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3D time-lapse RTM of DAS-VSP field data

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Summary

Accurately monitoring the subsurface movement and storage of CO_2 is critical in mitigating the impacts of climate change. In this regard, reverse-time migration (RTM) stands at the forefront of geophysical imaging techniques, offering insights into the geological reflectivity amplitude that hosts CO_2 plumes. This research uses the 3D GPU-based VSP RTM developed by Cai et al. (2018) and applies it to time-lapse Distributed Acoustic Sensing (DAS) data, to advance the visualization and understanding of CO_2 plume development over time. The study demonstrates RTM's effectiveness in capturing dynamic changes within CO_2 plumes by conducting tests on both baseline and monitoring synthetic data, followed by an application to field data from the Snowflake field for the years 2018 and 2022. The research has the potential to enhance CO2 sequestration efforts significantly.

Data

To collect 4D Vertical Seismic Profile (VSP) data near the CO_2 injection well, Snowflake studies were conducted in 2018 (Hall et al., 2019) and 2022 (Innanen et al., 2022) by researchers from the University of Calgary's CREWES project collaborated with Carbon Management Canada (CMC) at the Newell County Facility in Alberta, Canada. Figure 1 shows the shot geometry of Snowflake's data. Observation well 2 is located at the center of the shot points, while the injection well is situated northeast of observation well 2, exactly 20 m away. The baseline data includes 386 shots, while the monitor comprises 441 shots. The spacing between the baseline accelerometer receivers changed from 1 meter, covering the range of 0 meters to 266.4 meters, to 2 meters, from 266.6 meters to 324.2 meters. Similarly, the spacing for the monitoring accelerometer receivers changed from 1 meter, from 0 meters to 140.3 meters, to 2 meters, from 140.3 meters to 324.2 meters.

In Figure 2, the raw baseline and monitoring DAS data are displayed alongside windowed seismic data spanning the first 800 ms. DAS technology measures strain rate along the fiber, a property affected by the well's vertical alignment and its incorporation into a continuous loop. This can result in upward and downward vertical fiber regions, making depth registration essential for accurate analysis. The baseline data has a DAS data spacing interval of 0.667 meters, while the monitoring data has a spacing interval of 1 meter. Following depth registration, the upward and downward fiber regions are stacked and transformed from strain ratio to velocity. The upgoing field data is then extracted from the processed data using FK filtering.

3D DAS-VSP RTM

We have utilized code initially developed for 3D RTM, as explained by Cai et al. in 2018. To take into account the azimuthal characteristics of the field data shot geometry, we have introduced imaging dependent on the azimuth. Our approach involves several crucial steps on the GPU. Firstly, we use an optimal finite-difference (FD) method based on least-squares to solve the acoustic wave equation (Cai et al, 2015). Secondly, we use a hybrid absorbing boundary condition

(ABC) to suppress undesirable reflections from the boundaries. Thirdly, we adopt a combinatorial strategy that focuses on optimal checkpointing and efficient boundary storage to handle large-scale data. This strategy aims to balance memory usage and recomputation requirements. Finally, we determine the imaging scope by selecting the azimuth range. We use a Ricker wavelet with a dominant frequency of 30 Hz to generate the source. The total record time is 800 ms with a time interval of 0.5 ms. For the GPU-based hybrid ABC, the boundary width grids were set to 10, and the number of checkpoints was 2.

