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Seismic Monitoring Feasibility Study of CO2 Injection into Saline Aquifer - A Case Study from Otway Basin, Australia

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SUMMARY

CO2 sequestration into underground formations requires the application of well panned monitoring methodology. One of the key elements in the design of the monitoring strategy is the prediction of rock property changes resulting form injection of CO2. In this study we investigate whether seismic methods can be used to detect small quantities of CO2 injected into saline aquifer. To do this we generated accurate, noise polluted time lapse synthetic models. We pushed the noise level to an extreme case to arrive at the limiting conditions for the application of time-lapse survey.

Despite the fact that synthetic noise models can never quite simulate the in situ conditions, results of the modelling shows that we can expect to detect time-lapse seismic response. Moreover this is true even for the worst possible data quality we experienced during repeated seismic test surveys in Otway basin. Thus as much as qualitative analysis is concerned it is clear that even sparse time lapse 3D seismic surveys are sufficient for monitoring of CO2 injection at Naylor site. However, to map distribution of CO2 plume in space or to attempt quantitative analysis we need the highest possible S/N ratio and high resolution seismic data.

Introduction

Carbon dioxide projects consider various geological formations as candidates for CO_2 storage. Most natural and at the same time the lowest risk approach is to utilise depleted gas and oil fields for CO_2 storage as its containment in such fields is practically guaranteed. The first phase of the Otway Basin pilot project explores the monitoring possibilities when CO_2 is injected into a depleted gas field. Clearly we expect very subtle to un-measurable 4D seismic effects, particularly when CO_2 is injected into a small, deep and structurally complex gas reservoir as is the case for Naylor field in Otway basin. We deployed somewhat specific monitoring strategies for Naylor (Urosevic et al, 2007, 2008). The main idea is to have assurance surveys which will be also used to detect possible upward migration of CO_2. The only possibility at Naylor site is that CO_2 migrates up one of the two big faults into a Paaratte saline aquifer. Thus verifying a "no-CO_2-leak" in Paaratte we also indirectly confirm CO_2 containment in depleted Waarre-C gas reservoir. Moreover the second phase of Otway project aims to evaluate various trapping mechanisms by injecting small amount (up to 10000 t) of 80/20% CO_2/CH_4 mixture into saline aquifer (the Paaratte formation). Hence these two phases are related through the seismic response to CO_2 injection into Paaratte. Consequently it is of critical importance for both phases of the project to evaluate time-lapse seismic signature for Paaratte saline aquifer.

In this study we investigate whether seismic reflection methods can be used to detect small quantities of CO_2 in Paaratte formation "5" which is at depth of around 1 km and contains relatively permeable sands. In a noise-free environment we certainly expect significant changes in reflection amplitudes when displacing formation brine with a gas mixture. To come closer to simulating a real field experiment we need to depart from noise-free conditions. Hence accurate, "noise polluted" synthetic study is required to identify if these changes can be conserved with data quality that we can reasonable expect to acquire at Otway site. Moreover pushing the noise conditions to extreme will give us the limiting case that will provide us with a type of sensitivity analysis for the case of gas mixture injection into saline aquifer.

Modelling of CO_2 injection time-lapse seismic response

The following steps were utilised to create a relevant synthetic seismic study:

1. Initial seismic model was designed from reservoir simulation study
2. Hydrodynamic modelling of the injection (reservoir simulation) was combined with the rock physics modelling to predict most likely changes in rock properties
3. Post-injection depth model design for modelling time lapse seismic response changes
4. Generation of synthetic seismic time sections (two dimensional)
5. Generation of a background noise across the entire frequency range of the primary signal
6. Repeatability study with variable S/N

A layered model, based on interpretation of real seismic data, with log-derived interval velocities was used for the simulation study. The model was designed to cover a depth interval from 0 m to 2000 m. Horizons were mapped from a line extracted from pre-production large scale 3D survey recorded in 2000.

To construct velocity depth model we utilised interpreted time horizons which were subsequently converted to depth through interval velocities calculated from zero-offset VSP data recorded in Naylor-1. The final models before and after CO_2 injection are shown in Figure 1. Initial model contains 9 horizons across depth range of 300 m to 1500 m. The tenth "layer" is then obtained after CO_2 injection into Paaratte formation 5. The shape of the "plume" in the Paaratte formation is defined by hydrodynamic modelling (Figure 2) which predicts CO_2 distribution in the reservoir 120 days after injection of 10000 t of CO_2 gas mixture is accomplished.

