Time-lapse Monitoring of CO_2 EOR and Storage with Walkaway VSPs

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Summary

At the Violet Grove pilot project, 100 km southwest of Edmonton, Alberta, CO_2 is being injected into the Cardium Formation in the Pembina Oil Field for enhanced recovery and carbon sequestration purposes. The reservoir is being monitored using simultaneously acquired time-lapse multicomponent surface and borehole seismic surveys. The baseline survey was acquired in March 2005 prior to CO_2 injection. The first monitor survey was acquired in December 2005 after eight months of CO_2 injection. The borehole seismic data displays higher bandwidth and increased resolution than the surface seismic data. Comparisons between the baseline and monitor borehole seismic surveys show an increase in reflectivity at the reservoir, and crosscorrelations show a time shift of 0.2 ms on two of the walkaway lines.

Introduction

Many of Western Canada's major oil and gas fields have been depleted through primary production and secondary recovery methods. Injecting CO_2 into a reservoir enhances oil recovery (EOR), reduces water usage, and has the potential benefit of CO_2 sequestration thereby reducing greenhouse gas emissions into the atmosphere. However, the injected CO_2 must be monitored to show that it is being trapped in these reservoirs and not leaking back to the surface.

At Violet Grove, the injected CO_2 is being monitored using a sparse multicomponent surface seismic program coupled with a borehole seismic array. Together, these provide lateral coverage of the survey area as well as high-resolution images near the observation well.

Project Background

The Cardium Formation is the main reservoir rock in the Pembina Oil Field. It is Cretaceous in age and consists of one conglomerate unit and three sandstone units with a total thickness of about 20 m. It is capped by the black shales of the Lea Park Formation and underlain by the Blackstone Shales. The dominant fracture trend in this area is NE-SW. The Cardium Formation is a poor P-wave reflector and exploration in the area has historically been driven by geology rather than geophysics. The top and base of the reservoir appear as a weakly tuned event in seismic data.

PennWest Petroleum provided access to an old production well for use as a monitoring well. In February 2005, eight 3C geophones as well as six pressure and temperature sensors, and two fluid sampling ports were cemented into the well near reservoir depths. The geophones are located between 1497 and 1640 m depth with a 20 m vertical spacing.

The baseline survey was acquired in March 2005 using a 2 kg dynamite charge at each shot location. The seismic survey consisted of two east-west source-receiver lines and one north-south line with offsets from the monitor well between 1200 and 1700 m (Figure 1). There were 75 shot points on each source-receiver line. CO_2 injection commenced a week after the baseline survey at a rate of approximately 70 tonnes/day. The first monitor survey was acquired in December 2005.

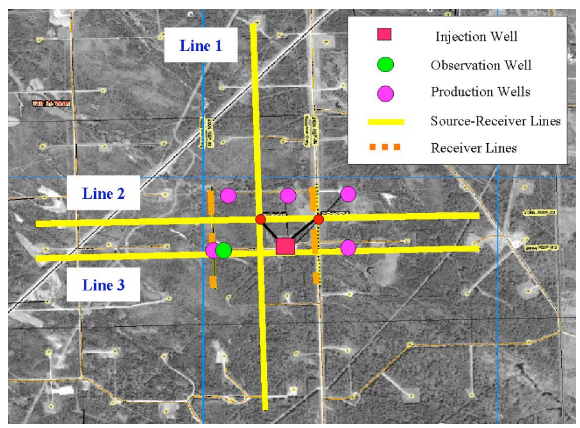

Figure 1: Arial view of the Violet Grove CO_2 Injection Site.

VSP Processing

To maintain consistency, the baseline and monitor surveys were processed using the same processing flow. Each line was processed as a separate walkaway dataset. An anisotropic velocity model was built using a calibrated sonic log from a nearby production well. The anisotropy at the receivers was analyzed using apparent phase slowness and polarization angles derived from the data (Horne and Leaney, 2000). The average values obtained for epsilon and delta at the receivers were 0.14 and 0.07 respectively.

These values were used as a constraint when the velocity model was inverted for anisotropy. In the inversion, anisotropy was allowed to increase linearly with depth. Time residuals after inversion were less than 3 ms (Figure 2).

