Modeling in situ 4D seismic response for Otway basin CO_2 sequestration project

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Summary

Injection of CO_2 into a depleted gas field, Otway basin, Australia, is expected to create very subtle changes in elastic properties of the reservoir. This is a serious challenge for the monitoring program at this site. Here, we perform a series of numerical experiments to evaluate the likelihood of detecting a weak 4D signal caused by CO_2 injection. We simulate seismic response changes due to variable near surface conditions. We also take into account the expected ambient noise level. To come to realistic input parameters a detailed analysis of borehole seismic data (several Vertical Seismic Profile, or VSP surveys) is performed. We then analyze the possibility of extracting 4D seismic signatures of CO_2 from the simulated low repeatability seismic data.

Introduction

CO_2 capture and storage is one of the most promising techniques to reduce CO_2 emissions into the atmosphere. A feasibility study, onshore Otway basin, Australia, aims at evaluating the viability of CO_2 storage into a depleted gas field. Of particular interest for this study is the assessment of monitoring methodologies: injection of CO_2 is expected to cause very subtle changes in elastic properties of the reservoir rock. Such conditions present a serious challenge for the application of time-lapse seismic monitoring technologies. However, poor repeatability caused by significant changes in weathering properties (ground saturation level, variations in the composition of the near surface) and ambient noise (wind, machinery at work) could easily overcome predicted 4D seismic response changes (~5%) caused by CO_2 injection (Li et al., 2005). In this framework, an extensive VSP monitoring program has been planned at the Otway site. To investigate the applicability of VSP surveys, we numerically simulate seismic response for in situ conditions. Subsequently, we try to extract a weak CO_2-related 4D seismic signature from the data.

We use a finite difference elastic code to model the seismic response from repeat walkaway VSP surveys, which will be acquired several months after CO_2 injection starts (April 2008). To get a set of realistic parameters for the modeling study we first analyze available field data.

Base line data

The first pilot VSP study has been conducted in May 2006. Zero offset VSP (ZVSP), offset VSP (OVSP) and Walkaway VSP (WVSP) data were acquired in the monitoring Naylor-1 well, using high precision three-component accelerometers. A compressional slowness log, from 490 to 2129 m MD, and a density log from 1927 to 2143 m MD have also been acquired. This survey aimed at testing VSP methods for CO_2 injection monitoring at Otway. The signal strength, frequency content and processed image quality were of primary interest. Comparative analysis between pilot VSP and 2D surface seismic data (Urosevic et al, 2007) showed that VSP methods are preferred at this site because they preserve higher frequencies. Subsequently, in 2007, in the newly drilled injection well (CRC-1), ZVSP, OVSP, and the first 3DVSP in Australia, have been acquired. Logs of compressional slowness (128 to 2224 m MD), shear slowness (460 to 2220 m MD) and density (two intervals from 808 to 1543 m MD and from 2002 to 2190 m MD) are also available.

Model building

The initial model building was based on the logs acquired in the monitoring well, Naylor-1. The compressional slowness was calibrated using VSP data. Knees were chosen to minimize the influence of the velocity correction on the impedance curve. Block shift corrections were preferred to preserve the dynamic of the sonic curve. The corrections were mild over the entire interval. An accurate checkshot curve was built from ZVSP that was recorded from 2010 m MD to 120 m MD (the entire log interval is covered). Shear slowness had to be constructed from compressional slowness since no measurement was recorded. A constant ratio Vp/Vs = 2 was adopted, which approximately matched the ratio observed at the nearby

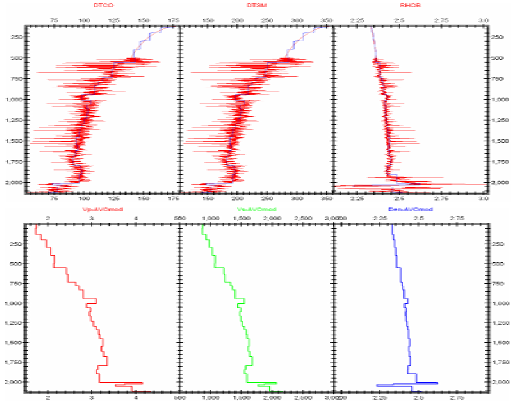

Figure 1: Top: log zoning and blocking results. From Left to right: compresional slowness, shear slowness, density. Log values in red, blocking results in blue. Bottom: velocity model, from left to right, compressional velocity, shear velocity, density.

