Monitoring CO_2 storage during EOR at the Weyburn-Midale Field

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Carbon dioxide (CO_2) and hydrocarbons both occur as natural accumulations within the Earth and share an intertwined industrial history. Research in the 1950–1960s demonstrated that CO_2 had potential as a miscible agent for enhanced oil recovery (EOR), but commercial-scale implementation of this method was limited by the availability of a large supply of inexpensive CO_2. By the mid-1980s, CO_2 from large natural occurrences in the southwestern U.S. was being transported by pipeline to oil fields in the Permian Basin of Texas, which allowed deployment of CO_2 flooding as a large-scale tertiary EOR method. It is estimated that tertiary oil recovery using CO_2 could add as much as 13 billion barrels to existing recoverable resources in the U.S. (USDOE, 2002).

To date, CO_2 supply has continued to be a limiting factor to more extensive implementation of CO_2 flooding for EOR. However, this will soon change.

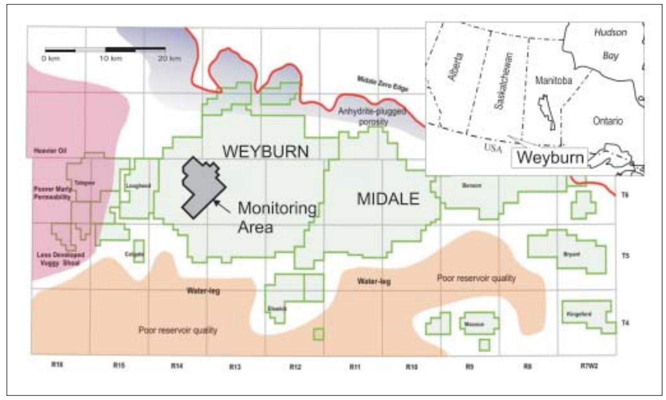

Figure 1. Map of the EnCana Weyburn and Apache Midale EOR fields including reservoir quality. Upper inset shows location of the field in southeastern Saskatchewan. Monitoring area identifies the region shown in Figures 5 and 6.

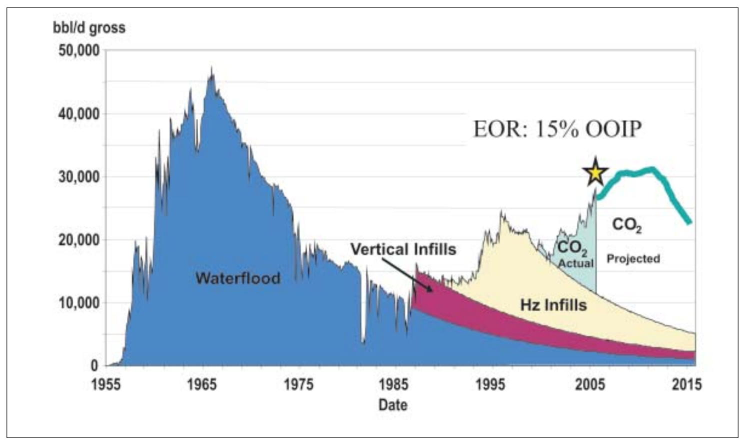

Figure 2. Production history for the EnCana Weyburn unit.

It is now widely recognized that man-made CO_2 released into the atmosphere is a significant contributor to the greenhouse gas effect and related global warming. With plans to drastically reduce the venting of CO_2 through capture at the source, vast volumes of CO_2 will need to be sequestered. This will make new sources of CO_2 available for EOR. However, since EOR is capable of using only a fraction of the CO_2 that must be sequestered, saline aquifers will likely provide the vast storage capacity that is required. For example, within the Western Canada sedimentary basin, it is estimated that approximately 500 megatonnes of CO_2 could be stored through EOR operations, with an additional 5000 megatonnes of storage in depleted oil and gas reservoirs. This compares with an estimated CO_2 capacity of 1 billion megatonnes in saline aquifers. Although EOR operations will play a very minor role for CO_2 storage in the long-term, they do provide readily available, large-scale pilot project sites for testing and developing technologies and protocols required for long-term storage of CO_2. Furthermore, most EOR sites reside in areas where the local populations are familiar with resource-related industrial activity, and EOR provides an initial financial incentive for CO_2 storage.

