

IEA Weyburn CO₂ Monitoring and Storage Project: Geoscience Framework Update¹

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Abstract

Geological storage of CO₂ is considered to be among the most promising methods of effectively reducing greenhouse gas emissions to the atmosphere. The IEA Weyburn CO₂ Monitoring and Storage Project is a research effort studying geological storage of CO₂ within Mississippian carbonates of the Weyburn Midale Pool in southeastern Saskatchewan. The Geoscience Framework portion of this project provides data on the integrity of the geological container that will be used for risk analysis and to model the long-term fate of CO₂ in the subsurface.

All major stratigraphic units throughout the geologic column, and many subordinate evaporite layers, are being mapped within a 200 x 200 km region of southeastern Saskatchewan and parts of Montana and North Dakota. Approximately 1600 km of 2D seismic data in this area will be integrated with the stratigraphic information which will help to define basement structures that may have influenced depositional features. Hydrogeological data are undergoing rigorous examination to update basin hydrostratigraphy to better define the distribution of flow units and the directions and rates of subsurface and near-surface fluid movements. Detailed geological investigations are being performed on selected geological units to better determine the character of aquitards (seals) and aquifers. The occurrence and distribution of surface lineaments have been mapped in detail to assess which lineaments are surface expressions of deeper geological features that may influence subsurface fluid movement. Soil gas studies are being performed to monitor soil gas compositions and to determine if and how soil gas contents change across surface lineaments. The above data are being integrated into a common earth model to describe the geosphere within the Weyburn Project area.

Keywords: *greenhouse gas mitigation, geological storage of CO₂, CO₂ sequestration, Weyburn, Williston Basin, common earth model.*

1. Introduction

Geological storage of CO₂ is emerging as one of the more promising techniques for mitigating release of anthropogenic CO₂ to the atmosphere (Gale 2002; Shaw and Bachu, 2002), and may become an important process for achieving reductions of greenhouse gas emissions as outlined by the Kyoto Protocol (Thambimuthu *et al.*, 2002). The IEA Weyburn CO₂ Monitoring and Storage Project (the Weyburn Project) is an extensive research program investigating long-term geological storage of CO₂ within the Weyburn Midale Pool of southeastern Saskatchewan (Gilboy *et al.*, 2001; Whittaker *et al.*, 2002). To the end of 2002, approximately 2.45 million tonnes (48.3 BCF) of CO₂ have been injected into Mississippian carbonates of the Midale Beds as part of a 1.5 billion dollar EOR program directed by EnCana Corporation. Around 3500 tonnes (70 MMCF) of CO₂ per day are currently being injected at near 1400 MPa into the 1500 m-deep reservoir after having been pumped 320 km from its source at the Great Plains Gasification Plant in Beulah, North Dakota. Under these conditions, CO₂ is in a supercritical state within the reservoir where it becomes miscible with oil, reduces oil viscosity, and increases hydrocarbon recovery. Produced oil is treated to release entrained CO₂ which is subsequently collected and re-injected into the reservoir; about 990 tonnes (20 MMCF) CO₂ and associated gas are being recycled in this manner every day. At the end of the injection phase of the EOR project approximately 25 years from present, around 20 million tonnes anthropogenic CO₂ is expected to be stored within the Midale carbonates at the Weyburn Midale Pool. The injection of CO₂ into this depleting oil field has resulted in a daily incremental oil recovery of 795 m³ (5000 bbls) per day and is expected to extend the life of the field by 25 years with an additional 20.7 x 10⁶ m³ (130 x 10⁶ bbls) oil recovery.

¹ Support has been provided by the PTRC of Regina through the generosity of many sponsors, including SIR, to the IEA Weyburn CO₂ Monitoring and Storage Project.

The Weyburn Project study is divided into six major tasks: Field Support and Coordination, Geoscience Framework, Geochemical Monitoring, Geophysical Monitoring, Storage Performance, and Storage Economics. Within the Geoscience Framework Task, work is coordinated by Saskatchewan Industry and Resources (SIR) in association with the North Dakota Geological Survey (NDGS), the Universities of Regina, Saskatchewan and Alberta, Saskatchewan Research Council (SRC), J.D. Mollard & Associates (JDM), the British Geological Survey (BGS), the Instituto Nazionale di geofisica e vulcanologia (INGV, Italy), and the Bureau de recherches géologiques et minières (BRGM, France). The overall coordination of the project is conducted through the Petroleum Technology Research Centre of Regina. Efforts in the Geoscience Framework Task are directed towards delineating geological features through detailed and regional geological and geophysical mapping, and refining the hydrogeological system in the eastern Williston Basin including shallow bedrock and drift aquifers. The results of remotely sensed imagery analysis, used to compare surface elements with deeper geological features, also are helping to plan soil gas monitoring studies.

