Geological Characterization of the Weyburn Field for Geological Storage of CO_2: Summary of Phase I Results of the IEA GHG Weyburn CO_2 Monitoring and Storage Project [1]

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Abstract

The IEA GHG Weyburn CO_2 Monitoring and Storage Project was designed to study methods for monitoring CO_2 movement in the subsurface and to determine the security of storing CO_2 in depleting oil reservoirs for hundreds to thousands of years. The Weyburn Project was associated with EnCana Resource's CO_2-miscible flood operations at the Weyburn Field in southeastern Saskatchewan. Initial planning of the research program began in July 2000 and the first phase of research was completed in September 2004. The project was highly diverse and contained programs involving regional geoscience investigations, reservoir simulations, 4-D geophysical monitoring surveys, reservoir fluid and mineral sampling, geochemical modeling, well-bore integrity studies, geomechanical property investigations, risk and performance assessment, and economic viability studies, among others. Geological characterization was undertaken at two scales: one a regional investigation of a 200 x 200 km area centred on the Weyburn Field; the other a more detailed examination of the geosphere in an area extending 10 km beyond the limits of the planned CO_2 flood. The geological framework was defined through geological mapping, regional seismic data, shallow and deep hydrogeological investigations, high resolution aeromagnetic geophysical surveys, airphoto and satellite remotely sensed imagery analyses, and detailed stratigraphic and diagenetic studies. The geological characterization portion of the project provided fundamental information for other areas of study regarding geological storage of CO_2 such as reservoir simulation and risk assessment. Much of the geoscience data were integrated into a 3-D geological model, or System Model, that was used for numerical risk and performance assessment. The results of the geoscience studies indicate that the Weyburn Pool is a very suitable location in which CO_2 may be stored securely for several thousand years. Numerical modeling studies suggest around 23 million tonnes (MT) CO_2 will remain in the reservoir at the end of EOR operations, and that no CO_2 will migrate above the reservoir caprock in over 5,000 years.

Keywords: *Weyburn Project, CO_2, sequestration, geological storage, Midale Beds, Mississippian, Williston Basin.*

1. The IEA Weyburn Project

The IEA GHG (International Energy Agency, Greenhouse Gas R&D Programme) Weyburn CO_2 Monitoring and Storage Project (Weyburn Project) was initiated to study the potential for geological storage of CO_2 in a depleting oil field in southeastern Saskatchewan. In October 2000, EnCana Resources (at that time PanCanadian Energy) began an EOR (enhanced oil recovery) project designed to recover an additional 20.7 x 10^6 m^3 (130 x 10^6 bbls) oil by injecting CO_2 into the Mississippian Midale Beds thus extending the life of the Weyburn Oil Field by 25 years. About 5,000 tonnes/day (3 x 10^6 m^3) CO_2 are purchased from Dakota Gasification Company's Great Plains Synfuels Plant in Beulah, ND, and transported via pipeline 320 km to the Weyburn Field. The >95% pure CO_2 is injected into the reservoir as a supercritical fluid which becomes miscible with the residual oil thereby reducing the viscosity of the oil and improving ultimate hydrocarbon recovery. The Weyburn Project, coordinated through the Petroleum Technology Research Centre in Regina, Saskatchewan, developed a research program to accompany EnCana's EOR project to investigate methods of monitoring the movement of CO_2 in the subsurface to: 1) enhance the effectiveness of the miscible flood, 2) determine the potential of the reservoir to serve as a vessel for long-term (*ca.* 5,000 years) storage of the anthropogenic CO_2, and 3) to determine the economic feasibility of long-term storage. The Weyburn Project began in July 2000 and was completed in September 2004 at which time the results of many of the studies were presented at the 7th International Conference on Greenhouse Gas Control Technologies held in Vancouver.

[1] Funding provided by numerous government and industry sponsors coordinated through PTRC (Petroleum Technology Research Centre) of Regina.

The diversity of investigations involved in the Weyburn Project required grouping studies into eight Principal Tasks which included more than 70 Subtasks. The Principal Tasks include: field-based programs jointly funded by EnCana and the Weyburn Project, Geoscience Framework, Geochemical Modeling, Geophysical Monitoring, CO_2 Storage Performance, Storage Economics, Project Control, and European Commission Studies. Funding of more than $20 million for the project was provided by fifteen sponsors including Saskatchewan Industry and Resources (SIR), Natural Resources Canada, United States Department of Energy, Alberta Energy Research Institute, the European Community, and ten industrial sponsors in Canada, the United States, and Japan. More than 20 research and consulting organizations performed research within this study and provided additional in-kind support worth $20 million. A second phase to the project is currently in planning.

