

Estimating injection-induced V_p changes using cross-well seismic full-waveform inversion at the Aquistore CO₂ storage site, Canada

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Summary

Carbon capture and storage (CCS) is an important means of reducing carbon dioxide (CO₂) release into the atmosphere. Different time-lapse seismic imaging methods with various resolutions can track the extent of the CO₂ plume within subsurface geological storage formations. Full-waveform inversion (FWI) of seismic data provides high-resolution seismic velocity models. Although time-lapse full-waveform inversion (TL-FWI) has shown potential for monitoring the subsurface, it is more complex than classic FWI. This is because the time-lapse changes are usually limited in terms of extent and magnitude. There are also different sources of non-repeatability (NR) between the baseline (BL) and monitor acquisitions. In this study, we apply TL-FWI to cross-well seismic data acquired at the Aquistore site in Saskatchewan, Canada, after the injection of more than 390,000 tonnes of CO₂. The objective of this study is to analyze the effectiveness of TL-FWI for detecting velocity variations due to the injected CO₂. While there are different sources of NR in this study, the employed technique can identify the injection zones. This shows the potential of FWI for estimating the velocity changes at this site.

Introduction

Carbon capture and storage (CCS) is accepted as an important means of reducing carbon dioxide (CO₂) release into the atmosphere. Various geophysical methods can be used for monitoring and ensuring secure subsurface storage of injected CO₂. Time-lapse seismic data are effective for detecting the injection-caused changes in the subsurface (Dupuy et al., 2017; Harris et al., 2017). Full-waveform inversion (FWI) of seismic data is a high-resolution inversion technique (Tarantola, 1984) that can be used for monitoring the subsurface (Dupuy et al., 2017; Xiong and Lumley, 2025). Although time-lapse full-waveform inversion (TL-FWI) has shown potential for monitoring the subsurface, it is more complex than classic FWI. This is because the time-lapse changes are usually limited in terms of extent and magnitude. There are also different sources of non-repeatability (NR) between the baseline (BL) and monitor acquisitions (Zhou and Lumley, 2021; Mardan et al., 2023a).

This study focuses on the P-wave velocity (V_p) estimation at the Aquistore site in Estevan, Saskatchewan. In this study, we apply TL-FWI to cross-well seismic data acquired at the Aquistore site after injection of more than 390,000 tonnes of CO₂. We aim to image time-lapse anomalies in terms of P-wave velocity at different injection zones. This study is conducted in the presence of different sources of NR and yet, the results show the potential of FWI for estimating the velocity changes at this site.

The objective of this study is to analyze the effectiveness of TL-FWI for imaging velocity variations due to CO₂ injection at the Aquistore site. In the next sections, we present the Aquistore site and

the theory of FWI. Then we examine the dataset, and processing steps. Finally, we present and discuss the results of this study.

Aquistore CO₂ Storage Site

The Aquistore Project is located near Estevan, Saskatchewan, Canada. It has two wells for the purposes of injection and monitoring underground storage of CO₂. Figure 1 shows the location of the injection and observation wells with blue and red circles, respectively. The 200 m-thick storage reservoir comprises the Deadwood and overlying Winnipeg Formations. The Deadwood Formation is composed primarily of sandstone with silty-to-shaley interbeds. The Winnipeg Formation is composed primarily of sandstone with silty-to-shaley interbeds. The Winnipeg Formation includes the Icebox (shale) and Black Island (sandstone) members (Movahedzadeh et al., 2021). The Icebox shale is ~15 m thick and forms the reservoir cap rock. Downhole spinner logs acquired at the site indicate that ~10% and ~90% of the injected CO₂ resides within the Black Island member and Deadwood Formation, respectively. More information about this project can be found in White et al. (2016).

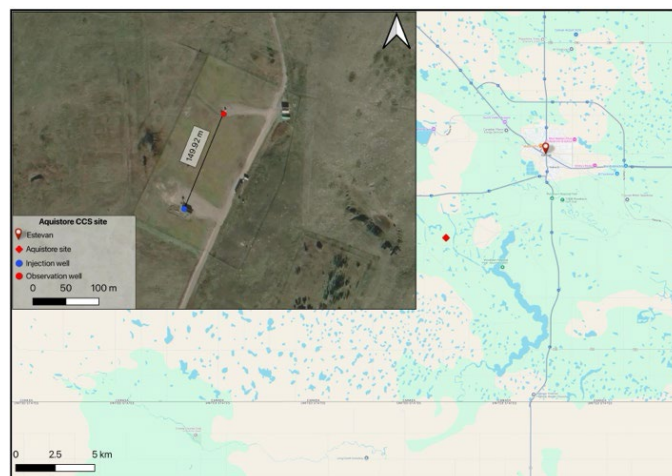


Figure 1 Location of the Aquistore site, SW of Estevan. Inset shows satellite image (location indicated by red diamond on the map) with the locations of the injection and observation wells.

