Onshore Time-Lapse Borehole Seismic Project for CO2 Injection Monitoring

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SUMMARY

An innovative time-lapse borehole seismic project for onshore CO2 injection monitoring was conducted in 2010 for ZeroGen in Australia. The goal of the seismic project was to investigate borehole seismic methods to monitor the effects of supercritical CO2 injection in tight, saline reservoir rocks. Results from processing data acquired before and after injection show that a time-lapse, pseudo-4D VSP approach detected likely changes in subsurface acoustic behaviour. A comprehensive borehole seismic program, consisting of two rig source VSPs, an offset VSP, and four Walkaway VSP surveys, was acquired pre-CO2 Injection in the vertical well and then repeated post-injection. Data were acquired using an eight-shuttle VSI seismic tool down-hole and a vibroseis mini-buggy as source. Data processing focused on achieving a repeatable workflow to ensure that time-lapse effects can be effectively analysed. A near surface basalt layer significantly affected both measured time and recorded signatures. This required special handling of surface statics and of source signature variations. The pre- and post injection survey results were analysed for acoustic changes related to the injection program. A time-lapse change in acoustic response in the injection interval was observed on all available borehole seismic datasets. The processed offset and Walkaway VSP images also provided estimates of lateral extent and orientation of these anomalies. Detection of time lapse changes in such a small injection test requires an investigation into the underlying causes such as fluid and pressure effects and the possibility that such techniques might be used to monitor pressure evolution in similar injection sites.

Key words: Borehole Seismic, CO2 Injection Monitoring, Time-lapse, Onshore, VSP

INTRODUCTION

ZeroGen Pty Ltd undertook a major prefeasibility study for a clean coal power project in onshore Queensland, Australia which included integrating coal gasification with carbon dioxide capture and storage to produce low emission power. The CO2 storage reservoir studied was in the nearby Northern Denison Trough, near Springsure see Figure 1. It comprised a competent regional shale seal and possible reservoir units between 800m and 1200m below the surface. Several delineation and evaluation wells were drilled including a dedicated injection well (ZG-11). AGR managed the exploration drilling and testing operations to define the properties of reservoir units within a possible CO2 storage acreage. One of the goals of this project was to test the suitability of time-lapse borehole seismic methods to monitor subsurface changes due to CO2 sequestration. To this end a comprehensive borehole seismic program was acquired pre-CO2 Injection in the ZG-11 well and then repeated post-injection. Data were acquired using an eight-shuttle VSI seismic tool down-hole and a vibroseis mini-buggy as source.

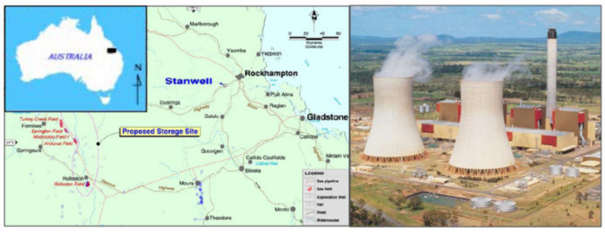


Figure 1. Queensland Onshore CO2 Injection Location

Onshore borehole seismic surveys have been used before in CO2 sequestration related projects (Urosevic et al., 2009). Several papers report on the specific challenges related to onshore seismic operations (Pevzner et al., 2010), in particular source repeatability for time-lapse measurements. Processing of such datasets has been reported with mixed results and to date there remains some uncertainty regarding the applicability of these methods for onshore CO2 injection monitoring.

This paper describes the acquisition and processing methods chosen for this project specifically designed to overcome commonly encountered problems related to onshore time-lapse experiments. We show that significant time-lapse changes in acoustic response in the injection interval can be observed on all available borehole seismic datasets.

METHOD AND RESULTS

In the following sections several key steps for obtaining a suitable dataset for time-lapse analysis will be presented.

Acquisition Program

A repeat borehole seismic survey plan consisting of two rig source VSPs, an offset VSP (OVSP), and four Walkaway VSP surveys was designed for monitoring acoustic changes due to CO2 injection in the vertical ZG-11 well. By using Walkaway VSP lines with several different azimuths a minimal acquisition footprint was achieved (compared to a 3DVSP scenario) while still obtaining spatially orientated information. Figure 2 shows the layout and extent of the surveys.

