Overview of Microseismic Response to CO₂ Injection into the Mt. Simon Saline Reservoir at the Illinois Basin-Decatur Project

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Abstract:

The Illinois Basin - Decatur Project safely and successfully injected, over three years, nearly 1.1 million tons (1 million tonnes) of supercritical carbon dioxide (CO₂) into the base of a 1,640 ft (500 m) thick saline sandstone reservoir at a depth of 7,025 ft (2.14 km). The injection interval, with its high porosity and permeability, allowed for injection pressures to be far below fracture pressures during the daily 1,102 ton (1,000 tonne) injection rate. Microseismicity was monitored 1.5 years before injection, through the 3 years of injection and now during permanent shut-in which began in November 2014. The overall average of locatable events per day, during injection, was a little over 4, and events appear to be related to development on previously undetected planes of weakness. Some of these planes and active areas may be related to features developed during diagenetic or compactional processes associated with the Precambrian surface topography. Microseismicity during transient shut-in did not show a rate of decrease, large changes in magnitude, distance from the injection well, or depth.

Keywords

CO₂ Sequestration, Microseismicity, Induced, Illinois Basin - Decatur Project

1. Introduction

The Illinois Basin - Decatur Project (IBDP) is a carbon capture and storage (CCS) project of the Midwest Geological Sequestration Consortium, which partnered with the Archer Daniels Midland Company (ADM) and Schlumberger Carbon Services to inject supercritical CO₂ at a rate of approximately 1,102 tons (1,000 tonnes) per day for three years into the basal part of the 1,640 ft (500 m) thick Mt. Simon Sandstone unit at a depth of 7,025 ft (2.14 km). The injection site is located on the property of ADM where CO₂ is produced in their ethanol production process. Nearly 1 million tonnes of CO₂ were injected into the Mt. Simon saline reservoir over three years, from 17 Nov 2011 to 26 Nov 2014. The site had an extensive pre-injection investigation of site conditions and baseline monitoring of the air, soil, and bedrock, which continued through the injection period and into the current post-injection monitoring period.

Microseismicity ($\leq$ magnitude 2.0) is a common occurrence resulting from injection into deep reservoirs. This has resulted in occasional felt events, greater than magnitude 2, at the surface by local residents in other parts of the country, where the injection of waste water has been at or near the crystalline basement. At the time that IBDP was being conceived, the concern for microseismicity related to injection was important and the need for study was included in the

project design. Other CCS projects, nearly all smaller than IBDP, in various different strata and all with different operational processes have reported microseismicity, but none greater than magnitude 2 or felt. Because of the scale of injection at fairly high injection rates, it was felt that this project would be an excellent proxy for a commercial setting. Understanding microseismicity is an important aspect of the intellectual pursuit for this project especially since the microseismicity was initiated at very low pore pressure increases and there has been no decrease in microseismic activity with pressure decreases during multi-week transient shut-in.

2. Site Characteristics

2.1 State & Regional

The target Mt. Simon Sandstone saline reservoir is a widespread thick sandstone unit found in many of the Midwestern states. The Mt. Simon reaches its maximum thickness of approximately 2,600 ft (790 m) in northeastern and east-central Illinois and thins outward from there. The upper part of the Mt. Simon has been used in Illinois for geologic storage of natural gas since 1957.

The IBDP site is located in east-central Illinois in the north-central area of the Illinois Basin in the midcontinent region of the United States (Figure 1), southwest of the thickest section of Mt. Simon. The injection well and monitoring wells are on or near the property of ADM at their ethanol production facility in Decatur, Illinois. In general, this area has relatively flat lying bedrock strata with a slight dip of approximately 1° to the southeast and is far from known structures in the basin. The closest structures are minor anticlines with small structural closure. These anticlines are about 25 mi (40 km) south and 19 mi (30 km) north of the site. The closest mapped fault is a small fault in Pennsylvanian strata in a coal mine about 62 mi (100 km) southwest of the site and fault zones with offsets in Paleozoic strata down into the upper Cambrian are about 124 mi (200 km) north and southeast of the IBDP site (Nelson, 1995). The mapped faults are inactive structures with no documented seismicity.

