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Time-lapse FWI of the Snowflake data at CaMI

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Summary

Applying full-waveform inversion (FWI) to walkaway vertical seismic profile (VSP) data provides a high-resolution approach for monitoring subsurface changes, such as those caused by CO2 injection. This study investigates the potential of acoustic FWI to detect time-lapse changes associated with injecting ~60 tons of CO2 at a depth of 300 m. Using both synthetic and field data, we demonstrate that FWI resolves small-scale subsurface changes in the Basal Belly River Sandstone (BBRS) formation. Our results highlight the method's capability to capture subtle reservoir changes introduced by CO2 sequestration.

Time-lapse FWI

The Containment and Monitoring Institute (CaMI) Field Research Station (FRS), located ~200 km southeast of Calgary, Canada, serves as a small-scale CO2 storage site (Macquet et al., 2019). By 2022, approximately 60 tons of CO2 had been injected into the 7 m-thick BBRS formation at depths of 295–302 m. Two walkaway VSP datasets, acquired in 2018 and 2022 by CREWES, serve as the baseline and monitor surveys (Hall et al., 2019; Innanen et al., 2022).

In the 2D walkway VSP acquisition, the offsets range from 10 m to 480 m. The survey includes a total of 47 VSP gathers, with a nearly uniform spatial interval of 10 m. To meet the required resolution, we set the grid cell size to 2 m. The receiver intervals were resampled to 2 m spacing to improve the spatial resolution. In this work, we conducted FWI of Vp using the vertical component of the field VSP data. Our inversion workflow follows the traditional FWI technology (Tarantola, 1984) implemented in an open-source software package IFOS2D (Bohlen, et al., 2016). In Figure 1, we present three VSP gathers from the baseline data (first row) and the monitor dataset (second row), along with their differences (third row). These gathers reveal strong upgoing reflected waves from the BBRS layer, and their differences highlight the seismic response changes introduced by CO2 injection.

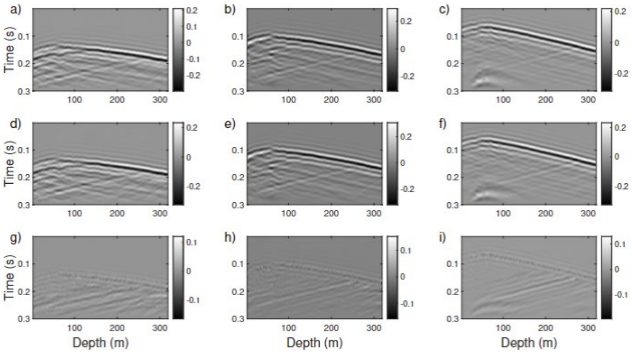

Figure 1: Three VSP gathers from the baseline dataset (first row) and the monitor dataset (second row), as well as their differences (third row).

The inverted baseline model is presented in Figure 2c, which displays effective model updates within a 300 m offset with the observation well positioned at 0 m. Comparing it with the initial model from Figure 3a, we observe that FWI significantly enhances the model's resolution by introducing fine details into the initial model. The high-velocity BBRS layer is resolved in the inversion result, located at approximately 300 m depth.

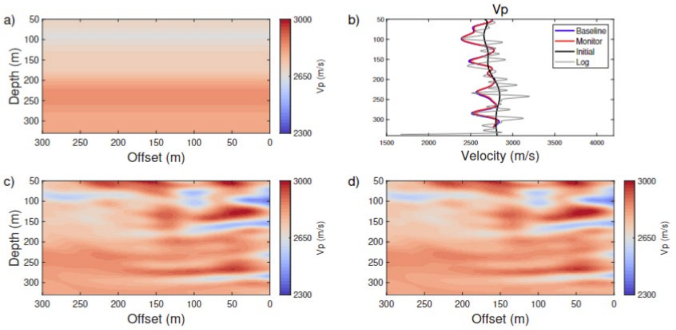

Figure 2: (a) The initial Vp model constructed by smoothing the well log data. (b) Comparison of the smoothed Vp log, the 1D initial Vp model, and the vertical profiles in the inverted baseline and monitor models. (c) The inverted baseline model. (d) The inverted monitor.

Following the parallel strategy, we obtained the time-lapse Vp change introduced by CO2 injection as shown in Figure 3a. This result demonstrates that the time-lapse change is successfully captured within the 7 m-thick BBRS layer at a depth of approximately 300 m. However, time-lapse noise is also observed above the reservoir in the image, which is consistent with the 4D noise present in the datasets. To validate that the time-lapse change imaged by the FWI of field VSP datasets is truly introduced by CO2 injection, we conducted verification using a synthetic model. The true baseline model and time-lapse model are shown in Figure 4a and b. We use the same workflow and acquisition geometry as in the field data inversion. In Figure 3c, we present the inverted time-lapse change using the synthetic model by the PRS. The synthetic test closely replicates the results observed in the field data, showing a clear time-lapse change within the thin layer. This consistency between synthetic and field results confirms the capability of 2D FWI to effectively detect and identify time-lapse changes in the reservoir.

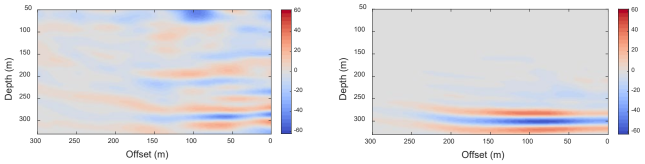

Figure 3: (a) The inverted time-lapse change using field VSP data by the parallel strategy. (b) The time-lapse change inverted by the synthetic data.

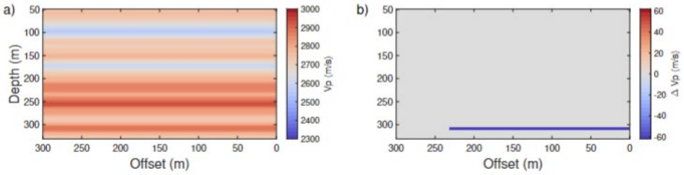

Figure 4: (a) The true baseline Vp model, (b) The true time-lapse Vp model.

Conclusions

The application of 2D FWI to the baseline and monitor Snowflake VSP datasets has achieved a successful CO2 injection monitoring at CaMI. The time-lapse results from both field and synthetic data show that this technology can produce high-resolution and detailed subsurface and reservoir properties, and effectively detect and identify time-lapse velocity changes introduced by CO2 injection.

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