Subsurface characterisation for future CCS applications using uncommon 3D surface and borehole seismic survey geometries at Harvey, Western Australia

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SUMMARY

Within the South West Hub Project we conducted a comprehensive integrated study to map the fault and fracture network surrounding the Harvey 3 well to obtain an understanding of their propensity to act as conduits for the injected CO_2. Here we report only on the seismic investigations that had two objectives: The first one was to provide precise structural model for subsequent geo-mechanical studies. The second objective was design more environmentally friendly acquisition and overcome the land access issues. This is of a crucial importance at Harvey where farmers are opposed to any land disturbance that can affect their activities. We thus designed a comprehensive survey that addressed both objectives. The survey included a conventional component consisting of simultaneous recorded 3D surface and 3D VSP data sets and an alternative component that recorded multi-offset VSP survey along the public roads. 3D imaging results using diverse VSP geometries were compared to 3D surface data. Both products, borehole and surface 3D images, were used for the structural analysis. Multi-offset VSP survey on the other had was reanalysed using different decimation strategies for the purpose of optimising CO2 sequestration monitoring strategy. The main outcome of this analysis was the imaging concept that is limited only to public roads which bypasses access restriction and improves chance for better public acceptance in the future.

Key words: 3D seismic surveys, MOVSP, CO_2 geosequestration

INTRODUCTION

The South West Hub Project, led by the Department of Mines, Industry Regulation and Safety (DMIRS) has been investigating potential target injection and storage formations in the Harvey region of Western Australia for future carbon capture and storage (CCS) activities. This staged project involves collecting and analysing data and samples from the Lesueur Sandstone formation to test its feasibility as a CO_2 reservoir. DMIRS face the challenge of proving containment security for the SW Hub and the local community is expecting a sound scientific evaluation of containment potential for CO_2. It is extremely important to the project to characterise of the potential reservoir and its related structures that is largely based on the residual trapping mechanism. Hence, a large 3D seismic survey covering 110 km^2 of the potential storage area was acquired in 2014. This survey was designed to image deeper structures below 300 m depth and was not meant to represent a base-line survey for potential injected plume monitoring purposes. It was utilised to position the stratigraphic wells the Harvey 2, 3 and 4.

The Harvey 3 (H-3) well was drilled targeting the potential storage zone for CO_2 geo-sequestration which was west of a major dislocation, the so-called F10 fault. However, this zone remained inadequately covered with seismic due to the land access issues at that time.

After an unfortunate large bush fire proximal to the H-3 well in 2016, an opportunity for additional seismic investigations was raised. However, various other restrictions forced us to come up with a fairly non-standard survey design. This survey had multiple objectives to mitigate risks associated with the potential future CO_2 sequestration program. Primarily, we focussed on the structural characterisation of the area surrounding the H-3 well. Additional efforts included seismo-stratigraphic studies and a quantitative analysis of the strata overlying the prospective reservoir. Finally, we aimed to establish an environmentally friendly seismic acquisition methodology as presented in this work.

DATA ACQUISITION

The seismic surveys consisted of simultaneous borehole and surface recordings in an unconventional way. The downhole surveys included an important borehole component, which involved 550 multi-offset Vertical Seismic Profiling (MOVSP) source positions. A zero-offset VSP, five 2D seismic lines, and a small 3D surface seismic surveys were acquired sharing the same source points with the 3D VSP survey (Fig. 1). The surface fold map involving all available shots is also shown on this figure. Ten three-component (3C) slim-wave shuttles (Sercel) with a 15 m spacing were used to cover the entire length of the H-3 well for the MOVSP survey. A 3D VSP survey was also recorded at one of the MOVSP depth range of 900-1035 m which locates around 500 m above the top of the reservoir. This survey utilised 350 additional source points (14 source lines) which were also utilised for the 3D surface seismic in the W-E direction.
Two vibroseis trucks (UniVib) in a flip-flop shot pattern at 550 surface locations were utilised to have a total of 5,500 OVSP points. MOVSP points were located along easily

accessible dirt public roads, for which the permissions to conduct surveys are usually granted and can be used for future CO_2 monitoring surveys. Sweep parameters were 6-150Hz, 24 seconds, single sweep/ vibrators positions (VPs). 1000 additional VP points were used for 3D VSP and 3D surface seismic. The acquisition was conducted in 11 days by a crew of eight people (staff and PhD students). MOVSP points included in a 3D grid produced an extended but irregular fold map, which required specific processing steps for reducing the acquisition footprint. The processing was completed for the following geometries:

