Time-lapse seismic monitoring of CO_2 injection into a depleted gas reservoir—Naylor Field, Australia

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The CO2CRC Otway Project conducted under the Australian Cooperative Research Centre for Greenhouse Gas Technologies is the first of its kind, where CO_2 is injected into a depleted gas reservoir. The use of depleted gas fields for CO_2 storage and or enhanced gas recovery is likely to become globally adopted. Therefore, the CO2CRC project provides important experience for monitoring under these conditions. However, injection of CO_2 into a depleted gas reservoir (residual gas saturation zone in this case) does not present a favorable condition for the application of geophysical monitoring techniques, and particularly seismic methods.

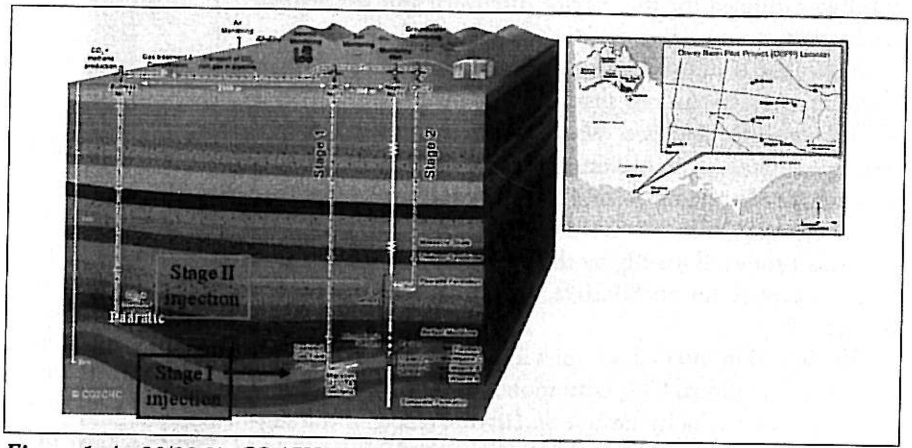

Figure 1. An 80/20 %, CO_2/CH_4 stream is produced at Buttress and transported to CRC-1. The previous production well, Naylor 1, is turned into a monitoring well for well I of CO2CRC Otway Project.

We expect that the injection of CO_2 into a CH_4-depleted reservoir can only produce subtle changes in elastic properties of the reservoir rock which may be very difficult to measure. Therefore, an accurate prediction of the CO_2 injection-caused seismic response changes in seismic response caused by CO_2 injection is necessary for the design of an appropriate monitoring strategy. Consequently, rigorous rock physics investigations were conducted, followed by detailed reservoir simulation studies. Numerical modeling studies incorporated 1D, 2D, and 3D geological models plus short and long-term CO_2 effects. Simulation of the seismic signature changes over time-related CO_2 injection were followed by field tests to evaluate acquisition parameters and in-situ soil conditions that could impact the repeatability of successive monitoring surveys.

