Weyburn Oilfield Core Assessment Investigating Cores From pre and post CO₂ Injection; Determining the Impact of CO₂ on the Reservoir

Gavin K.S. Jensen

Abstract

The purpose of this paper is to detail a mineralogical examination of core samples obtained from a recently drilled well in the Weyburn oilfield in southern Saskatchewan, Canada. The research was undertaken as part of the Saskatchewan CO₂ Oilfield Use for Storage and EOR Research project (SaskCO₂USER) managed by the Petroleum Technology Research Centre (PTRC), and jointly funded by the US Department of Energy and the Saskatchewan Government. The SaskCO₂USER program has built on over a decade of research by the IEA GHG Weyburn-Midale CO₂ Monitoring and Storage Project (WMP).

The WMP included several studies of the geochemical evolution of the reservoir in response to CO₂ injection through a combination of predictive modelling, fluid sampling and laboratory assessments. The recently drilled wells have however provided a rare opportunity to directly study samples of reservoir rocks exposed to the CO₂ flood for over a decade, and provide some potential calibration of previous research.

This research utilized SEM, QEMSCAN, cathodoluminescence, and EDS mapping to determine if there has been any change on the mineralogical framework in the reservoir over a decade of CO₂ injection. Previous research has interpreted that ionic trapping has been occurring in the Weyburn reservoir since a year after injection. Although various WMP studies made the interpretation that dissolution and mineral trapping of injected CO₂ will be active

processes in the Weyburn field. This study found that there were no significant mineralogical changes in the samples analyzed from the recently drilled observation well.

Keywords: CO₂ geological storage, Weyburn, Reservoir characterization, CO₂-water-rock interactions

1.0 Introduction

The Weyburn field, operated by Cenovus Energy, currently contains the world's largest amount of injected and geologically stored anthropogenic CO₂, with over 29 million tonnes of CO₂ stored as of December 2015, with an additional 2.5 million tonnes stored annually. The Petroleum Technology Research Centre (PTRC) has orchestrated over a decade of research under the project; IEA GHG Weyburn-Midale CO₂ Monitoring and Storage Project (WMP). The latest phase of research managed by the PTRC involving the WMP is the Saskatchewan CO₂ Oilfield Use for Storage and EOR Research project (SaskCO2USER).

This portion of the project, conducted by the Saskatchewan Geological Survey, and examines core and the potential mineral reactions as a result of injected CO₂ on the rock framework and pore space. This unique field scale "laboratory" will provide a rare opportunity to investigate the effects of injected CO₂ on the carbonate framework and pore space at an active injection site leading to a better understanding of the response of the carbonate framework and pore space to over a decade of CO₂ injection.

Two observations wells were recently drilled (December 2009 and January 2011) in the active CO₂-EOR portion of the Weyburn field. Extensive core intervals and numerous drill stem tests (DST) were obtained from the two wells. By comparing the wells recently cored to wells that were cored prior to CO₂ injection; the influences of a decade of injected and subsequently stored CO₂ on the reservoir can be observed, if any.

Previous research has demonstrated that CO₂ injection has impacted the geochemistry of the injected reservoir (Shevalier et al., 2013, Mayer et al., 2013). Once CO₂ is injected into a carbonate reservoir, which Weyburn is composed of, it is subjected to numerous chemical and physical reactions (Gunter et al., 1993, Betz et al., 2005). Two of the geochemical reactions that will occur are CO₂ dissolution and carbonate mineral dissolution (Gunter et al., 1993); these reactions have been determined by changes in pH, total alkalinity, and calcium concentrations (Emberley et al., 2005).

