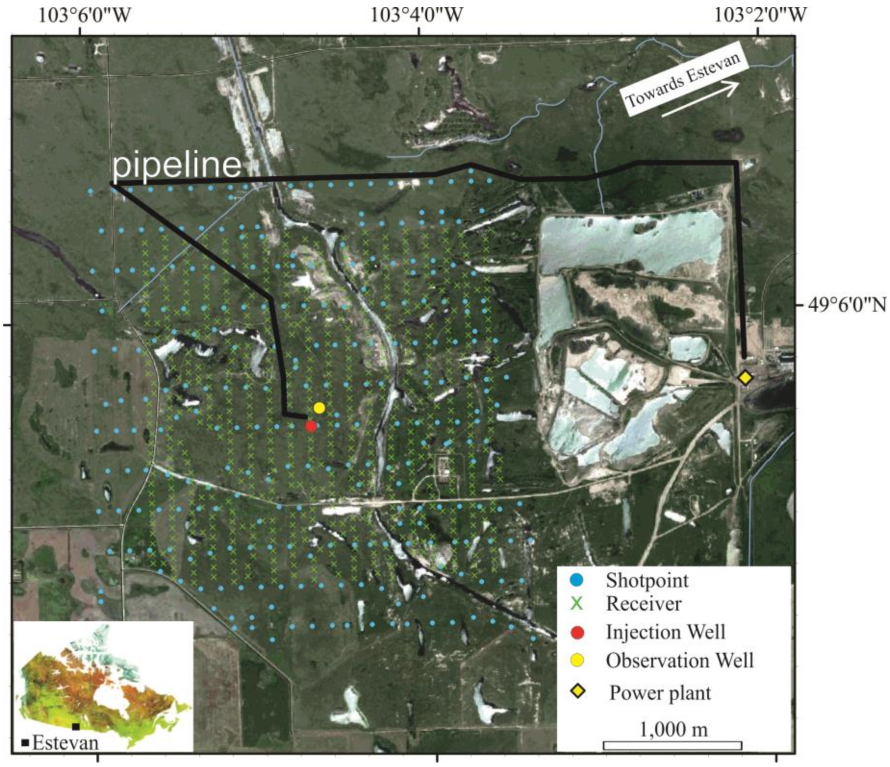

Figure 1 *Surface map of the Aquistore CO_2 injection site. The receiver locations of the 3D surface seismic survey are shown in the figure. The shot locations of VSP/surface surveys are also shown. The injection and observation wells are located almost in centre of the study area. The pipeline that transports CO_2 from the power plant to the injection well is also shown (black line). Inset shows the location of the town of Estevan.*

Table 1 *Time-lapse processing steps applied to DAS and geophone data*

Rejection of non-repeatable shots	If shot location has moved > 5m or Nrms amplitude around first arrivals is non-repeatable.
Amplitude scaling of monitor data to baseline (shot to shot comparison)	rms amplitude of first arrivals at depth range of 200-1500 m is considered.
Median filter to remove down-going (direct) waves and top mute the first arrival.	This process mostly preserves up-going (reflected) waves.
f-k filtering to remove converted waves	The migration algorithm is designed to image P-P reflection.
Deterministic deconvolution and band-pass filtering	A 150 ms source wavelet is considered for deconvolution based on first arrival of each shot. Frequency range of 5-10-55-65 Hz is used for band-pass filtering.
Designing a velocity model	Velocity logs from injection and observation wells are considered to build velocity model.
3D Kirchhoff depth migration	Stacked cube is generated from depth of 1500-3300m. Migration aperture is 30°. Rho filter is also applied.
Phase-time matching	To align phase and time between vintages at depth range of 1300-3300 m.
Shaping filter	Depth range of 1300-3300 m is considered.
Amplitude matching	Depth range of 1300-3300 m is considered.

During prestack processing, it is important that amplitudes in each monitor shot are equalized to those in the corresponding baseline shot, and filtering steps (i.e., median filtering and f-k filtering) are designed to preserve reflected waves and remove direct waves (down-going waves) and converted waves. The band-pass filter is designed to increase the signal-to-noise ratio. The velocity model for depth migration is prepared from available petrophysical measurements, i.e., injection and observation well logs. Cross-equalization of the migrated and stacked baseline and monitor volumes further increase repeatability in the reservoir. Our first step to evaluate time-lapse amplitude differences is to subtract the baseline volume from the monitor. The results from the DAS and geophone data are shown in Figures 2 and 3. Figure 2a, 2b and Figure 3a indicate that the difference between the monitors and the baseline at a depth range of 2400-3300 m is very small, however higher amplitude changes are observed at depths of about 3300-3350 m. Those depths correspond to the bottom of the reservoir (dashed ellipses in Figures 2a, 2b and 3a). The effects of increasing amounts of CO_2 are observed from monitor 1 to monitor 2 in the DAS data (Figure 2a and 2b). Our second step is to calculate the normalised root-mean-squares (Nrms) of the amplitude differences between each monitor and the baseline (Figures 2c, 2d, and 3b). Nrms values greater than 0.7 observed in regions of otherwise good repeatability are considered to be significant and likely indicative of the presence of injected CO_2 (Harris et al. 2017). Nrms values in monitor 1 for both the DAS and geophone data at 3330 m depth show the effect of injection northwest of the injection well (Figure 2c and Figure 3b). Figure 2d presents Nrms values for monitor 2 (DAS data) at 3330 m depth. The effect of injection is observed northwest of the injection well and around the observation well. It seems that CO_2 has moved north between monitor 1 and monitor 2. High Nrms values east and southeast of the wells and at the northeast margin show the effects of non-repeatable noise that the processing flow was not able to remove (Figure 2c, Figure 2d, and Figure 3b).