CRC-1 well, where both compressional and shear slownesses are available. The available density log was used (1927 to 2143 m MD), and Gardner relationship was calibrated to extrapolate the density log using the sonic data. The three log curves were then extended up to surface following the compaction trend of the upper interval (500 to 1000 m MD).

Zoning and blocking were completed over the entire log interval. About 34 layers were detected with an average thickness of about 60 m. Considering a low central frequency (30 Hz) used for synthetic generation (to save computational time), this layer thickness satisfies Backus criterion (Backus, 1962). The resulting velocity model is shown in Figure 1.

Another critical input parameter for the modeling is attenuation: we have to select the appropriate Q factor. For that purpose we analyzed ZVSP data recorded in both wells (Naylor-1 and CRC-1). Compresionnal quality factor (Qp) analysis was performed using the classical spectral ratio method, which compares the decay of high frequencies between two selected traces. This spectral ratio method is generalized in a multi spectral ratio approach (Leaney 1999), which uses all possible pairs of shots or receivers to improve the statistical significance of Qp estimates. The total number of trace pairs available from N traces in a dataset is N(N-1)/2. In practice about half of the receiver pairs have insufficient time differences and can be discarded based on a quality of fit criterion (we imposed a correlation coefficient greater than 75%). The only input variables to the Qp estimation are the low and high frequency cut-offs (30-120 Hz for Naylor-1 ZVSP, and 5-100 Hz for CRC-1 ZVSP) and optional coherency smoothing parameters. Figure 2 shows Qp estimates versus receiver-pair midpoint for the entire VSP interval. Estimates are confidence color-coded based on inverse slope standard deviation with smaller values being blue and larger values being yellow-red (minimum value of 75%).

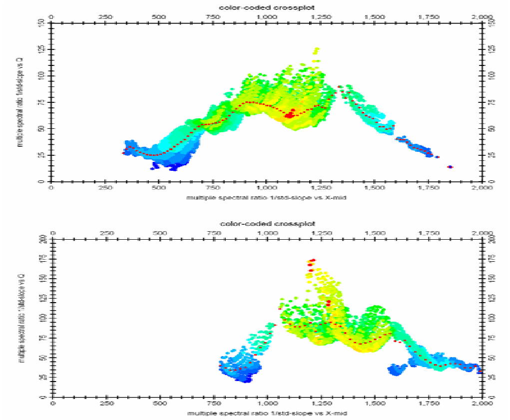

Figure 2: Q factor analysis using multispectral ratio approach. Top: analysis performed on Naylor-1 ZVSP. Bottom: analysis performed on CRC-1 ZVSP. Red points correspond to the best Q-value estimate, with the highest correlation coefficient. Blue points correspond to a correlation coefficient of 0.75. The overlaid curve (red dot) corresponds to the weighted average, as a function of common mid-point value.

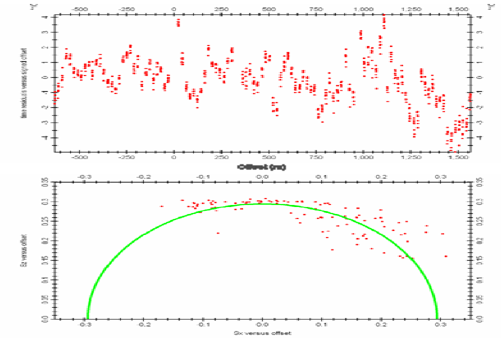

Figure 3: Anisotropy determination. Top: time residuals in ms in an isotropic 1D model. Residuals are almost zero, which indicates an isotropic behavior of the overburden. Bottom: Miller-phase anisotropy determination. Data points appear in red, while the results of a forward modeling in an isotropic medium are shown in green. Again, the measured data are consistent with an isotropic behavior of the underground.