Theory

FWI is a high-resolution inversion technique that uses the entire content of seismic traces for estimating the physical properties of the subsurface (Tarantola, 1984). This method is a local optimization technique that minimizes the least-squares misfit between the recorded, d , and modeled data as,

$$\min_{\mathbf{m} \in \mathbf{M}} \chi(\mathbf{m}) = \|F(\mathbf{m}) - d\|_2^2 + R(\mathbf{m}), \quad \text{eq. 1}$$

Where F is the forward modeling operator, \mathbf{m} is a vector of physical properties of the subsurface (e.g. P-wave velocity), and R is regularization term.

FWI is a highly nonlinear and ill-posed problem. To make this problem better posed and reduce the generated artifacts, different regularization methods can be used (Asnaashari et al., 2013; Mardan et al., 2023b). This issue is more critical for TL-FWI, because 4D anomalies are usually

small in terms of the extent and magnitude and it is challenging to differentiate them from the inversion artifacts. To increase the accuracy of this study, prior regularization is used to make sure that the estimated model corresponds to the information obtained from the injection and observation wells (Asnaashari et al., 2013). This regularization term is imposed as

$$R = \lambda \|\mathbf{m} - \tilde{\mathbf{m}}\|_2^2, \quad \text{eq. 2}$$

where λ and $\tilde{\mathbf{m}}$ are the regularization parameter and the obtained model at the wells.

Field Data Inversion

In a time-lapse seismic study, it is important to minimize the changes in the acquisition geometry and equipment (Zhou and Lumley, 2021; Mardan et al., 2023a). However, this is not always possible for a variety of technical reasons. In the Aquistore project, there are different sources of NR for the BL and monitor surveys (Table 1). For the BL, the source was deployed in the observation well and receivers in the injection well. This could not be repeated for the monitor acquisition because the injection well was pressurized. This required the use of a lubricator on the injection wellhead which precluded deployment of the long geophone array which was the substitute for the BL hydrophone array. Hence, the injection well was used as the source well in the monitor survey where the sources are located with 4.5 m spacing. The employed receivers in the BL survey are hydrophone that record the data with 0.25 ms sampling rate. The receivers in the monitor survey are 3-component clamped geophone and the data recorded with a sampling rate of 0.5 ms. Beyond these sources of NR, the source and receiver coverage interval are different between the two acquisitions. The diameter of the source was too large to allow it to pass through the packer at the top of the reservoir interval, and thus source points for the monitor survey were limited to the zone above the reservoir. As shown in the next sections, this reduction in the depth interval covered by the source points leads to an incomplete imaging of the reservoir in the monitor survey.

Table 1 The BL and monitor acquisition parameters and different sources of non-repeatability.

Parameters and equipment	Acquisition in 2013 (BL)	Acquisition in 2021 (monitor)
Source interval	2889-3374 m	3000-3138 m
Source spacing	1.5 m	4.5 m
Source well	Observation	Injection
Receiver well	Injection	Observation
Receiver type	Hydrophone	3C-clamped geophones
No. of receivers	20 (1.5 m apart)	12 (30 m apart)
Receiver interval	2953-3372 m	2985-3342 m
Interval spacing	1.5 m	1.5-3 m
Sample rate	0.25 ms	0.50 ms
Injection well tubing fluid	Brine	CO ₂
Injection well pressure	Ambient	Pressurized

Figure 2a and 2b show two shot gathers of the acquired BL and monitor data. Figure 2c and 2d show the processed gathers of these surveys, respectively. The seismic data processing includes tube-wave removal, bad-trace elimination, F-X deconvolution, trace interpolation, structurally-oriented and band-pass filtering. As input to FWI, the processed data are muted starting at 15 ms after the P-wave first arrival (Figure 2c and 2d).

