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An Early Look at a Time-Lapse 3D VSP

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SUMMARY

In 2007 Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) started a project to evaluate the available technology for monitoring the movement of CO2 in an underground reservoir. In stage one of this project CO2 and methane are being produced in a nearby well, then the CO2/CH4 is being injected back down a second well into a depleted gas sand. The movement of the CO2 up-dip needs to be remotely monitored. One of the technologies being evaluated to monitor the movement of the CO2 is 3D VSP.

The CRC-1 injector well is instrumented with 10 3C downhole accelerometers. A baseline 3D VSP survey was shot around this well in late 2007 and was followed by a repeat survey in 2010. We hope to monitor the movement of CO2 around the CRC-1 well by observing changes in the time-lapse signature.

Introduction

Since 2007 the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) has been managing a CO_2 injection demonstration project (The Otway Project). One goal of this project is to evaluate the available technology for monitoring the movement of CO_2 in an underground reservoir. The injection stream consisting of 80% CO_2 with the remainder being CH_4 is being produced from a nearby field, and piped to an injector well (CRC-1) into a depleted gas sand (Waarre-C). The movement of the CO_2 up-dip was planned to be monitored using repeated 3DVSPs from the injector well, prior to injection. Additionally two surface seismic 3D's were acquired and processed for a 4D signal (Dodds et al 2009).

The CRC-1 injector well is instrumented with 10 3C downhole accelerometers. A baseline 3D VSP survey was shot around this well in late 2007 and was followed by a repeat survey in 2010. The two surveys were acquired with different sources; weight drop in 2007 and mini-vibrator in 2010. The expected 4D response from modeled change in impedance (3-6%) was expected to be at the limit of detection. This was primarily due to presence of depleted methane in the target reservoir, with a small contrast with the injected CO_2 (Li et al, 2006). There were also environmental challenges to source repeatability from seasonal fluctuations in water table depth (Dodds et al 2009). The primary value of the survey was for detection of any changes that may occur if the CO_2 was to penetrate the seal into the overlying saline reservoir.

In this project two different sources were used in the 2 surveys. We compensate with several innovations in the processing including a model based residual static technique. We have used time-lapse metrics designed for surface seismic to measure the success of the processing. We have achieved reasonably good results at this stage in the processing. A time-lapse event is evident near the depleted gas sand level.

Data Acquisition

On December 2007 the first 3DVSP data set was acquired simultaneously with 3D surface seismic operations. Well access restrictions limited the number of days available for borehole seismic acquisition, resulting in a reduction in source positions for the 3DVSP data set. We used a weight drop source for this baseline survey. Between the two surveys 65kT of CO_2/CH_4 was injected at the CRC-1 well.

In January 2010 the first repeat 3D VSP survey was acquired. The repeat survey was shot using mini-vibrators as the source. Previous work had shown that the weight-drop and mini-vibrator produced similar frequency responses and energy (Urosevic et al, 2008). Seasonal variations in water table at the time of acquisition were determined to have a bigger effect on source signature than the actual sources used.

The differences in source types and number of sources directly influenced the processing necessary to uncover any differences in the images generated by the CO_2 injection.

Time-Lapse Processing

In the figure below we show the unprocessed Z axis data from one receiver and all shots from a north-south source line near the wellhead. It is immediately evident that there is a large difference in the data quality. The repeat survey, shot with mini-vibrators, is much wider bandwidth. There is also a timing difference of about 14ms at repeated shot locations which is mainly due to different instrument delays in the 2 recording systems. Time picking is complicated by the different wavelets involved in the two surveys.

