Occurrences of CO_2 within Southwest Saskatchewan: Natural Analogues to the Weyburn CO_2 Injection Site [1]

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Abstract

On the western flank of the Williston Basin in southwestern Saskatchewan, CO_2 occurs in natural accumulations within Devonian carbonates and Cambrian siliciclastics. Inert gases from some carbonate reservoirs contain greater than 80% CO_2 and have sustained flow rates up to 425 000 m^3/day. Early estimates of this resource suggested nearly two million tonnes of CO_2 or about one billion cubic metres of recoverable gas are present in these rocks. These natural CO_2 occurrences are found about 400 km west of the site of the IEA Weyburn CO_2 Storage and Monitoring Project, which is directed toward assessing the potential for safe geological storage of anthropogenic CO_2 in Mississippian carbonates. This study is focused on the Devonian natural CO_2 accumulations because of geological similarity to the Weyburn injection site and because they contain the greatest amount of CO_2.

Inert gases in southwestern Saskatchewan, including variable amounts of N_2, He, and CO_2, are generally trapped in Devonian strata of the Duperow Formation within a succession of thin cycles of carbonates capped by evaporite units. The cycles resulted from deposition within shallow, periodically restricted waters along a carbonate platform. The strata vary from dolomitized limestones to limestones. Within reservoir intervals, porosities are generally around 6 to 8%, but may be as high as 18%. The porous intervals are capped by dense anhydrite layers ranging in thickness from less than two meters to more than 10 m. The Duperow Formation also contains argillaceous intervals that help define stratigraphic subdivisions within this succession.

Anomalously high geothermal gradients in the subsurface of southwestern-most Saskatchewan are likely related to tectonic and igneous processes associated with nearby Tertiary intrusions at the Bearpaw and Little Rocky Mountains in Montana. The intrusives have been dated at around 50 million years and were related to tectonism associated with the Cretaceous Cordilleran Orogeny. Carbon dioxide found in Devonian rocks of southwestern Saskatchewan was probably generated during intrusion of hot alkaline magma into Lower Palaeozoic carbonates in Montana. The CO_2 migrated north about 100 km to its present location where dissolution of salt layers below the reservoirs had formed local structures that trapped the gas. Updip reductions of porosity and regional basement features have also influenced the containment of CO_2. At present, the CO_2-bearing intervals within the Devonian carbonates occur at depths between 1675 to 2050 m below surface. They are overlain by about 350 m of Devonian and Mississippian carbonates, and an approximately 1500 m-thick package of Mesozoic shales, siltstones, and sandstones.

Carbon dioxide is being injected at the Weyburn Field into Mississippian carbonates at 1500 m depth that also are cyclic deposits formed in a shallow setting and that have porous intervals capped by variably thick evaporite units. Trapping mechanisms include an updip reduction in porosity and the overlying Mesozoic succession is similar to that found above the natural CO_2 accumulations. The CO_2 occurrences in Devonian carbonates of southwestern Saskatchewan represent a natural analogue for the Weyburn injection site due to their similar basinal environment and geological framework.

Keywords: *CO_2 storage, natural analogue, carbon sequestration, Devonian, Duperow, Williston Basin, platform carbonates, southwest Saskatchewan.*

1. Introduction

Early exploratory wells drilled in southwest Saskatchewan during the 1950s encountered naturally occurring CO_2, N_2, and He. These gases are trapped in clastic reservoirs of the Cambrian Deadwood Formation, and in carbonate reservoirs of the Middle Devonian Winnipegosis and Souris River and Upper Devonian Duperow formations (Lee,

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1962; Lane, 1987). Because of the increased interest in storing anthropogenic CO_2 in geological reservoirs as a method of mitigating CO_2 emissions to the atmosphere, the geological settings of natural occurrences of these gases is of scientific interest. This is particularly pertinent in the Williston Basin where CO_2 is currently being injected into Mississippian beds of the Weyburn Oil Pool in southeastern Saskatchewan as part of an Enhanced Oil Recovery (EOR) program. This report is mainly focused on the geological setting of natural CO_2 occurrences in carbonate rocks of the Devonian Duperow Formation in southwestern Saskatchewan because of the geological similarity with reservoir rocks of the Weyburn site.

2. Regional Geology

Carbonates of the Devonian Duperow Formation are now included as deposits within the Williston Basin, which is an elliptical depression about 560 km in diameter and centred in North Dakota (Figure 1), but these shallow platform carbonates and evaporites were initially formed along the eastern margin of the Devonian Elk Point Basin (Moore, 1989). The Elk Point Basin trended northwest and was bounded by the Precambrian Shield margin in the east, the Transcontinental Arch to the south, and open circulation to the northwest. Common consensus states that a Precambrian positive feature existed immediately south of the study area in northern Montana, based on onlap and thinning of the Devonian Winnipegosis and Dawson Bay formations (Figure 2) onto this feature. The basal Duperow strata south of this area are thin or absent as a result of onlap (Kent, 1968; Pilatzke *et al*., 1987; Burke and Heck, 1988). Subsequent crustal and basinal downwarping resulted in the present study area being included in the western portion of the Williston Basin by Mississippian time.

The structure of western North America has been influenced by crustal shortening associated with the Antler Orogeny centered in Nevada during the Upper Devonian–Early Mississippian (Goebel, 1991). This orogeny also corresponds with a major mass extinction (the global Frasnian-Famennian event) coincident with the Upper-Lower Birdbear contact as shown in the detailed stratigraphic chart for the Upper Devonian series in southwestern Saskatchewan (Figure 3). Further crustal shortening and uplift occurred in western North America during the massive Cordilleran Orogeny during the early Tertiary. Locally, the major structural elements include the Sweetgrass–North Battleford Arch over the inter-provincial border with Alberta (Kent, 1968).

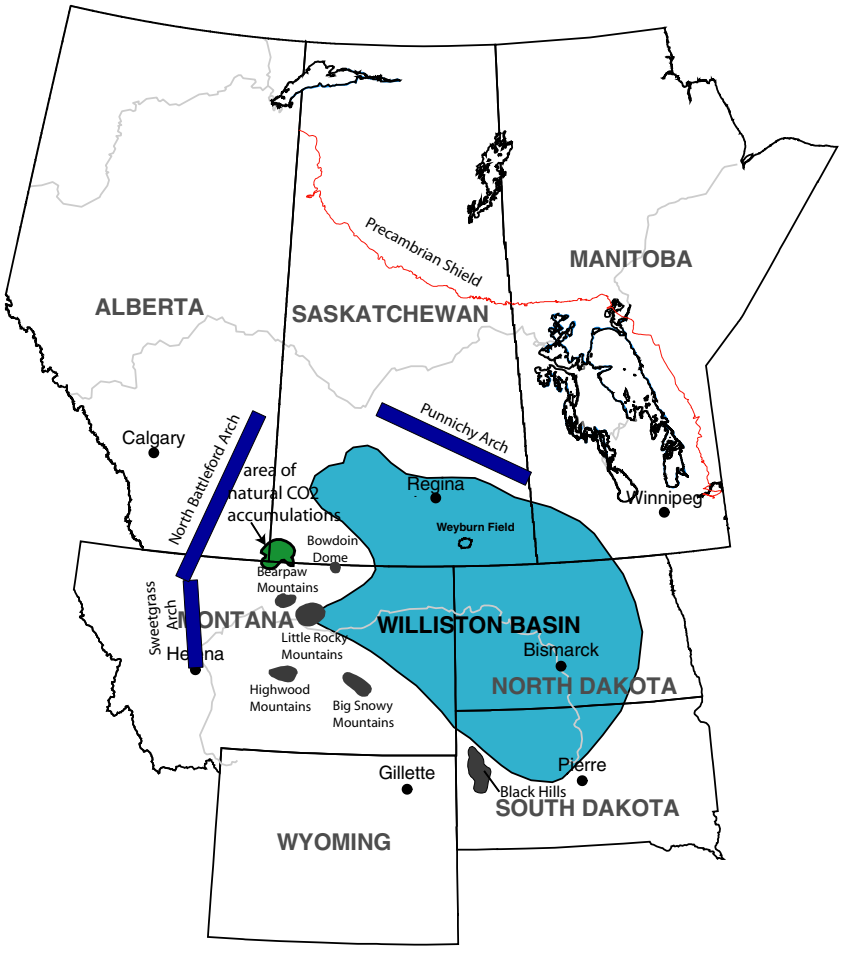

Figure 1 - Map showing the location of the Williston Basin and natural CO_2 occurrences in the subsurface of southwestern Saskatchewan relative to the position of the Weyburn CO_2 injection site.

