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# Seismic monitoring of $CO_2$ injection into a depleted gas reservoir – Otway Basin Pilot Project, Australia

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**Abstract**

The use of depleted gas fields for $CO_2$ storage as well as CO2-based enhanced gas recovery are of global importance. Thus, the CO2CRC Otway Basin Pilot Project provides important experience in establishing whether such scenarios can be monitored by geophysical techniques, in particular seismic time-lapse methodology.

Injection of $CO_2$ into a depleted gas reservoir (with residual gas in the Otway case) does not present favourable conditions for the application of geophysical monitoring techniques. Simulation of the $CO_2$ injection process at Otway shows that changes in elasticity of the reservoir rock will be quite small and difficult to monitor even with the most powerful time-lapse (TL) seismic methodologies. Consequently, the design and implementation of the monitoring program had to address these issues. To increase the sensitivity of TL seismic we combined 3D VSP with 3D surface seismic. For land seismic case, we achieved excellent repeatability with 3D time lapse surveys, which at the reservoir level produced normalised RMS difference values of about 20% for surface seismic and 10% for 3D VSP, respectively. Still due to very small time lapse signal, the primary use of 3D surface seismic was for assurance monitoring. Borehole seismic measurements confirmed that time-lapse is too small to be reliably estimated and analysed from repeated seismic measurements. Finally, post-injection reservoir simulation and accompanying seismic modelling suggest that a prolonged $CO_2/CH_4$ injection should produce only negligible change of the elastic properties of the Naylor reservoir.



Sequestration, time-lapse, 3D seismic, modelling

## The Otway test

Within the Otway Basin Pilot Project, of the Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), approximately 65,000 tons of $CO_2/CH_4$ mix in the ratio of 80/20 was injected into the Waarre C formation (depleted Naylor gas reservoir) over the last two years. The $CO_2$ was produced and transported from a nearby natural accumulation, via pipeline and injected into a sandstone reservoir (Figure 1A). The advantage of injecting $CO_2$ into a depleted gas field is access to well-established infrastructure, pre-existing geophysical

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exploration information, production history and well data. This has significantly reduced the cost and time to implement the program.

The Naylor reservoir is located in a titled fault block structure, sealed by the Belfast Mudstone. Its small size (0.5km$^2$), relatively large depth of around 2 km and thickness of less than 25 m on average, presents a challenge for detailed reservoir characterisation and certainly for the design of a geophysical monitoring program at this site (Figure 1B and C). Potential fault reactivation due to $CO_2$ injection into Waarre C reservoir and upward migration of fluid into saline Paaratte aquifer was also under investigation in the project (Figure 1C).