CO₂ dissolution (Solubility trapping)

Calcite dissolution

Carbonate mineral dissolution (Ionic trapping)

CO₂ dissolution, reaction (1) represents this process it lowers the pH and increases the HCO₃⁻ concentration of the formation fluid. Calcite dissolution, displayed by reaction (2) yield higher carbonate alkalinity and higher cation concentrations. When both reactions occur, reaction (3), for each mole of CO₂ that is injected and reacts will yield one mole of cation (Ca⁺² can also be substituted for Mg⁺² in dolomitic reservoirs), and 2 moles of HCO₃⁻ dissolved in the formation waters. Previous research at Weyburn has concluded that there has been a drop in pH, a rise in brine alkalinity, an increase in calcium concentration in the brines, and a decrease in the resistivity of the brines (Shevalier et al., 2013). These authors state that the findings indicate that solubility trapping occurred after the first 6 months of CO₂ injection and that after one year of injection ionic trapping had commenced indicated by increasing calcium and alkalinity, as well as under saturation with respect to calcite (Shevalier et al., 2013). The sampling techniques for

the Shevalier paper were direct well head sampling of produced formational fluids and gas. Interpretations were made based on the geochemical analysis, provided from the aqueous and gaseous sampling, however there was no mineralogical inspection completed of the rock framework. This project had the opportunity to examine the reservoir that has been subjected to a decade of CO₂ injection. If in fact carbonate mineral dissolution is occurring, as suggested from Shevalier (2013) there should be evidence a significant reaction occurred within the mineralogy between the pre-CO₂ and post-CO₂ wells examined in this study. The utilization of analytical techniques such as QEMSCAN, cathodoluminescence (CL), SEM imagery, and EDS mapping can aid in elucidating the influence of a decade of injected CO₂ on the Weyburn reservoir.

2.0 Geological Setting

The Weyburn field is located in SE Saskatchewan (Figure 1), along the Mississippian subcrop trend. Mississippian aged strata in Saskatchewan are characterized by alternating carbonate and evaporite deposits, the depositional setting for these formations is a shallow epeiric sea (Fuzesy, 1960). The Weyburn reservoir is comprised of the Midale Beds which are within the Mississippian Charles Formation located at a depth of 1350-1450 m and produce a medium gravity oil with an average API of 30.7° (Kent, 1984; Freitag et al., 2004). The Midale Beds are separated into two units, the lower limestone “Vuggy” and the upper dolostone “Marly” and is capped by the Midale Evaporite, an anhydrite seal (Fuzesy, 1960; Kent, 1984). The Midale Beds lie conformably on the Frobisher Beds, and are overlain by the Ratcliffe Beds (Figure 2). The Mississippian strata are truncated by the sub-Mesozoic unconformity to the northeast. The Watrous Formation lies above the Mississippian and acts as the regional seal. Cenovus has subdivided the Midale Marly and Vuggy into representative flow units based on

lithology, porosity and permeability, (Burrowes and Gilboy 2000) displayed in Figure 3. The Midale Marly (M0, M1,M3) is defined by high porosity (average 26%) and a highly variable permeability (average 10mD). The Upper Vuggy Intershoal (V1) is characterized by low porosity (average 10% and low permeability (average 1mD). The Midale Vuggy (V2-V6) shoal displays a lower porosity (average 15%), but a high permeability (average 50 mD) (Burrowes and Gilboy, 2000). Detailed descriptions of the reservoir’s geology and hydrogeology have been provided by Jensen (2013).

Figure 1: Regional scale study area with Phase 1A, 1B, 1C of the CO₂ injection areas in the Weyburn field

Figure 2: The sub cropping Mississippian strata in southeast Saskatchewan in relation to the sub-Mesozoic unconformity.

Figure 3: Schematic representation of the Weyburn reservoir, displaying the subdivided flow units as described by Burrowes and Gilboy (2000).

3.0 Sampling and Methods

Samples were taken from cores stored at the Subsurface Geological Lab in Regina, Saskatchewan. Samples for QEMSCAN analysis were taken from slab cores, thin sections were taken from the same portion of the core where the QEMSCAN was completed. As previously mentioned, two observations wells were recently (December 2009 and January 2011) drilled in the Weyburn field. The well from December 2009 is in Phase 1C and has been subjected to less injected CO_2 than the well drilled in January 2011, which is located in Phase 1A. The Weyburn CO_2 injection developed with injection in first 1A (northern most), then in 1B and finally 1C (southernmost) over the last decade. This paper will focus on the observation well in Phase 1A (7-30-6-13W2M) as it has been subjected to CO_2 for the longer length of time as well as a greater volume than the well in Phase 1C.