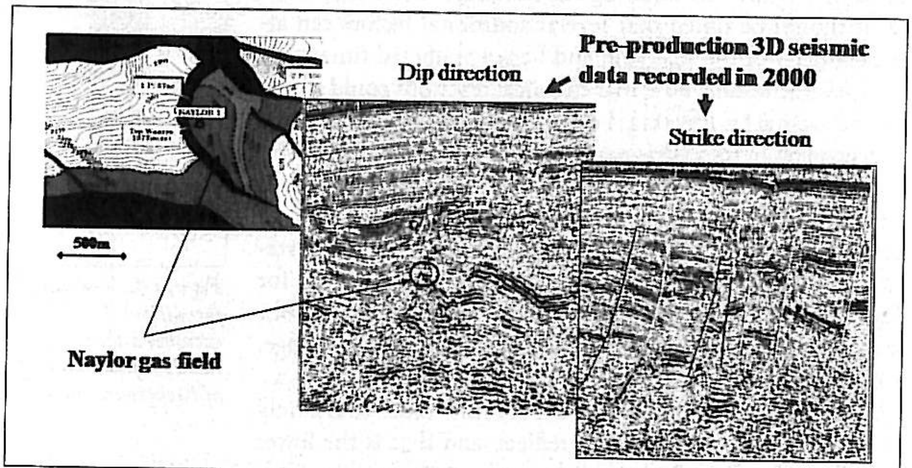

Figure 2. A small, thin, heterogeneous, relatively deep, and depleted Naylor gas reservoir is surrounded by complex faulting. The field extent, the main bounding faults, and large-scale structural elements in the region are depicted from left to right, respectively.

The final monitoring program combines both surface and borehole seismic methods. Surface seismic provides a global vision of the underground in a qualitative sense as traditionally poor repeatability of land seismic may obscure the time-lapse effect related to CO_2 injection. Vertical seismic profile (VSP) surveys are expected to provide an improved characterization of the reservoir and possibly direct observation of reservoir changes because of their superior repeatability and resolution compared to surface seismic. An upward migration of CO_2 along the reservoir bounding faults into the overlying Paaratte saline aquifer should be readily detected by time-lapse 3D seismic, either surface or borehole.

The results achieved so far with pre-baseline (test), baseline 2D, and 3D VSP data, and time-lapse 3D surface seismic are very encouraging. We conclude that both in-situ effects and the sensitivity of high-resolution seismic measurements exceed our expectations and predictions derived through simulation studies.

Seismic monitoring program at Otway

The supply and injection of CO_2 into the depleted Naylor reservoir is depicted in Figure 1 and it is also discussed in more detail in Dodds et al. (2009). In the current phase (Phase I of the project), the CO_2/CH_4 mix is injected into the depleted Naylor gas field. The geological complexity of the Naylor gas field and its small extent (0.5 km^2) present challenges for detailed reservoir characterization and certainly for the design of a geophysical monitoring program at this site (Figure 2). A regional type of 3D oil and gas exploration survey shot in 2000 was utilized for the Naylor discovery and subsequent production.

Assuming a homogeneous reservoir and no significant chemical interactions, our modeling predicted that injection of CO_2 into the depleted Waarre C reservoir will produce very subtle changes in elastic properties (Figure 3). Impedance changes in the range of 3–6%, depending on the level in the reservoir, were predicted for the Waarre C sand. This change is produced mainly by the pore-pressure increase and density decrease for an 80/20%, CO_2/CH_4 mix injected in the CRC-1.

The injection interval occupies a residual gas zone. An estimated 20% residual CH_4 saturation falls in the flat region of the well known velocity-saturation curve. Hence, in the simple case of homogeneous reservoir (pure quartz), the resulting change in elastic properties is expected to be small. Considering that the repeatability of land seismic is often poor, it was not clear whether the resulting seismic effects could be detected. It should be noted that several additional factors can affect elasticity of the reservoir, and hence predicted time-lapse (TL) seismic results. Potential chemical reactions could soften the rock frame by affecting the grain cement. This would amplify changes in the elastic parameters of the reservoir. Greater heterogeneity of the reservoir rock and/or patchiness could further contribute to the magnitude of the TL seismic effect. Finally, for the predicted impedance changes, the corresponding amplitude changes are much greater (2–3 times for Warra-C). In reality, the change in reflectivity could be four or more times greater than the predicted impedance change, particularly if chemical reactions take place at grain contacts. We concluded that the in-situ TL seismic effect could only be greater than the modeling predicts, and that is the lower bound for planning.

To detect changes in the elasticity of the reservoir rock caused by CO_2 injection at around 2 km depth, a high degree of survey repeatability is needed, which also presumes a high signal-to-noise ratio (as discussed in more detail by Pevzner et al., 2009) would be necessary for monitoring of CO_2 sequestration at Otway. Furthermore, considering the small reservoir extent and the relatively small quantity of CO_2 to be injected (around 66,000 t), a high-resolution seismic survey had to be implemented at this site. Finally, the dominant wavelength produced by surface seismic at the reservoir level is around 85 m; hence, the average reservoir thickness of 20 m falls within the tuning thickness. This could mask CO_2-related changes in the reflectivity and had to be considered.