The central section of the state has the lowest seismicity as shown in Figure 2. This figure demonstrates the estimated locations of historical epicenters and locations defined by the seismographs of the national seismic network. The closest seismograph station is at Hopedale, IL about 47 mi (75 km) northwest of the IBDP site. The lowest magnitude detection level of felt events and by the national seismic stations for the Decatur area are estimated to be in the low magnitude 2s. Background microseismicity (< 2.0) in the IBDP area was provided by 18 months of monitoring prior to CO₂ injection using two onsite vertical borehole arrays (Smith and Jaques, 2016).

The in situ stresses found in the bedrock are fairly consistent in the northern three-quarters of the state of Illinois with the highest stress in the horizontal direction as shown by in situ stress measurements that nearly surround the IBDP site from 44 to 174 mi (70 to 280 km) distance. Stress values are from a variety of measurement techniques including hydraulic fracturing, overcoring, and a borehole pressure meter and show $S_{Hmax} > S_{hmin} > S_v$ (Figure 3). These are consistent in direction and principal stress orientations as found throughout much of the Upper Midwestern and Eastern United States, Ontario Province and Canadian Shield by Zoback and Zoback (1980); Evans et al., (1989); Lucier et al., (2006); Maloney and Kaiser (2006); and

Arjang and Herget (1997). Regionally the strike of the maximum stress direction ranges from N 60°-75° E and the deepest measurements in Illinois are in Precambrian strata from depths of 2,264 to 4,757 ft (690 to 1,450 m) below the ground surface. The vertical stress is usually calculated by integrating the overburden density when overcoring does not provide the value.

2.2 Decatur Site

Most of Illinois was overridden by glaciers during the Pleistocene, leaving a 115 ft (35 m) thick deposit of till at the IBDP site. Below the glacial deposits, the overall bedrock stratigraphy (Figure 4) at the IBDP site is:

- 722 ft (220 m) of Pennsylvanian strata mostly shales with minor limestones and coal layers over;
- 1,214 ft (370 m) of Mississippian strata predominately limestones over;
- 127 ft (39 m) thick New Albany Shale (third seal) over;
- 397 ft (121 m) Devonian and Silurian strata over;
- 208 ft (63 m) thick Maquoketa shale (second seal) over;
- 2,133 ft (650 m) thick Ordovician strata over;
- Cambrian strata that contains the 492 ft (150 m) thick Eau Claire formation that is the primary seal over the 1,640 ft (500 m) thick Mt. Simon Sandstone; the CO₂ reservoir over;
- 50 to 115 ft (15 to 35 m) thick pre-Mt. Simon, Cambrian sandstone over the Precambrian crystalline basement.
- The contact between the Cambrian pre-Mt. Simon and the Precambrian is an unconformity representing a gap of about 900 million years (Leetaru and Finley, 2012).

The Mt. Simon unit at this site is described in great detail in Freiburg et al. (2014). It is divided into three major sections based on lithostratigraphy. The three major sections are further divided into units based on major depositional facies of fluvial braided river, floodplain, and alluvial plain deposits; eolian (windblown deposit) sandsheet, dune, and interdune deposits; and shallow marine deposits.

- Lower Mt. Simon - The Lower Mt. Simon contains the best reservoir properties which are predominantly in fluvial braided river and alluvial plain deposits. The Lower Mt. Simon had early feldspar dissolution resulting in clay minerals coating the quartz grains and lining the pore spaces. This prevented formation of late quartz cementation, as seen in the Middle Mt. Simon, thus preserving the large pore spaces resulting in an excellent reservoir. The high porosity confined to the Lower Mt. Simon is displayed in the geophysical downhole logging results (Figure 5).
- Middle Mt. Simon - The Middle Mt. Simon has poorer reservoir properties because of quartz cementation in pore spaces that developed much later after deposition and burial; during higher temperatures and pressures.
- Upper Mt. Simon – The Upper Mt. Simon represents a transition from fluvial or playa (shallow lake) deposits to eolian or interdune deposits to the overlying marine and tidal deposits of the Eau Claire Shale, the primary seal. Its reservoir properties are only slightly better than the Middle Mt. Simon.

The pre-Mt. Simon is lithologically similar to the Mt. Simon, but has distinct depositional changes and has a disconformable contact with the Mt. Simon. It is generally well-cemented and compacted throughout, resulting in a significantly lower porosity and permeability (Figure 5). Fine-grained and clayey sandstone beds occur throughout the unit between coarser sandstone beds. The basal contact with the Precambrian is a sharp nonconformity. The upper and lower 1.1 ft (0.34 m) sections of the pre-Mt. Simon contain angular clasts of the underlying basement rhyolite.