Determining the integrity of the geologic container for long-term storage of CO₂ is a primary focus of the Weyburn Project. Integration of the various research components of the Geoscience Framework into a unified model of the geosphere around the Weyburn Midale Pool, and of a large portion of the Williston Basin, is essential for performance and risk analysis modeling of the long-term fate of CO₂ in the subsurface.

2. Geoscience Framework

The Geoscience Framework Task is currently entering into a phase of integration involving a number of diverse, large, internally consistent datasets that have been, and are currently being, generated as a result of the Weyburn Project. The aim of this paper is to provide an overview of the current status of ongoing research activities within the Geoscience Framework Task of the Weyburn Project; preliminary results of two mapping studies are presented separately within this volume (Christopher and Yurkowski, this volume; Kreis *et al.*, this volume).

The region of investigation by the Geoscience Framework Task is a 200 x 200 km area centred on the Weyburn Field that includes much of southeastern Saskatchewan and the adjoining parts of North Dakota and Montana (Figure 1). Depth to basement in this area ranges from 1.5 km to over 3.5 km so that a volume of sedimentary rocks approximately 100 000 km³ is being evaluated. Brief descriptions of the work being performed by various research groups within the Geoscience Framework Task are presented in the following sections.

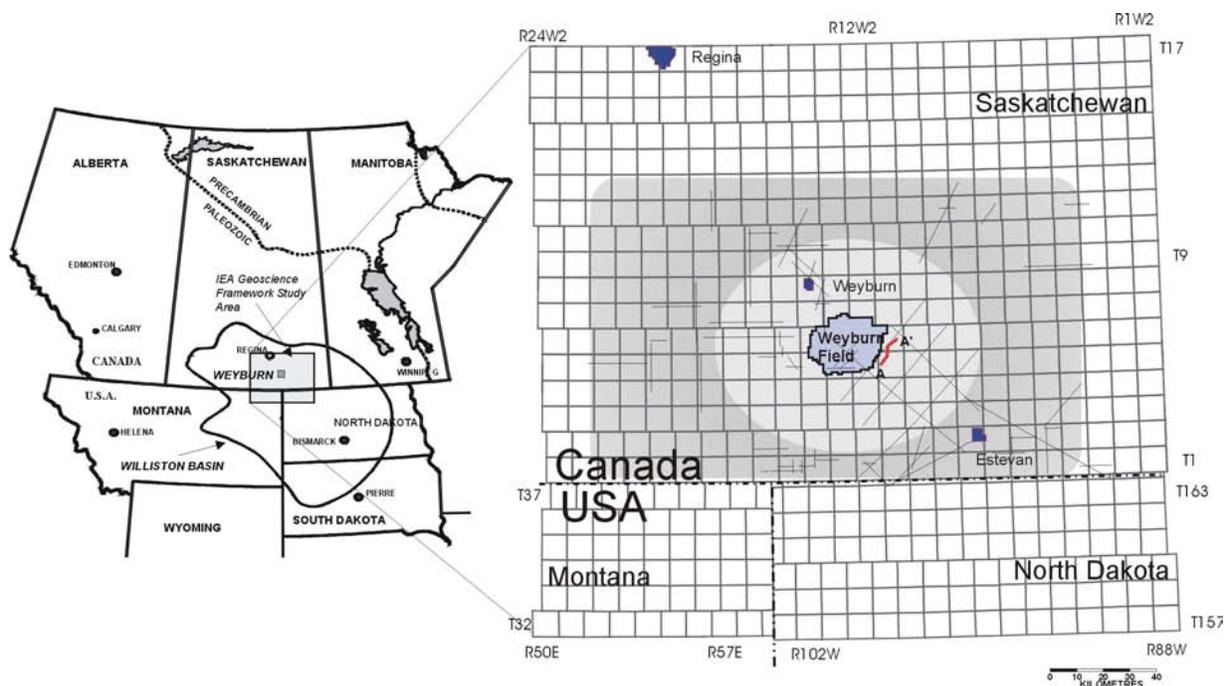


Figure 1 - Location of the Weyburn Project study within the Williston Basin and in relation to the Weyburn Field. Regional mapping has been largely completed throughout this entire region. The elliptical shaded region surrounding the Weyburn Field indicates the area subjected to more detailed investigations and risk analysis. The lines having various orientations indicate the locations of 2D seismic lines obtained to date. The larger shaded rectangle represents the approximate area encompassed within the seismic volume shown in Figure 4. Line of section A-A' presented in Figure 3 is shown just east of Weyburn Field.

