Illinois Basin – Decatur Project Pre-Injection Microseismic Analysis

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Abstract:

The Illinois Basin – Decatur Project (IBDP) is a large-scale carbon dioxide (CO₂) injection and storage demonstration project. Over a three-year period one million metric tons of CO₂ were injected deep into the Mt. Simon Sandstone, a deep saline reservoir in the Illinois Basin. This study examines the microseismic data gathered for the period from May 2010 to November 2011, which preceded the CO₂ injection.

Microseismic events are detected through permanent geophone arrays installed in two wells. A CO₂ injection well drilled to the depth of 7,236 feet (2,205 m) is outfitted with a 4-component geophone array. Situated approximately 185ft away (56m), the 3,502 feet (1,067m) deep geophysical monitoring well contains a 3-component geophone array.

During the pre-injection period, a total of 7,894 microseismic events were detected and 99% of these correlate with drilling and other well-related operations. Eight local microseismic events were identified that appear unrelated to well activity and appear representative of the background level of microseismicity.

Regional seismicity was also examined by changing triggering parameters and producing a second dataset. Under this configuration, the system detected twelve regional seismic events that correlate to the United States Geological Survey (USGS) earthquake record, and approximately 1,100 distant events are believed associated with quarry-related blasting operations.

Keywords

Microseismic, CO₂ Sequestration, Geophone, Event location

1. Introduction

The Illinois Basin – Decatur Project (IBDP), located in Decatur, Illinois, is a large-scale carbon dioxide (CO₂) injection and storage project. The overall objective of this project is to demonstrate the injectivity, capacity, and containment of the Mt. Simon Sandstone and overlying Eau Claire Shale seal. The IBDP injected one million metric tons of CO₂ over a three-year period into the Mt. Simon Sandstone, a deep saline formation in the Illinois Basin.

Microseismic detection is one of a number of monitoring activities associated with this project. This paper describes the monitoring system and the detection of microseismicity before CO₂ injection commenced in November 2011. The importance of this baseline is twofold. First, this baseline work validated the operation of the system through detecting both local and regional events of known time and origin. Second, this baseline establishes the degree of microseismicity before CO₂ injection started. This way one could be certain that microseismicity seen during the injection period was indeed related to the injection operation.

Three wells for this project have been drilled at the Archer Daniels Midland Company (ADM) site in Decatur, Illinois (Figure 1). A CO₂ injection well (CCS1) was drilled to the depth of 7,236 feet (2,205 m) and is completed with the WellWatcher PS3* passive seismic sensing system 4-component geophones [1]. A shallow geophysical monitoring well (GM1) contains the OYO Geospace Technologies (OYO), 3-component geophone array [2]. The verification well (VW1) does not have any geophones but houses the Westbay system, which is a multilevel groundwater characterization and monitoring system used for multi-zone sampling, pressure, and temperature monitoring. The Westbay system and the microseismic monitoring system are just two of the Monitoring, Verification, and Accounting (MVA) methods employed for the IBDP. Formation perforations within VW1 were useful in calibrating the operation of the geophone arrays. Figure 2 shows the configuration of the installed geophone arrays used for continuously recording the seismic activity.

Figure 1: Map view of IBDP wells.

Figure 2: In ground equipment configuration for the IBDP. The WellWatcher PS3 geophone array is installed in the CCS1 well; the OYO, 3-component, 31-level array is contained in the GM1 well.

The microseismic system has been fully operational and recording continuously since May 2010, and has generated approximately 10 terabytes (TB) of data between May 2010 and November 2011. This original microseismic data stream was stored locally on the Microseismic Integrated Data Acquisition System in Decatur; later, the disks were transferred to another Linux-based computer for processing.

2. Material and Methods

Permanent geophones are installed in the wells, with three geophone levels in CCS1 and 31 levels in GM1. Each geophone level consists of either 3 or 4 geophones; their orientation is given by V for vertical or H for horizontal [3]. Installed in CCS1, the WellWatcher PS3 consists of 4 geophones per level, which are in a tetrahedral configuration [4]. With one vertical geophone, the remaining three “H” components are not really horizontal, Figure 3. They each have vertical and horizontal components that enable some redundancy, which makes the system more robust. The 4-component measurements have to be transformed into 3-components during microseismic processing. Installed in GM1, the 31-level OYO geophones [2] have three geophones per level in the classic, orthogonal configuration, Figure 3.

Figure 3: Orthogonal and tetrahedral geophone configurations.

The raw microseismic data stream is recorded in 10-second SEG2 files. The data sampling rate during the pre-injection period was every 2 milliseconds (ms) (500 samples per second). The dataset composition is described in terms of date ranges, number of files, number of triggers and events identified. Table 1 summarizes this 10 TB pre-injection block of data.