The IEA Weyburn-Midale CO_2 Monitoring and Storage Project has been conducting storage-related research since 2000 (e.g., Li 2003; Davis et al. 2003; White et al. 2004), piggybacking on the commercial EOR operations of EnCana Corporation. A focus of the project is the testing and development of monitoring methods that allow effective tracking of CO_2 in the subsurface. Efficient distribution and containment of CO_2 within the target zone is essential for both optimized EOR and maximizing subsequent long-term CO_2 storage. Time-lapse seismic imaging, supplemented by other complementary techniques such as passive seismic monitoring, fluid-flow simulations, and geochemical monitoring of production fluids, has proven to be an effective means of tracking the distribution of CO_2 within the reservoir.

The Weyburn-Midale Field

The Weyburn-Midale Field lies within the Williston Basin in southeastern Saskatchewan (Figure 1). It originally contained an estimated 1.9 billion barrels of oil, with approximately 524 million barrels recovered from 1953 to 2000 through primary production, water flood, and well-infilling programs (Figure 2). Following initial CO_2 injection tests conducted in the Midale Field by Shell in the 1980s and 1990s, PanCanadian (now EnCana Corporation) initiated field-scale CO_2 flooding in 2000 in the Weyburn Field. The initial injection rate was 2.7 million m^3/d (or 5000 tonnes/day) and eventually increased to ~10,000 tonnes/d, with individual well injection rates ranging from 0.04 to 0.3 million m^3/d. Apache Canada began CO_2 injection in 2005 in the adjacent Midale field. It is anticipated that EOR operations in the two fields will produce an additional 215 million bar-

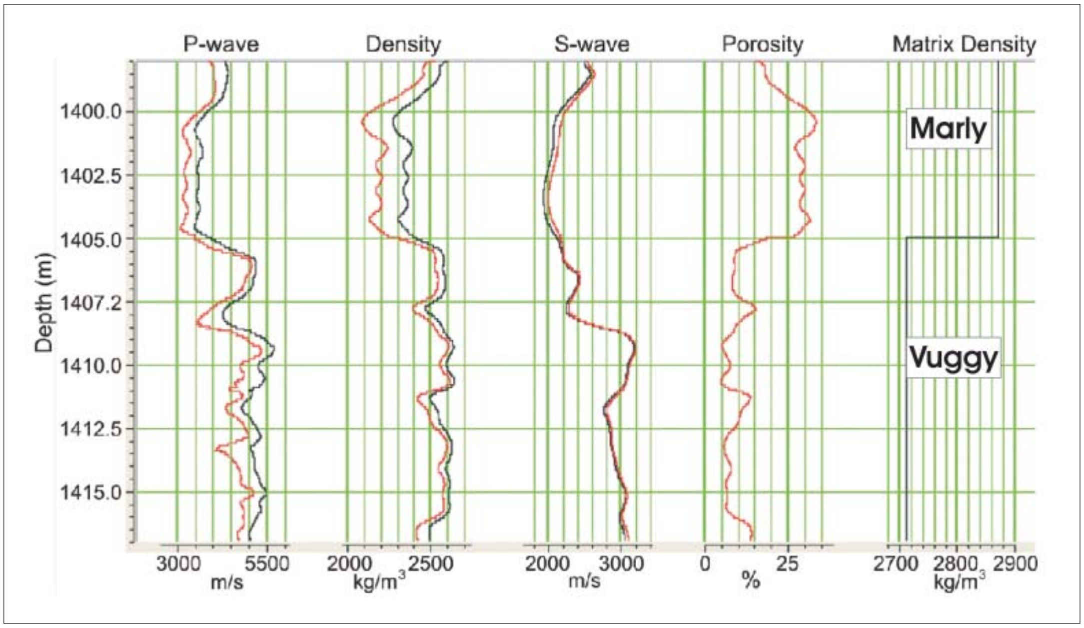

Figure 3. Log-based fluid substitution results calculated using the Gassmann equation. The original logs are shown in black, and logs with simulated CO_2 injection (substitution of brine by 30% brine and 70% CO_2) are shown in red. The rock matrix properties used in this modeling were based on laboratory core-property measurements by Brown in 2002.

