Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 63 (2014) 2836 – 2847

Energy Procedia

GHGT-12

Integrated reservoir monitoring at the Illinois Basin – Decatur Project

Marcia L. Couëslan[a]†, Robert Butsch[b], Robert Will[c], and Randall A. Locke II[d]

[a]Schlumberger Carbon Services, 200, 125 – 9th Ave SE, Calgary, Alberta, T2G 0P4, Canada
[b]Schlumberger Carbon Services, 14090 SW Freeway, Suite 240, Sugar Land, Texas, 77478, United States
[c]Schlumberger Carbon Services, 1875 Lawrence Street, Suite 810, Denver, Colorado, 80202, United States
[d]Illinois State Geological Survey, 615 E. Peabody Drive, Champaign, Illinois, 61820, United States

Abstract

The Illinois Basin – Decatur Project (IBDP), a United States Department of Energy funded project, is a fully integrated industrial carbon capture and storage (CCS) project where carbon dioxide (CO_2) is captured from the Archer Daniels Midland Company (ADM) corn processing plant at the in Decatur, Illinois, USA. The captured CO_2 is dehydrated, compressed, and then injected deep into the Mt. Simon Formation. IBDP commenced injection in November 2011 and has a goal of injecting one million metric tonnes of CO_2 into the lower Mt. Simon Sandstone over a three-year period. A range of monitoring, verification, and accounting (MVA) tools are being used to monitor the CO_2 plume development in the deep subsurface. These monitoring tools include time-lapse RST* reservoir saturation tool logging in the project wells, continuous pressure and temperature measurements from multiple levels above, within, and below the storage formation, deep fluid sampling with associated geochemical analysis, time-lapse three-dimensional (3D) vertical seismic profile (VSP) surveys, and microseismic monitoring. MVA data has been used to quantitatively and qualitatively calibrate the reservoir simulations. As a result, the project now has robust, history-matched reservoir simulations that predict CO_2 and pressure plume development over time. MVA data and modelling results indicate that the CO_2 plume has spread within a thin, high permeability zone in the lower Mt. Simon Sandstone and that a low permeability zone in the upper part of the lower Mt. Simon Sandstone is currently acting as an effective baffle to CO_2 migration and pressure transmission above 2,094 m (6,870 ft). Lessons learned over the course of IBDP are being applied to the adjacent Illinois Industrial CCS Project.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Illinois Basin – Decatur Project; monitoring, verification, and accounting; CO_2 saturation logging; pressure and temperature monitoring; microseismic monitoring; time-lapse 3D VSP

† Corresponding author. Tel.: +1-403-671-5217.
E-mail address: Marcia.coueslan@gmail.com

Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.306

1. Introduction

The Illinois Basin – Decatur Project (IBDP), a United States Department of Energy funded project, is managed by the Midwest Geological Sequestration Consortium, which is led by the Illinois State Geological Survey (ISGS) at the University of Illinois. Located on the Archer Daniels Midland Company (ADM) property in Decatur, Illinois, IBDP is a fully integrated industrial carbon capture and storage (CCS) project in which carbon dioxide (CO_2) is captured from the fermentation process used to produce ethanol at the ADM corn-processing plant [1]. IBDP has a goal of injecting one million tonnes of CO_2 into the basal part of the Mt. Simon Sandstone over a three-year period. CO_2 injection commenced in November 2011, and as of September 1, 2014, approximately 925,300 tonnes of CO_2 had been injected.

2. Project Background

The primary formations of interest for IBDP are the Ironton-Galesville, Eau Claire Shale, Mt. Simon Sandstone, Pre-Mt. Simon Sandstone unit, and the Precambrian basement (Fig. 1). The Ironton-Galesville is a saline formation and serves as the first monitoring interval above the regionally extensive Eau Claire Shale. The Eau Claire Shale is composed of tight limestone, interbedded shales and siltstones. The Eau Claire is the primary seal for the Mt. Simon Sandstone and is approximately 152 meters (m)/ 499 feet (ft) at the IBDP site. The Mt. Simon Sandstone is a regional blanket sandstone that is the primary target for geologic carbon storage in the Illinois Basin; it is approximately 453 m (1,486 ft) thick [2]. The lower Mt. Simon Sandstone has average interval porosities of 20% and permeability of 185 millidarcy (mD). However, there are low permeability units within the lower Mt. Simon Sandstone with permeabilities <1 mD the most notable of which is the low permeability streak located at approximately 2,092 – 2,094 m (6,863 – 6,870 ft) depth [1]. Prior to injection, it was unknown how these lower permeability units would affect the migration of CO_2 in the lower Mt. Simon Sandstone, as they did not appear to be laterally extensive based on the well log data from the project wells. The Mt. Simon Sandstone is underlain by a thin low reservoir quality Pre-Mt. Simon Sandstone unit that has distinct lithology and porosity from the Mt. Simon Sandstone and the Precambrian basement [3].

Site characterization work began in 2007 and continued up until commencement of injection in November, 2011. The IBDP injection (CCS1) and geophysical monitoring (GM1) wells were drilled in 2009 while the verification well (VW1) was drilled and completed in 2010 (Fig. 2). In addition, a verification well (VW2) was drilled for the adjacent Illinois Industrial Carbon Capture and Storage Project (IL-ICCS) in 2012 (Fig. 2). Extensive logging data and core have been acquired in all of the project wells and 3D surface seismic data was acquired to characterize the site beyond the project wells. Much of the site characterization data also serves as baseline data for the Monitoring, Verification, and Accounting (MVA) program.