The number of triggers represents the total number of possible events detected by the system, and so includes many false triggers. Given the sensitivity of the system, false triggers are caused by any combination of transient electrical glitches and well-related activity like pipeline maintenance. The distinction is that a false trigger will not have a P and S wave signature common to microseismicity or place an event in the subsurface.

Start Date	End Date	Disk	Dataset	Number of SEG2 Files	Number of Triggers	Number of Events
01-May-2010	04-Jul-2010	silos	20100501 – 20100704	533,496	42,159	0
05-Jul-2010	04-Sep-2010	silol	20100705 – 20100904	535,400	4,886	1
05-Sep-2010	05-Nov-2010	silol	20100905 – 20101105	535,669	10,553	7,765
06-Nov-2010	06-Jan-2011	silol	20101106 – 20110106	535,680	1,030	97
07-Jan-2011	10-Mar-2011	silol	20110107 – 20110310	530,435	177	1
11-Mar-2011	14-May-2011	silol	20110311 – 20110514	533,043	1,216	16
15-May-2011	15-Jul-2011	USB	20110515 – 20110715	532,173	1,752	8
16-Jul-2011	15-Sep-2011	silol	20110716 – 20110915	535,415	1,133	4
16-Sep-2011	15-Nov-2011	silol	20110916 – 20111115	527,040	5,669	2
Totals:					68,575	7,894

Table 1: Pre-Injection Dataset Summary.

2.1 Trigger Parameters

The WellWatcher PS3 installed in CCS1 has the best sensors for detecting microseismic events because they are at the deepest levels and are less prone to surface noise. The downhole cable construction also offers greater immunity from electrical interference than the OYO geophone cable in GM1. Electrical interference is an issue at the site due to an electrical substation that is in close proximity to the wells and two electrical lines that run along the road immediately west of the site. Therefore, only the WellWatcher PS3 has been used in the triggering (event detection) process, with any 4 of the 8 geophone channels being triggered. However, data from both geophone arrays, WellWatcher PS3 and OYO, are used in computing the location of events.

Prior to event detection a series of three filters are used, which includes a filter to remove regular noise, a band pass filter to remove high and low frequencies, and a short term/long term average function. The data is first filtered using an error prediction filter to remove regular noise such as 60 Hz electrical noise and associated harmonics. The error prediction filter builds an 80-coefficient polynomial that follows the seismic trace. So, for each calculated sample (i.e. output

of the error prediction), the calculated value of the polynomial is subtracted from the raw sample of the trace. This results in the removal of repetitive noise such as electrical or low frequency pumping noise. Any high frequency seismic impulses that suddenly occur are not "predicted" and thus are output from the filter. To allow the filter to track changing conditions, such as changing electrical noise (say 60Hz power might change to 61Hz for example), the filtering algorithm is provided with an "update rate" value to reflect how quickly the filter modifies the coefficients of the filter in order to track variations in the repetitive noise.

The second filter is a band pass filter to remove low and high frequencies. Lastly, a form of short term average (STA) divided by the long term average (LTA) function is then applied to the filtered data, and it is the result of this function that is compared to a threshold in order to determine if a trigger has occurred and should be recorded. The thresholds used are given in Table 2; for example, if $STA/LTA > 6.0$ millivolts, then the channel triggers.

In order to obtain a triggered record, any 4 of the 8 channels must satisfy the threshold within 100 ms. After a triggered event has been identified, no other triggers can occur for 250 ms. This is an industry standard process called voting [5].

This trigger configuration has been designed to detect very small microseismic events while minimizing the number of false triggers. This optimized configuration was also used during the CO₂ injection phase of the project and has since detected several thousand events over the course of injection.

While the geophones in CCS1 and GM1 are primarily intended for detecting local microseismic events, they also detect the low frequency signatures from distant events such as earthquakes. The P and S waves (Compressional and Shear waves) associated with earthquakes have a large separation in arrival times. However, the triggered microseismic datasets only record a 5 second window so the triggered data may only contain a P or S wave arrival which can make it difficult to determine the exact type of signal recorded.

In order to help verify the types of some of these long-offset triggered events, the data were processed using a different trigger configuration to specifically find any low frequency and distant events. This dataset was recorded with a long pre-trigger and a record length of 80 seconds. The trigger parameters used to detect regional events is given in Table 2 and used a 20 Hz low pass filter. Under this event trigger configuration, approximately 1,100 distant events were detected.