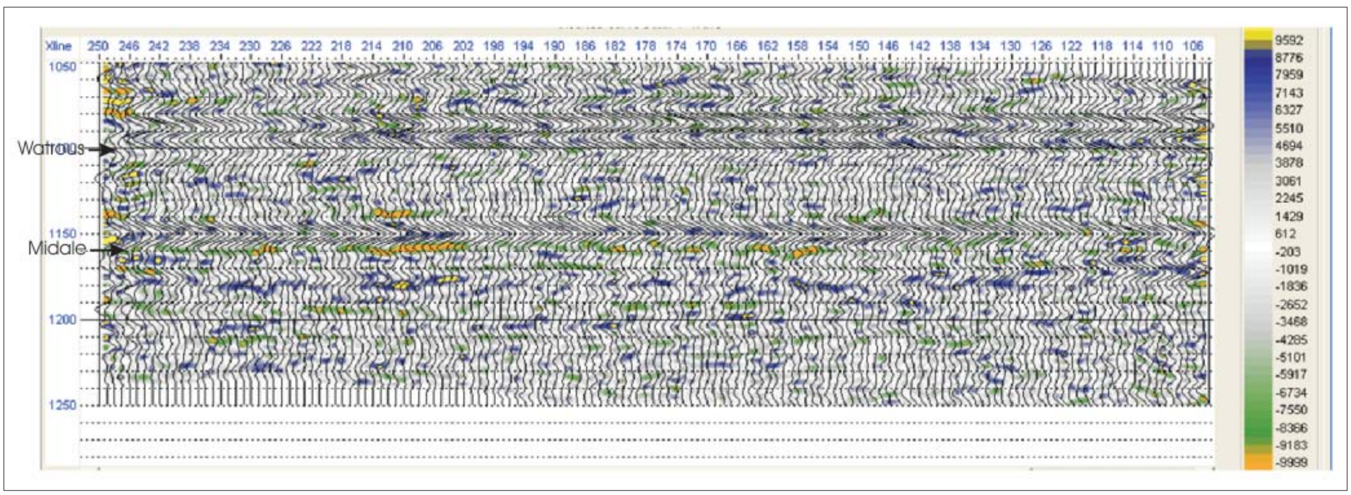

Figure 4. Time-lapse amplitude differences (2004 minus baseline data) are shown in color for a slice through the 3D difference volume. The baseline data are shown as a wiggle trace overlay (deflection to the right=positive amplitude). The top of the Watrous (seismic peak) and the Midale Marly (seismic trough) units are indicated. The vertical axis is two-way traveltime (ms), and the horizontal axis shows crossline numbers (10 crosslines constitute 400 m).

rels of oil and sequester approximately 35 million tonnes of CO_2. Cumulative stored CO_2 surpassed 12 million tonnes in 2008, making Weyburn-Midale the largest land-based CO_2 storage project in the world.

Weyburn oil reserves lie within a thin zone (< 30 m) of fractured carbonates in the Midale beds of the Mississippian Charles Formation at a depth of ~1450 m. The reservoir is comprised of vuggy limestone ("Vuggy") and overlying marly dolostone ("Marly") that are sealed above by anhydritic dolostones and anhydrites. Upward migration of the CO_2 is impeded by the evaporite caprock, which is overlain by a series of aquitards, including the Lower Watrous Member, which forms the most extensive primary seal to the Weyburn system (Whittaker et al., 2004). The dominant fracture set within the reservoir strikes NE-SW subparallel to the regional trajectories of maximum horizontal stress. Horizontal wells within the EnCana Weyburn Field are oriented parallel to the predominant fracture direction.