a) Regional Geological Mapping

A main goal of regional mapping is to identify subsurface features that influence the structure and conductivity of reservoirs in and around the Weyburn area, and to better delineate aquitards and aquifers underlying, overlying and laterally equivalent to the Mississippian reservoirs. Over 130 stratigraphic picks are identified from the base of Cambrian to the top of bedrock for this project. SIR and NDGS geologists have coordinated their efforts to provide similar picks and nomenclature in this study. All wells that penetrate to the Devonian and deeper as of January 2001 were used within the study area (Figure 2). In addition, the studies of Mississippian and Mesozoic strata were augmented by adding wells to obtain a minimum of three per township where possible, so that approximately 2900 wells are used in the regional geological mapping aspect of this study. Additional wells also are studied within more focused studies of Mississippian, Lower Watrous, and Lower Colorado Group strata.

Cambrian, Ordovician, Silurian, and Devonian Mapping

Mapping of Cambrian, Ordovician, Silurian, and Devonian rocks within the Weyburn Project area has been largely completed by SIR and NDGS. In addition to major stratigraphic units, a number of thinner and less continuous evaporite units within these strata have been identified and mapped to determine their influence on deep-basin hydrogeology and also to identify locations affected by subsurface dissolution. The Devonian Prairie Evaporite Formation (Figure 2) exhibits regions of extensive dissolution, some of which has affected overlying strata. Similar features are observed in most of the subordinate evaporitic units. Additional maps of Devonian strata produced for the Weyburn Project are presented in Kreis *et al.* (this volume).

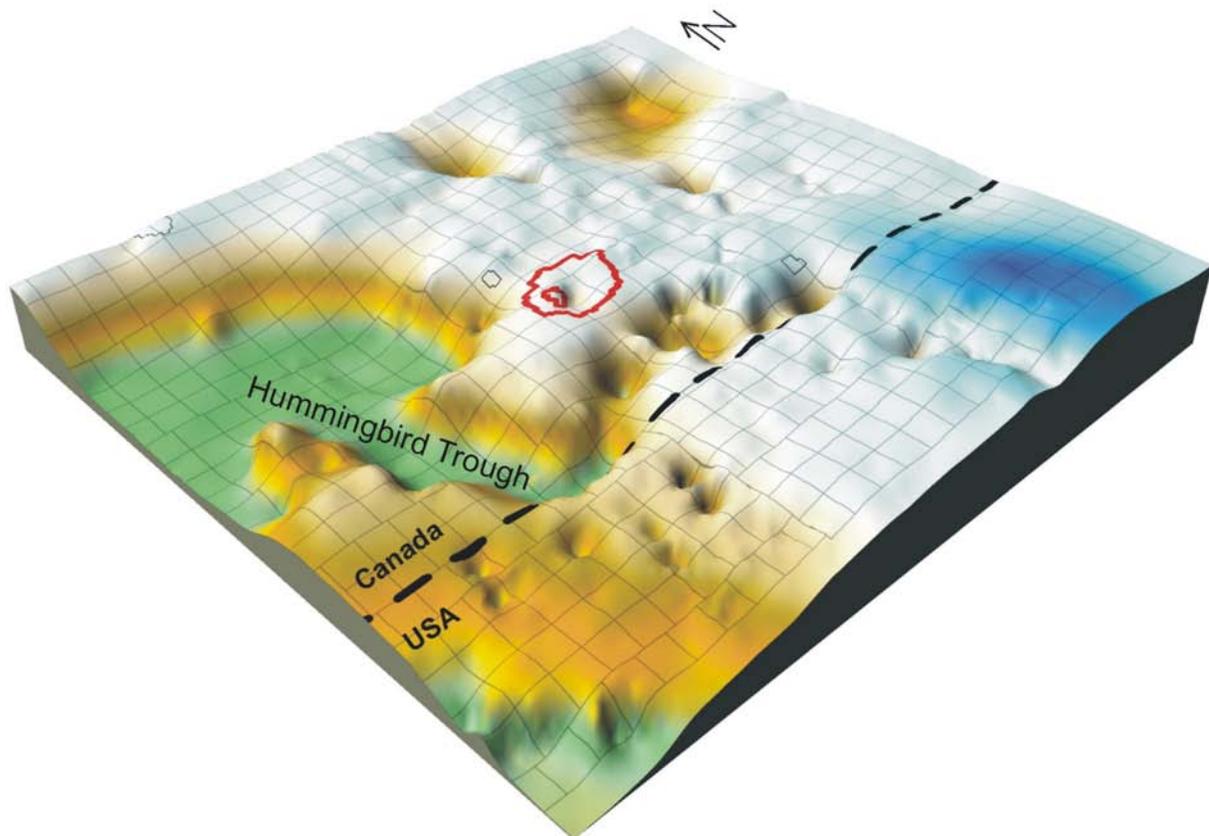


Figure 2 - Surface map illustrating thickness variations within the Devonian Prairie Evaporite Formation salt in the Weyburn Project study area. The area of significant salt removal along the western part of the map corresponds with the location of the Hummingbird Trough. Numerous areas of dissolution of variable size occur within the deposit, some of which are potentially associated with brecciation of overlying strata.