Wells were selected based on whether a core was taken from the Midale interval and their proximity to the recently drilled observation well. Extensive cores from 1957 in phase 1A of the injection area were available. The Weyburn field underwent a water flood in the 1960's, the

water used to flood the field was a mixture of Cretaceous aged Mannville formation water and produced formation water from the Midale. The chemistry of the Mannville, lower TDS, varies from that of the Midale. This chemistry difference could potentially alter the rock framework or pore space. However, results presented in this paper illustrate that the reservoir has not significantly changed from either a water flood or a CO₂ flood, in the region of the observation well (7-30). Three cores from 1957 were sampled to account for reservoir heterogeneity; the sampled wells are all within 1km from the recently drilled observation well (Figure 4A). A volume of 365e⁶m³ of CO₂ has been injected within a 1km radius of the observation well prior to the commencement of drilling, January 2011 (Figure 4B). Drill stem tests conducted during drilling of both observations wells confirmed the presence of CO₂ in the reservoir.

This study focused on the Midale beds which is the main injection and production formation for the WMP. Quantitative Evaluation of Minerals by Scanning (QEMSCAN) was used to measure the quantitative mineral modal abundance and porosity in each sample. QEMSCAN analysis and SEM imagery was completed at the Saskatchewan Research Council (SRC) Labs in Saskatoon, Saskatchewan. Thin sections were then prepared from the core samples for analysis at the Instrumentation Facility for Analytical Microscopy (IFFAEM) located at the University of Calgary. Cathodoluminescence (CL) analysis and energy dispersive (EDS) X-ray mapping were completed at the IFFAEM. Mineral grains are identified using back-scattered electron imaging and qualitative energy dispersive (EDS) X-ray spectra. EDS x-ray mapping can be used to detect individual elements present in specific crystals with a 20 µm spacing interval. EDS x-ray mapping can determine if traces of other minor elements such as iron or magnesium can be observed in calcite or dolomite crystals. CL was also utilized to determine if the internal structure of the rock framework differed in the pre-CO₂ versus the post-CO₂ cores. CL can provide the basis for understanding the origin, diagenesis and porosity development that can occur in carbonate

rocks (Marshall 1988; Barker and Kopp 1991; Pagel et al. 2000). CL can distinguish the carbonate phases, cement growth on pre-existing crystals as well as porosity evolution; such petrographic analysis can aid in understanding if different conditions were present in the formation and diagenesis of carbonate reservoirs (Hiatt and Pufahl, 2014). Previously analyzed core data was also included to increase the sample population. Porosity and permeability data was completed at Core Labs Calgary from pre and post-CO₂ wells.

Figure 4: A) Observation well 7-30-6-13W2M, with the three pre-CO₂ wells that were sampled, with distances from the observation well. B) Observation well 7-30-6-13W2M, with the volumes of CO₂ within a radius of 1km that was injected prior to January 2011 (drill date of observation well).

4.0 Results

As mentioned, 3 wells from 1957 were sampled; their Dominion Land Survey (DLS) locations are 2-30-6-13W2M, 4-30-6-13W2M, and 10-30-6-13W2M, the observation well drilled in January 2011 UWI is 7-30-6-13W2M (Figure 4A). The results from the QEMSCAN analysis (Table 1), display that the Marly samples are predominantly dolomite, while the “Vuggy” samples are predominantly calcite. In the “Vuggy” samples very small halite inclusions are present, they are reported as calcite with CL and/or calcite with Na CL in the collected spectra. Quartz, gypsum/anhydrite, potassium feldspar and pyrite were all observed in trace amounts. Celestine was observed in minor amounts in the following “Marly” sample 10-30-6-13W2M. The pore volume ranges in the “Marly” from 0.29-1.45% and from 2.24-12.3% in the “Vuggy.” The post-CO₂ pore volume in the “Vuggy” is 8.5%, the pre-CO₂ wells have pore volumes below and above that value, ranging from 2.25-12.3%. QEMSCAN samples have similar mineralogical assemblages to the samples previously determined by Linear Programming Normative Analysis (LPNORM) from Wilson and Monea, (2004). For example, the well located at 2-30-6-13W2M was analyzed by both methods; in the V2 flow unit, however the sample depths were 4m apart. The LPNORM analysis reported a similar mineralogy as the QEMSCAN analysis with the exception of the amount of anhydrite present. As other samples from the V3, and V4 flow units in the same well did not have anhydrite present, this difference could be due to slight variations in the reservoir . It should be noted that both analytical techniques were able to provide reproducible and accurate mineralogical results in the Weyburn reservoir. However the porosity values reported from the QEMSCAN analysis are lower than reported by Burrowes and Gilboy (2000). This could be due to the manner in which the porosity was determined by QEMSCAN. . The porosity for the QEMSCAN samples were defined by the presence of a pore in a two dimensional scan of the core. Conversely, the porosity data from Burrowes and Gilboy were determined via three-dimensional flooding analysis of the core. Therefore the three-dimensional data would access a