From the hydrodynamic modelling the following reservoir properties were used: pressure = 12 MPa, temperature = 48°C, porosity = 25%, water salinity = 750 ppm.

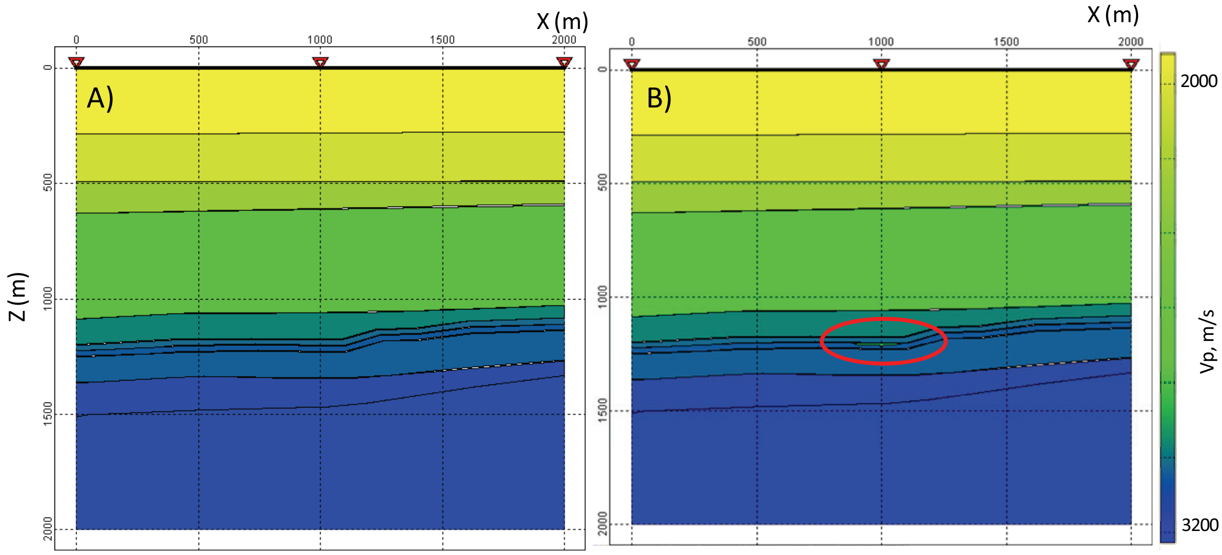

Figure 1: *Pre-injection (A) and post-injection (B) velocity-depth models.*

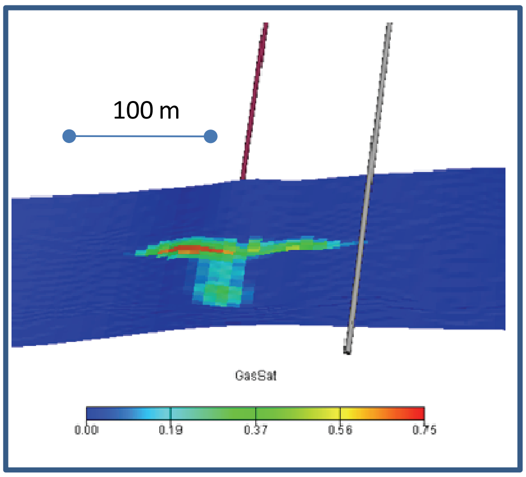

Figure 2: *A cross-section showing density distribution for a case of 10000 t of CO_2 injected (time 120 days).*

Fluid elastic properties were first computed and then a standard fluid substitution technique we obtained following pre- and post-injection rock properties using approach of Wisman and Urosevic (2007).

- Pre-injection: 100% brine, Vp = 3.05 km/s, Vs = 1.65 km/s, r = 2.32 cm3
- After injection: 20% brine, 80% free gas, Vp = 2.83 km/s, Vs = 1.73 km/s, r = 2.12 g/cm3

Using these new values the corresponding velocity-depth model after injection of 10000 t of CO_2 into the lower Paaratte layer is constructed (Figure 1B).

The exploding reflector method was then implemented using Tesseral package to create synthetic seismograms.