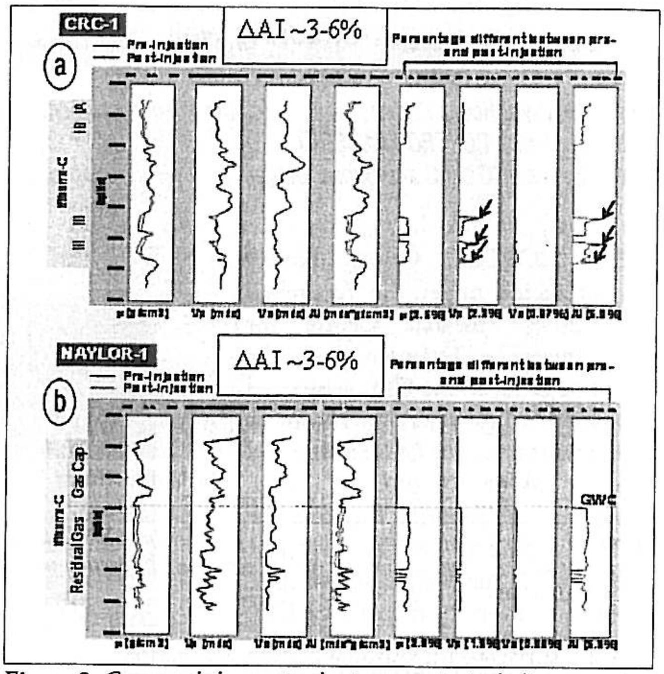

Figure 3. Computed changes in elastic properties including acoustic impedance for two wells. In both cases (a and b) impedance changes are around 6%.

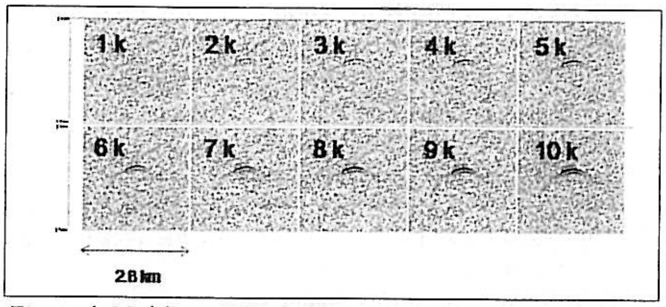

Figure 4. Modeling a "CO_2 leak" scenario in the Paaratte saline formation. The CO_2 quantities shown are thousand tonnes. CO_2 occupies a thin layer, with small areal extent (less than Fresnel radius). Hence diffracted energy is roughly proportional to CO_2 volume. 30% of background noise was used in this simulation.

Upward migration of CO_2—modeling a leak scenario

Early CO_2 leak detection is one of the primary objectives of any monitoring and verification (M&V) program. To investigate the possibility of detecting CO_2 migration into overlying formations, we simulated the case of CO_2 upward migration into the Paaratte, a saline formation that is some 600–650 m shallower than Waarre C (Figure 1). Any CO_2 that potentially escapes along some of the existing faults is likely to accumulate in the overlain Paaratte saline aquifer. Realistically, this could only be very small amounts within the time frames of our trials. Hence, we conducted a 2D sensitivity modeling study that utilized CO_2 quantities in the range 1000–10,000 t. These relatively simple numerical tests showed that TL seismic surveys with a reasonably good signal-to-noise ratio should detect upward migration of very small quantities of CO_2 (2000–3000 t) into the overlying formation (Figure 4).

