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Energy Procedia 1 (2009) 2349–2356

Energy Procedia

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GHGT-9

Integrated geophysical and geochemical research programs of the IEA GHG Weyburn-Midale CO_2 monitoring and storage project

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Abstract

Commercial-scale CO_2 injection has continued at the Weyburn field in Saskatchewan since 2000 as part of EnCana's enhanced oil recovery (EOR) project. As of Sept. 30, 2008, a total of ~18 megatonnes of CO_2 had been injected of which ~11 megatonnes remains (stored) in the reservoir. Geophysical and geochemical research activities carried out during Phase I (2000-2004) of the IEA Weyburn Project's Monitoring, Measurement and Verification (MMV) program have been continued and augmented during the Final Phase (2007-2011) and interim period. CO_2 migration within the reservoir is tracked using several geophysical techniques, including 4D multi-component seismic monitoring at intervals of 12-36 months and continuous subsurface passive recording of microseismic activity. Compositional evolution within this dynamic spatial framework is monitored by sampling and geochemical analysis of production fluids every 6 months, while potential CO_2 seepage to the surface is assessed through analogous time-lapse monitoring of shallow groundwater and soil gas. Additional key components of the Final Phase research program include discriminating pressure and fluid saturation effects in the seismic data through shear-wave data processing and inversion of amplitude versus offset information, forecasting dynamic CO_2 mass partitioning and long-term storage containment efficacy through reactive transport simulation, and evaluating the impact of CO_2 impurities and mineral trapping on reservoir/seal integrity through experimental work. Finally, the 4D seismic reflection and fluid chemistry data will be fully exploited to improve site characterization and dependent predictions of CO_2 storage performance using a novel stochastic inversion technique that integrates geophysical/geochemical monitoring and modeling activities.

Keywords: monitoring; storage;

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1. Introduction

The IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project has been studying long-term CO_2 storage at the EnCana Weyburn field in Saskatchewan since 2000. As of September 30, 2008, a total of ~18 megatonnes of CO_2 have been injected, with ultimate post-EOR storage of 20-30 megatonnes anticipated. A comprehensive suite of geophysical and geochemical monitoring techniques was implemented during Phase I (2000-2004) of the project's Monitoring, Measurement and Verification (MMV) program. This work clearly demonstrated the ability to track CO_2-induced physical and chemical changes in the reservoir, and qualitative comparisons showed that the CO_2 distributions inferred from these monitoring data were generally consistent with those predicted by reservoir simulation studies [1]. The objective in the Final Phase (2007-2011) is to further constrain and better quantify these observation-inferred distributions by refining, augmenting, and explicitly integrating those monitoring techniques that proved successful in Phase I. Toward this end, geophysical and geochemical research programs are under way that are focused on storage monitoring, methodology/prediction, and supporting lab-scale experimental studies. The geophysical and geochemical components of monitoring and methodology/prediction work have been designed to address the relevant CO_2 migration, sequestration, and isolation performance issues. The ultimate goal of this part of the project is explicit integration of these components together with key elements of site characterization to achieve simulation capabilities that reproduce historical pressure and production data while honouring diverse geophysical and geochemical monitoring results.

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doi:10.1016/j.egypro.2009.01.305

2. Reservoir Geology and the CO_2 Flood

CO_2 is being injected as part of EOR operations in the Weyburn reservoir -- a thin zone (< 30 m) of fractured carbonates within the Midale beds of the Mississippian Charles Formation at a depth of ~1450 m. Upward migration of CO_2 beyond the reservoir is impeded by the Midale Evaporite caprock, which itself is overlain by a series of aquitards including the Lower Watrous Member which forms the most extensive primary seal to the Weyburn system [2]. The Midale beds are naturally vertically fractured. The dominant fracture set within the reservoir strikes NE-SW as determined from core and imaging logs [3], and is sub-parallel to the regional trajectories of maximum horizontal stress [4]. The vertical stress at the reservoir level due to the lithostatic load is ~34 MPa, and the minimum horizontal stress is ~18-22 MPa in this region [5].

Following 36 years of water flood, CO_2-based EOR began in September of 2000 in 19 patterns (1A area in Fig. 1) of the EnCana Weyburn unit at an initial injection rate of 2.69 million m^3/day (or 5000 tonnes/day). Individual-well injection rates range from 0.04 to 0.3 million m^3/day. As of July 2008, a total of ~9800 tonnes/day of CO_2 was being injected within the entire Weyburn unit.