The structure map of the Duperow Formation is shown in Figure 4 along with other structural elements and the locations and formations in which inert gases have been detected in southwestern Saskatchewan. Deposition and precipitation of material that now form the Prairie Evaporite Formation occurred mainly in the northwest-trending Devonian Elk Point Basin. Precipitation was dominated by halite and ultimately potash by the end of the Middle Devonian. Subsequent dissolution of the evaporite deposits in the subsurface has occurred over a large area of southwest

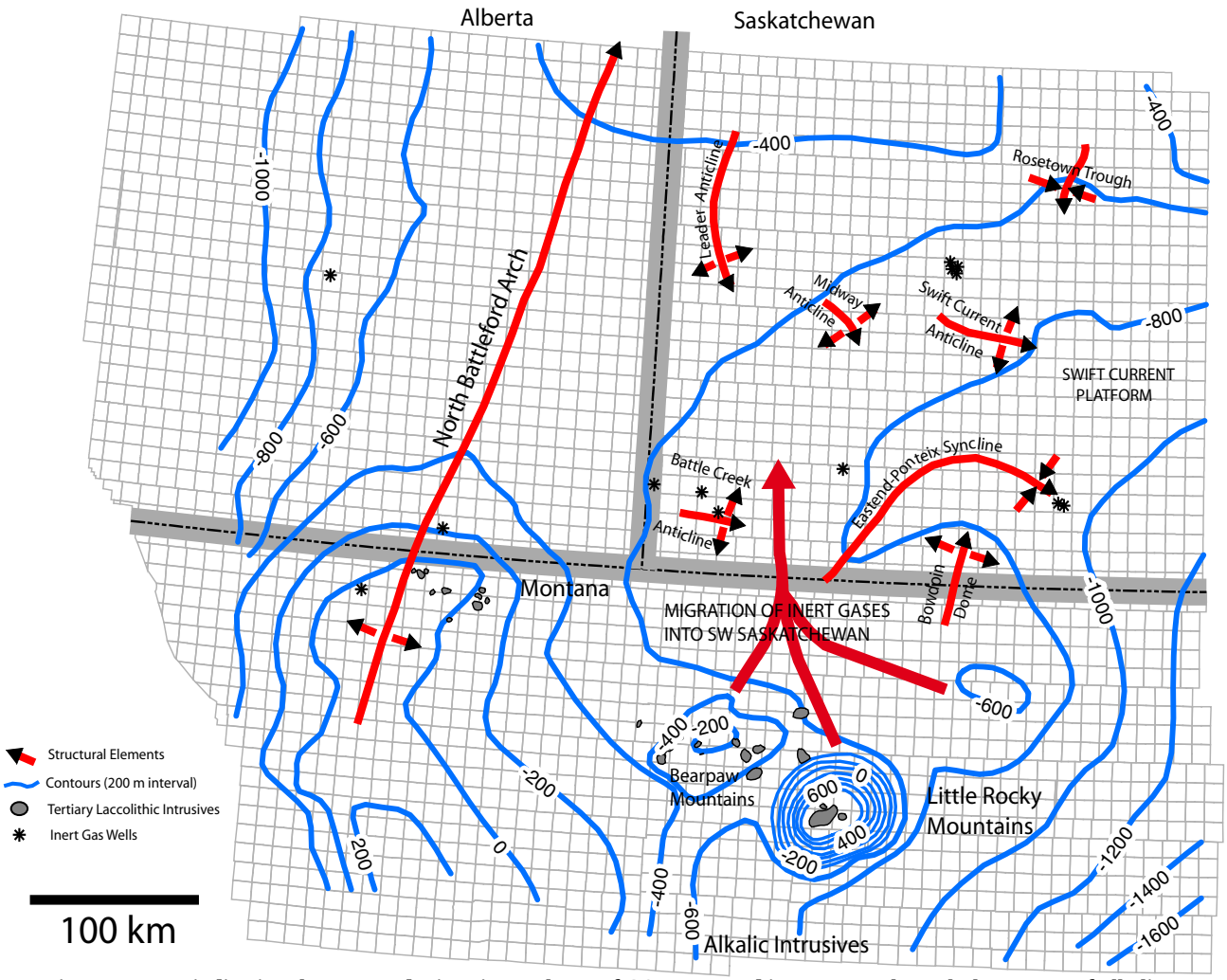

Figure 2 - Map indicating the proposed migration pathway of CO_2 generated in Montana through the contact of alkalic magma with limestones approximately 50 million years (my) ago. The locations of known natural inert gas occurrences in the area are shown along with several basement and intra-sedimentary structures. Structure contours represent Duperow and equivalent strata in region.

Saskatchewan. The region of dissolution is broadly bounded by the western margin of the Swift Current Platform and the eastern limits of the Missouri Coteau beyond the limits of the map shown in Figure 4. Salt dissolution and associated collapse and brecciation of strata have influenced the structure of all the overlying strata, including the Duperow Formation which is of interest here.

Local features influenced by Prairie Evaporite dissolution include the Leader Anticline, Battle Creek Anticline, Bowdoin Dome, Midway and Swift Current anticlines, plus the Eastend-Ponteix Syncline and Rosetown Trough. Significant local structural uplift occurred from Tertiary alkalic intrusives in the Bearpaw Mountains, Little Rocky Mountains, and Bowdoin Dome intrusions in northern Montana (see Figures 2 and 4). These intrusives have been dated at 50 my (Eocene) (Marvin *et al.*, 1973).

3. Sedimentology of the Duperow Formation

Kent (1987) resolved the regional stratigraphy of the Duperow Formation in southwestern Saskatchewan and correlated it laterally with the Leduc Reef buildups and Ireton Shale Basin to the west in Alberta. The Duperow Formation is composed of shallow carbonate facies frequently capped by intervening evaporites associated with marine regressions (Kent, 1968). The Duperow Formation is subdivided into the Saskatoon, Elstow, Wymark (Lower, Middle, and Upper units), and Seward (Units A and B) members in ascending order (Figure 3). The Seward is distinguished from the Wymark Member by significantly greater argillaceous content and higher gamma-ray