A. 3D surface seismic cube
B. 4x2D seismic lines
C. 3D VSP cube
D. ZVSP, OVSPs
E. MOVSP involving roads only
F. MOVSP involving all shots (3D + roads).

The acquisition of this complex data set was carried out in two stages (Urosevic et al., 2017, Urosevic et al., 2018 and Yavuz et al., 2018). The first stage consisted of MOVSP surveys with ten component shuttles of the Sercel Slim-Wave VSP tool deployed in the H-3 well. However, the survey was conducted with eight to nine shuttles (Table 1). 451 VPs were positioned along the dirt roads for each depth level (Fig. 1). The same VPs were repeated for each depth level, which added up to a total of 4510 VPs. For only one depth level, we used public roads and a 3D source-receiver grid to generate a 3D surface reflection cube and a 3D VSP data set simultaneously (Table 2). 1280 shots were utilised in the second stage. Along the 3D source grid 829 VPs were fired for the simultaneous acquisition of the 3D surface and VSP data sets. Hence, we achieved 451 OVSP surveys, which allowed us to produce an independent depth image in the plane connecting each VP to the borehole. Alternatively, all 4510 points could be utilized, which would be equivalent to a 3D VSP survey using the continuous geophone array along the entire borehole trajectory. 4510 VPs may further decimated in several stages to infer the minimum amount of MOVSP points required to produce an acceptable quality depth image around the borehole. This optimization is can provide an alternative cost effective approach for future surveys. Finally, to further refine novel approaches in the application of borehole subsurface characterization and/or CO_2 monitoring methodologies the MOVSP images (full set and divided) can be compared to 3D VSP.

Table 1. Acquisition parameters. It should be noted that some surface lines utilized 3C receivers, which allows us to generate an expanded image around the H-3 well for all three directions (X, Y and Z).

Stage I		Stage II	
Number of Source Line	6	Number of Source Line:	15
Number of Sources	451 per VSP level	Number of Sources:	829
Source Spacing (m)	15	Source Spacing (m)	30 m
Source Line spacing (m)	440	Source Line spacing (m)	260 m
Total Source Line Length (km)	9.1 km	S/R Line Lengths (km)	23.45 & 22.27
Number of Receiver Line	1 (H-3 well)	Number of Receiver Line:	14
Number of VSP levels	10	Receiver Lines 9-14	372 3C geophones
Number of Receivers	78 depth locations	Number of receivers	1503
Receiver Spacing (m)	15	Receiver Spacing (m)	15 m
No of shuttles	8-9	Receiver Line spacing (m)	150 m
Depth coverage	290 – 1445 m	Borehole depth level (m)	500-605
Source 26k lb Vibroseis: Single sweep: 6-150Hz, Linear over 24 s			

Table 2. MOVSP depth levels in order of execution. For each depth level, 451 VP points were spread along dirt roads (Fig. 1). The total number of MOVSP shots is 4510. 3D VSP data acquisition was executed last.