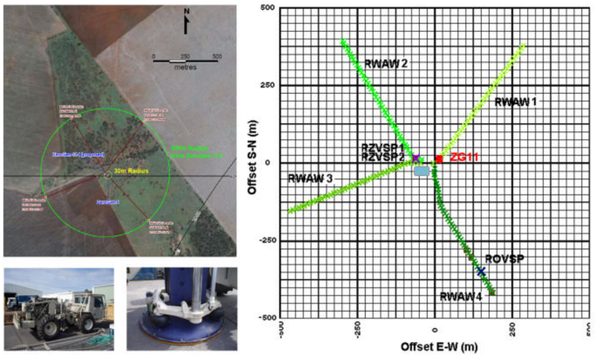


Figure 2. Borehole Seismic Surveys – Source Map

A fixed offset VSP was also acquired to provide a secondary dataset for anisotropy calibration of the velocity model that is unaffected by the onshore near surface static variations.

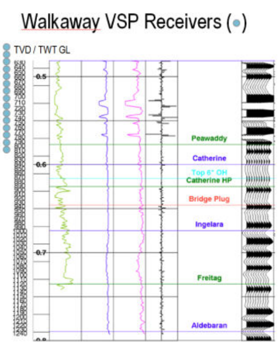
Furthermore the rig source VSP survey was repeated twice after injection. We will show that this is instrumental in confirming where valid time-lapse interpretation is possible.

Due to the long interval between Pre- and Post-Injection surveys (September vs. December) significant vibroseis signature changes were expected due to near-surface ground condition and water table fluctuations. This could not be prevented. Instead every effort was made to provide accurately repeated source positions by careful pegging of the VP locations.

The data were acquired using an eight shuttle Versatile Seismic Imager (VSI) tool with receivers every 15 m down-hole and an IVI vibroseis mini-buggy with a 16500 lbs hold-down weight as source.

CO2 was injected in various intervals and stages between the Pre- and Post Injection surveys. Figure 3 presents time-depth information of key formations as well as Walkaway VSP receiver locations.

Another change to the program to optimise it for time-lapse evaluation was the addition of an overlapping level between the two 8 shuttle VSI tool settings in the Walkway VSP surveys. This allowed repeatability to be determined more accurately.



Injection Intervals

Formation Top	MD RT (m)	TVD GL (m)	TWT (ms)	Seismic Pick
Catherine	845.5	840.6	600	ZC < Trough
6" OH	878.8	873.9	616	-
Catherine HP	896.0	891.2	625	ZC < Peak
Bridge Plug	941.0	936.1	646	-
Ingelara	1004.0	999.1	675	ZC < Trough
Freitag	1125.3	1120.4	736	Trough
Aldebaran	1238.9	1234.0	790	Trough

Figure 3. Main Injection intervals and Receiver Depths

Data Processing

Data processing of the acquired borehole seismic surveys focussed on achieving a repeatable workflow to ensure that time-lapse (4D) effects can be effectively analysed. Besides ground condition variations, a near surface variable basalt zone significantly affected both measured time and recorded signatures. This required special handling of both surface statics (using a calibrated 1D anisotropic model) and of source signature variations (processing the data in common shot gather domain). The acquired offset VSP survey was very important for this model calibration.

The most important aspect of borehole seismic processing for time-lapse analysis is to ensure that processing steps and parameters as well as input datasets are identical. Great care was taken to ensure that source and receiver positions could be repeated accurately. After correlation, stacking and header updates the navigation was double checked using reference shot position numbers and initial time picks of the overlapping receiver positions. Figure 4 shows an example of how an incorrect station number showed up as an increased time difference. The final datasets contained exactly the same set of traces pre- as well as post injection.

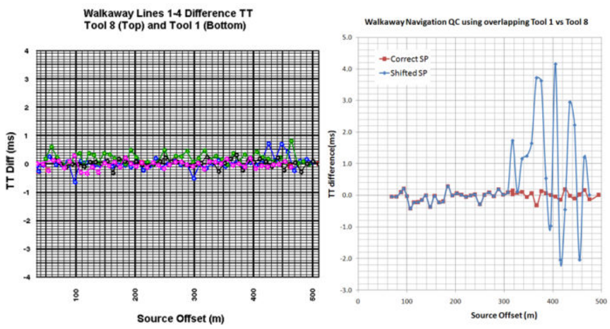


Figure 4. Improved Source Position QC using overlapping levels

Processing steps include standard borehole seismic processing techniques (Pereira and Jones, 2010) including generalised median velocity filtering, parametric wave-field decomposition, wave-shaping deconvolution, geometrical spreading correction and generation of corridor stacks or CDP mapped images. All these steps were done in common source domain to minimize the effects of source signature and timing differences.

