# Seismic monitoring of a $CO_2$ flood at Weyburn field, Saskatchewan, Canada: demonstrating the robustness of time-lapse seismology

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## Summary

The Weyburn $CO_2$ flood is the largest horizontal injection program in the world, involving a 30 m thick fractured carbonate reservoir at 1400 m depth. The Reservoir Characterization Project of the Colorado School of Mines used new triaxial vibrators to acquire the first high-resolution 4-D, 9-C land seismic survey in Canada to monitor the flood. A baseline survey was shot in 2000 prior to $CO_2$ injection and a monitor survey was acquired in September 2001 after 23 BCF of $CO_2$ was injected via horizontal wells. A P-wave difference volume gave a high-resolution time-lapse seismic image of the $CO_2$ flood in a pilot 4–pattern area and showed $CO_2$ fingering along off-trend high permeability zones. These zones are conduits for movement of $CO_2$ out of pattern and the cause of early response and breakthrough. This vital information can be used to modify the injection program to more effectively sweep the reservoir.

## Introduction

Weyburn field is located on the northeast flank of the Williston Basin in southeast Saskatchewan, Canada. Approximately 1000 wells, including 137 horizontal wells with 284 lateral legs, were used to recover 24% of the 1.4 billion barrels of oil originally in place. PanCanadian, the operator, converted 19 patterns of horizontal wells to $CO_2$ injection to increase production by at least 15% incremental oil. Injection of 3 to 7 mmcf/day/well has occurred since early October 2000.

Weyburn's carbonate reservoir is made up of two parts: a low permeability, high porosity 7 to 10 m upper unit, the Marly; and a high permeability, low porosity 15 to 20 m lower unit, the Vuggy. The Marly averages 26% porosity and 10 md permeability. Horizontal wells drilled since 1991 in Weyburn Field have targeted the Marly as a zone of bypassed pay. These wells demonstrated the Marly unit was not as effectively swept as its underlying counterpart, the Vuggy. The Vuggy averages 11% porosity and 15 md permeability. The flow capacity of the formation is the product of permeability and net thickness. The Marly has a low flow capacity relative to the Vuggy and correspondingly low sweep efficiency. The potential for bypassed oil in the Marly is greater with $CO_2$ flooding than it is with waterflooding because of the comparatively high mobility of $CO_2$.

Bunge (2000) documented open and healed fractures in the reservoir from formation micro-scanner and micro-imaging logs run in horizontal wells. He also delineated faults with up to 4 m vertical displacements based on gamma ray log correlation. Fracture zones promote vertical mobility and channeling of $CO_2$ out of pattern. The faults and older fracture systems that are plugged with anhydrite are potential barriers or baffles in this reservoir.

Monitoring is necessary because $CO_2$ may flow downward into the Vuggy from horizontal injectors in the Marly with a corresponding reduction in sweep efficiency. The objectives of seismic monitoring are the lateral and vertical sweep. Nine-component seismology offers the best technology possible for monitoring both the lateral and vertical sweep. The different components have different sensitivity to fluid saturation, pressure, and reservoir properties. Time-lapse, 9-C seismology facilitates reservoir management decisions early in the flood to improve recovery.

## Multicomponent (9-C) Seismic Monitoring

The 4-D, 9-C seismic survey at Weyburn was designed to provide high resolution time-lapse imaging over four $CO_2$ injection patterns (Figure 1). The thin reservoir, relative to the seismic wavelength, makes it necessary to use seismic amplitudes to monitor the injection program. Reservoir simlation and modeling suggests that velocity changes due to fluid, pressure,and composition changes could cause a four to five percent decrease in p-wave velocity and

