G036

Application of Diffracted Wave Analysis to Time-lapse Seismic Data for CO2 Leakage Detection

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SUMMARY

Time-lapse (TL) seismic technology has been utilized in CO2 geo-sequestration to verify the CO2 containment within the reservoir. A major risk associated with geo-sequestration is possible leakage of CO2 from the storage formation into upper layers. Therefore, the deployment of carbon capture and storage (CCS) projects requires reliable and fast detection of relatively small volumes of CO2 outside the storage formation. To do this, it is necessary to predict typical leakage scenarios and improve the subsurface leak-detection methods. The upward migrated CO2 will form small secondary accumulations with limited lateral extend. In contrast to petroleum exploration methods, which mostly utilise reflected waves, this spatially small CO2 amounts will produce seismic signals corresponding to diffracted waves. In this work, we present a technique that can enhance CO2 leakage detection based on diffracted wave analysis in time-lapses seismic data. Focusing on diffraction energy, we aim to image small objects with limited lateral extend, such as a plume containing with less than 10,000 tonnes of supercritical CO2. Using seismic forward modelling, we examine the sensitivity of the method to the amount of CO2 leaked into a formation.

Introduction

Time-lapse (TL) seismic technology has been utilized in CO_2 geo-sequestration to verify the CO_2 containment within the reservoir. A major risk associated with geo-sequestration is possible leakage of CO_2 from the storage formation into upper layers. Therefore, the deployment of carbon capture and storage (CCS) projects requires reliable and fast detection of relatively small volumes of CO_2 outside the storage formation. To do this, it is necessary to predict typical leakage scenarios and improve the subsurface leak-detection methods.

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In this work, we present a technique that can enhance CO_2 leakage detection based on diffracted wave analysis in time-lapses seismic data. Focusing on diffraction energy, we aim to image small objects with limited lateral extent, such as a plume containing with less than 10,000 tonnes of supercritical CO_2. Using seismic forward modelling, we examine the sensitivity of the method to the amount of CO_2 leaked into a formation.

The method

Landa and Keydar (1998) proposed a method designed to detect small objects using diffracted waves. By analysing the diffracted wave field, this method produces a so-called *D-section* (diffraction section) that contains only diffracted energy. In the context of CO_2 leakage, we are interested in imaging the diffracted waves that are induced by the presence of a small object, i.e. the CO_2 plume. Using TL approach, we can acquire seismic data before and after CO_2 injection, cross-equalise these two data sets, and subtract them from one another, thus removing the seismic response of any constant geological structure. This process should illuminate the diffracted waves produced by the CO_2 plume and separate them from the reflections which are dominant in seismic data. The algorithm used to detect the diffractors is based on measuring the coherency of the data by using the semblance function S with normalized input to output energy ratio (Taner and Koehler 1969),

$$S = \frac{1}{N} \frac{\sum_{t=-m}^{+m} \left(\sum_i f_{it(i)} \right)^2}{\sum_{t=-m}^{+m} \left(\sum_i f_{it(i)}^2 \right)}, \tag{1}$$

where the inner summation of the sample $f_{it(i)}$ is performed for all the traces (index i) at a given time (index t), and the outer summation is performed over a given time window of width *2m* (*N* is the number of channels). Semblance S is computed along the traveltime curve of the diffracted wave. This will focus the energy back to the apex of the diffraction hyperbola at the location of the plume using the following equation:

$$t_x = \sqrt{t_\circ^2 + \frac{4x^2}{v^2}}, \tag{2}$$

where x is the lateral distance from the diffractor, t_0 is the two-way traveltime at the apex, and v is the NMO velocity obtained from the velocity analysis. The input data to compute the *D-section* is the difference stack section that is expected to contain only the diffracted wave energy produced from the CO_2 plume.

Seismic forward modelling

We created two different 2-D depth models simulating the stage 2 of the CO2CRC Otway Project. This stage includes CO_2 injections into saline aquifer, the Paaratte formation, at around 1500m depth and aims to understand the CO_2 behaviour in saline formations. The models consist of thirteen layers with a small plume added into saline aquifer at depth ~1.5 km as shown in Figure 1(a). The synthetic datasets were generated using 50-Hz Ricker wavelet. The velocities are based on the interval velocities calculated from zero-offset VSP data acquired at Naylor-1 monitor well (Pevzner et al. 2009). The fluid substitution modeling was performed to calculate the physical properties of the host formation in order to predict the change of the acoustic/elastic properties of the rock after injection, i.e. V_P, V_S, and density, resulting in the following values:

- Pre-injection: 100% brine, V_P= 3375 m/s, V_S= 1801m/s, ρ = 2322 kg/m3.
- Post-injection: 70% brine and 30% gas, V_P= 3164 m/s, V_S= 1821m/s, ρ = 2172 kg/m3.

