Time-Lapse (4-D) Seismic Monitoring of Massive CO_2 Flood at Weyburn Field, S. E. Saskatchewan

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ABSTRACT

Introduction

The miscible CO_2 flood in the Weyburn Field is a massive process for enhanced tertiary oil recovery and greenhouse gas sequestration, the largest of this kind ever in western Canada. Since October 2000, a large CO_2 volume of 50~90 MMCF per day has been injected into the thin, highly fractured carbonate reservoir at a mean depth of 1,450 m. Time-lapse seismic surveys were acquired to characterize the reservoir and fluid properties, to track the movements of CO_2 flood fronts, and to integrate the dynamic seismic information with production history, geology, and reservoir simulation. The baseline survey was shot before injection and a subsequent survey was repeated after 14 months of flooding.

High-repeatability 4-D data within a bandwidth of 8-145 Hz were recorded using the MegaBin technique. Dual processing with independent flows was adopted for 4-D P-P processing, yielding similar time-lapse anomalies of significance. 4-D AVO and inversion are being finished to help distinguish effects of saturation and pressure changes. Various seismic attributes (such as amplitude, impedance, time delay) were found very sensitive to the presence of CO_2 fluid even in the hard carbonate rocks. 4-D P-S wave data were processed to provide information about fracture distributions and their impacts on anisotropic fluid flow behaviours. The time-lapse results are currently being integrated with other types of data.

Reservoir Geology And Co_2 Flooding

Located in southeast Saskatchewan, Weyburn Field is a mature carbonate pool of 1.4 billion barrel reserves, discovered along the Mississippian subcrop belt on the flat northern flank of the intracratonic Williston Basin (*Fig. 1*). It covers an area of about 180 km^2 and produces crude oil (~29° API) from the Midale carbonates of Mississippian Charles Formation, deposited in a periodically restricted, shallow epeiric depositional setting, exhibiting abrupt vertical facies transitions. The Midale beds are sandwiched between the overlying Midale Evaporite anhydrites and the underlying low permeability dolomites and anhydrites of Frobisher beds. The reservoir rocks represent the erosional remnants of a considerably extensive marginal ramp.

The reservoir contains two lithostratigraphic units: a lower limestone-dominated unit called "Vuggy", and an upper, mainly dolostone unit called "Marly". The Vuggy can be subdivided into the shoal and intershoal sequences. Gross thickness varies from 10 to 22 m in the Vuggy and 1 to 11 m in the Marly. The combined net pay ranges from 5 m to over 30 m, average 10 m. Primary depositional settings and textures, secondary diagenetic overprints, and rheological responses to imposed stress have caused remarkably varying reservoir flow characteristics (*Table 1*). The reservoir is further complicated by