The results of the project were ultimately grouped into four major themes: Geological Characterization; Prediction, Monitoring, and Verification of CO_2 Movements; CO_2 Storage Capacity and Distribution Predictions and Application of Economic Limits; and Long-Term Risk Assessment of the Storage Sites. This document will provide an overview of the Geological Characterization Theme and briefly summarize its findings. The complete summary report for the project (Wilson and Monea, 2004) is available for download.

2. Geological Characterization Theme

a) Scope of Investigation

The Geological Characterization theme of the Weyburn Project was one of the largest and most diverse aspects of the study. The overall goal was to evaluate the geological integrity of the Weyburn Oil Pool and the surrounding geosphere for storing injected CO_2 for hundreds to thousands of years. This involved providing a regional geological dataset in which other, more detailed, studies may be placed. More detailed descriptions of the individual research studies within the Geoscience Framework portion of the Weyburn Project are provided in Whittaker *et al.* (2002, 2004), Whittaker and Gilboy (2003), and Whittaker (2004). The regional geological mapping was performed from the Precambrian surface to ground surface across a region 200 x 200 km centred on the Weyburn Field (Haidl *et al*., in press). This area included much of southeastern Saskatchewan and portions of northwestern North Dakota and northeastern Montana (Figure 1). Geological mapping was performed by geologists of SIR and the North Dakota Geological Survey (NDGS), and consulting geologists Patty Thomas, Jim Christopher, Don Kent, and Arden Marsh. Approximately 2000 km of regional 2-D seismic data within this region were processed and examined at the University of Saskatchewan to identify the distribution of faults and fractures within the system. High resolution aeromagnetic data (HRAM) were supplied and interpreted by Gedco of Calgary which greatly aided in establishing a 3-D network of regional fault and subsurface tectonic lineations. J.D. Mollard and Associates (JDM) of Regina performed a detailed surface examination of lineament patterns using airphoto and satellite imagery to determine whether subtle surface features may reflect vertically translated expressions of subsurface structures. Within the regional study, a detailed hydrogeological study of the bedrock aquifers (and aquitards) was undertaken at the University of Alberta to determine controls over subsurface fluid movements including rates, directions, and other physicochemical characteristics (Khan and Rostron, in press). Shallower hydrogeological studies, in Upper Cretaceous, Tertiary, and Quaternary strata, were performed across the extensive region by the Saskatchewan Research Council (SRC). A smaller area was also targeted to develop a detailed geological, or system, model for use in numerical simulations and risk assessments of subsurface CO_2 movement and storage. This area extended about 10 km beyond the limits of the EOR region (see Figure 1). Within this focused area, detailed shallow hydrogeological mapping was performed by JDM. A side-project to delineate more precisely a shallow aquifer that potentially contained potable water near the Weyburn Field, the Weyburn Valley Aquifer, was also undertaken by SRC and JDM. Additional stochastic simulations using the deep hydrogeological data of specific aquifers was performed at the University of Alberta to provide additional information on fluid characteristics for this region. Till samples were collected near the oil field by the SRC and British Geological Survey to assist in the interpretation of soil-gas monitoring studies performed as part of the monitoring aspect of the project (White *et al*., 2004). Detailed geological mapping of the Midale and Frobisher evaporites, the top and bottom reservoir seals, respectively, was performed by researchers at the University of Regina and Don Kent Consulting Geologist Ltd. Special focus was also placed on the Alida Beds, the Lower Watrous redbeds, Colorado Group strata, and the sequence stratigraphy of the Mississippian System in the Williston Basin by researchers at the University of Regina.

b) Results

The Weyburn reservoir, in the Midale Beds of the Mississippian Charles Formation, is at an average depth of 1.5 km and includes an upper dolostone unit, the Marly, with an average thickness of about 6 m, and a lower limestone unit, the Vuggy, that averages around 15 m in thickness (Burrowes, 2001). The Vuggy contains porous grainstones developed along a carbonate shoal which form good-quality reservoir, and low porosity mudstones, interpreted to represent intershoal deposits that are of poor reservoir quality (Figure 2). Most oil production from the Weyburn Pool prior to the CO_2-miscible flood was from the Vuggy shoal regions. CO_2 is currently being injected into the Marly dolostones to access residual oil, although the CO_2 is moving through both the Marly and Vuggy.