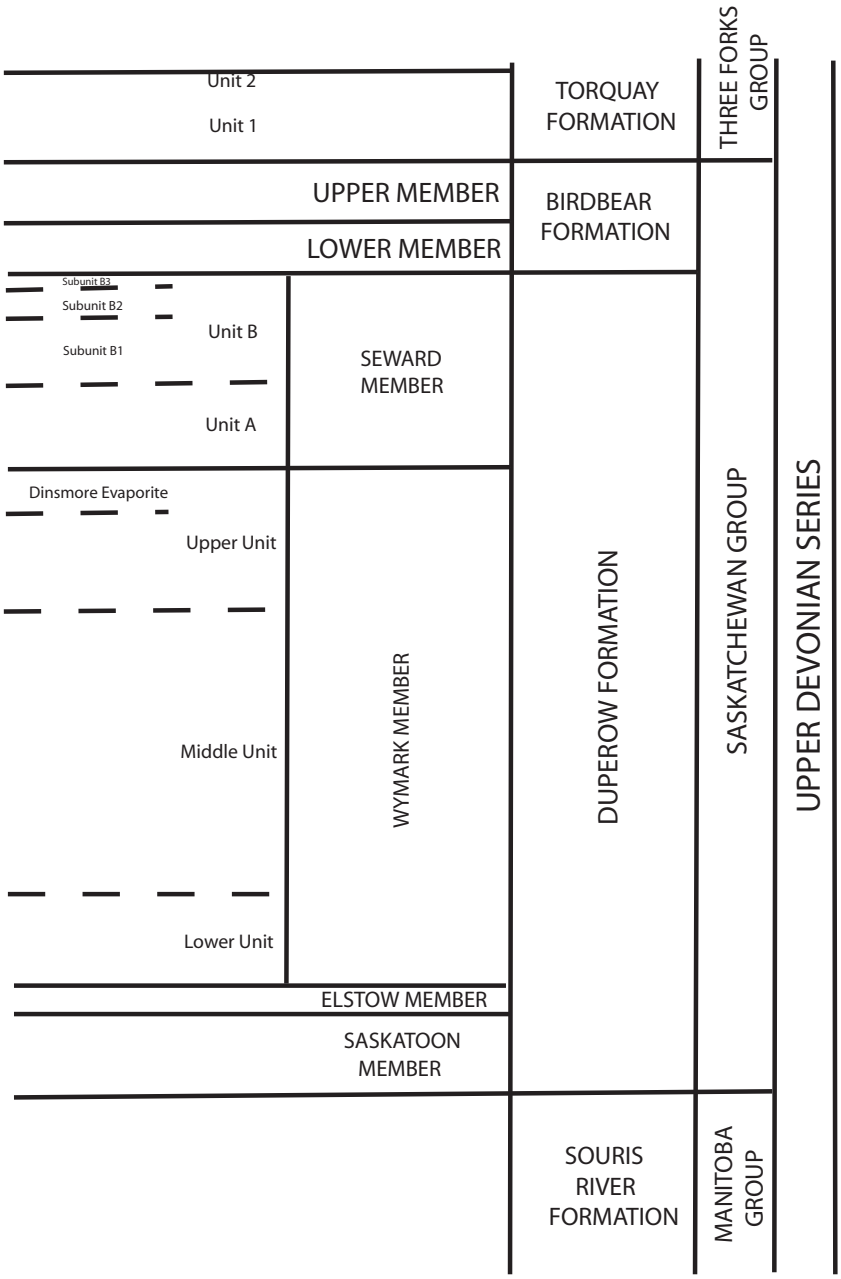

Figure 3- Detailed stratigraphy of the Upper Devonian series in southwestern Saskatchewan.

response on electrical logs. Individual units within the Seward and Wymark members are capped by thin evaporites that act as aquitards to vertical fluid migration. Calcitic botryoidal (radiaxial fibrous) marine cements are present in the basal Seward Unit A indicative of early marine cementation (Davies and Nassichuk, 1990). Karsting also has affected the Middle Wymark Member as recognized in two cores studied, 15-11-6-20W3 Eastend and 3-10-14-14W3 Wymark, and shown in the regional south-north cross section of Figure 5. The top of the Wymark Middle Unit through the study area also appears to represent a significant sequence boundary. Wymark Middle Unit strata are truncated along the upper contact suggesting that erosion has occurred on this surface. In addition, a section has likely been removed associated with the karsting such that up to 18 m of section may have been removed from this unit. The work from this study suggests that the Middle Wymark Member represents the most significant sequence boundary in the Duperow Formation in terms of stratigraphic trapping potential in southwestern Saskatchewan. The Elstow and Saskatoon members (base of the Duperow section) are absent in northern Montana (Kent, 1968; Pilatske *et al.*, 1987), as indicated by the positive basement high in this area. Carbon dioxide and inert gases (He and N_2) are generally encountered in the Middle and Upper units of the Wymark Member.

The Upper Devonian Duperow Formation in southwestern Saskatchewan shows facies variability both laterally and vertically that results in thin, widespread depositional cycles that are suggestive of a stable cratonic and climatic environment (Figure 6). For example, individual markers within the Duperow may be correlated for 160 km across the basin center (Burke and Heck, 1988). Stromatoporoid growth (reef or mound development) was limited to the Upper Wymark Unit (as observed in the 15-11-6-20W3 and 5-12-6-20W3 Battle Creek cores). Duperow strata generally exhibit shallowing-upward cycles of carbonate deposition in very shallow settings that may be capped by evaporite formation. These anhydrite layers at the top of individual cycles are considered to be effective seals to fluid migration. The cycles are broadly similar to those observed in the Mississippian strata of the Weyburn Pool, but the Mississippian cycles show more rapid fluctuations in sea level and, consequently, more exposure surfaces (Burrowes, 2001). The shallow peritidal depositional setting, however, was similar for each location (Figure 7).

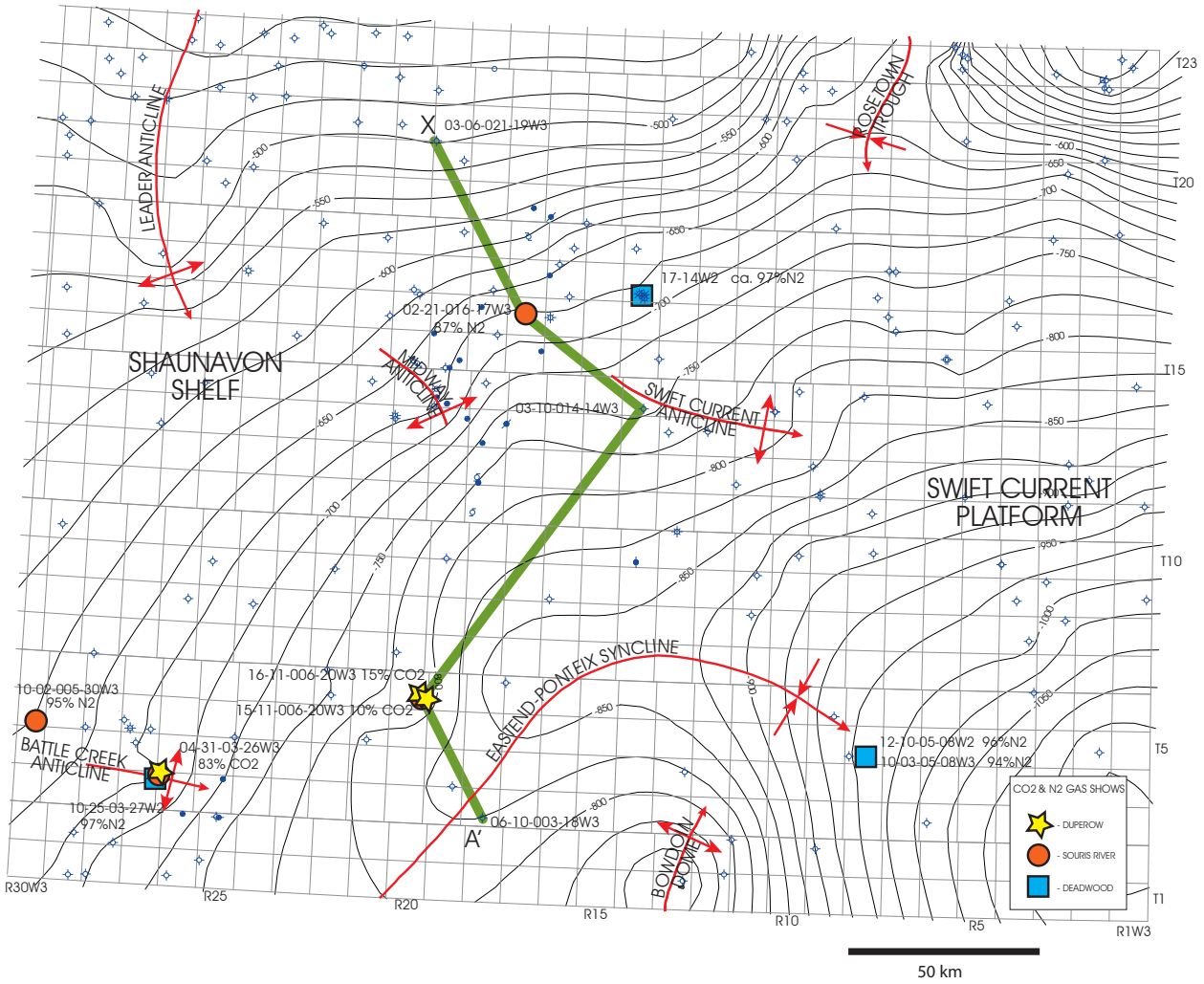

Figure 4 - Structure map of the Duperow Formation displaying locations and formations in which CO_2 and N_2 have been found. The location of the cross section shown in Figure 5 is shown by line A'-X. Contour intervals are 25 m.

