Greenhouse gas sequestration in abandoned oil reservoirs: The International Energy Agency Weyburn pilot project

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ABSTRACT

Carbon dioxide sequestration in geological reservoirs is being evaluated internationally as a viable means of long-term CO_2 storage. The International Energy Agency Weyburn CO_2 Monitoring and Storage Project is designed to investigate the technical and economic feasibility of CO_2 storage in a partially depleted oil reservoir in conjunction with enhanced oil recovery operations. Two key elements of the project are (1) the establishment of a regional geoscience framework as a means for prediction of the long-term fate of injected CO_2, and (2) development and application of geophysical/geochemical monitoring and verification methods to track the spread of CO_2 within the reservoir. To date, 1.90 billion m^3 of CO_2 have been injected into the reservoir, the effects of which are imaged by the various monitoring methods.

INTRODUCTION

Carbon dioxide is the primary anthropogenic greenhouse gas in the modern-day atmosphere and is a critical component in models of global climate change (IPCC, 2001). It is estimated that ~6 gigatons of carbon enters the environment annually as a result of global energy-related CO_2 emission, with North America being responsible for ~20%–25% of this total (International Energy Agency [IEA], 2000). Recognition of the importance of CO_2 emissions has stimulated research toward mitigation of CO_2 effects as mandated under the Kyoto Protocol of the United Nations Framework Convention on Climate Change.

CO_2 sequestration in geological reservoirs is being evaluated internationally as a viable means of long-term CO_2 storage and climate change mitigation (EAGE, 2000). In 2000, the IEA Weyburn CO_2 Monitoring and Storage Project was initiated to investigate the technical and economic feasibility of CO_2 storage in a partially depleted oil reservoir (Government of Canada, 2000). The IEA Weyburn project is exploiting EnCana Corporation's $1.5 billion, 30-year commercial CO_2 enhanced oil recovery operation, which is designed to recover an incremental 130 million barrels of oil from the Weyburn field through the injection of gaseous CO_2 under pressure. Specifically, the IEA Weyburn Project aims to comprehensively monitor and verify the progress of the CO_2 flood and establish the likelihood of safely storing the CO_2 in the reservoir for the long term. Toward this end, a multidisciplinary, integrated program has been formulated to address critical issues central to safe and cost-effective, long-term storage of CO_2. In this article, we focus on the regional geoscience framework and the monitoring and verification components of the project.

GEOLOGICAL SETTING AND HISTORY OF THE WEYBURN FIELD

The Weyburn oil field is located southeast of Weyburn, Saskatchewan, within the north-central Williston Basin, which contains shallow marine sediments of Cambrian to Tertiary age (Fig. 1). The Weyburn field, which covers ~180 km^2, was discovered in 1954 and hosted an estimated 1.4 billion barrels of oil. Primary production within the field continued until 1964, when the initiation of waterflood resulted in oil production peaking at 46,000 barrels/day in 1965. Waterflood has continued since then, with horizontal infill drilling commencing in 1991. Approximately 24% of the original oil in place had been recovered by 2000 when CO_2 injection began.

Weyburn oil reserves reside within a thin zone (maximum thickness of 30 m) of fractured carbonates in the Midale beds (Fig. 2) of the Mississippian Charles Formation, which were deposited in a shallow carbonate shelf environment. The reservoir comprises two intervals, an upper Marly dolostone (0–10 m thick) and lower Vuggy limestone (0–20 m thick) that are sealed by anhydritic dolostones and anhydrites of the Midale Evaporite. The Midale Marly unit ranges from chalky dolomudstone