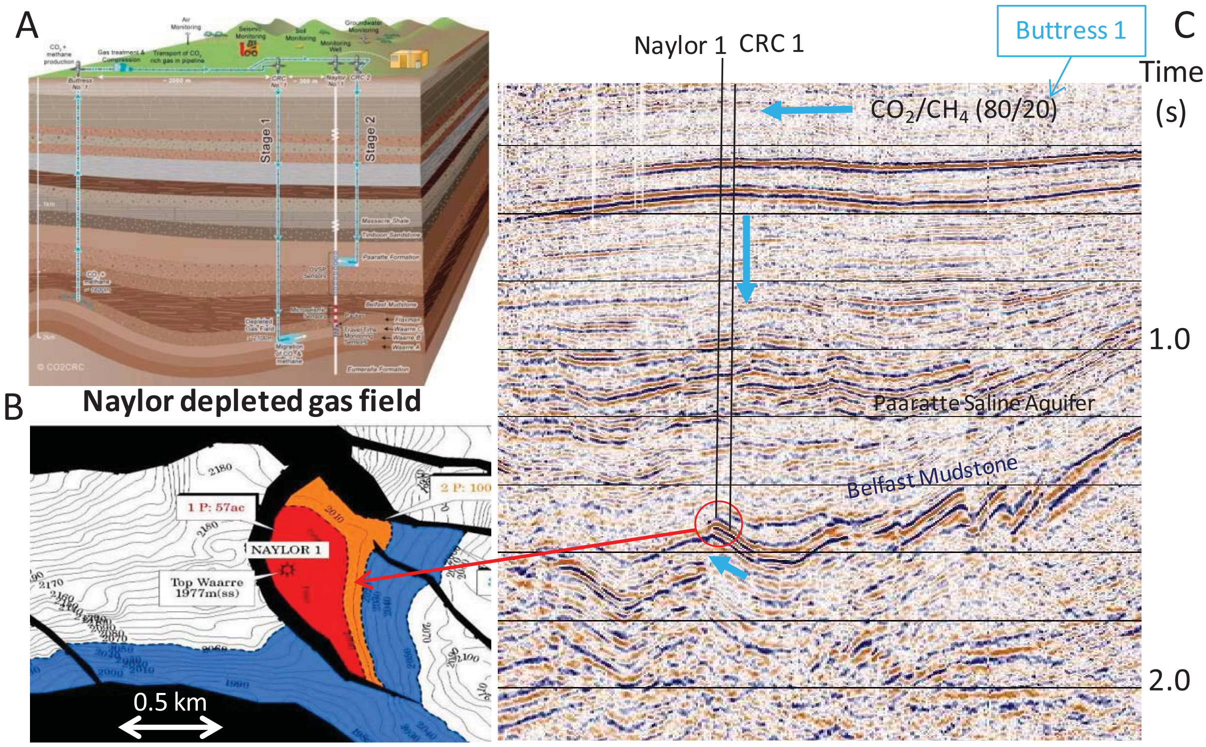


Figure 1. Schematic of Otway $CO_2$ injection project (A), structural depth map of Naylor field prior to production (B) and an in-line extracted from the regional 3D seismic survey conducted in 2000 (C). Naylor reservoir is encircled in red in C. It is set against the Naylor fault which could be considered as critically stressed.

Reservoir simulation predicts that the supercritical state $CO_2$ will migrate up-dip through the region of residual methane until it encounters the resistance of 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. During migration, the injected $CO_2$ will become enriched with CH4 but remain as a supercritical fluid (Figure 2). The $CO_2$-$CH_4$ exchange in the pore space is expected to have little effect on the elastic properties of the reservoir rock. Hence, prior to injection we carried out numerous numerical modelling experiments. Impedance differences on the order of several per cent (3-5%, depending on the reservoir level) are expected. This translates into approximately 10 % change in the reflectivity. For real rocks which are heterogeneous the TL signal could be higher. Thus, to be able to detect such changes, we need to design and conduct exceptionally repeatable time-lapse seismic surveys. The repeatability of conventional land surface seismic methods is known to be poor (Vandeweijer et al. 2009, Vedanti and Sen 2009). In our case, a change in reflectivity of around 10% should be very difficult, if not impossible, to detect by time lapse reflection land seismic methods (Urosevic et al., 2010b). To increase our chances for the detection of $CO_2$-related changes in the reservoir, we also included borehole seismic methods into M&V program at Otway site as borehole seismic have superior resolution and repeatability with respect to surface seismic. However, borehole seismic suffers from a limited spatial extent over which it can provide an image. Ideally, the two methods (borehole and surface seismic)

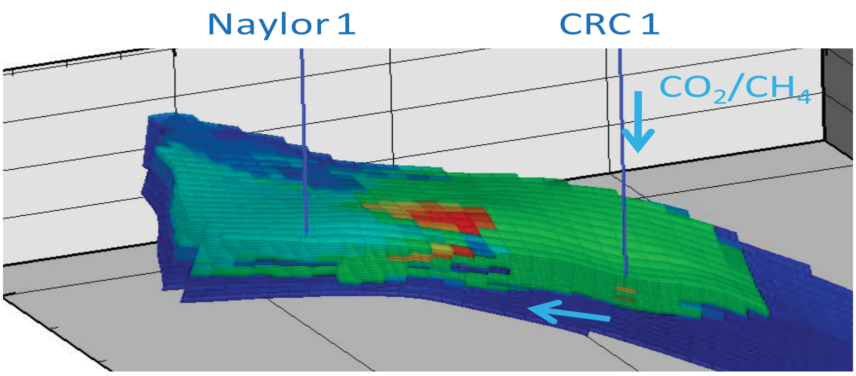


Figure 2. Reservoir studies: $CO_2/CH_4$ mix flow preferentially from the injection point (CRC-1) towards the high elevation point (Naylor-1). Methane cap at Naylor 1 counteracts the migration of $CO_2$ leading to a formation of a ring-like shape (from M. Leahy and J. Ennis-King, 2008).

are combined to achieve good spatial coverage, high repeatability and the sensitivity needed to detect small physical changes in a reservoir. Such idea was implemented for monitoring $CO_2$ injection into depleted Naylor gas field at Otway, where we simultaneously acquired 3D high resolution seismic reflection with three-component 3D Vertical Seismic Profiling (VSP) data. Finally, permanent geophone installation was implemented in Naylor 1 borehole (monitoring well). The string combined different instruments with specific geometry in order to acquire diverse measurements and also enable frequent active and also passive observations (Dodds et al, 2009).