4. Structure and Trapping

The main trapping mechanisms for CO_2 (and other inert gases) in the Duperow Formation are local structures associated with Devonian Prairie Evaporite dissolution. Lane (1987) notes the two Battle Creek wells (4-31-3-26W3 and 10-25-3-27W3, Figure 4) have about 16 m of closure according to seismic interpretation. Lane (1987) estimated total CO_2 recoverable resources to be between 28.3 and 56.6 x 10^9 m^3, of which 2 x 10^9 m^3 are considered proven. A salt collapse feature occurs within the Upper and Middle units of the Wymark Member in the 5-7-14-10W3 Braddock well core. The collapse includes polymictic breccia, clay diagenesis, and silicification features. Collapse in this well occurs from the top of the Upper Wymark Member stratigraphically downward. Halabura *et al.* (2003) suggest these collapse features occur through fracture enhancement resulting from dissolution by fluids originating near the surface rather than fluid migration up fractures from an active aquifer below. Although collapse features may produce trapping features, they may also compromise reservoir integrity so that their influence on overlying strata should be considered in assessing potential sequestration sites. Aside from collapse features, it was difficult to determine the general fracturing characteristics in the reservoirs because of the limited core availability.

Stratigraphic trapping associated with facies distribution does not appear to be an important mechanism in the Devonian rocks of this region.

5. CO_2 and Inert Gas Distribution

Several drillstem tests undertaken in the Duperow Formation reported CO_2 and inert (He and N_2) gas potential in the study area (Figure 4). The most significant CO_2 accumulation is 83% CO_2 within the Middle Wymark Member at 4-31-3-26W3 Consul (Lane, 1987). Many authors suggest that subsurface CO_2 and inert gas occurrences are related to

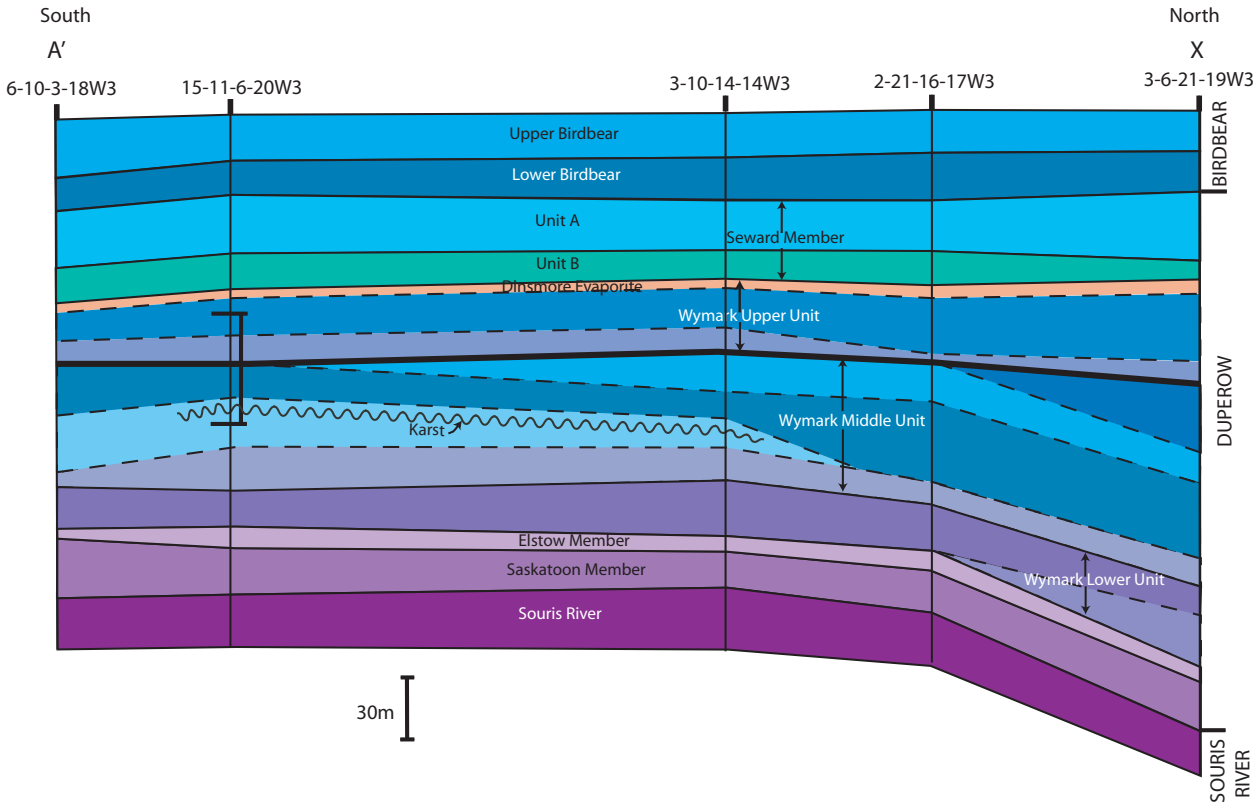

Figure 5 - North-south cross section through the Devonian Duperow Formation in southwestern Saskatchewan. For location of cross section see Figure 4. The interval in the Wymark Middle and Upper units that contained the most CO_2 is shown as the black vertical line in well 15-11-6-20W3. The Dinsmore Evaporite serves as an effective upper seal to the reservoir layers.

the migration of gas into overlying aquifers from underlying igneous activity (Stevens *et al.*, 2001; Moore *et al.*, 2003). Kent and Kreis (2001) recognized anomalously high geothermal gradients in Mississippian Lodgepole Formation oil wells along the Battle Creek–Rangeview Structure in which heavy oil (10 degree API gravity) flows to surface. The high geothermal gradient likely results from the igneous activity nearby in Montana. Alkalic intrusives were emplaced in Montana approximately 50 my ago (Marvin *et al.*, 1973) during igneous activity associated with the Bearpaw Mountains, Little Rocky Mountains, and potentially also with the Bowdoin Dome. Carbon dioxide and inert gases (N_2 and He) have been detected in the clastic Cambrian Deadwood Formation, and the carbonate Middle Devonian Dawson Bay and Winnipegosis formations, and the Upper Devonian Duperow Formation. If reaction of limestones with alkalic intrusions generated the CO_2 or if the inert gases are directly associated with the igneous source, the lateral migration path would have been around 100 km (Figure 2).

Creany *et al.* (1994) suggest that migration and maturation of hydrocarbons occurred in the Western Canada Sedimentary Basin during the Late Cretaceous and Early Tertiary (Palaeocene) due to burial and thrusting associated with mountain building along the western margin of North America (Cordilleran Orogeny). Because the Devonian section in Saskatchewan is immature with respect to hydrocarbon generation due to the shallow burial history of the area, hydrocarbons did not migrate into the porous reservoirs of southwest Saskatchewan until uplift in the Rocky Mountains. Hydrocarbon migration in southwest Saskatchewan occurred prior to alkalic igneous activity so that inert gas migration would have occurred after oil migration. If any hydrocarbons were present in these reservoirs, and minor staining has been observed, it may be possible that the inert gases displaced them. Regardless, the gases have likely been in the Duperow reservoirs since the Tertiary (Palaeocene), or for about 50 my.