It was also necessary to build a model of the subsurface for the several reasons:

- Obtaining a reference model for calculating residual static corrections
- VSP ray tracing modelling to help understand subsurface reflection coverage
- Advanced wave-field separation techniques require a model to guide the algorithms (wave-field separation, amplitude corrections, enhancement, etc)
- The imaging (CDP mapping) process requires a background velocity model
- Use a single model for both pre- and post-injection surveys to ensure maximum repeatability for time-lapse analysis

A 1D anisotropic layered model was build from the pre-injection borehole seismic time-depth information, shot hole surveys and the calibrated sonic compressional and shear slowness and density logs.

The statics issue, which is always a significant problem for onshore seismic surveys, is handled here by using the calibrated model to ray trace theoretical arrival times from source to receiver. The measured times are compared with these calculated times and the residual is filled as a static shift in the headers of the acquired data. To ensure that only a single source static is used for a specific shot location, a weighted median average is taken and applied to the seismic traces. Figure 5 shows an example of a Walkaway line before and after static shifting, demonstrating the greatly improved alignment of acoustic events.

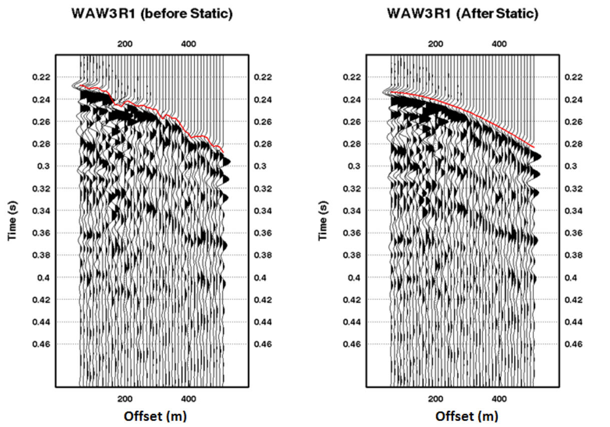


Figure 5. Model based static corrections

Processing results were also affected by tube wave energy and reduced coupling in the shallow part of the cased hole as well as by strong signal attenuation and complex multiples generation in the zone above the injection interval. The Walkaway VSP receivers below these formations show better results, albeit with smaller lateral coverage. Imaging results are not free from these multiples, but we found that these effects are generally repeatable and therefore still enabling 4D analysis.

An important data processing aspect to improve time-lapse analysis is that no trace-mixing enhancement was used for the Offset VSP and Walkway VSP data here in order to avoid smearing of small time-lapse effects. Similarly final time (TWT) images were produced using the VSP Common Depth Point (CDP) mapping technique.

This method is in practice similar to a Kirchhoff migration using a very small aperture. It was chosen for this project for the following reasons:

- No smearing of small time-lapse effects
- Model driven (Repeatability)
- Clear analysis of Reflector Origins

In CDP Mapping the data is not migrated, but transformed from borehole seismic data into CDP image domain by stacking inside a sliding window along equi-offset lines determined by ray tracing through the model.

Time-lapse Analysis

The Pre- and Post CO2 Injection borehole seismic survey results were analysed for acoustic 4D changes related to the CO2 Injection program. The rig source VSP was repeated twice in the Post Injection program. This allowed a better comparison, showing a significant time-lapse change in acoustic response in the main injection interval as shown by the VSP up going difference wave-fields in Figure 6. Time Lapse difference effects in this interval are also confirmed by analysis of the rig source VSP transit time and interval velocity measurements.

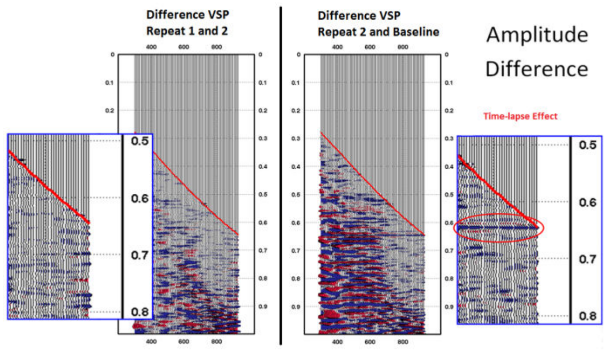


Figure 6. Rig VSP shows time-lapse amplitude effect

The processed offset and Walkaway VSP borehole seismic images show similar results (Figure 7) and also provide estimates of lateral coverage. The lateral extent of the observed 4D effects varies with line orientation from 50m to 100m from the down-hole well location and appears largest in easterly direction.

