Time-lapse processing and imaging of the Snowflake 3D DAS VSP CO_2 monitoring dataset

Xiaohui Cai[1], Kristopher A. Innanen[1], Qi Hu[1] Ziguang Su[1], and Donald C. Lawton[1,2]
[1]Dept. of Earth, Energy, and Environment, University of Calgary
[2] Carbon Management Canada

Summary

Distributed Acoustic Sensing (DAS) data acquired in a Vertical Seismic Profile (VSP) configuration is being actively considered as a candidate low-cost monitoring technology for CO_2 injection and storage. The University of Calgary "Snowflake" 3D VSP experiment, currently with two surveys spanning 2018-2022, was carried out in part to aid in this assessment. Optimizing 3D time-lapse VSP-DAS data processing and imaging involves several open questions, some of which we address in this study. Our primary focus is on enhancing the quality of upgoing wave data through a comprehensive approach, including phase analysis, denoising, separation of upgoing and downgoing waves, and wavelet characterization. Additionally, to further enhance imaging results, we employ both azimuthally-dependent and reflection angle-dependent reverse time migration (RTM) methodologies. The final imaging results arising from this approach lead to VSP-DAS time-lapse imaging, which may not only be relevant in the CO_2 monitoring problem but in a range of applications of this technology.

Introduction

Our research focuses on seismic imaging utilizing time-lapse data, specifically before and after CO_2 injection events, providing a unique vantage point to observe temporal changes induced by CO_2 injection in geological formations. Through the analysis of seismic data acquired at various time intervals surrounding CO_2 injection activities, our aim is to enrich our understanding of the subsurface response to carbon capture and storage (CCS) operations. Seismic imaging with time-lapse data holds significant importance in geophysical exploration, especially within the realm of CCS applications, enabling us to identify changes in subsurface structures, and evaluate the efficacy of CO_2 storage reservoirs. Through this study, we aim to highlight the potential of time-lapse seismic imaging in advancing CCS research and promoting the secure and sustainable deployment of carbon sequestration technologies.

RTM is a powerful depth migration technique used to create high-resolution images of complex subsurface structures (e.g., Baysal et al., 1983; Cai et al, 2018). Angle-Domain Common Image Gathers (ADCIGs) are crucial in seismic data processing as they offer a comprehensive view of subsurface structures at various reflection angles, aiding in accurate imaging and velocity analysis (Xu et al., 2011; Tang and McMechan, 2018). They also assist in migration aperture and anisotropy analysis, enhancing our understanding of complex geological formations.

DAS technology, utilizing fiber-optic cables instead of traditional sensors, facilitates the recording of seismic data with high sensitivity to the direction parallel to the fiber (Daley et al., 2016; Spikes, 2019). This makes DAS particularly suitable for acquiring VSP surveys. The report presents 3D Snowflake field imaging results, highlighting methods for characterizing injectivity using sensing modes with strong low-cost potential, such as VSP and DAS.

Data processing

To collect time-lapse VSP data near the CO_2 injection well, the "Snowflake" dataset surveys were conducted in 2018 and 2022 (Hall et al., 2019; Innanen et al., 2022) by the CREWES Project at the University of Calgary, in collaboration with Carbon Management Canada (CMC), at the Newell County Facility in Alberta, Canada. Figure 1 illustrates the shot geometry of baseline (2018) and monitoring (2022) data, with Observation Well 2 positioned at the center of the shot points, and the injection well located northeast of Observation Well 2, precisely 20 meters away. The baseline dataset comprises 386 shots, while the monitoring dataset consists of 441 shots. Figure 2 presents the raw baseline and monitoring DAS data. The baseline data features a DAS data spacing interval of 0.667 meters, while the monitoring data has a spacing interval of 1 meter.

Because different DAS interrogators were involved in 2018 and 2022, we analyzed their respective phases with the aim of proceeding to consistent time-lapse data. The baseline DAS data collected in 2018 measured strain rates. Initially, we integrated the baseline data over time to get strain data (Figure 3). However, upon comparison with the 2018 integrated data from the 2022 DAS data, we observed a disparity in phase. Furthermore, due to the low signal-to-noise (S/N) ratio of the raw data, time-domain integration led to significant low-frequency noise, ranging from 0 to 10 Hz. Given these challenges, we applied a 180-degree phase shift to the 2018 data. Subsequently, the processed 2018 data exhibited improved phase alignment with the 2022 data, without compromising the S/N ratio.