The CO_2 interval in the well containing the most CO_2 in the Duperow Formation (well 4-31-3-26W3 tested almost 83% CO_2 in the top of the Wymark Middle Member) was never produced and was plugged in 1955. In 2001, a new well was drilled at the same location to exploit a shallower natural gas occurrence within the Jurassic Upper Shaunavon Formation at around 800 m depth. Gas tested from the new well contains only trace amounts of CO_2. Moreover, in the immediate vicinity of the CO_2 deposit, gas-receiving stations, which essentially serve to integrate gas from a number of shallower wells, do not contain measurable amounts of CO_2. It is inferred, therefore, that

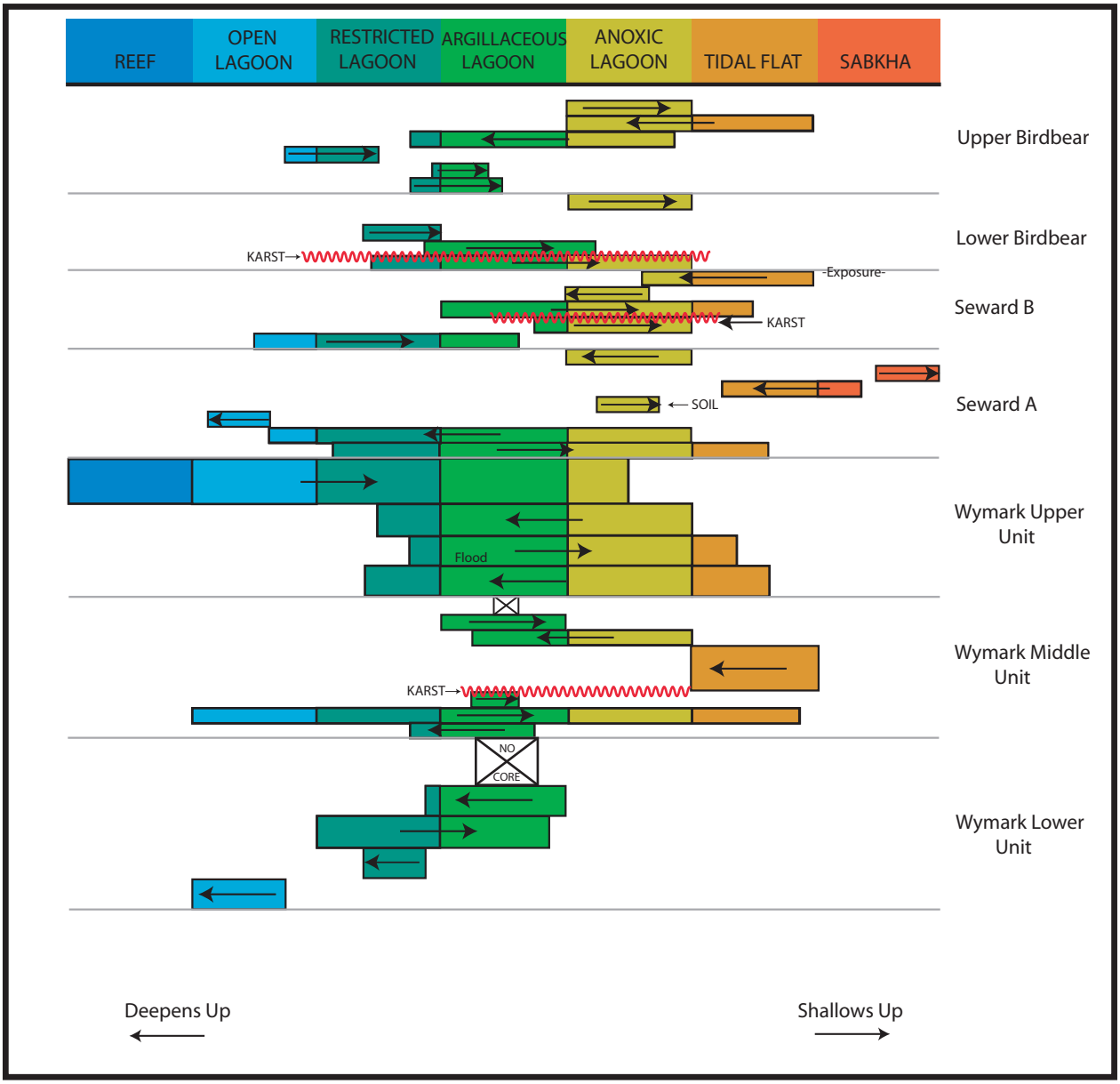

Figure 6 - Diagram showing variations in depositional environments throughout the Upper Devonian Duperow Formation in southwestern Saskatchewan. The depositional settings are generally shallow, peritidal carbonate shelf environments, similar to those in which the Mississippian Midale Beds of the Weyburn Field were deposited. The arrow direction indicates the relative change in water depth with time.

leakage from natural CO_2 reservoirs into shallower horizons in southwestern Saskatchewan has not been significant during the past 50 my.

6. Comparison with the Weyburn Reservoir

The geological setting of the Devonian Duperow Formation in southwestern Saskatchewan is quite similar to that of the Mississippian Midale Beds of the Weyburn Pool in southeastern Saskatchewan. Figure 8 shows the relation between the general stratigraphy of each location as they occur within the overall depositional package of the Williston Basin. The strata are largely continuous between the regions, although the Mississippian Midale Beds have been truncated by the Sub-Mesozoic Unconformity surface in the western portion of the basin. Duperow strata, however, are present and are essentially laterally continuous at both locations, with the exception of some karstification and erosion associated with the Wymark Middle Member. At each location, the CO_2-bearing units are

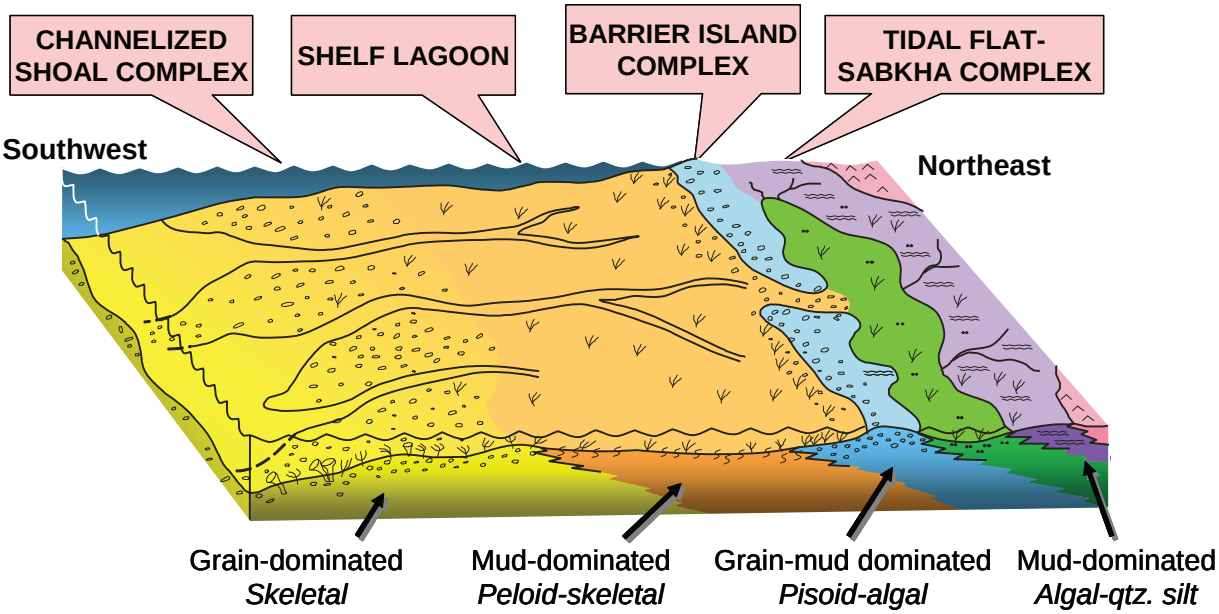

Figure 7 - Depositional environment in which the Mississippian Midale Beds of the Weyburn Field were deposited (Burrowes, 2001). These environments are generally similar to those in which the Devonian Duperow beds were formed in southwestern Saskatchewan (compare with Figure 6). Figure used courtesy of EnCana Corporation.

overlain by approximately 1500 m of clastic Mesozoic strata that contain several thick shale sequences which are highly effective aquitards.

The reservoir system in the Weyburn Field is a combination of stratigraphic, diagenetic, hydrodynamic, and structural traps. The Mississippian Midale Beds pinch out at the Sub-Mesozoic Unconformity where diagenesis has also occurred to markedly reduce porosity (Figure 9). The reservoir layers are sealed by the Midale Evaporite, a 2 to 11 m thick anhydrite layer formed in a restrictive, salina-like environment. The reservoir layers are shallow, peritidal carbonate deposits that have been variably dolomitized. The lower Midale Vuggy unit is a limestone that has about 2 to 15% porosity, whereas the upper Midale Marly unit is a dolostone that has an average of about 27% porosity.

