Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 00 (2008) 000–000
Energy Procedia
www.elsevier.com/locate/XXX

GHGT-9

Seismic Monitoring and Verification for the CO2CRC Otway Basin Project, Part 2: acquisition and analysis of borehole seismic data

M. Urosevic*, A. J. Campbell#, L. Dahlhaus#, A. Gendrin#, W. S. Leaney#, S. Tcherkashnev#, M. Verliac#

*

**Curtin University, Perth, GPO BOX U1987, WA 6845*
#Schlumberger Oilfield Australia Pty Ltd,
The Capital Center, 256 St George's Terrace,WA

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

The Otway Project conducted under the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) is the first of its kind, where CO2 is injected into a depleted gas reservoir. The use of depleted fields for CO2 storage is likely to become widely adopted globally and, therefore, the project will provide important experience for monitoring under these conditions. However, such scenario is not favorable for the application of geophysical techniques for the purpose of CO2 monitoring and verification (M&V) because the injection of CO2 into a CH4 depleted reservoir is modeled to produce very subtle changes in elastic properties of the reservoir rock which may be very difficult to measure. Consequently geophysical program for the Otway site was design according to the expected time-lapse effects. It combines both surface and borehole seismic methods. Surface seismic should provide a global vision of the underground and an indirect confirmation of the CO2 containment by recording no differences between the successive time-lapse experiments. Vertical Seismic Profile (VSP) surveys are expected to provide an improved characterization of the reservoir and hopefully a direct indication of the fluid distribution and/or its potential upward migration along the reservoir bounding fault pattern. Indeed the results of the current analysis of both pre-base line (test) and base-line 2D and 3D VSP data are encouraging. The availability of vector wave field (three-component) data recorded in VSP surveys should significantly improve the outcomes of M&V program at Naylor site.

Keywords: Storage; CO2; VSP; 3C; imaging

1. Introduction

Within the CO2CRC project around 100,000 tons of CO2 will be injected into Waarre C Formation over two years. The CO2 is extracted and safely transported from a nearby natural accumulation, via pipeline and injected

* Corresponding author. M. Urosevic, Tel.: +61-8-9266-2296; fax: +6189266-3407.
E-mail address: M.Urosevic@curtin.edu.au.

into sandstone reservoir (Figure 1). The advantage of injecting CO2 into a depleted gas field is having access to well-established infrastructure, pre-existing geophysical exploration information, production history and well data. On the downside, the geological complexity of the Naylor gas field and its small extent (0.5km^2) presents challenge for detailed reservoir characterization and certainly for the design of a geophysical monitoring program at this site.

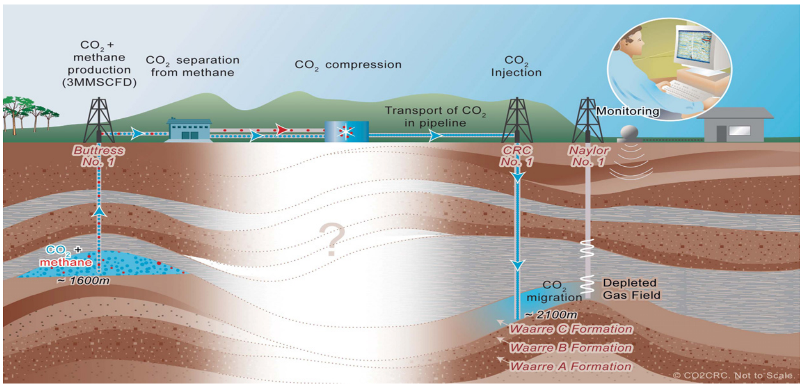


Figure 1. Schematic diagram of CO2 production, transportation, injection and monitoring at Otway site.

CO2 injection takes place in CRC-1 well, 300m away from the monitoring Naylor-1 well. CO2 is injected just below a free gas cap, in the reservoir zone with approximately 30% residual gas (CH4) saturation causing CO2 plume to rise through buoyancy into the pore space originally occupied by methane. Reservoir simulation predicts that the supercritical state CO2 will migrate up-dip through the region of residual methane until it reaches the free gas cap that remains at the crest of the reservoir, at which point it will accumulate under the gas cap as a thin layer (Figure 2). During migration the injected CO2 will become enriched with CH4 but remain as a supercritical fluid. The CO2-CH4 exchange in the pore space is of course expected to have little effect on the elastic properties of the reservoir rock. This was confirmed by a series of numerical modeling experiments (Li et al, 2006).