Velocity anisotropy estimation was attempted using the walkaway line-A acquired in Naylor-1 well (Figure 3). For this purpose, we use a "piece-wise gradient inversion" approach, which is relying on first arrival transit times (P arrivals). It is using an exact anisotropic ray tracer through a layered 1D model to invert for profiles of ellipticity and anellipticity. The initial model is isotropic (Vp,Vs) and is built from ZVSP transit times. Figure 3 shows the residual of the Walkaway line after ray tracing through the isotropic 1D model. The point corresponding to the projected source offset 0m is the centre of the tool array. This result shows that there is almost no time residual even at larger offset, which reflects a quasi-isotropic behavior of the underground. This conclusion is confirmed by a second method of anisotropy determination, the Miller-Phase method (Miller and Spencer, 1994), which also relies on the analysis of the first arrival transit times. By comparing observed transit times recorded by a receiver array, apparent vertical and horizontal P slownesses can be computed. A cross-plot of these two quantities (Sx and Sz) allows us to determine polar anisotropy parameters. As shown in Figure 3, the results are consistent with the forward modeling response of an isotropic medium.

Synthetic seismogram generation

The above measurements allowed us to build a series of 1D models, using a finite difference code, in order to predict what should be the 4D signature in situ, at the Otway basin.

The changes in the near surface were one of the key 4D effects to model. The attenuation changes of the upper layer were found to be dominant in preparatory surface seismic surveys run before injection (Urosevic et al., 2008). These variations could mask the 4D effect due to CO_2 injection in the reservoir. In the Otway basin, we expect this change to affect the first 10 to 15 m of the underground. To mimic this effect, our models include a layer, 15 m thick, close to surface, with varying Q factor value. At first, we considered Q values comprised between 100 and 30, as the best case scenario. As expected, relatively high Q, for the near surface zone, did not produce strong 4D effect. Then, we assumed that the effective Q factor for the weathered zone could be strongly affected by the very soft surface cover caused by agricultural work. Besides, the thickness of the layer affected by weather variations might be larger than 10-15 m. As a consequence, the effect of Q values of 20, 10, 5 and even 1 in the upper layer are explored.

Our goal is to compare the 4D effect, created by the upper layer changes, with the 4D effect resulting from the injection of CO_2 in the reservoir. To model the effect of CO_2 injection in the reservoir, we input Wisman et al. (2007) results, who use a rock physics simulator described in Li et al. 2005. They expect the injection at the Naylor-1 well to result in variations of Vp and Vs of +0.5%, and variation of density of +3%. We thus increase the velocity and density values at the reservoir level, using these percentages, to mimic injection at the Naylor-1 well.

Further, we generate our synthetic datasets using the source and receivers locations that will be used for acquisition of a series of walkaway lines during injection. For one of the boreholes, Naylor-1, where a permanent receiver string is deployed, the logistical difficulties could limit maximum offset to 500 m. For such a short range of source offsets, we can use a 1D model approximation. For a wider range of offsets, it would be appropriate to model the variation in CO_2 concentration as a function of offset.