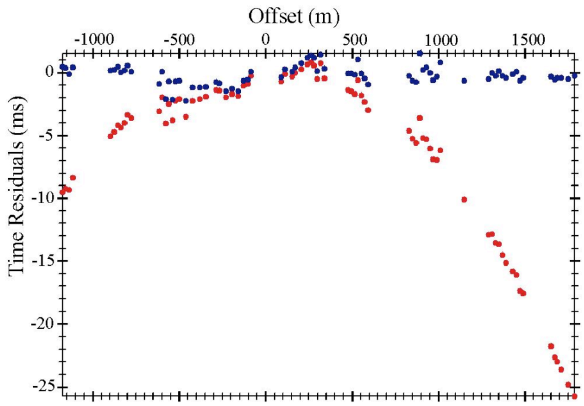

Figure 2: Time residuals for an isotropic velocity model (red) and the anisotropic velocity model (blue). Residuals are less than 3 ms after inversion.

Initially, the hodograms from the raw x, y, and z components of the data were analyzed to determine how the first arrival energy was distributed between the x, y, and z energy planes. The analysis demonstrated that the energy fell into distinct polarization planes. At the far offsets, the energy was evenly distributed between the vertical and horizontal components while the energy at the near offsets fell almost entirely in the vertical component (Figure 3). Ultimately, the raw data was rotated into the true earth frame (N, E, V) prior to the wavefield separation.

A least squares vector wavefield separation technique and the anisotropic velocity model were used to separate the data into the following components: down and upgoing P, down and upgoing Sv, and down and upgoing Sh (Leaney, 2002). This technique deals with irregular source-receiver geometries and can incorporate anisotropy into the wavefield separation. Figure 4 shows an example of the upgoing P- and Sv-wavefields from receiver 4 on the east-west line that runs closest to the monitor well (Line 3).

The upgoing P- and Sv-wavefields from each survey were migrated with the anisotropic velocity model and a 1D VTI Kirchhoff migration algorithm. Figure 5 shows the comparison between the P-wave surface and borehole seismic data for Line 3. The VSP images show excellent ties to the surface seismic data as well as increased vertical and lateral resolution. The migrated VSP data clearly images the Cardium Formation for a radius of about 100 m around the observation well.

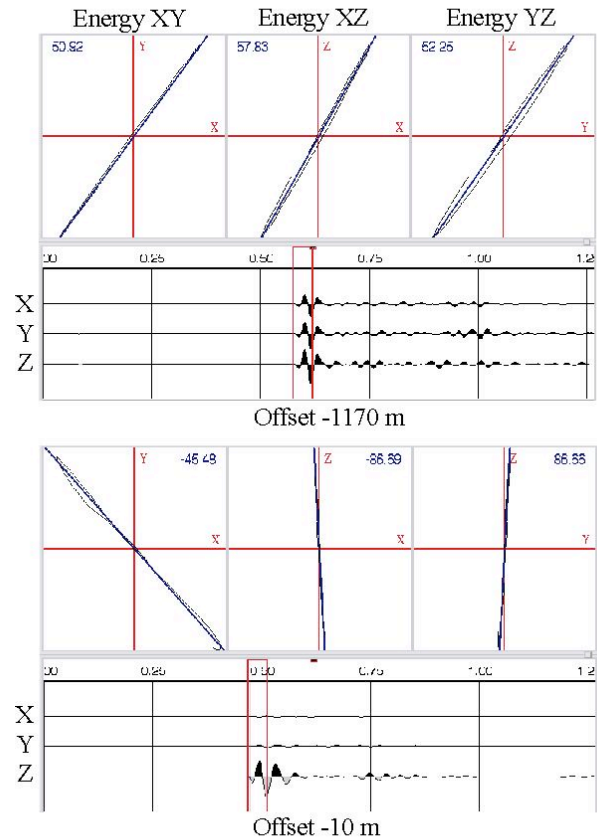

Figure 3: Hodogram displays from 1170 m and 10 m west of the monitor well. At the far offset, the energy is evenly distributed between the x, y, and z energy planes. At 10 m offset, almost all of the energy is confined to the vertical component.

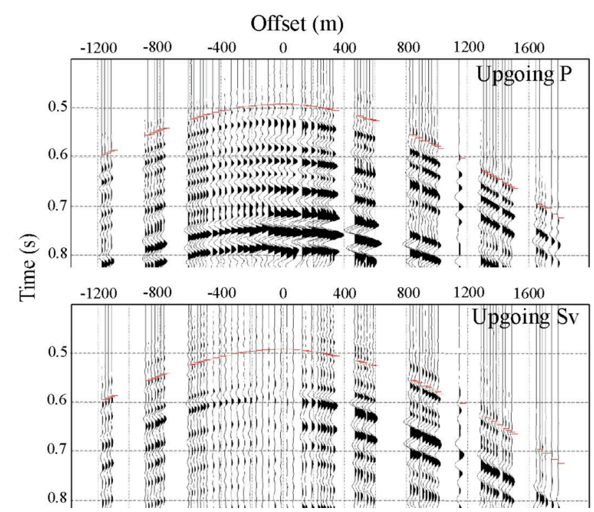

Figure 4: The upgoing P- and Sv-wavefields from the wavefield separation from receiver 4, Line 3.

