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Feasibility of time-lapse seismic methodology for monitoring the injection of small quantities of CO_2 into a saline formation, CO2CRC Otway Project

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Abstract

A key objective of Stage 2 of the CO2CRC Otway Project is to explore the ability of geophysical methods to detect and monitor injection of greenhouse gas into a saline formation. For this purpose, injection of some 10,000 – 30,000 tonnes of CO_2-rich mixture into the Paaratte formation, a saline aquifer located at a depth of about 1,400 m, is planned. Before such an injection experiment is undertaken, we assess the feasibility of geophysical monitoring using computer modelling. To examine the detectability of the plume we need to estimate the time-lapse signal and time-lapse noise. The time lapse signal is modelled using flow simulations, fluid substitution and seismic forward modelling. In order to assess the applicability of time-lapse seismic to monitor the injection, the predicted signal is compared to the time-lapse noise level from the recent 4D seismic survey acquired at the Otway site in 2009-2010. The methodology is applied to two alternative reservoir intervals located at a depth of 1392-1399 m and 1445-1465 m below the sea level, respectively. These intervals are considered to be the two possible options for the injection. The results show that injection into the lower interval will produce a plume of a larger thickness and smaller lateral extent, and a seismic response that is more likely to be detectable. The developed feasibility assessment workflow, and the results of its application to the Otway site, can be used to assess the ability of seismic methods to detect and monitor greenhouse gas leakage in other CCS projects.

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1. Introduction

The CO2CRC Otway Project is Australia's first demonstration of the deep geological storage or geosequestration of carbon dioxide (CO_2). Stage 1 of the project consisted of the injection of 65,445 tonnes of CO_2-rich mixture into a depleted gas reservoir at the Naylor Field, Otway Basin, Victoria, Australia [1]. Stage 2 involves injection of the same gas mixture into the Paaratte formation, a saline aquifer located in the same area at a depth of approximately 1,400 metres below mean sea level [2]. The main objective of this experiment is to explore the ability of geophysical methods to detect and monitor the greenhouse gas mixture in a saline formation. For this purpose, injection of some 10,000 – 30,000 tonnes of the gas mixture is planned. Before such an injection experiment is undertaken, it is important to assess the feasibility of geophysical monitoring using computer modelling.

The purpose of this study is to investigate whether the time-lapse seismic reflection imaging methods can detect changes of the seismic response caused by injection of a small amount (10,000 – 30,000 tonnes) of 80/20% CO_2-CH_4 mixture into the Paaratte formation. Three repeated 3D seismic surveys were performed in 2008, 2009 and 2010 in the Otway area as part of Stage 1 of the Otway Project [3, 4]. Of these three 3D surveys, the surveys performed in 2009 and 2010 have the highest data quality due to the use of an optimal seismic source (mini-vibrator) and high fold. These 3D surveys will serve as baseline surveys for the Stage 2 monitoring program. The monitor surveys will be repeated with the same acquisition parameters.

To simulate the field experiment more adequately, we need to estimate the time-lapse signal due to gas injection and compare it with the time-lapse noise. Hence accurate, "noise polluted" synthetic datasets are required to identify whether these changes can be detected with data quality that can reasonably be expected to be attained at the Otway site. Thus, our approach consists of two main stages: modelling of the time-lapse signal and assessing the level of time-lapse noise.

2. Reservoir modelling

Modelling of the time signal is based on the results of reservoir simulations, which in turn require a static geological model as input. The static model was built using the horizons extracted from the regional seismic data [5]. This model includes two possible perforation intervals. The upper interval is located at a depth of between 1392-1399 m TVDSS (true vertical depth below mean sea level). The reservoir, which was also the target for a comprehensive residual saturation and dissolution experiment [6], is a thin (7 m), high porosity clean sandstone section. Whereas the lower possible perforation interval located between 1445-1465 m TVDSS is much more heterogeneous (clean sandstone to shaly sandstone) with a thickness of approx. 15-20 m.