**Seismic monitoring program**

Substantial field testing was conducted during 2006 and 2007 (Dodds et al., 2009; Urosevic et al., 2009). The main objective was to evaluate repeatability as a function of the source type, recording geometry, and seasonal variations in terms of the soil condition changes. Following these experimental or pre base line surveys, in the period 2007/8 to 2010, comprehensive sets of time-lapse seismic data were acquired (Table 1).

| Data type/year | Baseline (prior CO2 injection), **2007/8** | Monitor I (33 Kt of $CO_2$ injected), **2009** | Monitor I (65 Kt of $CO_2$ injected), **2010** |
|---|---|---|---|
| Surface seismic | 3D seismic with weight drop source and 440 active channels | 3D seismic with vibroseis source and 880 active channels | 3D seismic with vibroseis source and 880 active channels |
| Borehole seismic | Zero-offset, offset and 3D VSP with weight drop source (3D VSP – only odd source lines) | | Zero-offset, offset and 3D VSP with vibroseis source (3D VSP – all source lines) |

Table 1. Time-lapse data acquired at Otway site. Weight drop source (WD) was used for acquisition of base line data; Viboseis (15,000 Lb IVI minibuggy) was used for subsequent surveys.

Considering that Naylor reservoir is surrounded by several large faults, it was necessary, in the monitoring program, to account for potential fault reactivation and upward migration of $CO_2$ (Figure 1). The only possible accumulation of the leak was in the Paaratte saline formation. For that purpose we used reservoir simulation results to model a "seismic leak scenario" which demonstrated that small quantities of $CO_2$ are likely to produce very strong changes in the elastic properties of the host rock that would be readily detected by time lapse seismic monitoring (Figure 3). This result has demonstrated that primary objective of 3D time lapse reflection surface seismic should be the assurance monitoring rather than direct detection of CO2 migration and distribution in the reservoir.

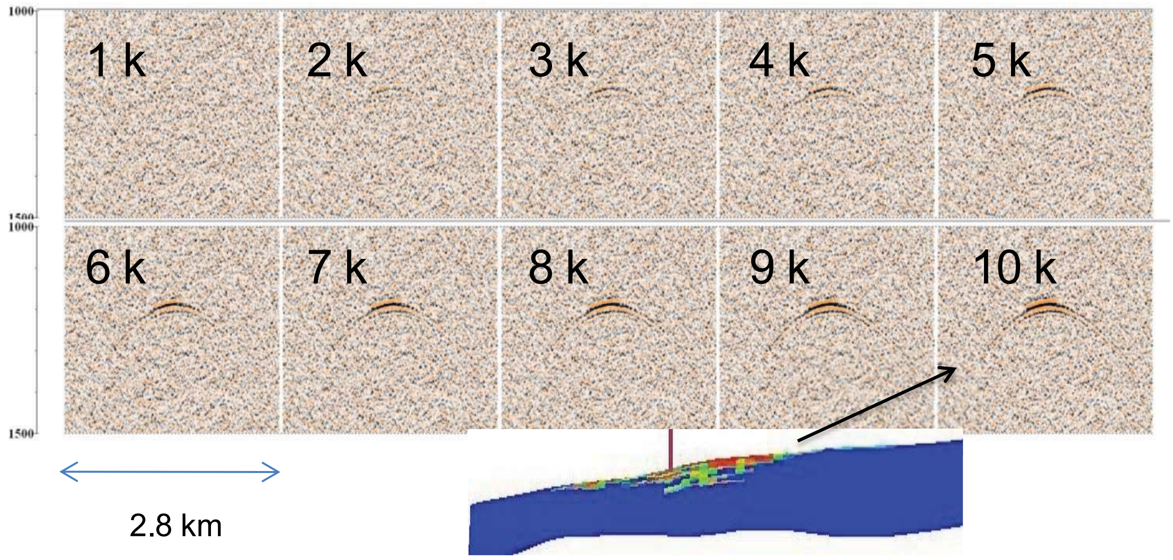


Figure 3. Seismic 4D modelling of the "leak" scenario in case $CO_2$ migrates along Naylor fault into Paaratte formation (see also Figure 1A). Distribution of $CO_2$, extracted from reservoir simulation, shows up as diffraction, in this case submerged into the background noise proportional in magnitude and frequency content to the actual one observed during field experiments.