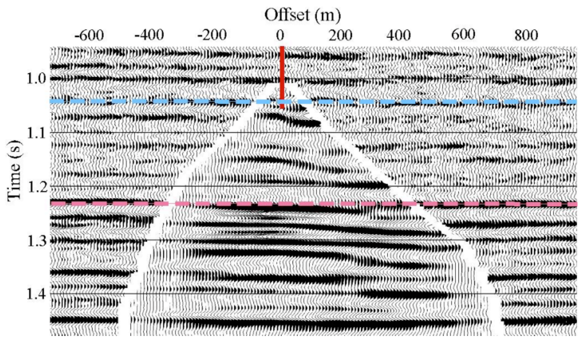

Figure 5: Tie between the P-wave VSP and surface seismic data for Line 3. The Cardium Formation is in blue, the Viking Formation is in purple.

Time-lapse Results

Most of the shot locations between the baseline and monitor surveys were repeated with an accuracy of 10 cm or less. Shots that varied by more than 50 cm were rejected from the time-lapse analysis. Comparisons of the raw data from Line 2 in the baseline and monitor surveys show the high degree of similarity between the surveys (Figure 6). In Figure 6, a bulk time shift of 3 ms can be seen between the surveys; a similar time shift was seen in the surface seismic data. The time shift was accounted for by shifting the monitor survey based on the difference in baseline and monitor travel times for receiver 1, which sits above the reservoir.

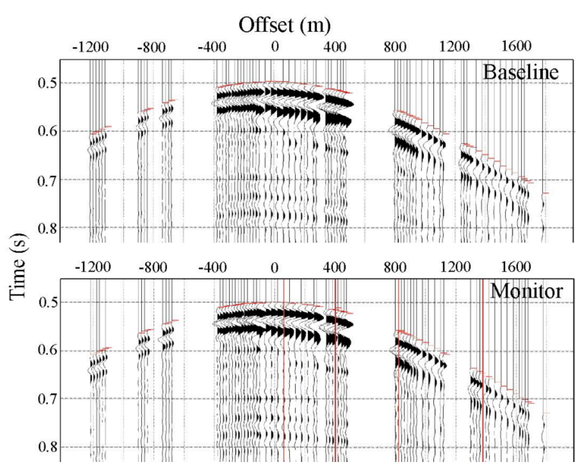

Figure 6: Comparison of the raw data from receiver 4 on Line 2. The two datasets show a remarkable degree of similarity. The red lines in the Monitor display indicate non-repeated shots that have been removed from the dataset.

Comparisons between the baseline and monitor surveys looked for changes in the reservoir amplitudes, timing of events, and the amplitude and phase spectra. Results from Line 2 show the clearest time-lapse differences. The amplitudes at the Cardium event have increased in the eight months between the baseline and monitor surveys (Figure 7). A similar increase in amplitudes has not been identified on later events.

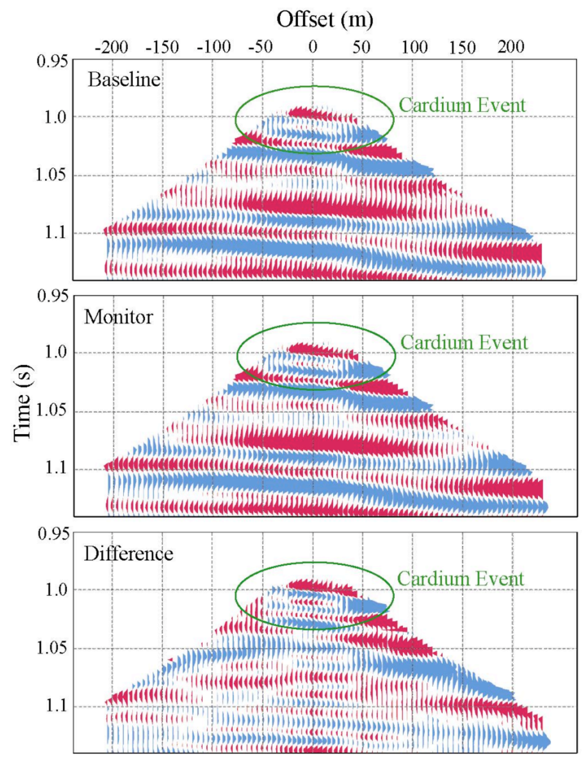

Figure 7: Comparison of the time migrations from the baseline and monitor surveys. The differences at the Cardium are directly related to the increase in amplitudes at the reservoir. The difference display has been scaled up 4 times from the baseline and monitor migrations.