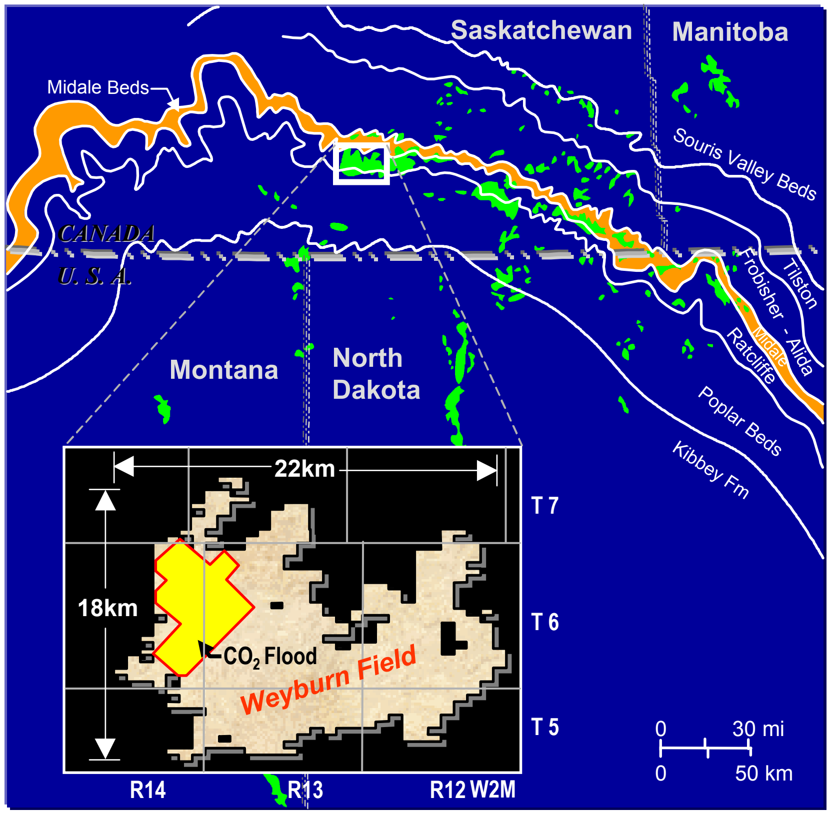

Figure 1 Location of the Weyburn Field. Subcrop trends and oilfields (green) in Mississippian formations in the northern flank of the Williston Basin are shown (modified from Kent, 1985).

the presence of subvertical natural fractures, both open and cemented, dominantly in the SW-NE orientation. Secondary fractures in SE-NW directions were also observed in some areas.

Production history of the field includes primary depletion after the 1954 discovery, subsequent waterfloods in mid-1960's up to today, aggressive vertical infill drilling in the 1980's and horizontal drilling starting from early 1990's, as well as the current CO_2 injection.

The unswept reserves in the porous Marly dolostones are the main target for CO_2 flooding. Hancock (1999) has described the 75 injection patterns that are to be used at Weyburn to maximize its production and recovery. The current flood in

Phase 1 is within a nearly 27-km^2 area, where our 3-C 4-D monitoring was carried out. This phase comprises six WAG (water alternating gas) as well as 13 SSWG (simultaneous but separate water and gas injection) patterns. The SSWG strategy is a technical innovation, involving the use of horizontal injectors and producers (for details, see Li and Majer, 2002). A large quantity of almost pure CO_2 is continuously injected into Marly. Naturally, due to the differences in pressure and permeability between Marly and Vuggy, the injected CO_2 will migrate not only laterally but also downwards into Vuggy to displace the residual oil. Subsequent water injection into the verticals controls the CO_2 injection and flow directions. The main goal is to drive CO_2 into the Marly with buoyancy and viscous forces. The displaced oil will be produced by vertical as well as horizontal wells. Produced CO_2 will be recycled and re-injected.

Table 1 Weyburn Midale reservoir attributes

Reservoir Zone	Lithology & *Textures*	Porosity *(avg.%, Type)*	Matrix Permeability *(avg.,md)*	Heterogeneity	Fracture Density
Marly	**Dolostone** *mudstone, wackestone*	**20-37** (26) *intercrystalline moldic*	**<0.1 - 100** *(10)*	**Low** *bioturbation dolomitization*	**Low - Moderate** *(2-4m spacing) >25% Ø~unfract.*
Upper Vuggy *"Intershaol"*	**Limestone** *packstone, wackestone*	**2-15** (10) *interparticle intraparticle*	**<0.01 - 20** *(1)*	**Medium** *thick bedded, bioturbation*	**High** *(<1m spacing)*
Lower Vuggy *"Shoal"*	**Limestone** *mudstone to grainstone*	**5-20** (15) *fenestral vuggy*	**<1 - 500** *(20)*	**High** *well bedded, high order cyclicity, complex diagenesis*	**Moderate - High** *(<1-2m spacing) microfractured*

Miscible CO_2 flooding is a complex process. Compositionally the supercritical CO_2 and the oil phases change with time, pressure, and position in the reservoir. It is important, therefore, to understand the mechanisms in which the injected CO_2 may cause changes in the multi-phase system, which will have effects on the time-lapse seismic responses. Martin and Table (1995) presents a detailed discussion of carbon dioxide flooding mechanisms.