After these 1D and 2D numerical tests, it became clear that surface 3D TL seismic can be used to verify indirectly the CO_2 containment in the reservoir (Waarre C), and can be used for early leak detection. The only condition is that we

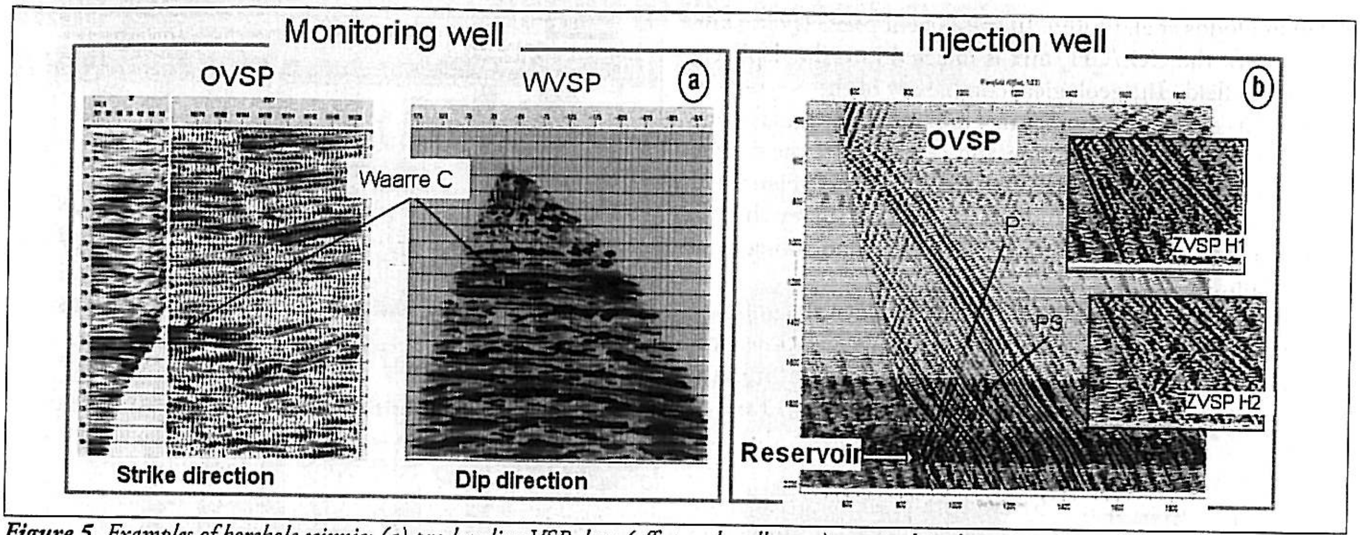

Figure 5. Examples of borehole seismic: (a) pre-baseline VSP data (offset and walkaway) acquired in the monitoring well (Naylor-1) with IVI mini-vibe and (b) pre-injection offset VSP acquired in injection well (CRC-1) with Curtin's free fall "weight drop" source. High-quality data were obtained in both cases.

have TL surveys with reasonably high S/N ratio.

Pre-baseline surveys

To help optimize the design of the time-lapse seismic monitoring program at Otway we conducted several test surveys (pre-baseline) between 2006 and 2008. Pre-baseline data acquisition included both surface and borehole measurements. The objectives were:

- understand in-situ seismic response
- investigate repeatability (coupling effects and their variability, effect of soil saturation and hardness, coherent and ambient noise)
- find an inexpensive yet effective seismic source for subsequent 3D surveys
- design acquisition parameters and optimum geometry for 3D borehole and surface time-lapse surveys
- obtain time-depth curve
- stress direction
- produce initial images over a part of the reservoir
- compare borehole to surface seismic results
- determine position for the new injection well (CRC-1)

