Investigating Geological Storage of Greenhouse Gases in Southeastern Saskatchewan: The IEA Weyburn CO2 Monitoring and Storage Project

Steve Whittaker


Abstract

The potential of storing greenhouse gases in geological formations in the northeast portion of the Williston Basin is being investigated by researchers involved in the IEA Weyburn CO2 Monitoring and Storage Project. This project is linked to a CO2 miscible flood EOR program operated by EnCana Corporation in the Weyburn Midale Pool of southeastern Saskatchewan. A major component of the project is to assess the integrity of the geological system through the construction of a geological framework in a 200 x 200 km region around the Weyburn Field. A multidisciplinary approach was required that involved stratigraphers, hydrogeologists, geophysicists, geochemists, and specialists in remote sensing imagery analysis. Strata were examined from the Precambrian basement to ground surface to identify the principal trapping mechanisms and flow characteristics within this part of the basin and to determine their impact on the potential for long-term storage of CO2. A geological model of an area extending 10 km beyond the limits of the EOR region was constructed for use in risk and performance assessment. In total, over 175 individual products were produced in the geoscience framework task area resulting in a world-class dataset for study towards geological characteristics of the Williston Basin.

Keywords: Williston Basin, CO2 sequestration, geological storage of greenhouse gases, Weyburn Field, Midale Beds, IEA Weyburn Monitoring and Storage Project.

1. Project Overview

The International Energy Agency (IEA) Weyburn CO2 Monitoring and Storage Project is a research program launched in July 2000 to study geological storage of CO2 within the Mississippian Midale reservoir of the Weyburn Oil Field, southeastern Saskatchewan. The Petroleum Technology Research Centre (PTRC) of Regina is coordinating the overall project through cooperation with EnCana Corporation, which operates the Weyburn Midale Pool and is injecting CO2 into the reservoir as part of a miscible flood enhanced oil recovery scheme. In September 2000, PanCanadian Energy (now EnCana Corporation) initiated the first phase of the CO2 flood in 19 inverted nine-spot patterns that by March 2004 had expanded to 32 patterns. During the next four years, the CO2 flood will be expanded into a total of 75 patterns. Anthropogenic CO2 is purchased from the Dakota Gasification Company’s synthetic fuel plant in Beulah, North Dakota and transported to the Weyburn Field through a 320 km pipeline. The CO2 is more than 95% pure and is being injected into the reservoir at a rate of 3 x 10^6 m^3 per day (105 mmscfd) along with an additional 0.7 x 10^6 m^3 per day (25 mmscfd) of recycled and associated gas. Approximately 22 million tonnes of CO2 will ultimately be injected into the reservoir over the project life with a net potential storage of about 15 million tonnes CO2 which otherwise would have been vented to atmosphere. As of March 2004, 3 x 10^9 m^3 (98 BCF) of CO2 had been injected into the reservoir.

The viability of storing CO2 securely in the subsurface for hundreds to thousands of years is the primary focus of the research project as geological storage is generally considered the safest and most practical method for reducing emissions of CO2 and other greenhouse gases into the atmosphere (e.g., Gale, 2002). Issues generic to geological storage and specific to the Weyburn site being addressed in this project include: a) determining the main factors influencing CO2 distribution within the reservoir, b) monitoring CO2 movement in the subsurface, c) identifying factors that contribute to containment, and d) assessing the amount of CO2 that can be considered to be permanently stored. Also being evaluated are economic variables associated with storage projects that can be applied to EOR situations or non-EOR scenarios such as CO2 storage within saline aquifers. Results from these studies can be tailored to apply to many sedimentary basins worldwide and may ultimately be used by regulatory bodies to develop policy guidelines regarding the security of geological CO2 storage. In addition, the techniques and knowledge

---

1 Funding provided by numerous government and industry sponsors coordinated through the PTRC of Regina.
gained from this project can be used to develop screening methods for selecting and designing future CO₂ storage sites.

