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Time-Lapse Seismic Monitoring in CO_2 Enhanced Oil Recovery and Storage at Weyburn, SE Saskatchewan

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Summary

Southeast Saskatchewan's Weyburn Unit has successfully injected Carbon Dioxide (CO_2) as part of its Enhanced Oil Recovery (EOR) operations for over 20 years. Since the miscible flood began in 2000, the Weyburn Unit has sequestered over 34 million tonnes of CO_2, with an ultimate storage capacity estimated at 55 million tonnes. CO_2 flooding has contributed ~90mmbbl (~6% R.F) of incremental oil to the 521mmbbl total recovered barrels to date (~35% R.F.). Since 1997, time lapse (4D) seismic has been an essential surveillance tool to ensure safe and optimized development continues throughout the field. Multiple 4D seismic surveys have been acquired to monitor the evolution of CO_2 flood (see ***Figure 1***) and identify sweep inefficiencies, infill drilling opportunities, and detect potential Out of Zone (OOZ) concerns involving in abandonment or other intervention tactics. 4D seismic plays an integral role in understanding the Weyburn Unit's CO_2 flood performance, and aids in strategic planning and time critical field optimization.

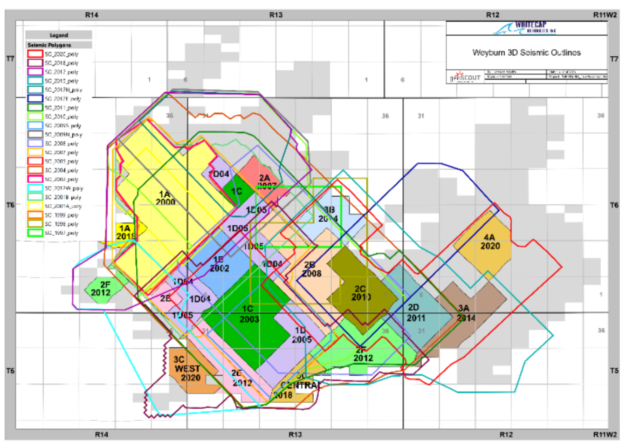

Figure 1. Weyburn Unit Area 3D Seismic Coverage

Geology Background

The Weyburn Unit is located in the northern part of Williston Basin in Saskatchewan. Medium sour crude is extracted from the Midale Beds of the Mississippian Charles Formation, at an average depth of 1450m TVD. The Midale carbonates were deposited as part of a regional brining upward cycle with complex sequence stratigraphic relationships and diagenetic overprinting.

The reservoir can be subdivided into two informal units with contrasting flow properties: 1) the Marly, a low permeability, mostly sucrosic dolomite, and 2) the underlying Vuggy, a highly fractured and heterogenous limestone with variable permeabilities and rock textures. Textural complexity is a result of primary paleoenvironmental controls, erosive episodes, and secondary dissolution. The Vuggy 'Shoal' (***Figure 2***) was deposited in a shallow marine peritidal environment where carbonate grain development and periodic exposure produced high quality reservoir rock with permeability ranges from 1md to 500mD (averaging 20mD) with porosity of ~15%. In contrast, the Vuggy 'intershoal' beds consist of subtidal facies with considerably smaller pore throat sizes and lower matrix permeability. The Marly dolomites are considerably more homogeneous than the Vuggy limestones, and form a low-permeability flow unit with an average porosity of 26%. Horizontal drilling primarily targets the Marly beds, where high hydrocarbon pore volumes and uniform pore throats allow for effective EOR application of CO_2. In our area of study, the Vuggy ranges from 10–22 metres in thickness while the Marly is ~10 metres thick on average. Both Marly and Vuggy beds dip and thicken to the SW (see ***Figure 2***).