Details of these investigations are given in Dodds et al., Pevzner et al., and Al-Yabri et al. (2009). Hence, only the main results are summarized here. In brief, borehole seismic data, pre-baseline and baseline, acquired in injection and monitoring wells, produced exceptionally good quality images (Figure 5a). The frequency content and the repeatability of borehole seismic (VSP) were very good. Both offset VSP (OVSP) and walkaway VSP (WVSP) with a surface seismic source provided superior images in comparison to the 3D seismic data acquired in 2000. Very strong converted S-waves reflected off the Waarre C reservoir can easily be recognized (Figure 5b). This also provides potential to incorporate shear waves into future TL analysis. Surface seismic tests (Dodds et al.) showed that even a quasi-weight drop (free fall concrete breaker) can be used to acquire good quality seismic data. Eventually, within the time frame and possibilities of the project and the site restrictions (upon the source in particular), the TL 3D surface seismic program was designed to maximize S/N ratio (minimize non-repeatability) by employing very high fold and keeping source-receiver lines close together.

The final M&V program over the depleted gas field was designed with a primary objective to verify the containment of CO_2 in the Waarre C reservoir. Since only the F10 weight-drop source was available for this stage, the 3D reflection survey was designed with the following objectives:

- minimal footprint (acquisition in dry period, December–January)
- very high nominal fold (over 100) to partially compensate for moderate to low S/N and hence relatively high non-repeatability
- utilization of all seismic channels for each shot
- minimum acquisition time (reduce the impact on the local farming community)

The acquisition parameters were: source line separation = 100 m, total 30 lines; receiver line separation = 90 m, total 10 lines; receiver increment =10 m; source increment = 20 m; total number of active channels = 440; receivers = 10 Hz, single; shots = stack of four at each position after first settling shot; total number of shots = 2196; nominal fold = higher than 50 across the target area (bins 5 × 10); acquisition system = Seistronix 24-bit distributed system; sample rate = 1 ms; recording time = 3.5 s; shooting pattern = odd source lines for five active receiver lines R1-R5, and even shot lines for active receiver lines R6-R10; and acquisition time = 16 days.