Time-lapse seismic monitoring

The estimated effects of CO_2 injection on seismic properties within the reservoir interval are shown in Figure 3. As can be seen, the P- and S-wave velocities change by mean values of ~-8% and 1.5%, respectively, when brine is largely replaced by CO_2. The associated decrease in bulk density is accentuated in the Marly dolostone due to its higher porosity. The magnitude of these changes is large enough to produce an observable seismic response to CO_2 injection. Simulation of the effects of pressure indicate that P-wave velocities are reduced by <4% due to reduced effective pressure associated with injection. However, it is recognized that there is increased uncertainty in these simulation results for low ef-

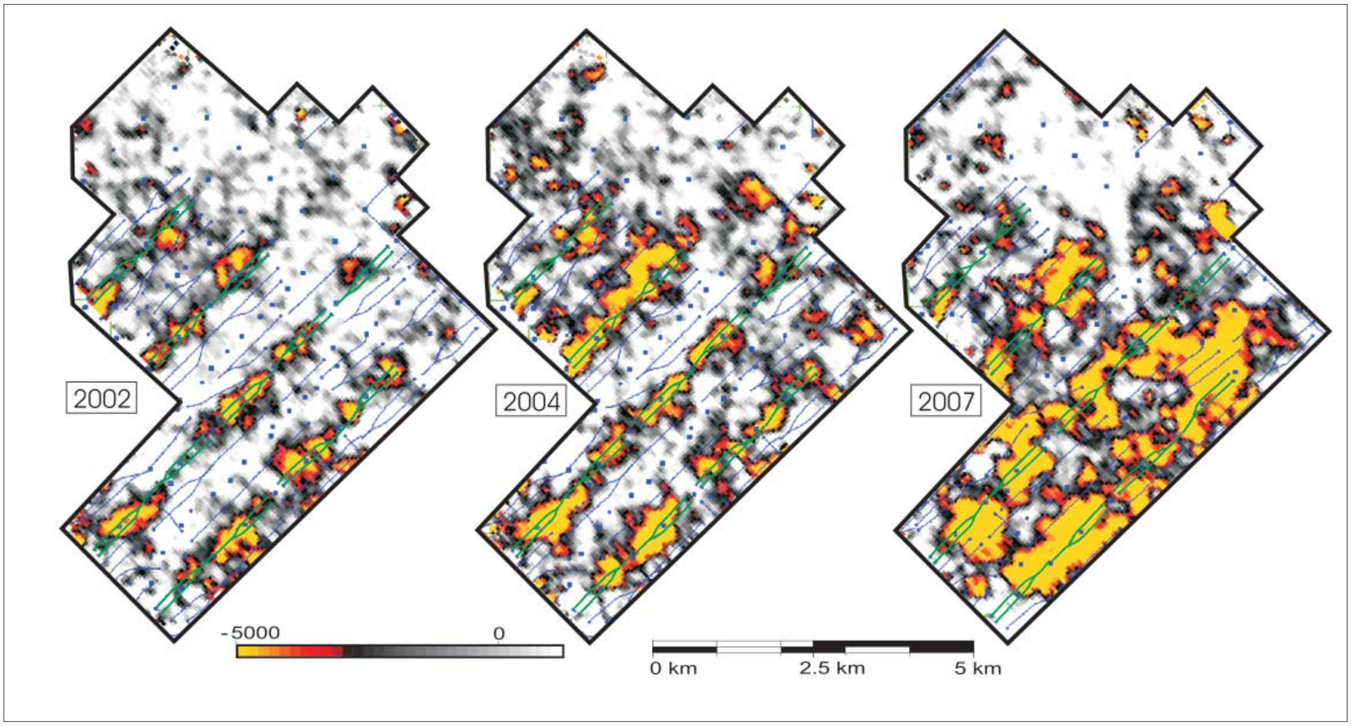

Figure 5. *Time-lapse amplitude difference maps for the Midale Marly horizon. Only the negative amplitude differences are shown to accentuate CO_2 saturation effects. Dual-leg wells are either production (black) or CO_2 injection (green) wells.*