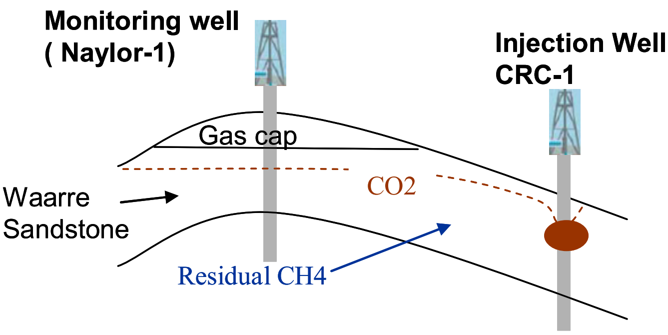


Figure 2. Schematic diagram of injection and fluid distribution in Waarre sandstone.

Overall, around 3% change in density and 1.5-2% change in P-wave velocity were predicted at the monitoring well (Naylor-1) as the result of 100,000 t of CO2 injected into Waarre C from CRC-1 well, within the first 3 years. Moreover these changes will be principally caused by a rise in the reservoir pore pressure (~4 MPa difference) rather than CO2-CH4 displacement/exchange in the pore space. Resulting 4D seismic response in clearly predicted to be very small. Optimistically we can say that the predicted response is on the low side as the real rocks may be heterogeneous and patchy which could amplify predicted time-lapse seismic response changes. However we do not expect significant difference between predicted and measured seismic response changes.

2. Initial investigations at Naylor site

Monitoring of a deep, yet small and complex reservoir, could only be attempted with seismic methods, surface and borehole because of their resolving power. While direct detection of CO2-related effects is not expected, time-lapse seismic monitoring is a crucial component of the project as it is needed to provide assurance that the injected CO2 stream remains confined to the target. Thus, primary role of seismic monitoring can be in this case formulated as being indirect. This is particularly true for surface seismic measurements which are in general less sensitive than borehole measurements.

To investigate the potential of using borehole seismic methods for monitoring at Otway site we conducted several Vertical Seismic Profiling (VSP) tests in Naylor-1 well (Figure 3), which included:

1. Zero-offset VSP or ZVSP
2. Offset VSP or OVSP
3. Walk-away VSP or WVSP

High precision Schlumberger's VSI (VSIT-C) tool (GAC-D, 10 shuttles) and a high frequency mini-vibroseis (6000 lb) energy source were combined for the acquisition. Data quality was very good considering the low-power source and the presence of near surface limestone (karst). ZVSP data exhibit significantly higher resolution than pre-existing (pre-production) 3D surface seismic data. An example is shown in Figure 4. Reflection from the thin intra-reservoir shales can be seen in the corridor VSP stack which is not observable in the surface seismic data. Similarly superior resolution was achieved with OVSP and WVSP images even with minimum data processing efforts.

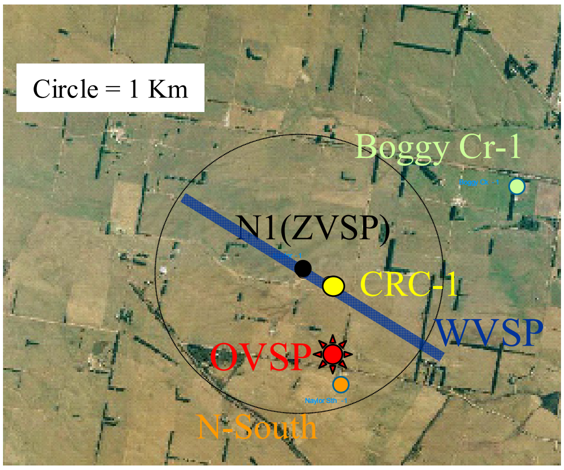


Figure 3. Pre-production VSP surveys.

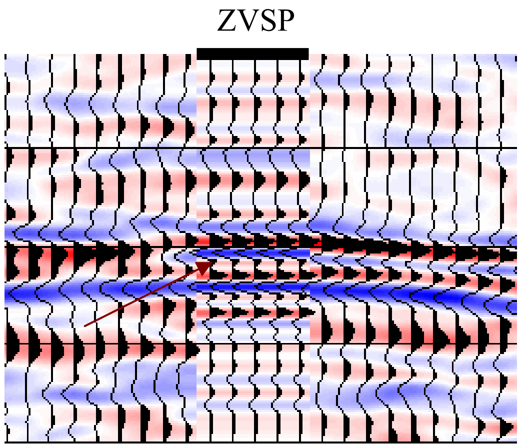


Figure 4. ZVSP inserted into 3D seismic. Intra-shale layer is clearly visible, as marked with arrow.