Channel	Name	Threshold (mV)	Filter 1 Predict	Filter 2 Band Pass	Filter 3 STA/LTA V6
Trigger Setting for local events					
1	PS3_1_V	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
2	PS3_1_H1	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
3	PS3_1_H2	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
4	PS3_1_H3	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
5	PS3_2_V	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
6	PS3_2_H1	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
7	PS3_2_H2	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
8	PS3_2_H3	6.0	Len=80; Update=0.01	20Hz – 200Hz	40ms/500ms
Trigger Setting for of low frequency, long-offset events (regional events)					
2	PS3_1_H1	4.5	N/A	20Hz Low Pass	500ms/6000ms
5	PS3_2_V	4.5	N/A	20Hz Low Pass	500ms/6000ms
6	PS3_2_H1	4.5	N/A	20Hz Low Pass	500ms/6000ms

Table 2: Microseismic event detection triggers parameters for local and regional events.

3. Results

3.1 Near-Offset Locatable Events

The detection, recording, and reporting of microseismic activity is complicated by what constitutes an event. To clarify some nomenclature used here, the microseismic dataset is broken down into four high-level categories. Figure 4 illustrates the breakdown of these categories: (1) First, there is the microseismic record that can consist of Terabytes of raw data. (2) The raw data are passed through filters to detect local or regional events resulting in “triggered events.” Among the triggered events there are many false triggers due to transient electrical glitches. (3) Having removed the false triggers, the remaining waveforms are detected events. (4) The detected events can be divided into non-locatable and locatable events. The non-locatable events relate to subsurface microseismicity, but due to poor signal-to-noise ratio or ambiguous P and S wave pairs, the events can’t be properly picked. This leaves the locatable events where the P and S waves are of sufficient quality and can be reasonably picked resulting in events placed or located in the subsurface.

Figure 4. Microseismic event nomenclature and IBDP locatable, local events.

Microseismic recording on the IBDP started in May of 2010. Prior to injection from 2 May, 2010 through 15 November, 2011 (the start of injection) there were 562 days of recorded data that resulted in a total of 68,575 triggered events; 7,894 of these triggers were determined to be detected microseismic events. Of the 7,894 detected events, potentially 2,000 are locatable, Figure 4. The process of locating an event requires manually picking the P and S waves among the different geophone levels. Microseismic positional (location) determination is never precise given the anisotropic and heterogeneous character of the subsurface. These parameters can never be 100% known and naturally results in some spatial uncertainty in an event's location in (x,y,z).

Most of these 2,000 locatable events can be attributed to the drilling of VW1 as the P and S waves for these events have a common signature that points to the VW1 well during the drilling phase (23 September 2010 through 22 November 2010), Figure 5. Given the manual nature of waveform picking, just 74 of these VW1 drilling events were selected and analyzed to determine their location. Four other categories of located microseismic events were also found in the time preceding CO₂ injection and include: VW1 perforation shots, VW1 near-well activity, local microseismic events, and distant events. These particular distant events were not sought in this instance, but were detected in this filter that was otherwise meant for local events.

Based on the local triggering parameters, the distribution count for these events is shown in Figure 5. A representative portion of the located events dataset is given in Table 3 which shows time, coordinates (x,y,z), magnitude and distance to the events.

Header details for Table 3 are shown below:

- Date and Time: Coordinated Universal Time (UTC).
- East (ft): X-coordinate of the located event, Illinois State Plane East (1,201), NAD27.
- North (ft): Y-coordinate of the located event, Illinois State Plane East (1,201), NAD27.
- DEPTH (ft, TVDSS): Z-elevation of the located event at total vertical depth subsea.
- RMS (micron/sec): Root mean square of the event's signal.
- DIST (ft): Distances to the located microseismic events were computed from the injection interval in the CCS1 injection well given by (x=342,848, y=1,169,545, z= - 6,323 mean seal level (MSL) feet.
- MAG: microseismic moment magnitude.

Figure 5: Located pre-injection microseismic events at the IBDP using local detection filters.