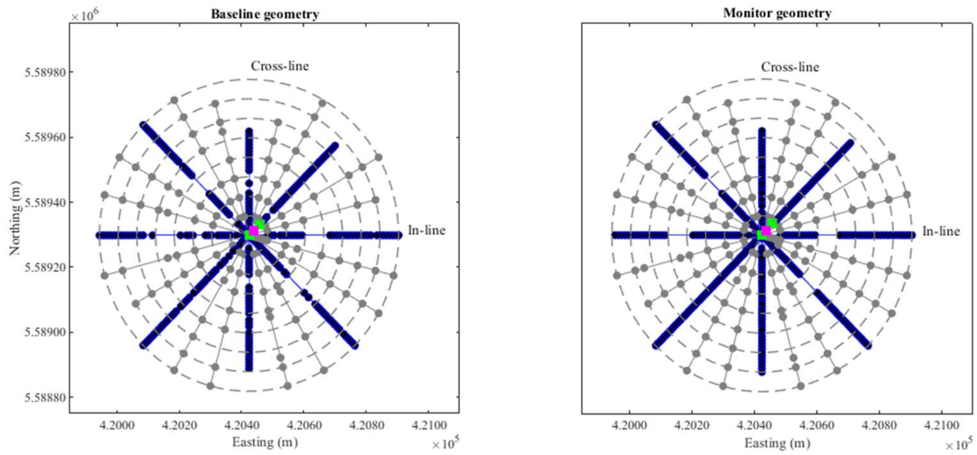

Figure 1. Baseline (left) and monitoring data's (right) shots geometry.

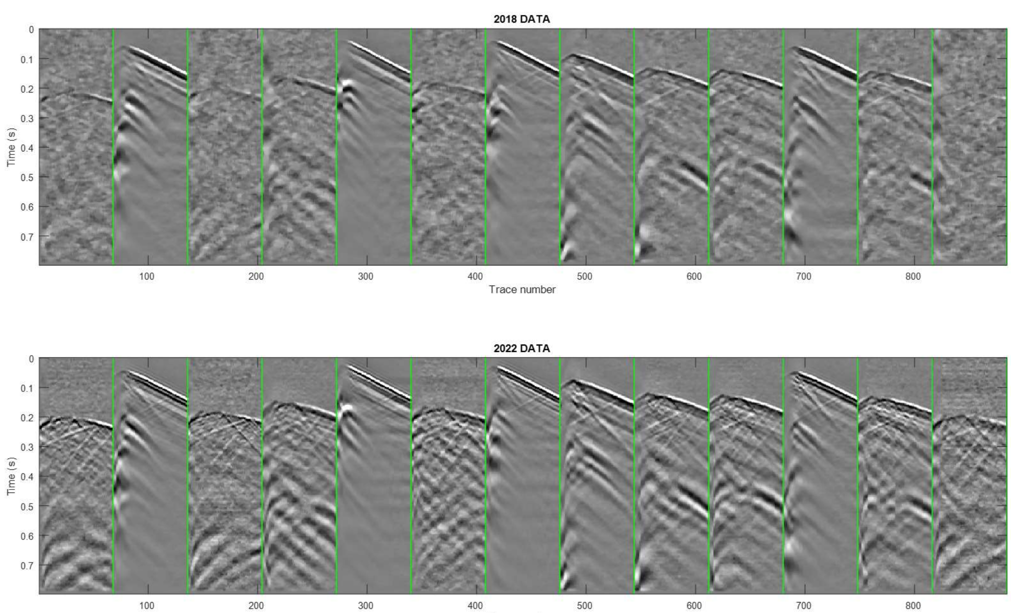

Figure 2. The raw baseline (top) and monitoring (bottom) data.

Figure 3 represents the synthetic model created by well-log data and the smoothed migration model. The P-wave sonic logs data from the surface to 223 m have been interpreted by the softsand model and Gassmann's equations (Hu and Innanen, 2019), while the information from 224 m to the bottom of the well is acquired by well logs. The 3D size of this model is 1000 m x 1000 m x 350 m. As the injection of CO_2 can cause a change in the P-wave velocity of the subsurface medium, we have set the difference between the monitoring velocity model and the baseline survey line model caused by changes in CO_2 plume as shown in Figure 4. The resulting images' slices for the baseline and monitoring surveys are shown in Figure 5 and effectively show the layered structure. The results of the time-lapse RTM are displayed in Figure 6, which is consistent with Figure 4. It is concluded that the RTM could image reflectivity caused by changes in P-wave velocity, thereby indicating the CO_2 plume. Finally, we apply the 3D VSP RTM method to time-lapse Snowflake field data. The baseline and monitoring field data imaging results (Figure 7) can reflect the subsurface reflectivity coefficient. The difference between monitoring and baseline data is shown in Figure 8. From the conclusion of the synthetic data, Figure 8 also indicates the presence of a CO_2 plume in the CMC Newell County Facility.