Funding for the monitoring and storage project is provided by fifteen sponsors including Saskatchewan Industry and Resources, Natural Resources Canada, the United States Department of Energy, the Alberta Energy Research Institute, the European Community, and 10 industrial sponsors in Canada, the U.S., and Japan. More than 20 research and consulting organizations are performing research within this study. Phase I of the research project is scheduled to be completed by June 30, 2004. A second phase is being considered to continue and ultimately conclude the investigations. Such a large and diverse project has necessitated significant organization including the division of research into eight Principal Tasks as shown in Figure 1. These Principal Tasks are further sub-divided into more than 70 subtasks indicating the significant undertaking involved to coordinate work plans and integrate results. This summary will focus on work performed within the Geoscience Framework Principal Task (Task 2 of Figure 1).

2. Geological Characterization

a) Objective

The main objective of the geological framework task is to assess the integrity of the geological container encompassing the Weyburn Unit for effective long-term storage of CO₂. This objective has been addressed through characterization and delineation of primary and secondary trapping mechanisms and the identification of potential pathways for preferential CO₂ migration. Much of this work was performed in a region extending 200 x 200 km centred on the Weyburn Field (Gilboy et al., 2001; Whittaker and Rostron, 2003). Data generated during these assessments were also used to develop a 3-D geological model that includes features and properties of strata within an area extending 10 km beyond the CO₂ flood extent. This model is used as the framework for a formal risk assessment of the long-term fate of CO₂ injected into the subsurface at Weyburn (Figure 2), which is one of the primary goals of the entire project. In developing this model, however, over 175 individual deliverables were produced by researchers working within all aspects of the geoscience framework.
In total, 11 subtasks were active in the geoscience framework task, and involved about 40 researchers. Regional geological mapping was performed jointly by the North Dakota Geological Survey (NDGS), Saskatchewan Industry and Resources (SIR), and consultants working for PTRC. Detailed geological studies of specific units were undertaken at the University of Regina and by the Bureau de recherches géologiques et minières, France (BRGM). Hydrogeological investigations were coordinated through the University of Alberta (UA). Investigations into the deep basin hydrogeological aspects of the project were performed by the UA, whereas shallow hydrogeological studies were conducted by J.D. Mollard and Associates (JDM) of Regina and the Saskatchewan Research Council (SRC). Regional seismic studies involved researchers at the University of Saskatchewan with contributions from Gedco of Calgary which also provided interpretations of HRAM (High Resolution Aeromagnetic) data. Integrated into the geophysical studies were surface lineament analyses by JDM who also provided guidance for planning soil gas surveys conducted by the British Geological Survey (BGS), BRGM, and the Instituto Nazionale di Geofisica e Vulcanologia of the University la Sapienza Roma, Italy (INGV). In addition, a study was conducted on the natural occurrence of CO$_2$ in the subsurface of the western Saskatchewan portion of the Williston Basin. Fourteen cores from several Mesozoic and Paleozoic formations were also collected and preserved for future geomechanical and petrophysical studies in the Weyburn area.

b) Geological Framework

A geological framework was constructed for a region extending 200 x 200 km around the Weyburn Field that includes portions of Saskatchewan, North Dakota, and Montana. A fundamental aspect of this construction was the picking of over 130 stratigraphic units from the Precambrian basement to surface, incorporating about 100 000 km$^3$ of sedimentary rocks in the study block. It was determined that large-scale studies such as this are needed to effectively reveal basin hydrogeological flow characteristics and the tectonic framework that can greatly influence depositional patterns of sedimentary packages and fracture development. More detailed studies were focused on an
area that extends 10 km beyond the limits of the CO₂ flood and for which a system model was developed for use in risk assessment (Figure 2).