greater volume of the core thus the porosity should be greater than the QEMSCAN analysis. This could account for the lower porosity reported by QEMSCAN analysis. For this reason, and to increase sample population, core analysis of previously analyzed permeability and porosity data of similar depths to the QEMSCAN samples were included (Table 2). Similar flow units were chosen from the wells to compare the porosity and permeability data, unfortunately the post CO₂ well (7-30) was not cored in the Midale Marly unit. The pre-CO₂ wells display a similar values and range of porosity data in the V2, and V3 flow units compare to the post-CO₂ (7-30) well, with the exception of the 10-30 well, where some of the porosity values are double what are in the other wells, however the permeability values are in the same range as the other wells. These high porosity values could be due to the heterogeneity in the reservoir. There seems to be no significant increase in porosity and permeability at the post-CO₂ well compared to the pre-CO₂ wells that are in a close proximity.

Location	4-30-6-13W2M	4-30-6-13W2M	10-30-6-13W2M	10-30-6-13W2M	2-30-6-13W2M	7-30-6-13W2M
Pre/Post injection	Pre	Pre	Pre	Pre	Pre	Post
Sample Depth (m)	1386	1390.9	1368.5	1374.1	1393.4	1385.7
Flow Unit	M1	V2	M1	V2	V2	V2
Calcite	0.93	90.89	1.25	91.86	86.67	89.41
Calcite with Cl	0.00	1.81	0.00	0.17	0.38	1.19
Calcite with Na Cl	0.00	2.89	0.00	0.08	0.13	0.59
Celestine	0.00	0.00	0.22	0.00	0.00	0.00
Dolomite	95.13	0.80	92.10	1.10	0.11	0.12
Gypsum/Anhydrite	1.03	0.82	0.98	1.68	0.01	0.03
Halite	0.02	0.06	2.02	0.00	0.00	0.04
K-Feldspar	0.54	0.07	0.19	0.02	0.06	0.02
Pyrite	0.07	0.03	0.12	0.05	0.00	0.00
Quartz	1.99	0.39	1.67	0.17	0.33	0.09
Pores	0.29	2.24	1.45	4.87	12.30	8.51

Table 1: Modal abundances from QEMSCAN analysis of pre & post CO₂ injection wells, values are displayed in volume percent. QEMSCAN analysis for the "Marly" in wells 7-30-6-13W2M and 2-30-6-13W2M were not completed due to time constraints.