TL seismic results

The 2008 baseline 3D survey was acquired simultaneously

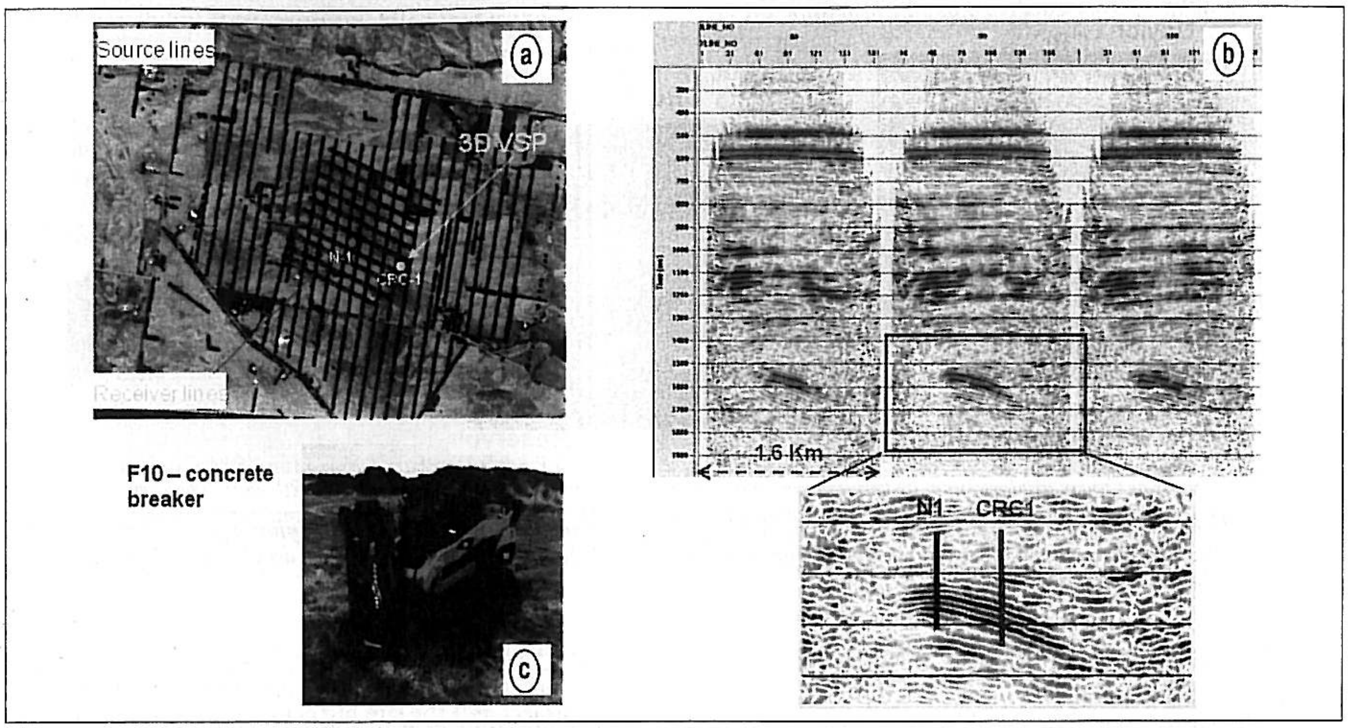

Figure 6. (a) Baseline 3D seismic survey conducted in January 2008: blue = receiver lines, red = source lines. 3D VSP data (CRC-1) were acquired simultaneously with surface seismic. (b) Extracted migrated inlines from 3D survey. (c) Curtin's free fall "weight drop" that is modified F10 concrete breaker was used to acquire these data sets.

with 3D VSP, which utilized the Schlumberger VSI shuttle with nine 3-C elements in well CRC-1 (injection well). This provided considerable savings. Moreover, source statics computed from surface refraction data could now be used for processing 3D VSP data. Similarly, the 3D velocity model derived from the reflection data can be utilized for prestack depth migration of the 3D VSP data set. Finally, the velocity profile derived from zero-offset VSP can be utilized for depth conversion, well tie, inversion, and prestack imaging. The baseline survey started in mid-December, 2007; the VSP surveys were completed in eight days while surface seismic acquisition continued after the Christmas break into January 2008. Acquisition included a number of repeated shots for calibration and repeatability studies. Initial processing and analysis of the 3D VSP data was handled by S. Leaney and A. Campbell from Schlumberger Houston. They have produced impressive initial results (Urosevic et al., 2009).

The baseline reflection seismic data were processed in parallel by a commercial seimic data processing company, DECO Geophysical (Moscow), and by Curtin and CSIRO personnel. This provided a rapid, high-quality data turnover, and allowed the researchers time to fine-tune analysis whilst satisfying management timelines. The results produced by both parties were of high quality and similar to each other. The first set produced by DECO is shown in Figure 6, together with 3D field data geometry. The Waarre C reservoir is clearly visible and easily interpretable. This was an impressive result achieved with an unconventional impact source, such as Curtin's weight drop (F10 concrete breaker).

The first repetition (the first monitor survey) was acquired in 2009. This survey was shot after some 35,000 t of CO_2