The traps in Duperow strata are mainly related to structures formed by dissolution of underlying salt layers. The porous layers within the Duperow, however, are sealed by variably thick (usually greater than 2 m) anhydrite layers, such as the Dinsmore Evaporite, that formed in restricted environments. The reservoir layers are generally limestones to slightly dolomitized limestones formed in a low-energy, shallow carbonate shelf environment. The reservoirs often exhibit vuggy porosity and, although core analyses are not abundant, measured porosities for the reservoir units range from 6 to 18%. A comparison of the respective reservoir petrography from the Weyburn Pool and Devonian CO_2 reservoirs of southwestern Saskatchewan is shown in Figures 10 to 14.

7. Conclusions

Carbon dioxide occurs naturally in Palaeozoic carbonate and clastic reservoirs in southwestern Saskatchewan. Most of the CO_2 is trapped in limestones of the Devonian Duperow Formation. The Devonian strata are cyclic, shallow water deposits that have porous intervals sealed by relatively impermeable evaporite deposits. These peritidal carbonates are very similar to the Mississippian Midale Beds of the Weyburn Pool. The Devonian rocks of southwestern Saskatchewan are overlain by approximately 1500 m of clastic Mesozoic strata, which include several thick aquitard packages that are also present above the Weyburn Pool. Analyses of natural gas produced from Mesozoic reservoirs within the southwestern region indicate that no detectable amounts of CO_2 have migrated from Palaeozoic strata into the shallower layers during the past 50 my. The areas of natural CO_2 occurrences in southwestern Saskatchewan are suggested to represent natural analogues to the CO_2 injection site at the Weyburn Field in southeastern Saskatchewan based on their geological similarity.

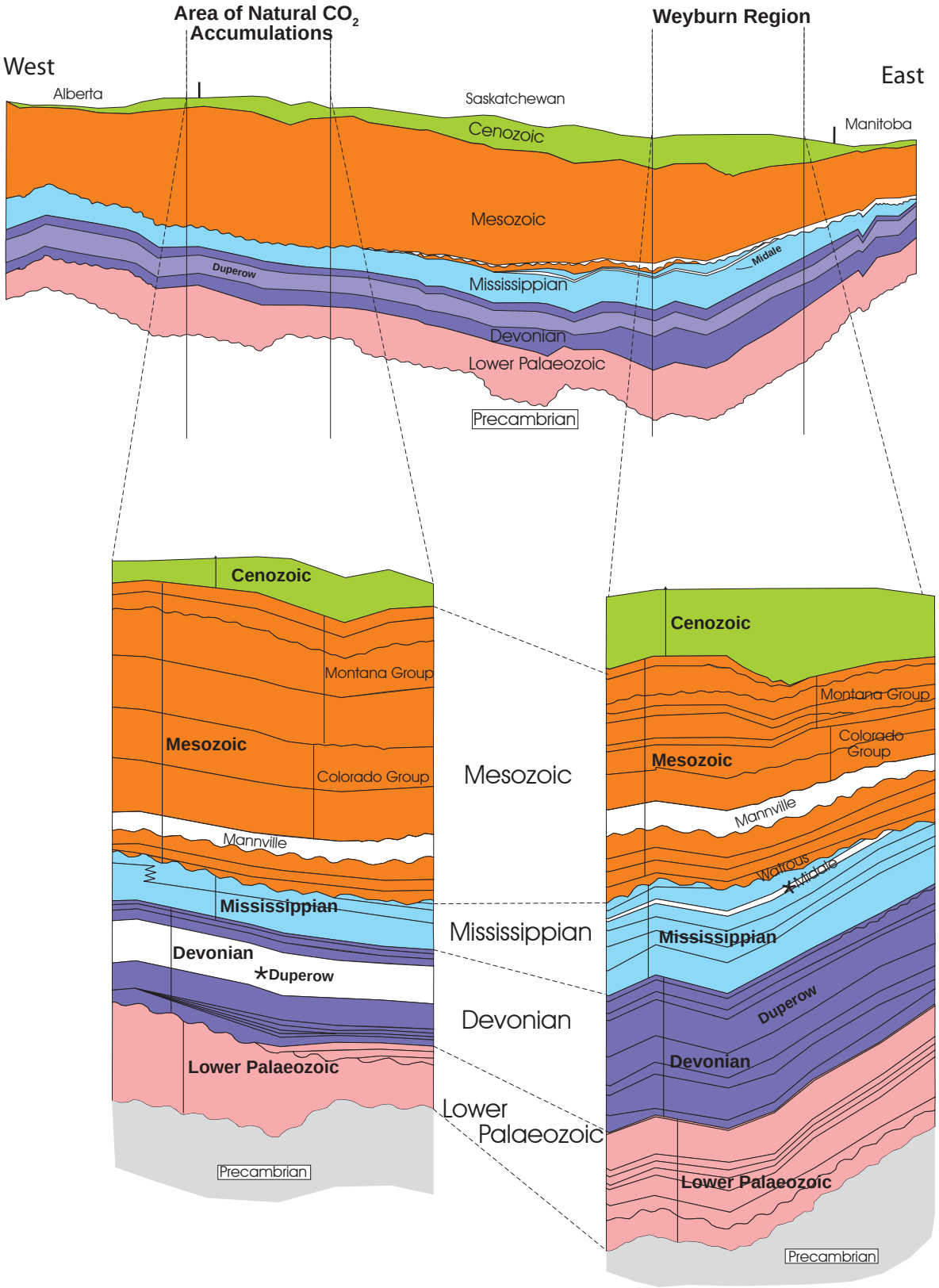

Figure 8 - Comparison of the geological setting between the natural CO_2 sites in southwestern Saskatchewan and that of the Weyburn injection site. The top diagram depicts the relatively continuous strata across the intervening distance between the two areas. The detailed geological columns indicate the broad similarity of geological setting in both areas; the CO_2 is contained in Palaeozoic carbonate reservoirs capped by anhydrite layers and in turn overlain by approximately 1500 m of Mesozoic shales, siltstones, and sandstones. At the Weyburn site, CO_2 is being injected into the Mississippian Midale Beds (see *), whereas the naturally occurring CO_2 is found mainly in the Devonian Duperow Formation in southwestern Saskatchewan (see *).