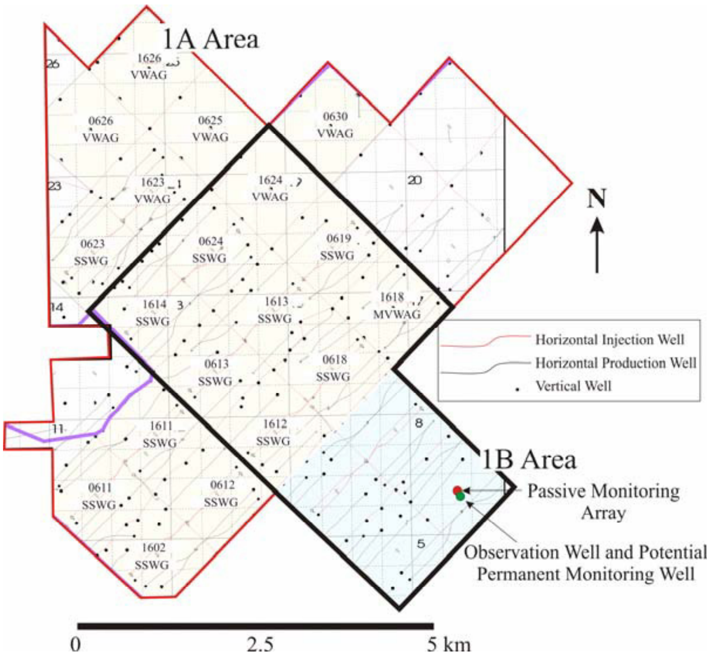

Figure 1 Location map of the Weyburn CO_2 flood/EOR area showing 23 injection patterns. The heavy black outline identifies the focus area for the geophysical/geochemical research program in the Final Phase of the Weyburn-Midale Project. The proposed site of a 200 –geophone permanent surface seismic monitoring array is the 1B area (blue rectangle). Individual patterns are numbered and the type of injection strategy being used is annotated.

3. Geophysical Research Program

The objectives of the geophysics research program are to: monitor the changes in subsurface distribution and concentration of injected CO_2; monitor levels of microseismicity induced by CO_2 injection; assess the economy, accuracy and applicability of monitoring methods for determining CO_2 volumes, distribution, concentration and leakage from the reservoir; and to determine the monitoring technologies needed as a function of time and estimated risk level. The technical work program for both geophysics and geochemistry was developed based primarily on gaps and suggestions for further work established at the end of Phase I of the project [1], recommendations from an expert review panel, and key technical gaps identified by the IPCC Special Report on Carbon Dioxide Capture and Storage [6].

3.1 Storage Monitoring

Time-lapse seismic: The effectiveness of time-lapse seismic monitoring was clearly demonstrated in Phase I of the project with results immediately amenable to qualitative assessment of CO_2 distribution in the subsurface. To advance the quantitative interpretation of time-lapse seismic monitoring, further work is required to calibrate the method. To accomplish this, 3D-3C time-lapse seismic surveys will be continued along with simultaneous measurement of *in situ* properties (see below). As the injection process is dynamic, seismic data and *in situ* measurements must occur in the same time frame to make comparison valid. Time-lapse seismic monitoring will focus on a subregion of the field (see Fig. 1) which will encompass the existing downhole passive monitoring array and observation wells, as well as the prospective site of a new dedicated monitoring well. Plans have been developed for deployment of a permanent surface seismic array in the 1B area (see Fig. 1) that will further facilitate time-lapse seismic monitoring.

In situ measurements: Current interpretations of CO_2 induced anomalies in the time-lapse seismic data are made based predominantly on core-scale rock property measurements [7] extrapolated using rock physics models (primarily Gassman's relation). The "actual" effect on seismic properties of CO_2 needs to be measured *in situ* to better calibrate the seismic interpretations. Full suites of time-lapse geophysical logs will be acquired for direct comparison with the time-lapse seismic results. Downhole spinner surveys will be utilized to test for preferential flow paths (e.g., fracture systems) that have been postulated based on the seismic monitoring results in Phase I. The effects of pressure and saturation need to be separated in determining the distribution of CO_2 in the reservoir from time-lapse seismic monitoring. Pressures measured at the wellheads, supplemented by limited downhole pressure measurements, will be utilized to further model the contribution of pressure effects to the observed seismic anomalies. Also, within the passive monitoring area, pressure measurements will benefit geomechanical modeling work and correlations with microseismicity.

Dedicated monitoring systems: The need for long-term monitoring in CO_2 storage projects suggests the suitability of permanently installed monitoring systems that are capable of providing semi-continuous surveillance. Plans have been developed for deployment of a dedicated permanent surface seismic monitoring array and a permanently instrumented monitoring well. The objective of deploying a dedicated 2D surface seismic array is to demonstrate improved data repeatability afforded by a semi-permanent installation, increased flexibility in terms of time between monitor surveys, and the adequacy of "sparse" data for the purposes of time-lapse monitoring. The proposed surface seismic array comprises 200 3-component geophones deployed at intervals of 150-200 m on a regular grid covering the 1B area (see Fig. 1). Similarly, the permanent monitoring well will make ongoing downhole measurements of pressure, temperature, fluid saturations and microseismicity that can be compared with other monitoring parameters.