Well ID	Flow Unit	Pre/Post CO ₂	Sample Depth (m)	Sample Length (m)	KMax (mD)	Porosity (%)
07-30-006-13W2M	V2	Post	1384.72	0.74	0.11	9.3
	V2	Post	1385.99	0.96	0.3	12.1
	V2	Post	1386.95	0.91	1.69	8.6
	V3	Post	1387.86	0.61	1.72	9.2
	V3	Post	1388.99	0.6	14	14
	V3	Post	1389.59	0.56	0.37	11.5
02-30-006-13W2M						
	M1	Pre	1385.49	0.3	0.2	17.9
	M1	Pre	1385.8	0.24	3.3	26.1
	M1	Pre	1386.04	0.27	0.2	14
	M1	Pre	1386.32	0.3	0.6	16.3
	V3	Pre	1393.08	0.24	315	16.4
	V3	Pre	1393.33	0.21	7.4	10.8
	V3	Pre	1393.54	0.12	11	11.1
04-30-006-13W2M	V3	Pre	1393.66	0.27	n.a.	7.6
	M1	Pre	1385.92	0.21	0.7	21.6
	M1	Pre	1386.32	0.21	0.4	22.3
	M1	Pre	1386.53	0.18	0.9	21.9
	M1	Pre	1386.71	0.3	1.8	26.4
	M1	Pre	1387.02	0.12	0.2	9.7
	V2	Pre	1389.67	0.3	0.4	12.8
	V2	Pre	1389.97	0.21	0.2	10.1
	V2	Pre	1390.71	0.21	0.2	7.7
10-30-006-13W2M	V2	Pre	1390.92	0.21	0.4	9.6
	V2	Pre	1373.7	0.12	0.4	15.4
	V2	Pre	1373.82	0.27	3.1	26.6
	V2	Pre	1374.09	0.24	3.9	29.4
	V2	Pre	1374.34	0.24	0.7	29.4
06-30-006-13W2M	V2	Pre	1374.58	0.27	6.4	30.5
	V2	Pre	1374.86	0.27	0.9	14.7
	M1	Pre	1384.7	0.3	0.9	11.7
	M1	Pre	1385.01	0.3	1.3	16.9
	M1	Pre	1385.31	0.24	0.2	15.2
	M1	Pre	1385.55	0.15	0.4	15.9
	M1	Pre	1385.71	0.21	3.7	16.7
	V3	Pre	1390	0.18	0.4	13.7
	V3	Pre	1390.19	0.3	0.8	10.9
	V3	Pre	1390.49	0.27	0.4	11
	V3	Pre	1390.77	0.27	0.4	11.3
	V3	Pre	1391.04	0.21	0.2	13.2

*Marly not analyzed in wells: 7-30-6-13W2 and 10-30-006-13W2

n.a. = not analyzed

Table 2: Porosity and permeability core data from pre- and post CO₂ wells. All results from Core Laboratories, Calgary

Numerous scanning electron microscopy (SEM) images were taken from the pre and post-CO₂ wells. There were little to no differences in the Marly between the pre and post-CO₂ samples (Figure 5). The pre and post-CO₂ Vuggy samples did display a slight difference, the calcite crystals within the vugs appear to have an “overgrowth” in the pre-CO₂ samples (Figure 5A) however the calcite crystals in the post-CO₂ samples do not have the same “overgrowth” (Figure 5B). This difference could be attributed to the formation of new calcite crystals (i.e. mineral trapping), or the “overgrowth” could have been dissolved or physically removed off the calcite

215 grains due to CO₂ injection. CL analysis and EDS mapping will aid in determining if new calcite
216 crystals have started to form in the reservoir.

217 Cathodoluminescence (CL) and EDS x-ray mapping were utilized to determine if the calcite
218 grains formed recently as a result of CO₂ injection or if they were already present. Due to
219 budgetary and time constraints, two wells were analyzed a pre-CO₂ well (4-30-6-13W2M) and a
220 post-CO₂ well (7-30-6-13W2M). Both samples were from the “Vuggy” portion of the Midale, this
221 was selected because it represented the best opportunity to observe calcite dissolution and/or
222 calcite precipitation in the large pore space available in the “Vuggy” zone. There was no
223 difference in the internal structure of either the calcite, or dolomite crystals in the pre and post
224 samples that were analyzed (Figure 6). It was thought there could be a variable zonation within
225 the grains if they formed under a different environment than the original grains or if they rapidly
226 formed once CO₂ had been injected. EDS x-ray mapping results indicate there was no
227 observable difference in the trace elements within the calcite, and dolomite crystals that were
228 analyzed (Figure 7). If an elemental difference existed in the calcite or dolomite grains it could
229 be inferred that the grains formed under different conditions or at different times, due to the
230 wells close proximity to one another.

231

232 Figure 5: SEM images of pre-CO₂ well 4-30-6-13W2M (A) and post-CO₂ well 7-30-6-13-W2M (B)

233

234

Figure 6: Cathodoluminescence (CL) images of pre-CO₂ well 4-30-6-13W2M (A) and post-CO₂ well 7-30-6-13-W2M (B)

A)

B)

Figure 7: EDS images of pre-CO₂ well 4-30-6-13W2M (A) and post-CO₂ well 7-30-6-13-W2M (B). The colours in each image represent the trace elements that are present. The element (s) that are listed on the bottom left of each image, are the ones analyzed in the images. Corresponding colours in the image indicate the presence of the element.