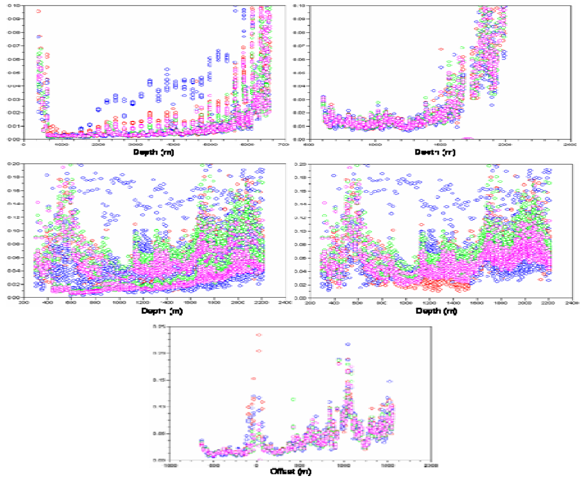

Figure 4: Signal over noise analysis for available VSP surveys. Top-left: Naylor-1 ZVSP. Top-right: Naylor-1 OVSP. Middle-left: CRC-1 ZVSP. Middle-right: CRC-1 OVSP. Bottom: Naylor-1 walkaway line A. Different colors correspond to different time windows for noise evaluation.

Noise effect

Finally, we include the effect of ambient noise as measured on real VSP data. Noise will be critical for extraction of a weak 4D effect (Wisman et al., 2007). Two main sources of noise have been identified: transit time jitter and electronic noise.

A weight drop source will be used for repeat walkaway lines acquisition. It is difficult to couple this source with the acquisition system, and the association results in first arrival jitter of ~1ms. It is critical to compensate for this effect, which could alter the 4D signal. Before stacking, we shift repeat shots to a median transit time. Before subtracting the datasets to identify a 4D effect, we shift each trace of the walkaway synthetic survey so that the Transit times of the 2 surveys (before and after injection) are the same.

To estimate the noise level we use VSP data acquired in Naylor-1 and CRC-1 and we measure the magnitude of the signal/noise ratio. The results are presented in Figure 4. The signal value is defined as the maximum amplitude of the measured trace. For each survey, repeated shots have been systematically acquired, which allows us to estimate the noise value as the difference between successive

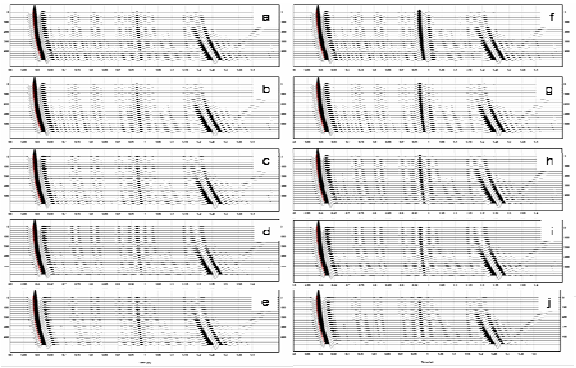

Figure 5: Influence of surface layer attenuation. Target at ~ 0.95-1s. Left column: the results of two modeling iterations are subtracted, which both correspond to pre-injection models. Right column: the results of two modeling iterations are subtracted, one corresponding to pre-injection values, the other to post-injection values. The reference survey has a surface layer with Q=100. From top to bottom, the surface layer for the other survey takes values of (a, f): Q = 30; (b, g): Q = 20; (c, h): Q = 10; (d, i): Q = 5; (e, j): Q = 1. 4D effects due to surface layer changes overcome 4D effects due to injection only for extreme Q values of 1, which is not physically realistic.

repeated shots. It is clear from Figure 4 that the signal to noise (S/N) ratio is highly variable. It decreases with distance to the well (walkaway line), and depth of the receivers. A good estimate of the S/N ratio at the depth of the repeat walkaway receivers (1400-1500 m MD), and for a range of source offsets (0-500 m), is at best ~0.02 and varies between the surveys. Repeatability issues due to source positioning are not considered in this study.