GSA Today; v. 14; no. 7, doi: 10.1130/1052-5173(2004)014<4:GGSIAO>2.0.CO;2

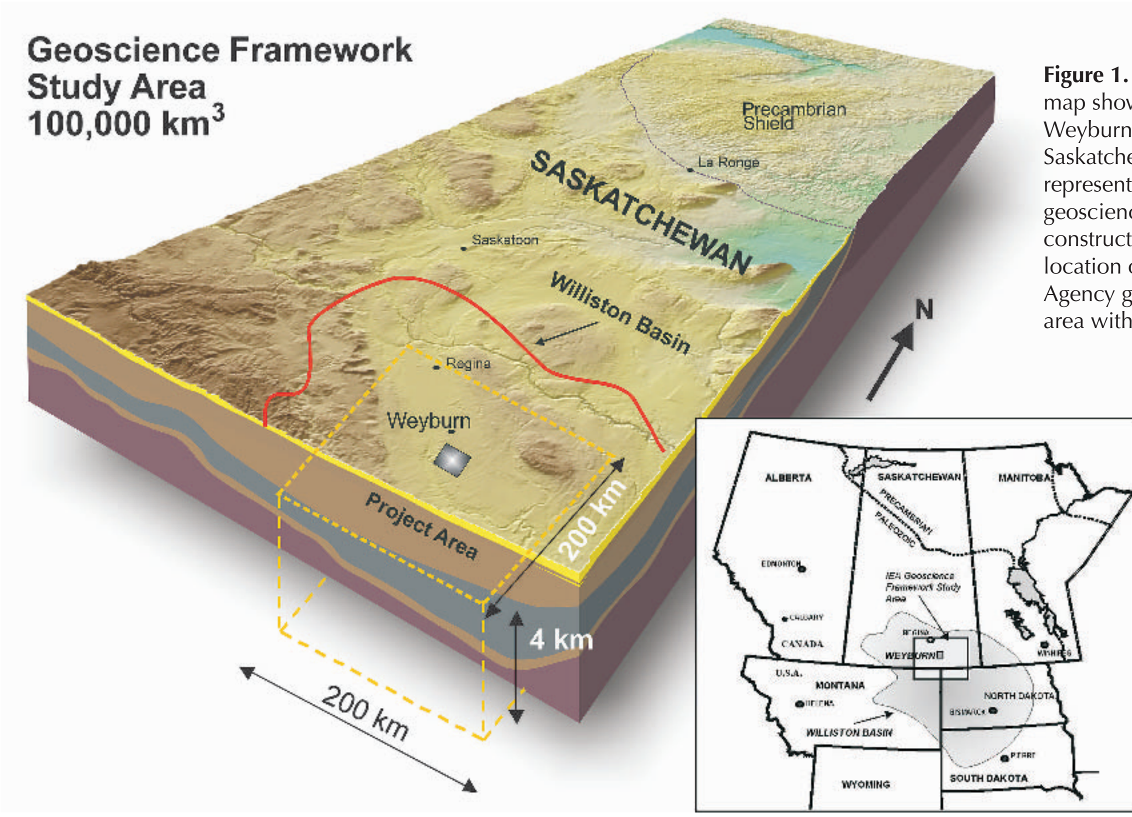

Figure 1. Three-dimensional map showing the location of the Weyburn study area in southeastern Saskatchewan. The dashed cube represents the area where the geoscience framework is being constructed. Lower inset shows the location of the International Energy Agency geoscience framework study area within the Williston Basin.

to calcitic biofragmental dolostone with intervening thin beds of biofragmental limestone. The fractured, Vuggy unit includes a lower, peritidal "shoal" sequence with common secondary (vuggy) porosity, and an upper shallow marine "intershoal" sequence dominated by fine-grained carbonate sands. The Midale Marly has relatively high porosity (16%–38%) and low permeability (1 to >50 millidarcy), whereas the Midale Vuggy has relatively lower porosity (8%–20%) and higher permeability (10 to >300 millidarcy). The higher permeability within the Vuggy unit resulted in preferential recovery of oil from this unit during the waterflood stage of production.

The dominant fracture set within the reservoir strikes NE-SW as determined from core and imaging logs (Bunge, 2000). This orientation is sub-parallel to the regional trajectories of maximum horizontal stress (Bell and Babcock, 1986) and is parallel to the horizontal well direction. The vertical stress at the reservoir level due to the lithostatic load is ~34 MPa as estimated from a density log, and the minimum horizontal stress is ~18–22 MPa in this region (McLellan et al., 1992).

THE CO_2 FLOOD

The CO_2-based enhanced oil recovery (EOR) scheme was initiated in

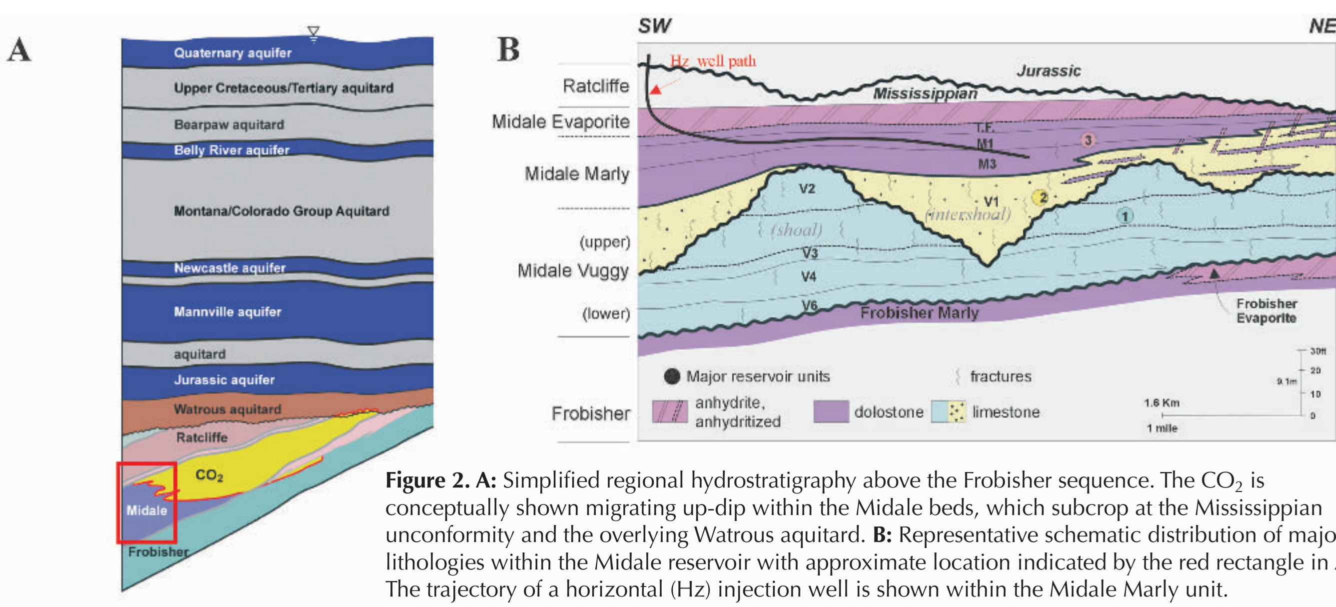

Figure 2. A: Simplified regional hydrostratigraphy above the Frobisher sequence. The CO_2 is conceptually shown migrating up-dip within the Midale beds, which subcrop at the Mississippian unconformity and the overlying Watrous aquitard. **B:** Representative schematic distribution of major lithologies within the Midale reservoir with approximate location indicated by the red rectangle in A. The trajectory of a horizontal (Hz) injection well is shown within the Midale Marly unit.