The flow simulations were performed by a compositional numerical reservoir simulator for a number of injection scenarios involving injection between 10,000 and 30,000 tonnes of the gas mixture into two alternative perforation intervals in the CRC-2 well. An injection rate of 111 tonnes per day was assumed. The phase behavior of the CO_2-CH_4 mixture was modelled using the Peng-Robinson [7] equation. The dissolution of CO_2 in formation water is modelled by the correlations proposed by Chang et al. [8]. Two-phase (brine–gas) flow modelling utilizes relative permeability and capillary pressure functions adapted from the published core flood data for CO_2-brine flow in a Paaratte core [9].

3. Model of elastic properties

Modelling the effect of the plume on seismic data consists of three main steps:
- Building an elastic model of the subsurface before injection.
- Estimating the changes of elastic properties likely to occur due to the presence of the plume.
- Computing the seismic response with and without the plume.

The first step is to build an elastic model of the subsurface without the plume. Information on elastic properties of the subsurface comes from well log data and seismic data (VSP and surface seismic). Well log data have the highest vertical resolution and can therefore be used to model the effects of fine layering. However, well log information is only available in a small number of well locations. On the other hand, information from seismic data has broader spatial coverage but much lower vertical resolution. The results of the flow simulations show that the gas plume in both intervals will have a relatively small thickness (2-4 m and up to 15 m, respectively). Thus the main challenge of the seismic program is detection of the very thin plume. Therefore, it is essential to model the effects of thin layering as adequately as possible. To this end, we build the elastic model of the subsurface from the well logs.

First, we build a 1-dimensional (1D) model from well logs from the CRC-2 and CRC-1 wells and estimate the changes in elastic properties for different plume thicknesses. These models are later used to perform accurate and efficient full-waveform modelling of the seismic data. We then build a 3D model of the subsurface by laterally interpolating and extrapolating log data from three wells along horizons mapped from 3D seismic data. To estimate changes of elastic properties away from the well, we use the flow simulation results, based on the porosity in the static geological model and the interpolated log data. These input parameters, particularly wet velocity and porosity, need to be consistent. To achieve this we adjust the velocities and densities within the injection interval and keep the porosity model unchanged, since it determines the volume of the fluids in the flow simulations. More precisely, we populate the geological model with P-wave and S-wave velocities based on rock physics models calibrated to the log data in the CRC-2 well. These models are also used for 2D seismic finite difference forward modelling along a line crossing the plume. This is done to account for the finite lateral extent of the plume and lateral variations of its thickness.

4. Changes of rock properties due to CO_2/CH_4 injection

In order to predict the change in the elastic properties, we employ the Gassmann fluid substitution workflow [10, 11]. In the case of the Paaratte injection interval, the elastic properties of the rock saturated with brine and the injected gas (mixture of CO_2 and CH_4) are calculated from the elastic properties of the rock saturated with formation brine, the properties of the fluid mixture, the solid grain material and porosity. To assume realistic fluid saturations and properties we utilize the flow simulation results for a number of injection scenarios.

From the predicted gas composition, the elastic properties of the free gas are computed by an equation of state based on the GERG 2004 model [12] implemented by J. Ennis-King (personal communication). The in-situ brine bulk modulus is computed from the empirical formula of Batzle and Wang [13], while the brine density is obtained from the flow simulation results.

To estimate the fluid bulk modulus of the CO_2/CH_4/brine mixture, we apply Wood's mixing rule [11]. The use of Wood's equation assumes uniform saturation, a reasonable assumption for porous sandstones at seismic frequencies. Since the considered perforation intervals vary from clean, high porosity sandstone to shaly sandstone, an effective bulk modulus of the rock is calculated for a mixture of clay and quartz (using an average of the Hashin-Shtrikman bounds).