Date and Time	East (ft)	North (ft)	DEPTH (ft,	RMS (micron/sec)	DIST (ft)	MAG
VW1 Drilling Activity						
04-Oct-2010 21:59:25	342.82	1,170.07	2177	1.4	4,180	-1.55
04-Oct-2010 23:02:15	342.97	1,170.56	1992	1.8	4,451	-1.58
05-Oct-2010 15:53:14	343.09	1,170.53	2296	2.1	4,153	-1.83
06-Oct-2010 15:09:42	342.86	1,170.46	2449	2.4	3,981	-1.70
74 events picked,	•	•	•	•	•	•
only partial	•	•	•	•	•	•
set shown.	•	•	•	•	•	•
13-Nov-2010 20:29:05	342.90	1,170.28	5921	1.0	846	-1.80
15-Nov-2010 02:51:33	342.90	1,170.22	6114	1.3	711	-1.66
16-Nov-2010 01:57:02	342.88	1,170.20	4692	1.4	1,758	-2.06
VW1 Perforation Shots						
02-May-2011	342.94	1,170.58	6242	1.4	1,048	-1.36
02-May-2011	342.92	1,170.56	6209	1.8	1,024	-1.61
02-May-2011	342.89	1,170.51	6197	2.1	978	-1.69
02-May-2011	342.93	1,170.57	6092	2.4	1,062	-1.68
02-May-2011	342.93	1,170.48	6028	1.1	991	-1.60
02-May-2011	342.93	1,170.49	5936	1.2	1,028	-1.62
02-May-2011	342.94	1,170.49	5786	1.7	1,098	-1.55
02-May-2011	342.89	1,170.51	5213	1.5	1,474	-1.39
02-May-2011	342.92	1,170.49	5022	1.0	1,612	-1.40
02-May-2011	342.87	1,170.24	4250	1.3	2,187	-1.18
02-May-2011	342.90	1,170.28	4188	1.4	2,260	-1.27
Well Related Activity						
15-May-2011	342.99	1,170.37	5688	0.6	1,052	-1.97
15-May-2011	342.98	1,170.36	5781	0.6	991	-2.12
15-May-2011	342.94	1,170.42	5696	1.5	1,082	-2.41
15-May-2011	342.95	1,170.40	5752	1.4	1,038	-2.33
15-May-2011	342.86	1,170.35	5665	3	1,044	-2.31
15-May-2011	342.97	1,170.40	5746	1.1	1,039	-2.02
16-May-2011	342.96	1,170.39	5615	3.1	1,114	-1.91
15-May-2011	342.99	1,170.37	5688	0.6	1,052	-1.97
Local Microseismic						
06-Sep-2010 06:06:38.5	343.18	1,169.80	5548	4.2	882	-2.16
09-Feb-2011 09:56:19.3	338.14	1,167.75	6180	3.0	5,032	-1.52
15-Apr-2011	342.92	1,170.10	6451	1.5	577	-1.84
25-Apr-2011	343.57	1,171.08	6149	1.1	1,710	-2.20
04-May-2011	342.65	1,170.68	6542	3.0	1,178	-1.98
28-May-2011	348.06	1,175.51	6093	2.4	7,933	-1.64
21-Oct-2011 03:35:04.3	342.17	1,168.57	6034	4.9	1,217	-1.96
21-Oct-2011 03:35:05.5	342.08	1,168.42	5868	3.8	1,430	-1.95
Distant Events caught in local event filter.					miles	
28-Aug-2010		These seven distant (i.e. long-offset) events were identified during the near-offset microseismic analysis.			~ 15	
01-Jan-2011 01:07:48.8					~ 18	
24-Apr-2011					~ 40	
20-Jul-2011 09:21:59.5					~ 10	
08-Aug-2011					~ 50	
08-Aug-2011					~ 50	
26-Aug-2011					~ 17	

Table 3: Located Microseismic events and magnitudes.

The pre-injection microseismic event locations are mapped in Figure 6 where the microseismicity has been sorted into four categories by color. The fifth category consisting of seven distant events is not shown in this local site map.

Figure 6: Microseismic event locations, map view and side view. Well CCS1, GM1, and VW1 are associated with the IBDP. Black dots are well head locations. Well locations CCS2, GM2, and VW2 are also shown for the Illinois Industrial Carbon Capture and Sequestration (ICCS) Project and were not present during the pre-injection period.

The microseismic dataset of located events (Table 3) revealed some obvious clustering that facilitated the interpretations. Plotting the events in depth as a function of time (Figure 7) reveals the association with known IBDP operations. Located microseismic activity is found to correlate with the drilling, perforations and swabbing operations in VW1. The remaining local microseismic events did not appear to relate to any of these activities and thus form their own set. For completeness, the distant events that got caught in the local detection filter were also added to Figure 7 which shows their occurrence in time; their depths shown here are arbitrary.

Figure 7. Microseismic events (107 total) in depth versus time. Three clusters of events have been correlated to well operations involving VW1. Eight local microseismic events appear unrelated to well activity.

The moment magnitudes of the located, pre-injection microseismic events were plotted as a function of time and show a variation of approximately an order of magnitude between the smallest and largest events (Figure 8). Again, these data forms clusters in time that associate with well operations. In general, the local microseismic activity was no greater in magnitude than the drilling or perforating of VW1. The implication is that, although more frequent, the microseismicity associated with drilling and perforating a well is comparable with the amplitude of naturally occurring microseismicity. However, the source mechanisms associated with these events are very likely different, thus an exact one-to-one comparison is not possible.