September of 2000 in 19 patterns[1] of the EnCana Weyburn unit at an initial injection rate of 2.69 million m^3/day (or 5000 tonnes/day). The present rate of CO_2 injection is 3.39 million m^3/day of which 0.71 million m^3/day is CO_2 recycled from oil production. The CO_2 EOR is contributing over 5000 barrels/day to the total daily production of 20,560 barrels/day for the entire Weyburn unit. As of May 30, 2003, cumulative CO_2 injected was 1.90 billion m^3. The CO_2 flood will be expanded gradually over the next five years into a total of 75 patterns with ~10.8 billion m^3 (or ~20 million tonnes) of injected CO_2 anticipated over the lifetime of the project. The source of CO_2 is the Dakota Gasification Company's synthetic fuel plant located in Beulah, North Dakota. The CO_2 is transported 320 km via pipeline to the Weyburn field.

The reservoir is at ~1450 m depth in the EOR area and has a mean temperature of 63 °C. Estimated pore pressures of ~14 MPa existed when the field was originally discovered, and during waterflood they ranged from 8 to 19 MPa. Recently measured pore pressures range from 12.5 MPa to 18 MPa with an average of ~15 MPa. These conditions exceed the critical point pressure and temperature (7.4 MPa and 31 °C) of CO_2, and thus the injected CO_2 initially exists as a supercritical fluid in the reservoir. It is anticipated that the injected CO_2 will cause minor dissolution of carbonate minerals, as CO_2 will dissolve to some extent in water present in the reservoir, forming bicarbonate until equilibrium is reached. This is ionic trapping of CO_2. The presence of minor amounts of silicate minerals within the reservoir may also enhance the capacity of the reservoir to sequester CO_2 through mineral trapping as reactions between the silicates and CO_2 may lead to the precipitation of carbonate minerals.

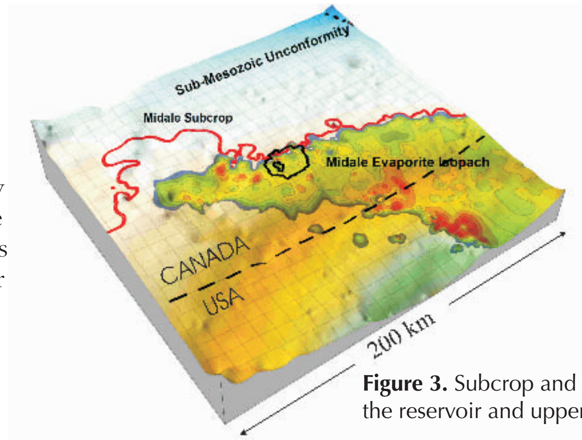

Figure 3. Subcrop and isopach of the reservoir and upper seal.

THE REGIONAL FRAMEWORK

The motivation for developing the regional geological framework is to establish a means for predicting whether injected CO_2 may migrate beyond the immediate injection site over the long term. To address this requirement, key elements of the regional framework that must be identified include potential fluid pathways, including faults, fracture zones and controlling depositional features, such as zones of salt dissolution. CO_2 traps and trapping mechanisms (e.g., seals and aquitards) within the stratigraphic column must be identified as well, and the transport properties of deep aquifers (e.g., porosity, permeability, fracture distribution, formation-water flow rates and directions) need to be established.

The conceptual model of CO_2 storage is shown in Figure 2. CO_2 is injected into the Midale reservoir beds where the overlying Midale evaporite forms the primary physical barrier to CO_2 migration. However, the Midale reservoir beds are truncated to the northeast (as mapped in Fig. 3) where they subcrop beneath redbeds (dolomitic to anhydritic siltstones and mudstones) of the Watrous Formation. This forms a secondary seal. Above the Watrous aquitard, there are several regional aquifers sandwiched between thick shaley aquitards, which constitute the major flow units and flow barriers of the hydrostratigraphic framework.

