Elastic full waveform inversion for time-lapse analysis of a CO2 injection at CaMI.FRS using synthetic VSP

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Summary

Full waveform inversion (FWI) is investigated as an assessment tool to image elastic variations in a clastic reservoir due to the effects of a carbon dioxide (CO_2) injection at the Containment and Monitoring Institute Field Research Station (CaMI.FRS). Three injection stages are modeled and compared using a vertical seismic profiles (VSP) as acquisition design for synthetic data. Two elastic parameterizations to describe the subsurface and two inversion strategies on how to use multi-component data were tested. Inverted models converged towards the true solution with variations associated on how the inversion was framed. Changes at the reservoir level were constrained laterally and vertically. A continuous reduction on the compressional wave (P-wave) velocity was successfully imaged from a baseline to a final injection stage. Both, increment and reduction between stages were recorded for the shear wave (S-wave) velocity. Density was simulated but not directly inverted in this study, due to significant cross-talk.

Introduction

Full waveform inversion (FWI) has demonstrated to reproduce high resolution models in reservoir settings. In production processes like carbon dioxide (CO_2) storage, this technique is currently under investigation as a tool to assess subsurface changes. The Containment and Monitoring Institute Field Research Station (CaMI.FRS) is a well-characterized test site that might allow field scale testing of FWI, especially for monitoring purposes. At this site, a controlled injection of CO_2 is currently under development. While field data from a baseline phase from CaMI.FRS (i.e., prior gas injection) is starting to produce elastic inversion results (Eaid et al., 2021; Keating et al., 2021). The question of whether, and how, a time-lapse signal should be expected to be resolvable with a monitoring FWI is currently a high priority.

Elastic FWI makes use of a complicated relation between data and model parameters to solve the forward and inversion problems in an inversion scheme. Hence, successful applications of this technique depend on several factors like signal-to-noise ratio (S/N) of the data, acquisition design, subsurface parameterizations, and others. Vertical seismic profiles (VSP) are interesting surveys to assess FWI in its capacity to serve as a reservoir monitoring tool. These surveys offer features like high S/N, a fixed configuration, and multi-components wave modes that might help to overcome some of the drawbacks posed by FWI applications.

VSP are amongst the surveys that have been periodically recorded while CO_2 is injected in clastic reservoir at CaMI.FRS. In this work, we study some the extents and constraints of elastic FWI for time-lapse analysis at three stages of CO_2 injection for this site as proposed by Macquet et al. (2019). Our results demonstrate feasible application of FWI for the upcoming stages at the FRS with synthetic multi-component VSP. We observed variations in the inverted models based on inversion scheme, elastic parameters used to describe the medium, model residuals and measured reservoir changes.

Method

In VSP surveys, seismic is usually acquired using three-component (3-C) geophones. This facilitates the recording of compressional waves (P-waves) and the polarised components of shear waves (S-waves) in three directions, which are known as the vertical (Z) and the horizontal (X) components of a VSP record. In both components, transmitted and reflected waves are present. Though, due to a shorter traveled distance the amplitude of the first is usually better preserved in these surveys (i.e., less affected by phenomena related to subsurface properties) than the latter.

To exploit some of the mentioned benefits of VSP, we examined two suggested elastic parameterizations for FWI using two inversion strategies. For the first strategy, we utilized simultaneously both, Z and X components of the survey. Whereas, for the second strategy, we defined a sequential inversion, using the Z component until reaching a level of model convergence in a frequency band, and then, continuing the inversion with the addition of the X component alongside Z.

Macquet et al. (2019) proposed three stages of gas injection for the Basal Belly River Sandstone (BBRS) at CaMI.FRS. The first one is a baseline phase, prior to any gas injection, which is followed by a medium and final phase of injection after 266 tons and 1664 tons of CO_2, respectively. We used these projections to construct the true models for density and P-and S-wave velocities (V_p and V_s) from 60 m to 350 m depth. For intervals with missing information, we used available VSP surveys and empirical relationships to estimate the missing values. Then, to generate the initial models for all stages, we smooth the true baseline models with a Gaussian smoother with a half-width of 25 m.

For modeling synthetic data, a frequency domain FWI algorithm was used. We simulated the permanent VSP receiver acquisition with vertical receivers located at an observation in the middle of the model between 190 m to 305 m depth with a spacing of 5 m. For sources, we considered surface explosive sources with a separation of 60 m each. These were simulated with thirteen frequency bands from [4-6 Hz], to [4-8 Hz], [4-10 Hz], [4-12 Hz], [4-14 Hz], [4-16 Hz], [4-18 Hz], [4-20 Hz], [4-22 Hz], [4-24 Hz], [4-26 Hz], [4-28 Hz], and [4-30 Hz], where each band consisted of fifteen evenly separated frequencies.