Results

From an analysis of VSP data we created a set of realistic input parameters for modeling that enabled us to study the influence of the following factors:

- the near surface layer
- the processing errors
- the noise level

Figure 5 illustrates variations in the seismic response due to changes in the near surface layer. This was simulated by varying the Q factor which should mimic the influence of weather and seasonal changes, or more directly, variation in ground saturation and the resulting scattering magnitude. Significant variations in the signal amplitude and frequency content were observed in the field data as a result of ground saturation change (Urosevic et al., 2008). For borehole seismic, if our hypothesis is correct, which assumes that only the first 15 m of the underground are affected by weather change, the influence will not be overwhelming. Q values of 1 in the first 15m are necessary so that surface 4D effect overcomes CO_2 produced 4D seismic response change. However, as explained above, Q values of 1, which are not physically realistic, could actually represent a thicker layer with a larger Q value, or the combination of a very soft shallow surface layer with a very low Q value with a 15 m thick surface layer affected by weathering, with a more reasonable Q value.

The next factor, the processing error and/or appropriate approach is illustrated in Figure 6. A very simple processing flow consisting of: trace normalization, 9 levels mean separation, trace by trace deconvolution, shift to a common transit time before subtraction (cross-equalization) proved to be effective in minimizing the errors. The advantage of this very basic processing chain is that it is totally deterministic. The strong shear wave visible around 1.2s cannot be removed through such a processing, though. This shear wave is due to the difference in Q between the first 15 m surface layer and the underlying terrain.

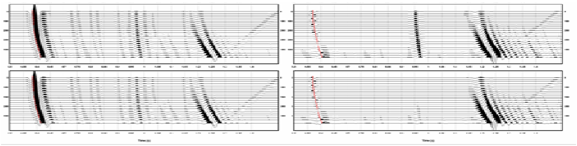

Figure 6: Influence of processing. Target at ~ 0.95-1s. Each image corresponds to the difference between two modeling results, one with a Q value of 100 for the surface layer, the other with a Q value of 5 (extreme) for the surface layer. Top: difference between pre- and post- injection conditions. Bottom: the two images used for subtraction correspond to pre-injection conditions. Left: no processing. Right: basic processing.

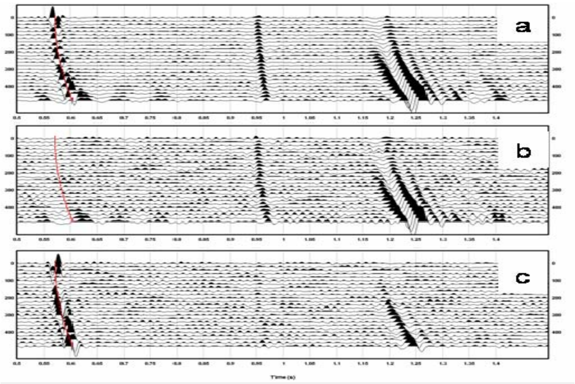

Figure 7: Influence of the noise. Target at ~ 0.95-1s. Each image corresponds to the difference between two modeling results, one with a surface Q value of 100, the other with a surface Q value of 5 (extreme). Each subtraction is between pre- and post-injection conditions. a: sigma = 0.001. b: sigma = 0.002. c: sigma = 0.005.

Finally, Figure 7 shows that the noise has a strong influence on 4D signal identification. A noise sigma of 0.005 is enough to mask any 4D effect due to injection! The noise sigma measured on the available VSP survey is ~0.02 (Figure 4). This shows that ~16 repeat shots should be acquired for each point to overcome the noise level (improvement of noise sigma is √N, N: number of acquisitions averaged).

Conclusion

The results of this study show that time-lapse walkaway VSP surveys planned for monitoring of CO_2 sequestration process at the Otway site, with some careful processing and acquisition could enable direct identification of very subtle 4D seismic response changes. Variable ground conditions however do present a serious challenge for monitoring. Ambient noise level should also be taken into account and compensated for during data acquisition and processing stages. A specific acquisition strategy which deploys frequent repetition of selected shots, may improve repeatability. Direct detection of 4D seismic response changes by a conventional surface seismic methodology is unlikely at this site

Acknowledgements

We thank CO2CRC and Schlumberger for their support to the project. Sandeep Sharma, Don Sherlock contributed significantly to the project and are gratefully acknowledged. We thank Ann-Sophie Boivineau, Jalal Khazanehdari, who provided useful inputs to this paper.