Comparison of 4D VSP and 4D surface seismic results, operations and costs: CO2CRC Otway project case study

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CO2CRC Otway project

• **Stage I** – CO₂ injection into a depleted gas reservoir
  - 80/20 % of CO₂/CH₄ stream produced from Buttress, transported and injected into CRC-1 well (initial production well)
  - 2 km depth
  - 64,000 tonnes

• **Stage II** – CO₂ injection into saline aquifer
  - Up to 10,000 tonnes
  - 1.4 km depth
The reservoir

Small, thin, heterogeneous and deep depleted gas reservoir, surrounded by complex faulting,

CO₂/CH₄ – mix injected and monitored with the most sensitive seismic techniques

Naylor gas field

Pre-production 3D seismic data recorded in 2000
Waarre C TL effect modelling

- Acoustic inversion (using the baseline seismic data, 2008) -> initial impedance model
- Hydrodynamic modelling -> changes in pore fluid in time
- Fluid substitution using the initial impedance model + predicted gas saturation
- Seismic modelling using new impedance model to predict TL effect
Baseline data (model) and predicted signal

2008

2010-2008

NRMS, %, 60 ms
Stage II

- CO$_2$/CH$_4$ plume in saline aquifer
- Depth $\sim$1.4 km
- Overall volume < 10,000 tonnes
- Thin, less then 200 m in diameter

Results of hydrodynamic modelling
(10 000 tonnes of CO$_2$, 90 days), [Y. Cinar, 2009]
Changes of rock properties due to fluid substitution

Injection of CO\textsubscript{2} in supercritical form into saline aquifer with 25% porosity
Time-lapse signal for the different volumes of injected/leaked CO$_2$/CH$_4$ gas mixture

[Alonaizi et al., 2011]
Goals of the seismic monitoring program

- Assurance (no leakage)
- Attempt to detect CO$_2$ movement in the reservoir
- Evaluation of various time-lapse seismic monitoring techniques
Seismic monitoring – Final program

• Time lapse 3D surface seismic
  – Least sensitive and repeatable but provides coverage of entire reservoir and beyond
  – Necessary for ‘assurance monitoring’ to detect loss of primary containment
  – No 4D effect expected in general

• Time lapse borehole seismic
  – CRC-1: 3DVSP with 3C geophones (Schlumberger’s VSI)
    • Improved sensitivity and resolution relative to surface data, improved repeatability
    • More chance for direct CO$_2$ monitoring, limited coverage
  – Naylor-1: Permanent downhole sensors (LBNL)
    • Potentially most sensitive and repeatable
**Survey Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey</td>
<td>Otway 3D</td>
</tr>
<tr>
<td>Location</td>
<td>Otway Basin, Victoria, Australia</td>
</tr>
<tr>
<td>Date</td>
<td>1) December 2007–January 2008</td>
</tr>
<tr>
<td></td>
<td>2) January 2009</td>
</tr>
<tr>
<td>Number of Source Lines</td>
<td>29 Lines</td>
</tr>
<tr>
<td>Number of Source Points</td>
<td>2181 Points</td>
</tr>
<tr>
<td>Number of Receiver Lines</td>
<td>10 Lines</td>
</tr>
<tr>
<td>Number of Receiver Points</td>
<td>873 Points</td>
</tr>
<tr>
<td>Number of Swath</td>
<td>2</td>
</tr>
<tr>
<td>Bin Size</td>
<td>10 m in-line by 10 m cross-line</td>
</tr>
<tr>
<td>Total Number of Bins</td>
<td>30821</td>
</tr>
<tr>
<td>Nominal Stacking Fold</td>
<td>100</td>
</tr>
<tr>
<td>Offset Range</td>
<td>50-2150 m</td>
</tr>
<tr>
<td>Receiver line orientation</td>
<td>West-East</td>
</tr>
<tr>
<td>Source Line Orientation</td>
<td>South-North (1-27 lines), West-East (28-29 lines)</td>
</tr>
</tbody>
</table>

**Source Parameters**

- **Source Type**
  - Weight Drop (concrete breaker) – 750 kg, free fall from 1.2 m – 2008
  - IVI Mini-vibe 2009

- **Stacking fold**
  - 4

**Source Geometry**

- **Source Line Spacing**
  - 100 m
- **Source point Spacing**
  - 20 m

**Receiver Parameters**

- **Receiver Type**
  - 10 Hz - geophones
- **Recording Pattern**
  - Orthogonal cross-spread pattern
  - (odd source line were recorded by fist 5 receiver lines, even source lines - by 6-10 receiver lines)

- **Receiver Line Spacing**
  - 100 m
- **Receiver Point Spacing**
  - 10 m

**Recording Parameters**

- **Record length**
  - 4 s
- **Sample Interval**
  - 1 ms – 2008, 2 ms - 2009
- **Recording Filters**
  - No filters were applied in the field

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**Source lines** and **Receiver lines**
Seismic operations