Reservoir

The Weyburn Pool is 180 km² in area having about $225 \times 10^6$ m³ ($1.4 \times 10^9$ bbls) original oil in place in the Midale Beds of the Mississippian Charles Formation. The pool was discovered in 1954 and placed on water flood during 1964 (El Sayed et al., 1993). Infield drilling and an aggressive horizontal drilling program during the 1990s temporarily reversed a trend of declining production. It is expected the CO₂ miscible flood program will extend the life of the pool by approximately 25 years and result in production of an additional $20.7 \times 10^6$ m³ ($130 \times 10^6$ bbls) of oil. The Midale reservoir is composed of two main layers: an upper, low-permeability chalky dolostone unit locally known as “Marly” and a lower, more permeable and fractured limestone unit termed “Vuggy”. Detailed geological descriptions of the Weyburn Reservoir can be found in Wegelin (1984) and Burrowes (2001).

Most production prior to the CO₂ flood focused on the Vuggy layer, but CO₂ is currently being injected mainly into the Marly layer with the miscible sweep considered to be recovering oil from both units. To the end of February 2004, incremental oil recovery attributable to the CO₂ flood was $530$ m³ (9000 bbls) per day. EOR efforts are focused mainly in the western half of the Weyburn Pool where reservoir conditions are best. Although high-quality Midale Bed reservoirs are found both east and west of the Weyburn Pool, in general, reservoir quality diminishes laterally outward from the main EOR area. This is an important factor in assessing long-term subsurface storage of CO₂. Figure 3 outlines some of the bounding conditions present in the vicinity of the Weyburn Pool.

Regional Geological Mapping

Regional geological mapping is necessary to establish a consistent geological dataset to form the framework for all other regional and more focused geoscience investigations regarding long-term CO₂ storage. The regional mapping component involved identifying more than 130 stratigraphic units from basement to surface mainly through

Figure 3 - Bounding conditions of the Mississippian Midale Beds of the Weyburn Unit as shown in plan view. To the north of the Weyburn Pool, the Midale Beds are truncated along the Sub-Mesozoic Unconformity where extensive porosity reduction has occurred through diagenetic processes. South (down-dip) of the pool reservoir quality is poorer and the rocks are generally water charged as indicated by the shaded (light brown) region. West of the EOR region, the carbonate facies include more poor quality intershoal areas and may have variably higher water saturations in the pink shaded area. East of the EOR area, reservoir quality may diminish somewhat, but overall facies are broadly similar to, and show considerable lateral continuity with, the Weyburn reservoir. RA, Risk Assessment.
geophysical log interpretation, but also using core studies where necessary and where material was available. Geological structural and isopach maps were constructed for all units and were primarily computer generated with minimal editing. To develop the geological framework, the mapping efforts were sub-divided into the following sedimentary packages: Lower Paleozoic (Cambrian through Silurian), Devonian, Mississippian, and Mesozoic.

Lower Paleozoic Mapping

Lower Paleozoic mapping led by Fran Haidl and Andrew Nimegeers of SIR and Paul Diehl of NDGS, focused on the major aquifer and aquitard units, and also identified and mapped some thin discontinuous evaporite units. These units have significance not only in unraveling basin history, but may be important in revealing information regarding deep-basin flow and locations of subsurface dissolution. Both processes are fundamental in developing subsurface traps.

Devonian Mapping

Along with delineating the major aquifers and aquitards, mapping of Devonian strata led by Randy Burke (NDGS), Kim Kreis (SIR), and Patty Thomas (PTRC) was also focused on highlighting regions showing preferential salt removal or salt absence. These regions often exhibit a spatial relation with underlying tectonic features identified through the geophysical component of this project. Salt removal was a fundamental consideration through this project as this process may produce collapse features in overlying strata that potentially may result in crossformational fluid flow. For example, beneath the Weyburn Pool an estimated thinning of nearly 30 m in the Prairie Evaporite suggests a possible zone of dissolution. This thinning was, however, compensated by thicker deposits of later Devonian and early Mississippian age indicating all dissolution occurred prior to reservoir formation. Regions of dissolution may be significant in forming regional traps as is likely the case for natural CO2 accumulations in western Saskatchewan. Kreis et al. (2003) contains many of the Devonian maps of this project, although these will be superceded by a series of maps to be published in 2004.