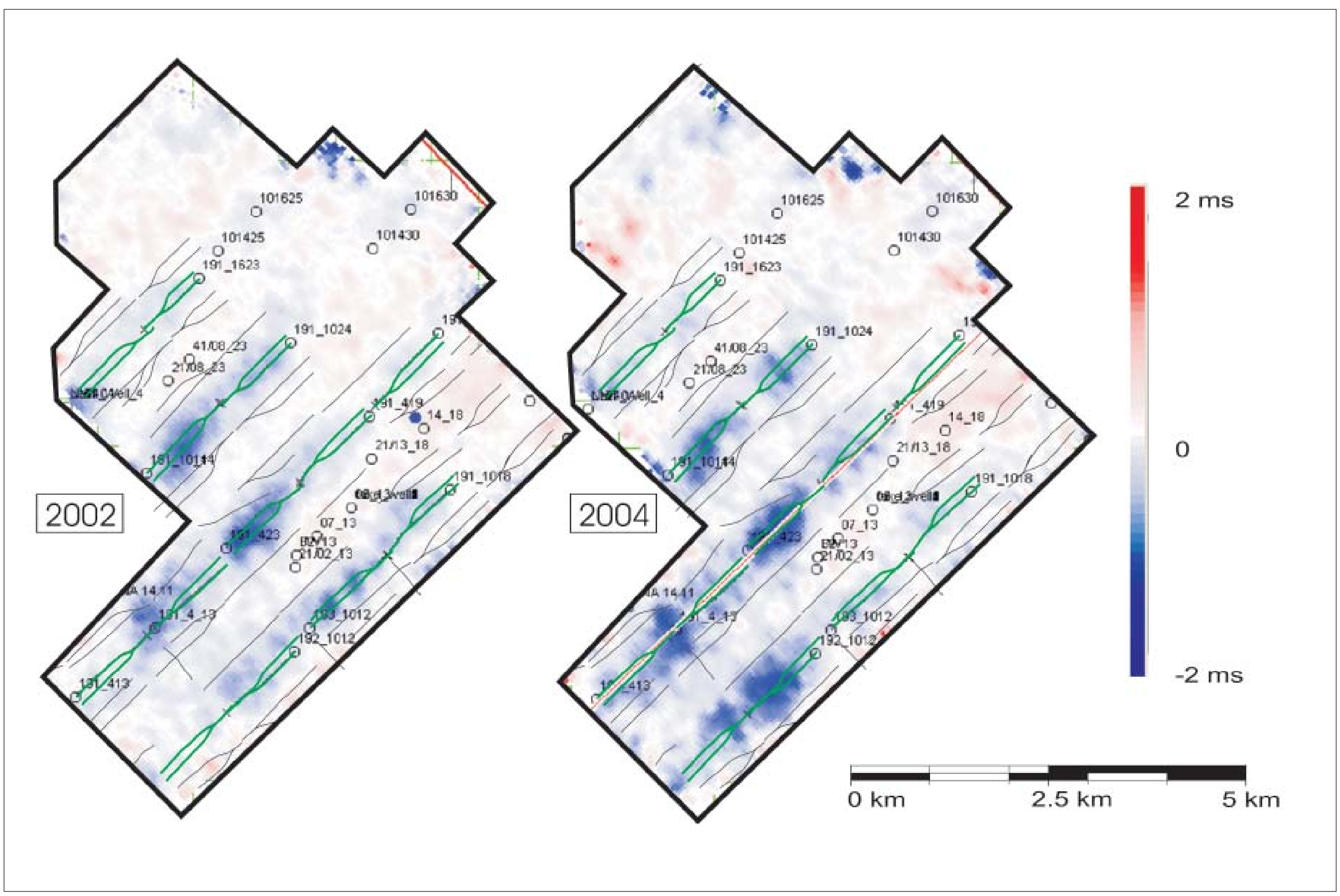

Figure 6. *Time-lapse traveltime difference maps determined for a subreservoir horizon representing traveltime anomalies associated with propagation through the reservoir.*

fective pressures due to the difficulty of making laboratory velocity measurements on core samples under these conditions.