High data quality was recorded on all three components in VSP surveys. Strong converted shear waves (converted at limestone interface) were detected in all cases. Shear wave splitting was also clearly recorded which enabled us to precisely estimate direction of fast shear (S1) that coincided with known direction of the dominant horizontal stress direction in this area (150^0N). Hence analysis of both fields (P and S-waves) and also shear wave splitting could provide additional information, much needed at this site, for direct analysis and detection of CO2-related seismic response changes.

3. Monitoring program

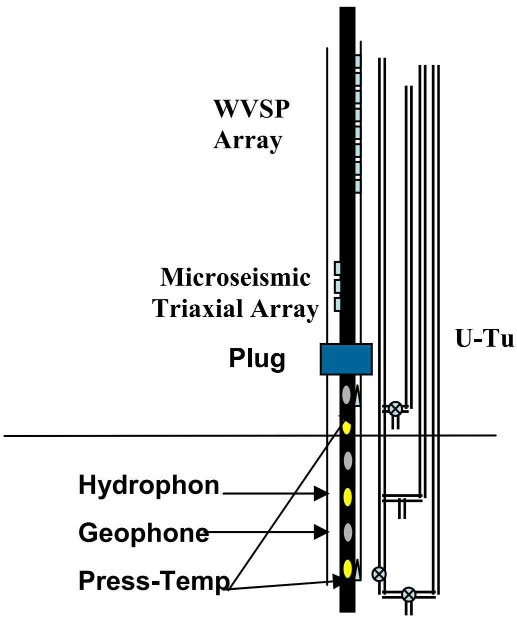
The detection of CO2 migration and its distribution in the reservoir through observation and analysis of 4D seismic effects are particularly challenging in land seismic, due to weather and season induced variation of the near surface layer properties. These changes in the near surface layer may unfortunately produce very strong 4D seismic effects than could entirely overcome those caused by injection of CO2 into the reservoir. While these effects are hard to mitigate it is clear that borehole seismic measurements offer improved repeatability in comparison to surface seismic measurements. From the initial VSP tests it was also clear that VSP surveys offer superior data quality and improved resolution in comparison to surface seismic data. Consequently it was decided that borehole seismic measurements will comprise the principal monitoring methodology at Naylor site. Finally designed CO2 monitoring program at Naylor site consist of the following:

1. Time-lapse ZVSP, OVSP and 3D VSP measurements in CRC-1 (base line + repeat)
2. Instrument Naylor-1 well (mix array consisting of 1C, 3C geophones and hydrophones implemented by Lawrence Berkeley National Laboratory-LBNL) for frequent time-lapse VSP measurements (all types)
3. Time-lapse 3D surface seismic (base line + repeat)

A combination of three sets of measurements was required for several reasons:

a) Permanent installation is difficult to implement and is prone to failure of instruments over time.
b) Comprehensive instrumentation of the permanent receiver array meant that the resultant VSP image (3D) may be patchy due to insufficient receiver array density
c) Monitoring strategy will principally rely on VSP survey in CRC-1 as those are guaranteed to provide the highest quality
d) Surface seismic is needed principally as a support to 3D VSP measurements (source statics, velocity cube and 3D horizons)
e) VSP measurements needed for precise time-to-depth conversion of surface seismic
f) In case CO2 migrates up the fault system into a shallower saline aquifer we expect that the 4D seismic effects will be directly detectable by both surface and borehole measurements
g) Simultaneous acquisition of 3D surface and VSP data make these measurements affordable and effective.

- Naylor-1 borehole was instrumented principally for fluid sampling and P,T measurements (Figure 5). A complex seismic receiver system was subsequently combined with U-tubes to enable both active and passive measurements.



Such permanent receiver installation enables the following:

- Frequent surveys (inexpensive time-lapse surveys)
- High-Resolution Travel Time (HRTT) measurements using variety of seismic sources including continuous sources.
- Analysis of transmitted and reflected P and S wavefields with receiver above, in the reservoir and bellow the reservoir sands.
- Implementation of various VSP survey geometries, in particular multi-azimuth and 3D measurements

Figure 5. A complex array of receivers consisting of 3C geophones, single component geophones and hydrophones was combined with several U-tubes and permanently installed in Naylor-1 well.