5.0 Discussions

In the post-CO₂ core there was no evidence of dissolving the existing rock framework thus creating new pore space and conversely there was no evidence of precipitation of new minerals

in the core was subjected to the CO₂ flood for 10 years. Previous research has identified that there is a geochemical change in the produced formation fluids and gases in the reservoir (Shevalier et al., 2013; Mayer et al., 2013). However, this research has found that there was no mineralogical change from the data collected at the observation well drilled in 2011. There has been a geochemical change in the majority of the reservoir as found by Shevalier (2013). It is feasible that there are portions of the reservoir are experiencing ionic trapping as suggested by Shevalier and Mayer (2013), and other portions which have been subjected to lower volumes of CO₂ ionic trapping is not happening. The location of the observation well (7-30) is in the Northeastern corner of Phase 1A. CO₂ concentrations from Shevalier (2013) indicate that area possess some of lowest values in the study area (Figure 8A). Additionally some wells possess less than 10 mole % CO₂ at Monitoring trip 16; October 2010 (Figure 8B). Mayer (2013) interpreted that ionic trapping was occurring in the reservoir, based on carbon isotopes, the same wells were sampled as Shevalier. Therefore, ionic trapping could possibly be occurring in portions of the reservoir that have been subjected to the greatest volumes of CO₂, while in other areas such as the location of the observation well (7-30) ionic trapping is not occurring based on the findings in this study. A few possible reasons for ionic trapping not being observed at the observation well (7-30) are; the fluid with dissolved CO₂ could potentially have not swept this portion of the reservoir and therefore no reaction has have taken place, or the volume of CO₂ charged fluid was minimal and the change is not observable.

Additionally, the findings from Ryerson et al., (2013) suggest that in a similar mineralogical environment, 400 km west of Weyburn a natural accumulation of CO₂ has existed for as long as 50 million years, and the primary CO₂ trapping mechanisms are physical and solution trapping.

Figure 8: A) CO₂ mole % from baseline to monitor 16 (August 2000-October 2010). B) CO₂ mole % Monitor 16, October 2010
Phase 1A, both from Shevalier et al., 2013

6.0 Conclusions

Comparing analytical data in this paper from pre-CO₂ and post-CO₂ cores indicates there are no significant mineralogical changes from the injected CO₂, in the portion of the reservoir where the observation well (7-30) was drilled. Also, there seems to be no increase in porosity or permeability, when compared to previously drill wells, indicating that ionic trapping is not occurring at location of the observation well. There is no visible support, in the region of the observation well (7-30), of the interpretations made by Shevalier and Mayer (2013) that ionic trapping was occurring one year after injection commenced in the Weyburn reservoir. This could be occurring in regions of the reservoir however it is not occurring at the location of the observation well (7-30). Additionally, a natural CO₂ accumulation that has existed for 50 million years in a similar carbonate lithology, some 400 km west of Weyburn possess the primary CO₂ trapping mechanisms of being physical and solution trapping.

Drilling more observation wells and analyzing the core would aid in determining the effects of CO₂ on the mineralogy in the reservoir over time. Further research needs to be completed to determine if and the extent of ionic trapping that is occurring in the Weyburn reservoir, as these findings would aid CO₂-EOR operators, service providers and government regulators on how to better understand, manage, regulate and develop current and future CO₂-EOR projects.

6.0 Acknowledgements

The author wish to thank the United States Department of Energy, and the Government of Saskatchewan for sponsoring the Saskatchewan CO₂ Oilfield Use for Storage and EOR Research project (SaskCO2USER) thus making this work possible. The author also acknowledge the guidance from the Petroleum Technology Research Centre for this project, in particular the project manager Kyle Worth and the three anonymous reviewers who helped bring this paper up to publication standard.