3D three-component, time-lapse seismic data have been acquired over part of the EnCana Weyburn Field (Figure 1) in 1999 (baseline survey), 2001, 2002, 2004, and 2007 (monitor surveys I-IV) to monitor the CO_2 flood. A section through the P-wave 3D data volume from the baseline survey is shown in Figure 4 along with an overlay of the amplitude differences determined at the time of the Monitor III survey. Regions of negative amplitude difference can be seen at the reservoir level although they are relatively subtle. However, when the reservoir horizon is viewed in plan view, the effects of CO_2 injection and oil production are clearly visible (Figure 5), as are associated traveltime delays (Figure 6). Amplitude differences are more sensitive than the traveltime delay maps, particularly to CO_2 within the Marly unit. Traveltime and amplitude anomalies are well-developed in all of the dual-leg horizontal injection well patterns where a significant volume of CO_2 has been injected (~3–14% hydrocarbon pore volume). In most cases, there is generally good agreement between the injection volumes and the areal extent and/or intensity of the anomaly. In contrast, the seismic anomalies are not as prominent in the northern part of the area where vertical CO_2 injection wells are used, even though large volumes of CO_2 (up to 13% hydrocarbon pore volume) have been injected. The absence of seismic anomalies in this area is interpreted as due primarily to a combination of relatively low porosities in this region (particularly in the Marly unit) and to most of the CO_2 injected here residing in the Vuggy unit based on the simulation for this injection pattern.

A variety of evidence indicates that CO_2 saturation effects dominate over pressure-induced effects in the P-wave time-lapse seismic images, although core sample measurements (Brown, 2002) indicate that changes in V_P due to pressure increases can be comparable to saturation effects for pressure changes in the observed range (5–10 MPa). First, there is generally a poor correlation (or anticorrelation) between the amplitude of P-wave seismic anomalies and monitored or predicted pressure changes. Second, there is a good correlation between seismically predicted CO_2 thickness and known reservoir thickness when a fractional velocity change of 10–14% is assumed over the reservoir interval. Velocity changes of up to 10% can be accounted for by modeling of saturation effects, and, thus, there are relatively few regions where the modeled saturation relation does not adequately account for observed traveltime delays. These local discrepancies could be due to unaccounted pressure contributions responsible for maximum fractional velocity decreases of 3–4%. Finally, the absence of correlation between the P-wave and S-wave time-lapse anomalies (Davis et al., 2003) suggests that the prominent P-wave anomalies are primarily saturation-related.

Passive seismic monitoring

To monitor the dynamic response of the reservoir to CO_2 injection, an array of eight triaxial geophones was cemented in a vertical well within 50 m of a vertical CO_2 injection well.

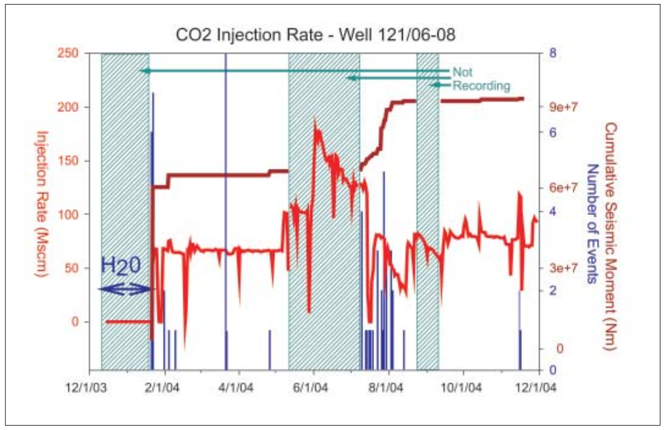

Figure 7. *CO_2 injection rate, number of seismic events, and cumulative seismic moment versus time for a 12-month period starting 1 December 2003.*