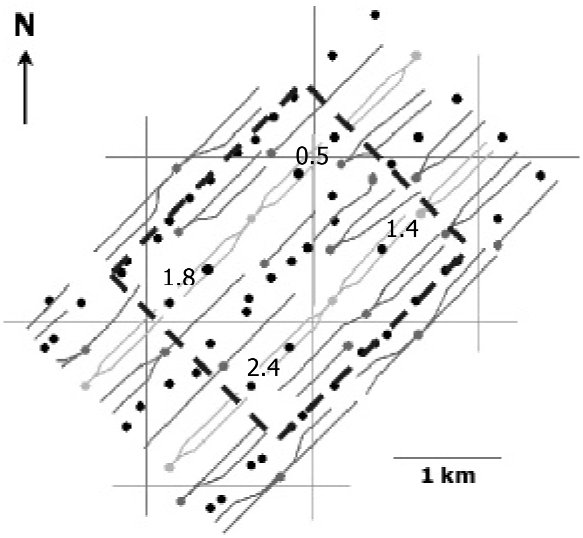

Figure 1. Layout of injection wells (light gray), production wells (dark gray), and outline of 4D seismic survey (dashed line). The numbers indicate amount of $CO_2$ injected in BCF in each horizontal well.

a two to three percent increase in shear wave velocity (Brown 2002). Further, the different components may respond differently to pressure changes, and the different lithologies within the reservoir.

The surveys were designed for high spatial sampling density and fold. The bin size is 20 m by 20 m. Useable P-wave fold is approximately 400 fold in the middle of the surveys and useable shear wave fold is approximately 140 fold in the middle. The surveys give as uniform an azimuth and offset distribution as possible. An IVI Tri-Ax three-component vibrator reduced the acquisition time for the 9C surveys.

All components were processed to preserve the integrity of the amplitude information contained within the datasets. The excellent data quality, high spatial sampling density, and fold helped facilitate the use of surface consistent linear processes. These processes are designed to minimize any artifacts in the time-lapse volumes.

## Dynamic Reservoir Characterization

Dynamic reservoir characterization refers to monitoring changes in a reservoir response by repeated measurements to detect the spatial distribution of rock/fluid property changes due to production transformations. A method to confirm the interpretation and significance of fault and fracture zones in the reservoir is to monitor these zones under dynamic conditions. The areas of response will correspond to the open fracture areas and those areas that do not respond are the low permeability areas that would be bypassed in the $CO_2$ flood. Through a series of seismic images over time, the difference between these images can be related to rock/fluid properties and their distribution in the reservoir.

Baseline multicomponent seismic data reveal the presence of faults with a few meters of offset at the reservoir level. The greatest fracture density occurs in proximity to the faults. The open fracture systems are conduits for lateral and vertical fluid movement in the reservoir. A Devonian Prairie Evaporite salt remnant or pillow occurs in the northwestern portion of the study area and salt dissolution has taken place in the southeast portion of the area. Devonian salt dissolution is the dominant cause of natural fractures in the reservoir causing a profound influence on the $CO_2$ flood. Reasnor (2001) linked large amplitude differences between the split shear waves to the presence of open fractures coincident with zones of underlying salt dissolution.

The P-wave difference volume (Figure 2) shows time-lapse P-wave anomalies near the three injection wells in which significant volumes of $CO_2$ were injected (Figure 1). The anomalies represent up to a 20% change in P-wave amplitudes due to the $CO_2$ injection. These anomalies spread out from the injectors along some of the fracture zones mapped from the shear wave analysis. The 4-D difference volume shows a conductive fracture zone on the southern side of the survey area. The well intersecting that conductive fracture zone may have to be shut down or packed off to prevent $CO_2$ from cycling through the fracture system. The western injection pattern has a concentrated anomaly between the legs of the horizontal injection well. The surrounding producing wells showed no $CO_2$ response, suggesting the $CO_2$ is moving vertically, out of the intended zone. The advantage of seismic monitoring is to detect channeling or loss out of zone and be able to take action early enough to maintain reservoir sweep.

The shear wave difference volume (Figure 3) also shows anomalies coincident with the $CO_2$ injectors. However, some of the anomalies are smaller and spatially shifted from the P-wave anomalies. This suggests, as expected, that the shear waves are sensitive to different time-lapse changes in the reservoir than P-waves. Further analysis of the multicomponent data will provide a detailed understanding of the time-lapse reservoir dynamics.