Results

An elastic medium was considered in this study. However, not all modeled parameters were directly inverted. While, P-and S-wave velocities were modeled, inverted or reconstructed when impedance was used; density (ρ) was only modeled or fixed to the initial model due to cross-talk. Overall, every inverted model converged towards the true solution at reservoir level. As Table 1 shows, model convergence and reservoir variations between injection stages varies depending of the selected parameterization and inversion strategy. This suggests that although it may be feasible to use FWI as tool to image the effects of CO_2 at CaMI.FR, how we frame the inversion matters.

Independently of the parameterization used, a sequential inversion of VSP components helped us to reached lower levels of model residual for almost all parameters. This can be related to the resolution of subsurface structures and how the wave modes are used the inversion. Without implementing simultaneously both components of VSP from the beginning of the inversion, we prioritized the resolution of large-scaled features over fine details, and, thus, improving the overall model convergence, as shown in Figure 1(c)-(d), 1(g)-(h), 1(k)-(l) and Figure 2(d)-(f), 2(j)-(l), 2(p)-(r). Although, imaging solely the large velocity structures with the vertical component might be enough for the baseline stage. As illustrated in Figure 1(i)-(j), 1(m)-(n) and Figure 2(m)-(o), 2(s)-(u), advanced stages of CO_2 injection might require the implementation of both Z and X components to resolve the small variations in the reservoir.

Parameterization	Parameter	Inj. Stage	Inversion Z+X Components			Inversion Z and Z+X Components		
			Residuals	Parameter variation (%)		Residuals	Parameter variation (%)	
				Near offset	Far offset		Near offset	Far offset
V_p-V_s-ρ Parameterization	V_p	Baseline	1.079	0.00	0.00	1.011	0.00	0.00
	V_s		0.928	0.00	0.00	0.907	0.00	0.00
	V_p	Medium	0.791	-10.89	-1.03	0.764	-12.49	-1.80
	V_s		0.786	2.52	7.05	0.806	2.19	6.42
	V_p	Final	0.643	-15.18	-3.55	0.611	-16.41	-5.34
	V_s		0.814	6.02	10.29	0.815	3.45	8.86
I_p-I_s-V_p Parameterization	I_p -> V_p*	Baseline	1.204	0.00	0.00	1.111	0.00	0.00
	I_s -> V_s*		0.973	0.00	0.00	0.912	0.00	0.00
	V_p		1.006	0.00	0.00	0.954	0.00	0.00
	I_p -> V_p*	Medium	0.933	-9.41	0.49	0.886	-13.25	-1.55
	I_s -> V_s*		0.839	4.51	15.10	0.798	-1.26	16.24
	V_p		0.894	-16.39	-1.43	0.758	-11.52	-1.26
	I_p -> V_p*	Final	0.781	-17.56	-3.29	0.734	-21.22	-4.78
	I_s -> V_s*		0.864	3.03	12.25	0.825	-1.26	14.11
	V_p		0.711	-22.98	-4.57	0.613	-20.77	-5.19

Table 1. Comparison of inverted model for the three modeled stages at two offset locations in terms of model residual and parameter variation. Inversion Z+X Components refers to a simultaneous inversion of VSP components. Inversion Z and Z+X Components refers to a sequential inversion of VSP components. Velocity-density (V_p-V_s-ρ) and impedance-velocity (I_p-I_s-V_p) are the parameterizations used.

Variations between injection phases were measure at 20 m and 120 m distance from the observation well, which we denoted as near and far offset locations. P-wave velocity was the most affected parameter by CO_2 effects at this site. For this one, we recorded a progressive reduction from the baseline to the final injection stage, where we measured a maximum of 21% and 5% decrease at the near and far offset location, respectively. For the case of S-wave velocity, variations were more erratic between injection phases. Depending of the parameterization used, we measured both increment and reduction of velocity values from the medium to the final injection stage, as shown in Table 1. Independently of the parameterization and inversion strategy, it appears than with increasing offset, P-wave variations tend to be attenuated; whereas S-wave effects increases. Thus, demonstrating that changes between parameters would be inversely proportional.