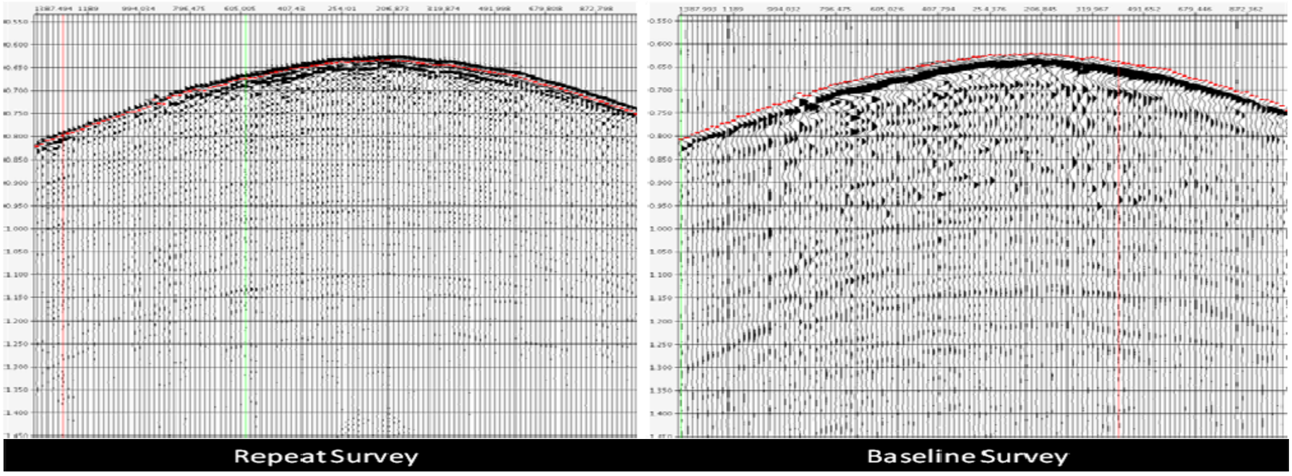


Figure 1 *Raw vertical channel, one receiver, all shots from an extracted north-south source line. Repeat on left, baseline on right.*

The baseline survey was processed in 2008 with traditional VSP processing practices. We used median filters to separate the upgoing and downgoing waves on the vertical channel. We used traditional VSP waveshaping deconvolution to zero-phase the data and suppress reverberations in the wave-train. The VSP decon successfully removed the signature differences between the weight drop source and the mini-vibrator source.

For the time-lapse processing we located the coincident sources for each survey before processing, using a small tolerance in x and y coordinates. The same traditional processing flow as used in the baseline survey was used in the repeat survey. Despite using the same median filters and deconvolution parameters we still had different frequency spectra after decon. This is particularly evident at the high end of the spectra. We decided to use a sharp high-cut filter to force the data to have similar spectral content before migration. After this final processing step we have very similar spectra for the deconvolved upgoing waves. We also have excellent agreement between the deconvolved traces of the baseline and repeat surveys.