3. Monitoring, Verification, and Accounting Plan

The IBDP MVA plan has a number of objectives including the management of MVA-related project risks, establishing baseline conditions, demonstrating that project activities are protective of human health and the environment, and providing accurate accounting of stored CO_2 [4]. A range of MVA tools are being used to monitor CO_2 plume development from the surface and in the deep subsurface; these include time-lapse RST to estimate CO_2 saturations adjacent to the project wells, continuous pressure and temperature measurements from multiple levels above, within, and below the storage formation, deep fluid sampling with associated geochemical analysis, time-lapse three-dimensional (3D) vertical seismic profile (VSP) surveys, and microseismic monitoring.

CCS1 is instrumented with two pressure/temperature sensors at the wellhead and at 1,928 m (6,325 ft) as well as two deep geophone levels that allow for microseismic monitoring at 1,750 m (5,741 ft) and 1,870 m (6,135 ft). The perforations in CCS1 are located in the lower Mt. Simon Sandstone between 2,128 – 2,149 m (6,982 – 7,050 ft). GM1 is located 60 m (197 ft) west of CCS1 and is instrumented with a permanent 3-component 31-level geophone array that was cemented from approximately 42 – 1,050 m (138 – 3,445 ft) measured depth [5]. The purpose of this array is twofold: 1) the acquisition of time-lapse 3D VSP surveys and 2) microseismic monitoring. In addition, a five level geophone array has been deployed in VW2 since September 2013 between 1,875 – 2,118 m (6,152 – 6,949 ft) measured depth to enhance the microseismic observation geometry and as redundancy.

VW1 is instrumented with a Westbay* multilevel groundwater characterization and monitoring system [4]. The Westbay completion allows the project to continuously monitor pressure and temperature at eleven different depths in the Ironton-Galesville formation (zones10 – 11), Mt. Simon Sandstone (zones 2 – 9), and Pre-Mt. Simon Unit (zone 1). Fluid samples can also be taken from each port at discrete time intervals for geochemical analysis. The low permeability streak in the lower Mt. Simon Sandstone is located between zones 3 and 4.

4. Results

4.1. Time-lapse RST Logging

Two pre-injection baseline and five time-lapse monitoring RST logs have been acquired in CCS1 and VW1 between August 2009 and July 2014. When the first time-lapse monitoring RST logging runs were acquired in CCS1 and VW1 in March 2012, CO_2 was observed in CCS1 between 2,057 – 2,149 m (6,748 – 7,050 ft). It had also broken through in VW1 at Zone3 between 2,118 – 2,121 m (6,950 – 6,960 ft) (Fig. 3).

Since the time of the first monitor surveys the distribution of CO_2 along CCS1 has stayed relatively constant while it has slowly increased along VW1 in several relatively thin intervals between 2,110 – 2,130 m (6,922 – 6,989 ft) by July 2013 (Fig. 3). As of July 2013, most of the CO_2 appears to be confined below 2,103 m (6,900 ft) (Fig. 3). The July 2014 survey is still being analysed at the time of writing.

4.2. Pressure Monitoring

Pressure measurements from VW1 further support the interpretation that the CO_2 is confined below a low permeability layer. Pressures measured at monitoring ports in Zones 1 to 3, located at 2,152, 2,128, and 2,117 m (7,060, 6,982, 6,946 ft) respectively, respond quickly to changes in injection operations (Fig. 4). The pressures at zone 1 clearly show that pressure is being transmitted to the Pre-Mt. Simon unit below the injection interval. However, the pressures at zone 4 (2,128 m, 6,982 ft) have shown a much smaller and gradual increase over time further supporting the interpretation that the low permeability layer is currently acting as a partial barrier to pressure transmission upward. The pressure data from CCS1 and VW1 have provided critical data for the calibration of the dynamic reservoir modelling for the project.

4.3. Deep Fluid Sampling

Three sets of baseline fluid samples were obtained from the fluid sampling ports through swabbing and sampling of the Westbay ports in VW1 prior to CO_2 injection. These samples were analysed for conductivity, total dissolved solids, alkalinity, and pH as well as the chemical species chlorine, bromine, sodium, calcium, potassium, and magnesium [4]. Six full or partial sampling rounds have been conducted since injection commenced in November 2011. Samples are not obtained from Westbay ports where the CO_2 is present based on the RST data; this includes zones 2 and 3. In July 2013 samples were obtained from zones 4 to 11. No geochemical changes were identified that would suggest that CO_2 had migrated above the low permeability layer between zones 3 and 4. Anticipated geochemical changes would certainly include decreased pH and variations in fluid chemistry.

4.4. Time-lapse 3D VSP Surveys

To date, two baseline and three monitor 3D VSP surveys have been acquired for the project. The three monitor surveys were acquired after approximately 74,000, 433,000, and 730,000 tonnes of CO_2 had been injected. Despite degradation of later 3D VSP imaging due to fewer shot points east of CCS1, the permanent geophone array in GM1 has recorded highly repeatable data over time based on the Normalized Root Mean Square (NRMS) repeatability metric [6]. The surveys have been acquired in a range of ground conditions from damp to dry to frozen, and it has been observed that ground conditions play a large role in the data repeatability from survey to survey. All of the monitor surveys have been compared to the Baseline 2 (B2) survey.

