9C, 4D Seismic Processing for the Weyburn CO$_2$ Flood, Saskatchewan, Canada

Robert R. Kendall[*]
Veritas DGC Inc., Calgary, Alberta, Canada
Robert_Kendall@veritasdgc.com

Robert Winarsky
Veritas DGC Inc., Calgary, Alberta, Canada

Thomas L. Davis
Colorado School of Mines, Golden, CO, USA

and

Robert D. Benson
Colorado School of Mines, Golden, CO, USA

ABSTRACT

We present a summary of the 9C, 4D processing used for the seismic monitoring of a CO$_2$ flood in the Weyburn Field, Saskatchewan, Canada. The resultant time-lapse anomalies for both the P- and S-wave volumes are coincident with the locations of the CO$_2$ injection patterns. Furthermore, the anomalies that we observe are extremely robust and are typically observed far before the final processed sections were produced. That is, they are evident on the differenced brute stacks. We believe this is largely due to the similarity of source and receiver locations during the monitor survey as compared to the baseline survey. The primary prestack processing steps include appropriate shot and receiver edits, source-related phase corrections, independent refraction statics, common velocity models (between baseline and monitor), independent residual statics, and a common pilot for trim statics. A post-migration cross-equalization algorithm is used prior to analysis of the differenced volumes.

Geological Setting

The Weyburn Field is located on the northeast flank of the Williston Basin in southeast Saskatchewan, Canada. Approximately 1000 wells, including 137 horizontal wells with 284 lateral legs, have been used to recover 24% of the 1.4 billion barrels of oil originally in place. Pan Canadian, the operator, converted 19 patterns of horizontal wells to CO$_2$ injection. Injection of 3 to 7 mmcf/day/well has occurred since early October 2000. The goal of the CO$_2$ flooding is to increase production by an estimated 15% incremental oil.

The most porous unit is the Marly, averaging 26% porosity. Permeability of this zone is low, averaging 10 md. Horizontal wells drilled since 1991 in Weyburn Field have targeted the Marly as a zone of bypassed pay. These wells have substantiated the belief that the Marly unit was not as effectively swept as its underlying counterpart, the Vuggy. The Vuggy averages 11% porosity and 15 md permeability. The flow capacity of the formation is the

product of permeability and net thickness. The Marly has a low flow capacity relative to the Vuggy and correspondingly low sweep efficiency. The potential for bypassed oil in the Marly is greater with CO_2 flooding than it is with water flooding because of the comparatively high mobility of CO_2.

9C Acquisition Design For Seismic Monitoring

The 4-D, 9-C seismic survey at Weyburn was designed to provide high resolution over four CO_2 injection patterns. During the acquisition of the monitor survey, all efforts were made to occupy the same source and receiver locations. The data were acquired in the fall of 2000, 2001 and 2002 respectively.

Because the reservoir is thin relative to the seismic wavelength it is necessary to use seismic amplitudes and not time delays in order to monitor changes in the reservoir. Therefore, the survey was designed for high spatial sampling, density and fold. Useable pure-mode fold is approximately 400 in the middle of the survey. The survey was designed to give as uniform an azimuth and offset distribution as possible.

The data were acquired using triaxial vibroseis sources that allow for expeditious 9C acquisition. The source-line interval was 80m, with a source interval of 80m at the edges of the survey and 40m near the center. In the vertical mode, three sweeps of 8-180 Hz over 10 seconds with a 4 second listen time were used (14 second record length). In the horizontal mode, four sweeps of 6-80 Hz over 10 seconds with a 6 second listen time were used (16 second record length). There were 28 source lines with 33 or 66 sources per line. Bunched 3C (3X3C) geophones were used with a receiver-line interval of 140m and a group interval of 40m. There were 20 receiver lines with 60 groups per line.

9C 4D Processing

The excellent data quality, high spatial sampling and high fold helped facilitate the use of surface consistent linear processes. These processes are designed so that true-amplitude analysis can be done. Rock physics and seismic modeling suggested that velocity changes due to CO_2 replacing brine and oil in the matrix could cause a 3 percent decrease in p-wave velocity and a 4 percent increase in shear-wave velocity. The high interparticle or pinpoint porosity in the Marly suggest that the p-waves should be more sensitive to changes in that unit. Whereas the fractures and channel porosity fabric in the Vuggy may be more detectable on the shear-wave data. In light of these predicted small changes in velocity and because the reservoir is thin relative to the seismic wavelength, it was presumed that seismic amplitudes were to be used for the detection of changes in the reservoir due to CO2 injection. Therefore, the primary processing objective was to preserve relative amplitudes between the baseline and monitor surveys.