Repeatability and noise sensitivity analysis

To be detectable, a time-lapse seismic signal caused by CO2 injection has to be greater than all other changes between baseline and monitor surveys. The repeatability analysis of the real field data acquired along 2D test line located inside of planned 3D survey identified that a low energy of the seismic source relative to the background noise will yield poor repeatability (Pevzner et al, 2009). To investigate Paaratte CO_2 injection scenario, we conducted synthetic sensitivity analysis where we analysed the effect of signal-to-noise (S/N) ratio on time-lapse signal predicted by rock-physics model. For that purpose we used source to background noise level similar to the one measured in the data, in situ. The analysis was conducted along the following steps:

1. To measure non-repeatability we selected two horizons; the shallow strong reflector (marker horizon) and a deeper, much weaker reflector situated within Paaratte sequence (Figure 3). Both horizons selected are above the injection zone.
2. Two realisations of random non-repeatable noise with spectrum exactly the same as measured in seismic data (5-100 Hz) were computed, one for the baseline and one for repeated data set. In both cases we had the same number of traces, samples, etc. as the synthetic seismic sections.

3. By mixing the random noise with ‘baseline’ and ‘monitor’ synthetic sections we produced sections with different signal to noise ratios.
4. S/N ratio and normalized root mean square difference (NRMS) value were computed on these noisy sections along “Marker” and “Paaratte” horizons within 100 ms time window.
5. The difference sections computed for different S/N ratios are panelled for inspection.

NRMS as defined by the equation provided by Kragh, E. and Christie, P. A. F. (2002). Signal-to-noise ratio was computed using approach based on estimation of normalised cross-correlation between neighbouring traces in each survey (Hatton et al., 1986). This allows us to obtain S/N ratio in assumption that noise is additive, uncorrelated and have zero mean value.

Example of ‘noise polluted’ seismic sections and their difference is presented in Figure 3. This case approximately corresponds to data quality observed on 3D survey acquired in 2007 in that area.

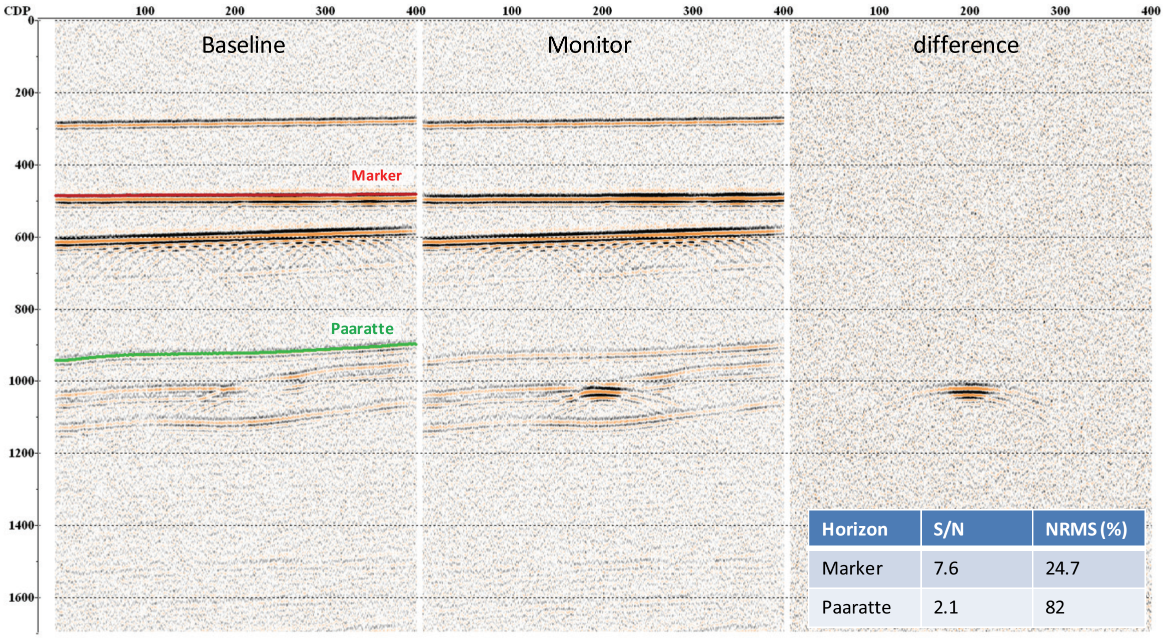

Figure 3: *Relatively noisy pre-injection, post-injection sections and their difference, horizons selected for sensitivity analysis marked with red (‘Marker’) and green (‘Paaratte’).*

Figure 4 presents a composite result which clearly demonstrates that even for an extreme noise level and related very low repeatability we can expect to readily detect injection of CO2 into Paaratte by time-lapse methodology.