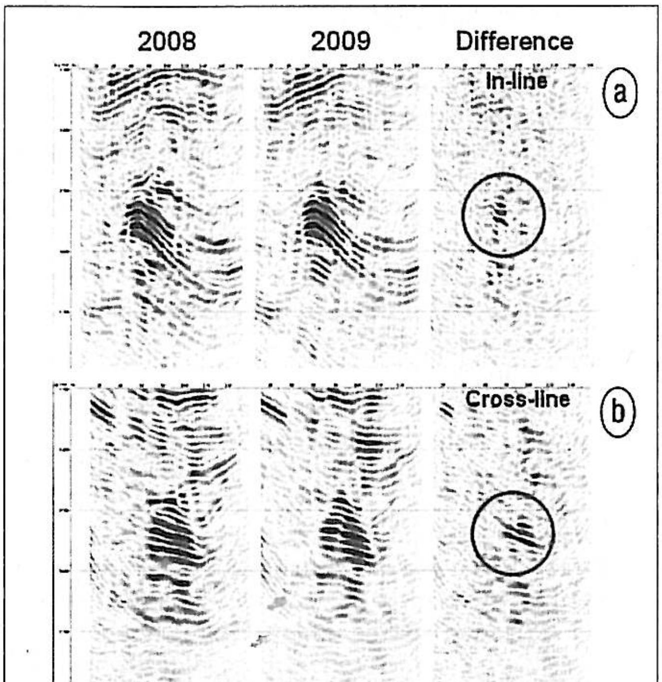

Figure 7. Cross-equalized baseline and monitor cubes at Otway and their difference. (a) Inlines and their difference (b) Crosslines and their difference. Anomalous difference at Waarre C is circled.

were injected into the Waarre C sand. The 2009 survey shared the same geometry with 2008 survey but utilized an IVI Enviro-vibe (15,000-lb peak force) vibroseis as the source. The vibroseis source provided data with higher quality (S/N ra-

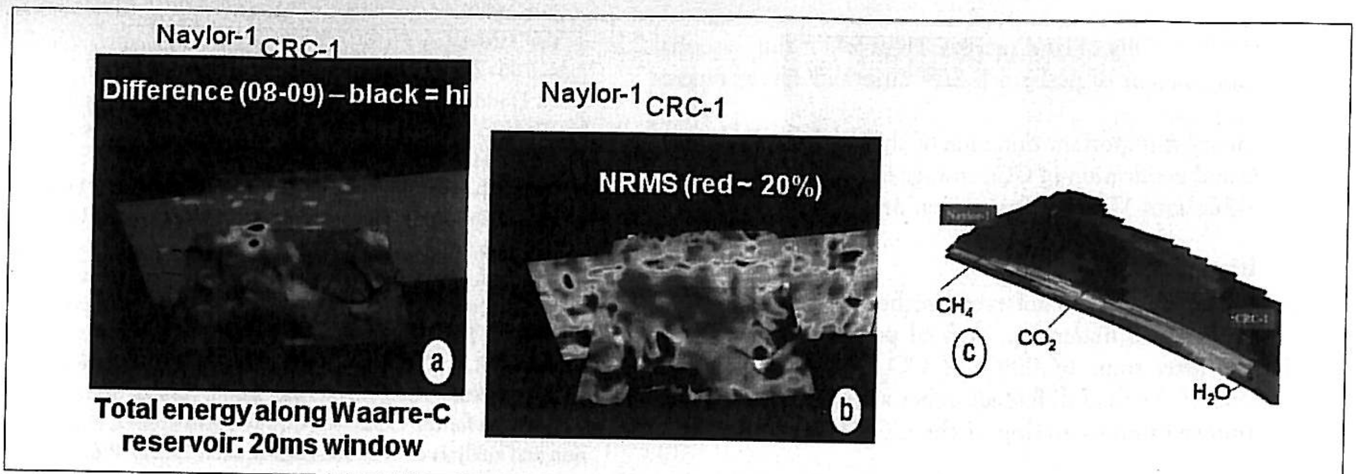

Figure 8. TL result at Otway displays anomaly between two wells (a) Total energy difference map compute over 20-ms window centered at Waarre C. (b) nrms along Waarre C. (c) Initial reservoir simulation result. Free gas at Naylor-1 is modeled to counteract the migration of CO_2 leading to formation of a "ring" structure (black zone in a and red zone in c). The seismic anomaly could be related to a cumulative effect of density decrease, pore-pressure increase, and possibly even some chemical interactions between the host rock and CO_2. Reservoir model by Josh Shu, 2006.

tio and richer frequency content) in comparison to the 2008 weight-drop data. The deployment of a vibroseis source for the monitor survey for Phase I enabled us to have, at the same time, high-resolution baseline data for Phase II of the project. Phase II will investigate issues related to CO_2 sequestration into a heterogeneous saline aquifer, the Parratte.