The Eau Claire Shale and upper Mt. Simon Sandstone should be unaffected by the CO_2 injection, which is why this interval was used to analyze the repeatability of the data. NRMS values over the Eau Claire Shale and upper Mt. Simon Sandstone (1,524 – 1,981 m, 5,000 – 6,500 ft) range from 15 – 20%, which is considered highly repeatable (Fig. 5a and c) [5]. However, over time, a repeatability anomaly has clearly been developed west of GM1 through the injection interval (1,981 – 2,195 m, 6,500 – 7,200 ft) from the Monitor 1 (M1) to the Monitor 3 (M3) surveys (Fig. 5b and d) [5]. This anomaly is suggestive of CO_2 plume development through the injection interval over time. As no anomalies have been identified at shallower depths; this suggests that there has been no significant accumulation of CO_2 above the lower Mt. Simon Sandstone.

4.5. Microseismic Monitoring

IBDP began recording baseline microseismic data using the geophone arrays in CCS1 and GM1 in May 2010; eighteen months of baseline microseismic data were recorded prior to the start of CO_2 injection. During this time, 7,894 microseismic events were detected most of which were associated with VW1 drilling activity. In addition, the baseline microseismic data includes eleven perforation shots and seven events that appear to be related to well operations in VW1, seven events that were considered distant, long-offset events unrelated to the project, and eight local microseismic events did not appear to be directly related to the wells.

Currently, the microseismicity at IBDP is monitored with a combination of the three geophone arrays located in CCS1, VW1, and VW2. Approximately 50% more of the detected events are now locatable with the addition of the five level array in VW2. Over 3,400 events have been located since injection commenced in November 2011. The average moment magnitude (Mo) of the events has decreased slowly over time and is presently -0.89. For a short period in January and February 2012 event rates peaked (~750 detected events per day). Since that time, events rates have decreased sharply with small intermittent peaks at irregular intervals that are often related to new cluster development or disruptions to regular injection operations.

Over time, the microseismic events have formed distinct clusters that develop quickly over a period of several weeks followed by a sharp decrease to low levels of sustained but intermittent activity (Fig. 6). The microseismic event locations are confined below the low permeability zone in the lower Mt. Simon Sandstone, Pre-Mt. Simon unit, and upper Precambrian basement (Fig. 7). While interpretation of the available 3D seismic dataset does not support the presence of pre-existing faults within these formations, the orientation of microseismic clusters is consistent with the in-situ stress regime of the lower Mt. Simon Sandstone in this area of the basin. First motion analysis indicates right lateral strike-slip motion on many of the clusters as opposed to fracture failure.

Integrated analysis of the microseismic data with the other operational data has shown that the observed microseismic activity is associated with fluctuations in the pressure front plume rather than the CO_2 plume. Disruptions to injection operations often lead to spikes in microseismic event rates while periods of steady injection are relatively quiet in terms of microseismicity. Spikes in microseismicity during injection shutdowns may be a result of pressure relaxation in the formation.

5. Conclusions

The continuous pressure monitoring within and above the injection zone in VW1 has provided invaluable information regarding vertical permeability and pressure communication within the monitoring formations; this information has been used to periodically calibrate the reservoir simulations. The time-lapse RST data has also been used to qualitatively calibrate the reservoir simulations. The project now has robust, history-matched reservoir simulations that predict CO_2 and pressure plume development over time.

The MVA data and modelling results indicate that the CO_2 plume has spread within a thin, high permeability zone in the lower Mt. Simon Sandstone [1]. All of the data also indicate that a low permeability zone in the lower Mt. Simon Sandstone is currently acting as an effective baffle to upward CO_2 migration and pressure transmission above 2,094 m (6,870 ft). The time-lapse RST data does not show any significant CO_2 accumulations adjacent to CCS1 or VW1 above the low permeability zone. The increase in pressure in Zone 4 above the low permeability streak has been gradual, and the pressure responses decrease in the overlying sampling ports in Zones 5 to 9. Fluid analyses from sampling ports in Zones 4 to 11 have not shown substantial changes in pH or concentrations of alkalinity, calcium, sodium, chloride, bromide or total dissolved solids since injection commenced that would indicate CO_2 movement out of the injection zone. Also, the time-lapse 3D VSP data do not indicate that there are any significant accumulations of CO_2 in the Eau Claire Shale or the upper Mt. Simon Sandstone based on the NRMS repeatability metrics.

MVA data integration has been particularly important to the analysis and interpretation of the microseismic data. Overall, rates of microseismic activity and the average moment magnitude of the events have decreased over time. Microseismic activity at the site is primarily associated with the development and fluctuations in the pressure plume as opposed the CO_2 plume. Clusters of microseismic events have developed at increasing distances from CCS1 as the pressure plume has expanded, and the events have been confined beneath the low permeability streak. Microseismic activity is not impacting storage security.

Lessons learned through the integration of the IBDP MVA data and reservoir simulations are being applied to the adjacent IL-ICCS Project particularly with regard to pressure transmission and microseismicity within and below the Mt. Simon Sandstone. The perforations in the new injection well will be placed above the low permeability zone in the lower Mt. Simon Sandstone thus isolating the plumes from the two projects.

*Mark of Schlumberger

Acknowledgements

The Midwest Geological Sequestration Consortium is funded by the U.S. Department of Energy through the National Energy Technology Laboratory via the Regional Carbon Sequestration Partnership Program (contract number DE-FC26-05NT42588) and by a cost share agreement with the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development (contract number ICCI0303 DEV03 2RF).