Mississippian Mapping

Mississippian strata encompass both the aquifers into which CO2 is being injected and also the primary seals for containing the CO2. The importance of this stratigraphic series is such that over 1700 wells were examined to create the Mississippian maps. This subtask was led by Don Kent and Patty Thomas (PTRC) and Tom Heck (NDGS). The Mississippian units mapped include the Souris Valley Beds, Tilston Beds, Alida Beds, Kisbey (K2) Marker, Frobisher Beds, Frobisher Evaporite, Midale Beds, Midale Evaporite, Oungre Unit, Oungre Evaporite, Greenpoint Anhydrite, Poplar Beds, and the Big Snowy Group. Away from the reservoir, the Midale Beds were mapped as upper Midale Beds and lower Midale Beds as the terminology marly and vuggy is not reflective of their character. Significant among the products of the mapping task is the revision of the Mississippian subcrop maps for the northeastern portion of the Williston Basin (Figure 4). Within the Mississippian interval, the influence of basement features on depositional patterns is more subtle than observed in both underlying and overlying stratigraphic packages. There was also considerable difficulty in carrying some stratigraphic units from the shallower shelf settings in the north to the deeper basin environment in the southern part of the mapping area. Kent et al. (this volume) discuss the results of the Mississippian mapping exercise in more detail.

Mesozoic Mapping

The Mesozoic units are significant in this region in that they contain the most important regional barriers to vertical fluid migration and also include the aquifers having the greatest transmissivity. Prior to this project, Mesozoic strata in the study region had, however, been far less well studied than the deeper strata in the basin. Mapping resulting from this study that was led by Jim Christopher (PTRC), Julie LeFever (NDGS), Melinda Yurkowski (SIR), and Arden Marsh (PTRC) has considerably refined the stratigraphy and our understanding of depositional controls in this sequence of rocks. The identification of a major depositional break, the sub-Pierre Shale unconformity, one of four major unconformities in the Mesozoic succession, and of numerous examples of deeper structural features influencing depositional patterns in overlying rocks has been particularly significant. Shales are the dominant lithology in the Mesozoic succession in terms of thickness and extent. The Mesozoic package becomes increasingly indurated with depth, which, above the Weyburn Pool, reaches about 1350 m. Aquitards include the Lower Watrous Formation, Colorado Group, and the Pierre (Bearpaw) Formation that are regionally extensive and form major barriers to vertical fluid migration. The major regional aquifer in the region is the Cretaceous Mannville Formation. Sandstones of the Newcastle Formation are also relatively extensive, but are encased within the thick shales of the Colorado Group, and were the focus of a more detailed study within the project by Hasan Ferdous (U of R). Less extensive sandstones (aquifers) are present in the Jurassic Shaunavon and Gravelbourg formations mainly east of the Weyburn Field. Argillaceous sandstones are also scattered within the Upper Cretaceous Lea Park and Belly
Figure 4 - Map of the structural surface of the Sub-Mesozoic Unconformity showing the subcrop locations of the major Mississippian units in the region. The subcrop lines are labeled at the zero edge of the respective units. The rectangular area around the Weyburn Field outlines the area of Risk Assessment.
River formations. Christopher and Yurkowski (this volume) discuss interpretations of Mesozoic geology based on this work in more detail.

### Detailed Geological Investigations

Focused geological studies on specific units using geophysical logs, core study, petrography, stable isotope geochemistry, and fluid inclusion analysis were performed by a group at the University of Regina led by Hairuo Qing. Research includes assessment of the integrity of the primary geological seals of the Weyburn Pool and evaluation of heterogeneities in some of the overlying aquifers. Primary seals include the Midale Evaporite, the Frobisher Evaporite, an altered zone at the subcrop of the various Mississippian units in southeastern Saskatchewan, and the regionally important Lower Watrous Formation. The spatial relation of these units to the Midale Beds is shown in Figure 5.