Figure 8. Microseismic events in magnitude versus time. Three clusters of events correlate to well operations involving VW1. The local microseismic events are comparable in magnitude to the drilling and perforating of VW1.

Pre-injection microseismicity was compared with activity during CO₂ injection (Figure 9). The 18-month pre-injection period is considered quiet when compared to the injection period. The injection of CO₂ is accompanied by microseismicity during both the active injection and transitory shut-ins. Pre-injection analysis sifted through the (many) smaller events to assess what activity was occurring. Smaller events generally have greater positional uncertainty (x,y,z). During injection, many small events still occur; azimuths obtained from the hodogram analysis of these small events leaves more uncertainty in (x,y,z). Generally more attention is given to the larger events, which naturally have a much better signal to noise ratio that results in greater certainty in spatial location (x,y,z). The pre-injection data sampling rate was 2 ms (or 500 samples per second). For CO₂ injection, the sampling rate was updated to 0.5 ms (or 2,000 samples per second) offering an enhancement in waveform quality, and thus greater positional accuracy.

Figure 9. Microseismic events in magnitude versus time for both pre-injection and injection periods are shown as blue points. Injection rate is in tonnes/minute (red curve).

Beyond the local microseismic activity, the geophone system detected approximately 1,100 distant events that occur between 8 am and 5 pm local time. These events are believed to be associated with quarry or mine related blasting operations. Most notably, the geophone system detected twelve regional earthquakes during the 18-month pre-injection period that correlate with the USGS regional earthquake record. These observations further validated the operation of the microseismic monitoring system.

The five microseismic categories (local microseismic events, VW1 drilling activity, VW1 perforation shots, well-related activity, and distant events) have been separated and detailed in the following sections.

1) Microseismicity Due to VW1 Drilling Activity

From 4 October to 16 November, 2010, approximately 2,000 small events were recorded that appear to be related to the drilling activity of VW1. Among these detected events, approximately 1,900 of these events are potentially locatable and a subset of 74 of these have been processed to determine their locations (x,y,z). This represents a small sampling, but is sufficient to show the general locations of these drilling events along VW1. Figure 10 clearly shows that the interval is between 1,992 feet and 6,114 feet (607 m and 1,863 m) with the majority occurring between 4,000 feet and 6,000 feet (1,291 m and 1,829 m) within the Eau Claire Formation. Depths are relative to mean sea level. A portion of scatter is attributed to the difficulty in obtaining accurate time picks associated with the small amplitude of the events. Scatter can also be attributed to the anisotropic and heterogeneous nature of the rock which cannot be 100% quantifiable.

The events have been color coded according to the date and time at which they occurred. The microseismic events occur at increasing depths as the drilling advanced from 4 October to 16 November, 2010.

These events are small and so obtaining accurate time picks and locations are difficult and time-consuming. The events range in magnitude between -2.68 to -1.44 and a number of factors make it difficult to obtain accurate magnitude values including:

- The amplitudes of the signals,
- Low sampling interval of 2ms,
- Increased background drilling noise.

Figure 10: Microseismic events associated with the drilling of VW1 from 4 October, 2010 to 16 November, 2010. As the drilling advanced in depth, so did most of the microseismic events. White dots represent key formation tops observed in each well.

2) VW1 Well Perforation Microseismicity

In preparation for installation of the Westbay system, eleven perforation shots were completed in VW1 on 2 May, 2011. These perforation shots were detected by the geophone systems. Nine of the perforations were made into the Mt. Simon Sandstone; two were located above the Eau Claire. These shots occurred at known times and depths. This crucial data facilitated the validation and calibration of the triggering and event detection process. Figure 11 reveals the locations of these events that have been detected and saved in the microseismic record.

Figure 11: Cluster of microseismic events that are related to well perforations in VW1. The microseismicity occurs during the perforation shots on 2 May, 2011. Zone numbering is from bottom (Zone 1) to top (Zone 11). White dots represent key formation tops observed in each well. Green lines represent well perforation depths.

3) VW1 Well Related Microseismicity

Two weeks following the perforation shots, a small cluster of events occurred near VW1. The signatures of the events within this cluster were similar. This activity was likely associated with VW1 well operations involving the swabbing of Westbay Zone 7. Swabbing is a reservoir fluid sampling method that initiates flow from the reservoir. The swabbing procedure was conducted during the evening hours of 15 May, 2011. Figure 12 reveals the locations of these microseismic events along with the known perforation depths.

Figure 12: Cluster of microseismic events that appear to be related to swabbing operations in VW1 that took place in Westbay zone 7 on 15 May, 2011. Zone numbering is from bottom (Zone 1) to top (Zone 11). White dots represent key formation tops observed in each well. Green lines represent well perforation depths.

