Pre-thru Post-Injection Monitoring of Microseismicity at Illinois Basin Decatur Project and Static and Dynamic Modeling Efforts for Monitoring and Event Prediction

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First part - Overview of the IBDP microseismicity:

Setting – formation characteristics
Stratified pressure response
Stress directions & influence on some microseismic cluster sequence
Monitoring arrays
Pre-Injection Seismicity
Microseismicity development through time during Injection & Post-Injection
Comparison to other injection sites and injection types
Mt. Simon – 500 meters thick

St. Peter Sandstone

Primary seal

Secondary seal

Tertiary seal

Injection at 2.1 km – 7,050 ft

Location of USDW in unconsolidated Quaternary deposits.
Map View of IBDP wells

- VW1: 916 ft (≈280 m)
- GM1: 196 ft (≈60 m)
- CCS1: 1000 ft (≈300 m)
Estimated top of Argenta (Pre-Mt. Simon) (feet)

Leetaru & Freiburg 2014
Mt. Simon Sandstone

Argenta - Pre-Mt. Simon SS Precambrian

Eau Claire Shale

Red = Porosity > 10%

Depth 2.1 km

Injection zone

Leetaru & Freiburg 2014
Mt. Simon

Highest Log Porosity = 27%
Highest Log Perm = 1066 mD

Argenta (Pre-Mt. Simon)

1mm

Fractured Precambrian

Highest Log Porosity = 14%
Highest Log Perm = 36 mD
Eau Claire
Mt. Simon SS
Injection Zone
Argenta – (Pre Mt. Simon)
Precambrian

VW1
Formation pressure readings
900 feet from Injection borehole

% Increase of Original Formation Pressures

0% 2.00% 4.00% 6.00%

Zones
1 2 3 4 5 6 7

Down hole Injection pressure @ CCS1 are 14% to 16% increase above original formation pressure
VW1 - Verification Well Pressure Monitoring Data

Zone 2: $\Delta p \approx 151$ psi (10.4 bar) or $\approx 5\%$ Formation increase

Zone 6: $\Delta p \approx 21$ psi (1.4 bar) or $<1\%$

From Schlumberger Carbon Services
Difference in Zone pressures at VW1 with 2 week shut in

CCS1 Bottom Hole Pressures as % of Original Formation Pressures dropped from 14% to 3.8%
\[ \Delta P_{\text{max at VW1}} = 5.2\% \text{ over original formation pressures for Zone 2} \]

64\% to 73\% of fracture pressures of Mt. Simon at Injection well

Pressures are stratified and upwards movement influenced by very thin mudstone layers 300 feet above injection zone
IBDP Well configuration and geophones

Valerie Smith
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SMC 1850 10 Hz

Omni 2400 15 Hz
1.5 Years of Pre-Injection Seismic Monitoring
May 2010-Nov 2011

7,894 events detected – 86% related to drilling and well activities

1,100 distant events – most related to distance to quarries in southern Illinois

8 local events unrelated to drilling and well activity
Local Microseismic Events: Pre-Injection
1.5 years of Pre-Injection Monitoring

8 Events

Max: -1.52
Avg: -1.83
Min: -2.16

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Additional Temporary Geophones in VW2 from 26 Sept 2013 to 25 Feb 2015

Five Omni 2400 15 Hz
200 ft apart from depths of 6,150 ft to 6,950 ft
Each Division in X & Y = 1,000 Ft or \approx 300 m
Jan 2012

CCS1
Feb 2012
Jul 2012

1.14

CCS1
Jan 2012

CCS1
April 2013
July 2013
Cluster 1 formed first at about 1,800 feet (550 m) from CCS1 before Cluster 2 at an average of 1,160 feet (350 m) from CCS1.

Estimates are that Cluster 1 Δ pressures were about 50 psi (3.5 bars) or 0.35 MPa at the time of first formation.