From the flow modelling and assuming uniform saturation, we conclude that the plume size corresponding to 10,000 t of CO_2 is 170m wide with the thickness of about 13 m. Our rock-physics modelling shows that CO_2 has an effect on seismic velocity. However, poor data condition can significantly reduce the TL signal. Therefore, to simulate real data conditions, we performed the following steps:
- Contaminate the data with random noise with the same amplitude spectra as for the seismic wavelet. The amount of noise added is sufficient to provide the same level of repeatability (NRMS ~ 30%) as observed on the real data (Pevzner *et al.*, 2011). Here we assume that presence of this noise is the only factor controlling the repeatability.
- Correct the plume amplitude response obtained from the 2D finite deference modelling to 3D situation.
- Downscale the amplitude of the diffracted waves in proportion to the CO_2 volume.

Results and discussion

We produced two stack sections, the baseline (without plume) and monitor section (with a CO_2 plume). The same amounts of noise were added to both sections. The noise has a significant effect on the diffracted waves, as shown in Figure 2 (b); this indicates that the diffraction energy is smaller and more sensitive to noise than the reflection energy. Therefore, dip moveout correction (DMO) has been applied to the data to enhance the diffracted wave energy, and thus to improve the detection.

In the noise free section, Figure 2 (a), we can see two diffraction events close to each other caused by the edges of the plume. We can observe a phase reversal between the two sides of the diffraction traveltime curve. This result is consistent with the work of Trorey (1970) and has been observed on field data as well (Harlan et al. 1983). Thus, applying equation (1) to both sides of the diffraction curve reduces the coherency of the signals due to 180 degree phase change at the apex of the hyperbola. Therefore, we produced two *D-sections* computed along each side of the diffraction hyperbola and then added them together. This process enhances the energy on each side of the plume by avoiding amplitude cancelation during the correlation process. Figure 3 shows a comparison between a *D-section* computed along both sides of the diffraction hyperbola (a), and *D-sections* computed separately for each side of the hyperbola and then added together (b); the latter section has better result and contains less noise.

In order to predict the minimum amount of CO_2 that is possible to detect based on our data conditions, we produced a number of stack sections corresponding to plumes containing different amounts of CO_2. Figure 4 shows the *D-section* (b) computed from a stack section (a) with 2,000 t of CO_2 plume. The CO_2 plume is depicted on the *D-section* as an anomaly, and can be easily identified. The minimum amount of CO_2 detectable from the data is about 2,000-3,000 tons. For less than 2,000 t of

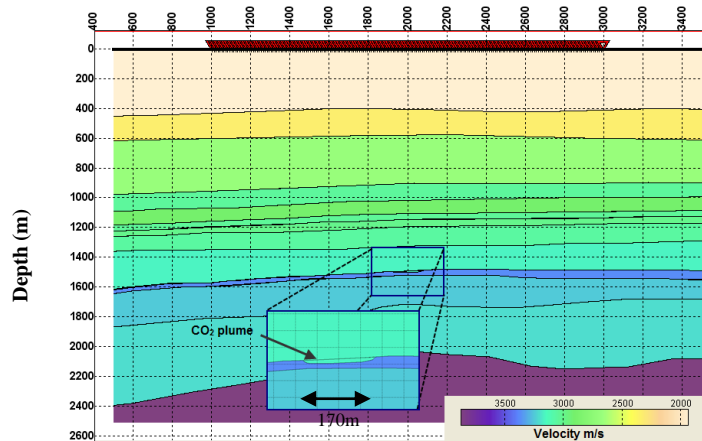CO$_2$, the diffraction amplitude becomes too weak and cannot be reliably detected with the presented method.

Figure 1 *(a) A velocity depth model created for the experiment, the plume with 170m length and 13m thick added in the monitor section.*
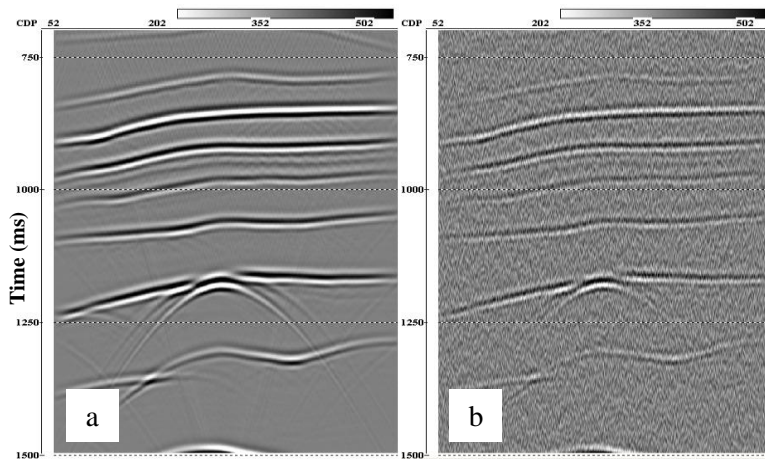