7.0 References

- Barker, C.E. and Kopp, O.C., eds., 1991: *Luminescence Microscopy and Spectroscopy: Qualitative and Quantitative Application.*, SEPM Short Course 25, 195p.
- Burrowes, G., and Gilboy, C., 2000. Investigating Sequestration Potential of Carbonate Rocks During Tertiary Recovery from a Billion Barrel Oil Field, Weyburn, Saskatchewan: The Geoscience Framework. IEA Weyburn CO₂ Monitoring and Storage Project Report.
- Emberley, S., Hutcheon, I., Shevalier, M., Durocher, K., Mayer, B., Günter, W.D., Perkins, E.H., 2005. Monitoring of fluid-rock interaction and CO₂ storage through produced fluid sampling at the Weyburn CO₂-injection enhanced oil recovery site, Saskatchewan, Canada. Applied Geochemistry 20, p. 1131–1157.
- Freitag, N., Zhang, P., Huang, S. Fluid and Phase Behaviour Monitoring between August 2000 and March 2004. Saskatchewan Research Council Publication Number p. 110-662-C-04.

- Fuzesy, L.M., 1960, Correlation and subcrops of the Mississippian strata in southeastern and south-central Saskatchewan. Saskatchewan Energy and Mines, Report 51, 61p.
- Gunter, W.D., Perkins, E.H., McCann, T.J., 1993. Aquifer disposal of CO₂-rich gases: reaction design for added capacity. *Energy Convers. Manag.* 34, p. 941–948.
- Hiatt, E.E. and Pufahl, P.K., 2014, Cathodoluminescence petrography of carbonate rocks: application to understanding diagenesis, reservoir quality, and pore system evolution: in Coulson, I. (ed.) *Cathodoluminescence and its application to geoscience: Mineralogical Association of Canada, Short Course Series Volume 45*, p. 75-96
- Jensen, G. K. S., Nickel, E.H., Rostron, B. J., 2013. Refinement of the Weyburn-Midale geological and hydrogeological model: Developing a better framework to determine reservoir response to injected CO₂ and subsequent CO₂ movement: in [Special issue] Wildgust, N. (ed.) *The IEAGHG Weyburn-Midale CO₂ monitoring and storage project. International Journal of Greenhouse Gas Control*, 16, S5-S14
- Kent, D. M., 1984. Depositional setting of the Mississippian strata in southeastern Saskatchewan: A conceptual model for hydrocarbon accumulations. *in: Lorsong, J.A. and Wilson, M.A. (eds), Oil and Gas in Saskatchewan, Sask. Geol. Soc., Regina, Spec. Publ. no. 7*, p. 19-30.
- Marshall, D.J., 1988: *Cathodoluminescence of Geological Materials*. Unwin Hyman, Boston, 146p.
- Mayer B., Shevalier M., Nightingale M., Kwon J.S., Johnson G., Raistrick M., Hutcheon I, and Perkins E., 2013. Tracing the movement and fate of injected CO₂ at the IEA GHG Weyburn-Midale CO₂ Monitoring and Storage project (Saskatchewan, Canada) using carbon isotope ratios: in [Special issue] Wildgust, N. (ed.) *The IEAGHG Weyburn-Midale CO₂ monitoring and storage project. International Journal of Greenhouse Gas Control*, 16, S177-S184
- Metz, B., O. Davidson, O., de Coninck, H.C., Loos, M, and Meyer, L.A., 2005 (eds.), *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442p.
- Pagel, M., Barbin, V., Blanc, P. and Ohnenstetter, D., eds., 2000: *Cathodoluminescence in Geosciences*. Springer-Verlag, Berlin, 514p.
- Ryerson, F. J., Lake J., Whittaker, S., and Johnson J.W., 2013. Natural CO₂ accumulations in the western Williston Basin: A mineralogical analog for CO₂ injection at the Weyburn site: : in [Special issue] Wildgust, N. (ed.) *The IEAGHG Weyburn-Midale CO₂ monitoring and storage project. International Journal of Greenhouse Gas Control*, 16, S25-S34
- Shevalier M., Nightingale M., Mayer B., Hutcheon I., Durocher K., Perkins E., 2013. Brine geochemistry changes induced by CO₂ injection observed over a 10 year period in the Weyburn oil field: in [Special issue] Wildgust, N. (ed.) *The IEAGHG Weyburn-Midale CO₂ monitoring and storage project. International Journal of Greenhouse Gas Control*, 16, S160-S176

357 Wilson, M., Monea, M., 2004. IEA GHG Weyburn CO2 Monitoring and Storage Project
358 Summary Report 2000–2004. Petroleum Technology Research Centre, Regina.
359
360