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CO_2 Storage Monitoring Efforts at the Weyburn-Midale Fields, Canada

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CO_2 is being injected into the Weyburn and Midale oil fields in Saskatchewan Canada to enhance oil recovery from these mature hydrocarbon pools that have been on production since the 1950's. To investigate the suitability of long-term storage of CO2 in depleting oil-fields and in deep-saline water bearing geological formations, the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project was designed to obtain data and field-test CO2 monitoring procedures in collaboration with EnCana's commercial EOR operations to provide insight into CO_2 behavior in the subsurface. Phase 1 of this study began in 2000 and has now entered the Final Phase with an almost 10 year history of injection and storage information. To date (early 2009) more than 14.5 million tonnes CO_2 having been stored in the two fields as of with over 2 million tonnes being added annually. Injection is around 6,500 tonnes CO_2/day and incremental oil production is around 20,000 bbls/day at Weyburn alone; eventual cumulative incremental oil production from both fields is estimated at 215,000 million barrels. It is expected that approximately 35 million tonnes of anthropogenic CO_2 will be stored in the reservoirs at the end of the EOR operations, but with significant capacity for additional storage.

Among the unique aspects of the Weyburn-Midale project is the wealth of geophysical and geochemical data from seismic monitoring and reservoir fluid sampling surveys that have been ongoing throughout the EOR operation. The many wells drilled in the fields and surrounding areas (ca. 2,000) provide extensive information to assist with regional site characterization, but, as importantly, the variety of these wells drilled during different eras using different completion methods provide significant data toward characterizing and understanding aspects of wellbore integrity. The CO_2 itself is unique in that it is from an anthropogenic source and is compressed and pipelined 320 km from the Dakota Gasification Company's synfuel plant in Beulah, North Dakota, northward directly into the Weyburn-Midale fields in Canada.

At both Weyburn and Midale fields, the CO_2 in injected as a supercritical fluid into carbonates of the Midale Beds of the Mississippian Charles Formation at depths around 1450 to 1500 m. The reservoir is generally less than 30m thick and comprises a limestone (known as the "Vuggy") and overlying dolostone (the "Marly"). The reservoir has an upper seal of anhydritized dolostones and anhydrites of the Midale Evaporite, and a similar, but less extensive, lower seal formed by the Frobisher Evaporite. Upward migration of the CO_2 is impeded by the evaporite caprock which in turn is overlain by a series of aquitards including the Lower Watrous Member which forms the most extensive primary seal to the Weyburn system. The Vuggy unit comprises a fractured reservoir and fractures are less abundant in the overlying Marly unit; fracture sets within the reservoir strike NE-SW sub-parallel to the regional trajectories of maximum horizontal stress. Horizontal wells within the EnCana Weyburn field are oriented parallel to the predominant fracture direction.

Baseline 3D-3 component seismic data were initially acquired over part of the EnCana Weyburn Field in 1999, and subsequent monitor surveys were performed in 2001, 2002, 2004 and 2007 to monitor progress of the CO_2 flood. The effects of CO_2 injection on seismic properties within the reservoir at Weyburn are to reduce the P- and S-wave velocities by about 8% and 1.5%, respectively when the brine is mainly replaced by CO_2. Bulk density is correspondingly decreased, and this change is most pronounced in the Marly dolostone because of its greater porosity compared to the Vuggy limestone. These effects on seismic properties are large enough to result in observable differences in seismic responses in the sequential 3D monitor surveys performed during the course of the CO_2 flood at Weyburn. In section, regions of negative amplitude differences at the reservoir level appear relatively subtle; however when viewed in plan view the effects of CO_2 injection and oil production are clearly visible (Figure 1). These differences are also visible as associated time delays, but amplitude variations appear to be more sensitive to CO_2 than time delays especially within the Marly unit. Essentially, where there has been a significant volume of CO_2 injected (around 3 to 14% hydrocarbon pore volume) using dual-leg horizontal injection patterns, amplitude and travel time anomalies are well developed, and show good agreement between injection volumes and the areal extent or intensity of the anomaly. In the northern part of the Field where vertical CO_2 injectors are primarily used, seismic anomalies are not as prominent even though significant CO_2 has been injected. This is likely because of generally lower porosities in this part of the field and also because most of the injected CO_2 is in the Vuggy unit based on reservoir simulation data. In general, evidence from the Weyburn data indicates that CO_2 saturation effects are more influential in the seismic response seen in the P-wave time-lapse seismic images than are pressure-induced effects. This is because 1) there is a weak correlation between P-wave amplitude anomalies and predicted pressure changes, and 2) time delays can be modeling using saturation effects and known reservoir thicknesses on velocity changes up to 10% and 3) there is no relation between P- and S-wave time-lapse anomalies suggesting P-wave anomalies are primarily saturation-related.