The matrix density is calculated directly from the density and porosity logs for the 1D model and kept constant (2.7 g/cm^3) for the 3D model. The dry bulk modulus of the rock is determined from the sonic velocities of the baseline models (fully brine saturated conditions) by solving Gassmann's equation. Then, Gassmann's equation is applied to calculate the elastic properties of the rock after injection.
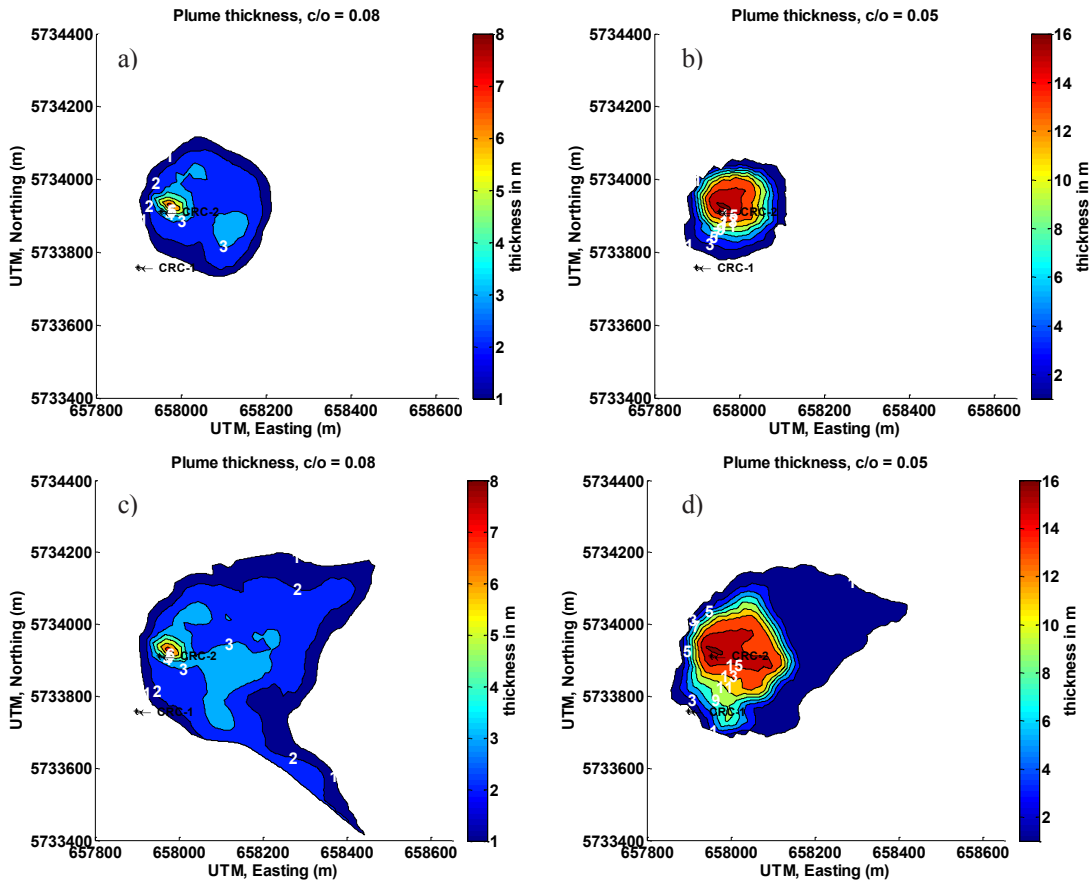

Fig. 1. "Seismic thickness of the plume for 10,000 tonnes (a, b) and 30,000 tonnes (c, d) of injected CO_2/CH_4 upper injection interval (a, c); lower injection interval (b, d), calculated for relative changes in AI that are greater than 8% and 5%, respectively