To develop a detailed understanding of the geology and hydrology from the Precambrian basement to the surface, a

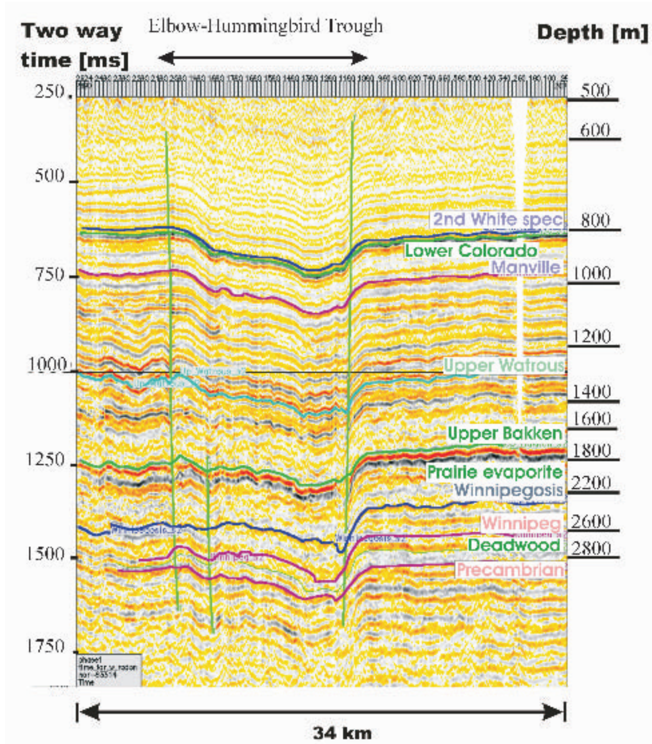

Figure 4. A representative two-dimensional seismic profile from the 1600 km of profiles that are being used with geophysical and core logs to construct the regional geological framework. Horizons that are picked regionally include the Precambrian unconformity, Deadwood, Winnipeg, Winnipegosis, Prairie Evaporite, Upper Backen, Upper Watrous, Manville, Lower Colorado, and 2nd White spec. The subvertical green lines represent interpreted lateral discontinuities in the picked horizons that could be faults or fracture systems that may potentially act as fluid pathways.

regional three-dimensional geological framework (shown conceptually in Fig. 1) is being constructed within an ~100 km radius about the Weyburn field. The framework is based on geological and geophysical compilations from the existing catalog of logged core from boreholes across the area, as well as reprocessing of 1600 km of seismic reflection profiles across the area with stratigraphic control provided by the correlation of seismic sections with geophysical logs. For example, the subcrop and reservoir interval and upper seal isopach are

[1]Pattern refers to a group of injection and production wells that occupy an area of approximately 1 km^2.

depicted in Figure 3. Similar maps are being constructed for other key stratigraphic units. Figure 4 portrays an example of the regional seismic reflection data with horizons that are being picked as well as interpreted "faults." The latter may act as potential pathways for fluid migration, but the actual hydraulic characteristics of these zones (porosity, permeability) are unknown.

Regional fluid flow-direction, flow-rates, and water chemistries of the 20 major aquifers between the Precambrian basement and the land surface are being mapped in the Weyburn Project area. In addition, permeability and porosity data from core analyses and drill-stem tests are being processed using geostatistical tools to obtain hydraulic parameters for each aquifer.

RESERVOIR CHARACTERIZATION AND CO_2 FLOOD MONITORING

As CO_2 is injected into the reservoir, its spread will be influenced by heterogeneous, anisotropic permeability, and it will displace and mix with existing reservoir fluids (oil, water, and gas) resulting in pore pressure and fluid composition changes within the reservoir. Furthermore, the matrix rock of the reservoir will respond dynamically to this process, potentially with associated microseismicity signaling local deformation (e.g., fracturing or pressurization of existing fractures). Typical magnitudes of injection-related microseisms range from –4 to 0 (Maxwell et al., 2003). The preferred fluid pathways may in fact be altered by the injection process as pressure changes within the reservoir may open or close fracture systems.

Monitoring of the CO_2 flood at the Weyburn field includes seismic and geochemical methods, which are intended to document as much of this dynamic process as possible. Baseline static characterization of the reservoir (e.g., porosity, permeability, fracture systems, fluid distribution) prior to injection is important in planning the flood and anticipating how it will proceed. Following flood initiation, the goal is to track the saturation and distribution of CO_2 within the reservoir, assess the interaction of the CO_2 with the other reservoir fluids, determine pressure variations, and identify off-trend flow so that the injection process can be adjusted accordingly. Finally, monitoring provides a means of verifying the volume of CO_2 that resides within the reservoir. Efficient and complete access to the reservoir volume and avoidance of premature flow-through of CO_2 to producing wells is important whether enhanced oil recovery or CO_2 storage is the ultimate goal.

Geochemical Monitoring

Chemical and/or isotopic compositions of aqueous fluids and gases are being monitored and compared to