Other geophysical methods: Alternate or complementary means of monitoring are being considered for use where seismic methods are not applicable either due to economic or technical reasons, or where complementary monitoring is required. For example, bulk electrical resistivity measurements potentially provide an independent way of monitoring CO_2 saturations. Metallic well casings can be used as long electrodes to measure the changes in subsurface resistivity caused by CO_2 injection. Numerical modeling will be conducted to assess the feasibility of using long electrode electrical resistance tomography (LEERT) [8] at Weyburn to monitor intra-reservoir CO_2 migration. The modeling will evaluate distinct well configurations in the 1B area (Fig. 1) and will assess electrical response after two months and after 12 months of CO_2 injection. Predicted changes in signal-to-noise levels will be compared against those observed in previous field projects to assess whether the injection signal is sufficiently above the likely noise floor. Synthetic data will be inverted to produce 2D resistivity change tomographs for those cases that are likely to have an acceptable signal-to-noise ratio.

Passive seismic monitoring: The overall goals of the passive monitoring program are to assess the safety (absence of significant induced seismicity) and security (caprock integrity) of the injection process, to monitor the geomechanical response of the reservoir, and to characterize fracture/fault systems within the reservoir. Passive seismic monitoring has been ongoing since August of 2003 [9, 10] using an 8-level (24-channel) downhole seismic monitoring array in the 1B area. Background seismicity was recorded for 6 months prior to the start of injection of CO_2 in a nearby well. Approximately 60 microseismic events were recorded with moment magnitudes of -3 to -1 with maximum detection distances of ~500 m during the 6-month period following the start of CO_2 injection in this well. The observed microseismicity occurred in three spatial-temporal clusters in association with abrupt changes in local injection/production activities. The accuracy of locations determined for these events was limited by the low-frequency and emergent nature of the seismic signals. The absence of significant induced microseismicity during the initial monitoring period attests to the safety of injection in regard to any possible damage to surface structures. However, the lack of microseismicity also means that passive monitoring will have limited use in tracking the spread of the CO_2 plume. Passive monitoring will be continued through the Final Phase as a means of demonstrating ongoing safe operation. Subsequent deployment of a second downhole array (either permanent or temporary) in vicinity of the original array should improve event location accuracy.

3.2 Methodology: Data Processing, Analysis, Inversion and Modelling

Data Reprocessing: The Phase I time-lapse seismic images that were used to qualitatively infer the distribution of CO_2 in the subsurface were principally obtained from P-wave data. In the Final Phase, the goal is to improve on the current time-lapse images, to better quantify the data repeatability, and to extract more information from the existing seismic data with the ultimate goal of achieving quantitative estimates of CO_2 distribution and saturation. Toward this end, the primary objective of data reprocessing will be utilization of the converted-wave (PS) and pure shear (SS) components as a means of improving pressure vs. saturation discrimination in the time-lapse seismic data.

Seismic Modeling and Inversion: A comprehensive approach will be adopted toward obtaining more accurate seismic-based spatial maps of CO_2 saturation and pore pressure changes in the subsurface. This will include rock physics analysis (see next section), seismic modeling, pressure-saturation inversion, and uncertainty estimation. 1D and 3D (prestack and post-stack) time-lapse seismic modeling will be conducted using the existing Weyburn Earth model to allow quantitative comparison of predicted changes in seismic response due to CO_2 injection and the observed change in seismic response from the time-lapse data. The predicted seismic responses will be calculated for either flow simulation results and/or saturation/pressure inversion results. Discrepancies between the predicted and measured time-lapse responses will allow further assessment of the inversion procedure and/or the flow model. Prestack amplitudes and travel times determined for the time-lapse seismic data will be inverted to produce maps (with corresponding uncertainty estimates) of pressure and CO_2 saturation changes corresponding to the times of each monitor survey. Prior to inversion, time-lapse prestack processing will be performed. Non-uniqueness of the inversion results will be reduced by including *a priori* data such as CO_2 injection volumes, geochemical information and other well data. Inversion results will be used to constrain flow simulations.

3.3 Process/property studies

Rock physics and fluid properties: New analyses will build on existing work from Phase I to further refine the dependence of seismic properties on CO_2 saturation and pressure changes. In particular, the role of increased sensitivity to effective pressure changes when pressures approach the "frac-point" pressure will be assessed. This analysis is key to inverting the time-lapse seismic results for pressure and saturation changes.