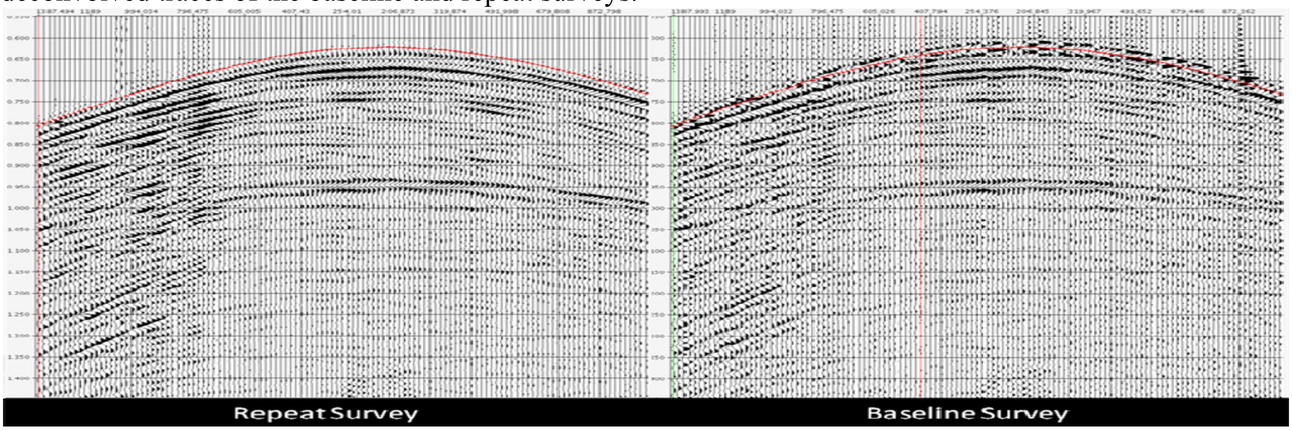


Figure 2 *Deconvolved upgoings after final high-cut filter, one receiver all shots from an extracted north-south source line.*

3D VSP Statics

Before migrating this data, we had to compensate for the statics evident in the data. We have developed a model based technique which removes trace to trace shifts due to source elevation changes, changes in ground conditions, model inaccuracies etc. and shifts the data to a common datum. To apply our "VSP residual statics" we need a borehole calibrated velocity model.

We created a flat background velocity model by first blocking the sonic log data to get interface locations and then updating Vp, ellipticity and anellipticity using the 3D VSP travel times from the baseline survey. We estimate the travel time residuals by ray-tracing through the velocity model using the survey geometry. The residual time is the difference between the actual field measured times and the ray trace times.

The downhole traces are static shifted by the residual times before migration. There is also a bulk shift of about 14ms in the residuals for the repeat survey which is due to the different sources used. This approach to residual statics also automatically corrects for the timing difference due to the different sources. Before migration we dropped deconvolved traces which have anomalously high RMS amplitudes. We also dropped traces which have unexplainable transit time differences between the baseline and repeat surveys.

Time-Lapse Metrics

We have used the standard surface seismic time-lapse metrics of NRMS and predictability (Kragh and Christie, 2001) to validate the processing flows used here and as a tool in improving the final time-lapse product. NRMS should be 0 for perfectly matched data, up to 200 for data for unmatched data. Predictability should be 100 for perfectly matched traces, 0 for traces with no match.

In the figure below we have estimated the time lapse metrics on the raw data from the vertical channel. Due to the different sources used, different bandwidths recorded, and different instrument delays we expect the NRMS of the differences to be large, and the predictability to be relatively small. The predictability has a mean value of 66 and NRMS is over 200. The raw data do not correlate well and have large RMS differences. After deconvolution, final filtering, and VSP residual statics we see a large improvement in the NRMS metric. There is an upwards trend in the predictability measurement as well, the black line is a predictability of 80.