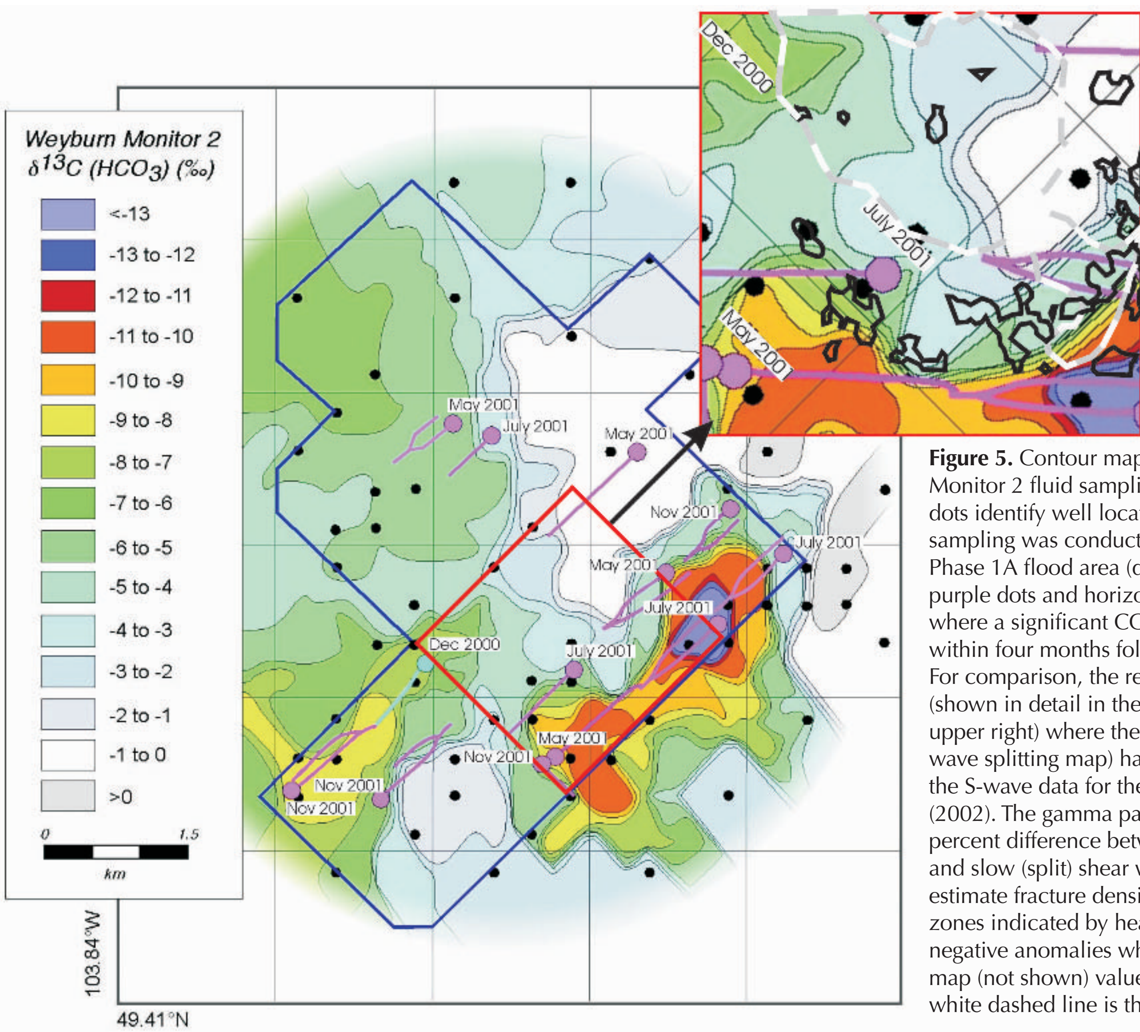

Figure 5. Contour map of the $\delta^{13}C$ values from the Monitor 2 fluid sampling survey (July 2001). Black dots identify well locations where fluid and/or gas sampling was conducted within the nine-pattern Phase 1A flood area (dark outline). The larger, purple dots and horizontal well legs identify wells where a significant CO_2 response was observed within four months following the sampling survey. For comparison, the red square identifies an area (shown in detail in the expanded inset panel, upper right) where the gamma parameter (or shear-wave splitting map) has been determined from the S-wave data for the Monitor 2 seismic survey (2002). The gamma parameter is a measure of the percent difference between the velocities of the fast and slow (split) shear waves and can be used to estimate fracture density and direction. In the inset, zones indicated by heavy black outlines identify negative anomalies where the gamma parameter map (not shown) values are <–10%. The heavy white dashed line is the salt dissolution edge.

