Integrating Induced Seismicity with Fault Interpretation at the Decatur, IL CCS Projects

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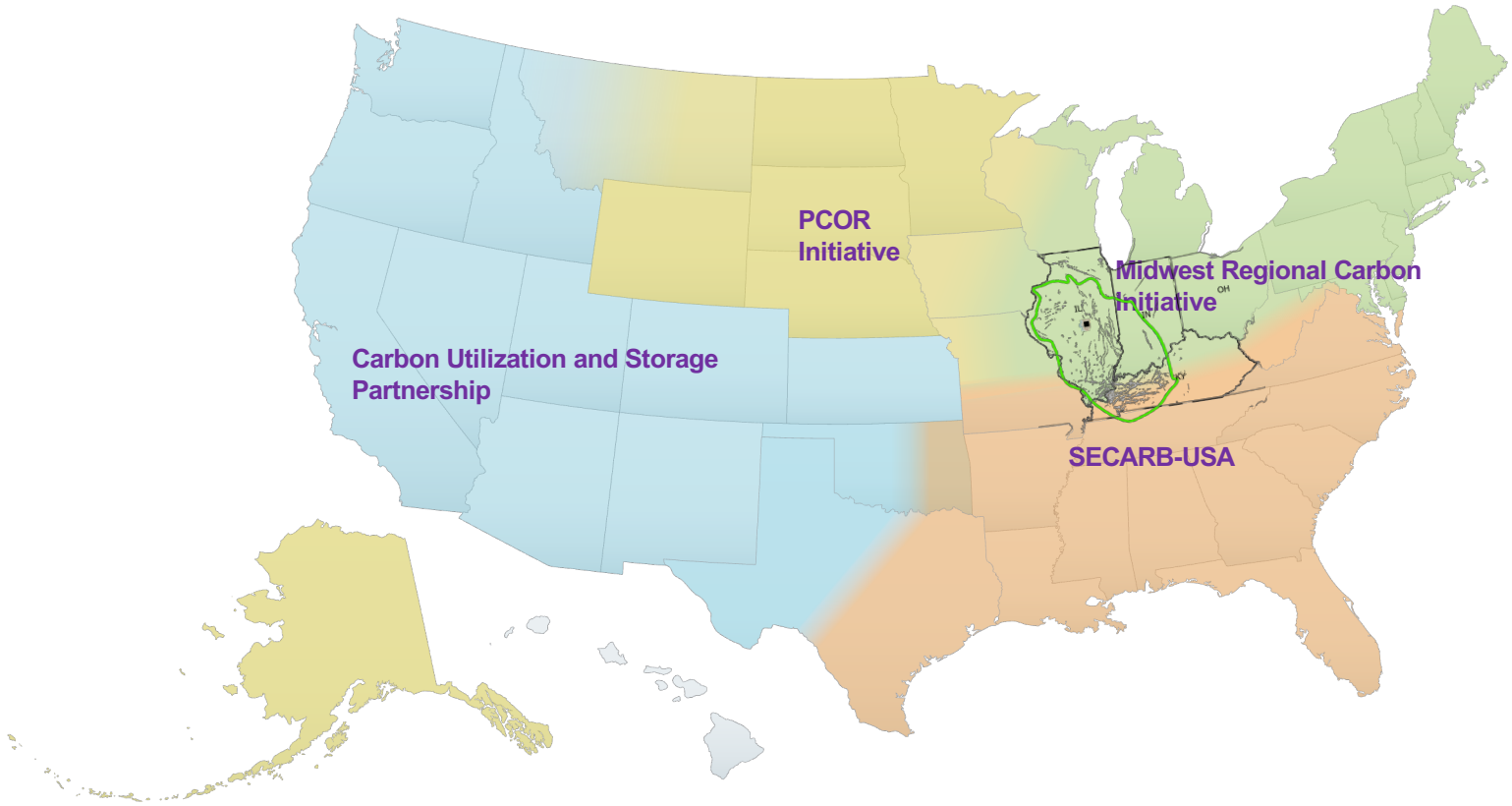
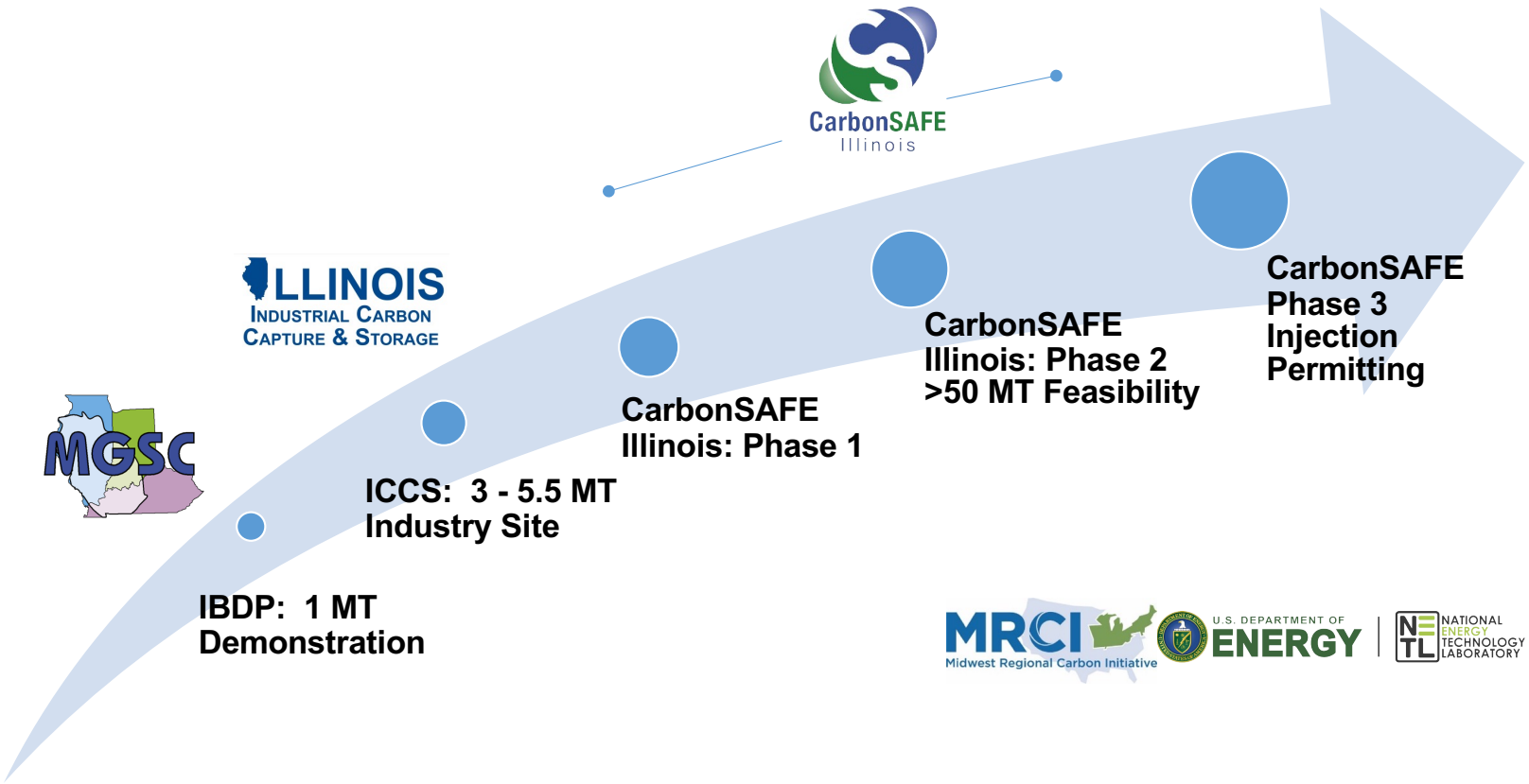
Oklahoma and the Energy Transition – OGS Workshop 2022