The Precambrian crystalline basement, as shown by sidewall cores and geophysical logs, is layered with rhyolite over granodiorite over granite. The rhyolite has been dated at 1.46 Ga (Leetaru and Finley, 2012). The rhyolite is significantly weathered as shown by mineral alterations decreasing with depth. The rock is highly fractured showing mineralization and/or slight alterations along the cracks. Highly fractured crystalline basement has been previously documented in north-west Illinois in a 5,250 ft (1,600 m) deep borehole with the lower 1,640 ft (500 m) encountering Precambrian crystalline basement with significant fracturing in the upper 1,148 ft (350 m) including two 330+ ft (100+ m) highly fractured sections (Haimson and Doe, 1983).

Four wells were drilled and logged using the latest geophysical logging techniques, and sidewall cores and whole core were cut at the IBDP site. These 4 wells are discussed below.

- CCS1 - The injection well was drilled in 2009 to a depth of 7,237 ft (2,206 m) terminating in the crystalline basement. This well is completed with two zones perforated for injection. The lowermost zone at a depth of 7,025 to 7,050 ft (2,141 to 2,149 m) is accepting the vast majority of the CO₂ based on spinner surveys. This well also had three multicomponent geophone arrays installed; briefly described below in 4.1.1 and in Will et al. (2016b).
- VW1 - Verification Well 1, designed for deep reservoir monitoring, was drilled in 2010, located about 1,007 ft (307 m) north of CCS1, to a depth of 7,272 ft (2,217 m), also into the crystalline basement. VW1 has sampling ports for formation water chemistry and has 11 levels of formation pore pressure and temperature monitoring.
- GM1 - The Geophysical Monitoring Well 1 located 196 ft (60 m) west of CCS1 and is 3,500 ft (1,067 m) deep. GM1 has 31 multicomponent geophones for Vertical Seismic Profile (VSP) monitoring and is also being used for microseismic monitoring.
- VW2 - The Illinois Industrial Carbon Capture and Storage Project owns the second deep reservoir monitoring well, VW2, and it is located 5,661 ft (1,725 m) north of CCS1 and was completed in October 2012. VW2 is 7,225 ft (2,202 m) deep also terminating in the crystalline basement (Figure 6). This well is pending completion at the time of writing this paper.

2D and 3D seismic surveys shot in the project area show the top of the Precambrian has topographic relief with several high knobs and valleys creating about 200 ft (61 m) of relief at the IBDP site (Figure 7). This relief is similar to other areas of Precambrian rock that were exposed to long term weathering.

3. Properties

3.1 Borehole Testing

A full suite of logs were performed in boreholes CCS1, VW1 and VW2 along with a few physical tests for reservoir characterization and modeling. Integration of early logs, core and pressure transient analysis for reservoir characterization can be found in Frailey et al. (2011). Later logging and core provided many additional properties. Some of the properties documented of value for understanding microseismic and analysis were: in situ stress and direction, fracture pressures, rock properties such as porosity, density and shear and compressive wave velocities. In situ stress and direction were documented by observation of tensile-induced drilling fractures and breakouts as shown by the FMI* fullbore formation microimager and a minifrac, injection and step rate tests. Tensile fractures and breakouts show the maximum horizontal stress to strike N 68° E. Minifrac test in the Eau Claire, cap rock formation, showed a minimum horizontal stress of 5,051 psi (34.8 MPa) at a depth of 5,335 ft (1.6 km). Injection and step rate tests in the Mt. Simon showed that the fracture pressures are 4,586 to 4,965 psi (31.6 to 34.2 MPa) at the depth of injection of 7,025 ft (2.14 km). This low value is associated with the highly porous, permeable, uncemented, low strength sandstone at this depth. Magnitude of in situ stresses is related to the rock mass quality and stiffness. Stresses accumulate and build up in stiff rock units that are massive and will only build up to a point in the weak, soft rocks. Evans et al. (1989) found this in the Appalachian Basin and Cartwright (1997) found a strong relationship between horizontal stress and elastic modulus of rocks associated with coal measure strata in the United Kingdom. The West Virginia Mountaineer proposed CO₂ injection site's in situ stress measurements show the same relationship of low measured stresses within low modulus/strength Cambrian sandstone proposed for injection. These low stresses are only about 65% of stresses in the high modulus/strength formations right above and below the weaker sandstone (Lucier et al., 2006). The vertical stress at the IBDP site shows a vertical stress gradient of 1.05 psi/ft (23.75 MPa/km) by the integrated density method.