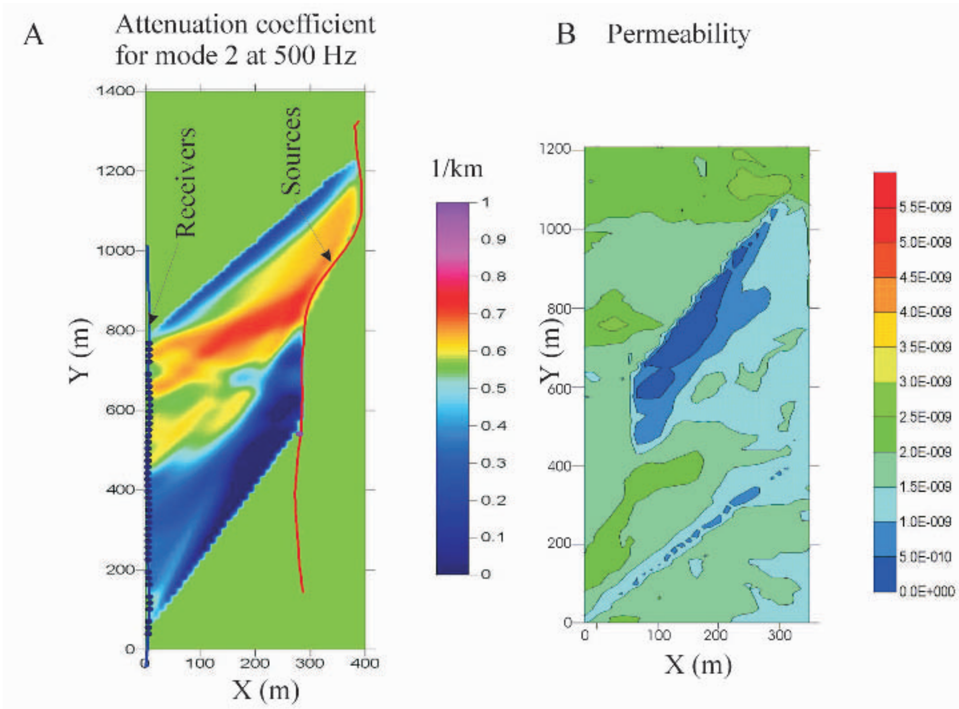

Figure 6. A: Horizontal crosswell attenuation tomogram for a sub-horizontal slice through the Marly unit (see Fig. 7 for orientation). The tomogram is determined for energy with a center frequency of 500 Hz. **B:** Permeability calculated using the attenuation values from A, based on the Biot relationship and using parameters (porosity and fluid viscosity) from the existing reservoir model. Units are in cm^2 (1 darcy = 0.987×10^{-8} cm^2).

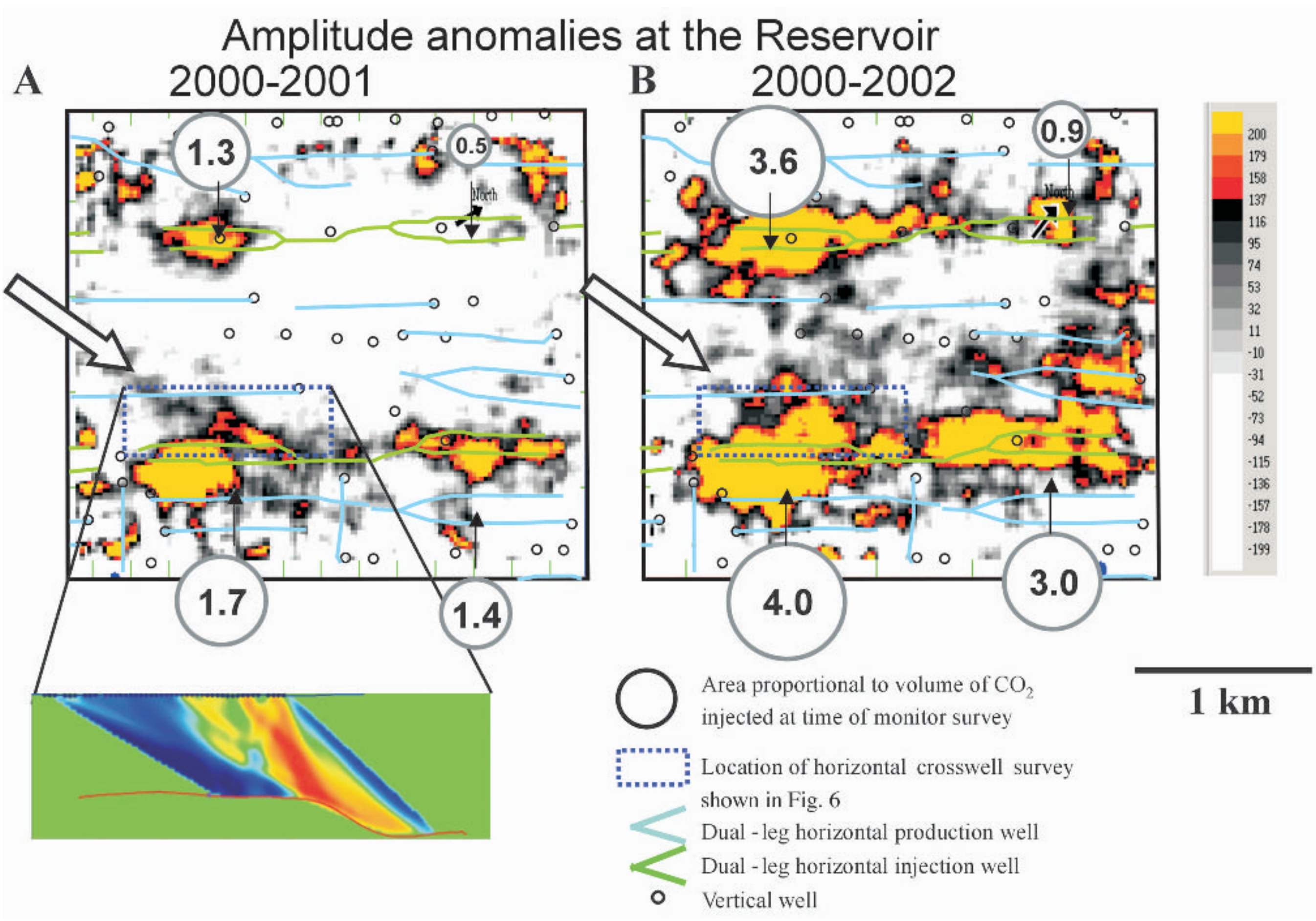

Figure 7. P-wave amplitude difference maps for baseline minus 2001 survey (A) and baseline minus 2002 survey (B), determined from the three-dimensional P-wave surface seismic data. The amplitudes were determined as the arithmetic mean over a 5 ms window centered on the reservoir horizon. The large circles represent the cumulative volume of CO_2 (at reservoir conditions in units of 10^6 m^3) that had been injected at the time of the monitor survey for each of the four dual-leg horizontal injectors. The large arrows indicate interpreted zones of off-trend CO_2 spread. In A, the attenuation tomogram from Figure 6 is shown in an expanded panel emanating from its position on the amplitude map.