Special thanks to the following people at the Illinois State Geological Survey and Schlumberger: Robert Finley, Sallie Greenberg, Robert Bauer, Daniel Byers, Hannes E. Leetaru, Paul Jaques, Valerie Smith, Wade Zaluski, Graham Payne, and Jim Kirksey.

References

[1] Finley, Robert J., Scott M. Frailey, Hannes E. Leetaru, Özgür Senel, Marcia L. Couëslan, and Scott Marsteller, 2013, Early operational experience at a one-million tonne CCS demonstration project, Decatur, Illinois, USA. 11th International Conference on Greenhouse Gas Control Technologies, Extended Abstract, Kyoto, Japan.

[2] Leetaru, Hannes E., John H. McBride, 2009, Reservoir uncertainty, Precambrian topography, and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin. Environmental Geosciences, **16**; 4: 235 – 243.

[3] Freiburg, J.T., Morse, D.G., Leetaru, H.E., Hoss, R.P., Yan, Q., 2014, A Depositional and Diagenetic Characterization of the Mt. Simon Sandstone at the Illinois Basin – Decatur Project, Carbon Capture and Storage Site, Decatur, Illinois, USA: Illinois State Geological Survey, Circular 583, p. 1-43 (in press)

[4] Locke II, Randall, David Larssen, Walter Salden, Christopher Patterson, Jim Kirksey, Abbas Iranmanesh, Bracken Wimmer, Ivan Krapac, 2013, Pre-injection reservoir fluid characterization at a CCS demonstration site: Illinois Basin – Decatur Project. 11th International Conference on Greenhouse Gas Control Technologies, Extended Abstract, Kyoto, Japan.

[5] Couëslan, M.L., S. Ali, A. Campbell, W.L. Nutt, W.S. Leaney, R.J. Finley, S.E. Greenberg, 2013, Monitoring CO_2 injection for carbon capture and storage using time-lapse 3D VSPs. The Leading Edge, 32 (10): pp. 1268 – 1276.

[6] Kragh, E., and P. Christie. Seismic repeatability, normalized rms, and predictability. *The Leading Edge*, **21**: pp. 640-647 (2001).

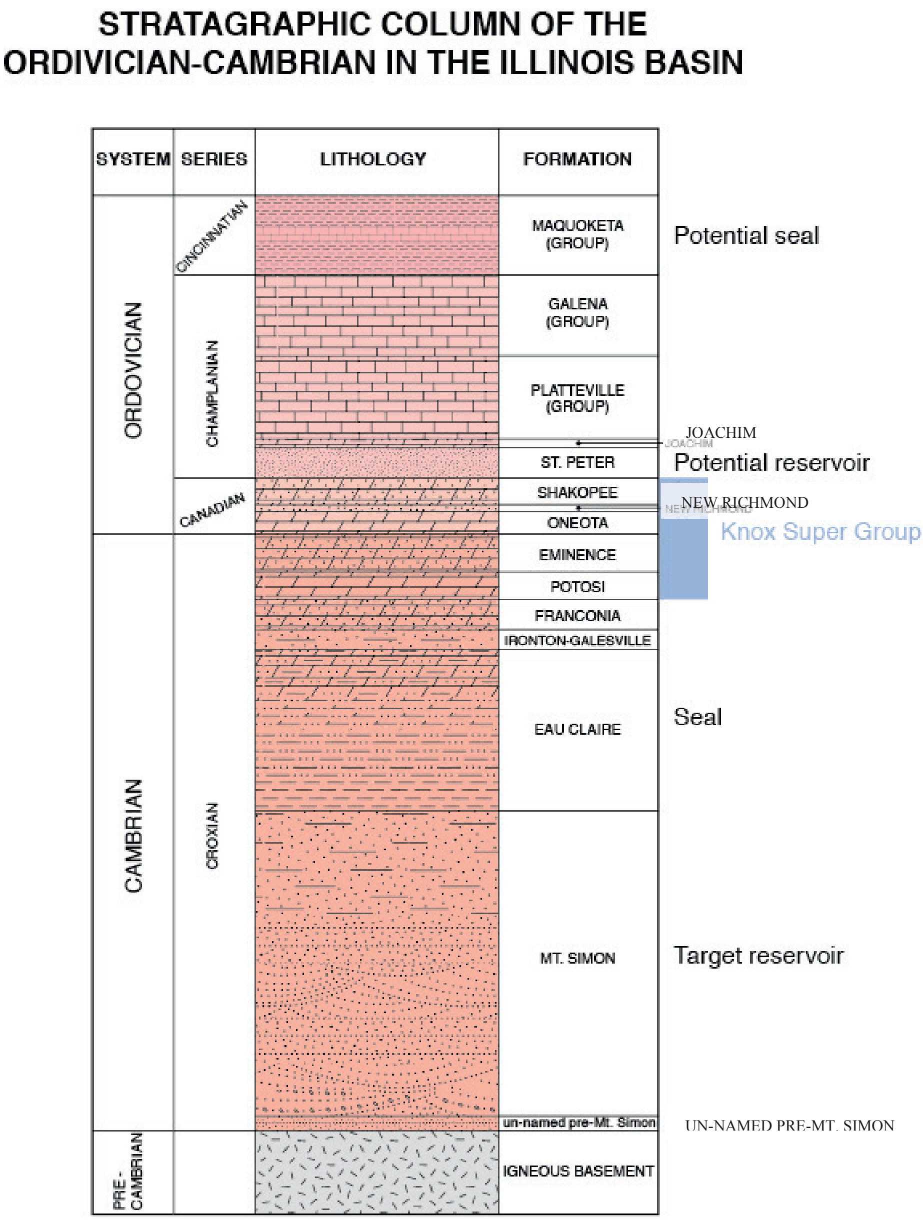

Fig. 1: Stratigraphic column of the Ordovician through Precambrian-aged geologic formations in the Illinois Basin