After common geometries were written, shot and receiver editing was done to remove locations that were either not occupied for both surveys or, in the rare

case, where the locations were deemed too far apart. The final edits resulted in approximately 7% editing of sources and less than 1% for the receivers. The primary reason for not being able to occupy the same location was due to the wet ground conditions during the baseline survey in 2000. For the monitor surveys in 2001 and 2002, the ground conditions were exceptionally dry. Therefore, it was necessary to calculate refraction statics independently for the two surveys. The three vintages of data are reasonably similar with respect to data quality, yet the 2002 vintage has the best signal to noise characteristics. Independent velocities were picked for the three surveys and they were nearly identical. This fact and the superior data quality on the baseline allowed the use of the velocities and mute from the 2000 survey. Residual statics were calculated independently.

Phase analysis of the shot stacks revealed a difference at the edge of the survey (4 source lines). It is not exactly clear what caused these differences. However, the difference (approximately 85 degrees) was accounted for and velocities and residual statics were rerun. The final prestack process was a trim static that is calculated using a common pilot that was derived from the 2000 vintage data. The volumes were then stacked and migrated. The final step, before analysis of the differenced volumes is a cross-equalization process that accounts for phase, static and amplitude differences on a trace to trace basis.

The P-wave and S-wave processing flows are nearly identical. However, the S-wave data is comprised of four volumes after Alford rotation (S11, S12, S21 and S22). The S11 and S22 or principal components are processed independently with different velocities and statics. The S12 and S21 or off-diagonal components are processed using an average of the velocities and statics from the main diagonals. Residual rotation analysis can be done at this point. Due to the reduced signal to noise ratio on the S-wave data, a prestack noise attenuation process (Radon-based) was applied in the shot domain. This step was not necessary for the P-wave processing.

Preliminary Data Analysis

While a full discussion of these results will be presented in another paper (Davis et al, 2002), we do include selected time slices of the final volumes. A more accurate representation of the anomalies is possible using horizon-based amplitude extraction of the final differenced volumes. Figure 1 is the amplitude extraction at the reservoir level, oriented to north and showing the horizontal injector and producer locations. Figure 2 is a time slice of the P-wave volume near the reservoir level showing two trends of anomalous amplitudes. Figures 3 and 4 show a time slice of the final differenced S1 and S2 volumes respectively. While the P-wave and S1 volumes exhibit similar trends, the S2 additionally shows the subtle development of a perpendicular trend, perhaps suggesting a sensitivity to the presence of fractures.

Conclusions

We have presented a summary of the 9C, 4D processing flow used for the analysis of a CO_2 flood in the Weyburn Field. The robustness of the time-lapse analysis was largely assisted by the acquisition design and the similarity of the source and receiver locations for the two surveys. The true amplitude processing approach has allowed for the detection of subtle amplitude anomalies that are in very good agreement with the reservoir production model and production/breakthrough data.