**Time lapse seismic results**

The land seismic 3D survey was designed with very high nominal fold (over 100) to maximise signal-to-noise ratio, and thus improve repeatability. High density shooting (over 700 shots/ $km^2$) and small receiver separation (10 m between single geophones) enabled the utilisation of very fine bin size (10x10 m) for imaging and later refinements in interpretation. The actual geometry of the survey was also affected by the site conditions and accessibility. For the borehole seismic program, we used high precision Schlumberger VSI tool, comprised of 10 elements spaced at 15 m (Urosevic et al., 2009).

Baseline 3D surface and borehole seismic surveys were conducted simultaneously starting in February 2007 and finalised in January 2008. Good quality seismic data were obtained with a 12 kJ "free-fall" concrete breaker used as a weight drop seismic source. The first 3D surface seismic reflection monitor survey was conducted in January 2009 after injection of approximately 33 Kt of $CO_2$. This time we used mini vibrator (IVI 15,000 lb) as the seismic source. Very good repeatability between the surveys was achieved despite the source change. This was in agreement with pre-baseline 2D tests which demonstrated that near-surface conditions and soil saturation affects data repeatability much more than the source type; after processing, as long as source strength is comparable between successive surveys (Pevzner et al., 2010). The normalised root mean square difference (NRMS) between the baseline and monitor survey was excellent, and at the reservoir level (2 km depth) was around 20%.

A post-injection survey, or the second monitor, was recorded in January 2010, four months after injection of 65,000 tonnes of $CO_2$ had been completed. This final stage also included recording of the first 3D VSP monitor survey. A mini-vibrator source was used to further improve repeatability between first and second monitor surveys. All three surface seismic data sets were processed at Curtin University. The results for all three years are shown in Figure 4 by a selected in-line from each cube. Again, very good repeatability was achieved but simultaneous pre-stack cross-equalisation of the monitor surveys conducted with IVI minibuggy with weight drop baseline data turned out to be non-trivial exercise. Current results show that the difference between successive surveys at Naylor level is close to the background noise level which is low but so is the time lapse signal (Figure 4). This can be better understood from the analysis of time lapse zero-offset VSP data conducted in CRC-1 well, which was carried out with the same seismic source (weigh drop).