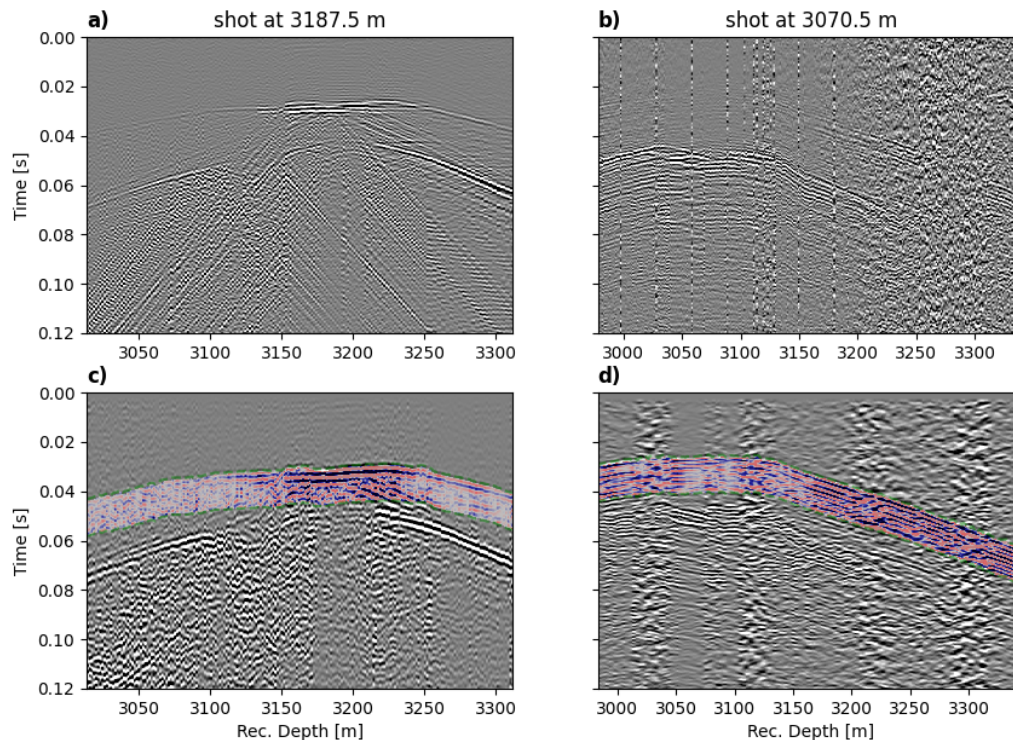


Figure 2 Two shot-gather examples for BL (left column) and monitor data (right column). (a and b) denote raw data and (c and d) show processed data. The data used for FWI include the 15 ms following the P-wave first arrival (shaded zone in c and d)).

The processed data were used to estimate a source function (wavelet) for each survey by using the autocorrelation and stacking methods. Figure 3 depicts the estimated source functions from the BL and monitor data. In the autocorrelation method, we use the average of the autocorrelation of all traces as the source function (dotted-black like in Figure 3). In the stacking method, all traces are aligned using the first-arrival time and their average is used as the source function (dash-red line in Figure 3). To perform FWI, we utilize the average of these two wavelets as the source function (solid black line in Figure 3).

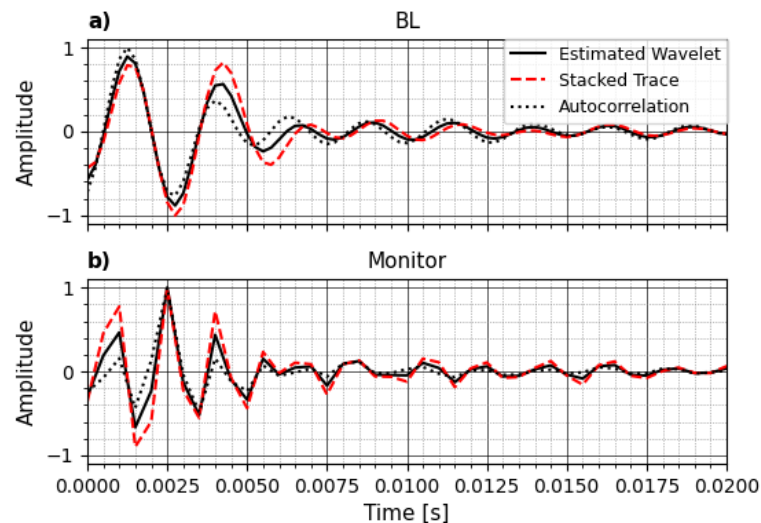


Figure 3 Estimated source function (solid black line) from (a) BL and (b) monitor data. The dash-red line shows the obtained wavelet from stacking all traces and the dotted-black line shows the estimated wavelet from autocorrelation of all traces. The solid black line is the average of two methods and it is used as the source function in this study.

FWI is an ill-posed local optimization method where the subsurface velocity is iteratively updated starting from an initial velocity estimate. To reduce this ill-posedness, we perform the inversion using the information in model domain (velocity). We create a model of the subsurface using well-log velocities that were acquired prior to the start of injection (Figure 4a). We regularize the BL inversion using this model to ensure that the estimated BL is consistent with the obtained value at the wells. For regularization (eq. 2) of the BL inversion, we utilize a 2D λ that is 0.7 at the location of wells and 0.2 in the center of the model. This forces the inversion process to comply with the velocity at the well locations and have more freedom in the middle of the model where we do not have measured values of the velocity. It should be noted that the regularization is not applied to the inversion of the monitor data.

