geoconvention Virtual Event September 13 - 15 2021

Time-lapse acoustic FWI of VSP data with applications to monitoring CO2 at the CaMI Field Research Station: a feasibility study

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Summary

We investigated the feasibility of modeling the effects of a CO_2 injection at CaMI FRS using an acoustic FWI algorithm. Adapting results for three phases of gas injection from previous studies, we reproduced the geometry acquisition from two proven VSP experiments with two source point dispositions. To simulate a time-lapse analysis, we modeled synthetic and observed datasets utilizing a multiscale approach with FWI. Results converged towards the true solution, demonstrating significant benefits to resolve velocity variations associated with reservoir changes from an initial model without prior information about CO_2 effects. Though, lateral resolution is noticeable diminished for far offsets. It does not appear to be particularly influenced by the distribution of receivers, as much as it is controlled by the number of modeled sources. Since, we obtained similar results using two receiver configurations. Comparison of inverted models helped us to determine a maximum reduction of 17% in P-wave velocity within reservoir levels.

Introduction

Seismic time-lapse analysis includes a combination of acquisition, processing and interpretation of seismic surveys throughout a determined period of time to image fluid-flow effects within a reservoir (Lumley, 2001). These variations in the elastic properties of the rocks are expected to lead changes in the seismic response, namely amplitude and travel time. In a subsequent step, seismic records can be inverted using imaging techniques as full waveform inversion (FWI). Several applications of this method have demonstrated computing features of subsurface properties that were not resolved by conventional velocity analysis (Smithyman et al., 2015; Pan et al., 2017). Hence, FWI might be a suitable technique for reservoir monitoring and seismic time-lapse analysis.

An extending branch of reservoir monitoring is carbon capture and storage. This method is expected to contribute mitigating the effects of climate change by controlled injections of carbon dioxide (CO_2) within geological formations that meet certain criteria. Following this idea, the Containment and Monitoring Institute (CaMI) developed a collaborative Field Research Station (FRS) in southern Alberta. At this location, a small volume of CO_2 is currently being injected in a thin interval denoted as Basal Belly River Sandstone (BBRS) within the Belly River Group.

To improve understanding technologies for geological containment and secure storage, several type of technologies are being tested at the FRS (Macquet et al., 2019). Within some of them, there are vertical seismic profiles (VSP). Utilizing previous model projections of CO_2 effects in the selected reservoir, we investigate the feasibility of an acoustic FWI algorithm to resolve variations in the compressional wave velocity (Vp) associated with the gas injection at three different stages.

Modeled stages of CO_2 effects

Assuming a brine saturated formation, Macquet et al., (2019) investigated the effects of an injection program of a maximum 1664 tons of CO_2 on the elastic parameters of the reservoir formation. The simulation considered variations on fluid and reservoir temperatures, a range of gas saturation between 0 to 0.5, and values of pore pressure between 2.95 to 5.75 MPa. Results suggested weak modifications in the density of reservoir fluid, and significant changes in the bulk and shear moduli of the dry rock after variations in reservoir conditions. From the modeled parameters, Vp is expected to experiment the largest effect with a 32% module decrease.
From these previous studies, three stages in the ongoing injection program have been distinguished, based on the evolution of the CO_2 effects. Here, we denote them as a baseline phase, a medium phase of 266 tons of injected gas and final phase of 1664 tons of injected gas. The general expectation is a horizontal migration of a CO_2 plume centered on the injection well within the reservoir level. This could reach an initial diameter up to 40 m and a further expansion up to 200 m after a medium phase injection and final phase injection, respectively (Figure 1).