The seismic forward modelling is performed in 1D for different plume thicknesses, 1 to 6.9 m, and a gas saturation of 15%, and 1-17 m and a gas saturation of 5 %, for the upper and lower injection interval respectively. The gas saturations are chosen to represent the relative changes of AI in the 3D model. For the 3D model we compute the change of P- and S-velocities, density and acoustic impedance (AI) for each grid point of the reservoir zone. Then, for each lateral location, the effective thickness of the plume is calculated as the sum of the thicknesses of those cells which have more than 8% change in AI for the upper injection interval and more than 5% change in AI for the lower injection interval. Figure 1 shows these thicknesses in map view for 30,000 tonnes and 10,000 tonnes. The lower perforation interval provides a thicker plume, but the average relative changes of AI are smaller with 6% compared to 10% in the upper injection interval.
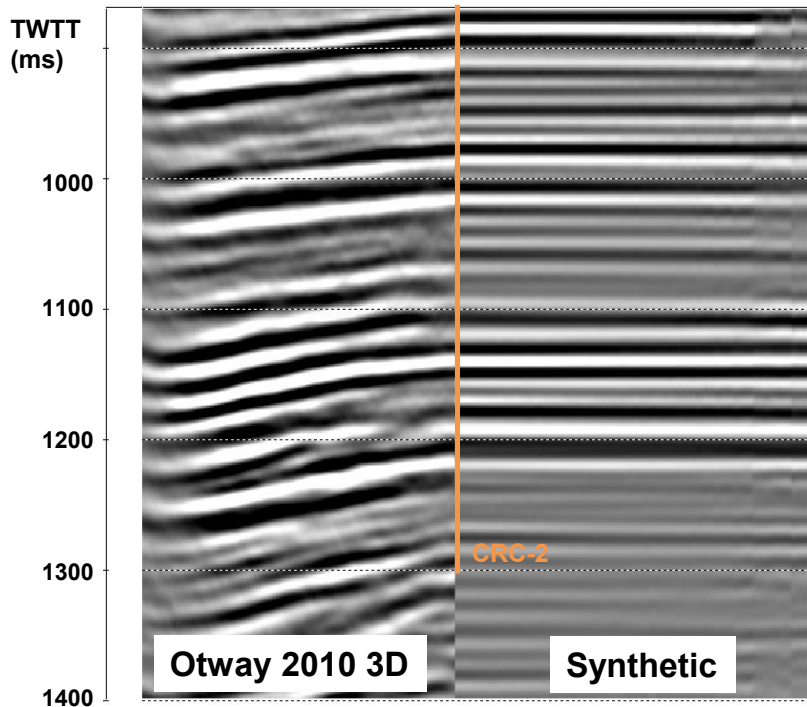
Fig. 2. Comparison between synthetic and Otway 3D baseline (2010) field data along an inline direction near the CRC-2 well

5. Seismic forward modelling of the time-lapse signal

Since the geometry of the overburden in the area is relatively flat, the forward modelling is done using the 1.5D reflectivity algorithm implemented in OASES software [14]. To reduce the computation time, for all traces the simulations for the baseline case were performed for 'flat geometry' elastic properties extracted from the CRC-2 well log data. Next, we substitute every trace from the actual Otway 3D seismic dataset (pre-stack) with the synthetic trace with the corresponding offset and process these data to the final stacked volume using the standard processing flow. By doing so, we obtain precisely the same offset/angle distribution which we have in the real data. This is important as the AVO effect in the case of gas injection can play an important role. Figure 2 shows the comparison of the stacked synthetic 'baseline' and field data along an in-line direction near the CRC-2 well location.

For the monitor case, the rock properties are altered in the gas saturated interval, whose thickness is obtained from flow simulations and fluid substitution. A set of 3D volumes representing different plume thicknesses while being still 1D (e.g. laterally infinite) is then computed. To simulate the finite lateral extent of the plume, synthetic 'monitor' survey volumes are computed by the interpolation between these volumes according to the plume thickness maps. The results for 30,000 tonnes of injected CO_2/CH_4 are shown in Figure 3.

To verify the validity of this workflow, we also perform 2D finite difference modelling along an inline direction (baseline and monitor) using the forth-order elastic 2D FDTD algorithm with a fine spatial grid and a cell size of 0.5x0.5 m. The 2D modelling showed almost the same amplitude of the time-lapse signal as the 1.5D modelling.