**Midale Evaporite**

The Midale Evaporite is a 5 to 11 m thick succession made up of laminated to massive anhydrites at its base grading to nodular and chicken-wire anhydrites at its top; dolostone interbeds are scattered throughout. Based on its dominantly layered texture the Midale Evaporite is considered to have formed within a salina setting. Fractures are present in the Midale Beds, but are rare in the Midale Evaporite in which they are mainly interpreted to be synsedimentary (Nickel and Qing, this volume). Sulphur isotope measurements of the primary Midale Evaporite anhydrites are similar to isotope values indicated for Mississippian seawater, which further suggests that limited

---

**Figure 5** - Cross section (north-south) through the Weyburn Pool (see Figure 3) showing the distribution of sealing units associated with the study. The primary sealing units are the Midale Evaporite, the altered zone, the Frobisher Evaporite, and the Lower Watrous Formation. The Midale Beds consist of an upper dolostone unit (Marly) into which CO₂ is currently being injected, and a lower limestone unit (Vuggy) from which most oil production was previously obtained. o/w, oil-water contact.
interaction occurred between post-depositional fluids and the Midale Evaporite, which appears to have been a highly effective seal to hydrocarbon migration for the past 50 million years.

**Frobisher Evaporite**

The Frobisher Evaporite forms a lower seal to the Weyburn reservoir and has a more nodular texture than the Midale Evaporite. The nodules are often separated by dolomicrite or argillaceous dolostone, a feature suggestive of this unit’s sabkha origin. The Frobisher Evaporite is generally not fractured, although the nodular character makes it slightly more prone to small-scale fractures than is the Midale Evaporite. In addition, the more common presence of dolomicrite between nodules suggests the Frobisher Evaporite may be potentially more susceptible to fluid migration as some core samples exhibit oil staining. The Frobisher Evaporite is absent beneath the southern portion of the Weyburn Pool.

**Altered Zone**

A diagenetically altered zone occurs in the subcrop region of the Poplar, Ratcliffie, Midale, Frobisher, and Alida beds throughout the Weyburn area and much of the rest of southeastern Saskatchewan. This zone, which ranges in thickness from 2 to 10 m immediately subjacent the Sub-Mesozoic Unconformity surface, shows almost complete porosity occlusion resulting from a complex process of micritization, dolomitization, and anhydritization, and that has made it a highly effective seal to fluid migration. Fluid inclusion studies have shown this diagenetic seal was in place prior to oil migration.

**Lower Watrous Formation**

The Lower Watrous Formation generally has very low permeability and forms the most extensive primary seal to vertical fluid migration in the vicinity of the Weyburn Pool and is an important trap for many of the Mississippian oil pools of southeastern Saskatchewan. Restricted fluid migration into the Lower Watrous has been observed elsewhere within the basin, usually in locations where an evaporite layer or altered zone is not present in the underlying Mississippian unit. Although the Lower Watrous is most porous in the lowermost section where porosities have been measured up to 11% (although they are generally lower than this), the effective porosity is considerably less at around 1%. Stratigraphically higher in the Lower Watrous, porosity is even further reduced. The Lower Watrous siltstones can be informally sub-divided into a lower interbedded sandstone-siltstone unit and an upper interbedded siltstone-mudstone unit, but in general it has a mixed lithology character. Constituent grains are mainly of granitoid origin with micrite lithoclasts in an argillaceous dolomitic matrix where clay content rarely exceeds 40%. Cements are generally dolomicrosparite and anhydrite, which commonly replaces carbonate and occludes porosity. The clays are mainly interstratified smectite/chlorite with illites also common.

**Colorado Group**

The Cretaceous Colorado Group is a thick succession mainly made up of regionally extensive aquitards including the Belle Fourche, Fish Scales, Westgate, and Joli Fou formations. Also within the Colorado Group is the Newcastle aquifer which has been observed to contain microfractures that may be lined by hydrocarbons. In the Weyburn region, the Newcastle Formation is mainly a fine-grained sandstone to siltstone present in three separate, stacked units each having a relatively continuous sheet-like distribution. The aquitards effectively entomb the Newcastle, limiting its effectiveness as a significant conduit for fluid migration.