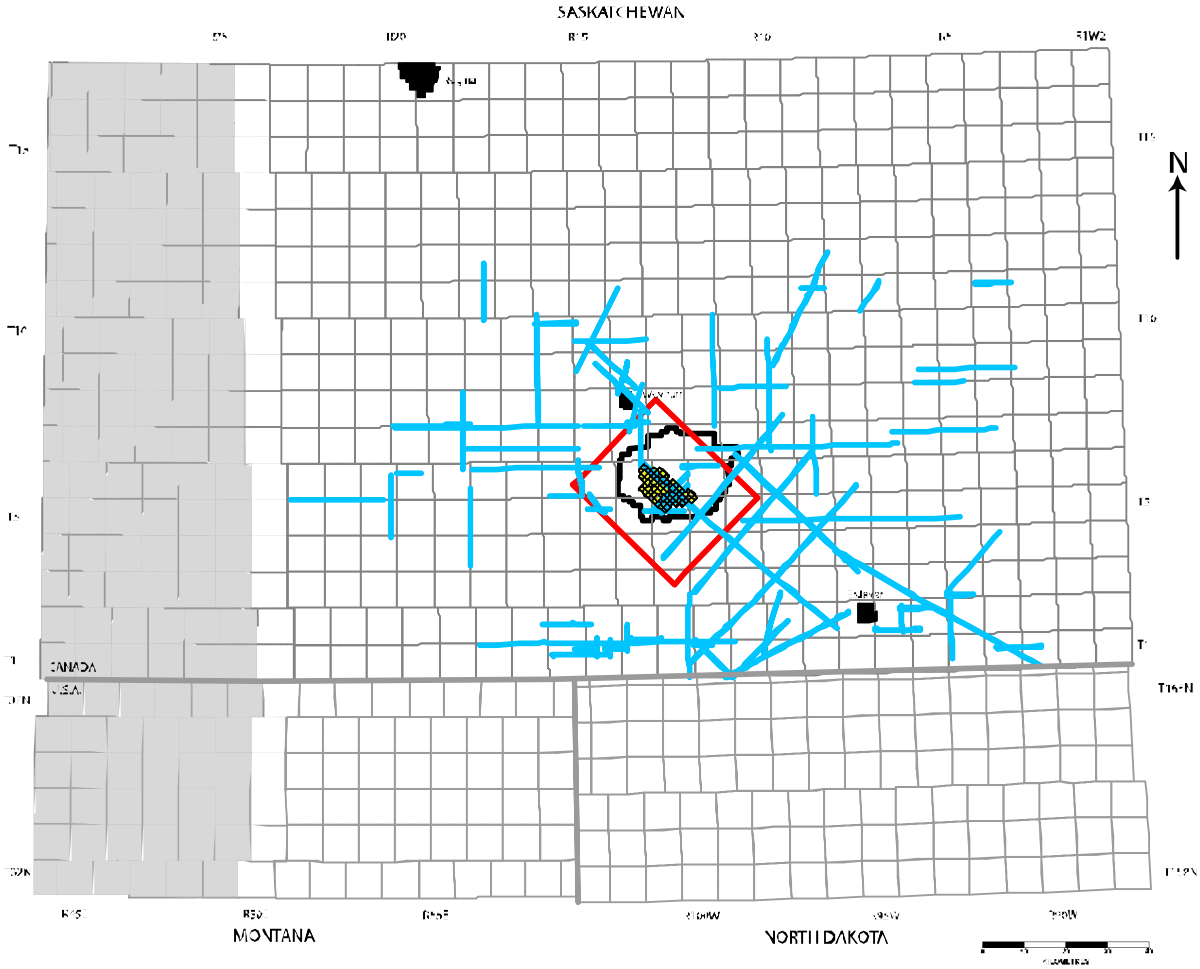

***Figure 1** - Map of the regional study area in the Weyburn Project. The shaded area along the west indicates an extension of the study area in which some hydrogeological mapping was performed. The geological model was constructed for the region outlined by the red rectangle around the Weyburn Field. The area of CO_2-flooding is depicted as the gridded region within the western portion of the field. The locations of 2-D seismic lines analyzed in the study are shown in blue.*