pre-injection baseline measurements to trace and predict the movement of CO_2 and other fluids within the reservoir. In particular, carbon isotopes ($\delta^{13}C$) are being used to track the spread of trace amounts of injected CO_2 as a precursor of the advancing CO_2 "front." This is possible due to the distinct isotopic signature of CO_2 ($\delta^{13}C$ value of –35 per mil) delivered from the synthetic fuels plant. Changes in fluid and gas compositions over time indicate that interaction is taking place between reservoir fluids, injected CO_2, and reservoir rocks. For example, following the start of injection, the $\delta^{13}C$ (HCO_3) values of reservoir fluids have decreased dramatically from original values ranging from –1 to –7 per mil to values of –4 to –11 per mil (Fig. 5). The decrease in $\delta^{13}C$ (HCO_3) values is most easily attributable to the dissolution of injected CO_2. For geochemical monitoring surveys conducted at times greater than eight months following the onset of injection, a very good correlation has been observed between CO_2 distribution (as estimated from $\delta^{13}C$) and wells where CO_2 has been detected in significant quantity within a period of four months following the survey (see Fig. 5).

Pre-Injection High-Resolution Seismic Crosswell Imaging

Seismic crosswell data are intended to image variations in reservoir properties occurring on the scale of meters. Combined with borehole sonic logs (centimeter scale), vertical seismic profile data, and surface seismic data (10s of meters scale), these data will provide proper scaling relationships for understanding reservoir properties and processes at the reservoir dimensions.

A horizontal crosswell survey was acquired in two parallel horizontal wells (Fig. 6) in August 2000, prior to the start of CO_2 injection (Majer et al., 2001; Washbourne et al., 2001; Li et al., 2001). A piezoelectric source was deployed in one well and a 48-level hydrophone string in the opposite well. The frequency band of the source was 200–2000 Hz, an order of magnitude higher than the surface seismic source. To our knowledge, this was the first-ever deployment of a large-scale crosswell survey between horizontal wells.

The horizontal crosswells were located within the Marly unit (see Fig. 2B) of the reservoir. This layer has a much lower velocity (3.5 km/s) than the bordering layers (~5.5–6.0 km/s) and thus acts as a waveguide for seismic energy propagating across the layer. A tomographic imaging approach was developed to use this guided or trapped wave energy. An attenuation tomogram for 500 Hz energy is shown in Fig. 6A, with a first attempt at integrating this result with the existing reservoir model shown in Fig. 6B. The tomogram has been converted from an attenuation image to permeability within the depth slice by using porosity and fluid viscosity from the reservoir model, and using Biot relationships to calculate the permeability. The resulting permeability values clearly depend on the parameters from the reservoir model and the assumed attenuation mechanisms, but the observed trends should be robust. The permeability values obtained range from 50 to 150 millidarcy which is comparable to the range of permeabilities measured within this unit (10 to 500 millidarcy). Of note, the spatial trends in the calculated permeability are at an angle to the horizontal injection wells (oriented along-trend) and are also oblique to the local seismic impedance and porosity trends (cf. Li et al., 2001), suggesting the presence of off-trend zones of enhanced permeability. It should be noted, however, that due to the acquisition geometry, the tomographic image cannot resolve permeable zones that are oriented parallel to the horizontal wells.

Time-Lapse Multicomponent Three-Dimensional Surface Seismic Monitoring

Time-lapse seismic methods provide a powerful means of monitoring the progress of the CO_2 flood over time. The use of multicomponent imaging techniques provides a means of isolating the various reservoir characteristics that are affected by the flood (fluid distribution and saturation, pore pressure, fracture permeability). For example, in a fractured porous medium that is isotropic (or for some classes of anisotropic media), the P-wave amplitude response is sensitive to both pore fluid saturation and pressure effects, whereas the S-wave amplitude response is generally less sensitive to the composition of the pore fluid (e.g., Wang et al., 1998; Brown, 2002; Cardona, 2002). Thus, P- and S-wave amplitudes provide a potential means of discriminating pore pressure vs. pore fluid saturation effects, except in regions of the reservoir where fracture-related anisotropy has lower symmetry (Cardona, 2002). Furthermore, it is reasonable to assume that the injected CO_2 will exist primarily as a supercritical fluid or in an oil-CO_2 solution, because of the relatively low solubility (~2 mol% at reservoir conditions) of CO_2 in water and the relatively high reservoir pressures. This simplifies the interpretation of the seismic response in terms of pore fluid composition. Rock property measurements indicate that the effect on seismic amplitude of CO_2 dissolved in oil is small until saturation levels reach 50% (Brown, 2002). Maximum CO_2-induced P-wave velocity decreases of 4%–6% are expected with associated reflection amplitude decreases of 15%–20% (Davis et al., 2003).