Reservoir geomechanics: The goal is to improve our understanding of the geomechanical response of the reservoir to EOR-related CO_2 injection and production. This will be achieved by analysis of passive monitoring data from the Weyburn-Midale field, including shear-wave splitting/anisotropy analysis to constrain fracture patterns and temporal stress variations. A geomechanical model will be constructed using Weyburn-Midale data (rock properties, geology, seismic, production) incorporating the flow properties of faults from an external worldwide petroleum database. This model will be utilized for coupled stress/fluid flow numerical simulations to predict the geomechanical response of the reservoir to both extraction and injection. Specific objectives include: 1) characterization of fault/fracture patterns near the reservoir if possible; 2) constrain the temporal behaviour of the stress field near the reservoir; 3) monitor fault/rock failure; 4) assess the potential for CO_2 escape along faults; 5) investigate hysteresis effects associated with pressure cycling; 6) assess the ability of passive seismic methods for monitoring the geomechanical response.

3. Geochemical Research Program

The geochemical research program includes explicitly integrated yet conceptually distinct monitoring, modeling, and experimental components. The principal objectives of this program are as follows: to monitor CO_2-induced compositional evolution within the reservoir through time-lapse sampling and geochemical analysis of produced fluids; to document the absence (or presence) of injected CO_2 within reservoir overburden through analogous monitoring of shallow groundwater and soil gas; to predict intra-reservoir CO_2 migration paths, mass partitioning among distinct trapping mechanisms, and reservoir/caprock permeability evolution through reactive transport modeling; to assess the impact of CO_2 impurities, mineral trapping, and fracture flow on long-term storage performance through experimental studies that directly support the monitoring and modeling work; and to provide a summary of geochemical monitoring/modeling techniques as well as the criteria/methodology for selecting an appropriate suite of such capabilities for site-specific deployment in CO_2-flood EOR/storage projects.

4.1 Storage monitoring

Time-lapse sampling and analysis of reservoir fluids: During Phase I, the compositional evolution that attends progressive CO_2-hydrocarbon-brine-rock mass transfer during CO_2-flood EOR/storage at Weyburn was documented by periodic (thrice yearly) sampling and comprehensive chemical/isotopic analysis of produced brines and gases from a suite of 50-60 wells within and nearby the 1A/1B area [1,11]. This unique database, which can be used to infer key reactions within the overall mass transfer process, provides an invaluable history-matching resource for reservoir simulation and reactive transport modeling studies, and will be fully exploited as such during the Final Phase (see sections 4.2 and 5 below). It will also be extended over the next three years on a limited scale. To facilitate complete data continuity, the 12th post-baseline survey will constitute a comprehensive sampling of the same 50-60 well suite sampled during the last Phase I trip (Monitor 11, September 2004). Subsequently, two trips per year are planned for 2009-2010; these will cover a 36 well suite within 1B area and the adjacent 9-pattern subset of area 1A, which corresponds to the targeted focus area of integrated geophysical/geochemical monitoring and modeling programs.

The compositional evolution of produced hydrocarbons (and progressively hydrocarbon-enriched CO_2) that characterizes the multiple-contact miscibility process of CO_2-flood EOR was also documented during Phase I by periodic sampling and analysis of six wells, again located within the Weyburn 1A/1B area [1,12]. This database, while limited, is nonetheless essential: together with the degree of aqueous solubility trapping deduced from brine analyses it facilitates history matching of CO_2 mass partitioning among reservoir fluid phases. Consequently, it too will be extended during the Final Phase, again on a more limited scale. Specifically, only the two wells that occur within the targeted focus area (area 1B and adjacent 9-pattern subset of area 1A) are slated for continued monitoring over the next three years, providing partial data continuity with Phase I efforts.

Time-lapse sampling and analysis of shallow groundwater and soil gas: Documenting acceptable isolation performance requires demonstration of the absence (or acceptably low concentrations) of injected CO_2 within reservoir overburden, ranging from the caprock to near-surface horizons. It is particularly important to ensure that water quality within overlying potable aquifers has not been compromised, and, of course, that surface release of injected CO_2 has not occurred. To address the former concern, annual sampling and geochemical analysis of shallow groundwater from farm and domestic wells (completion depths < 30 m) in the Weyburn Phase 1A/1B area, initiated during Phase I [13, 14] and maintained during the Interim Phase (annual surveys 2004-2006), will be continued in the Final Phase.

To address concerns regarding surface release of CO_2, annual soil gas monitoring surveys of a representative background site and 360-point grid within the Weyburn 1A/1B area were carried out by the British Geological Survey (BGS) during Phase I [1]. The magnitude and variation of CO_2 fluxes measured at Weyburn remained within the range of natural prairie soils, as confirmed by comparison with those measured at the background site. This result indicates that there has been no seepage of injected CO_2 to the shallow biosphere. Because further extension of this “clean” record is critical for public acceptance of geological storage as a safe mitigation strategy, continued soil gas monitoring is planned during the Final Phase.