**Hydrogeological Investigations**

Hydrogeological investigations are an essential component of any study into the subsurface storage of CO₂ to characterize the ambient or natural hydraulic setting of the appropriate region. They provide data about fluid flow within the deep hydrogeologic regime that are required to construct the geological model used in risk assessment. Shallow hydrogeological investigations are used to identify and delineate the distribution of potable and other shallow aquifers in the region for use in baseline studies.

**Deep Hydrogeological Studies**

For the system below about 300 m depth, mapping of hydrogeological parameters such as total dissolved solids, fluid pressures, and temperatures placed the geological succession within a hydrostratigraphic framework by delineating the major aquifers and aquitards in the area. From these data, the degree of density-driven flow was determined along with the flow patterns and flow rates within the major aquifers. This work is also used to determine the possible presence of cross-formational flow through the construction of hydraulic cross-sections, and
to assess the competence of aquitards as confining strata. For this project, all major aquifers have been mapped for variations in total dissolved solids, fluid pressure, hydraulic head, and temperature throughout the region. In addition, stochastic simulations were performed using drill-stem test data to provide permeability realizations for use in performance assessment.

A significant finding of the University of Alberta hydrogeological group led by Ben Rostron is that a deep hydrogeological regime is separated from an upper hydrogeological regime by the Watrous aquitards. This further indicates the effective sealing capacity of the Watrous Formation and the suitability of the Weyburn site for long-term geological storage of CO₂.

**Shallow Hydrogeological Studies**

Detailed mapping of surficial and shallow deposits including aquifer distribution was led by Jason Cosford (JDM) within a 3 x 3 Township area around the Phase 1a injection region. The entire nine-township area of study is underlain by Quaternary glacial drift except for some local exposures along eroded creek edges. Drift thickness can be up to 70 m over pre-glacial valleys in the area. Maps and numerous cross-sections including hydrochemical and hydrological data indicate that the intratill and intertill aquifers are generally isolated, thin, and occur at various depths within the till. Bedrock in the region consists of interbedded shales, siltstones, and sandstones of the Upper Cretaceous Bearpaw (Pierre), Eastend, Whitemud, and Frenchman formations and the Lower Tertiary Ravenscrag Formation. Bedrock aquifers are found only within sandy units of the Ravenscrag and Frenchman formations. These formations are underlain by the Bearpaw aquitard that serves as a barrier to groundwater movement due to its low hydraulic conductivity. In addition to the aquifer studies, surface maps were produced depicting the geological landforms, soil deposits, and salinity variations.

Shallow hydrological research led by Harm Maathuis (SRC) to characterize groundwater resources between ground surface and top of the Bearpaw Formation (Pierre Shale) was also performed in the larger study region. This work involved developing a digital topographic base map and compiling a comprehensive database of water quality, water level, and withdrawal data from Saskatchewan, North Dakota, and Montana. Maps constructed include the drift thickness, extent of the Empress Group, extent, thickness, and top of the Eastend and Ravenscrag formations, and the top of the Pierre Shale/Bearpaw Formation. In general, regional groundwater flow is controlled by topography and is ultimately focused toward the Estevan Valley aquifer system that is the major aquifer system in the study area. In the western portion of the study area, groundwater flow may be directed more towards the Yellowstone and Missouri pre-glacial channels, which are two of the four channels making up the Estevan Valley aquifer system.

During the shallow hydrogeological investigations, it was determined that the spatial distribution of a buried pre-glacial channel occurring near the injection area, the Weyburn Valley, needed to be further delineated. This project was coordinated by SRC with assistance by JDM and involved using electrical resistivity tomography (ERT) geophysical surveys to locate the main channel body and a 12-well drilling program to place test holes and monitoring wells. This aquifer had been well defined in the vicinity of the City of Weyburn, but its connectivity with the Estevan Valley aquifer system was uncertain. The Weyburn Valley has been found to be 1.4 to 4 km wide and likely has an upper and lower unit having a variable total thickness less than 30 m. A transmissivity barrier appears to exist between the Weyburn Valley aquifer and the Estevan Valley to the south. Water from the Weyburn Valley aquifer is not considered potable.