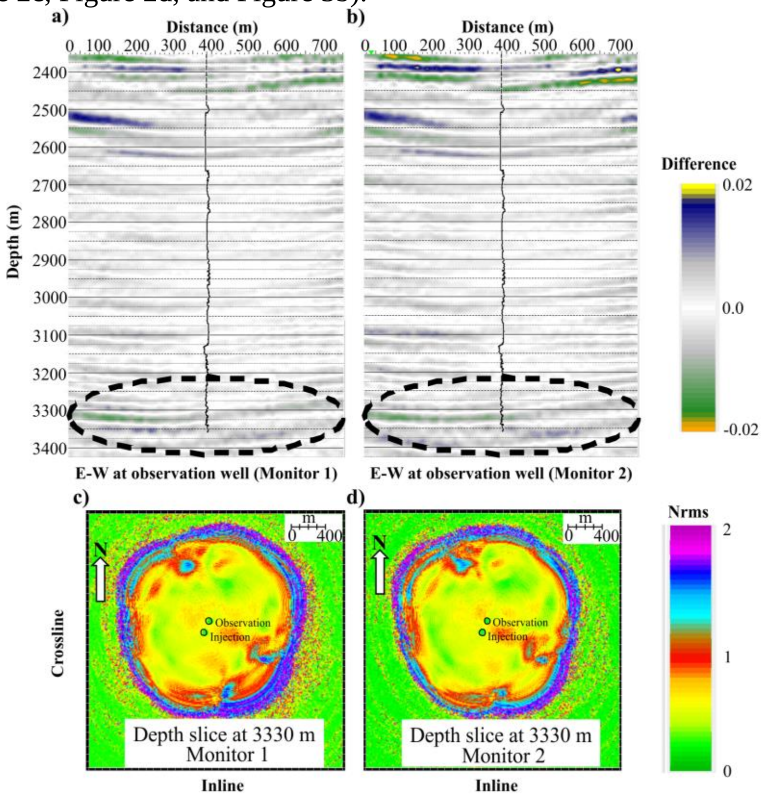

Figure 2 *Difference of migrated stacked sections of DAS data, a) monitor 1-baseline, and b) monitor 2-baseline. See Table 1 for processing steps. The sections present an east to west line through the observation well (see Figure 1 for the location of the observation well). Vp sonic log from the observation well is shown in a) and b). Dashed ellipses in a) and b) show the reservoir. Amplitude changes in the dashed area present the effect of injected* CO_2*. c) The slice shows Nrms amplitude differences between monitor 1 and the baseline at 3330 m depth. d) The slice presents the Nrms amplitude differences between monitor 2 and the baseline at 3330 m depth.*

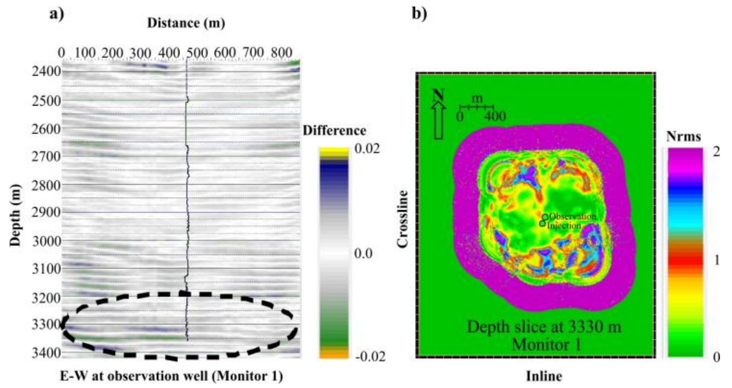

Figure 3 *a) Difference of migrated stacked sections of geophone data, which shows monitor 1-baseline. See Table 1 for processing steps. The section presents an east to west line through the observation well (see Figure 1 for the location of the observation well). Vp sonic log from the observation well is shown in a). Dashed ellipse in a) shows the reservoir. Amplitude changes in the dashed area present the effect of injected* CO_2*. b) The slice shows the Nrms amplitude differences between monitor 1 and the baseline at 3330 m depth.*

Conclusions

The DAS and geophone VSPs acquired at the Aquistore site before and during CO_2 injection provide an opportunity to evaluate if time-lapse surveys are able to show the effect of CO_2 injection. Although the reservoir is located at depths greater than 3300 m both the DAS and geophone data imaged the injection zone. The monitor 1 survey shows the concentration of injected CO_2 northwest of injection and observation wells. Monitor 2 indicates that the injected CO_2 has moved towards the north around the observation well.

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