Logging documenting porosity (Figure 5), shear wave velocities (V_s) and compressive wave velocities (V_p) (Figure 8), and density were used to calculate the dynamic properties of Young's modulus and bulk density and other properties showing variation within and between units. The Upper and Middle Mt. Simon has higher values compared to the Lower Mt. Simon and the injection zone shows even lower values, reflective of the poorly cemented, high porosity sandstone. The Middle Young's modulus is 5 to 6×10^6 psi (34.5 to 41.4 GPa) with a bulk density of 2.45 gm/cm^3 , while the Lower Mt. Simon has a Young's modulus of 2 to 3×10^6 psi (13.8 to 20.7 GPa) and a bulk density of 2.2 to 2.4 gm/cm^3 and the injection zone just above the pre-Mt. Simon has a Young's modulus of 1.7×10^6 psi (11.7 GPa) and a bulk density of 1.9 gm/cm^3 . The top of the pre-Mt. Simon just below the injection zone is a sharp mechanical property boundary with higher values similar to the Middle Mt. Simon but with slightly higher bulk densities of 2.3 to 2.6 gm/cm^3 . The Precambrian crystalline basement shows a higher porosity than the pre-Mt. Simon (Figure 5) because of the amount of open fractures and has a Young's modulus of 7 to 9×10^6 psi (48.3 to 62 GPa) with bulk densities of 2.5 to 2.6 gm/cm^3 .

3.2 Core Testing

In addition to the borehole logging, sidewall cores and whole core were recovered from three boreholes. The CCS1 borehole provided 30 ft (10 m) of Eau Claire and 60 ft (20 m) of whole core from the Middle and Lower Mt. Simon Sandstone. The VW1 well had over 588 ft (200 m) of whole core from the Eau Claire, each section of the Mt. Simon, the pre-Mt. Simon, and the Precambrian crystalline basement. VW2 had 396 ft (120 m) of Eau Claire, Middle and Lower Mt. Simon, and pre-Mt. Simon.

Laboratory analysis of the core provided rock strength properties, porosity and permeability, and diagenetic history from thin sections. The best reservoir quality rocks are located in the Lower Mt. Simon with average porosity of 22% and permeability of 200 mD. Individual intervals can have porosity as high as of 28% and permeabilities of 1,000 mD. The pre-Mt. Simon sandstone has a significantly lower average porosity of 9% and an average permeability of 2.3 mD than the overlying Mt. Simon (Leetaru and Freiburg, 2014).

Early rock strength testing was performed on limited core taken in injection borehole CCS1. Table 1 show values of the Eau Claire primary seal and Mt. Simon reservoir. The Mt. Simon samples are 246 ft (75 m) above the very high permeability injection interval for CCS1.

Table 1. Limited laboratory measurements of Eau Claire, seal, and Mt. Simon, reservoir.

Formation	Samples N	Depth	UCS**	Cohesion	Angle Internal Friction	Poisson's Ratio Static	Bulk Density gm/cm ³
Eau Claire	1	5,479 ft	10,979 psi	2,393 psi	42.9	0.27	2.4
		1,670 m	75.7 MPa	16.5 MPa			
Mt. Simon	2	6,768 ft	3,190- 3,916 psi	798-972 psi	36.9-37.9	0.16-0.17	1.9
		2,063 m	22-27 MPa	5.5-6.7 MPa			

**UCS = unconfined compressive strength

4. Monitoring and Results

An extensive array of monitoring technologies for the air, soil and bedrock, in the area, recorded conditions before injection as baseline, during injection and currently post injection. The equipment, monitoring, site conditions and preliminary results related to microseismicity will be discussed here.