Competent reservoir seals are essential for trapping the oil in place and ensuring permanent storage of anthropogenic CO_2. In the Weyburn Unit, seals are created through several different mechanisms. Tilted Mississippian reservoir beds are regionally truncated by the Sub-Mesozoic Unconformity and juxtaposed against the low permeability Jurassic/Triassic Lower Watrous Member above, forming an effective regional seal. A diagenetic alteration zone occurs subjacent to the unconformity, occluding any available porosity through cementation. Within the Charles Formation, the Midale Evaporite and the Frobisher Evaporite create seals above and below the Weyburn Unit reservoir beds, respectively. Additionally, the Midale reservoir quality deteriorates and becomes more heterogenous toward the NE subcrop edge. This drop in reservoir quality prevents the updip migration of CO_2 post injection.

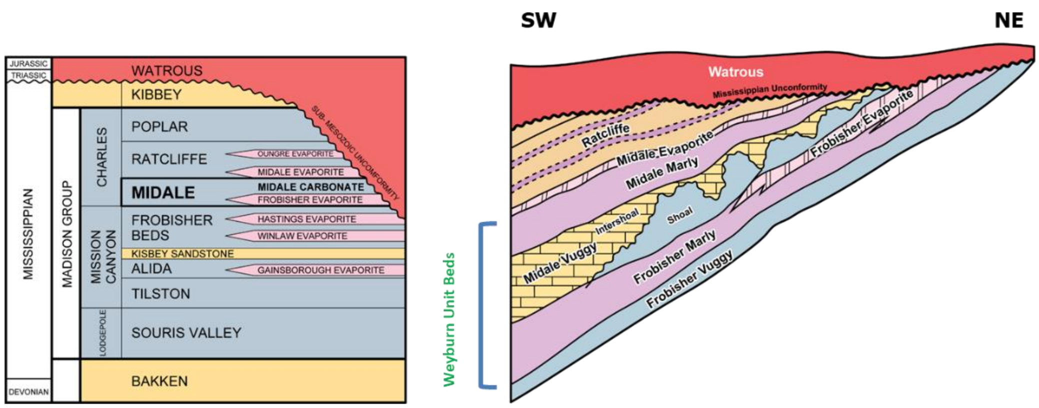

Figure 2. Weyburn Unit Stratigraphy and Geology Schematic

Reservoir Rock Physics Modeling and Seismic Responses

A keystone of Weyburn CO_2 monitoring and storage project is to optimize management of the reservoir for enhanced oil recovery and safe, efficient storage of CO_2. To facilitate this, detailed and collaborative rock physics modeling has been conducted by the Petroleum Technology Research Centre (PRTC) and Colorado School of Mines. This research initiative provides strong technical support and assurance that 3D surface seismic data is an appropriate tool to monitor CO_2 plumes and OOZ concerns with a time lapse survey component.

CO_2 effects on reservoir seismic properties have been observed utilizing physical core flood under lab conditions (anisotropic model), and isotropic Gassmann fluid saturation equations, as well as well log modeling. ***Table 1*** presents the comparisons of P-wave and S-wave velocity variations by adjusting fluid saturation and pressure at physical core flood model and Gassmann rock physics model, respectively. P-wave velocity (Vp) shows the most dramatic decrease with CO_2 replacement in both Marly and Vuggy formations; S-wave velocity (Vs) is less sensitive to the pore fluid. Pressure-related seismic velocity changes are relatively small. Both Vp and Vs measurements are relatively close under both models; the larger difference in the Vuggy formation might be explained by a higher presence of natural fractures there.

Table 1. Sensitivity of Vp and Vs to changes in fluid and pressure for Marly and Vuggy units, based on a) Gassmann isotropic rock physics model (labeled Iso) from ultrasonic core testing and geophysical logs and b) anisotropic rock physics model (labeled Aniso). The anisotropic model is a generalization that attempts to account for fractures observed in core and image logs from the reservoir (Bunge, 2000) Table is modified from Brown (2002).