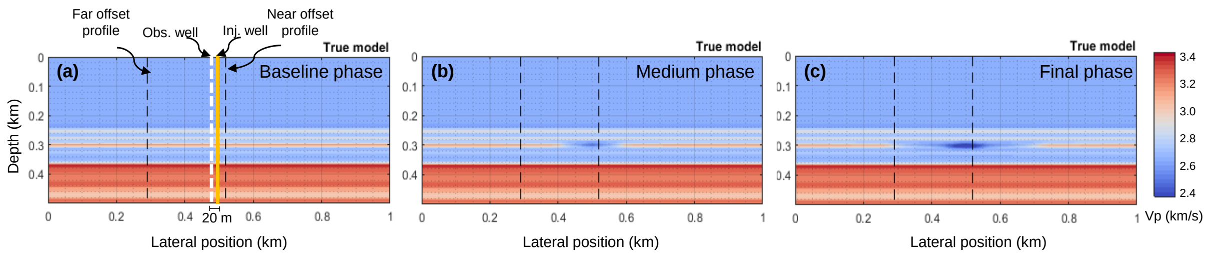

Figure 1. True Vp velocity models for CaMI FRS. The observation well and the injection well locations are highlighted in the first diagram with a white dashed line and a yellow line, respectively. Profiles locations are overlain in all models with black dashed lines.

Configuration of modeled seismic experiments

In recent years, multiple seismic datasets have been acquired along an observation well at CaMI FRS. This is located at a 20 m distance from the injection well, as display in Figure 1.a. For the current investigation, we only reproduced acquisition geometries of VSP that have been tested in the past at the FRS. Since our primary intention is understanding our capacity and limitations to model reservoir variations with the existing experiment design.

Following previous acquisition geometries, two receiver arrangements were modeled. The first one, denoted as permanent experiment, has sensors surveying depths between 190 to 305 m with a vertical spacing of 5 m. Whereas, the second configuration, denoted as 3D experiment, has vertical sensors spanning from the surface to 324 m depth with 1 m spacing.

Though, several source point distributions have been used for VSP acquisition, we analyzed only two spacing variations. First, we assumed and modeled a 60 m spacing, as a representative approximation for multiple surveys at the FRS. Secondly, we used a sparse source spacing of 142 m to evaluate performance of the algorithm; and draw comparison of the lateral resolution of the CO_2 plume.

Time-lapse modeling using full waveform inversion

We used an adaptation from Romahn's (2019) time domain acoustic FWI algorithm for modeling, which is based on finite difference approximation. For our velocity models, we defined a grid with a 5x5 m cell size for the horizontal and vertical scale, with a maximum lateral distance of 1000 m and 500 m in depth. To satisfy the stability condition for a Laplacian approximation of 9 points, we utilized a time step of 2.5×10^{-4} s.

Three fine-detailed velocity models were generated by Macquet et al., (2019) from well-log data and reservoir simulation for the study area. Each of these were smoothed, adapted and defined as true velocity models in our investigation by a Gaussian smoother with a half-length of 7. This step was decisive to keep balance between the models at the FRS and the seismic resolution of a minimum phase wavelet of 25 Hz. Though, noticeable spikes and fine features in the models were lost, the velocity trends were preserved. Hence, we are confident in modeling a close representation of the true Vp.

To simulate time-lapse analysis, we created three observed datasets using the true models that represented the different phases of CO_2 effects within BBRS. We followed a multiscale approach to invert models at each stage, for two VSP configurations. Nine expanding frequency bands were inverted from [4 Hz, 8 Hz] to [4 Hz, 12 Hz], [4 Hz, 16 Hz], [4 Hz, 20 Hz], [4 Hz, 24 Hz], [4 Hz, 28 Hz], [4 Hz, 32 Hz], [4 Hz, 36 Hz] and [4 Hz, 40 Hz]. A maximum of ten iterations per frequency band was permitted, and the starting velocity model for the three injection phases was a smoothed version of the true baseline with no prior information associated with gas variations.