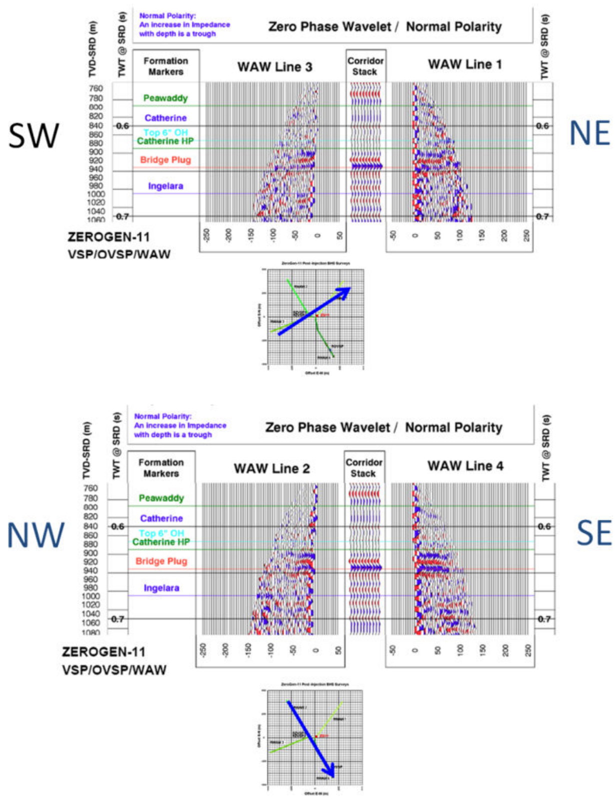


Figure 7. Walkaway VSP Time-lapse difference Images

Further study is required to understand these observed time-lapse effects. Recommended work includes fluid substitution modelling and synthetic seismic generation to investigate in detail the zone(s) affected by CO_2 injection. Also the effects of pressure variations and of different lateral depth of investigation of the various seismic and sonic measurements need to be studied. Integration with other borehole or surface measurements may further confirm the mechanisms behind the interpreted acoustic pseudo-4D effect shown in Figure 8.

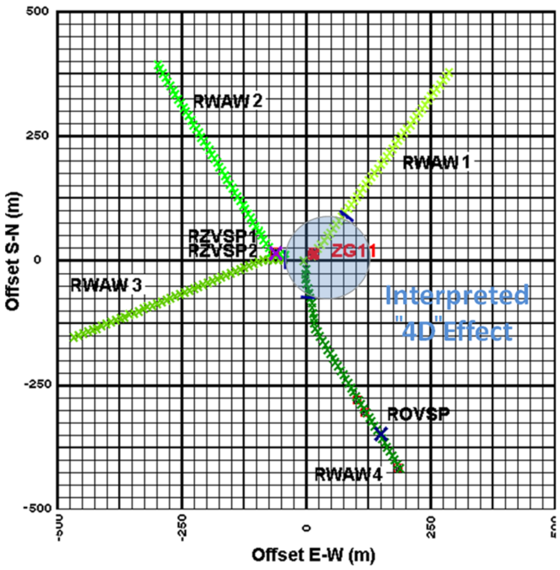


Figure 8. Interpreted lateral extent of time-lapse effects

Other areas of improvement can come from development of better onshore statics and de-multiple techniques in processing. CO_2 injection programs with multiple injection intervals require careful design of a bottom upwards approach to ensure repeat borehole seismic surveys can be interpreted effectively. Lumley (2010) shows that imperfections in processing due to multiple wave-scattering and mode-conversion can cause similar problems when interpreting time-lapse effects.

CONCLUSIONS

This study shows that onshore borehole seismic surveys might be used effectively to demonstrate acoustic changes in the subsurface related to a CO_2 injection program.

Both acquisition plans and processing strategies need to be thoroughly reviewed to optimise their applicability for subsequent time-lapse analysis. Examples are given of specific methods that allowed us to work with the main onshore issues of source signature variations and variable static corrections as well as the use of a common model for pre and post injection processing.

Significant time-lapse changes in acoustic response in the injection interval were observed on all available borehole seismic datasets. The processed offset VSP and Walkaway VSP images also provided estimates of lateral extent and orientation of these anomalies. This indicates that a monitoring program may be done with a few well chosen survey orientations.

Detection of time lapse changes in such a small injection test requires an investigation into the underlying causes such as fluid and pressure effects and the possibility that such techniques might be used to monitor pressure evolution in similar injection sites.

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