Stage	VSP depth level (m)	Nr. of shuttles	Nr. of shots	Comments
I	290-395	8	451	Public roads (PR)
	1340-1445	8	451	PR
	1235-1340	8	451	PR
	1115-1235	9	451	PR
	980-1100	9	451	PR
	845-965	9	451	PR
	740-845	8	451	PR
	620-725	8	451	PR
	380-485	8	451	PR
II	500-605	8	1280	3D grid + PR

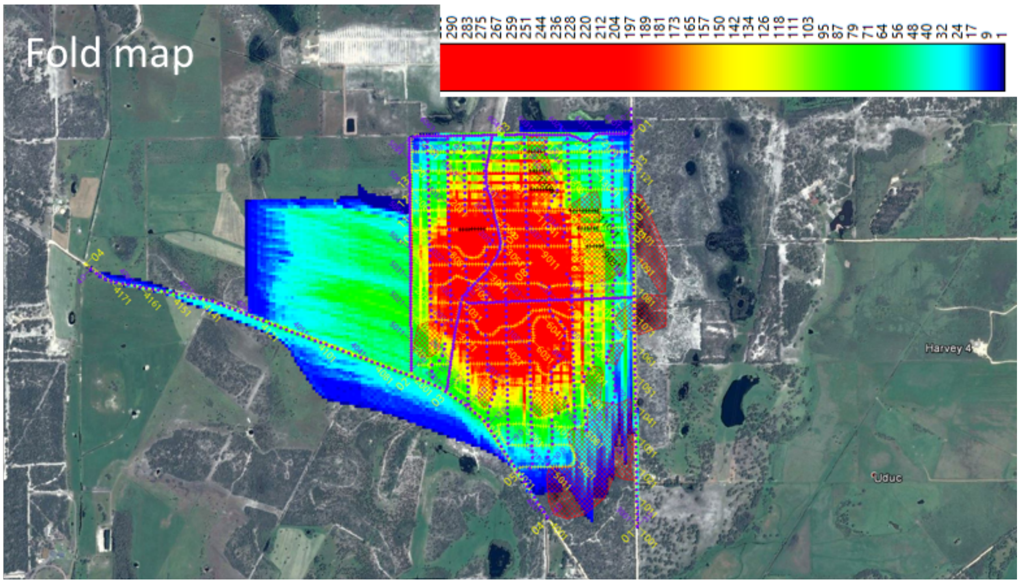

Figure 1. Surface seismic survey geometry around the Harvey 3 well. Yellow solid lines denote public roads. Orthogonal dashed lines stand for source lines (south-north) and receiver lines (west-east)