4.2 Storage prediction

Reactive transport modeling: During Phase I, reservoir simulation efforts focused on multi-scale history matching, EOR performance prediction, and CO_2 storage capacity and distribution forecasting. The storage capacity predictions were augmented by geochemical modeling work, which was used to predict the long-term efficacy of mineral trapping processes. During the Final Phase simulation efforts will exploit the reactive transport modeling approach, a unique methodology that explicitly couples multiphase flow and kinetically-controlled geochemical processes. Thus, it provides a unique link between—and necessary extension of— traditional reservoir simulation and geochemical modeling techniques. Building upon earlier work [15, 16, 17], advanced reactive transport modeling capabilities will be used to predict and evaluate observed CO_2 migration paths, EOR/storage performance, sequestration partitioning among distinct trapping mechanisms, reservoir/caprock permeability evolution, and isotopic variations. In these studies, prediction/observation discrepancies will be minimized by iterative model refinement per history matching of immiscible CO_2 migration (from seismic monitoring), enhanced oil and CO_2 recovery (from production records), evolving fluid compositions (from geochemical monitoring), and mineral trapping (as inferred from lab-scale experiments and observed from field samples using new laboratory techniques, as described below).

4.3 Process/property studies

Impact of CO_2 impurities on storage performance: The presence of CO_2 impurities (e.g., H_2S, SO_X) may significantly impact mineral dissolution/precipitation processes, porosity/permeability evolution, reservoir/seal integrity, and dependent EOR/storage performance. Laboratory batch and plug-flow reactors provide experimental forums that are uniquely well suited for quantifying such impacts. Leveraging previous experience [18], during Final Phase the consequences of injecting impure CO_2 (H_2S and SO_2 contaminants) on reservoir and seal integrity at Weyburn will be assessed using a matrix of closed (static) and open (flowing) system experiments that will be designed and simulated using lab-scale reactive transport modeling. Representative Weyburn reservoir and caprock samples from the 1A/1B area will be used in these experiments, which will be conducted at elevated P-T conditions to simulate the reservoir environment and/or accelerate mineral reaction rates.

Micron-scale reservoir matrix analysis: Although porosity/permeability evolution caused by CO_2-induced mineral dissolution/precipitation exerts an important influence on long-term storage performance, the slow kinetics of this process represent a significant barrier to identifying and quantifying these effects in the field over short time scales (up to several years) using standard analytical techniques applied to altered core. Hence, there is a need to develop and demonstrate new methods for accurately characterizing the effects of early-stage mineral reactions. Building upon recent work [19], during the Final Phase conventional and synchrotron micro-beam techniques will be used on pre- and post- CO_2 flood Weyburn core to examine the micron-scale 3D pore-space network and distribution of pore-lining minerals. The goal is to identify incipient mineral and petrophysical alteration effects associated with CO_2 injection. Core samples subjected to impure CO_2 at in the laboratory (preceeding study) will also be analyzed using this approach.

Fracture permeability and two-phase flow: The density, orientation, and permeability of natural fractures within the Weyburn reservoir will have a significant impact on fluid migration during CO_2-flood EOR and subsequent CO_2 storage. Accurate characterization of the fluid transport properties of these fractures will help optimize EOR operations and is required for modeling long-term storage performance. During the Final Phase, fracture permeability will be measured in reservoir cores as a function of effective stress, fluid pressure, and CO_2 saturation; fracture surface roughness will be measured and empirically correlated with stress-dependent relative permeabilities; and two-phase flow through acrylic casts of reservoir fractures will be analyzed as a function of fracture aperture and roughness as well as fluid density and viscosity.

Fracture permeability alteration and process scaling: Improved understanding of the manner in which coupled hydrological, geochemical, and geomechanical processes influence fracture flow is required for accurate forecasting of CO_2-flood EOR and long-term storage performance. More specifically, there is a pressing need to develop experimentally-calibrated physical and numerical models that explicitly integrate the geochemical and geomechanical components of aperture evolution, which effectively controls that of reservoir and caprock integrity. Building upon recent advances [20], during the Final Phase CO_2-induced alteration of natural fractures within Weyburn core will be investigated experimentally and computationally using this approach. After history matching experimental results, the lab-scale computational model will be used to address greatly extended space-time dimensions. Results from this scaling investigation will be used to propose effective constitutive relationships for incorporation into field-scale reactive transport models.