6. Time-lapse noise

Our ability to detect and analyze any signal is always limited by the noise level. In case of application of seismic reflection method to the reservoir monitoring this is the level of data repeatability or time-lapse noise. Previous studies of the factors affecting the repeatability of the Otway time-lapse data [4, 15] show that for this site the repeatability is primarily controlled by the presence of the ambient noise and seasonal variations in the upper part of the section.
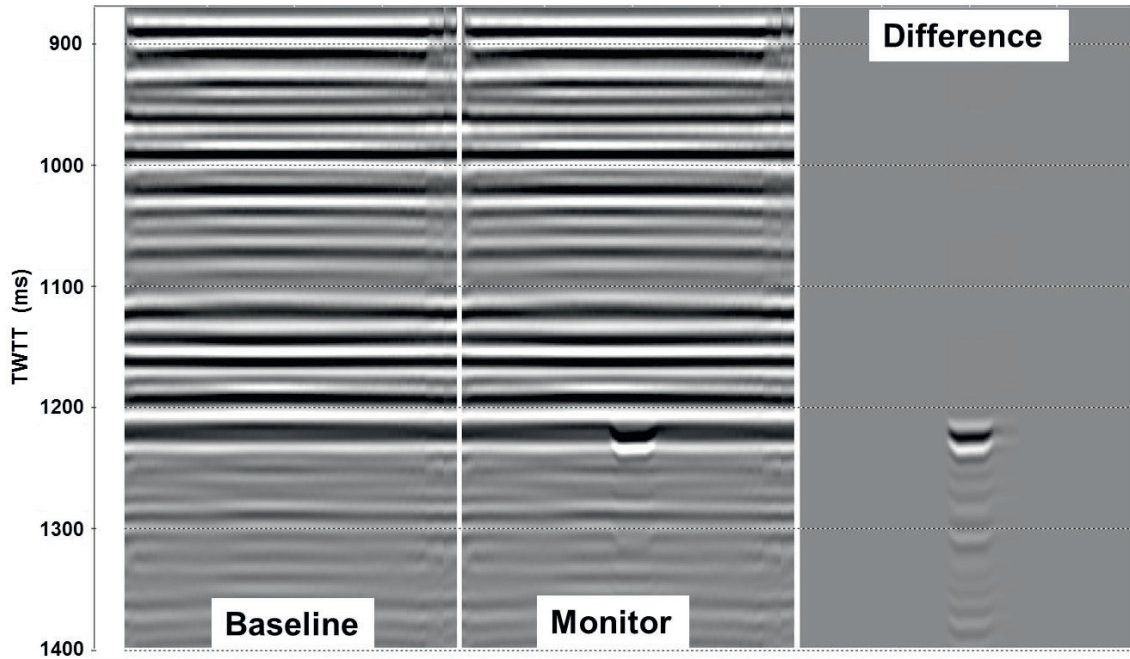

Fig. 3. Stacked synthetic baseline and monitor data for 30,000 tonnes of injected CO_2/CH_4 along an inline direction near the CRC-2 well and the difference volume (Monitor - Baseline)

In order to evaluate the effect of the noise on the time-lapse response, the straightforward approach is to combine simulated signal with some model of noise. One of the typical noise models used is the random band-limited noise [16]. This approach was recently applied to the Otway site [1, 3]. However a significant weakness of this model is that it ignores the spatial correlation of the time-lapse noise.

Three vintages of 3D seismic were acquired at the Otway site in 2007-2010 as a part of the first stage of the project. This gives an opportunity to use actual field realisation of the time lapse noise in this study as no signal-related changes are expected to exist in the part of the record that corresponds to the anticipated injection interval. We balance the amplitude of the field 3D data acquired in 2009 and 2010 to match the amplitude of the synthetic 'baseline' survey, compute the amplitude-calibrated difference between field 2009-2010 data and mix it with the modelled signal. The result of this operation is shown in Figure 4.