Pre-existing fractures close to 30 degrees from the maximum horizontal stress direction are optimally oriented in the direction expected for strike-slip movements.
Maximum Horizontal Stress Directions showing measurement techniques

Optimally oriented to slip: strike-slip

SHmax
Each Division in X & Y = 400 Feet or ≈ 120 m
Microseismic Cluster Activity: Relationship to Pre-Mt. Simon Structure
Cluster development in relation to stratigraphy

Cluster 1 & 11 development

Time – Dec 2011 to April 2013

Top Precambrian
Cluster 2 development

Time – Dec 2011 to April 2013

Feet MSL

Top Precambrian
Cluster 3 development

Time – Dec 2011 to April 2013

Range of Top of Precambrian along length of fault
Cluster 4 development

Time – Dec 2011 to April 2013

Range of Top of Precambrian along length of fault

1.14
Eau Claire – 1st seal

Mt. Simon Sandstone

Injection Zone

Pre Mt. Simon

Precambrian crystalline basement

1,100 ft (335 m) below caprock

Dec 2011 to Nov 2014
Permanent Shut In Started 26 Nov 2014
Formation pressure readings 900 feet from Injection borehole

% Increase of Original Formation Pressures

Zones

0%  2.00%  4.00%  6.00%

Down hole Injection pressure @ CCS1 16% increase over original formation pressure
Average Monthly Pressures as % Above Original Formation Pressures

73% of fracture pressure

[Graph showing trends over months from January 2013 to March 2016]
Dec 2011 to April 2016

26 Nov 2014
Shut In

-2.32 to 1.14 & 95% are 0 and less

-2.22 to 0.8 & 98.5% are 0 and less
Each square = 2,000 ft / 610 m
How does IBDP microseismicity compare to other sites?

There is limited published data from other CO$_2$ injection sites!

Compare to Wastewater Disposal, Enhanced Geothermal Systems (EGS), Enhanced Oil Recovery (EOR) data.
Wastewater
EGS
EOR
HF

Magnitudes of Seismic Event per Injection

Feel event

Damaging

Otway
In Salah
Weyburn
Aneth
Lacq
IBDP

Wastewater Disposal and Enhanced Geothermal Systems Seismicity

![Diagram showing normalised cumulative frequency against normalised earthquake timing with indicated percentages of 70%, 20%, and 10%.

Legend:
- All Mag
- Max Mag
- Combined
- Basel
- Soultz GPK3
- Soultz GPK4-1
- Soultz-GPK4-2
- Soultz GPK2]
b-value is a slope of Gutenberg-Richter relationship of magnitude of events vs frequency of the those events

b-value of about 1 indicates a movement on a pre-existing faults/fractures

Much higher b-values (2 to 2.5 for HF) indicate fracturing of intact rock

For EGS Bachmann (2010) shows a decrease in b-value following injection – decrease means a proportionally larger magnitude earthquakes compared to the smaller events. Leading to increase probability of large events during shut in.

b-values are the same for IBDP during injection and post-injection.
During Injection with 3 vertical arrays

\[ y = -1.0882x + 1.8288 \]
Warpinski 2012 (hydraulic fracturing)
Microseismic Activity: Overview

- Stratified pressures and Max. Δ P of 5.2% increase for one “zone”
- Max CCS1 DHP at 73% of fracture pressures
- Low permeability thin mudstone layers 300 ft above injection, restrict pressure increases upward, restricting microseismic development to 1,100 feet below Eau Claire caprock
- Form distinct clusters along undetected pre-existing faults/fractures
- Distributed between Lower Mt. Simon Sandstone, Argenta, and ~ 50% in Precambrian basement
- Injection magnitudes range from -2.32 to 1.14 & 95% are 0 and less
- Post-injection range from -2.22 to 0.8 & 98.5% are 0 and less (to 3/31/2016)
- b values of about 1 during and after injection indicate reactivation of pre-existing features
- Overall project average of microseismic events during injection using same seismic arrays was 3.2 per day