4) Local Microseismicity (unrelated to well activity)

The local microseismic events category is comprised of events that do not appear to be associated in time with known well activity, or have microseismic signatures consistent with the preceding groups. In total, only 8 events were characterized as local microseismic events at a locatable distance away from CCS1 (Figure 13a and 13b). All the events detected are characterized by having moment magnitudes of less than -1.5, and therefore the signal to noise ratio is relatively low, with peak velocity amplitudes of less than 0.2micron/sec. From the 8 events located, one of the best examples of the waveforms recorded in CCS1 is included (Figure 13a). The other 7 events detected suffer from lower signal amplitudes and increased contamination with noise from surface, which is more significant on the shallower geophones of GM1.

Figure 13a. Local microseismic event waveforms from CCS1 of an event detected on 21 October 2011 at 03:55:05

These events may be suggestive of the microseismic background level. Six of these events occur in the Mt. Simon Sandstone, two of these events appear in the underlying Pre-Mt. Simon. The 8 event points suggest a broad trend to the NE, but otherwise do not have any spatial or temporal correlation. In general, ignoring all the activity associated with VW1, the area was very quiet over the 18-month record preceding CO₂ injection.

Figure 13b. Local microseismic event locations unrelated to well activity. Well locations CCS2, GM2, and VW2 are shown for the Illinois Industrial Carbon Capture and Sequestration (ICCS) Project and were not present during the pre-injection period.

5) Distant Events (unrelated to well activity)

In the process of seeking local microseismic events, other distant events can get caught up in the search. Of the thousands of small, local, high frequency microseismic events detected, there were seven, low frequency, distant events that passed through the detection and filtering process. These could be earthquakes or possible surface activity such as quarry blasting. These events all had clear P- and S-wave arrivals. The time differences between the P- and S-waves were used to estimate the distance from CCS1, Table 3. Whereas these events were unintentionally detected during the search for local events, the results of the regional seismicity is described next where triggering and filtering methods are intended to detect low frequency, far-offset events.

3.2 Regional Seismicity

Using the long-offset trigger configuration, (described above in trigger parameters) there are two notable seismic categories observed during the regional and large earthquake analysis. The first category is earthquakes, a number of which have been detected and correlated to events documented by the USGS in their earthquake database. The second category involves approximately 1,100 smaller events believed to be associated with blasting operations in mines or quarries.

3.2.1 Earthquakes

A number of regional earthquakes were detected during the pre-injection period. Some of these events correspond with those documented in the USGS earthquake database [6]. One example earthquake recorded on the two WellWatcher PS3 levels shows the P- and S-arrivals with an arrival separation of approximately 30 seconds (Figure 14). This event is consistent in time, distance and orientation with the 3.9 magnitude earthquake located in east Missouri on 07 June, 2011. Other low frequency events were also detected. In total, 21 events were detected that had seismic signatures comparable to far-offset, earthquake-like events; 12 of these correlate in time with those found in the USGS database of regional earthquakes, Table 4. The earthquake events in Table 4 have been mapped in Figure 15.

Figure 14: Example of an earthquake (07 June, 2011) recorded on WellWatcher PS3 during the pre-injection period. P to S time difference = 3×10^4 ms= 30 seconds. This event corresponds to the 3.9 magnitude event in eastern Missouri. These waveforms typify the long-offset earthquake events that were detected.

No.	IBDP	Date Time	USGS	Latitude	Longitude	Depth	Magnitude
1	X	11-Aug-2010 06:12:31.2					
2	X	11-Oct-2010 13:33:40.0	X	35.306	-92.316	5.5	4
3	X	12-Oct-2010 17:59:46.6					
4	X	16-Oct-2010 09:43:18.0	X	35.288	-92.332	6.1	3.5
5	X	04-Nov-2010 20:38:44.3					
6	X	20-Nov-2010 19:06:35.0	X	35.319	-92.303	4.5	3.9
7	X	30-Dec-2010 12:55:22.0	X	40.43	-85.914	5	3.8
8	X	15-Feb-2011 05:36:31.2					
9	X	18-Feb-2011 04:59:50.0	X	35.257	-92.37	5.1	3.9
10	X	18-Feb-2011 08:13:35.0	X	35.271	-92.377	6.3	4.1
11	X	08-Apr-2011 14:56:32.0	X	35.261	-92.362	6.3	3.9
12	X	21-May-2011 02:53:29.7					
13	X	07-Jun-2011 08:10:36.7	X	38.077	-90.902	20.9	3.9
14	X	22-Jul-2011 19:12:12.3					
15	X	08-Aug-2011 18:01:25.5					
16	X	22-Sep-2011 23:32:09.0	X	36.818	-90.749	11.5	3.6
17	X	29-Sep-2011 15:45:49.2					
18	X	05-Nov-2011 07:12:45.0	X	35.55	-96.764	3.1	4.8
19	X	06-Nov-2011 03:53:10.0	X	35.532	-96.765	5.2	5.6
20	X	06-Nov-2011 04:35:06.4					
21	X	08-Nov-2011 02:46:57.0	X	35.531	-96.788	5	4.8

Table 4: Detected earthquakes from the IBDP geophone arrays at left. At right: events from the USGS earthquake database [6] that correlate in time with IBDP events. Number 13 is the 3.9 magnitude event shown in the previous figure.