4.1 Equipment

4.1.1 Geophones

Microseismicity was recorded by two vertical arrays: one in CCS1 and another in GM1. In CCS1, WellWatcher PS3* passive seismic sensing system was installed consisting of three 4-component geophones at depths of 4,925, 5,743, and 6,137 ft (1,501, 1,750, and 1,871 m). During installation, the upper geophone assembly did not properly release and clamp to the casing. All data have been collected by the two lowermost geophones and some data from the poorly clamped third set of geophones. All data are fed into a recording system and go through a

manual process to remove erroneous events that show up on the well bore diameter, assumed to be related to injection operations. The second vertical array is in GM1, 196 ft (60 m) from CCS1. These geophones are much shallower. There are 31 three-component geophones with 29 between the depths of 2,045 and 3,443 ft (623 and 1,049 m), and two others at much shallower depths of 135 and 355 ft (41 and 108 m) (Will et al., 2016b). These data are also fed into the same recording system used by the passive seismic sensing system (Will et al., 2016b). Both of these arrays were calibrated using drilling noise and perforation shots in borehole VW1, as described below in 4.2.1 and in detail in Smith and Jaques (2016).

4.1.2 Seismic Surveys

The 2D seismic lines were acquired in 2007 and 2013 and the 3D seismic surveys acquired in 2009, 2011 and 2015 in order to characterize the site rock mass, provide structural and stratigraphic information, produce a baseline before injection, and document any 4D changes. None of these surveys detected direct evidence of planes of weakness within the area. But the use of 3D curvature was used to detect extremely subtle discontinuities in the 3D seismic volume. This 3D curvature attribute at the approximate depth of the Mt. Simon/pre-Mt. Simon contact, showed a linear texture oriented in the direction of the microseismic clusters (Will et al., 2014) Figure 9.

All of the seismic lines and surveys, along with the multiple downhole geophysical investigations for formation properties, were incorporated to produce a series of static and dynamic models including, geologic, velocity and reservoir models (Senel et al., 2014 and Will et al., 2016). Also, inversion of the 3D seismic data along with reservoir properties acquired from well data were used to produce a reservoir flow simulation based on the integrated earth model. This model indicated that the CO₂ would follow along the high permeability layers and have very limited vertical migration (Leetaru et al., 2014). These same reservoir properties limit locations of pore water pressure changes.

4.1.3 Formation Pressure Monitoring

Formation pore water pressure monitoring is performed in VW1, 1,007 ft (307 m) north of the injection well CCS1. VW1 is completed with the Westbay system in which monitoring is performed through 11 perforations (producing ports referred to as zones) through the casing from 4,917 to 7,061 ft (1,499 to 2,153 m) deep with each zone isolated from the next with inflatable packers to insure zonal isolation. The lowest monitoring level is in the crystalline basement (Zone 1), eight zones are located in the Mt. Simon and two in the porous and permeable formation above the primary seal (Locke et al., 2013). Monitoring was performed during pre-injection to develop a baseline as well as during injection and currently post injection. These data provided original formation pressures showing an in situ hydrostatic gradient of 0.45 psi/ft (10.3 MPa/km) in the Precambrian and up through most of the Mt. Simon formation. The lower zones in VW1 closest to the high porosity/permeable layers in the injection well (CCS1), showed rapid pressure changes (rapid communication) with changes in injection pressures (Figure 10).

4.2 Microseismicity

4.2.1 IBDP Pre-Injection Microseismicity

Pre-injection microseismic monitoring covered the time period from 1 May 2010 to 15 Nov 2011, 564 days or a little over 1.5 years and was monitored by the two vertical arrays in CCS1 and GM1. The two arrays recorded over 68,000 triggered events. Most were related to surface noise, drilling of the VW1 borehole, well activities, VW1 perforation shots, and many distant events assumed to be mine blasts because of distance and time of day (8:00 to 17:00). Twenty-one distant natural earthquakes (12 in USGS catalogue) and eight local microseismic events were recorded which appear to be unrelated to well activity and presumed to be background events. These 8 events were located in the Mt. Simon and pre-Mt. Simon with 6 located within 1,500 ft (457 m) of CCS1 and two located 5,400 to 7,900 ft (1,646 to 2,408 m) from CCS1. These eight events had a magnitude range from -2.16 to -1.52 and an average of -1.83. Magnitudes recorded from drilling and well activity ranged from -2.6 to -1.6 (Smith and Jaques, 2016).