The advantage of monitoring the $CO_2$ process with multicomponent (9-C) seismic data is the opportunity to be able to differentiate the fluids within the matrix and fracture systems and also within the different units of the reservoir. The matrix in the Marly is sensitive to monitoring with P-wave amplitudes, whereas in fractured media like the Vuggy the shear wave splitting parameter is the best indicator of fluid saturant. Water will eventually be injected from vertical injectors in the Vuggy to keep the $CO_2$ from moving downward into the Vuggy. Monitoring the vertical sweep to see if the $CO_2$ bank is staying in the Marly will have a profound effect on the design and economics of the $CO_2$ flood.

## Conclusions

The economic benefit of seismic monitoring is better characterization of the reservoir to help manage the flood. Through repeated monitor surveys over time a series of seismic images can be made and related to rock/fluid properties and their distribution in the reservoir. Multicomponent seismology provides more accurate monitoring of reservoir dynamics including fluid saturant change.

At Weyburn field, this monitoring technology was applied to the thin carbonate reservoir to image a $CO_2$ flood. The data showed channeling and possible vertical movement of the $CO_2$, which limits the effectiveness of the enhanced oil recovery program. In particular, the p-wave anomaly near the southern and eastern injectors not only indicates $CO_2$ breakthrough will occur soon, but also defines where along the horizontal wellbore the breakthrough will occur. Such success in this environment was unprecedented and shows the robustness of the multicomponent seismic monitoring method.

## References

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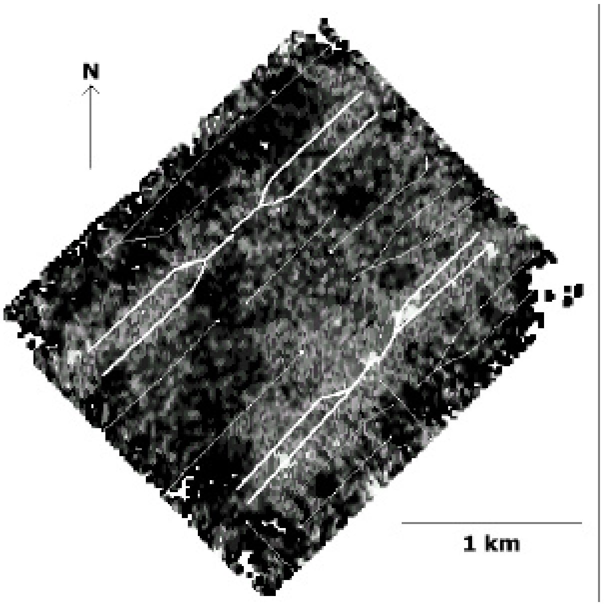

Figure 2. P-wave time-lapse amplitude difference for the reservoir horizon. Dark shades indicate little time-lapse change and light areas indicate sigificant change, up to twenty percent. The thick white lines represent the horizontal CO2 injection wells. Note the lack of an anomaly near the northern injector, which had very little $CO_2$ injected compared to the other injectors.

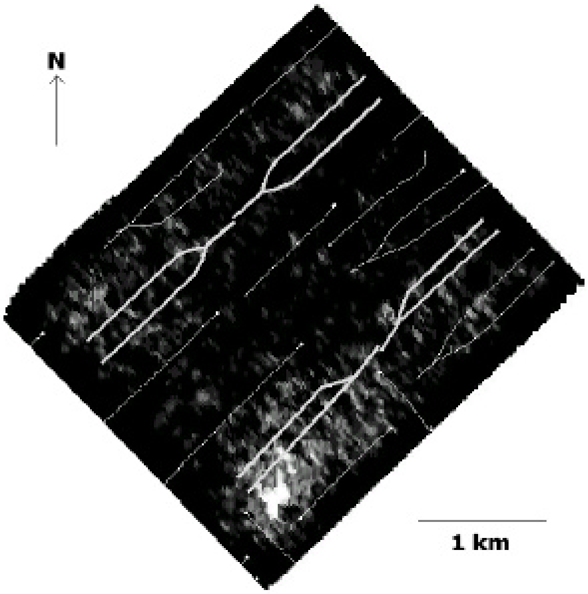

Figure 3. S2-wave time-lapse amplitude difference for the reservoir horizon. Dark shades indicate little time-lapse change and light areas indicate significant change. The thick white lines represent the horizontal CO2 injection wells. As in figure 2, note the lack of an anomaly near the northern injection well.