A study of till characteristics was also coordinated through SRC in conjunction with the BGS to examine variations in U and Th bearing minerals in till as the probable source for variations in thoron (²²⁸Rn) and radon (²²²Rn) contents in soil gas that had been identified through routine surveys performed by the BGS, INGV, and BRGM. Four continuous cores of the glacial deposits were obtained by the SRC and measured for water content, carbonate, grain-size distribution, whole-rock geochemistry, and trace-element concentrations (Maathuis, 2003). The BGS examined 24 samples for palynology, particle size, clast composition, mineralogy of the till matrix, gamma spectroscopy, heavy minerals, and U and Th geochemistry (Pearce et al., 2004). All samples contained well preserved palynomorphs of Devonian, Carboniferous, Late Cretaceous, and Quaternary age. Late Cretaceous dinoflagellate cysts and pollen grains are the dominant elements, indicating that the principal sedimentary input to the till is from Upper Cretaceous (Campanian-Maastrichtian) units with Devonian, Carboniferous, and Quaternary grains being subordinate (Riding, 2004). Heavy mineral contents are generally very low in the tills (<1%) with U-bearing minerals such as zircons being present in most samples along with trace amounts of monazite grains. Uranium may also be sorbed onto Fe- and Mn-oxides or associated with clay minerals.
Geophysical and Remote Sensing Studies

Regional Seismic Investigations

Approximately 2000 km of digital 2-D multifold seismic reflection data were processed by researchers at the University of Saskatchewan led by Zoltan Hajnal. These data were used to further investigate the subsurface structural configuration around the Weyburn Pool. In particular, seismic data are essential to elucidate subsurface discontinuities such as faults and fractured zones that potentially represent fast pathways for fluid migration. In addition, these data reveal considerable information regarding the basement tectonic features that influence depositional patterns in the overlying aquifers and aquitards. The influences of basement features on overlying strata are suggested to be reflected in regions of salt dissolution in the western part of the study region and many depositional and structural characteristics of Mesozoic strata overlying the Weyburn Pool.

Processing these data presented many challenges as the extensive region examined required a comprehensive near-surface static correction process to be applied. In addition, the different energy sources used to generate the seismic signal in the various datasets forced an integrated wavelet analysis. The resultant data are being used to generate structural and isopach maps to augment the regional geological mapping, particularly in areas lacking well control. Attempts are also being made to use seismic wave characteristics to generate porosity maps for specific geological intervals.

HRAM Investigations

High-resolution aeromagnetic data interpreted by Serguei Goussev of Gedco (Calgary) proved helpful in recognizing the spatial distribution of fractured zones and faults in the sedimentary section. HRAM data reveal structural trends across broad regions and provide an indication of the structural grain or fabric of the area. Because seismic lines used in this project tend to be widely spaced, correlation of faults from one line to another is difficult. By integrating filtered HRAM data with the seismic information, however, fault correlation is more accurate, and interpretations can be made regarding the 3-D orientation of faults and fractures. Such an integration was performed using 22 seismic lines provided by the University of Saskatchewan in a region approximately 100 x 100 km centered around the Weyburn Field.

Remotely Sensed Imagery Analysis

Airphoto and LANDSAT satellite imagery were used by Lynden Penner (JDM) to identify surface lineaments in the Weyburn study area that are considered to most likely overlie subsurface faults, fractures or other structural discontinuities. Through extensive comparison of the spatial relation of lineament zones with features on structural and isopach maps of geological units from basement to surface, a numerical rating scheme was developed to identify those lineaments considered most likely reflective of an underlying structural component. In addition, coincidence of lineaments with seismically identified structural discontinuities indicated a strong probability of their being genetically related. Together with seismic and HRAM data, surface-lineament orientations provided another means of interpreting 3-D orientation of faults and fractures. Integration of these three data sets has resulted in the identification and refinement of several basement features that are interpreted to extend upward through the sedimentary succession and which are ultimately expressed at the surface. Although the potential for enhanced transmissivity of fluids through the structures is uncertain, these features are still an important consideration in assessing geological sites for long-term storage of greenhouse gases. One such identified discontinuity, the Souris Valley Fault, is included in the geological model used for risk assessment.