- **Time:** 14 days per survey, +5 days mob/demob (surface seismic only)
- **Crew:**
  - Seismic source (~2 persons in baseline survey operating the weight drop vs. 3-4 persons operating the IVI minibuggy in monitor surveys)
  - GPS, real-time positioning of the seismic source – 1 person
  - VSP: 1 person
  - Surface seismic: 3-4 persons
  - Support personnel: 1 person
Raw data example
the same common shot gather for 2008 (left), 2009 (middle) and 2010 (right) surveys
Processing flow

- Data input (correlation with sweep signals for 2009-2010)
- Trace DC Removal
- Data equivalence and binning (bin size 10x10m)
- Elevation statics (30 m, 1800 m/s)
- Trace Editing
- Bandpass filtering (7-10-150-160 Hz)
- Spike and Burst Noise Attenuation
- Automatic gain control (500 ms, applied before decon and removed after)
- Spiking Deconvolution (minimum phase for 2008 and zero-phase for 2009)
- Velocity Analysis (two iterations)
- Residual Static Correction (Max Power Autostatics)
- Radon filter in cone window (AGC 500ms applied before and remove after)
- FX deconvolution before stack
- Coupled Time Variant Scaling
- Pre-stack static shifts matching
- True Amplitude Recovery (spherical divergence correction as 1/(time*vel**2))
- Normal Moveout Correction (30% muting)
- CDP stack (mean, power scalar for stack normalization 0.5)
- Post-processing (TV Whitening, FXY Deconvolution)
- Explicit FD 3D Time Migration
Post-stack cross-equalisation

- **Window**: 400-1400 ms (i.e. ABOVE the Waarre C)

- **Workflow**
  - Cross-correlation based static shifts analysis
  - Shaping filter
  - Amplitude balancing
Processed and cross-equalized data

Base-line, 2008  Monitor I, 2009  Post-injection, 2010
NRMS, 2008-2009, reduced geometry

STAGE 1 limit
NRMS, 2009-2010, full geometry

STAGE 2 limit
NRMS, 60 ms window, Paaratte

2008-2009

2009-2010, cut

2009-2010, full

Source

Fold
Achieved repeatability: NRMS difference (60 ms window) for 2010-2009 surface seismic
Difference volumes, reduced geometry

[Shulakova et al., 2010]
2010-2009, full geometry

[Shulakova et al., 2010, poster]
Expected TL signal vs actual seismic response in Paaratte

2008  2009-2008  2010-2009  Simulated response

7,000 t

1 km
3D VSP

- CRC-1
- Receiver interval 1500-1605 m (15 m spacing)
- 2007/8 – Weight drop, 1100 sp
- 2010 – IVI minibuggy, 2200 SP
4D VSP processing workflow (Campbell, A. & Shujaat, A. 2010)

1. Extract coincident sources and receivers
2. Regularization if necessary
3. Reconcile differing source signatures
   • Trace by trace decon shapes to common signature
   • Common bandpass after decon applied to fine-tune signature
4. Model building
5. Model based residual statics
6. Cross equalization if necessary
7. Data quality based source selection
   • Amplitude differences
   • Residual timing differences
   • 4D metrics
8. Imaging
Processed data

2007  |  2010  |  difference

ILINE_NO  |  1200 |  55 |
XLINE_NO  |  40   |  80 |
          |  40   |  80 |
          |  40   |  80 |
1200      |       |     |
1300      |       |     |
1400      |       |     |
1500      |       |     |
1600      |       |     |
1700      |       |     |
1800      |       |     |
Processed + cross-equalised
3D VSP, 2007, CD0, crossline 80

3D surface seismic, 2009, inline 100
Waarre C
Waarre C amplitude

2007

2010

2010-2007
Achieved repeatability: NRMS difference (60 ms window) for 2010-2008 3D VSP
4D VSP vs 4D land surface seismic

- **Coverage**: VSP provides limited coverage
- **Repeatability/TL signal-to-noise**: VSP provides much better repeatability
- **Field operations**
  - Acquisition time/performance: VSP is characterized by very short mob/demob
  - Disruption to farming activities: VSP does not require distributing cables/geophones
- **Processing**: VSP data processing is much faster
- **Cost**: surface seismic in case of Otway project was cheaper due to non-commercial rates
Conclusions

• Very good (post-stack) repeatability achieved combining weak and different source types, thanks to high spatial data density and high fold

• CO$_2$ upward migration (“Leak”) readily detectable with 3D TL seismic - no indication in TL data (using diverse measurements and studies)

• Clear, unique TL signal from Waarre-C not observed (CO$_2$ contained); very subtle TL signal – sensitive to processing/cross-equalisation schemes (analysis still ongoing)

• VSP shows superior repeatability and sensitivity with respect to surface seismic (also measure full wave field; possibility for development of alternative M&V methodologies)

• Way forward: Stage II
  – 2011-2012
  – Both surface 3D seismic and some borehole component
  – Permanent installation
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