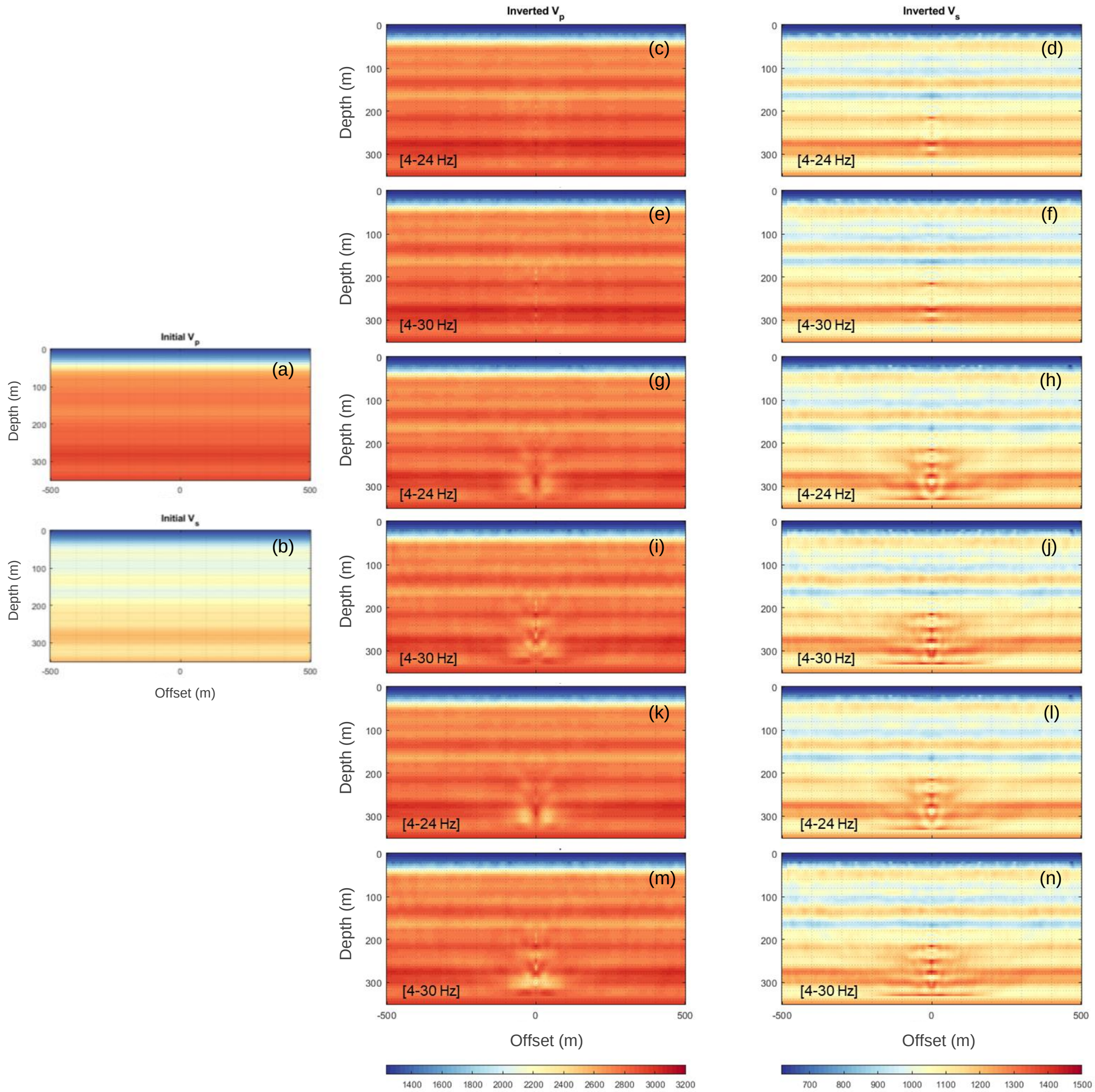

Figure 1. Initial and inverted models using velocity-density as parameterization and a sequential inversion of VSP components as inversion strategy at two frequency bands. (a)-(b) are the initial models, (c)-(f) are the inverted baseline, (g)-(j) are the inverted medium phase models after 266 tons of CO_2, and (k)-(n) are the inverted final phase models after 1664 tons of CO_2.