5. Formal Integration (Stochastic modeling)

During Phase 1, time-lapse seismic reflection data were used to map CO_2 migration, while an extensive fluid sampling program documented the concomitant geochemical evolution triggered by CO_2-fluid-rock interactions. During the Final Phase, these existing seismic and geochemical data sets—augmented by CO_2/H_2O injection and HC/H_2O production data as well as additional Final-Phase monitoring results—will be used to improve both site characterization and dependent predictions of long-term storage performance at Weyburn. The proposed methodology explicitly integrates reactive transport modeling, facies-based geostatistical methods, and a novel Monte Carlo Markov Chain (MCMC) stochastic inversion technique [21] to optimize agreement between observed and predicted storage performance. Such optimization will be accomplished through stepwise refinement of first the reservoir model—principally its permeability magnitude, anisotropy, and heterogeneity—and then geochemical parameters—primarily key mineral volume fractions and kinetic data. It is anticipated that these refinements will facilitate significantly improved history matching and forward modeling of CO_2 storage. We are unaware of any previous attempts to explicitly integrate seismic and geochemical data, which represent the fundamental components of CO_2 monitoring at Weyburn and future commercial storage projects. Thus, the proposed methodology is both new and broadly applicable.

6. Initial results from the Final Phase

Most of the work conducted during the Interim and start of the Final Phase involves acquisition of new data, with detailed analysis only having just begun. Time-lapse seismic surveys were acquired in 2004, 2005 and 2007 with the next monitor survey planned for late fall of 2008. Time-lapse images from 2002 and 2004 (Figs. 2 and 3) document the expanding volume of injected CO_2 within the reservoir interval. Initial time-lapse logging was conducted in 2005-2006 including a baseline in November, 2005 and 2 monitor surveys in May and December of 2006. Logs included neutron-density (open hole), resistivity, sonic, and RST saturation logs. Passive monitoring in the 1B area continued from the end of Phase I to the present has further documented very

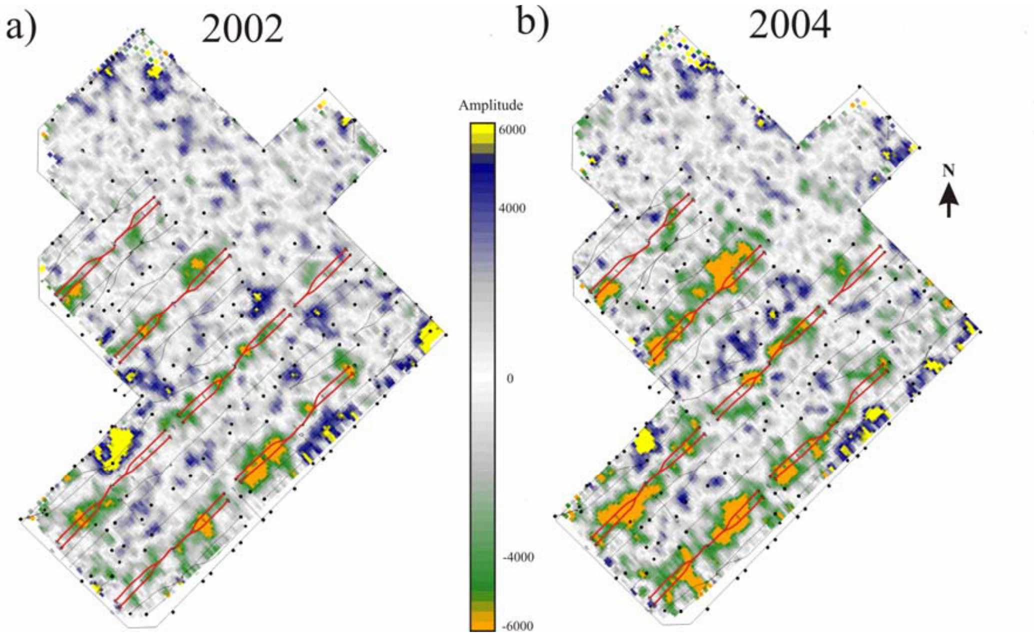

Figure 2 Time-lapse amplitude anomalies (relative to 2000 baseline survey) determined in the vicinity of the reservoir. Dual-leg horizontal injection wells are highlighted in red.

low levels of very low magnitude (-2.5 to -1.5) induced microseismicity associated with CO_2 injection. From April, 2004 to May, 2007 less than 100 events have been recorded that are clearly associated with the reservoir's response to CO_2 injection. Also, as observed in Phase I, the events occur in clusters in both space and time.

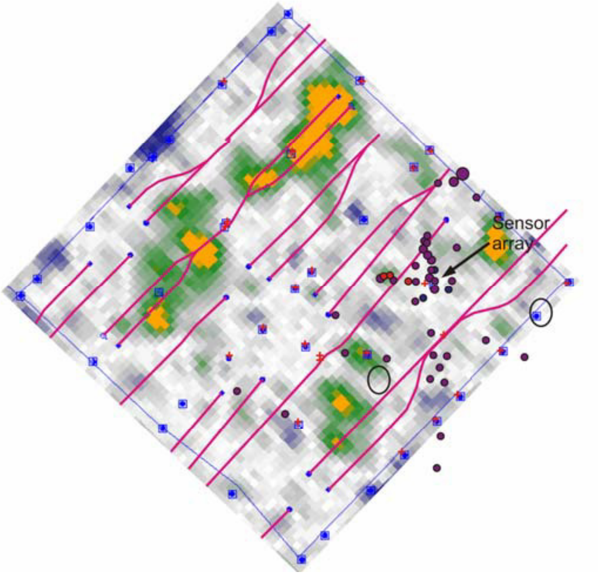

Figure 3 Microseismic event locations (dots) superposed on the 2004-2001 time-lapse amplitude difference map for the reservoir invterval in the 1B area. Events are shown from the recording period of Jan.-Mar., 2004 (from [10]).