4. Base-line measurements and results

In December 2007 we have simultaneously acquired 3D surface and 3D VSP data in CRC-1 well. Due to the specifics of the ground, permission issues and availability of the sources we have eventually implemented our own "CRC weight drop seismic sources" which in fact are free-fall concrete breakers mounted on a tracked Bob Cat or an excavator. Both source sizes provided very good quality (Figure 6) and surprisingly reasonable repeatability (Figure 7)

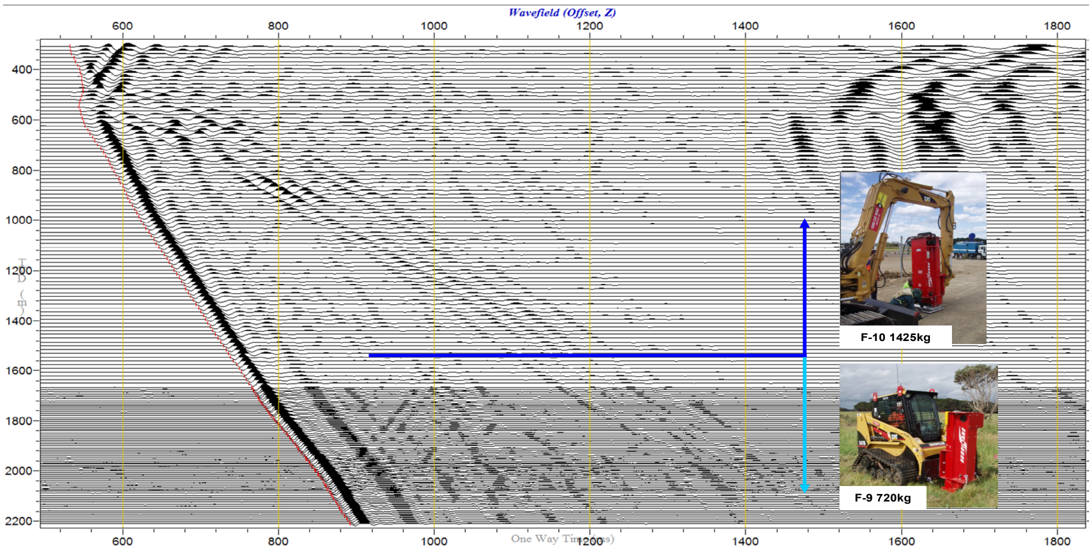


Figure 6. Two sources F9 (720 Kg) and F10 (1400 Kg) used for acquisition of ZVSP and OVSP. High quality was obtained with both sources, F10 having more energy shifted towards low side of the spectrum but significantly stronger output.

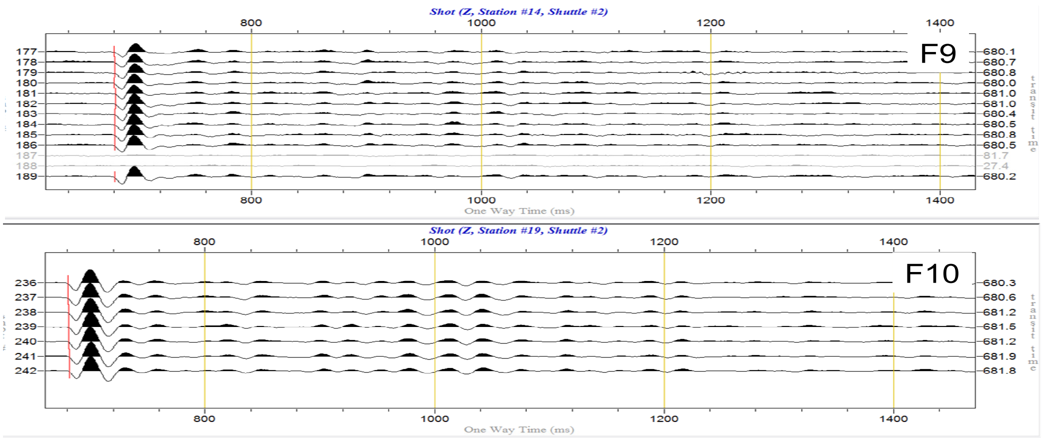


Figure 7. Result of repeatability tests conducted each day at the same station. A number of propriety repeatability tests were conducted by Schlumberger field crew.