Birefringence (i.e., splitting) of shear waves provides another independent means of characterizing an anisotropic medium. In the case of the reservoir, shear-wave anisotropy has been used to estimate fracture density, fracture direction, and location. It can also be used to monitor changes in the fractured medium over time due to dynamic changes in the reservoir processes. Davis et al. (2003) provide further details.

Time-lapse P-wave (2001 and 2002) amplitude difference maps for the first two monitor surveys relative to the pre-injection baseline survey (2000) are shown in Figure 7. P-wave amplitude anomalies are observed in the immediate vicinity of the horizontal injection wells. Generally, the areal extent of the anomalies surrounding any of the four dual-leg horizontal injection wells is proportional to the cumulative amount of CO_2 injected, whether the comparison is made for different injectors in the same monitor survey or for the same injector in subsequent monitor surveys. Preliminary volumetric calculations and sensitivity modeling suggest that the P-wave amplitude anomaly maps are primarily mapping the CO_2 saturation (pure phase and dissolved in oil) within the reservoir, with pressure effects having a secondary influence. The limited extent of the amplitude anomalies within the S-wave map (Fig. 2 of Davis et al., 2003) also supports this conclusion, as the S-wave anomalies should be more sensitive to pressure effects over most of this area. Detailed reservoir modeling and flow simulation is being conducted to calibrate the seismic results.

In addition to the main amplitude anomalies, there are also smaller off-trend anomalies that suggest that channeling of the CO_2 is occurring in some areas. One example of this is highlighted in Figure 7 (see arrow), where an E-W spur is observed emanating from the main anomaly. A similar trend is observed on the spatially coincident attenuation (or calculated permeability) image from Figure 6 (inset in Fig. 7) and to a lesser extent on the S-wave amplitude difference map (Fig. 2 of Davis et al., 2003). These observations imply the presence of enhanced permeability, which may be part of a larger pattern as described below.

A curvilinear pattern of S-wave identified anisotropy occurs along the bottom fringe of the sub-area (red rectangle) displayed in the inset of Figure 5, which correlates spatially with a similar pattern on the $\delta^{13}C$ map. This pattern generally follows the salt dissolution edge (white dashed line in inset of Fig. 5) of the underlying Prairie evaporite, suggesting that a network of fractures may exist within the reservoir in association with salt dissolution. Alternatively, the observed anisotropic zone may be associated with depositional facies-controlled fractures as it approximately corresponds to the transition from intershoal to shoal depositional facies in the Vuggy unit. In any case, both the seismic and geochemical results strongly suggest that the CO_2 flood is advancing preferentially along this zone of enhanced permeability.

Passive Monitoring

Long-term monitoring of microseismicity is intended to help assess the dynamic response of the reservoir to CO_2 injection and may prove useful as an alternate and/or complementary method of flood monitoring. Microseismicity will be analyzed to constrain the location, magnitude, source mechanism, and likely geologic source and frequency of occurrence of the characteristic seismicity and will be compared in detail with the CO_2 injection schedule and production rate variability. Local seismicity might be anticipated, for example, in association with CO_2-induced rock deformation (e.g., opening of existing fractures), rock failure due to salt dissolution in the underlying Prairie evaporite, or background seismicity associated with the regional stress regime.

Short-term monitoring to date has been unsuccessful in detecting significant microseismicity at the Weyburn field, in contrast to the experience in injection projects elsewhere (e.g., Maxwell et al., 2003). Short-term monitoring was conducted in 2001 for a period of several nights using the 48-channel hydrophone array deployed within the reservoir for the horizontal crosswell survey (see earlier section). Other attempts were made over a four-day cumulative period in 2000 and 2001 using the 12-level three-component downhole array deployed for vertical seismic profiling within a 200 m interval directly above the reservoir. To fully and finally assess microseismic levels at Weyburn, an eight-level array of three-component geophones has been cemented in place ~200 m above the reservoir. Data acquisition was initiated in August of 2003 and is intended to continue for at least six months.

CONCLUSIONS

The results obtained to date within the various elements of the Weyburn project are encouraging. The geoscience framework is at an advanced stage of construction and will form the basis for numerical modeling of the long-term fate of injected CO_2. The monitoring methods (seismic and geochemical) demonstrate that the response of the reservoir to CO_2 injection can be assessed and will be useful for the purposes of verifying the volume of injected CO_2. Ultimately, we anticipate that the results from the Weyburn project will contribute to rigorous assessment of the feasibility of using oil reservoirs for the sequestration of greenhouse gases.

ACKNOWLEDGMENTS

This article was written on behalf of the Weyburn project, which is run by the Petroleum Technology Research Centre of Regina, Saskatchewan, in collaboration with EnCana Resources (the operator of the Weyburn oil field). Financial sponsorship of the project is provided by Natural Resources Canada, the U.S. Department of Energy, Alberta Energy Research Institute, Saskatchewan Industry and Resources, the European Community, and ten industrial sponsors. Research is being conducted in North America and Europe, including federal and provincial government agencies, universities, and industry. This is publication 2003161 of the Geological Survey of Canada.

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Manuscript received October 14, 2003; accepted February 19, 2004. ❧