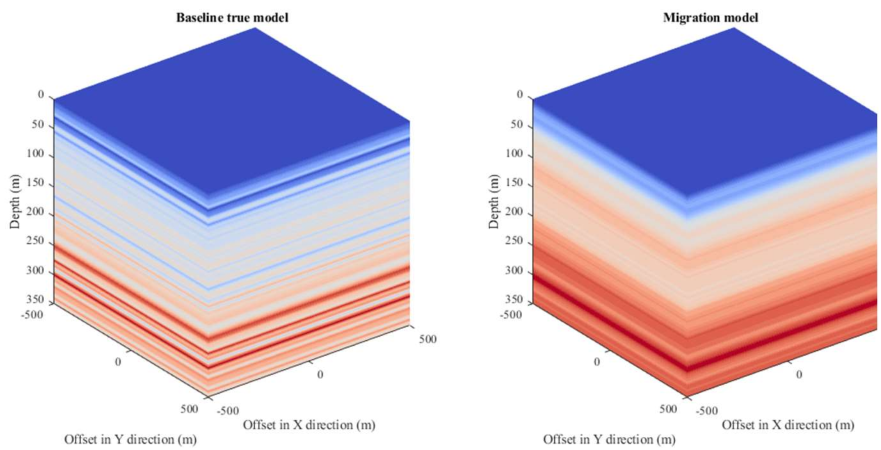

Figure 3. The baseline synthetic model (left) and migration model (right).

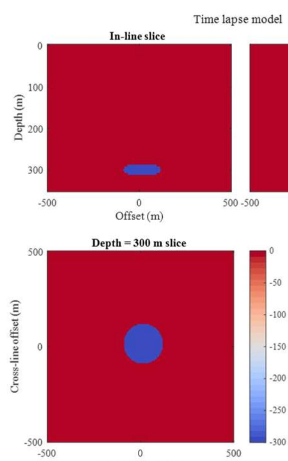

Figure 4. The time-lapse velocity difference slices along the coordinates of x = 0 m, y = 0 m, and z = 300 m.

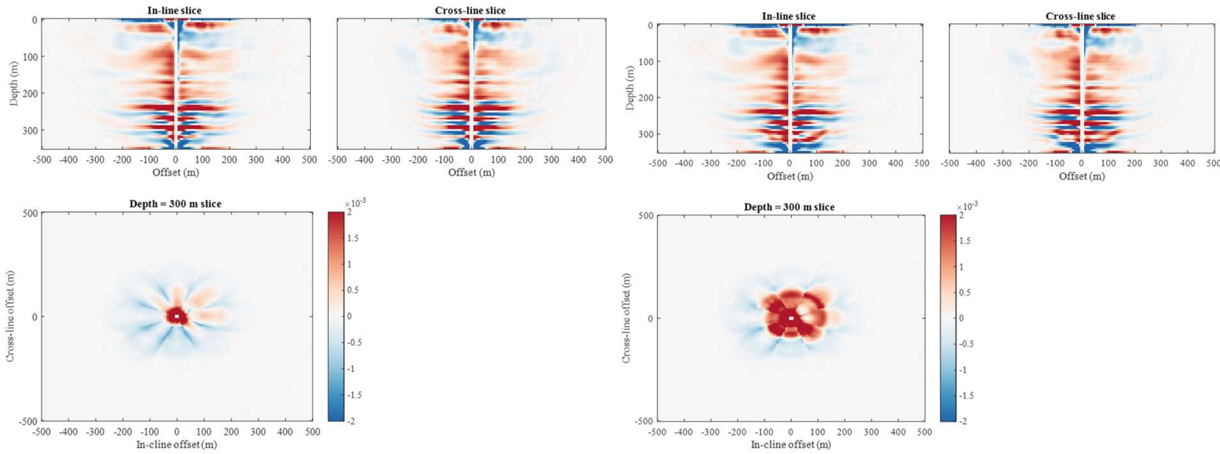

Figure 5. The baseline RTM imaging slices (left) and monitoring RTM imaging slices (right) for the synthetic model.