Conclusions

In this study, elastic full waveform inversion was investigated in its capacity to assess changes in a clastic reservoir due to a controlled injection of CO_2 at CaMI.FRS. Synthetic data was generated for three injection stages, following reservoir projections from previous studies and using a VSP configuration that is consistent with the permanent experiment deployed at the site. Inverted models demonstrate lateral and vertical resolution of gas effects for P- and S-wave velocity structures using two parameterizations and two inversion strategies. Comparison of results in a time-lapse fashion, allowed us to measure a continuous reduction of P-wave values in-between injection stages, with a maximum of 21% and 5% decrease at a near and a far offset location. Whereas, for S-wave both, increment and reduction were measured at the same locations, but without following a particular trend between injection phases. Results for inverted parameters vary depending of the parameterization and inversion scheme used on terms of model residual, content of frequency used, and measured variations in the reservoir. This suggest that it may be feasible to use FWI as tool to image the effects of CO_2 at CaMI.FR for upcoming injection stages, but careful considerations must be made when framing the inversion.

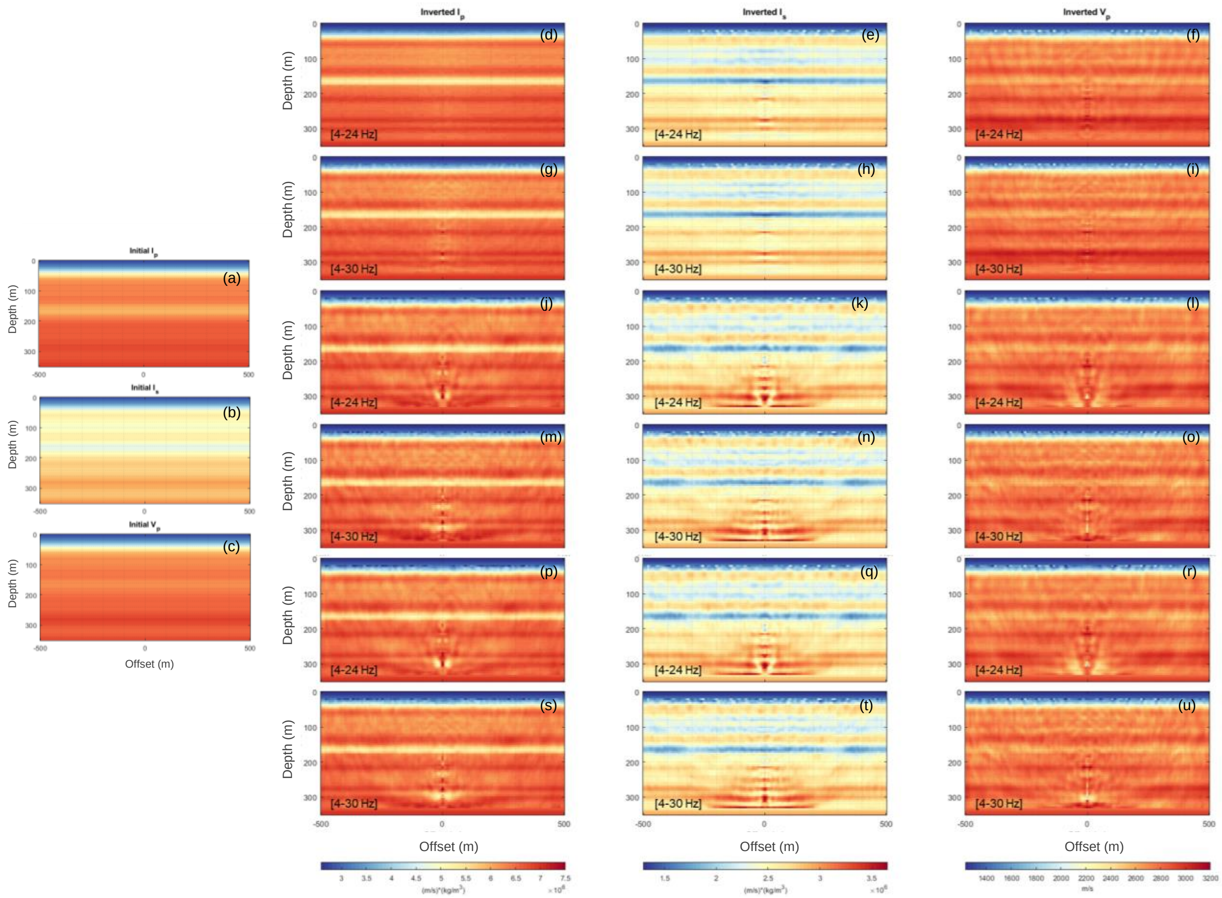

Figure 2. Initial and inverted models using impedance-velocity as parameterization and a sequential inversion of VSP components as inversion strategy at two frequency bands. (a)-(c) are the initial models, (d)-(i) are the inverted baseline, (j)-(o) are the inverted medium phase models after 266 tons of CO_2, and (p)-(u) are the inverted final phase models after 1664 tons of CO_2.

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