

Introduction

The Weyburn field, discovered 70 years ago, entered a second production phase using CO₂ for Enhanced Oil Recovery (EOR) in the early 2000s. Since then, it has sequestered over 34 million tons of CO₂, with an ultimate capacity estimated at 55 million tons (Chen et al., 2021). Since 2000, 4D seismic has been employed to optimize production, drilling plans, and understand flooding performance. To further track injection dynamics, spot seismic technology has been applied at the Weyburn field since 2021. Three spot seismic monitoring campaigns were conducted between 2022 and 2024, successfully detecting the CO₂ plume (Brun et al., 2022, Brun and Chen., 2023). Each campaign involved 16 spot locations, computed from the start based on flow model predictions. These spots help identify potential mismatches between predicted and actual CO₂ fronts, optimizing flood efficiency.

In 2024, Whitecap Resources conducted a 4D seismic survey to gain a comprehensive understanding of fluid dynamics across the field. This extensive monitoring was compared with spot seismic results to evaluate the reliability and complementarity of each technology. The successful matching of results from both 4D seismic and spot seismic indicates a promising combination of monitoring technologies. Spot seismic provides frequent and localized insights into fluid dynamics, while 4D seismic offers a spatial response every four years. By combining these technologies, costs can be optimized while enhancing CO₂ injection and Enhanced Oil Recovery (EOR) capacities. Dedicated spot seismic can pinpoint critical areas based on flow model outputs, allowing for the postponement or delay of 4D seismic without compromising sweeping efficiency.

Study

The Weyburn oilfield, discovered 70 years ago in Saskatchewan, Canada, serves as a carbon storage facility, increasing oil production while storing CO₂. This field is monitored as part of CO₂ injection for EOR, which began over 20 years ago. Since 2000, Whitecap Resources has implemented a dedicated monitoring strategy using 4D seismic technology to identify unswept areas and optimize drilling plans. To maximize monitoring potential, an agile and nimble spot seismic monitoring approach was introduced in 2022. Spot seismic allows for more frequent, agile, and environmentally friendly CO₂ monitoring. Its lightweight design makes it a cost-effective technology, providing reliable insights into CO₂ presence at specific locations known as Spots. The goal of frequent spot seismic monitoring is to trigger reservoir model updates and operation adjustment. When a model mismatch is detected, as it was in November 2022 (Brun and Chen., 2023), it is possible to trigger security operations (well completions) or further imaging of the field (4D image, VSP), using spot seismic to initiate reservoir model updates.

In 2022, Whitecap Resources selected 16 Spot locations based on injection/production well locations and the CO₂ reservoir model. Three spot seismic acquisitions have been performed over the Weyburn field. Each spot is highlighted by a single source-receiver couple (Figure 1), chosen according to the legacy 3D seismic, geophysical criteria (Morgan et al., 2020, Brun et al., 2021) and surface/subsurface obstructions (pipelines, roads, permit issues). The 2 first spot seismic acquisitions occurred respectively in March 2022 and November 2022, where CO₂ injection started in December 2021. The last acquisition was run at the same time of 4D acquisition, in November 2024. Monitors acquired at these times are compared to a baseline acquired during a 3D seismic acquisition in November 2020.

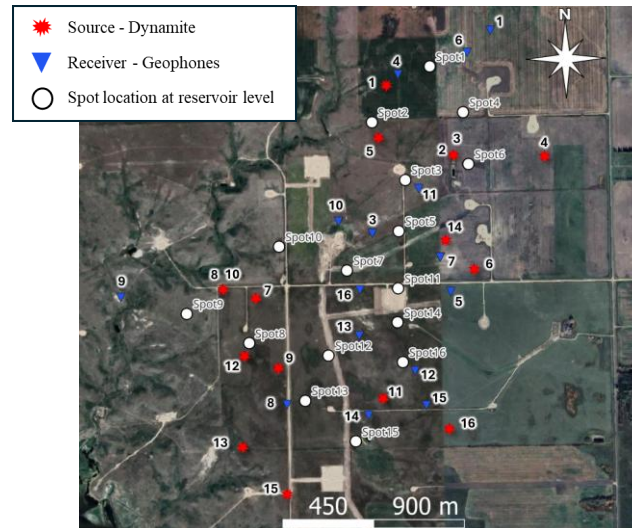


Figure 1 Spot seismic acquisition design showing spot (white) and associated source (red) and receiver locations in blue using the same digit code over the studying area (Eastern part of the Weyburn unit area) for the November 2024 acquisition.