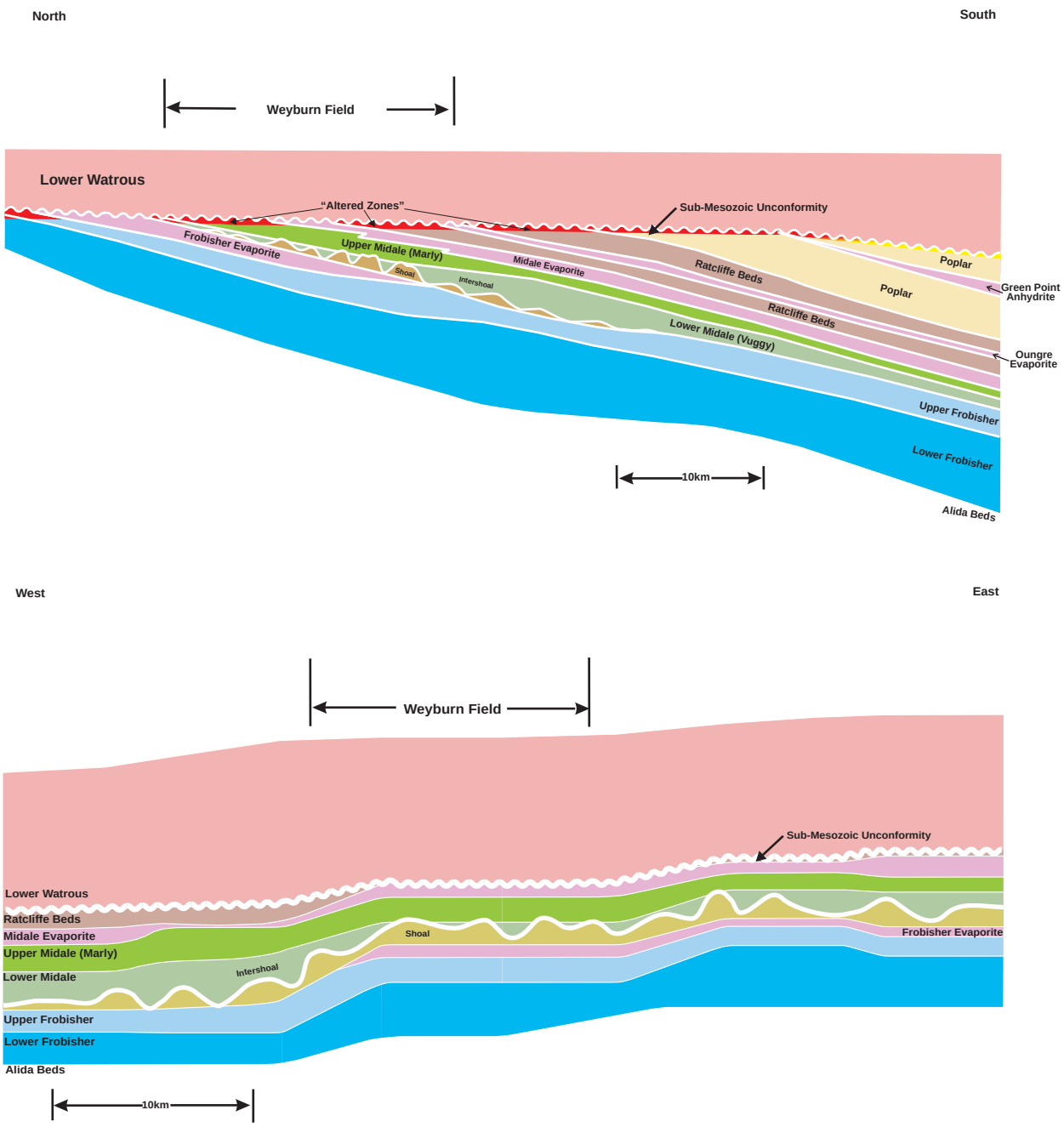

Figure 9 - The upper diagram is a schematic north-south cross section through the Weyburn Field illustrating truncation of inclined Mississippian strata at the Sub-Mesozoic Unconformity. Evaporite beds act as sealing units for more porous carbonate strata. In addition, porosity has been largely occluded through dolomitization and anhydritization in the diagenetically altered zone beneath the Sub-Mesozoic Unconformity. The Triassic Lower Watrous Member, which overlies the unconformity, is also an important primary seal for Mississippian reservoirs. The lower diagram is an east-west cross section through the Weyburn Field along the general strike of the Mississippian beds. The lateral continuity of Midale strata beyond the Weyburn Pool is strongest to the east where Vuggy shoals are commonly developed. To the west and south of the Weyburn Pool, shoal development is less prevalent and lateral continuity is weaker.

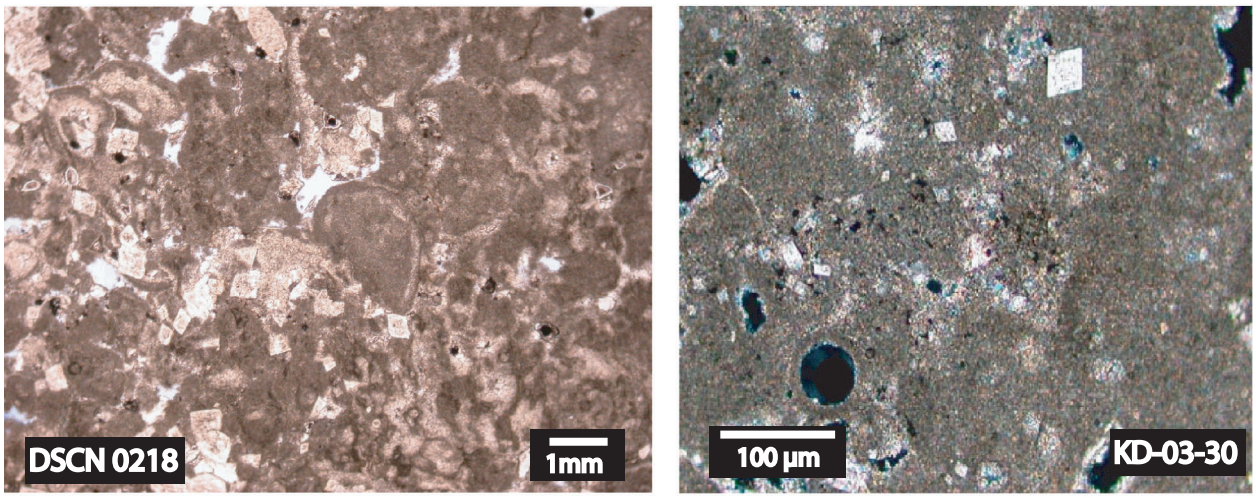

Figure 10 - Photomicrographs of fossiliferous lime mudstones. DSCN 0218 is from the Wymark Middle unit of the Devonian Duperow Formation (Imp et al Battle Cr. 4-31-3-26W3, 5632 feet [1716.63 m]). This is the reservoir layer containing natural CO_2. The slide contains a micritic calcite matrix with scattered rhombs of dolomite (10x magnification, plane polarized light). KD-03-30 is from the Midale Vuggy unit of the Weyburn Pool (14-30-6-13W2, 4496 feet [1370.38 m]), one of the reservoir layers being injected with anthropogenic CO_2 for EOR. The slide shows finely crystalline calcite (micrite) with scattered rhombs of dolomite. Field of view is approximately 500 microns.

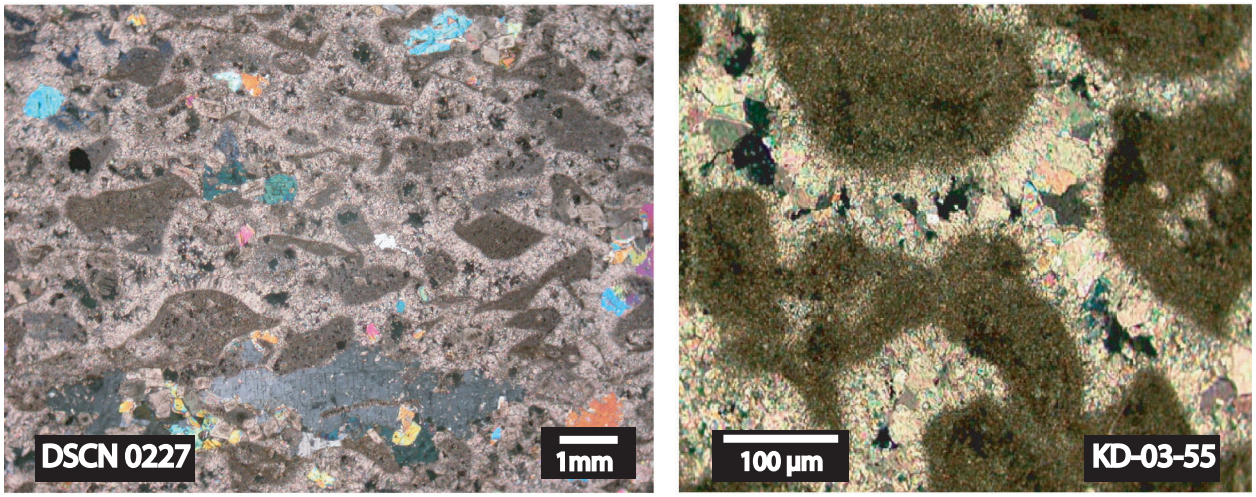

Figure 11 - Photomicrographs of peloidal lime mudstones. DSCN 0227 is from the Wymark Middle unit of the Duperow Formation (well T.W. Eastend Cr #1 15-11-6-20W3, 6141 feet [1871.78 m]) and shows a pelletal mudstone with numerous lenticular rip-up clasts. Early calcite cements form rinds around the clasts, and anhydrite cements fills pore spaces (10x magnification, plane polarized light). KD-03-55 is from the Midale Vuggy unit of the Weyburn Field (8-36-6-13W2, 4476 feet [1364.28 m]) and also shows sparry calcite cements filling voids around micritic patches (pelloids). Anhydrite cements are also present in this rock. Field of view is approximately 500 microns.