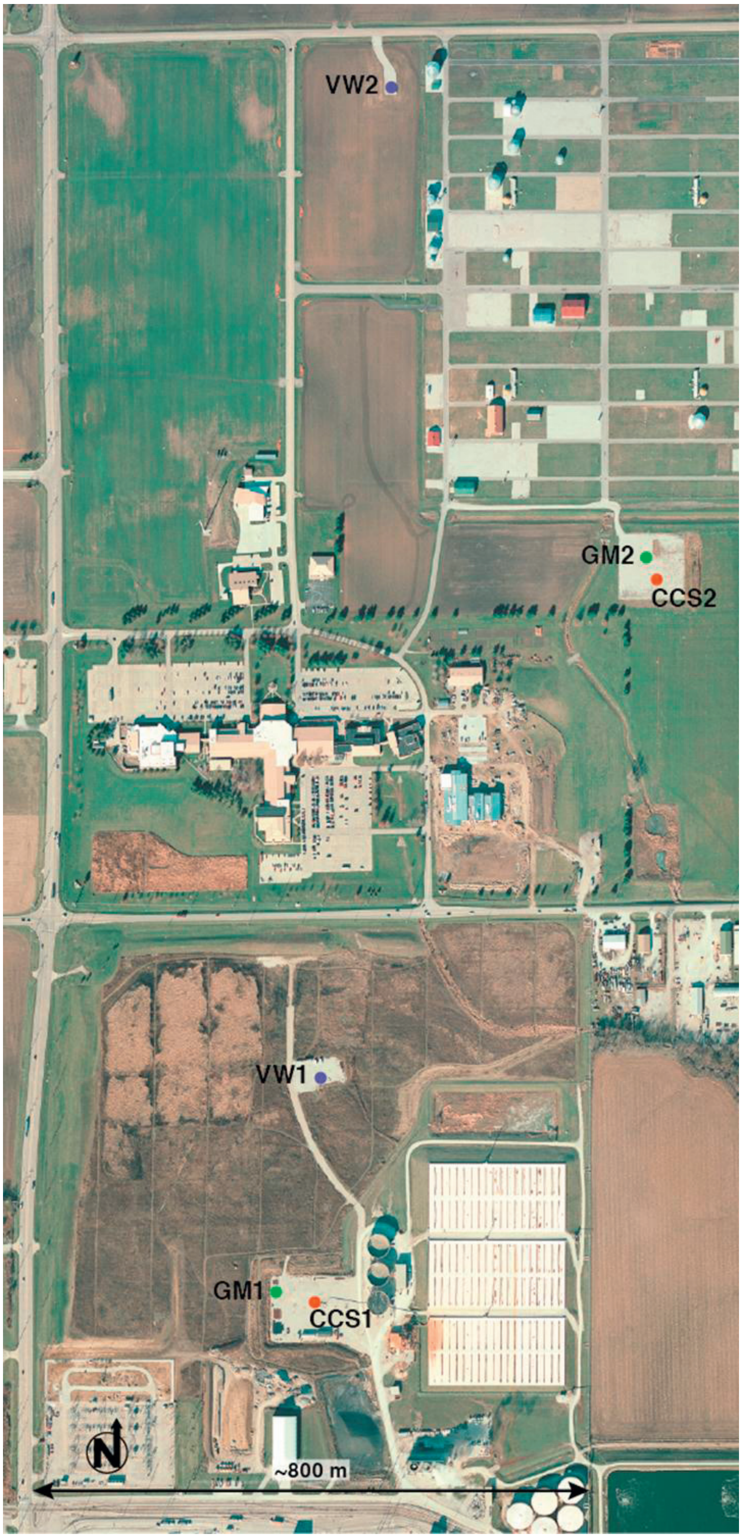

Fig. 2: IBDP site map with wells annotated.