Figure 2 *(a) A part of the stack sections of the geological model, (b) the same section after adding noise. Note how the noise is affecting the diffracted energy.*
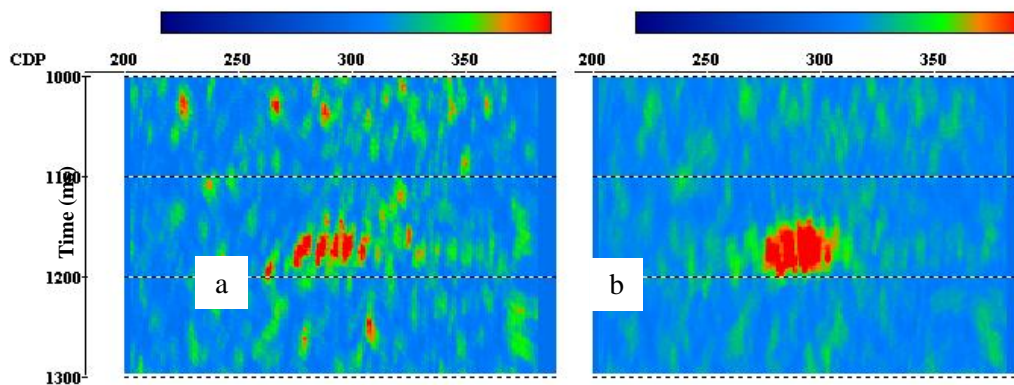

Figure 3 *A comparisons between two D-sections (a) computed over the full diffraction traveltime curve, and (b) a combined two D-sections computed over each side separately. Note on (b) the plume shows stronger anomaly and the noise is significantly suppressed.*
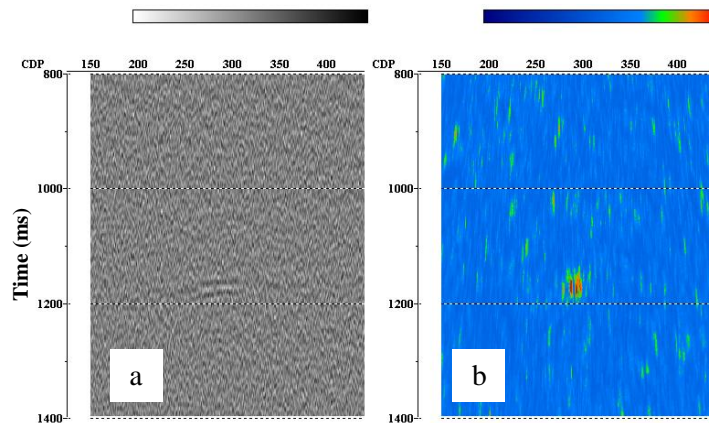
Figure 4 *A D-section (b) computed from TL stack section (a) of 2,000 tones of CO2 plume.*

Conclusions

We presented a technique that has the ability to image small CO_2 volumes from seismic data with low S/N ratio by measuring the coherency (semblance) along the diffracted-wave traveltime. The method has been applied to post-stack data, using the velocity field (the stacking velocity) which makes computing *D-sections* robust. Using TL data analysis, we are able to isolate the diffracted wave from other wavefield components. Applying the method along each half of the diffraction hyperbola and then combining them avoids amplitude cancelation. We found that the amplitude of the diffracted waves is much weaker than the amplitude of the reflected waves, which makes the diffracted events more sensitive to noise and difficult to detect on seismic data. Applying DMO to the data enhances the diffracted waves and reduces the noise on *D-sections*. From the synthetic data based on the geology of the CO2CRC Otway test site, the predicted minimum detectable amount of CO_2 plume is about 2,000 to 3,000 tones. The use of diffractions rather than reflections for monitoring small amount of CO_2 can enhance subsurface monitoring and detect relatively small amounts of CO_2.

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References

Harlan, W. S., Claerbout, J. F. and Rocca, F. [1983] Extracting velocities from diffractions. SEG Technical Program Expanded Abstracts 2(1), 574-577.

Landa, E. and Keydar, S. [1998] Seismic monitoring of diffraction images for detection of local heterogeneities. Geophysics 63(3), 1093-1100.

Pevzner, R., Shulakova, V., Wisman, P. and Urosevic, M. [2009] Seismic Monitoring Feasibility Study of CO2 Injection into Saline Aquifer – A Case Study from Otway Basin, Australia. 71st EAGE Comnference & Exhibition, Extended abstract.

Pevzner, R., Shulakova, V., Kepic, A. & Urosevic, M. [2011] Repeatability analysis of land time-lapse seismic data: CO2CRC Otway pilot project case study. Geophysical Prospecting, 59, 66-77.

Taner, M. T. and Koehler, F. [1969] Velocity spectra---digital computer derivation applications of velocity functions. Geophysics 34(6), 859-881.

Trorey, A. W. [1970] A simple theory for seismic diffractions. Geophysics 35(5), 762-784.