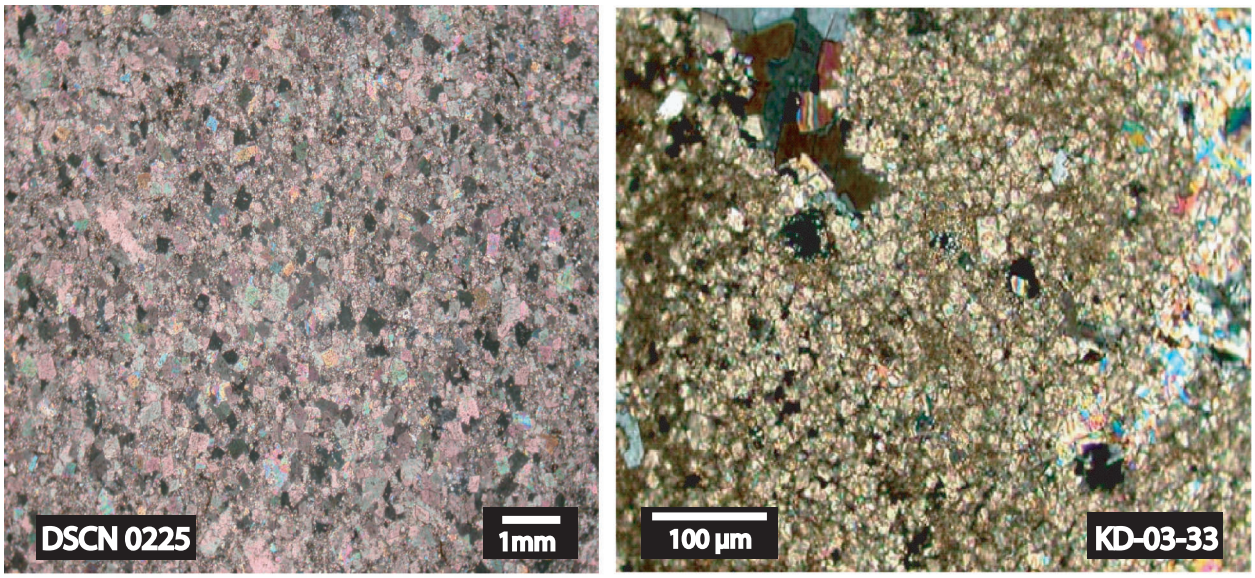

Figure 12 - Photomicrographs of dolomitized carbonate mudstones. DSCN 0225 is from the Wymark Upper unit of the Duperow Formation (Norcanoil Pennant, 4-14-18-16W3, 4827 feet [1471.27 m]) and shows relatively pervasive dolomitization. Dark flecks are organic matter (10x magnification). KD-03-33 is from the Midale Marly unit of the Mississippian Charles Formation of the Weyburn Field (8-25-6-14W2, 4517 feet [1376.78 m]). Medium crystalline dolomite rhombs are observed within a dominantly fine-grained dolomitic matrix. This is the reservoir layer in which CO_2 is currently being injected. Field of view is 500 microns.

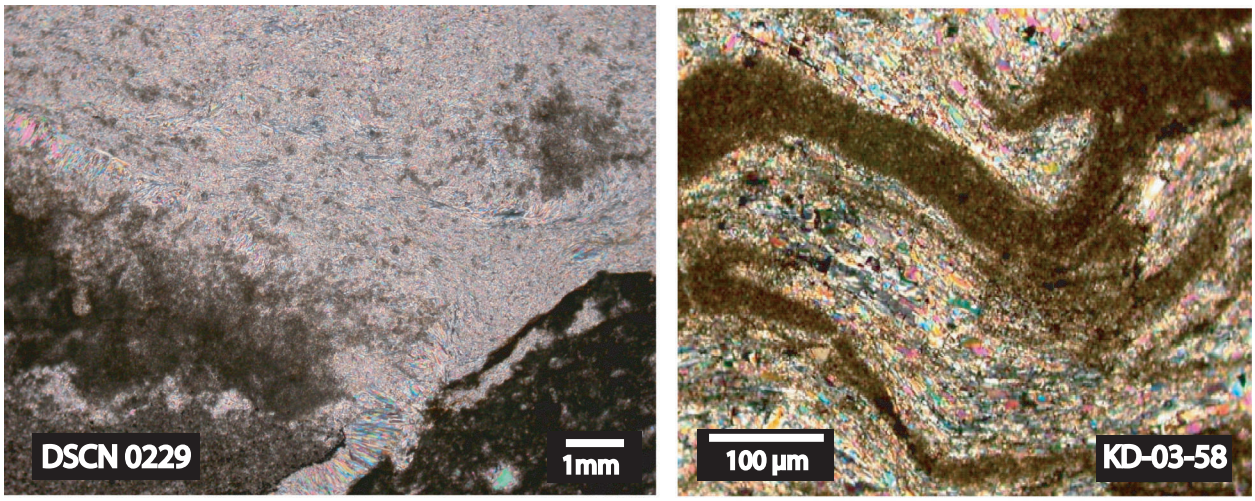

Figure 13 - Photomicrographs of nodular anhydrite. DSCN 0229 is from the Dinsmore Evaporite of the Wymark Upper unit of the Duperow Formation (T.W. Eastend Cr #1 15-11-6-20W3, 6014 feet [1833.07 m]). This rock is dominantly anhydrite and formed in a sabkha environment. This unit serves as the upper seal to the reservoir containing natural CO_2 (10x magnification). KD-03-58 is from the Frobisher Evaporite that forms the lower seal to the Weyburn reservoir (8-36-6-14W2, 4505 feet [1373.12 m]). Sinuous anhydrite nodules are separated by darker layers of dolomite and quartz. Field of view is about 500 microns.

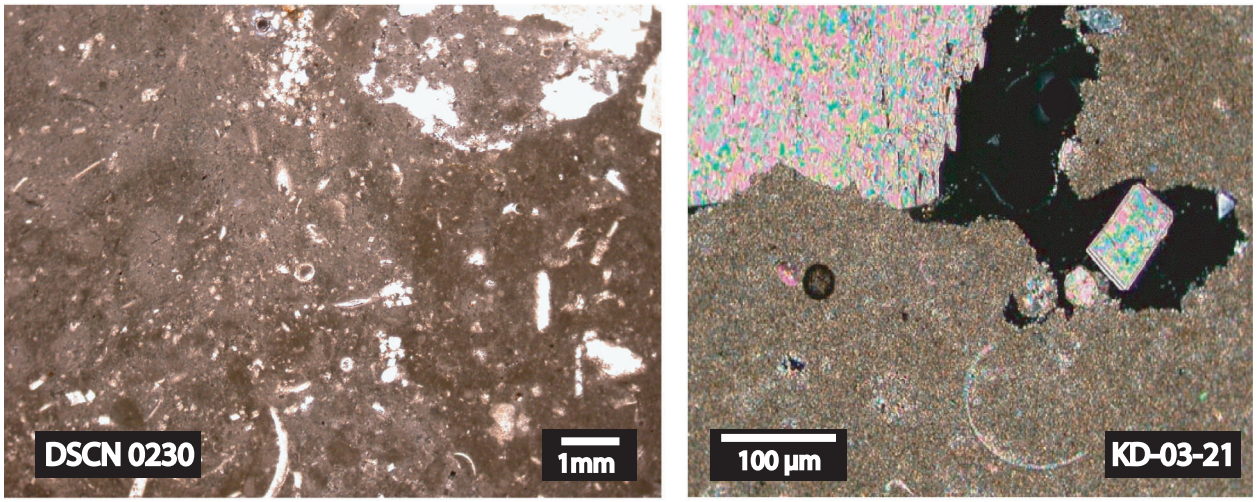

Figure 14 - Photomicrographs of fossiliferous mudstones to wackestones. DSCN 0230 is from the Wymark Upper unit of the Duperow Formation (T.W. Eastend Cr #1, 15-11-6-20W3, 6029 feet [1837.64 m]). Dissolution of ostracode shells and calcareous algae (upper right of slide) has enhanced porosity in this fine-grained lime mudstone. This rock formed in a very restricted (poor water circulation) environment (10x magnification). KD-03-21 is from the Midale Vuggy unit of the Weyburn reservoir (12-19-6-13W2, 4592 feet [1399.64 m]). Bioclasts have been dissolved and filled with secondary calcite cements in this micritic lime mudstone. Coarsely crystalline calcite cements are also seen to partially fill voids. Field of view is about 500 microns.

8. Acknowledgments

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9. References

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