4-D Data Acquisition And Processing

In 1999, prior to CO_2 injection, a decision was made to apply leading-edge 3-C 4-D technology to help track the movements of CO_2 flood fronts. Although some favourable conditions did exist, technical risks and uncertainty in different aspects presented to us enough challenges. Geologically, we dealt with a complicated carbonate reservoir with heterogeneous characteristics of rock properties (e.g., porosity and permeability) and complex nature of fracture systems. Whether the vertical and horizontal connectivity of pore systems and flow units in the multiple thin reservoir zones would provide favourable CO_2 movements was our concern. The key objectives of 4-D monitoring were to detect and map the spatial CO_2 distribution and anisotropic flow behaviours, determine the vertical flows between Marly and Vuggy, and identify early CO_2 breakthrough and any possible out-of-zone migration. Several issues, such as detectability of dynamic fluid changes, repeatability in acquisition and processing, vertical resolution for thin reservoir zones, and overall 4-D data quality (noise in particular) are key to the successful time-lapse applications.

To address these and other issues, research was conducted over the course of designing and implementing the 4-D project. A feasibility study using rock physics and laboratory measurements was performed. Seismic modeling via Gassmann fluid substitution was run to determine theoretical seismic responses to changing pressure and saturation as a result of CO_2 injection. The results revealed that P-wave velocity has a strong dependence on pressure as well as saturation variations, and pressure also influences the shear velocity. Density changes are not as significant. Specifically the impedance changes in CO_2 saturated rocks would range from 3% to 9% in more realistic cases. A 4-D technical risk matrix was constructed from the best available knowledge and experience. On this basis, we believed that 4-D seismic should be a viable monitoring tool for application at Weyburn.

Field data acquisition

To optimize image quality and improve operational and cost effectiveness, the MegaBin^{TM} technology, a successfully proven land 3-D acquisition method widely applied in EnCana's geophysical activities over the last many years (Goodway and Ragan, 1996), was used in field acquisition. A small-size test monitoring survey was first collected in early 2001 in order to determine time-lapse repeatability and to construct efficient 4-D processing workflows. Then, the formal 27-km^2 monitoring survey was acquired after 14 months of CO_2 flooding, in a similar winter condition to the baseline. High quality 4-D data were obtained. Even field raw records showed a high degree of repeatability between the time-lapse surveys. Useful frequencies as high as 145 Hz near the reservoir interval were recorded, which made mapping CO_2 effects possible.

4-D Data Processing

A dual processing strategy was applied. Close supervision and communication with independent contractors was emphasized to develop, test and employ efficient, quality-guaranteed 4-D processing sequences. Much attention was paid to a number of important steps including common grid regularization and 4-D fold, offset, azimuth regularization, closely supervised 4-D amplitude recovery, balance and match, carefully designed deconvolution and 4-D wavelet estimation, iterative independent and joint statics and velocity analyses, prestack and post-stack spectral balance and frequency enhancement, and 4-D cross-equalization and residual cross-equalization.

We found that the dual processing effort was justified and it helped yield remarkably repeatable high-fidelity 4-D images (or volumes). *Fig. 2* shows migrated P-wave sections from the time-lapse surveys, oriented in a NW-SE direction traversing four SSWG patters. The images in (a) and (b) are the baseline and monitoring data processed by contractor *A* while those in (c) and (d) are equivalent data by contractor *B*. Various horizons are denoted. Apparently, the two thin reservoir units, Marly and Vuggy, have been well resolved and characterized by a strong trough and a relatively weak peak, respectively. It is also clear that near the SSWG injector locations, amplitudes have increased from the baseline to the monitor, especially within the Marly zone, implying that the injected CO_2 does have impact on time-lapse seismic responses. One can also observe time delays in the monitoring image (b and d), starting from Marly through Alida, as highlighted. The resulting high image quality and fine resolution are two key factors ensuring a successful 4-D interpretation.