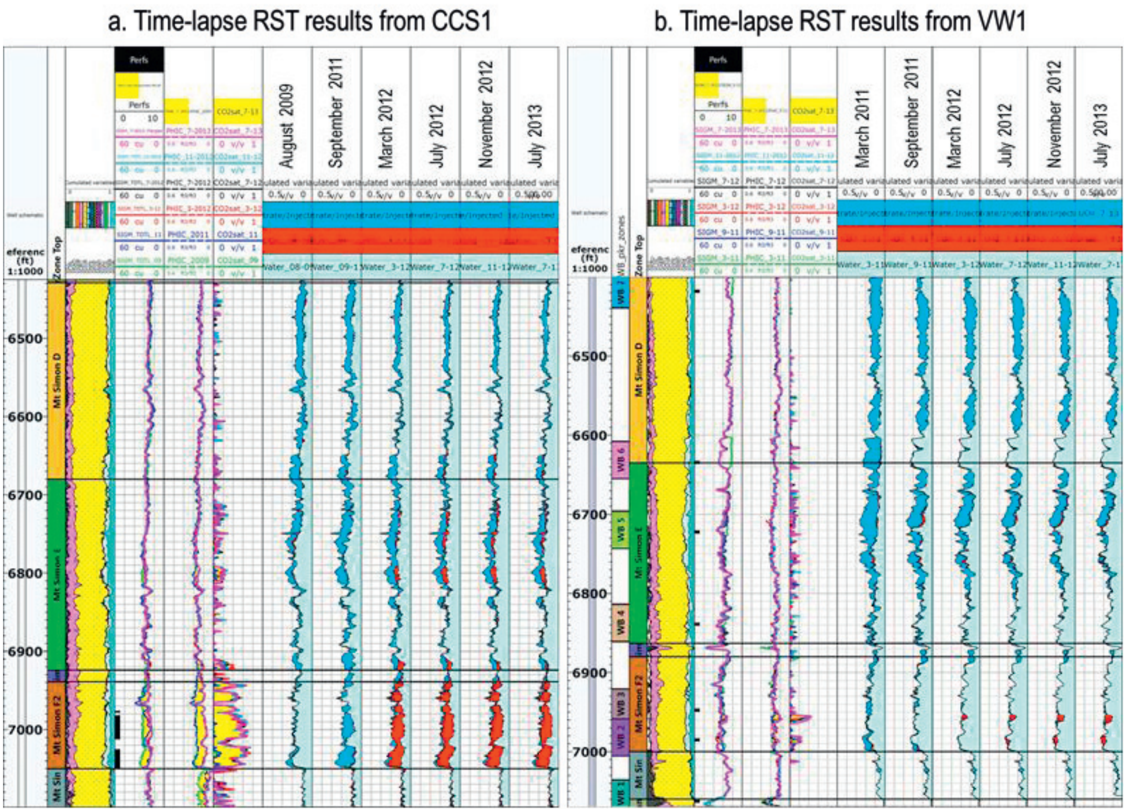

Fig. 3: RST logging results from a. CCS1 and b. VW1. Red shading indicates the presence of CO_2. Black points in track 4 indicate well perforations in CCS1 or sampling ports in VW1. CO_2 broke through at Zone 3 prior to Zone 2 in VW1. Note that red shading on the baseline surveys is likely due to residual drilling fluids adjacent to the wellbore.

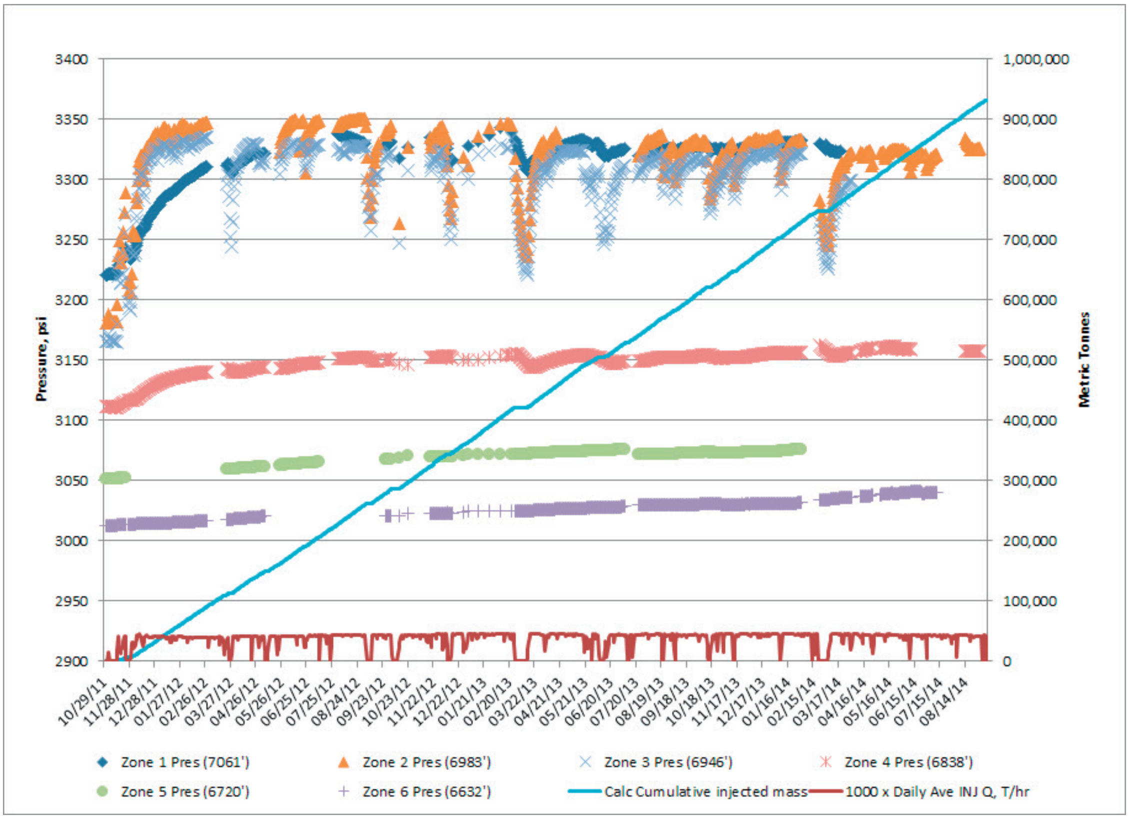

Fig. 4: Pressure data from Zones 1 – 6, injection rates, and the calculated cumulative injected mass of CO_2 since injection commenced in November 2011. Note that the pressure response in Zones 1 – 3 is quite reactive to changes in injection rate.