Mississippian Mapping

The Mississippian succession is being studied regionally by SIR and NDGS and in detail in selected areas by SIR and the University of Regina. The Mississippian sequence is of obvious significance in that the CO₂ is being injected into this interval. Mississippian maps generated have delineated the major aquifer units and also have identified many of the thinner and less continuous anhydrite units that occur within the project area. The nature of the subcrop of the Mississippian units with the Sub-Mesozoic Unconformity has also been refined in the region of study. Figure 3 is a northeast-trending cross-section showing the progressive truncation of anhydrite and carbonate units against the Sub-Mesozoic Unconformity.

An additional component to the Mississippian mapping in 2003 is to more accurately define the extent and continuity of the upper and lower seals to the Midale reservoir in, and slightly beyond, the Weyburn Midale Pool. Work on the upper seals, the Midale Evaporite and diagenetically altered carbonates along the subcrop, is being assisted by researchers at the University of Regina. The lower seal, the Frobisher Evaporite and its equivalent strata, is also being studied to identify the degree of connectivity between the Frobisher and Midale beds. Both studies investigate the effectiveness of their respective seals between Ranges 7 to 11W2, and from Township 5 north to the Frobisher Evaporite subcrop.

Mesozoic Mapping

Geologic mapping of the Mesozoic succession by SIR and NDGS is approximately two-thirds complete. Because the Mesozoic succession in this part of the Williston Basin has been perceived as having less economic potential than Mississippian and older rocks, it has previously received relatively little attention. A considerable increase in geological data has therefore arisen out of this mapping work, including the recognition of a major unconformity in Late Cretaceous strata between the Lea Park and Milk River formations. Many of the preliminary findings of the Mesozoic mapping project of southeastern Saskatchewan are presented in this volume in the paper by Christopher and Yurkowski (this volume).

b) Detailed Geological Mapping

Midale Seals

Detailed geological studies are being performed by researchers at the University of Regina on several geological intervals of specific interest to the Weyburn Project. Examination into the effectiveness and continuity of the Midale caprock in the region of the subcrop of the Weyburn Midale Pool area and immediate environs has previously been discussed and is coordinated with a similar program by SIR. Identifying the lithological and diagenetic characteristics of the upper seal is of fundamental importance to determining the integrity of the geological setting and this information will be essential for risk and systems analyses. Preliminary maps of the altered zones have been constructed and are being refined through integration with petrophysical (density) log examination.

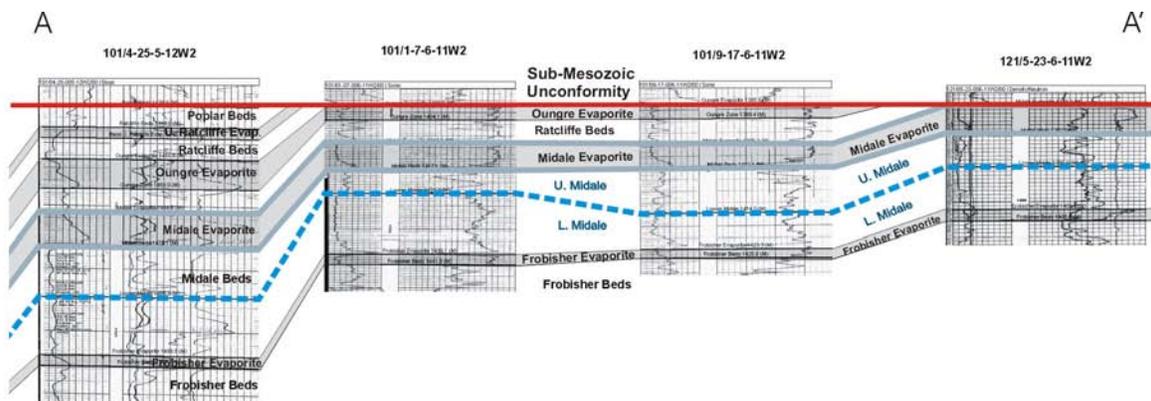


Figure 3 - Cross-section of Mississippian anhydrites and carbonates to the east of the Weyburn Field (see Figure 1 for location of section). The evaporite units form generally effective seals against upward migration of basinal fluids, whereas the carbonate units more readily conduct fluid migration. The spatial geometry and continuity of the anhydrite units and the petrophysical characteristics of the carbonate units are of fundamental importance to the integrity of the geological container and for risk analysis of CO₂ storage. Datum is the Sub-Mesozoic Unconformity.