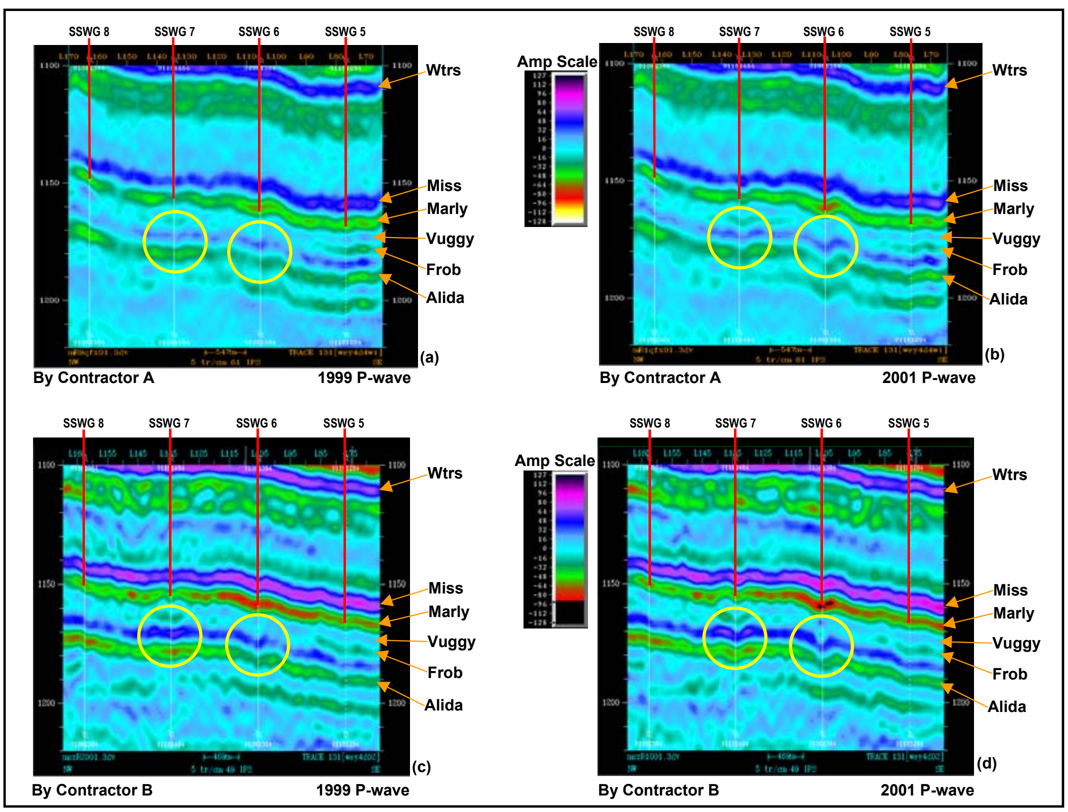

Fig. 2: A NW-SE 4-D section traversing 4 SSWG patterns. Dual processing yields almost identical results. Baseline (a) and monitor (b) processed by contractor A are compared to corresponding data (c) and (d), respectively, by contractor B.

Interpretation

4-D seismic is a powerful monitoring tool. Although, philosophically, the time-lapse data can be interpreted in different manners, the methodology adopted in this study has worked quite well. The multiple 4-D attributes were found more sensitive to reservoir changes than expected. They are very useful in cross-examining the validity of interpretation based on only individual attributes. More specifically, 4-D horizon amplitude differences between baseline and monitor surveys, windowed RMS or average 4-D amplitude differences, 4-D traveltime changes between zones of interest were all found sensitive to the presence of CO_2 in both Marly and Vuggy. A combined use of these, and other, attributes helped us to derive volumes and maps that assisted us in detecting and mapping out the locations of the injected CO_2 fluid, its moving paths, and some unexpected breakthroughs of significance.

Figure 3 shows the 4-D amplitude difference map made from the Marly trough between the baseline and monitor surveys. Within the CO_2 flood area, the 4-D maps show that, with exceptions, most time-lapse anomalies are parallel to the orientation of horizontal and vertical injectors, aligned in the NE-SW direction, which is the dominant fracture orientation. These anomalies are developed in a neighbourhood of each injection well, especially along the SSWG injectors, where the CO_2 concentrations tend to be high. Vertically, the seismic anomalies extracted for Marly and Vuggy imply that at many patterns, the CO_2 fluid has gone into both zones. Laterally, the CO_2 gas appears to spread steadily from the injectors towards the producers, especially in the southern area. But some "off-trend" anomalies, for example at patterns 10 and 12, are also clearly detected. These strong 4-D anomaly features, however, do not seem to be evident on similar maps obtained from the overburden formations. For instance, a 4-D amplitude map from Watrous shows nothing but chaotic distributions of low-magnitude amplitudes, implying that the injection has not influenced the younger formations and that CO_2 is staying sequestered.