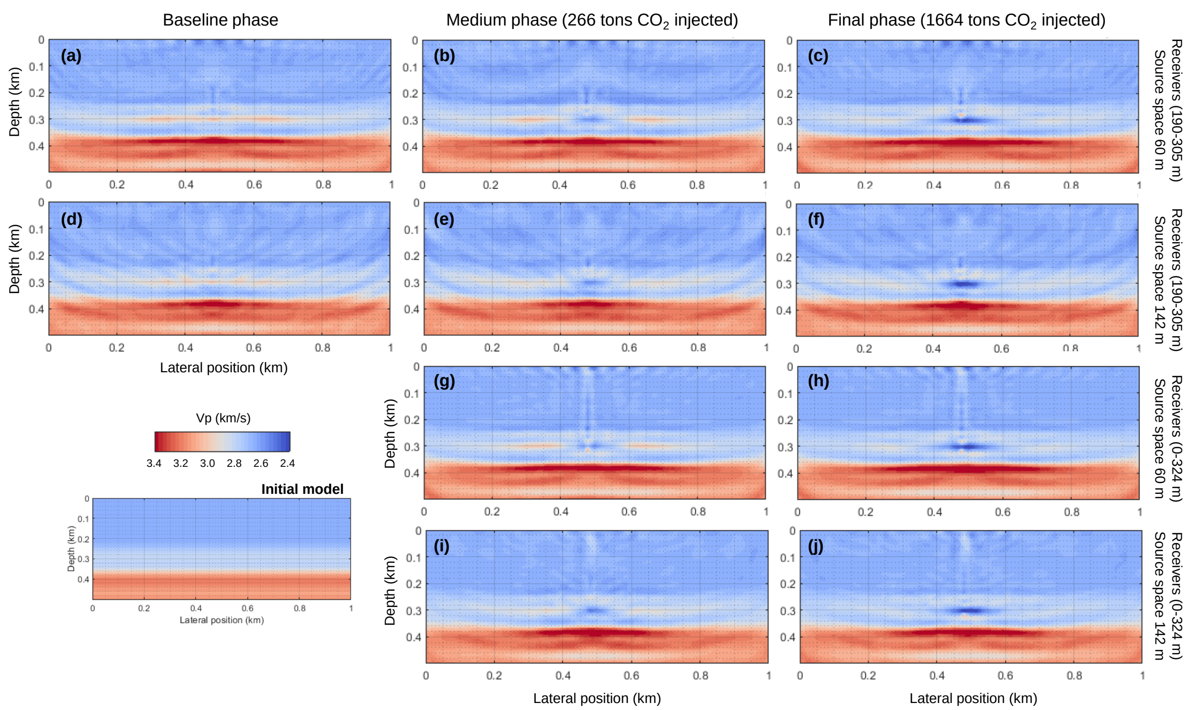

Figure 2. Inverted velocity models for the FRS from three stages of CO_2 injection. From top to bottom, horizontal panels were modeled using the permanent experiment with 60 m and 142 m source spacing; and using the 3D experiment with 60 m and 142 m source spacing.

As Figure 2.a-f displays, inverted models using the permanent experiment converged towards the true solution. Though, vertical extension of the CO_2 plume was delineated at reservoir level for all modeled stages, its lateral limits became more difficult to visualize with increasing offset. This constraint derives from a combination of an expected shrink of gas effects at the edges and a decrease in lateral resolution of the experiment itself due to less amount of ray paths surveying far offsets. In addition to these observations, Figure 2.d-f shows the impoverishment of the inverted model after a reduction in the number of source points for the same permanent experiment and FWI scheme. In this case, results display oblique patterns at several depth levels that gives information which areas of the model were sampled and updated in the inversion process. Since a source point diminution will lead to significant less ray paths surveying the subsurface, then it becomes more difficult to obtain an optimal image. Hence, as in the previous case, at near offsets the inverted velocity somehow converged towards the true solution, but as lateral distance increases the inversion resembles our smoothed initial model.

Results obtained using the 3D experiment do not appear to provide further enhancement at the reservoir interval, as Figure 2.g-j demonstrates. Edges of the CO_2 plume remain difficult to delimit for far offsets. Although, it is noteworthy that having more sensors proved to be beneficial for the inversion using a sparse source configuration because inverted models are arguably similar to the ones obtained using sources every 60 m. The only difference between both, it is the remnant of a smoothness from the initial model in the definition of the structures.