Background seismicity was recorded with the array between August 2003 and January 2004, prior to the start of CO_2 injection in the nearby well, and has continued to present documentation of very low rates of microseismic activity in general. Approximately 100 locatable microseismic events have been recorded at ranges of up to 500 m with moment magnitudes of -3 to -1. The majority of the recorded microseisms are characterized by low-frequency content (close to the resonant frequency of the geophones) and a dominant wavelength that ranges between 165 m and 275 m for assumed P-wave velocities between 3300 m/s and 5500 m/s. These conditions result in large location uncertainties that range from tens of meters to a few hundred meters. The highest frequency events are close to the injector and the observation well, which is consistent with rock-dispersion effects.

Figure 7 shows the occurrence of microseismicity during the 12-month period starting December 2003. In January, 2004, CO_2 injection began in the nearby vertical-injection well, resulting in associated microseismicity. The events were concentrated in a region between the injector and the closest active production well (191/1108). The seismicity began during the final stages of water injection with a second set of events during the changeover to CO_2 injection. Subsequent to the swarm of events near the start of CO_2 injection, low activity rates were recorded until 18–19 March 2004, when 15 events were detected near a production well (192/0908) that was shut down during this time. A similar seismic response was observed when this well was shut down in September 2003. Increased microseismicity was documented in July–August 2004 at the end of a period of increased injection rate. Unfortunately, the passive array was not functioning over most of the period of higher injection rate. Figure 8 shows a plan view of event locations for events occurring during the period of April–November 2004, with the 2004 time-lapse, seismic-amplitude difference map as a background. A total of 51 kT of CO_2 had been injected in the adjacent vertical-injection well by this time. The locations of the microseismic events over this period show a reasonably good correlation with the negative amplitude difference anomaly, suggesting that the microseismicity may be tracking the CO_2 distribution in this case.