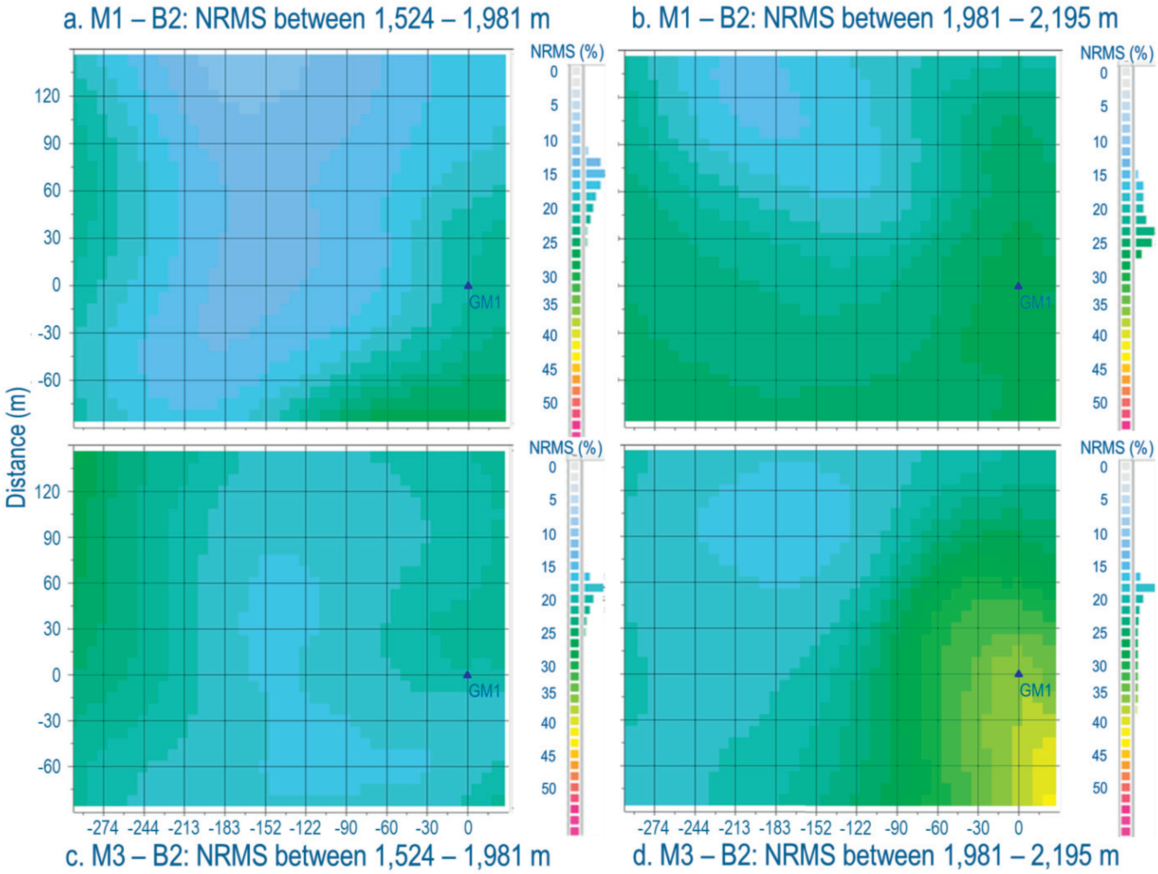

Fig. 5:a. M1 – B2 NRMS values through the Eau Claire Shale and upper Mt. Simon Sandstone (1,524 – 1,981 m) b. M1 – B2 NRMS values through the mid- to lower Mt. Simon Sandstone (1,981 – 2,195 m) c. M3 – B2 NRMS values through the Eau Claire Shale and upper Mt. Simon Sandstone d. M3 – B2 NRMS values through the mid- to lower Mt. Simon Sandstone