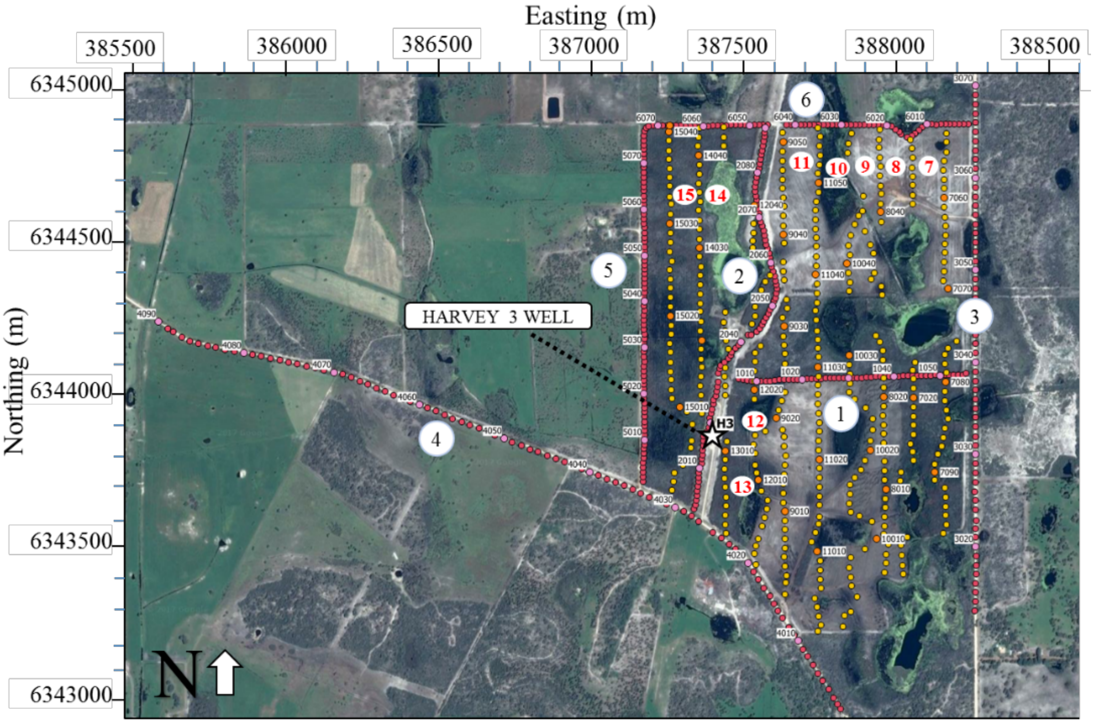

Figure 2. Location map of the acquisition geometry of the MOVSP and 3D surveys. Roads are indicated with number's 1 – 6. Lines 7-15 were within a 3D volume shot on virgin ground.

DATA PROCESSING AND ANALYSIS

A time-depth-velocity relationship from the zero-offset VSP data is processed initially. Binning of the full data set including all shot-receiver positions for 3D surface reflection processing is then applied (Figure 1). For structural characterisation, the full surface data set is initially processed with a conventional manner through the utilisation of pre-stack time migration (PSTM). Offset VSP (OVSP) data and ZVSP corridor stack were mapped to two-way time correlated well with surface seismic. In interactive velocity analysis, a ZVSP derived velocity function was used as a guide function, which was subsequently refined for an iterative time and depth image gather analysis. Following this, the preserved relative amplitudes processing is also enabled the subsequent qualitative and quantitative analysis from the data cube.

For the data processing and analysis of 3D VSP and MOVSP datasets, the shot lines were divided into two groups: (a) lines 1-6 that were acquired along the public, and (b) lines 7-15 that were distributed across several farm paddocks and comprised shot line grids for 3D surface and 3D VSP surveys (Figure 2). Set (a) consisted of 451 VPs, which were repeated 10 times for 10 consecutive borehole depth positions. VSP imaging of MOVSP and 3D VSP further optimised in various decimations to optimize the imaging and thus monitoring methodology that would involve borehole receivers and VPs placed along the tracks of opportunity.

A comparative assessment of the results was made using surface 3D and various VSP data sets. An in-house imaging algorithm was used for Kirchhoff VSP depth migration using the arbitrary geometry as an input data, which allowed us to output any selected plane. This is shown in Figure 4 where all the "road line" MOVSP data were used to image along a single west-east line. Such data also allowed us to choose only shots with the highest signal to noise ratio (SNR) to create a high quality depth image. This approach gave us significant flexibility to generate seismic images from VSP data in any particular direction for an optimized reservoir characterisation and monitoring.

VSP images are converted from depth to time and the image quality of all VSP data sets was assessed against the PSTM seismic cube. In the areas where we had high fold, the VSP image compares well with surface seismic image. In the direction of line 4 the fold is very low but event continuity can still be seen. As a product of different scaling by data fold, the true amplitude processing causes uneven amplitudes. Figure 4 shows a very significant result, where we compare the MOVSP image along public roads with the full MOVSPS data set and 3D VSP. Good quality images have been obtained by only using shots along public roads and produced comparable results for the full data set image.