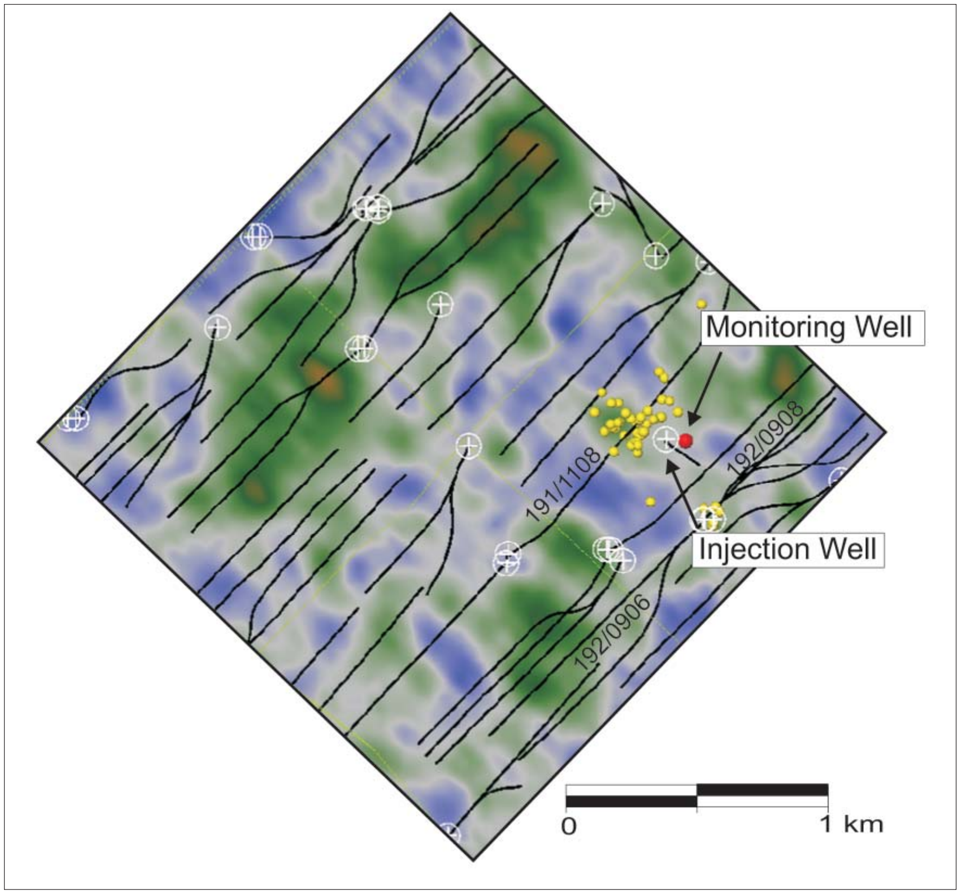

Figure 8. 2004 time-lapse amplitude difference map for the Midale Marly horizon and microseismic event locations (yellow dots) for the April–November 2004 period. Green-to-orange and blue colors represent negative and positive amplitude differences, respectively. Fifty-one thousand tonnes of CO_2 had been injected in the vertical injection well (labeled) adjacent to the passive monitoring array (monitoring well). Dual-leg horizontal wells are either CO_2 injection wells or production wells.

Conclusions

The ability of seismic methods to monitor physical changes in the Weyburn reservoir induced by CO_2 injection has been clearly demonstrated. Comparison of time-lapse anomalies observed at the reservoir level and at control horizons above the reservoir demonstrates that the seismic observations are robust, clearly exceed background noise levels, and show good repeatability. Generally, the areal extent of the seismic anomalies surrounding any of the dual-leg horizontal injection wells is directly related to the net cumulative amount of CO_2 injected. Rock and fluid property measurements, log-based synthetic seismic modeling, and reservoir simulation/production history matching with seismic constraints (White et al., 2004) all indicate that P-wave, time-lapse seismic monitoring is highly sensitive to the presence of a CO_2-rich gas phase within the reservoir, even at low levels of saturation (5–10%), whereas pressure effects are a secondary factor. Estimated maximum saturation effects include V_P decreases of 4–10% as compared to V_P decreases of < 4% for pressure effects. This sensitivity to low-saturation CO_2 makes the P-wave time-lapse images very good at mapping regions of the reservoir where CO_2 is present, but makes accurate volume estimation difficult. Reliable seismic-based volume estimates can only be made in conjunction with CO_2 saturation estimates from reservoir flow simulations. Approximately 100 microseismic events with magnitudes ranging from –3 to –1 were recorded during 60 months of monitoring with a seismic array just above the reservoir. Events appear to be associated with changes in production or injection changes (e.g., water-to-gas, injection rate), where local pressure transients might be expected. Magnitudes and occurrence frequency of microseismicity are low during periods of CO_2 injection.

Suggested reading. Annual Energy Outlook 2002 with Projections to 2020 (USDOE Web site, *www.eia.doe.gov*). "4D seismic monitoring of CO_2 flood in a thin fractured carbonate reservoir" by Li (*TLE*, 2003). "Multicomponent seismic characterization and monitoring of the CO_2 flood at Weyburn Field, Saskatchewan" by Davis et al. (*TLE*, 2003). "Greenhouse gas sequestration in abandoned oil reservoirs: The International Energy Agency Weyburn pilot project" by White et al. (*GSA Today*, 2004). "Geological characterization" by Whittaker et al. and "Prediction, monitoring and verification of CO_2 movements" by White et al. (both in *IEA GHG Weyburn CO_2 Monitoring and Storage Project Summary Report 2000–2004*). "Integration of Rock Physics and Reservoir Simulation for the Interpretation of Time-Lapse Seismic Data at Weyburn Field, Saskatchewan" by Brown (MSc thesis, Colorado School of Mines, 2002). TLE

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