Figure 15: Example of regional earthquakes detected during the pre-injection period. Item 13 is the 3.9 magnitude earthquake on 07 June 2011. These numbered events correspond to earthquakes in Table 4.

3.2.2 Far-Offset Blasting Operations

This triggered dataset contains many events that are very similar in character. Over 1,100 events have been detected that have a difference in P- to S-wave arrival times of approximately 20 seconds. These events occur at similar times every day with a peak frequency occurring during the late afternoon. The sources of these events are likely mines and quarries. Correlating detected events with specific mining operations is not an easy task and is beyond the scope of this investigation for the IBDP. To review blast records, such a task would involve making appointments for onsite visits with various mine operators [7].

Without knowing the actual source (mine or quarry), an example blasting event is shown in Figure 16 from an event recorded on 15 November, 2011. This event, with a P- to S-time and orientation similar to the majority of the 1,100 events detected, is typical of those occurring at

approximately 5 pm local time (CDT). A common mining practice is to schedule blasting at the end of the workday (5 pm) after workers have left the site. The workers can safely enter the area the following day after the dust has settled. The amplitudes of these blasting events are typically an order of magnitude smaller than the earthquake examples above (Figures 14 and 15). This event is approximately 105 miles to the southeast of CCS1 and is indicative of the 1,100 long-offset detected events originating in the proximity of Knox County, Indiana. This area and some of the adjacent counties have a substantial number of coal mining operations and limestone quarries.

Figure 16: Typical long-offset blasting event originating approximately 100 miles to the southeast of CCS1. P to S time difference = 2×10^4 ms = 20 seconds.

Of the 1,100 events, there appears to be a few groups that have very similar P- to S-times and orientations. A histogram of the P- to S-time in Figure 17 shows the time to the nearest hour that these long-offset events occur. The increase in the peak frequency at 5 pm suggests that these events are not natural phenomena but somehow linked to the working day from 8 am to 5 pm.

Figure 17: Histogram of long-offset, low frequency events using local time adjusted for daylight savings. Many events occur during the working day. Hodograms indicate many of the events are to the SE of CCS1.

The 1,100 long-offset events were sorted by P to S times to assess their distance distribution. Figure 18 shows that many of the events occur at 22,000 ms or 22 seconds which place them southeast of CCS1 in and around Knox County, Indiana. These events are believed to be associated with quarry and mine blasting operations.

Figure 18: Histogram of P to S arrival times for long-offset events. Note: multiply by 8.4 to get distance in meters. The P to S time of 22,000 ms corresponds to a distance of approximately 184.8 km or 115 miles.

3.3 Root Mean Square Plots

Event detection and location often becomes the focus of a microseismic monitoring program. However, a plan needs to be in place to manage the data volume. Just as important, it is necessary to have diagnostics that can help operators gauge system health. This is accomplished through the use of root mean square (RMS) plots that provide useful information presented in a concise format. With 500 samples every second per channel, data accumulates quickly and it is vital to know whether data channels are operating properly. Having a way of displaying a month of data on a single plot is very useful. An example of the RMS signal plot (in microns/second) is shown in Figure 19 for the bottom level of WellWatcher PS3. This level contains the deepest and quietest sensors in the microseismic monitoring network. One geophone-level here is comprised of four geophones in a tetrahedral configuration resulting in four channels (V, H1, H2 and H3) being plotted.

A file is generated every 10 seconds from the acquisition unit and contains 500 samples per channel. In a day there are 8,640 of these files. Every time a file is recorded, the RMS for each channel is calculated by computing the average of the squares of each sample, and then the square root (root mean square). This provides an aggregated magnitude of the recorded signal and can be considered representative of the background noise. The system also records the maximum value from each trace from each 10-second record. In order to further cut down the number of points, the system averages the RMS values from a number of 10-second records. For example, to get an hourly average it takes 360 RMS values and calculates the average. Similarly, it also takes the maximum values from the 10-second maximum values. These are useful because peaks related to microseismic events are preserved.