Time delays introduced by CO_2 flooding are another time-lapse characteristics we observed on the Weyburn 4-D data. The time delays are not only evident on the vertical sections (*Fig. 2*) but also mappable. As much as 4 ms in delays was observed near the reservoir zones but it decreases somewhat at deeper horizons. Apparently the very compressible CO_2 fluid has slowed down P-wave propagation within and through the affected reservoir interval.

It is believed that further detailed analysis of 4-D seismic information will help refine the reservoir model and derive a better understanding of the dynamic changes and status of CO_2 fluids in the reservoir zones. In particular, problem-solving oriented rock physics modeling and 4-D AVO and LMR inversion in conjunction with 4-D converted P-S wave analysis will lead to a better understanding and separation of pressure versus saturation effects and fracturing-induced azimuthal anisotropy. 4-D impedance inversion and time-depth conversion will enhance the definition of the already detected time-lapse seismic anomalies. Successful application of 3-C 4-D VSP analysis may provide some new insight into examination of resolution and fracture influences. Ultimately, 4-D seismic integration with geology, production history matching and forecasting, and other monitoring information (tracer study, geochemical studies, etc.), and effective visualization are of significant importance.

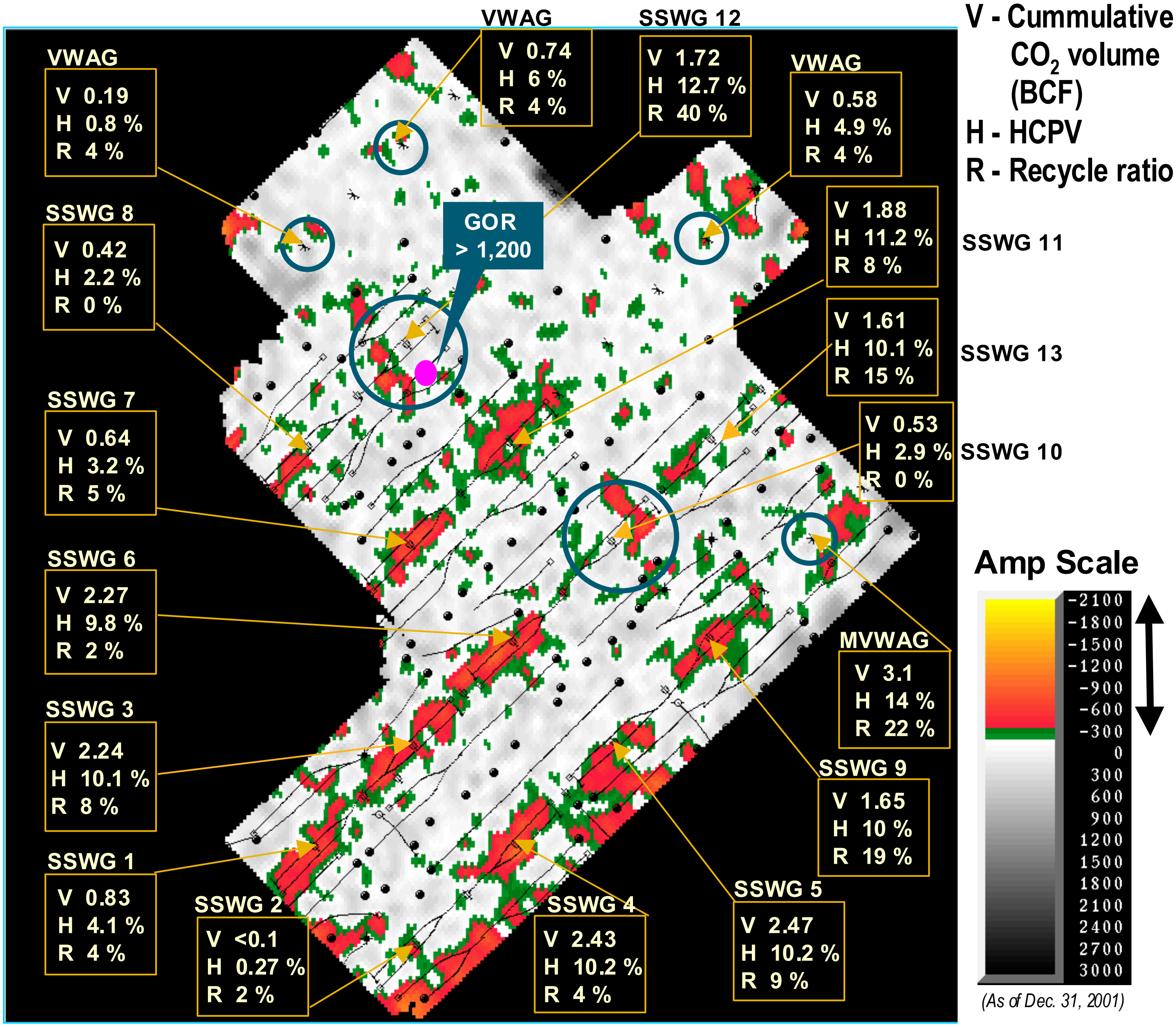

Figure 3 Integrating 4-D monitoring information with production engineering data (cumulative CO_2 injection volumes in billion cubic feet, hydrocarbon pore volume, and CO_2 recycle ratio).

Fig. 3 compares the 4-D anomaly map from Marly with some production engineering data such as up-to-date cumulative injection volume, hydrocarbon pore volume and CO_2 recycle ratio. In general, as we find, higher injection volumes correspond impressively to strong 4-D anomalies, for example, at patterns 3, 4, 5, 6, 9 and 11, where the HCPV on average is at or above 10%. Pattern 12, which exhibits an off-trend seismic anomaly, also has a high injection volume but shows an extremely high recycle ratio (40%). In the horizontal producers south of pattern 12, abnormal GOR over 1,200 was observed. Clearly, CO_2 breakthrough, probably introduced by NW-SE oriented fractures, had occurred.

Conclusions