It is apparent that the upper injection interval does not necessarily allow the detection of 10,000 tonnes injection with a high level of confidence. For this interval the time-lapse signal slightly exceeds the noise level. Injection of 30,000 tonnes improves the detectability. Injection into the lower interval is expected to

create much stronger signal for either of the modeled injection volumes. The spatial extent of the area where the RMS level of the signal (estimated in 30 ms window around the injection interval) exceeds the noise level by a factor of two has a diameter of ~170 m for 10,000 tonnes injection and ~270 m for 30,000 tonnes.
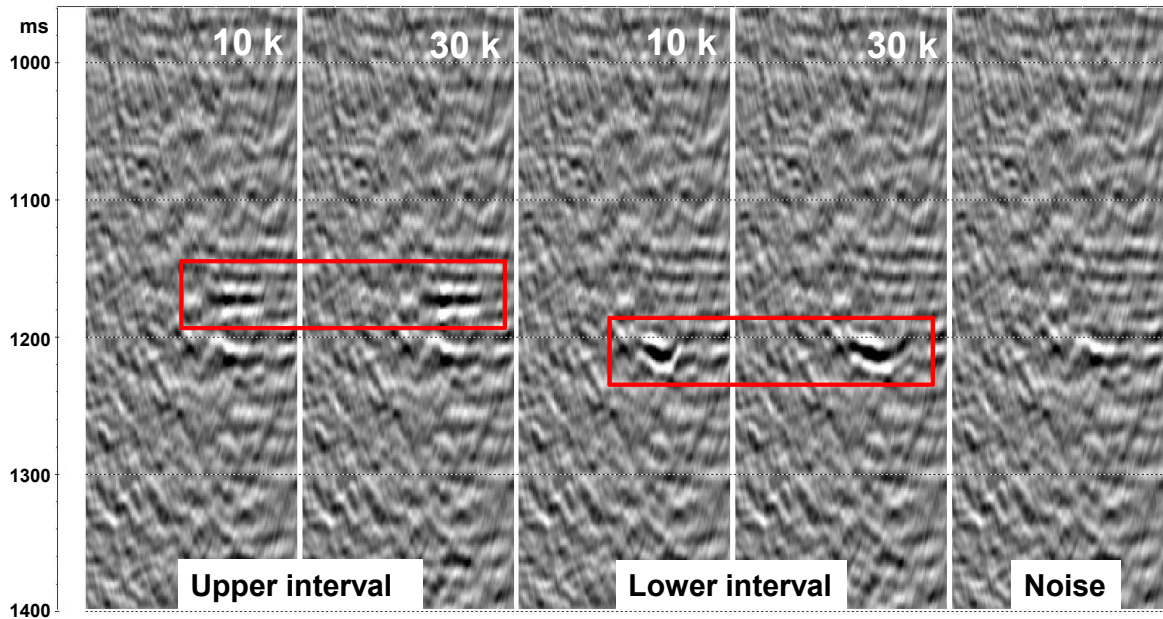

Fig. 4. Synthetic time-lapse signal superimposed with noise obtained from previous Otway 4D survey

7. Conclusions

To assess the feasibility of time-lapse surface seismic monitoring of CO_2 injection, a workflow is developed comprising flow simulations, fluid substitution and seismic forward modelling. This workflow is applied to gas injection into two potential reservoir intervals of the Paaratte formation (Otway Basin, Australia) located at a depth of 1392 and 1445 m TVDSS respectively. Reservoir flow simulations show that the plume in the upper interval has small thickness (from 2 to 3m) but large lateral extent (up to 400 m) and up to 10% change of acoustic impedance. The lower perforation interval provides a thicker plume (up to 15 m), but smaller lateral extent (~200 m) and the average relative changes of AI are smaller (about 6%). This in turn results in stronger time-lapse seismic signal from the plume in the lower reservoir interval. To analyse the detectability of this signal on the background of noise, the time-lapse noise was estimated from the previous (2009-2010) 4D data at the Otway site. Joint analysis of the modelled time-lapse signal and noise suggests that the plume in the lower interval is more likely to be detectable by 3D seismic with the same seismic source and acquisition parameters as in the 2009-2010 surveys. The developed feasibility assessment workflow, and the results of its application to the Otway site, can be used to assess the ability of seismic methods to detect and monitor greenhouse gas leakage in other CCS projects.

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