To perform time-lapse differences for Phase I, the 2009 vibroseis data had to be decimated to the 2008 weight-drop data due to a larger number of receivers used in 2009 (double). Parallel to 2008 and 2009 3D data analysis, we also revisited preproduction the 3D data recorded in 2000. We were then able to compare all three data sets acquired over Naylor Field in the last decade; preproduction 3D acquired with three big 60-klb HEMI vibrators; baseline (or postproduction) acquired with a free-fall weight drop, and a mini-vibe monitor (or post CO_2 injection) survey. Despite quite different sources, all surveys produced similar results; the best S/N was achieved with 2009 data. This is attributed to high fold rather than source strength.

The baseline and monitor 3D sets (2008 and 2009) shared the same processing sequence. It was found that a very small space variant time shift (most of the differences averaged to ±1 ms) and a single matching filter were sufficient to cross-equalize these two sets. Finally, a straight difference could be computed. This is shown in Figure 7, where selected inline and crossline sections illustrate the differences. A clear and interpretable difference cube was produced despite the initially grim predictions built upon numerical modeling results, which suggested a very subtle TL seismic effect likely to be unobservable.

A total energy difference attribute computed over a 20-ms window is shown in Figure 8a, and from this chair display it is clear that a very "clean" time-lapse result was obtained. This is further reinforced by computing a time-variant non-repeatability cube. The computation is performed over a sliding window of 100 ms (Figure 8b). This result shows that nonrepeatability over the reservoir interval is less than 20%, which for land seismic is an exceptional achievement, particularly if we remember that two different (and relatively weak by industry standards) sources were utilized for the baseline and monitor surveys. Finally, the time-lapse seismic anomaly appears to conform well to early reservoir modeling results (Figure 8c). Several years after production, a new smaller gas cap was re-established at well Naylor-1. This gas cap is expected to produce resistance to the buoyancy-driven CO_2 movement in the reservoir. Consequently, the CO_2 should accumulate around it and form a ring-like structure within the limitations of the bounding fault. This is where the TL seismic effect is most prominent, and most likely caused by the combined effects of a density decrease and pore-pressure increase. Since the observed effects are greater than predicted, it is possible that some chemical reactions could have happened at the grain contact (mineral dissolution), making the reservoir rock even more compliant.

Conclusion

Exceptionally challenging conditions for monitoring the CO_2 sequestration process at the Naylor site in the Otway Basin inspired "new thinking." Specifics of the site (permission, accessibility, availability) required the engagement of nonconventional sources and recording geometries, which also enabled rapid data acquisition. Very promising results were obtained with the first monitor survey. The predictions of the TL effect made for 66,000 t of CO_2 injected into Waarre C proved to be on the low side as the monitor survey showed that even 35,000 t is detectable by a surface seismic survey.

We achieved very high repeatability using two different and low-energy output sources. This result suggests that the repeatability of impact sources, including alternative impact sources such as the F10 rock breaker, are acceptable for some terrains such as Otway. Furthermore, a comparative analysis of the three different sources shows that high fold (and careful processing) is important for improving the S/N ratio and hence repeatability of land surveys. High fold is thus essential for improvement of post-stack S/N ratio and survey repeatability.

The most important outcome of this study is that monitoring and verification of CO_2 storage into depleted gas fields is possible with 3D TL seismic, even onshore.

Additional remarks

The Otway project has not even finished Phase 1, and Phase 2 plans are well underway. A final postinjection survey is planned after some 66,000 t of CO_2 have been injected. Analyses of the final difference cubes are expected to enable an improved understanding of the CO_2 distribution in the reservoir.

We hope that additional understanding of the TL seismic effect will be achieved through vector wavefield analysis, such as changes in the polarization direction of split shear waves and the splitting intensity. This so-called time-lapse anisotropy study will also be less sensitive to S/N ratio and may have the potential for a saturation estimate. By the end of the project in 2010, we hope to establish a general approach and methodology for monitoring of CO_2 injection into other depleted gas fields that may also be relevant for enhanced hydrocarbon recovery elsewhere. **TLE**

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