Change	Marly Unit, φ=24%				Vuggy Unit, φ=10%			
	Iso	Aniso	Iso	Aniso	Iso	Aniso	Iso	Aniso
	ΔV_p (%)	ΔV_p (%)	ΔV_s (%)	ΔV_s (%)	ΔV_p (%)	ΔV_p (%)	ΔV_s (%)	ΔV_s (%)
Brine to oil	-3.3	-3.4	1.1	1.1	-2.2	-2.8	0.4	0.4
Brine to CO_2	-6.0	-6.3	-2.5	-2.5	-4.2	-5.6	1.0	1.0
1 MPa Δ(Pore Pressure) @ 15 MPa	-0.64	-0.65	-0.90	-0.90	-0.18	-0.16	-0.15	-0.15

(IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000-2004)

Based on the established sensitivity of the reservoir seismic properties to CO_2 injection, more modeling of seismic responses has been conducted using well logs in conjunction with the rock physics model. ***Figure 3*** depicts the effect on the seismic reflection waveform due to CO_2 saturation vs. thickness (0-24m), as CO_2 migrates down from the uppermost Marly bed. The observable difference in the seismogram at ~1150ms changes drastically as CO_2 fills the upper 4m, but doesn't change notably after. The trough amplitude is associated with the Marly beds and the peak is associated with the Vuggy beds. As the CO_2 bank spreads downward into the Vuggy, the seismic response changes very little. It reflects the tuning effects in the reservoir due to thin beds of both Marly and Vuggy. The limited thickness of the reservoir beds means that the time-lapse seismic response will not generally resolve the CO_2 response of an individual bed, but can be used to delineate CO_2 plumes laterally in the reservoir.

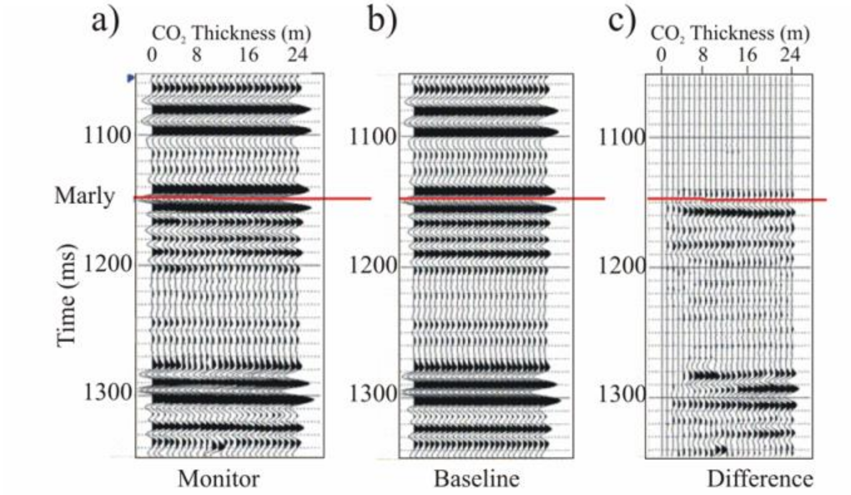

Figure 3. Monitor, baseline and difference synthetic seismograms for an injected CO_2 bank that starts at the top of Marly and increases in thickness from 0-24m (results from left to right in a and c). The Marly horizon is labeled. (IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000-2004)

Results, Observations, Conclusions

Multi 3D 3-component megabin surveys have been acquired since 1997 to monitor CO_2 plumes. P-wave 4D data have been mainly used to map the seismic effects of CO_2 injection and are used in operational surveillance. ***Figure 4*** illustrates the trough amplitude vintage difference (in red) within the Midale beds (both Marly and Vuggy) from different 4D surveys of 2004-1999, 2007-1999 and 2017-2004. The continuous extension and progress of increasing trough amplitude demonstrates increasing CO_2 injection volume and new CO_2 injection patterns.