4.2.3 CO₂ Induced Microseismicity: Other Sites

There are over ten CO₂ injection projects in the world that have reported on their injection, site conditions, and results of their monitoring programs. All are different with respect to type, depth and thickness of the unit accepting the CO₂ and pressures and volumes used during injection. All the sites' microseismicity (< magnitude 2.0) have locatable events with a similar range of magnitude from -2.0 to a high of about 1 at Aneth (Soma and Rutledge, 2013), Lacq-Rousee (Prinet et al., 2013), Otway (Rutqvist, 2012a), and Weyburn (Rutqvist, 2012b) and the highest of 1.7 at In Salah (Stork et al., 2014). All of these magnitudes are below being felt at the ground surface which typically would require magnitudes in the low to middle 2s. Each site is equipped with different acquisition systems and layouts, leading to varying detection capabilities. The reports from these sites indicated an average of less than one to ten locatable events observed per day.

4.2.4 IBDP Microseismicity During Injection

CO₂ injection started on 17 Nov 2011 and continued at a rate of approximately 1,102 tons (1,000 tonnes) per day to 26 Nov 2014, with various short interruptions to continuous injection. The overall average per month for the injection time period was about 30,864 tons (28,000 tonnes) or 45,778 cubic yards (35,000 cubic meters). Microseismic events started two months after initiation of injection and during the overall injection time period 4,747 events were located with an average of a little over 4 events per day with an average magnitude of -0.9. Ninety-four percent of events were less than magnitude 0 and two events were above 1 at 1.07 and 1.17. The amount of energy released represented by a -1 magnitude is about that of the typical inch long, pencil thick fire cracker. Using Zoback and Gorelick's (2012) magnitude versus slip surface size and displacement diagram, a magnitude -1 represents a slip of less than a millimeter on a plane of a couple of meters in size to a slip of a fraction of a tenth of a millimeter on a larger plane of tens of meters.

Monitoring has shown the CO₂ and formation pore pressure increases are stratified near the base of the Mt. Simon; the location of the injection zone. Thin silty mudstone layers in the Mt. Simon, over 1,000 ft (300 m) below the Eau Claire seal, form baffles to upward pressure and CO₂ migration. This control on pore pressure increases also controls location of the top of the microseismic events to a similar distance below the Eau Claire seal. The microseismic events

appear to be fairly evenly distributed amongst the Mt. Simon, pre-Mt. Simon, and Precambrian crystalline bedrock. The range of magnitudes of events is also nearly identical in each layer. The Precambrian had the highest magnitudes of 1.07 and 1.17, while magnitude highs of 0.88, 0.76 and 0.66 were recorded in the pre-Mt. Simon and Mt. Simon. The lowest moment magnitude detected in all three formations was near -2.0. The microseismic magnitudes, locations, and estimated slip plane size lessen the primary concern raised by Zoback and Gorelick (2012) with induced seismicity causing reactivated fault slippage through the cap rock seal; compromising the seal.

For injections with pressures below levels to fracture rock, induced seismicity typically occurs through the process of increasing the pore pressures in the already existing fluid filled spaces within a pre-existing fault, small slip or fracture. If the defect is oriented in a direction that in situ stresses are trying to force one side to slide past the other and the stress exceeds the friction of the defect, it will slip. Injection fluids increase the formation pore pressures and this may reduce the friction by pushing the defect's walls apart. Therefore the amount of pressure increase in the formation from injection plays a role in this mechanism. Published cases show injection pressures at other CO₂ sites are increasing the formation pressures by close to 32% to 80% over the original pressures (In Salah - Goertz-Allmann et al., 2014 and Shi et al., 2013; Weyburn – Verdon et al., 2011; Ketzin – Würdemann et al., 2010). At the IBDP site, the maximum increased pressures are 165 psi (1.14 MPa) or 5.2% above original formation pressures, as measured in VW1, 1007 ft (307 m) from the injection borehole and this pressure represent only 65% of the fracture pressure for the Mt. Simon injection zone.