The upper seals to the reservoir are the Midale Evaporite, a highly competent sedimentary anhydrite layer ranging in thickness from one to more than 10 m, and a diagenetic zone in which Midale carbonates have been extensively altered and anhydritized resulting in virtually complete porosity occlusion (Figure 2). This diagenetically altered zone occurs at the up-dip portion of the Midale Beds immediately subjacent the regional Sub-Mesozoic Unconformity. Above the Sub-Mesozoic Unconformity are the relatively impermeable beds of the Triassic Lower Watrous Member that serve as a regionally extensive aquitard across much of southern Saskatchewan. In fact the shaly, anhydritic siltstones of the Lower Watrous Member, or redbeds, arguably form the most important trap for hydrocarbon accumulation in the northern Williston Basin. The Watrous redbeds separate a deep hydrogeological system, which includes the Midale reservoir and essentially all Paleozoic strata, from intermediate and shallow hydrogeological systems. Intermediate (around 1000 to 300 m depth) and shallow systems are much less saline, and have higher permeabilities and faster flowing formation waters than the deep hydrogeological system. Hydrogeological data indicate no evidence for flow across the Lower Watrous Member between the deep and intermediate systems, thus, the Midale Beds are effectively hydraulically isolated from shallower strata. The Watrous aquitard, therefore, is an excellent regional seal for CO_2 injected into the Midale Beds. The Midale aquifer has low flow velocities (<1 m/yr) and mainly horizontally oriented flow which favours hydrodynamic trapping of CO_2 thereby reducing the effectiveness of formation-water acting as a transport agent for CO_2. The Weyburn Pool occurs within a tectonically quiescent region. Although large-scale regional fractures and faults are present in the larger region, most faults observed are mainly localized disturbances without recognizable offset. Regionally extensive faults that may occur within the vicinity of the Weyburn Pool also exhibit limited offset and have not compromised hydrocarbon retention for the past 50 million years. Therefore, such faults are considered to be closed and likely do not represent fast pathways for CO_2 movement within the subsurface.