Alida Beds

The continuity and nature of the anhydritized zone at the Alida Bed subcrop east of the Weyburn Midale Pool also is being studied using core and geophysical log examination coupled with detailed petrographic analyses. Four primary lithofacies packages in the Alida Beds have been outlined of which all have porosities sufficient to allow significant fluid migration to occur. The Alida caprock is dominantly anhydritic dolostone of variable thickness and may be absent in some locations.

Mississippian Sequence Stratigraphy

Additional core and geophysical log studies are currently placing the entire Mississippian succession within a sequence stratigraphic framework. This work may help to identify and resolve individual flow units within this important sedimentary package. To date, four key sequence boundary surfaces have been determined along with several significant transgressive erosional surfaces. Diagenetic processes associated with periods of exposure may have a marked impact on porosity and permeability characteristics along such surfaces.

Lower Watrous

Superjacent to many Mississippian reservoirs in the eastern Williston Basin, the Lower Watrous Formation forms a regional and effective seal to hydrocarbon migration. As such, these sandstones, siltstones, and mudstones are of considerable interest within the Weyburn Project as barriers to potential upward movement of fluids. Work at the University of Regina has identified several factors that may influence the sealing effectiveness of the Lower Watrous. One such feature is the presence of a 30 to 50 m thick fine-grained mudstone unit that retards the movement of fluids within the Lower Watrous. Current work involves lithologically subdividing the Lower Watrous to better trace variations in seal effectiveness across the Weyburn area. BRGM also is performing focused geological work on the Lower Watrous to obtain information for modeling geochemical interactions of migrating CO₂. Detailed petrography and quantitative petrophysical analyses will be done by BRGM along a series of wells orientated parallel to the principal subsurface flow direction. This work will derive detailed mineralogical, porosity, and permeability data for use in modeling factors affecting reactions and transport (advection, diffusion, dispersion) of CO₂ in the subsurface.

Lower Colorado

Detailed mapping is also being performed on Lower Colorado strata (Joli Fou, Viking/Newcastle, Westgate/Big River formations) by the University of Regina to determine the lateral and vertical continuity of seals and aquifers in these rocks. The Viking/Newcastle sands in particular represent a major conduit for fluid migration as they consist of multiple stacked, permeable units. A sequence stratigraphic model is being constructed for the Lower Colorado rocks to help delineate the geometry of the main aquifers and identify trends in petrophysical parameters.

c) Hydrogeological Investigations

Hydrogeological characteristics of sedimentary basins are critical to evaluating any geological site for CO₂ storage as these parameters indicate where and how fast CO₂ may move in the subsurface. The use of fluid flow rates coupled with petrophysical characteristics such as porosity and permeability are of fundamental importance in deriving models for system and risk analyses. The identification and mapping of shallow, potable aquifers also, clearly, is of importance for scenario development, monitoring strategies, and public awareness.

The hydrogeological work performed within the Geoscience Framework is being coordinated by the University of Alberta. Aquifers and aquitards studied by the University of Alberta group include those deeper than about 250 m to the Precambrian basement. Aquifers shallower than 250 m (uppermost bedrock and till) are being studied by JDM and SRC.

Basin Hydrogeology

The University of Alberta team is focusing on basinal hydrogeology and has refined the general hydrostratigraphy of the eastern part of the Williston Basin. By combining fluid density data and hydraulic head measurements, the University of Alberta researchers are calculating driving force ratios for regional aquifers that are more indicative of basin fluid-flow characteristics than by using potentiometric information alone. Similar measurements are being performed for all major aquifers within the basin and driving force ratio maps will be produced for all flow units. Ultimately the 3D flow field of the aquifers will be quantified to permit the assessment of potential subsurface CO₂ migration.

Shallow Hydrogeology

Shallow hydrogeological mapping is being carried out in detail within the immediate vicinity of the Weyburn Field by JDM and across the entire project area by the SRC to characterize groundwater conditions. This work has determined drift thickness variations across the region and has identified many of the shallow aquifers above and around the Weyburn Midale Pool. The aquifers are being described in terms of water quality, groundwater flow, hydraulic properties, and withdrawals. Surficial geological maps are also being prepared over an area immediately surrounding the Weyburn Midale Pool.