To make these simulations relevant to the case of 3D seismic data recorded 2000 we increased distance between traces to 20 m as was the biggest bin size used to process 3D pre-production survey in Otway basin. From this analysis we can conclude that a limiting NRMS value which can be still accepted for time lapse surveys is 125%, since we can still detect the signal. For this case S/N is approximately 1.5, that is signal is marginally above the background noise level. Indeed, if injection of gas into saline aquifer is supposed to produce one of the brightest seismic events in the whole section we should be able to observe it as long as we can observe any other reflection in the data.

Obviously these values are affected by random noise only. Our noisy models do not account for the variations in the near surface conditions and positioning errors which are important factors affecting repeatability of seismic time lapse land surveys (Urosevic et al., 2008).

However from the field tests conducted (Pevzner et al., 2009) we have no reason to believe that the actual NRMS will be higher than 80-100%, and which should be still detectable by time-lapse seismic. Still with field data we can expect to have significant contribution of source generated noise (in the low frequency range) and possibly even lower non-repeatability than predicted here.

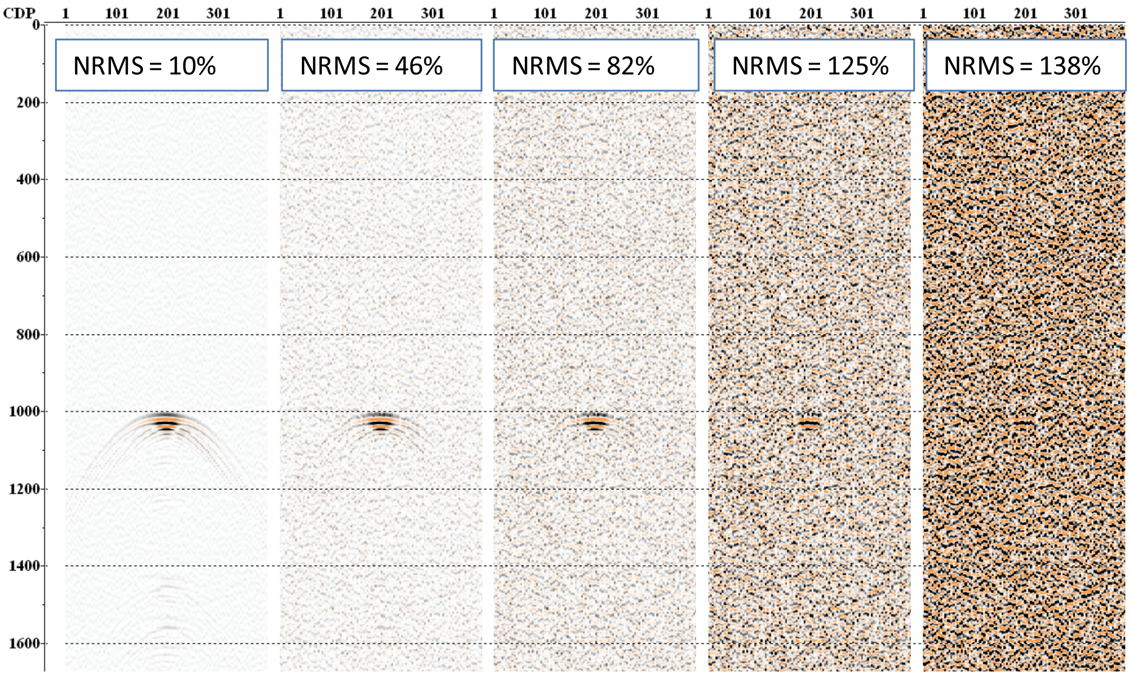

Figure 4: *Difference sections versus NRMS values obtained for Paaratte interval, step between traces is 20 m*

Conclusions

Feasibility study for the application of seismic monitoring for CO_2 injection into saline aquifer (the Paaratte formation) proved that we can expect to detect a time-lapse seismic response even for the worst possible data quality we experienced during seismic test surveys in Otway basin. However, to detect accurately distribution of CO_2 plume in space we need the highest possible S/N ratio. Moreover seismic measurements are also necessary to detect possible migration of CO_2 into overlain strata from the point of injection. In such scenario very small quantities of CO_2 could migrate upwards or along the fault plane. Hence high S/N and very good spatial resolution of seismic data is required to address such issues at Naylor site.

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