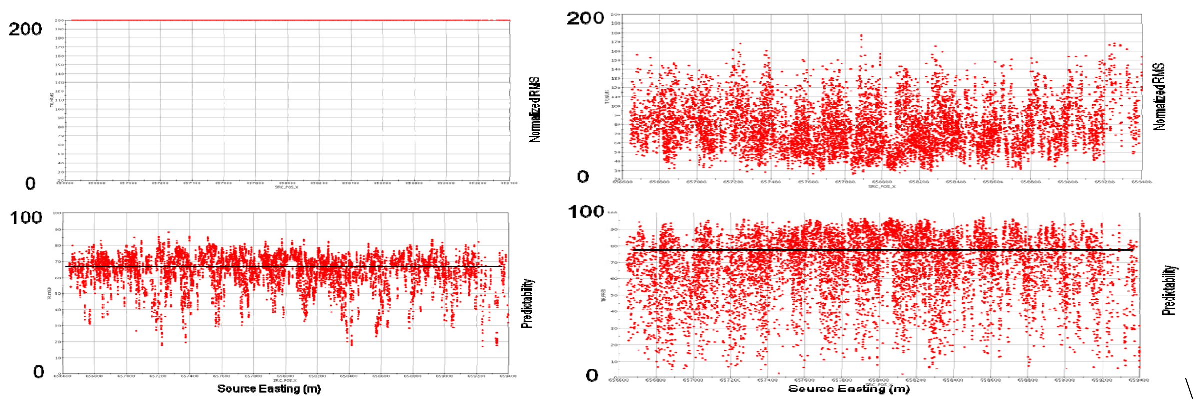
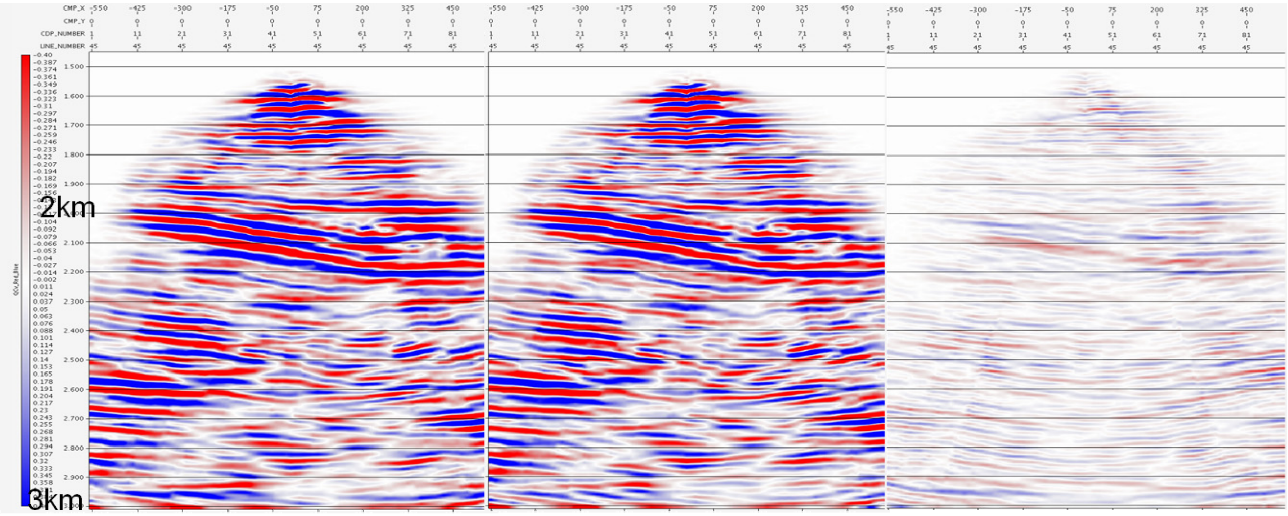


Figure 3 *Predictability (bottom) and NRMS (top) for raw Z data on left and deconvolved data on right.*

Imaging

The final steps in the time-lapse processing are imaging and differencing. We used ray-based GRT migration with a small aperture for imaging. The small aperture focuses the imaging around a known dip value. For the following examples a dip of 0 degrees and aperture of 7 degrees is used.

A novel technique to improve the time-lapse signature uses migration input data selection by predictability threshold. In the test shown below we have removed all traces prior to migration which have a predictability of less than 75%. Testing is not complete on the ideal threshold value. The two surveys show remarkable similarity after migration. We see the differences are generally small but the red area below 2.1km is prominent. We do not attempt to interpret the time-lapse signature in this paper, but the red area in the differences at around 2.1km is approximately the zone of CO_2 injection.



baseline repeat difference

Figure 4 *A slice through the migrated volumes after data selection using predictability.*

Conclusions

A combination of standard VSP techniques and several innovations in the processing of baseline and repeat survey produced a good set of final images with reasonable associated differences.

Standard VSP waveshaping deconvolution successfully shaped the weight drop source and the mini-vibrator source data to a common wavelet. The VSP residual static technique successfully removed the statics due to environmental changes. The technique also corrected for differing instrument delays for the two different sources.

The time-lapse metrics NRMS and predictability can be used to quantify the effectiveness of processing flows. The metrics can also be used to apply thresholds for selecting traces to be passed into migration. The resulting time lapse differences consistently show a significant difference at around 2.1km depth.

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