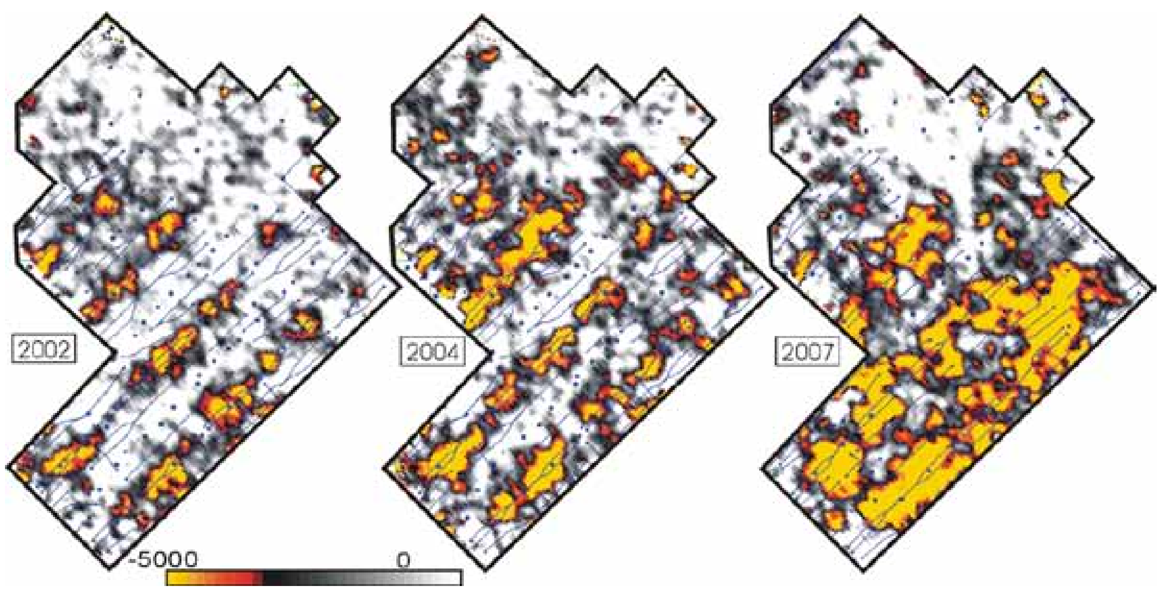

Figure 1: Amplitude difference maps for the Midale Marly horizon. Only the negative amplitude differences are shown to accentuate CO_2 saturation effects.

Passive seismic monitoring also is being performed in the Weyburn Field. An array of 8 triaxial geophones was cemented in a vertical well within 50 m of a vertical CO_2 injection well. Background seismicity was recorded between August 2003 and January 2004, prior to the start of injection in the nearby well. Monitoring has continued to present. Approximately 100 locatable microseismic events have been recored with moment magnitudes of -3 to -1. Most are low frequency with a dominant wavelength between 165 and 275 m for assumed P-wave velocities between 3300m/s and 5500m/s. The highest frequency events are generally nearest the injector. Figure 2 shows the occurrence of microseismicity during 12 months starting December 2003, one month before CO_2 injection began. Recorded microseismic events are mainly between the injector well and the closest production well and occurred during the final stages of water injection and the changeover to CO_2 injection. The locations of microseismic events over this time have a reasonable correlation with negative amplitude difference anomalies suggesting that microseismicity may track CO_2 distribution in this instance.