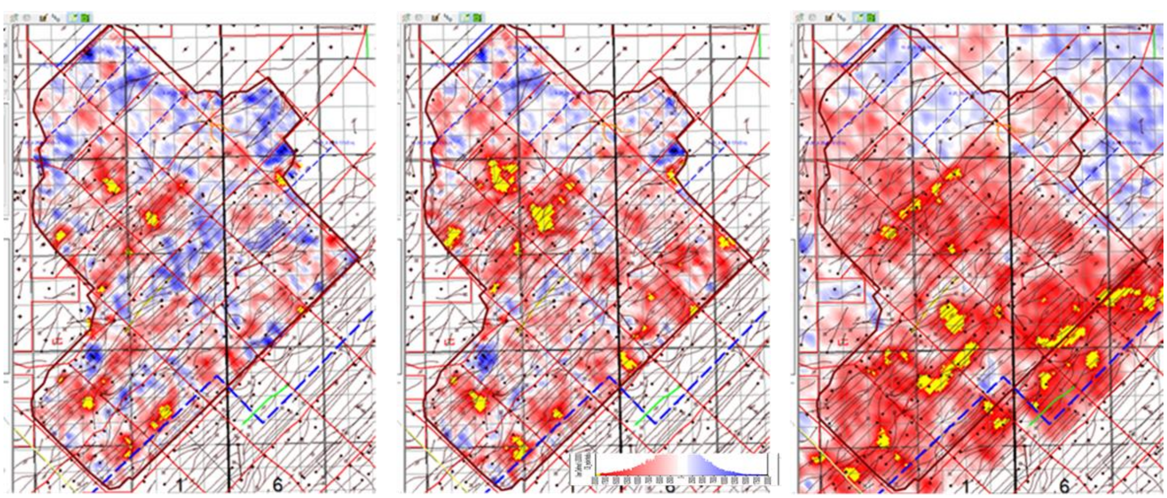

Figure 4. P-wave Midale 4D seismic trough amplitude vintage difference maps
from 2004-1999, 2007-1999 and 2017-2004 from left to right.

4D seismic amplitude difference maps not only effectively image the CO_2 sweep, but also play a strategic role with operational decision-making. 4D seismic helps optimize CO_2 injection volumes and timing of water injection cycles, helps identify abandonment candidates and ensures CO_2 is effectively sweeping the reservoir. ***Figure 5*** is an example showing how CO_2 migrated down through a poorly abandoned vertical well located between two horizontal injectors. 4D seismic from below the Midale showed CO_2 presence with strong trough amplitude (bright yellow) within Frobisher formation around the abandoned vertical well, which identified as CO_2 injection into a non-pay streak and a weak sweep efficiency within the Midale. In response, a re-abandonment job was assigned for the old vertical well and CO_2 conformance has been corrected.

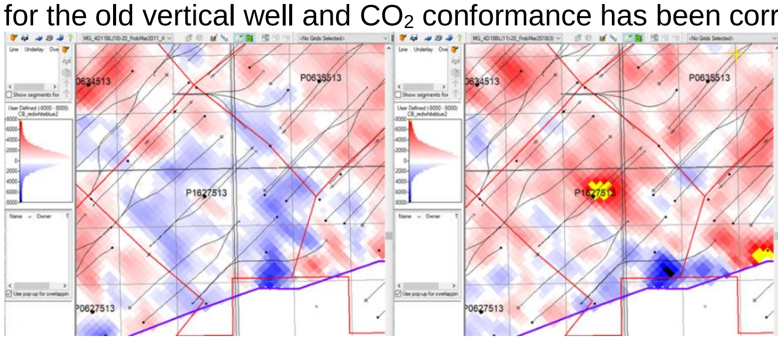

Figure 5. 4D Seismic Amplitude Difference Maps of 2014-2011 before CO_2 injection (left) and 2018-2011 with CO_2 injection started after 2014 (right) at Frobisher Marly. Strong trough amplitude anomaly occurred around the abandoned vertical between two horizontal injectors.

In conclusion, time-lapse seismic data has been an indispensable tool for CO_2 surveillance at the Weyburn CO_2 EOR and storage project. Further seismic AVO inversion and PP&PS joint inversion can be conducted to improve both temporal and lateral resolution of the seismic data and better image the thin bed reservoir.

Acknowledgements

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