The baseline and monitor survey data were crosscorrelated in a 30 ms window around the reservoir event. The crosscorrelations displayed a systematic increase in travel time of 0.2 ms for the event. Modeling of the reservoir with the Gassmann equation indicates that a 10% saturation of CO_2 should cause a decrease in P-wave velocities of about 5% and result in time shifts of less than 1 ms (F. Chen, personal communication, 2006). Once the full CO_2 front passes the monitor well, a greater time shift should be observed between the surveys. The amplitude and phase spectra of the two surveys are nearly identical at frequencies below 80 Hz without the use of a matching filter (Figure 8). The monitor survey has a slightly richer amplitude spectrum above 60 Hz.

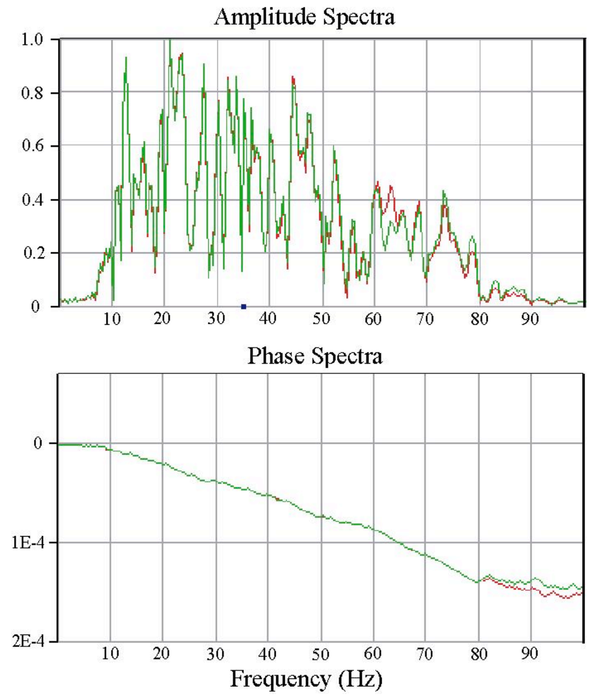

Figure 8: The amplitude and phase spectra of the zero offset trace after migration from the baseline (red) and monitor survey (green) from Line 2. A matching filter has not been applied to either dataset. The spectra are nearly identical below 80 Hz.

The time-lapse results from Line 1 and 3 are less conclusive. The differences between the baseline and monitor survey on Line 3 appear to be related to differences in the frequency content and phase of the wavelet rather than increases in amplitude on the Cardium event. On Line 1, differences related to amplitude changes on the Cardium event begin to appear at a distance of 35 m north of the monitor well. Crosscorrelations between the surveys from Line 1 also show a 0.2 ms time shift.

Conclusions

Both the P-wave and Sv-wave VSP images show excellent ties with the P-wave surface seismic data and have increased frequency bandwidth and resolution. The migrations image a 200 m area of the reservoir around the monitor well.

Crosscorrelations of the baseline and monitor surveys from Lines 1 and 2 show time shifts of 0.2 ms in a small window around the reservoir. This time shift is in the range of the shift predicted by the Gassmann equation modeling. The baseline and monitor surveys also have nearly identical amplitude and phase spectra up to 80 Hz. Results from the time-lapse analysis show an increase in the reflectivity of the reservoir of about 50% on Line 2 in the eight months between the surveys. The north end of Line 1 displays a similar increase in amplitudes at the reservoir. This indicates that the CO_2 flood is progressing southwest of the injector along the dominant fracture trend in the area. However, the main CO_2 front has not reached the monitor well or the nearby production well at this time.

The second monitor survey is due to be acquired in December 2006. As the CO_2 front progresses, it is expected that the reservoir reflectivity on Lines 1 and 2 will continue to increase and that the CO_2 will begin to affect the reflectivity on Line 3 as well. The time shifts seen in the crosscorrelations should increase as the CO_2 displaces more of the oil.

References

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