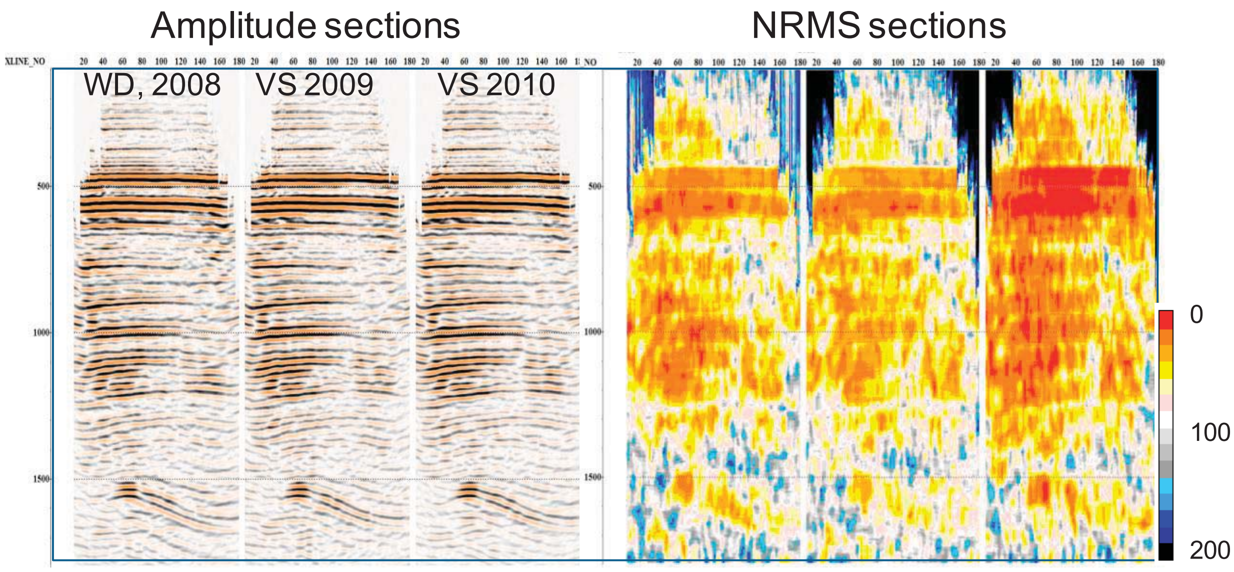


Figure 4. In-lines selected from 3D reflection cubes acquired in 2008 (base line), 2009 (first monitor) and 2010 (after injection was completed) are shown to the left. The similarity between the three sets is striking. Corresponding normalized root mean square differences sections are to the left. Scale 0-200 corresponds to possible range of NRMS values, 0 – signals are perfectly correlate, 200% - anti-correlate. At reservoir level (1.5 s) the NRMS is around 20% which is exceptionally good for time lapse land seismic.

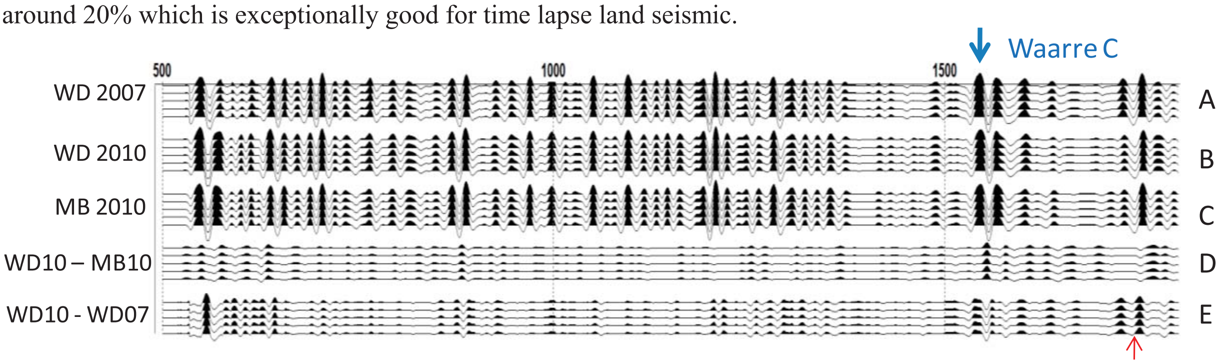


Figure 5. Raw zero-offset VSP (ZVSP) corridor stacks for: A) base-line ZVSP shot with weight drop (WD) in December 2007, B) Post-injection ZVSP acquired in 2010 with WD and C) repeated set with mini buggy (MB) vibroseis (envirovibe). Pre-post injection difference using the WD and MB source types is shown in D), while the difference between the same sources is shown E). Seismograms A-C demonstrate exceptional repeatability (NRMS at or below 20%). Result in D) shows that the time lapse signal (down the blue arrow) is just detected above the threshold. Result in E) also shows that some attenuation may have happened in the reservoir zone resulting in the difference below the reservoir (red arrow).

Raw corridor ZVSP stacks acquired before and after $CO_2$ injection and their successive differences, including the application of dual source in 2010, are shown in Figure 5. Despite exceptionally good repeatability of VSP surveys relative to surface seismic surveys, it is clear from Figure 5 that time lapse signal is just above the background noise level. Similarly, very subtle changes after injection of 65 Kt of $CO_2$ are also observed in cross-equalised 3D VSP images, acquired before and after injection (Figure 6 and Table 1). The anomaly there bears some resemblance to the predicted higher concentration of $CO_2$ by reservoir simulation in Figure 2 but also suggests some seismic migration artefacts in the north-east corner.