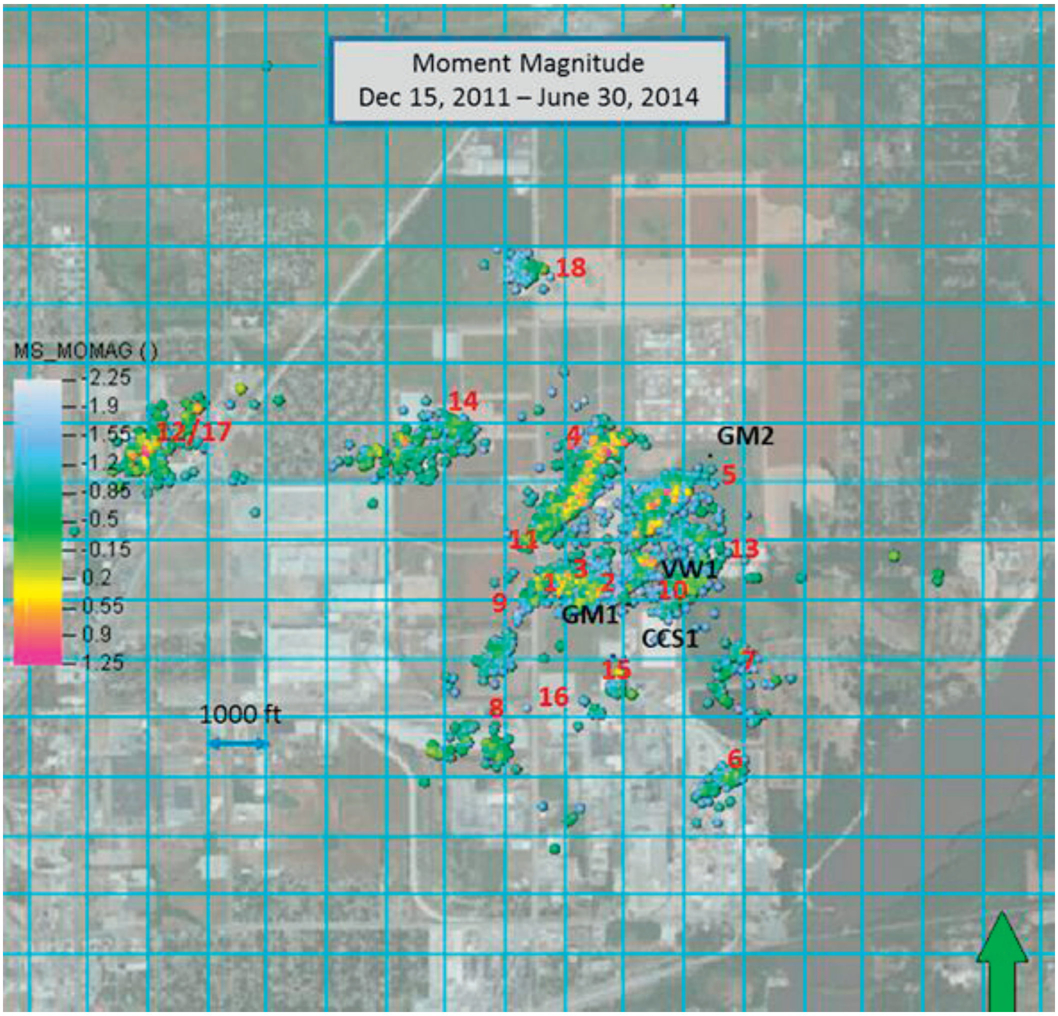

Fig. 6: Microseismic cluster development since December 2011. Clusters are numbered based on the order of their appearance. Events are coloured based on their moment magnitude.

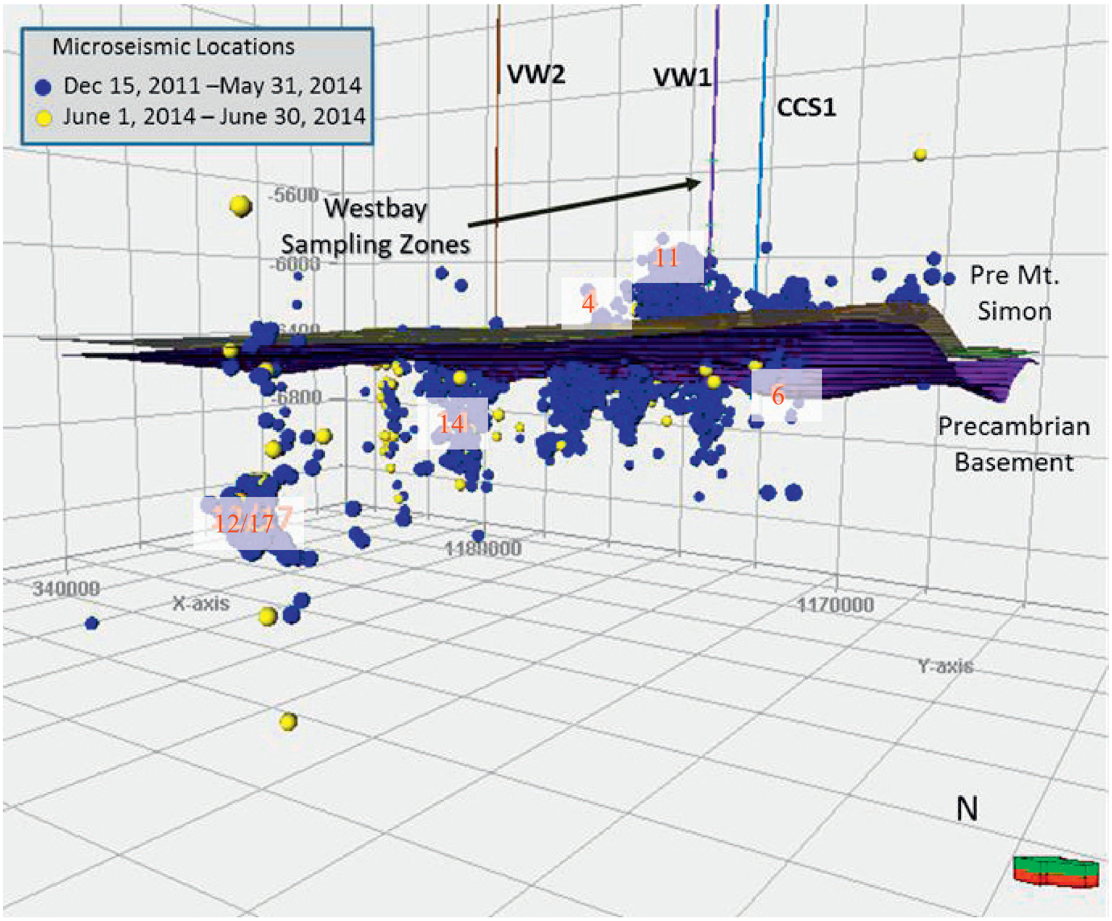

Fig. 7: Microseismic events in relation to the lower Mt. Simon Sandstone, Pre-Mt. Simon Unit, and Precambrian basement.