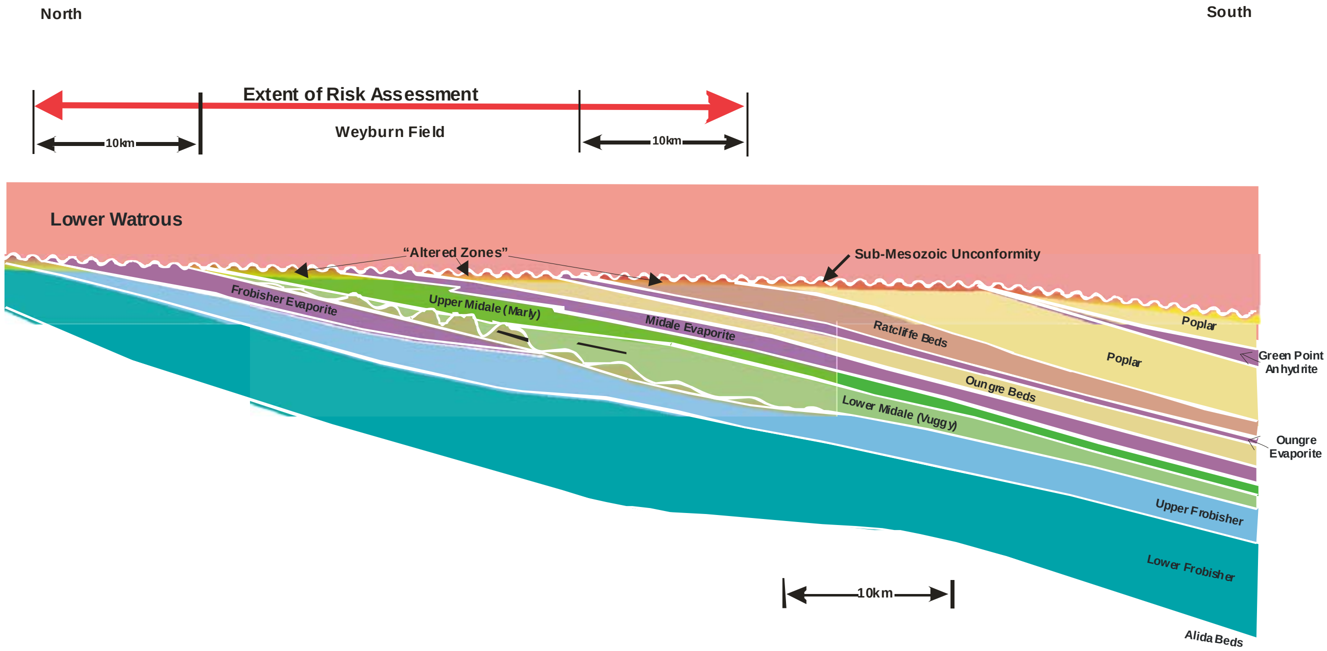

Figure 2 - Diagrammatic north-south cross section through the Weyburn Pool. The section shows the truncation of inclined Mississippian strata at the Sub-Mesozoic Unconformity. The Midale and Frobisher Evaporite beds, both sedimentary anhydrite units, act as seals for the porous carbonate rocks of the Midale reservoir. The Midale Evaporite is present across most of the Weyburn Pool; the Frobisher Evaporite is absent beneath the southern portion of the pool. The altered zones immediately below the unconformity are locations where diagenesis has severely reduced porosity through anhydritization and micritization in carbonates; these zones also are very important seals in the system. The Triassic Lower Watrous Member, which overlies the unconformity, is also an important primary seal for Mississippian reservoirs. Also shown on this cross section are the upper dolostone (Marly) and lower limestone (Vuggy) reservoir units.

A detailed 3-D geological model was constructed using the data obtained from the above studies. This model includes the geometry of the geological formations grouped into hydrostratigraphic units. Each hydrostratigraphic unit represents a rock package that acts mainly as an aquifer or as an aquitard (Figure 3). In the model, the units are populated with data such as porosity, permeability, salinity, temperature, pressure, and additional information where available. Also included in the model is a projected fault plane, the Souris Valley Fault, identified in this study. The depth of the model extends from ground surface to the base of the Tilston Beds, and the areal extent is 10 km beyond the limits of the CO_2 flood as described previously. This model served as the foundation for detailed numerical risk and performance assessment.

Results involving numerical reservoir simulation and history matching indicate that approximately 23 MT CO_2 will remain in the reservoir at the expected end of EOR operations in 2033 (Law *et al*., 2004). This is determined considering only the 75 patterns currently planned for EOR that involves only the western portion of the Weyburn Field. The driving force behind this project is, of course, that an additional 20.7 x 10^6 $m^3$of oil are also expected to be recovered by this process. Were CO_2 injection to be continued after the cessation of EOR operations to maximize CO_2 storage, however, it may be possible to store almost 55 MT CO_2 in the Weyburn reservoir (again, considering only the 75 patterns). Risk and performance assessment modeling performed to determine the long-term fate of the injected CO_2 indicates that no CO_2 will migrate above the caprock (*i.e.*, Midale Evaporite) in 5,000 years (Chalaturnyk *et al*., 2004). Approximately 27% of the CO_2 may migrate beyond the limits of the EOR region; of this about 18% moves into the underlying Frobisher Beds, 9% moves laterally within the Midale Beds, and around 0.02% will diffuse into, but not above, the Midale Evaporite. Numerical modeling of risk and performance of long-term subsurface storage of CO_2 is still in its early stages of refinement and the Weyburn results are among the first ever to be determined relative to an actual injection site using real field data. It is noteworthy that these results are supported by the geological investigations that also indicate that the Weyburn Pool is a suitable and secure location for the long-term subsurface storage of CO_2.

Additional studies that may be performed in the second phase of investigations include determining the nature of regional and smaller-scale faults with respect to their likelihood of serving as preferential pathways for CO_2 migration, the petrophysical character of shales and their ability to serve as seals to CO_2, detailed hydrogeological modeling, and improving on the geological models through increased petrophysical and geostatistical property attribution beyond the reservoir itself.