Of interest in the coming year is the delineation of buried preglacial valley aquifers that occur north and south of the current injection area in the Weyburn Field. This study will be directed jointly by JDM and SRC and will involve conducting electrical resistivity geophysical surveys followed by a drilling program to identify the extent and connectivity of the buried channels.

d) Regional Seismic Investigations

Approximately 1600 km of 2D seismic data is being reprocessed to assist in determining the subsurface character within the Weyburn Project study area. Structural contour maps and isopach maps are being generated and integrated with those determined by geological mapping. In addition, basin-wide structural patterns are being identified that will increase our knowledge of the Precambrian unconformity surface. A diagram depicting the interconnected nature of many of the processed seismic sections is shown in Figure 4. The 2D seismic data will be treated as a 3D network to permit improved interpretations of subsurface processes and features associated with basin development and evolution. In addition, petrophysical inversion will be applied to selected geological intervals to help identify preferential flow pathways in the subsurface around the CO₂ storage site. Seismic information will also be integrated with detailed and regional geological work to help refine the sequence stratigraphic framework of the Mississippian succession within the Project area.

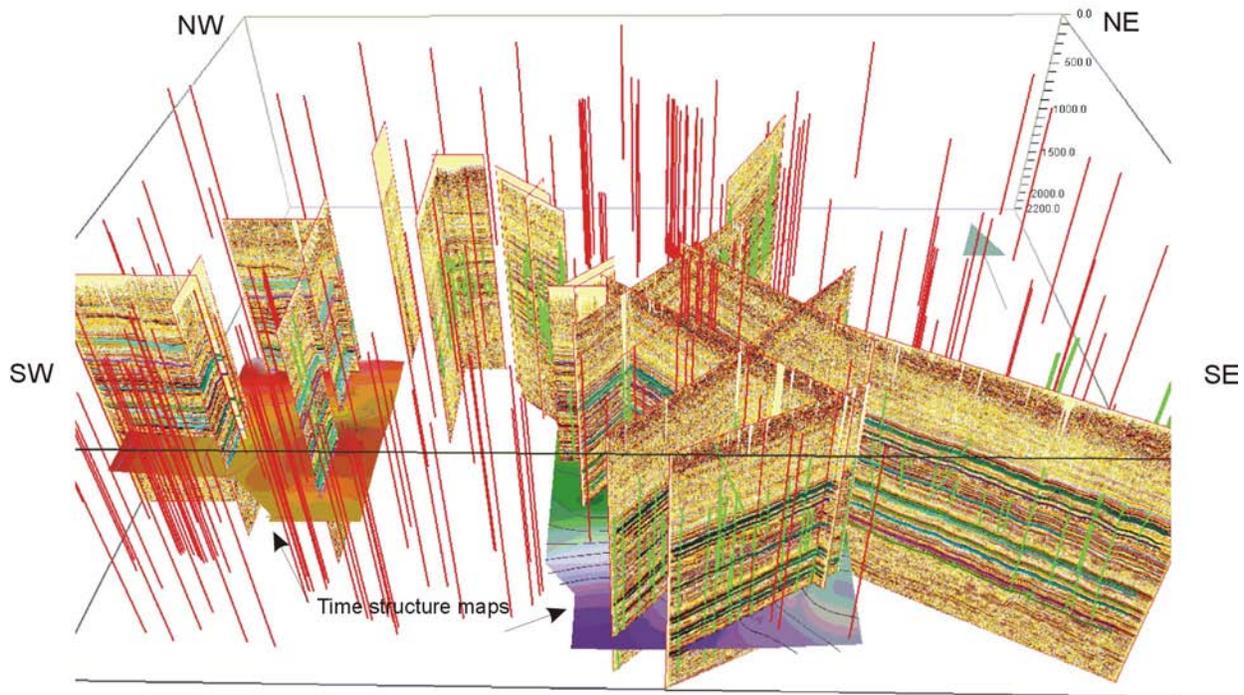


Figure 4 - Seismic volume showing a number of 2D time-migrated seismic sections being investigated in the Weyburn Project area. The shaded rectangular area of Figure 1 indicates the approximate area shown in this diagram. The vertical lines are selected deep wells in the area, some of which are used to tie the stratigraphy to the seismic data. Synthetic seismic sections have been computed for most of the 2D slices shown. The preliminary development of seismically identified surfaces is shown by the contoured surfaces associated with two clusters of seismic sections. With continued seismic processing, surfaces will be generated across most of the project area.

e) Remotely Sensed Imagery Analysis

JDM are examining airphoto and satellite (LANDSAT, RADARSAT) imagery data of surface lineaments in conjunction with geological and geophysical data to determine whether a spatial association exists between the surface elements and deeper geological features. Such an association may reflect the presence of fractured zones, faults, or regions of salt dissolution which may point to areas of preferential CO₂ movement. Surface lineaments are found to occur mainly in two orientations, northwest-southeast and northeast-southwest, that correspond to orientations of fracture sets measured in drift and bedrock across the region. A list of lineament zones having the most probable association with subsurface features is being developed to help with risk assessment and also with planning soil gas monitoring surveys. The spatial relationship between satellite-defined lineament zones and the distribution of the Davidson Salt is presented in Figure 5. Similar maps are being prepared for most of the mapped geological units by incorporating geological, geophysical, and hydrogeological information.

f) Soil Gas Monitoring

Soil gas monitoring is included in the Geoscience Framework Task this year and is a continuation of work performed over several previous seasons by researchers at BGS, BRGM, and INGV. This work is helping to develop procedures for monitoring CO₂ storage sites, and is also providing background data on soil gas compositions around the Weyburn injection area. Future surveys will transect surface lineaments identified by JDM to assess the relationship among lineaments, subsurface gas migration, and soil gas compositions.