Sampling and analysis of hydrocarbons from selected production wells in the Midale field (adjacent to Weyburn) was conducted during the Interim Phase (2005-2007). This study [22] established a repository of oil and gas samples from both CO_2-free and CO_2-exposed areas of the field, and, through acquisition of vapor-liquid equilibrium data, provided a conventional equation-of-state (EOS) characterization of Midale oil and gas for use within potential future modeling investigations. Also during the Interim Phase, a baseline groundwater quality survey of analogous shallow wells within and near the Midale field was conducted. In this survey, 24 wells were sampled and analyzed for major ions, trace elements, DOC, and TDS, providing a pre-injection baseline against which potential subsequent surveys during and after CO_2 injection will be compared [23]. Ongoing soil gas sampling during the Interim Phase (2005) further documented that surface CO_2 fluxes at Weyburn continue to remain within the range of natural prairie soils [24]. The twelfth post-baseline production fluid sampling survey was conducted in October of 2008, covering the same 50-60 well suite sampled during the last Phase I monitor survey.

7. Best practices for EOR-related CO_2 storage

The ultimate goal of the Final Phase geophysics/geochemistry research program is to contribute to best practices for EOR-related CO_2 storage. Specifically, we intend to include the following: 1) Summary of relevant geochemical monitoring and reactive transport modeling techniques together with the criteria and methodology for selecting an appropriate suite of such capabilities for site-specific deployment. 2) Evaluation of the applicability, effectiveness and limitations of different surface and subsurface monitoring techniques. 3) Characterization of the accuracy of monitoring technologies for quantitatively predicting the location and volume of CO_2 in the subsurface. 4) Identification of the parameters and conditions that control accuracy and precision and suggest/test methods that would lead to improvements in predictive and quantitative capability. 5) Determination of appropriate monitoring technologies needed as a function of time and risk.

Acknowledgements

The research program as described here has been designed and will be implemented by a team of individual researchers including M.-J. Kendall and J. Verdon (Leeds University), I. Morozov, T. Kotzer (University of Saskatchewan), M. Meadows (Fugro Seismic Imaging), Engineering Seismology Group Canada, B. Mayer and M. Shevalier (University of Calgary), H. Maathuis and N. Freitag (Saskatchewan Research Council), E. Perkins and S. Talman (Alberta Research Council), A. Ramirez, S. Carroll, and S. Carle (Lawrence Livermore National Laboratory). Also, EnCana has contributed data and field access that make this research possible.