Massive miscible CO_2 has been injected into a complex fractured carbonate reservoir at the Weyburn field. Multi-component 4-D monitoring was chosen to monitor the flood. High-resolution 4-D P-wave data were successfully obtained from the field and used to map the features of CO_2 movements within the two thin zones of different lithology. Effective field acquisition method and careful dual processing contributed significantly to the success of 4-D applications. Although CO_2 flooding has performed very well and caused a multi-fold volume increase over conventional production in the flood area, 4-D seismic has detected some abnormal flood patterns. Possessing the ability to detect, map and even predict the flood behaviours is very important to the operating team.

The 4-D seismic technology provides an effective means for qualitative as well as quantitative dynamic reservoir characterization and economic monitoring. However, 4-D interpretation is an intensive task. New quantitative interpretive techniques need to emerge. Multi-tasked, cross-disciplinary, multi-scale integration of 4-D seismic data with reservoir geologic modeling, production history matching, borehole seismic, and other monitoring data is essential and being undertaken in our work. Based on the achieved success, a newer round of 4-D monitoring survey was acquired in December 2002 that again yields similarly excellent results. This case study demonstrates that 4-D seismic monitoring is a practically powerful strategic tool for many intermediate- to large-scale EOR and offshore development projects. Its importance in mitigating risks, improving/speeding reserve recovery, and reducing costs cannot be overlooked.

Acknowledgments

The author wishes to acknowledge the co-sponsorship of this project by EnCana Corporation, its Weyburn Unit Partners, and IEA/PTRC (Saskatchewan). The team members in EnCana's Calgary headquarters and Weyburn Field Office provided much needed assistance and coordination during field surveys and analysis. Tesla Exploration and Trace Exploration acquired the time-lapse data. B. Ragan was responsible for designing and coordinating field acquisition. Veritas Geophysical, 4th Wave Imaging, and Sensor Geophysical processed the 4-D data. In particular, N. Henderson, R. Kendall, P. Anderson, D. Lumley, D.

Adams, P. Cary, A. O'Byrne, A. Marshall, and B. Hoffe are thanked for their valuable work, discussion and support in data processing. G. Syhlonyk and B. Goodway were involved in the early work of rock physics and modeling. The author is also deeply grateful for the support, understanding, encouragement of Weyburn Business Unit Management and their permission to publish the article.

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