F10 source was implemented during simultaneous acquisition of 3D VSP and 3D surface seismic data as more energy was required for surface seismic data in order to record reflections of the target sand. Due to much higher quality of VSP data only every second source line was recorded by the down-hole receiver array (Figure 8). Still very high quality VSP images were obtained. A preliminary 3D migration using a single, ZVSP – derived interval velocity field, any sources lines 200 m apart, produced very good result (Figure 9). Surface seismic data were recorded with 450 channel Seistronix system own by the department of Exploration Geophysics, Curtin University.

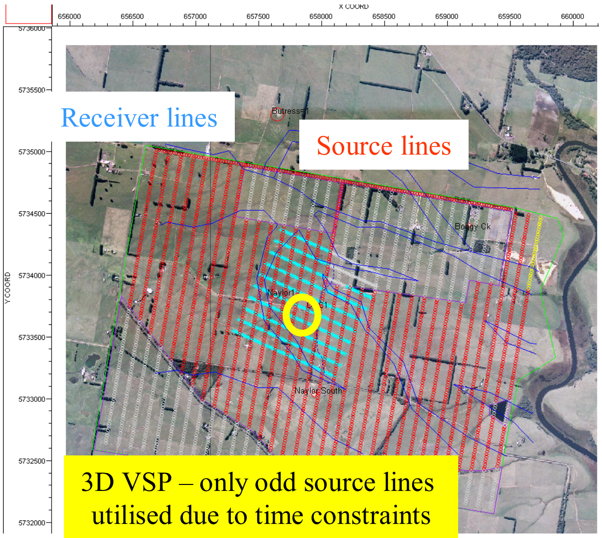


Figure 8. Disposition of receiver (light blue) and source lines (red) used for simultaneous acquisition of VSP and surface seismic data.

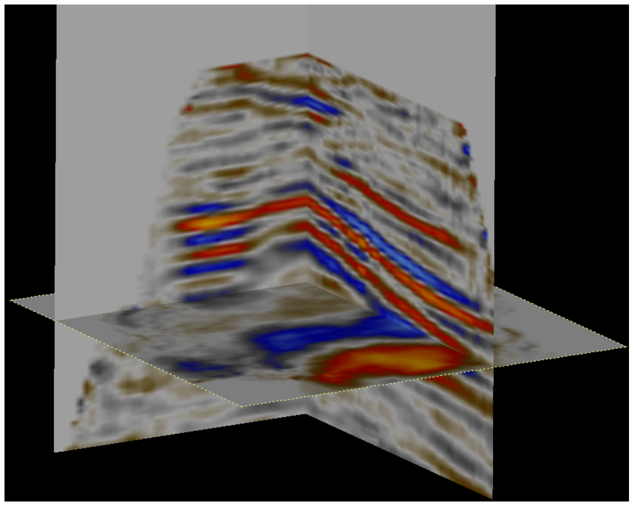


Figure 9. 3D pre-stack depth migration of VSP data acquired in CRC-1 well.

Currently we are analyzing converted wave fields and refining 3D VSP image in preparation for repeated measurements which will be conducted in 2009. Permanent sensor installation is used at this stage for HRTT and repeatability tests with explosive sources and is subject of separate reporting.

5. Conclusions

Exceptionally challenging conditions for monitoring CO2 sequestration process at Naylor site, Otway basin required "new thinking" and implementation of different and comprehensive seismic program. Specifics of the site (permission, accessibility, availability) required engagement of non-conventional sources and recording geometries which also enabled rapid data acquisition.

Very subtle changes of elastic properties of the reservoir rock arising from injection of CO2 we hope to detect directly by a comprehensive set of time-lapse VSP surveys conducted in both wells or indirectly by surface seismic data, meaning that negative 4D effects suggest containment of CO2 in the reservoir. Additional hope for the direct detection of CO2 related changes lie in utilization of vector wavefield and analysis of split shear waves and their polarization direction. We hope that we will soon establish a general approach and methodology for monitoring of CO2 injection into depleted gas fields that may also be relevant for enhanced gas recovery elsewhere.

6. References

Li., R, Urosevic, M., and Dodds, K., Prediction of 4D seismic responses for the Otway Basin CO2 sequestration site, 76th Ann. SEG Conf. (2006) New Orleans, USA, SM 1.4.

7. Acknowledgment

We are grateful to the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) for permission to publish this work. We thank Schlumberger for data acquisition, financial support and the permission to show initial 3D VSP images.