References

Davis, T.L., Terrell, M.J., Benson, R.D., and Kendall. R.R., 2002, Seismic monitoring of the CO_2 flood at Weyburn Field, Saskatchewan, Canada, Extended Abstracts, SEG Annual Convention, Utah.
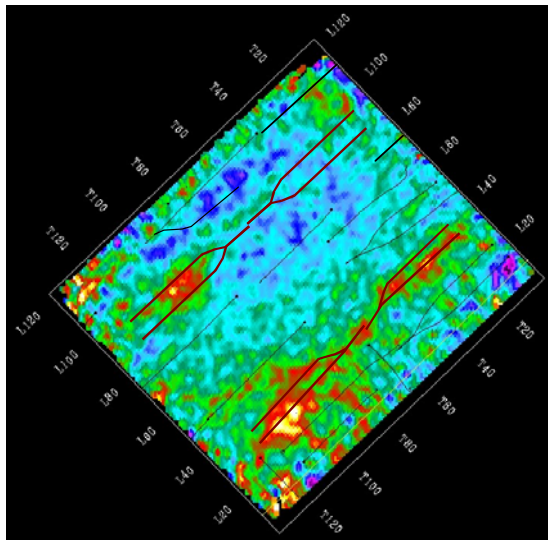
Figure 1: Horizon based extraction of 4D volume (2000-2001) showing injector and producer locations. The injector locations are shown in dark black and coincide with the P-wave 4D time-lapse anomalies.
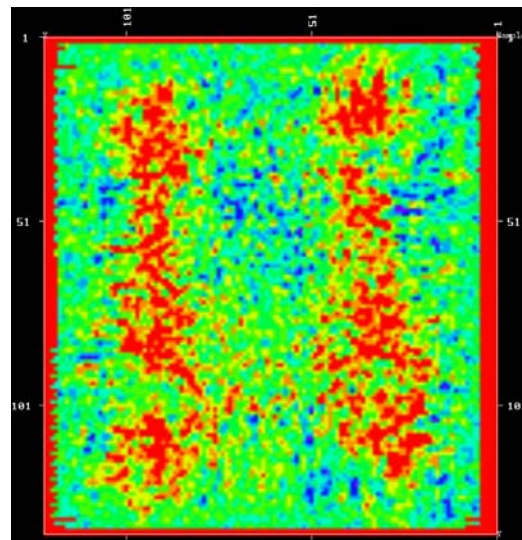

Figure 2: The time slice through the cross-equalized P-wave volume for 2000-2002. Note the enhanced response to CO2 in the upper left pattern. This pattern started injection after the 2001 survey.
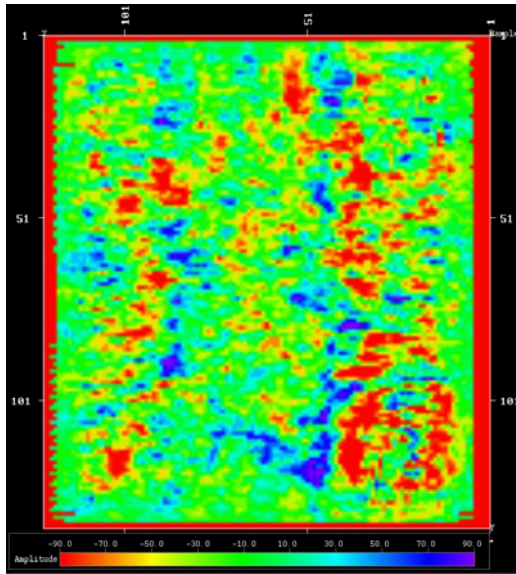
Figure 3: The time slice of the cross-equalized S1 volume approximately at the zone of interest. Note the similarity to the P-wave time-lapse volume.
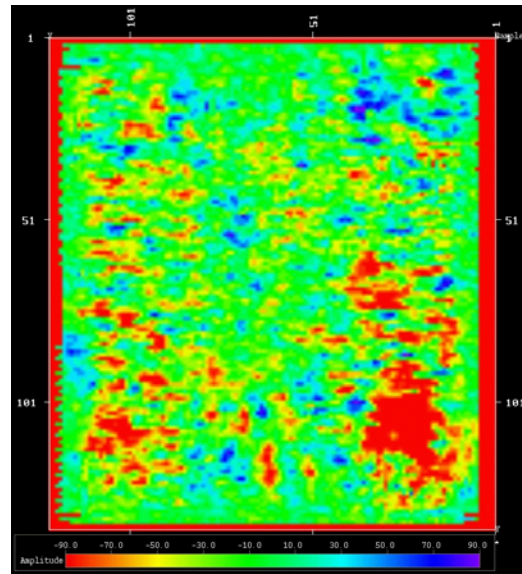

Figure 4: The time slice of the cross-equalized S2 volume approximately at the zone of interest. Note the additional anomalous zone at the bottom of the display, perpendicular to the anomalous zones observed on the P-wave and S1 time slices. This additional anomaly is coincident with a zone of early breakthrough of CO_2 in the producing wells. Also note the delay of the S2 (3132ms) as compared to the S1 (3108ms) suggesting 24ms of shear-wave splitting.