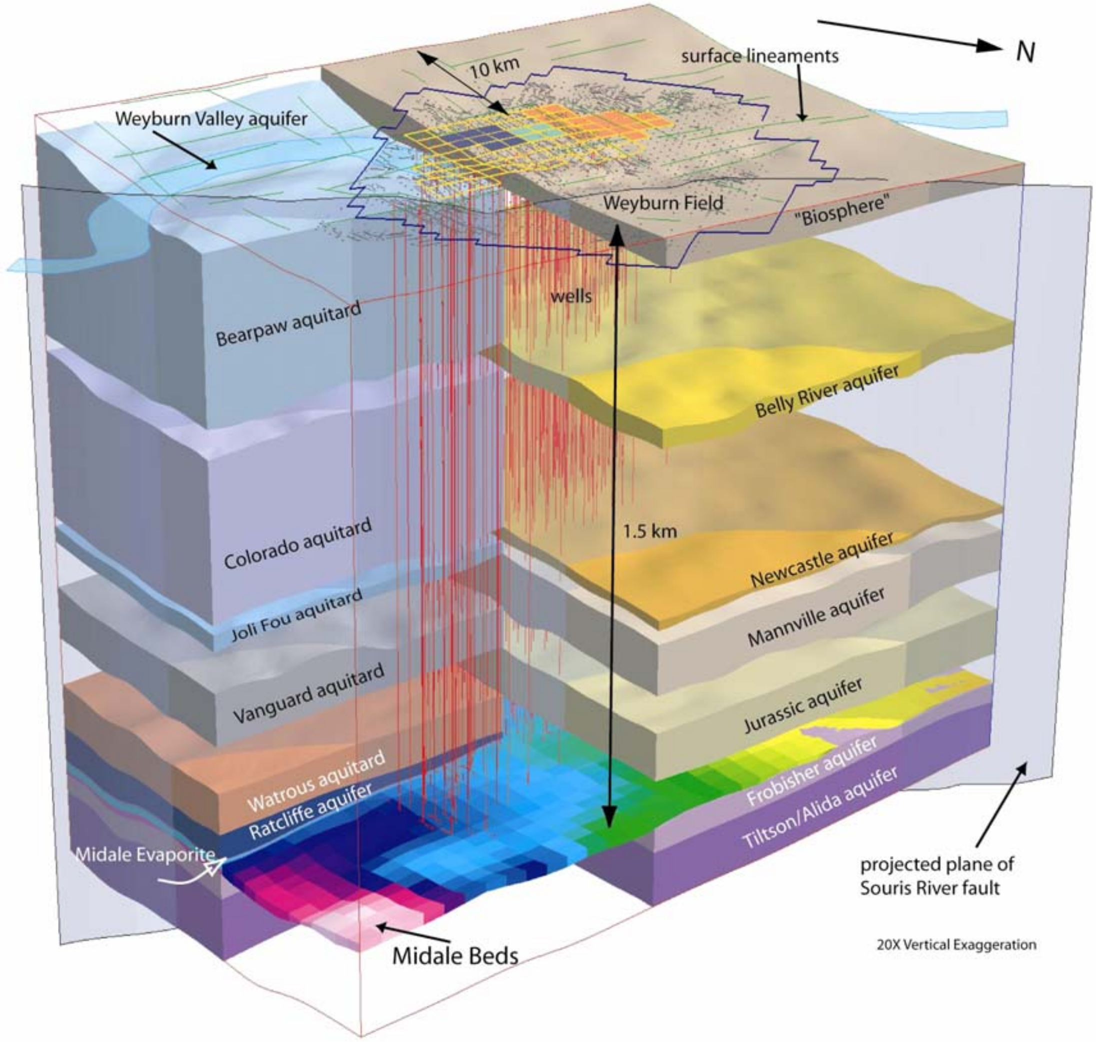

Figure 3 - Cutaway block diagram of the geological model developed for the Weyburn Project. The model depicts the major hydrostratigraphic units; on the left are aquitards and on the right are aquifers. The yellow grid on the ground surface indicates the area planned for CO_2 injection, with field areas already undergoing CO_2-flooding shown as filled colours. Lineaments identified from satellite images and airphotos are presented as green lines on the surface, and the location of the shallow Weyburn Valley aquifer is also shown. The colour variations in the Midale Beds represent variations in salinity within this aquifer. All layers in the model are similarly populated with various property data. The plane of the Souris Valley Fault is shown for reference. The System Model used in risk assessment contains information regarding anthropogenic features such as wells, and pressure and fluid distribution related to oil-production methods.

3. Summary

Detailed geological characterization was performed to assess the geosphere encompassing the Weyburn Pool area regarding its suitability for long-term geological storage of CO_2. The characterization included regional and detailed geological mapping, hydrogeological studies, regional geophysical investigations including seismic and HRAM, and remotely sensed imagery studies. A detailed 3-D geological model was constructed from much of these data for use in numerical risk and performance assessment. The results from these and other studies conducted as part of the IEA Weyburn Project indicate that up to 23 MT CO_2 will remain in the reservoir at the end of EOR operations and that this CO_2, which otherwise would be vented to atmosphere, will remain securely stored within the geosphere for more than 5,000 years. Investigations into the geological characterization of the region and rigorous numerical modeling have each indicated that the Weyburn Pool is a highly suitable location for long-term geological storage of CO_2.

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