Geological Synthesis (Figure 6)

Integration of geological information generated by the above studies is necessary to provide a credible assessment regarding the security of the Weyburn Pool for the long-term storage of CO₂. Although no formal definition of “long-term” for storage of greenhouse gases has been established, it is generally considered to represent a period of hundreds to several thousands of years. Within the IEA Weyburn Project, long-term assessment is being considered for the period of 5000 years. To do this, formal risk assessment techniques are being applied using both probabilistic and deterministic methods. Both methods require a robust geological model on which to base their assessment model. The geological model was constructed using Gocad geological modeling software and populated with properties and data provided by the many researchers involved in the geoscience framework task and in other principal tasks. The current model is designed to be input into a numerical flow simulator for deterministic risk assessment. The model can, however, be tailored for requirements by different assessment techniques and scenario evaluations.
Figure 6 - Depiction of the geological system assessed in the IEA Weyburn Project. The model used in risk assessment contains information regarding the structural geometry, porosity, permeability, pressure, and flow characteristics of major aquifers and aquitards. The Mesozoic and Upper Mississippian hydrostratigraphic units are shown on the diagram, as are arrows depicting the regional hydrogeological flow direction within the aquifers. Aspects of the system also considered include surface features such as lineaments and rivers, shallow hydrogeological characteristics, well distributions, and production history. A polygon shows the approximate region where detailed investigations were conducted surrounding the EOR region.

Data requirements were identified during the early stages of the project, and were amended and modified during the course of the study. Integration was required and occurred at every stage of the project and involved linkages among most subtasks. Integration meetings involving researchers of the geoscience task were held twice yearly, as were Project Control and Sponsor’s Meetings involving all researchers from all tasks. These four annual meetings were necessary to focus research efforts, discuss results, and to identify linkages and gaps in research. Additional meetings and conference calls were an ongoing part of the integration effort.

Although the geological model was a specific output required from the geoscience framework group for this project, the more than 175 individual products generated by this group during this project will ultimately provide a tremendous amount of information for the geological community in general. Moreover, this project is serving as a template for present and future geological mapping projects that span several jurisdictions and cover extensive areas such as described by Kreis et al. (this volume).

3. Summary

The geological setting of the Weyburn Pool is considered highly suitable for long-term subsurface storage of CO₂. Primary seals of the reservoir are competent. Fractures in these seals are only rarely found, and mainly formed shortly after deposition with no discernable record fluid conductance. The Lower Watrous Formation forms a regionally extensive aquitard as part of the primary sealing system that effectively separates a deep hydrogeological system from a shallower hydrogeological regime. Overlying the Watrous Formation is an approximately 1 km thick succession of predominantly shales and siltstones forming several thick and extensive barriers to upward fluid migration. Regional tectonic elements including faults and fractured zones are present within the study region, although none have been found to exhibit any indication of fluid conductance or influence over hydrogeological characteristics. Significant salt dissolution that occurred within the risk assessment study area took place prior to reservoir development and did not compromise the geologic container. Overall, one of the most important results from this work is the gathering of a large amount of information that is pertinent to improved understanding of the geological characteristics of the Williston Basin.
4. Acknowledgments

As indicated in the text, around 40 enthusiastic scientists have worked on various aspects of the geological framework as part of the Weyburn Project, and this summary steals bits and pieces from all their studies. Although only the principal researchers for various areas were identified in the text, much of the hard work was performed by a small army of graduate students, research assistants, and consultants to whom I am very grateful for all their efforts. Much of their work will be published forthcoming in much greater detail. In particular, I would like to thank Chris Gilboy (SIR), and Kyle Worth, Arden Marsh, and Tom Love (PTRC) for their invaluable support in this undertaking.

5. References