Based on the previous results, we proceeded to measure the change on Vp at our defined profile locations for a 60 m source spacing distribution. At far offsets, the variation of velocity reaches up to 4% reduction during the final stage of gas injection, whereas at near offsets this value is approximately 17% for the same stage. Figure 3 shows a time-lapse view at these two locations utilizing inverted velocities from FWI. As mentioned before, results using our two receiver configurations are strongly similar around reservoir levels.

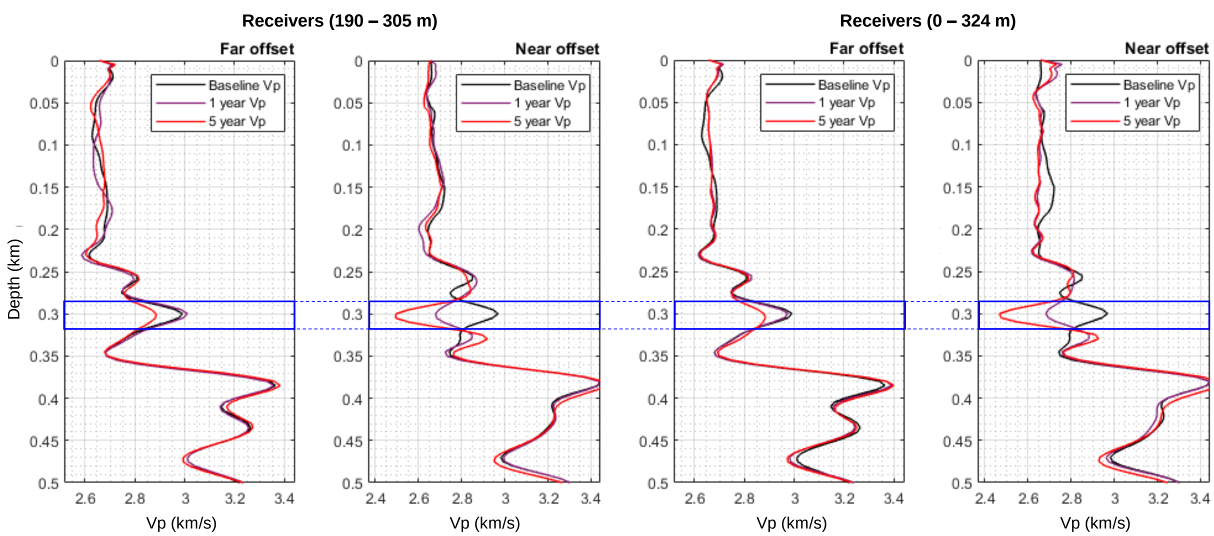

Figure 3. Time-lapse evolution based on inverted Vp for three stages of CO_2 injection. Reservoir level is highlighted with blue boxes.

Conclusions

Acoustic FWI modeling using two sensor configurations of VSP highlights the potential and limitations of the method to resolve reservoir variations produced by an injection program of CO_2 at CaMI FRS. Model convergence towards the true solution from a starting model without prior knowledge about gas effects remarks the adaptability of the technique. Though, it poses weight on strategies to build an accurate velocity model. Lateral resolution of CO_2 effects is profoundly influence by the number of modeling sources and offset distance, but not entirely limited by the number of receivers. Since, we were able to obtain similar results modeling both, a restricted reservoir-oriented and dense (starting from surface) receiver arrangement. In both cases, Vp changes in far offsets were vaguely constraint due to a decrease of ray paths surveying further locations, which could be improve by adding more sources. Still, it is remarkable that for a thin reservoir of about 6 m, we were able to compute substantial changes in the compressional wave velocity. A time-lapse analysis from this location, based purely on FWI, helped us to determine an approximate reduction of Vp of 4% and 17% at a far offset and near offset location, respectively.

Acknowledgements

The authors thank the sponsors of the Consortium for Research in Elastic Wave Exploration Seismology (CREWES) for continued support. This work was funded by CREWES industrial sponsors, and by the NSERC grants CRDPJ 461179-13 and CRDPJ 543578-19. We are also acknowledge the Containment and Monitoring Institute for providing critical information in this investigation.

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