Methods

To ensure the best possible processing results, time-lapse seismic acquisitions must be sufficiently repeatable. Careful source and receiver repositioning must be conducted from one acquisition to another to ensure optimal repeatability (Duret et al., 2024). The maximum shift over the data used for the detection is about 10 meters. Without any processing, the raw seismic average NRMS is 35% and the associated correlation coefficient between each monitor is 93%. These quality levels demonstrate excellent repeatability to perform time-lapse detection. The processing of the 16 Spots was made using 1D processing on each Spots separately and by computing time shift and amplitude changes over the 3 monitors acquired in the past 3 years, in comparison to the baseline acquired in 2020 (Figure 2).

The first step of pre-processing is to correct the potential source-receiver locations mismatch by aligning the traces using an overburden window located above the reservoir. Then, a basic processing sequence consisting in a bandpass filter, whitening and amplitude correction, when necessary, was applied on the data, with the aim of increasing the repeatability of each Spots. As a result, for some spots the processing applied was able to decrease the NRMS by 20%.

Finally, CO₂ was detected by analyzing time shift and amplitude changes at reservoir levels, by comparing the monitors with their baseline. A delta time shift is then calculated by subtracting the 2 mean timeshift, respectively computed over one overburden window and one window underneath the reservoir. Amplitude changes were also detected at reservoir level using the corr-nrms indicator, combination of normalized root mean square divided by the correlation coefficient indicator (Al Khatib and Mari, 2023).

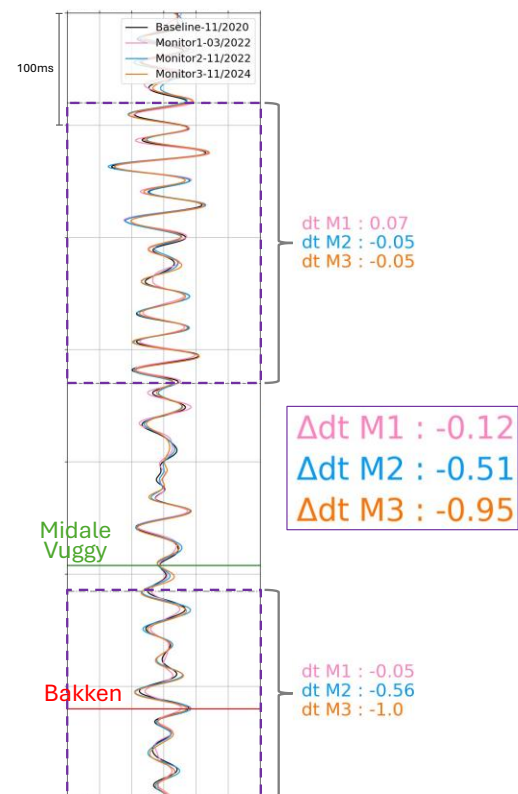


Figure 2 Spot 12 Monitoring Shot Gather (MSG) showing increasing CO₂ time shift effect at reservoir, over time.

Results

Spot seismic technology is carefully used to validate or invalidate reservoir models. A spot is always located to check for containment or conformance over the field (Gestin et al., 2025), relying on flow model outputs and risk assessment analysis. For conformance spots, their positions are compared with the flow model, and actions are planned in case of mismatches based on their level of concern. In the Weyburn area, the CO₂ reservoir model from 2022 was used to locate all 16 spot locations and assess sweeping efficiency and model predictivity. The studying area consists of several injectors and producers, all oriented NE-SW (Figure 3). In March 2022, most spots within the CO₂ plume extension prediction detected CO₂, primarily through time shift effects. However, Spot 16 showed a model mismatch with CO₂ detected outside the predicted CO₂ plume. By November 2022, with a second spot seismic acquisition, this mismatch persisted, which further confirmed the CO₂ migration direction, and could provide guidance for reservoir model updates.

Well information is also used to understand fluid dynamics and confirm spot detection, with injectors and producers in the area alerting in case of CO₂ production and hazardous pressure measurements. None of these issues materialized, indicating controlled sweep efficiency. The spot seismic mismatch from March 2022 (Figure 3a) had also been confirmed by a small amount of CO₂ produced in the nearby well.