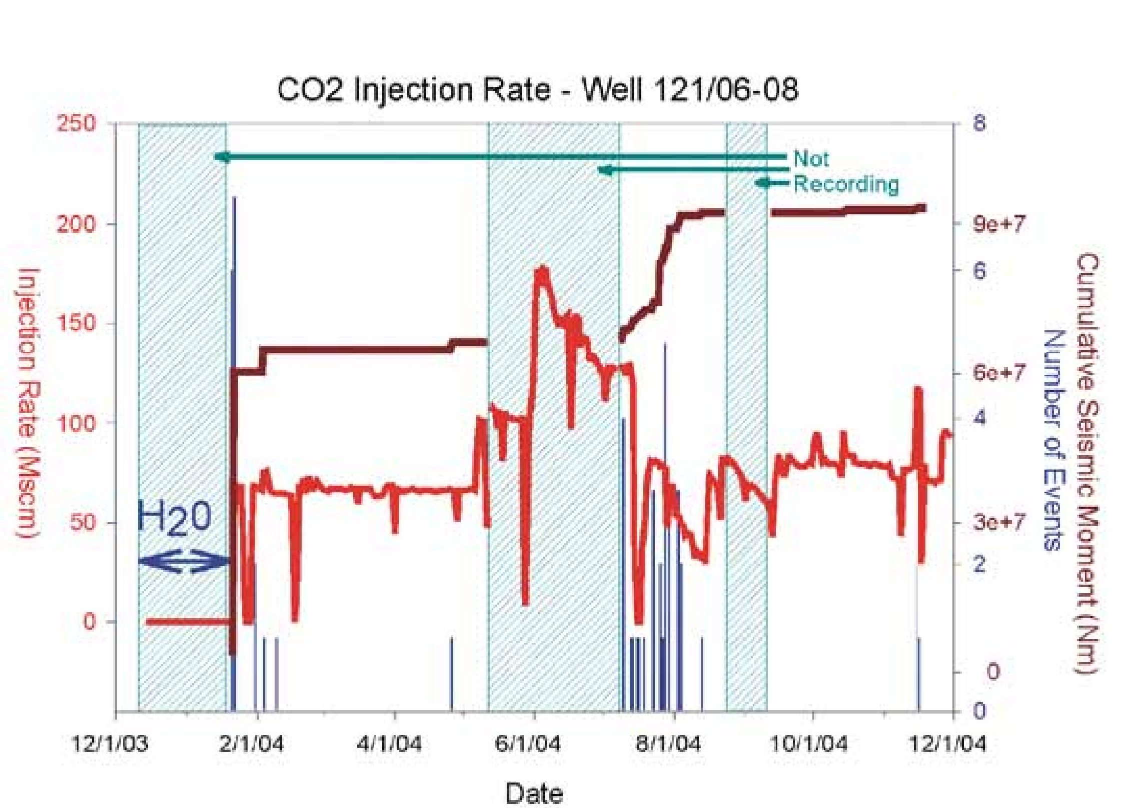

Figure 2: CO_2 injection rate, seismic event counts and cumulative seismic moment versus time for 12 months starting December 1, 2003.

Geophysical methods have been demonstrated to monitor physical changes in the Weyburn reservoir induced by CO2 injection. Time-lapse imagery is repeatable and exceeds background noise levels, with the areal extent of the anomaly generally related to the cumulative amount of CO_2 injected. Microseismic events apparently are related to changes in production or injection where local pressure transient conditions may be present. Generally the magnitude and occurrence of microseismicity is low during periods of CO_2 injection.