References

1. White, D.J., Hirsche, K., Davis, T., Hutcheon, I., Adair, R., Burrowes, G., Graham, S., Bencini, R., Majer, E., and Maxwell, S.C., 2004. Theme 2: Prediction, Monitoring and Verification of CO_2 movements, in M.Wilson and M. Monea (eds.) IEA GHG CO_2 Monitoring and Storage Project Summary Report 2000-2004, PTRC, Regina, 2004.
2. Whittaker, S., Rostron, B., Khan, D., Hajnal, Z., Qing, H., Penner, L., Maathuis, H., and Goussev, S., 2004. Theme 1: Geological Characterization, in M.Wilson and M. Monea (eds.) IEA GHG CO_2 Monitoring and Storage Project Summary Report 2000-2004, PTRC, Regina, 2004.
3. Bunge, R.J., 2000. Midale reservoir fracture characterization using integrated well and seismic data, Weyburn Field, Saskatchewan, M.Sc. Thesis, Reservoir Characterization Project, Colorado School of Mines, Golden, Colorado, 204 p
4. Bell, J.S., and Babcock, E.A., 1986. The stress regime of the western Canadian Basin and implications for hydrocarbon production, Bulletin of Canadian Petroleum Geology, 34, 364-378.
5. McLellan, P.J., Lawrence, K., and Cormier, K., 1992. A multiple-zone acid treatment of a horizontal well, Midale Saskatchewan, Journal of Canadian Petroleum Technology, 31, 71-82.
6. IPCC Special Report on Carbon Dioxide Capture and Storage, 2005.
7. Brown, L.T., 2002. Integration of Rock Physics and Reservoir Simulation for the Interpretation of Time-Lapse Seismic Data at Weyburn Field, Saskatchewan, M.Sc. thesis, Reservoir Characterization Project, Colorado School of Mines, Golden, Colorado, 208 p.
8. Daily, W., Ramirez, A., Newmark, R., and Masica, K., 2004. Low-cost tomographs of electrical resistivity, The Leading Edge, 472-480.
9. Maxwell, S.C., White, D.J., and Fabriol, H., 2005. Passive seismic imaging of CO2 sequestration at Weyburn, 67th EAGE Conference and Exhibition, Madrid, Spain, expanded abstract, 4p.
10. Deflandre, J.-P., Andonof, L.J., Fabriol, H., and White, D., 2006. Induced microseismicity and CO_2 injection at the Weyburn oil field: improvement in source locations, *In* Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway, 3p.
11. Emberley, S., Hutcheon I., Shevalier, M., Durocher K., Mayer B., Gunter W.D., Perkins, E.H., 2005, Monitoring of fluid-rock interaction and CO2 storage through produced fluid sampling at the Weyburn CO2-injection enhanced oil recovery site, Saskatchewan, Canada: Applied Geochemistry, v. 20, n. 6, p. 1131-1157.
12. Freitag, N.P., Zhang, P.Y.P., and Huang, S.S., 2004, Fluid and phase behavior monitoring between August 2000 and March 2004: IEA GHG Weyburn CO2 Monitoring and Storage Project: SRC Pub. No. P-110-662-C-04, 83 p.
13. Maathuis, H. and M. Simpson, 2003, *Regional hydrogeology of the Weyburn CO2 Monitoring Project area: Task 2.2.3 – Regional "Shallow" Hydrogeology, Volumes I and II*. SRC Pub. No. 11410-1E03, 45p.
14. Mollard, J. D. and J. I. Cosford, 2003, *Shallow hydrogeology of the Weyburn Phase 1A EOR area*: Internal report, IEA GHG Weyburn CO2 Monitoring and Storage Project, 40p, 114 Figs.
15. Law, D., Huang S., Freitag, N., Perkins, E., Wassmuth, F., Dunbar, B., Asghari, K, 2004. Theme 3: CO_2 storage capacity and distribution predictions and the application of economic limits, in M.Wilson and M. Monea (eds.) IEA GHG CO_2 Monitoring and Storage Project Summary Report 2000-2004, PTRC, Regina, 2004.
16. Johnson, J.W. Nitao, J.J., and Knauss, K.G., 2004, Reactive transport modeling of CO_2 storage in saline aquifers to elucidate fundamental processes, trapping mechanisms, and sequestration partitioning: in Geol. Soc. London Spec. Pub. 233 *Geologic Storage of Carbon Dioxide*, Baines, S.J., and Worden, R.H., eds., p. 107-128.
17. Johnson, J.W., Nitao, J.J., Morris, J.P., 2005, Reactive transport modeling of cap rock integrity during natural and engineered CO_2 storage: in *Carbon Dioxide Capture for Storage in Deep Geologic Formations: Vol. 2*, Thomas, D.C., and Benson, S.M., eds., p. 787-813.
18. Knauss, K.G., Johnson, J.W., and Steefel, C.I., 2005, Evaluation of the impact of CO_2, co-contaminant gas, aqueous fluid and reservoir rock interactions on the geologic sequestration of CO_2: Chemical Geology, v. 217, n. 304, p. 339-350.
19. Glemser, C.T., 2007, Petrophysical and geochemical characterization of Midale carbonates from the Weyburn oilfield using synchrotron X-ray computed microtomography: M.Sc. Thesis, Univ. Saskatchewan (Saskatoon, SAS), 132 p.
20. Detwiler, R.L., 2008, Experimental observations of deformation caused by mineral dissolution in variable-aperture fractures: J. Geophys. Res. (Solid Earth), v. 113, v. B8.
21. Ramirez, A.L., Nitao, J.J., Hanley, W.G., Aines, R.D., Glaser, R.E., Sengupta, S.K., Dyer, K.M., Hickling, T.L., and Daily, W.D., 2005, Stochastic inversion of electrical resistivity changes using a Markov Chain, Monte Carlo approach: J. Geophys. Res., v. 110, n. B2.
22. Freitag N.P., 2007, Baseline oil and gas sampling of the Midale Field: IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project: SRC Pub. P-110-798-C-07, 39 p.
23. Maathuis, H., and Zlipco, D., 2007, Groundwater quality survey Apache Area, near Weyburn, Saskatchewan: SRC Pub. 12031-1C07, 23 p.
24. Jones, D.G., and Beaubien, S.E., 2006, Soil Gas Monitoring at the Weyburn Unit in 2005: COAL Rxxx, DTI/Pub URN 06/xxxx, 79 p.