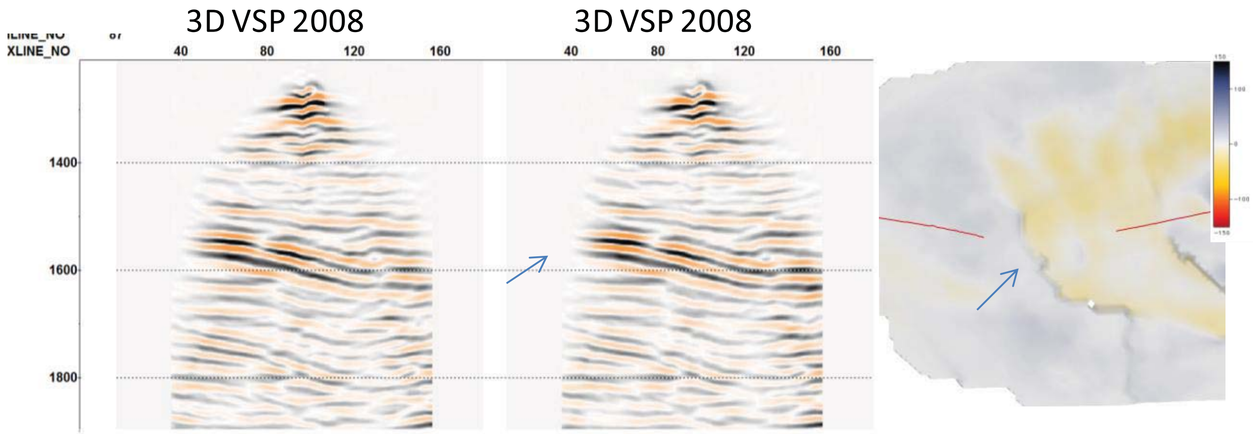


Figure 6. VSP image extracted from 3D baseline survey acquired with WD (left), the same section extracted from post-injection VSP survey acquired with MB (middle) and the difference along Waarre C horizon.

Finally, returning to the issue of assurance monitoring, we conducted extensive study over the Belfast shales and Paaratte saline aquifer to verify absence of leaks. This could have been only accomplished with the surface seismic as 3D VSP images did not cover this depth level. By comparing the differences between successive seismic surveys over Paaratte interval to the modelling results, we demonstrate that no significant amount of $CO_2$ has escaped Waarre C reservoir and migrated up the fault into overlain strata (Figure 6).

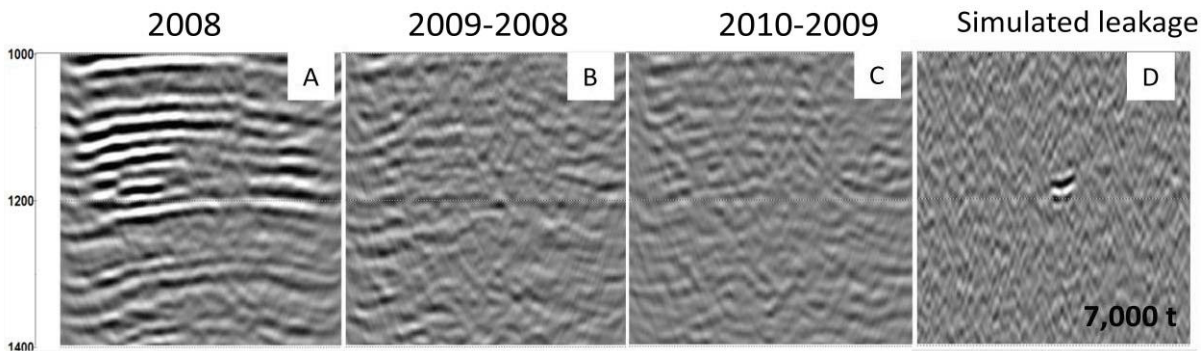


Figure 6. Seismic sections extracted from 3D migrated cubes: A) Baseline, B) Difference first monitor – baseline and C) second – first monitor survey. Simulated seismic response (migrated) is shown in D).

**Rock physics modelling**

In the final analysis, extensive numerical tests were conducted to analyse variation of time lapse seismic signal intensity for different $CO_2$ saturation levels. We included known cases of 33 Kt and 65 Kt but also a hypothetical case of injection of 100 Kt of $CO_2/CH_4$ mix into Waarre C reservoir. The input models were based on logs and extensive reservoir modelling results. TL signal was analysed at wells (Naylor-1 and CRC-1) and also in between the wells where increased saturation zone could be expected (see Figure 2). For that purpose we included an additional well (Dummy) in the middle. This was necessary for establishing an optimum quantity of $CO_2$ needed to produce a detectable time lapse seismic signal. The most important prediction was with respect to the difference between 65Kt and 100Kt due to some concerns that 100Kt could have provided a much clearer time lapse seismic signal.