To address the source of gases measured in the soils, a detailed till characterization program will be carried out this year by BGS and SRC. Till samples will be taken at regular intervals to around 30 m total depth at soil gas sampling sites that have been identified to have relatively elevated contents of some gases including radon and thoron. The till will be studied palynologically and analyzed for carbonate content, particle size distribution, clast composition, mineralogy including heavy mineral separation, gamma spectroscopy, uranium and thorium geochemistry, major and trace element analysis, and depth profiling of radon content.

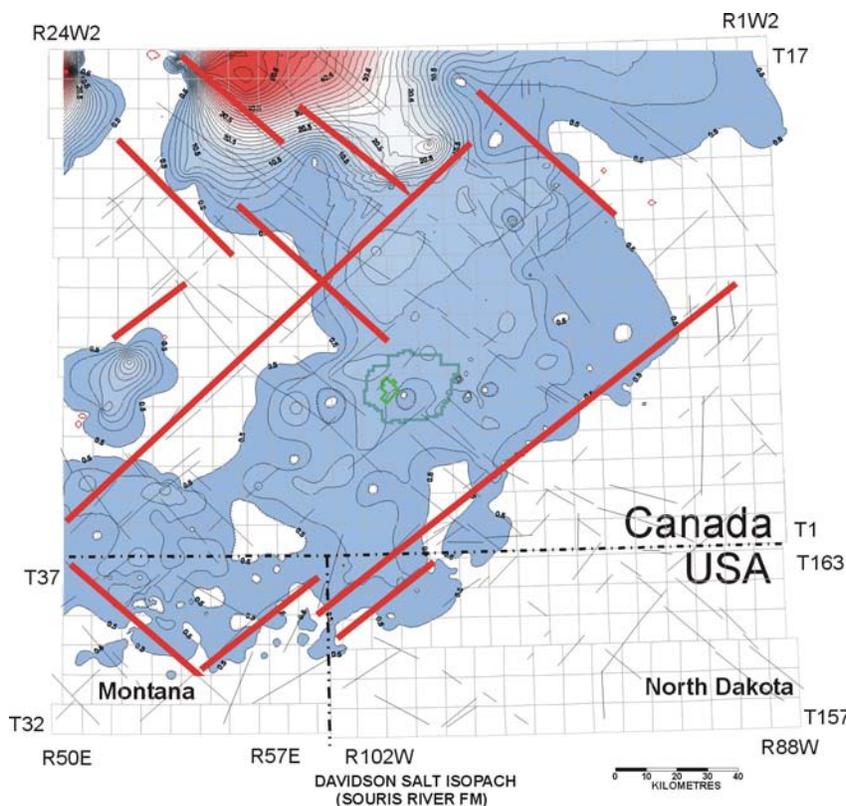


Figure 5 - Lineaments identified through analyses of LANDSAT imagery are overlain on the isopach map of the Davidson Salt. Thinner black lines represent zones of lineament occurrences. Thicker red lines are zones of lineaments correlated with subsurface features; in this case, limits of Davidson Salt distribution. The association of specific lineament zones with multiple geological units will be used to identify lineament zones of principle interest within the Weyburn Project.

g) Geoscience Integration

Integration of results of the above studies is ongoing to establish a comprehensive geological model, or common earth model, to help identify geological controls over CO₂ storage and migration within the geosphere around the Weyburn Midale Pool. Integration of the individual studies involves all researchers and is being coordinated through SIR. Gocad, a 3D visualization and modeling software package, is being used, in part, to integrate many of the datasets. Ultimately, stratigraphic, seismic, hydrogeological, petrophysical, and surface data will be used together to define the geosphere around Weyburn. These data will then be subjected to flow modeling for assessment of the long-term fate of CO₂ in the subsurface. Figure 6 provides an example of data integration and the development of a preliminary geological model for the Weyburn area.