4.2.5 Cluster Development

Locatable microseismic events started two months after initiation of injection, with two events in December 2011 and 13 in January 2012. These events were close to 2,000 ft (600 m) from CCS1 and as events continued at this distance, new ones started closer to the injection well at a distance of about 1,000 ft (300 m) away, each ultimately forming separate elongate clusters. As clusters became evident, they were numbered in the sequence of appearance, producing 18 numbered clusters. The sequence of clusters did not all develop in order of greater distances from the injection well. An early example of this was the development of Clusters 1 through 4. Cluster 1 is on average 1,800 ft (548 m) from CCS1, Cluster 2 nearly half that distance on average about 1,100 ft (335 m), Cluster 3 at 1,500 ft (457 m), and Cluster 4 at a distance of 2,700 ft (823 m). Many other later clusters also developed out of sequence with increasing distance from the injection well.

Clusters continued to add microseismic events through time; during injection and transient shut-in periods. Most developed an elongated pattern in the SW-NE direction. It appears that not just pore pressure increases played a role in the sequence of some cluster development, but the angle of the pre-existing planes of weakness or defects in relation to the direction of the maximum horizontal stress. Pre-existing weak planes or defects close to 30 degrees from the maximum horizontal stress (S_{Hmax}) direction are optimally oriented in the direction expected for strike-slip movements.

Some microseismic events from hydraulic fracturing are triggered along pre-existing natural fractures that are favorably oriented for slip (Pearson 1981; Rutledge and Phillips, 2003; and Shapiro et al., 2006). Baig et al., (2012) found for hydraulic fracturing of some horizontal wells, that events tended to fall along two main trends: the early events follow a trend roughly 30 degrees from S_{Hmax} and the later events follow a lineation approximately parallel to S_{Hmax} . The first cluster is optimally oriented to slip given the direction of S_{Hmax} . Yang et al., (2013) found similar trends for hydraulic fracturing in the Bakken formation where detected microseismic events from many stages trend ~30 degrees from the direction of S_{Hmax} .

This appears to hold true for the IBDP microseismic sequence of cluster development, with Cluster 1 at 28 degrees from S_{Hmax} , Cluster 2 at 11 degrees, Cluster 3 at 9 degrees and Cluster 4 at 3 degrees. The strike of each plane was developed by a best fit plane through the 3D cloud of events (Figure 11). The strike of the planes in relation to the in situ S_{Hmax} fits the first motion analysis indicating right lateral strike-slip motions on many of the clusters (Couëslan et al., 2014). These planes are interpreted to be the reactivation of pre-existing features as shown by the Richter-Gutenberg plots for all the microseismicity, which show b-values close to 1 (Figure 12). Will et al. (2016) presents an in depth analysis of the data integration and reservoir response resulting in microseismicity.

4.2.6 Microseismicity During Transient Shut-In

The longest continuous shut-in during the three years of injection was for a 2-week period in March 2013. This shut-in along with corresponding pressure drops in Zones 1, 2, and 3 appears in the middle of Figure 10. Comparison of locatable events for a stable, continuous 2-week injection period before shut-in, 1-14 Feb 2013 and the 1-15 Mar 2013 shut-in period, shows similar number of events (51 versus 52), similar range of depth of events from 6,060 to 6,760 ft (1,850 to 2,060 m), overall slightly lower magnitude of shut-in events by only 0.25, and the distance from the injection well for the events during injection ranged from 500 to 4,000 ft (150 to 1,219 m) away, while during shut-in the range was from 1,100 to 5,000 ft (335 to 1,524 m) away and occurred at mostly similar locations where events were occurring prior to shut-in.

Another analysis was performed for six months of 2014 using hourly data for locatable events. Shut-in hours represented 10.9% of the time. The average events per injection hours were 0.204 events per hour while during shut-in it averaged 0.222 events per hour. Both of these analyses are an incomplete analysis of a 3D space and pressure drops in that space and their possible role in event initiation. Further analysis of extended pressure decreases and microseismicity awaits permanent long-term shut-in.