The results of the modeling are summarised in Figure 7 for the cases of 65 Kt and 100 Kt of $CO_2$ injections into Waarre C sand. Like for the case of field data we computed normalized RMS amplitude differences in a window around the reservoir for three wells. These results clearly show that a prolonged injection (to up to 100Kt) will produce no measurable differences of the time lapse seismic signal.

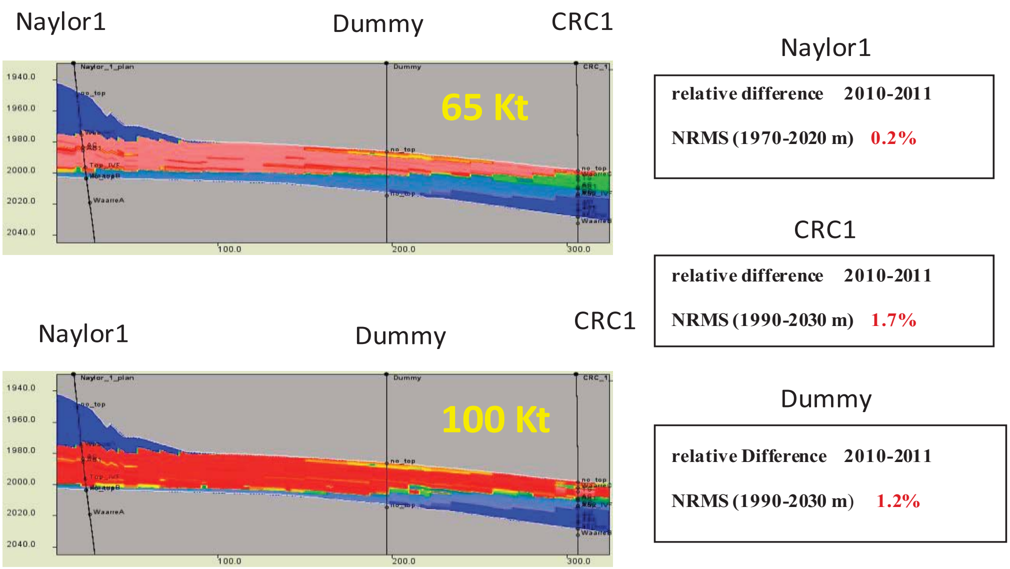


Figure 7. Reservoir simulation results for injection of 65 Kt and 100 Kt of $CO_2$, and corresponding differences at three wells (including Dummy well) between "seismic surveys". The differences of normalised root mean square amplitudes in a fixed window (like for field data) is used to compute percentage changes at wells.

**Conclusions**

Exceptionally challenging conditions for monitoring $CO_2$ sequestration process at the Naylor site, Otway basin required "new thinking" and implementation of different and comprehensive seismic program. High spatial data density, high fold and high quality processing produced excellent repeatability at the target level of both 3D surface reflection and 3D VSP data. However, very small time lapse seismic signal presented a challenge for data processing and subsequent analysis of the differences between successive seismic surveys. A subtle seismic anomaly was eventually detected after injection of small quantities of $CO_2$ of 33 Kt and 65 Kt, respectively. This is very encouraging considering that we used weak seismic sources and two different source types for time lapse studies. Currently, comparing the time lapse seismic signals extracted from surface seismic and VSP, it appears that the changes in the reservoir are indeed very subtle and that very minor changes in the processing sequence(s) could produce markedly different results. This is to be expected as differencing small numbers yields high instability of the results. We therefore expect that yet another round or more of reprocessing is necessary to converge towards unique difference cubes. Same is valid for 3D VSP processing.

At present we can conclude that 3D surface seismic confirms no leak situation which demonstrates clearly that no significant amount of fluid has escaped from the reservoir into overlain strata. Time lapse VSP difference appears to show that some anomaly is present in between the two wells as suggested by reservoir simulation studies. Finally we show that prolonged injection of CO2 is unlikely to produce detectable difference in time lapse seismic signal.

**Acknowledgement**

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