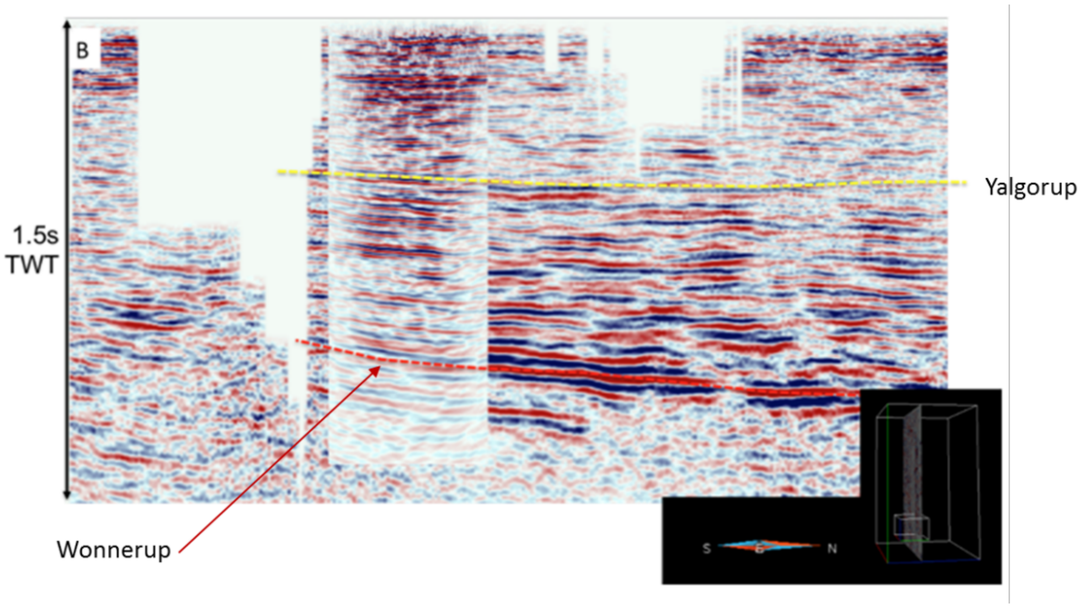

Figure 3. Nested 3D inline spliced into the regional Harvey 3D survey. New survey provides much more details in the first 1.5 sec.

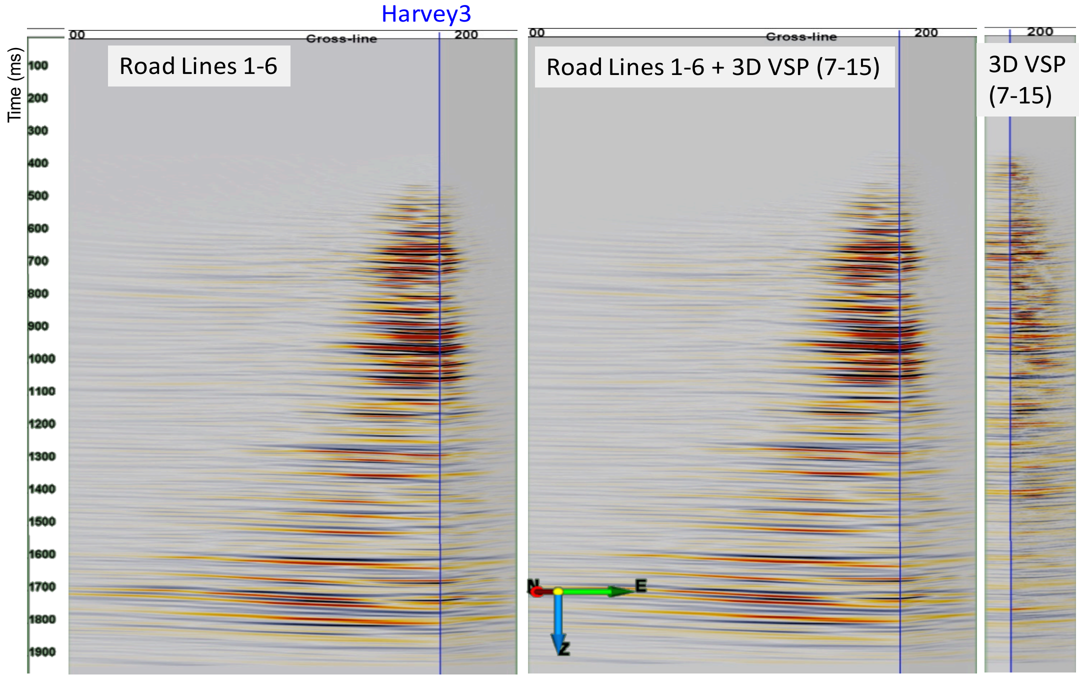

Figure 4. VSP depth images obtained from: Shots along lines 1-6 (left), entire data set that is shots along lines 1-15 (middle) and 3D VSP obtained with shots along lines 7-15 (right). Note that first two panels are nearly identical so that contribution from line 7-15 is small.