One of the challenges encountered in processing the DAS data with the 2018 vintage is its comparatively low S/N ratio. To address this, we employed multiple denoising techniques. The first step involved suppressing noise using an algorithm based on sparsity-promoting curvelet transforms (Candes and Donoho, 2005). In the second step, a bandpass Butterworth filter with a frequency range of 5-100 Hz and zero-phase was applied. In the third step, a median filter was employed. This denoising process effectively mitigated linear noise components, Gaussian noise, and artifact noise (Figure 4).

It is common practice to utilize only upgoing waves for imaging, as downgoing waves often degrade the final imaging results. To separate these wave types, we applied a median filter, followed by FK filtering to effectively separate the upgoing waves (Figure 5).

Finally, we addressed the choice of wavelet. Initially, we analyzed the sum of the frequency spectra across all traces, as well as a single trace in the near offset (Figure 6). From this, we estimated a spectrum with a maximum frequency of 100 Hz and a dominant frequency of 20 Hz. We observed consistent time-domain first peak times and phases between the 2018 and 2022 data. We applied a low-pass filter with a cutoff frequency of 100 Hz and computed a phase conversion to transform the wavelet to a minimum phase, which was utilized for subsequent RTM imaging.

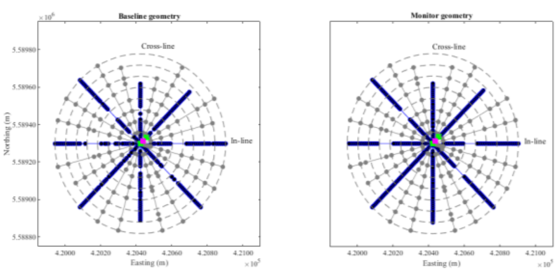

Figure 1. Baseline (left) and monitoring data's (right) shots geometry.

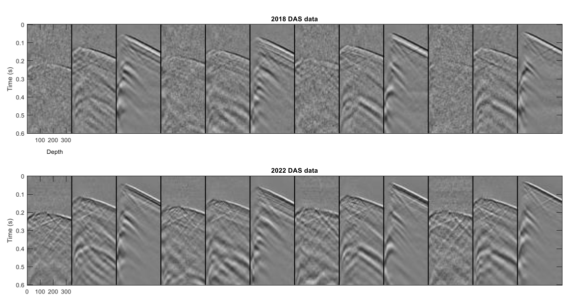

Figure 2. The raw baseline (top) and monitoring (bottom) data.

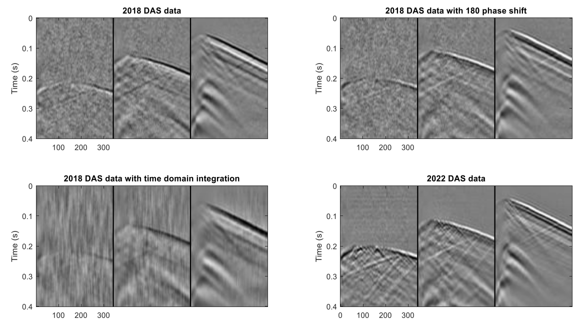

Figure 3. Raw and phase-shifted baseline data and monitoring data.

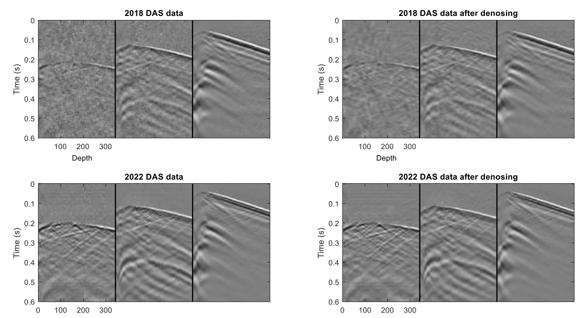

Figure 4. Raw and denoised baseline and monitoring data.

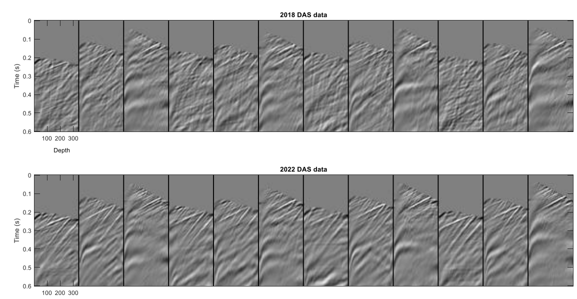

Figure 5. Baseline (top) and monitoring (bottom) upgoing data.

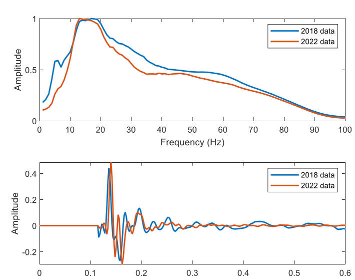

Figure 6. Baseline and monitoring data in frequency domain (top) and time domain (bottom).

