Applying elastic FWI to time-lapse VSP data for quantitative CO_2 monitoring

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ABSTRACT

With growing concerns over global warming, monitoring CO_2 emissions is vital for understanding and mitigating its effects. This is especially important in industrial contexts like carbon capture and storage (CCS) and enhanced oil recovery (EOR), where accurate monitoring of CO_2 injection underground ensures operational efficiency and environmental safety.

The Carbon Management Canada's (CMC) Newell County is a platform for the development and validation of CCS technologies (Lawton et al., 2019). In 2018, a vertical seismic profile (VSP) survey was conducted as a baseline study for subsequent time-lapse monitoring of CO_2 injection. Full-waveform inversion (FWI) has been used to characterize the subsurface structures at the site, yielding encouraging results (Eaid et al., 2023; Hu et al., 2024). Following the injection of 50 tonnes of CO_2, a monitoring survey was conducted in 2022, with nearly identical survey geometry and sensor types deployed (Hall et al., 2019; Innanen et al., 2022).

FWI and VSP are two crucial technologies used for conducting time-lapse analysis of CO_2 in this project. FWI is a powerful tool for imaging complex geological structures by integrating relatively complete seismic data information (Virieux and Operto, 2009; Pan et al., 2019; Keating and Innanen, 2019; Hu et al., 2023). In comparison to surface data, VSP data contain richer information about transmission waves, allowing for the reconstruction of low wavenumber details in the model. Furthermore, incorporating the corresponding well-log data typically available in a VSP survey provides a reliable starting model for FWI, which helps alleviate issues with local minima.

In this study, we extend FWI analysis to the 2022 monitor survey to predict CO_2 distribution and migration. To prepare the data for inversion, we apply a series of pre-processing techniques to mitigate non-repeatability noise between the 2018-2022 VSP surveys, thereby highlighting the 'true' differences resulting from the injection. Then, we apply elastic FWI to three-component accelerometer data to reconstruct the subsurface models of P-wave velocity (*Vp*), S-wave velocity (*Vs*), and density (ρ). We also test different time-lapse inversion strategies, such as parallel, sequential, and double differences (Asnaashari et al., 2015), and eventually select the optimal models that align best with our geological understanding for the CO_2 scenario. The estimated elastic models could be used as input data for subsequent rock physics analysis aimed at quantifying the spatial distribution of CO_2 saturation.

As shown in Figure 1, the predicted changes in subsurface elastic properties are primarily observed around 300 m, corresponding to the CO_2 injection zone. The variations in *Vp* range from 130 m/s to 210 m/s, while the changes in *Vs* are minimal, and the density changes are around 50 kg/m^3. These variations are reasonable from a rock physics perspective. Although some artifacts are present in the non-reservoir sections (depths less than 250 m), the amplitudes of these artifacts are significantly smaller than those exhibited in deeper parts of the model. Overall, this result is reasonable, but there is still room to reduce non-repeatability noise and improve model accuracy, particularly for density.

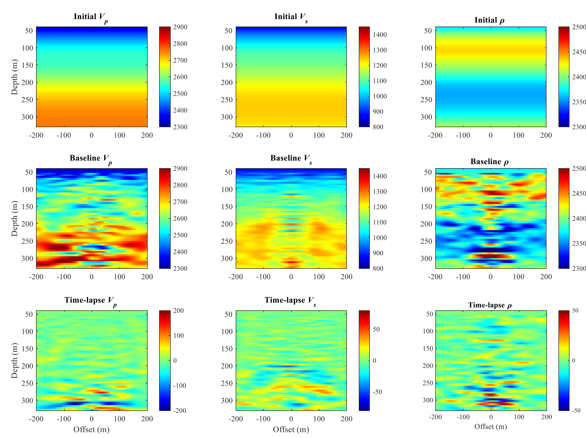

Figure 1. Top row: initial models of P-wave velocity, S-wave velocity, and density. Middle row: inverted models from the 2018 baseline data. Bottom row: Time-lapse model changes predicted for the 2022 monitor survey.

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