We also aimed to test the applicability of Full Waveform Inversion (FWI) of VSP data for rock characterisation. The main reason for looking into the VSP FWI approach was a greater SNR in comparison to surface recording and provided a very good starting model for the inversion. An additional and very important aim was to evaluate the feasibility of using single offset VSP for reservoir characterisation through inversion. This was an extreme (but not impossible) case that simulated very limited land accessibility for either reservoir characterisation or follow up monitoring. The results of the FWI test (full elastic case) conducted with single offset shot VSP data are displayed in Fig. 5. Simple input models for Vp, Vs and ρ produced reasonable inversion results (Figure 9). This is very promising result which could pave the way for a new approach to seismic monitoring of CO_2 sequestration at Harvey, WA and potentially other sites.

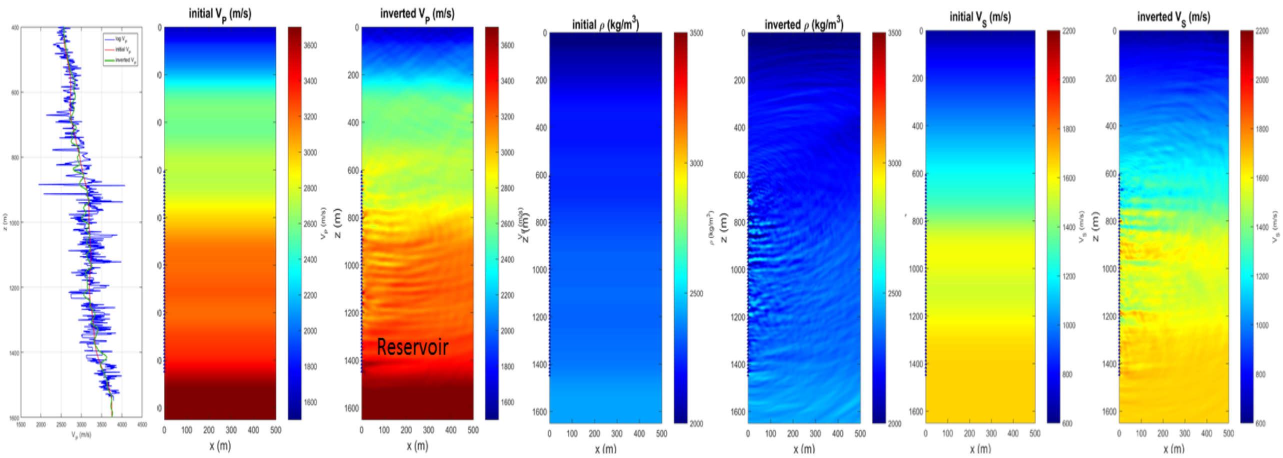

Figure 5. FWI of OVSP data. Log data (blue) and inverted Vp (red) are shown on the left, followed by: Intitial Vp mode and inverted Vp, initial density and inverted density and initial Vs model and inverted Vs.

CONCLUSIONS

The results obtained with the 3D surface, 3D VSP and individual OVSPs are encouraging with respect to looking into alternative, low footprint, site characterisation and subsequent CO_2 sequestration monitoring. MOVSP surveys offer flexibility for depth imaging and show significant potential for devising an alternative monitoring program that is likely to be accepted by the wider community as it is less invasive. The quality of individual OVSP shots enabled us to run initial Full Waveform Inversion (FWI) tests. The high-quality inversion results obtained were essential for the lithological characterisation of the reservoir, which is an unconventional sealing unit dependent on solubility and residual trapping and of particular importance in this study. A new monitoring methodology that utilises opportunistic MOVSP surveys combined with the application of FWI may be the only possible way to proceed with CO_2 sequestration projects in environmentally sensitive areas.

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