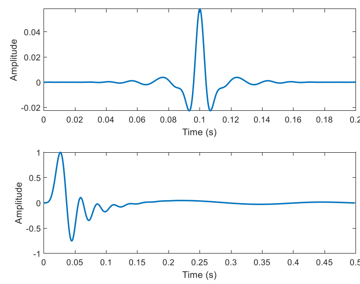

Figure 7. The EnviroVibe source wavelet after low-pass filtering (top) and phase shifting (bottom).

3D DAS-VSP RTM

The 3D RTM code we used is documented by Cai et al. (2018). In it, we introduce azimuth-dependent imaging techniques to accommodate the azimuthal characteristics of the shot geometry. Our methodology involves several pivotal steps executed on GPUs. Initially, we employ an optimal finite-difference (FD) method based on least-squares to solve the acoustic wave equation, as discussed by Cai et al. (2015). Subsequently, we integrate a hybrid absorbing boundary condition (ABC) to mitigate boundary reflections. Additionally, we adopt a combinatorial strategy focusing on optimal checkpointing and efficient boundary storage to manage large-scale data, aiming to balance between memory utilization and re-computation requirements. Finally, we define the imaging scope by selecting the azimuth range. Based on an efficient boundary storage strategy, during the reverse time propagation process, we obtain both the forward and backward wavefields at the same time step. Concurrently, we compute the propagation angle of the seismic source at each time step, which can be regarded as an additional dimension in the code. Figure 9 illustrates the forward wavefields at three different time steps along with their corresponding propagation angles based on the layered model (Figure 8).

Figure 10 displays the VSP imaging results at various angles, indicating a close resemblance between the imaging results from 0 to 60 degrees and those from 0 to 90 degrees. Figure 11 illustrates the geometry of the layered model alongside the corresponding ADCIG. The ADCIG generally exhibits a layered structure, providing supporting evidence for the accuracy of the velocity model.

Figure 12 represents the smoothed migration model from well-log data. The 3D size of this model is 1000 m in East-West and North-South directions, with a depth of 350 m. Subsequently, we apply the 3D VSP RTM method to the time-lapse Snowflake field data. Figures 13 and 14 depict the imaging results of the baseline and monitoring field data, respectively, focusing on angles ranging from 0 to 60 degrees, thereby providing insights into the subsurface reflectivity coefficient. Notably, Figure 15 illustrates the difference between the monitoring and baseline data, suggesting the potential presence of a CO_2 plume at the CMC Newell County Facility.

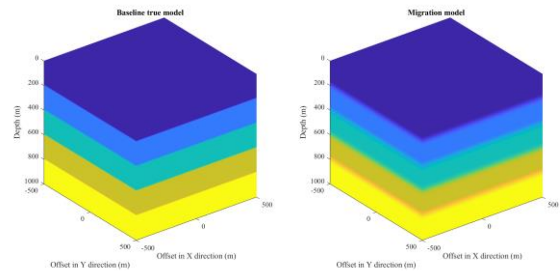

Figure 8. Synthetic layered model.

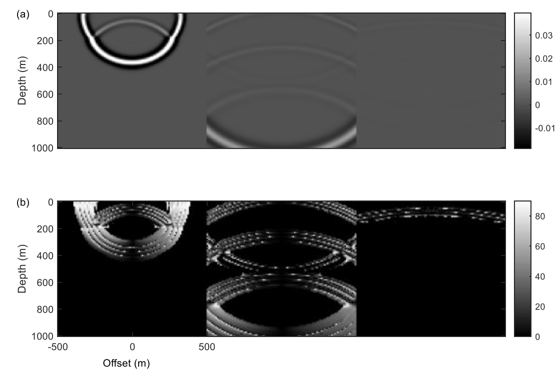

Figure 9. (a) Forward modeling snapshots and (b) The angle between the forward wavefield propagation and the normal direction.

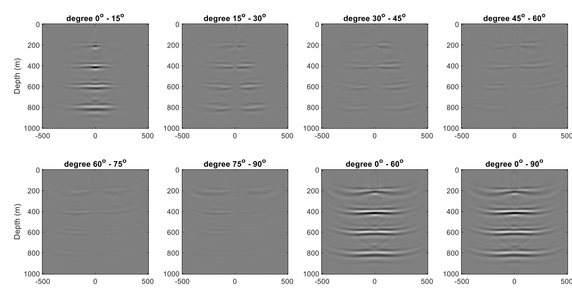

Figure 10. Imaging with different angle ranges.