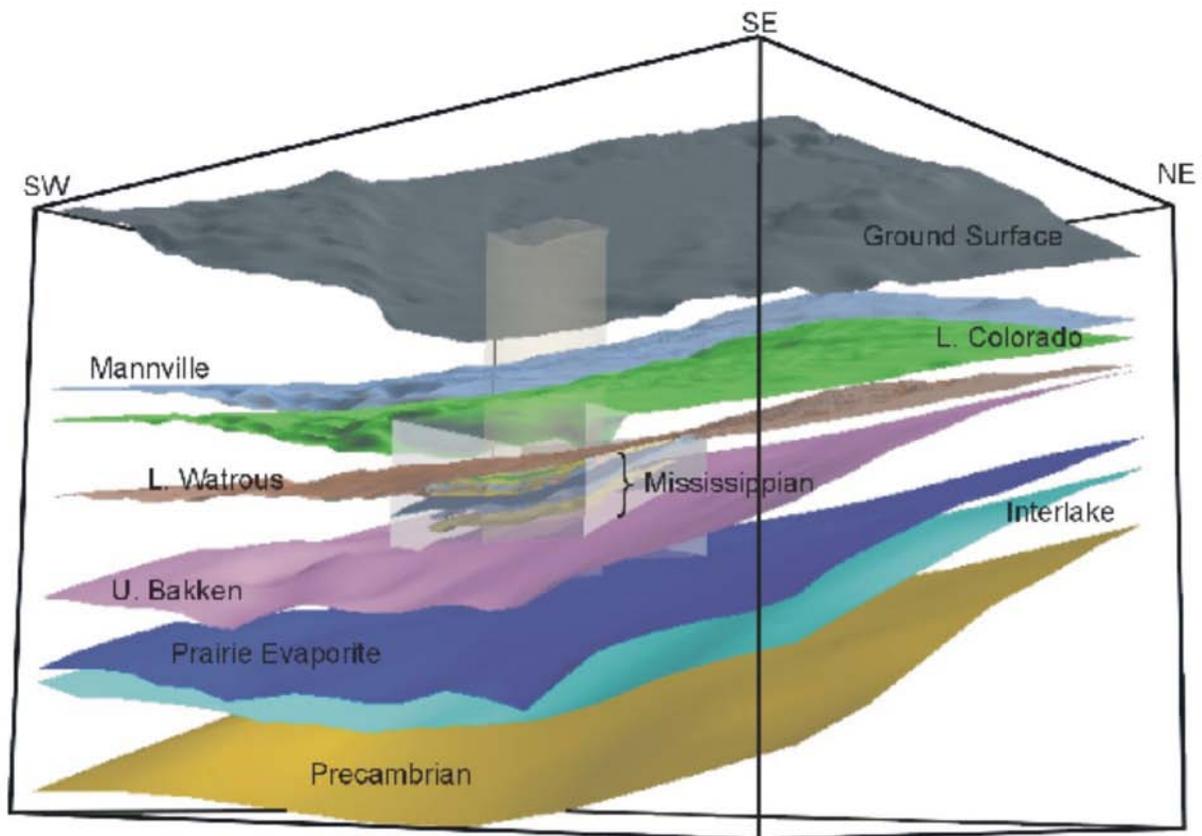


Figure 6 - Three-dimensional model of the Weyburn Project study within the Williston Basin. In the centre of the model are Mississippian strata surrounded by a translucent box suggesting the increased focus on these rocks within a smaller region than the overall project area. The central transparent vertical shaft represents the downward projection of the Weyburn Field. The overlying Mesozoic strata and underlying Paleozoic strata are shown here in full extent across the entire project area. Models of this type allow data from several sources to be integrated to confidently construct subsurface geometry and stratal relationships. In addition, properties such as porosity, hydrochemistry, and temperature can be placed within the model for geostatistical analyses. Results of the geological model will be used for defining the integrity of the geological system at Weyburn and for risk and scenario analyses.

3. Summary

The Weyburn Project is a leading example worldwide for the application of geological storage of CO₂ to address greenhouse gas emissions. It has attracted sponsorship from industry and governments from Europe, Japan, USA, and Canada, as well as global interest as a major research undertaking. The Geoscience Framework studies are providing invaluable information regarding the geological integrity of the Weyburn site, as well contributing significantly to understanding the subsurface geology of the Williston Basin. A significant goal of the IEA Weyburn CO₂ Monitoring and Storage Project is to provide direction for the study, analysis, and selection of future geological storage sites of CO₂, particularly those in carbonate strata, for mitigation of greenhouse gas emissions which will likely become a major initiative in the near future.

4. Acknowledgments

We thank the many individual researchers within the Geoscience Framework and other major Tasks within the IEA Weyburn CO₂ Monitoring and Storage Project for their assistance and provision of data. Sandor Shule, Lynden Penner, Patty Thomas, and Kim Kreis provided data for several of the figures used in this summary.

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