5. Summary

The IBDP, a carbon capture and geologic storage project, has safely and successfully injected nearly 1.1 million tons (1 million tonnes) of CO₂ over a three year period into the base of the 1,640 ft (500 m) thick Mt. Simon Sandstone unit at a depth of 7,025 ft (2.14 km). The site had an extensive pre-injection investigation of site conditions and baseline monitoring in the air, soil, and bedrock, which continued through the injection period and currently into the post-injection period. The injection zone in the Mt. Simon is highly porous and permeable because of a

diagenetic process that inhibited silica cementation, which resulted in low increases in formation pore pressures during the 1,102 tons (1,000 tonnes) CO₂ injected per day. Microseismicity ($\leq$ magnitude 2.0) monitored by several vertical arrays at depth, showed the locations to be controlled by pre-existing planes of weakness influenced by the low pore pressure increases. The early sequence of microseismicity was influenced more by planes critically oriented to the maximum horizontal stress direction, than by proximity to the injection well. The microseismicity-defined planes or elongated clusters, span the lower Mt. Simon, pre-Mt. Simon and top of the Precambrian and were not detected with 2D or 3D seismic imaging.

The overall average number of events per day during injection have been a little over four with a range of magnitudes from -2.12 to 1.17, which is similar to reported ranges at other CO₂ injection projects. Ninety-four percent of the microseismicity had magnitudes of 0 and below, with an overall average magnitude of -0.9. Microseismicity did not change much during transient shut-in and accompanying pressure drops. The longest continuous shut-in was two weeks and the number of microseismic events did not decrease; overall range of magnitudes were slightly lower by 0.25 and events occurred nearly throughout similar distances and locations from the injection well as before shut-in. Understanding microseismicity is a major research interest and the unique IBDP data set will contribute to the global understanding of microseismic activity related to CO₂ injection and storage. Monitoring and analysis continues as permanent shut-in started on 26 Nov 2014.

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6. Acknowledgement

This work was conducted under the Midwest Geological Sequestration Consortium which is funded by the U.S. Department of Energy through the National Energy Technology Laboratory (NETL) 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 through the Illinois Clean Coal Institute.

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Figure 1. Location of Illinois Basin – Decatur Project (red dot) in relation to Illinois Basin and surrounding structures (from Leetaru et al., 2014).

Figure 2. Historic and instrument located earthquakes in Illinois from 1795 to 2015.

Figure 3. In situ stresses showing principal stresses of measured sites surrounding the IBDP from 44 to 174 mi (70 to 280 km) away. Measurements made specifically for in situ stresses using the hydraulic fracturing, overcoring and borehole pressure meter methods. Data from Bauer et al., (1991), Beerkircher (1994), Haimson (1974), Haimson and Doe (1983), Hanna et al., (1986), Shuri and Kelsay (1984), and URS (2001).

Figure 4. Geologic column of the IBDP site showing Mt. Simon reservoir, seals and geologic system nomenclature.

Figure 5. Cross section across the IBDP study site showing the Mt. Simon and Pre-Mt. Simon Sandstones and part of the Eau Claire cap rock and Precambrian crystalline basement formations. Three subintervals of Mt. Simon (Upper, Middle and Lower) are shown along with porosity logs highlighted with red shaded areas of curves where porosity is 10% and higher. Highest peaks are approaching 30% porosity.

Figure 6. Diagram showing configuration of borehole and monitoring equipment for the IBDP site in relation to stratigraphy. The WellWatcher PS³ geophone array in the CCS1 well, the OYO, 3 component, 31-level array in the GM1 well and the VW1 containing the Westbay system for sampling and pressures readings at 11 levels (from Will et al., 2014).

Figure 7. Topography of the base of the Mt. Simon Sandstone from the seismic reflector of the pre-Mt. Simon sandstone over the 3D seismic survey area of the IBDP. Three boreholes shown from south to north are; CCS1, VW1, and VW2 (from Leetaru and Freiburg, 2014).

Figure 8. Shear wave velocity readings from top of Mt. Simon (blue) to pre-Mt. Simon (red) and Precambrian (green). Lowest velocity right above Pre-Mt. Simon is the high porosity/permeability layers where CO₂ injection occurred in CCS1. Purple line is compressive wave velocity for same borehole.

Figure 9. Horizontal slice through the maximum 3D curvature seismic attribute at approximate depth of the Mt. Simon/pre-Mt. Simon interface showing SW-NE fabric and similarly aligned microseismicity (from Will et al., 2014).

Figure10. Diagram of pressure readings in lower 6 levels (zones) of VW1 and pressure reading at the injection well along with cumulative injected mass (from Senel et al., 2014).

Figure 11. Clusters 1-4 directions in relation to maximum horizontal in situ stress and average distance from injection well CCS1.

Figure 12. Richter-Gutenberg plot of all the microseismicity during the three years of injection.