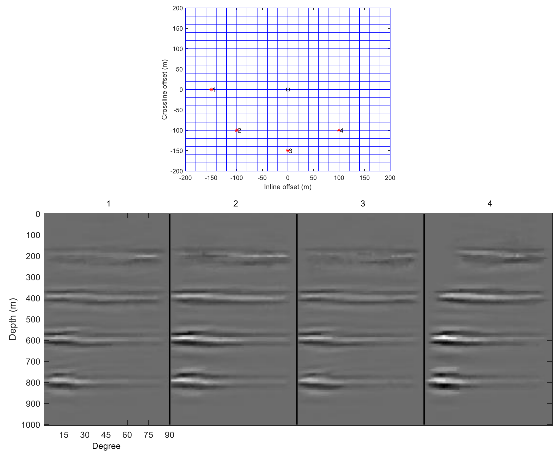

Figure 11. Shot and receiver geometry (top) and the corresponding ADCIG gather (bottom).

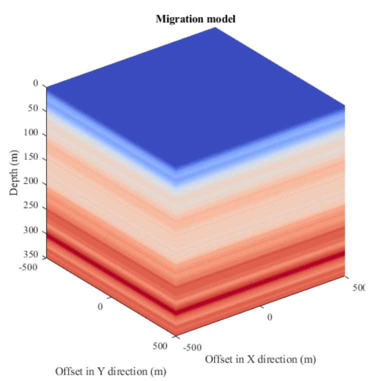

Figure 12. Migration model.

Conclusion

The use of 3D time-lapse imaging techniques to characterize underground CO_2 changes holds significant importance. The processing of 3D DAS data in this study aimed at achieving a balance between data fidelity and S/N ratio, resulting in a well-defined upgoing wavefield. Combining azimuthal and reflection angle-dependent imaging techniques yielded the final imaging results. The differences observed between baseline and monitoring data also define the extent of CO_2 variations underground. A comparison of these results with other plume characterization approaches is currently underway.

Acknowledgments

This work was funded by CREWES industrial sponsors and NSERC (Natural Science and Engineering Research Council of Canada) through the grant CRDPJ 543578-19. The data were acquired by the University of Calgary through a collaboration with the Carbon Management Canada Newell County Facility.

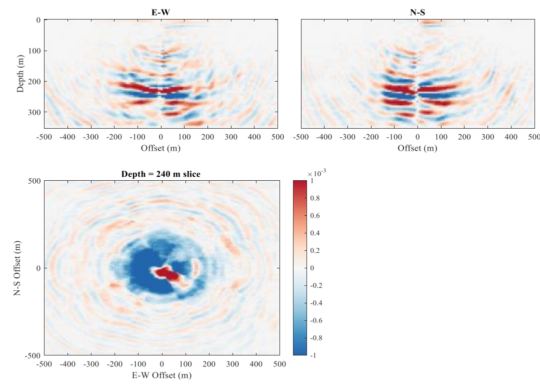

Figure 13. The RTM imaging slices for the baseline field data.

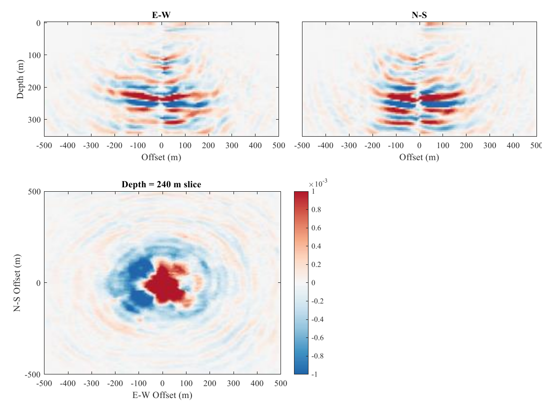

Figure 14. The RTM imaging slices for the monitoring field data.

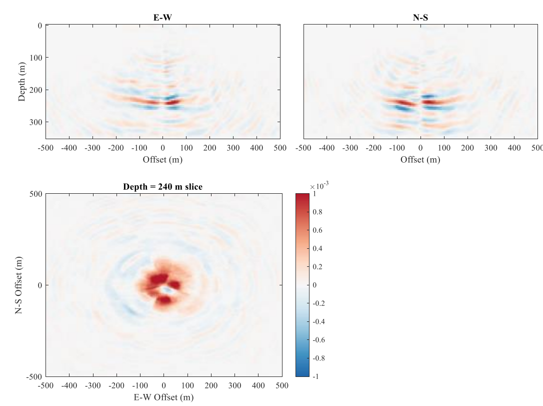

Figure 15. Difference between the baseline and monitoring RTM images.