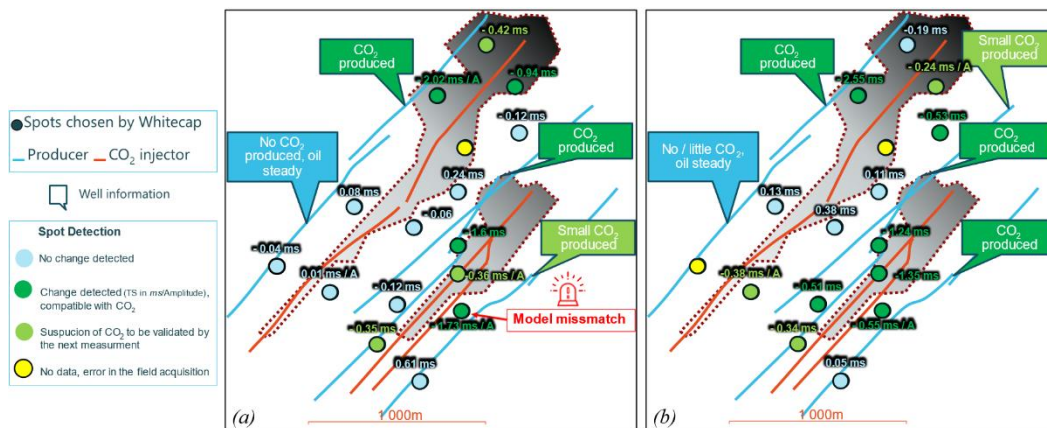


Figure 3 Time shift and amplitude detections (green, blue and yellow spots) results from (a) March 2022 and (b) November 2022, over reservoir flow model from March 2022 (gradient black to white) with production/injection well information.

Spot seismic is a novel approach to active seismic applications (Morgan et al., 2020), although its geophysical basis remains equivalent to conventional active seismic technology. To further assess the reliability of spot seismic, results were compared with the 4D seismic map (Figure 4). The 4D seismic changes map is computed by extracting amplitude changes at the top of the reservoir unit. The spot seismic methodology uses a combination of time shifts below the reservoir and amplitude changes at the top of the reservoir to detect CO₂ injection signatures. Based on the

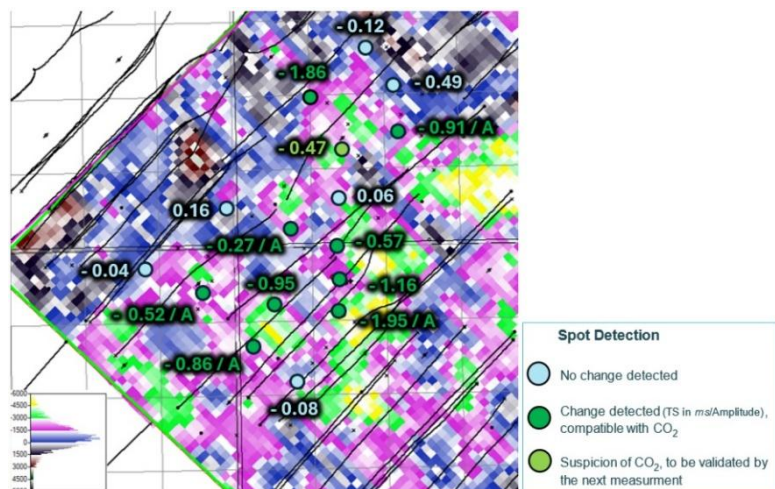


Figure 4 Spot detection (times shift in ms / Amplitude) comparison with 4D seismic amplitude map. Negative amplitudes indicate CO₂ concentration.

comparison of both technologies' results, the 4D seismic is matching with the spot seismic detection between November 2024 monitor and baseline from 2020. Furthermore, it also verify the reliability and value of frequent in between 4D spot detection as the mismatch identified in March 2022 is located into a high CO₂ concentration area in 2024.

Spot seismic can provide insights into reservoir dynamics much more frequently compared to conventional seismic imaging technology. Combining spot seismic and imaging technology enables the development of an efficient, frequent, and cost-effective monitoring strategy over the Weyburn area.

Conclusion

Novel technologies such as spot seismic are often approached with caution regarding CO₂ injection and Measurement, Monitoring, and Verification (MMV) plans for regulators. The successful comparison of spot seismic with 4D seismic, highlighted staged and frequent spot seismic detection could provide reliable supports for dynamic reservoir simulation and injection strategy. By combining in-well monitoring, flow model predictions, passive seismic, and active seismic at every step of the CO₂ injection, flow dynamics can be observed anytime and anywhere, increasing confidence in the ongoing CO₂ injection. Frequent tools such as spot seismic, passive seismic, or gauges can also provide useful and reassuring information to the public, enhancing social acceptability. Meanwhile, more expensive technologies with advanced reservoir dynamic knowledge can be used for verification and can be triggered by frequent monitoring technologies.

Acknowledgements

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