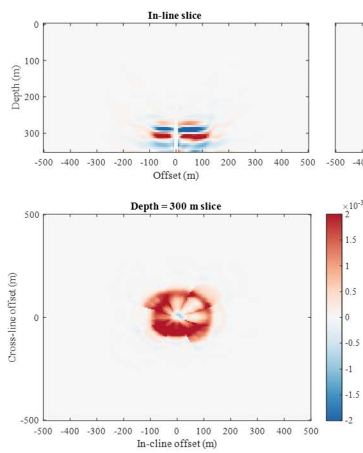

Figure 6. The time-lapse RTM imaging slices for the synthetic model.

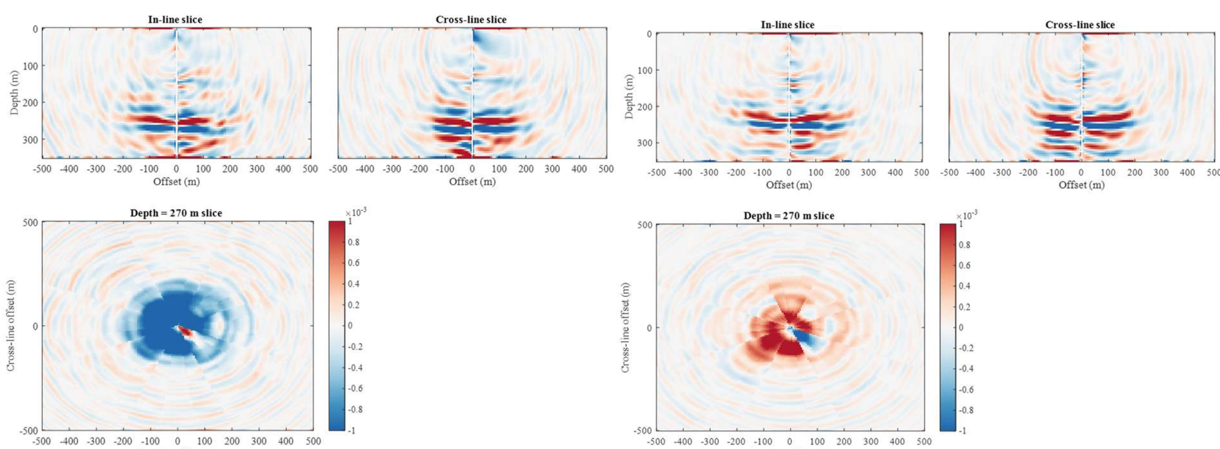

Figure 7. The baseline RTM imaging slices (left) and monitoring RTM imaging slices (right) for the field data.

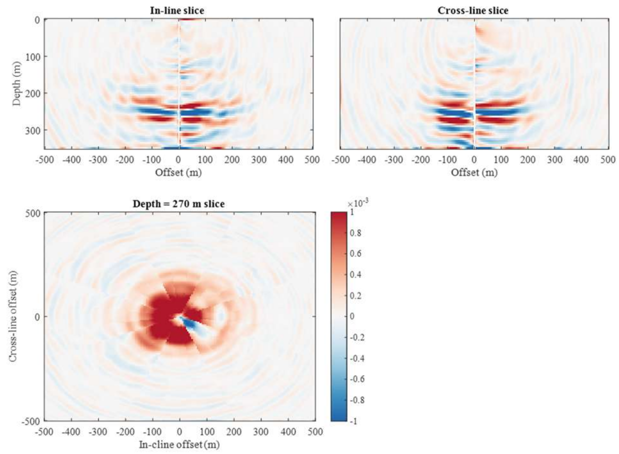

Figure 8. The time-lapse RTM imaging slices for the field data.

Conclusions

The study has shown that 3D GPU-based VSP RTM is an effective method for visualizing the dynamic changes of CO_2 plumes in geological formations. By analyzing time-lapse DAS images, we have provided clear evidence of the method's effectiveness in understanding CO_2 migration patterns. There is potential for improving the final results in the future, such as introducing 3D reflection angle/azimuth-dependent RTM.

Acknowledgments

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