Thus, the hourly RMS values are calculated as follows:

1. Every 10 seconds a SEG2 file is recorded and is comprised of 5,000 samples per channel. An RMS value is calculated for each channel from the 5,000 samples to produce a single RMS value per channel.
2. These RMS values are then averaged over a one hour window.

The significance of the RMS plots is that they provide analysts and operators crucial information about the system including:

- System downtime gaps.
- Step changes in RMS noise levels can indicate a problem such as bad connection on a connector, a failed sensor, problem with the acquisition, or problem with grounding, etc.
- Shifts in the tracers can show changes in external noise levels such as traffic, construction, well activity etc.

- RMS plots quickly provide reassurance that the entire datasets contains valid data without having to check all the data.
- The plots show unfiltered data, so any electrical noise affecting acquisition due to poor grounding will show up.
- RMS values from the WellWatcher PS3 are typically between 0.01 and 0.1. Around 0.01 is typical when things are really quiet and free of any injection noise. Around 0.1 tends to be representative of background noise levels for the shallower sensors affected by surface noise or injections. If out of this range, then it usually indicates that something needs to be investigated and understood.

The RMS plots given in Figure 19 show a three-month period leading up to the drilling of VW1. Individual traces correspond to the four geophone channels with the fifth trace representing event detection rate. In this example, two weeks after the drilling of VW1 commenced, the rate of microseismic event detection is seen to increase around 6 October, 2010.

Figure 19: Example RMS plots for the period preceding and during the drilling of VW1.

4. Discussion

Microseismic monitoring quickly produces a large dataset that requires significant filtering and triggering methodologies to produce a set of triggered events of potential interest. Triggered events need to be further screened to produce detected events through the removal of false triggers like electrical glitches. Detected events are comprised of P and S arrival times that place events in the subsurface. The quality and signal-to-noise ratio of these P and S waves will determine whether an event can be picked and located. Not all events can be located, but their presence may correlate in time to located events and signify increased activity.

As part of the MVA work for the IBDP, the microseismic monitoring provided valuable insight into subsurface activity that would otherwise go unnoticed. The monitoring of microseismic activity before the injection phase of the project was significant in several regards. During this time the system was configured and geophone orientations were determined. The system's sensitivity was validated in terms of detecting site-specific subsurface operations, local background microseismicity, and detecting regional earthquakes. This analysis benefited from the extensive recordkeeping of site operations. Together with regional seismicity, these observations helped build confidence in the system's operation and performance. Any system installation of this type will have site-specific noise issues that include electrical interference and seismic interference due to trains or other industrial equipment. It is important to understand the nature of these sources and how it may impact the signal-to-noise ratio of geophone channels that are measured in millivolts. In light of all of these variables, the signal filtering and triggering needs to be optimized for the detection of microseismic events. With the monitoring system in place, RMS plots were useful as a diagnostic tool in gauging system integrity.

5. Conclusions

Microseismic monitoring during the 18 month pre-injection period at IBDP produced 10 TByte of data. This dataset was filtered and processed for detection of local microseismic activity. Regional earthquake seismicity was also examined by changing triggering parameters and producing a second dataset.

With trigger parameters set for local events, a total of 7,894 microseismic events were detected where approximately 2,000 are locatable. These events are largely associated with the drilling of VW1. Although only 74 of these events were selected and processed for location, they follow the drill path downward in depth and also correlate in time. Approximately 1,900 of these events share similar waveform characteristics and P- to S-times which correlate to the drilling of VW1. Other local events were also found to correlate with known activity at the site and include: 11 events traceable to the 11 perforation shots in VW1, and 7 other events related to the swabbing of the Westbay system, zone 7 in VW1.

There were 8 local microseismic events detected that appear unrelated to well activity. These events are believed to be representative of the background or ambient level of naturally occurring

microseismic activity. Lastly, among the local microseismic analysis, there were seven, low frequency, long-offset events completely unrelated to the project that got caught in the filter.

With long-offset triggering parameters the processing detected 12 regional (natural) earthquake events that were correlated with earthquakes documented by the USGS. This provided reassurance that the monitoring system was robust. The long-offset triggering method also revealed approximately 1,100 distant events that are believed associated with quarry or mine related blasting operations. Although the exact source is not known, these events occur between 8 am and 5 pm local time and are situated 100 miles (160 km) to the southeast in and near Knox County, Indiana.

Gathering the baseline microseismic record enabled the understanding of ambient conditions while increasing the awareness of site-specific noise sources. The baseline record helped assure that microseismicity seen later during the project's injection phase was indeed injection related. Event detection triggering parameters used in this study helped to optimize the trigger setup used for microseismic monitoring during the entire 3-year injection phase of the project. For both CCS and oil and natural gas projects, it is important to work out microseismic monitoring strategies and challenges early in the operation.

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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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