We utilize a smooth model of well-log velocity as the initial model (Figure 4b). Employing the I-BFGS optimization method and batches including 16 shot gathers with 6 iterations for each batch, the BL and monitor models are estimated as shown in Figure 4c and 4d. For inversion of the monitor data, the estimated BL model (Figure 4c) is used as the initial model. The time-lapse model is estimated by subtracting the baseline model from the monitor model. The result is shown in Figure 4e where the perforation (injection) zones are shown with grey lines.

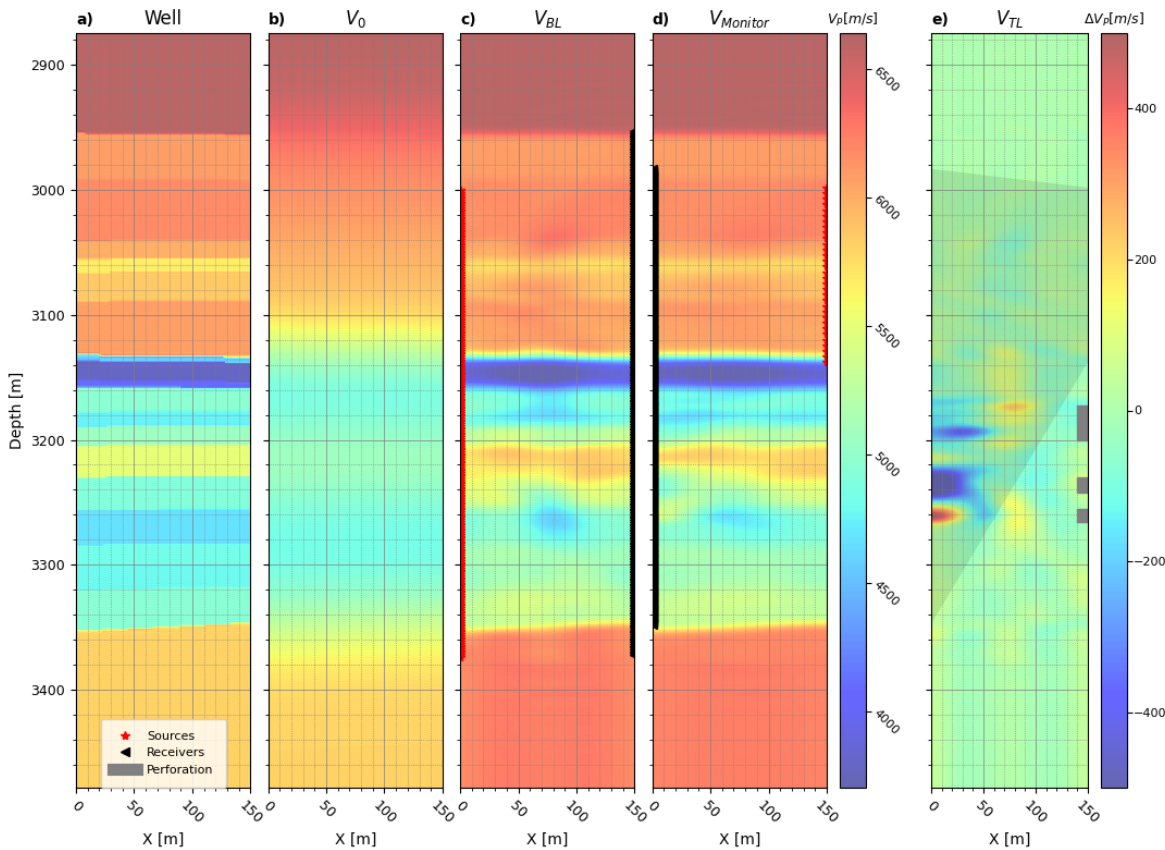


Figure 4 a) Prior information obtained from well velocity log. (b) Initial model for FWI obtained by smoothing the well data (a). Estimated (c) BL and (d) monitor models. (e) Estimated time-lapse model. The injection and monitor wells are located on the right and left sides, respectively, of each panel.

Inspection of the velocity difference image reveals two zone where velocities are reduced by ~8%. These anomalies are not detected close to the injection well, because the monitor data do not have good coverage (gray polygon in Figure 4e) close to this well. The two zones of velocity reduction correspond to the two perforation zones that have actively taken CO₂. This is an expected result.

Conclusions

In this study, we have assessed the ability of time-lapse full-waveform inversion (TL-FWI) to estimate CO₂-caused P-wave velocity changes in the storage reservoir at the Aquistore CO₂ storage site. Different sources of non-repeatability in this project prove an impediment to obtaining complete intra-well velocity images, but we show that by employing TL-FWI with proper regularization, it is possible to detect the velocity changes in the injection zones. It is also shown that the limited coverage of monitor acquisition makes it impossible to estimate the changes close to the injection well. To address this issue, more efficient denoising techniques and including the late arrivals in the inversion process are required.

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