Initiatives to Accelerate CCUS in the United States



CCS in the Illinois Basin



Decatur CCUS Project Descriptions

Illinois Basin – Decatur Project

- Large-scale demonstration
- Volume: 1 million tonnes
- Injection period: 3 years
- Injection rate: 1,000 tonnes/d
- Compression capacity: 1,100 tonnes/day

Contribution:

- Geologic and Social Site Characterization
- Reservoir Modeling and Risk Assessment
- MVA Development and Engineering Design
- Stakeholder Engagement

Status:

- Post-injection monitoring ended April 2020
- Project completed June 2021

Illinois Industrial CCS Project

ILLINOIS
INDUSTRIAL CARBON CAPTURE & STORAGE

- Industrial-scale demonstration
- Volume: up to 5 million tonnes
- Injection period: 3 years (or longer)
- Injection rate: 3,000 tons/d
- Compression capacity: 2,200 tonnes/day

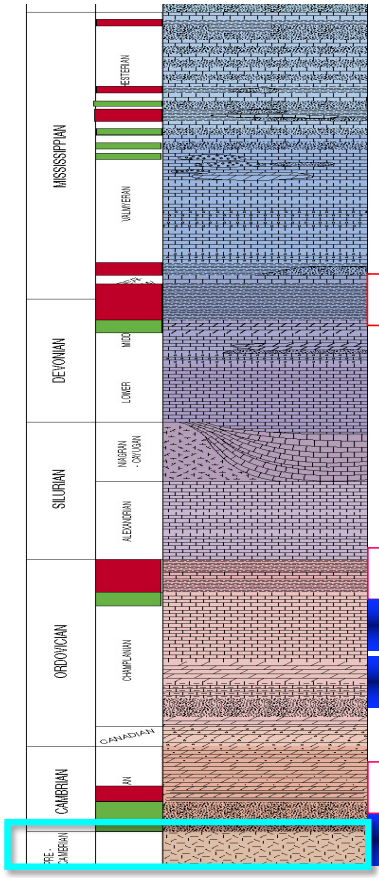
Contribution:

- Commercial-scale up surface and subsurface
- Intelligent Monitoring
- Class VI permitting

Status:

- Injection Began April 7, 2017
- Optimization of capture process
- >2,000,000 tonnes to date

Illinois Basin Geological Setting



New Albany Shale

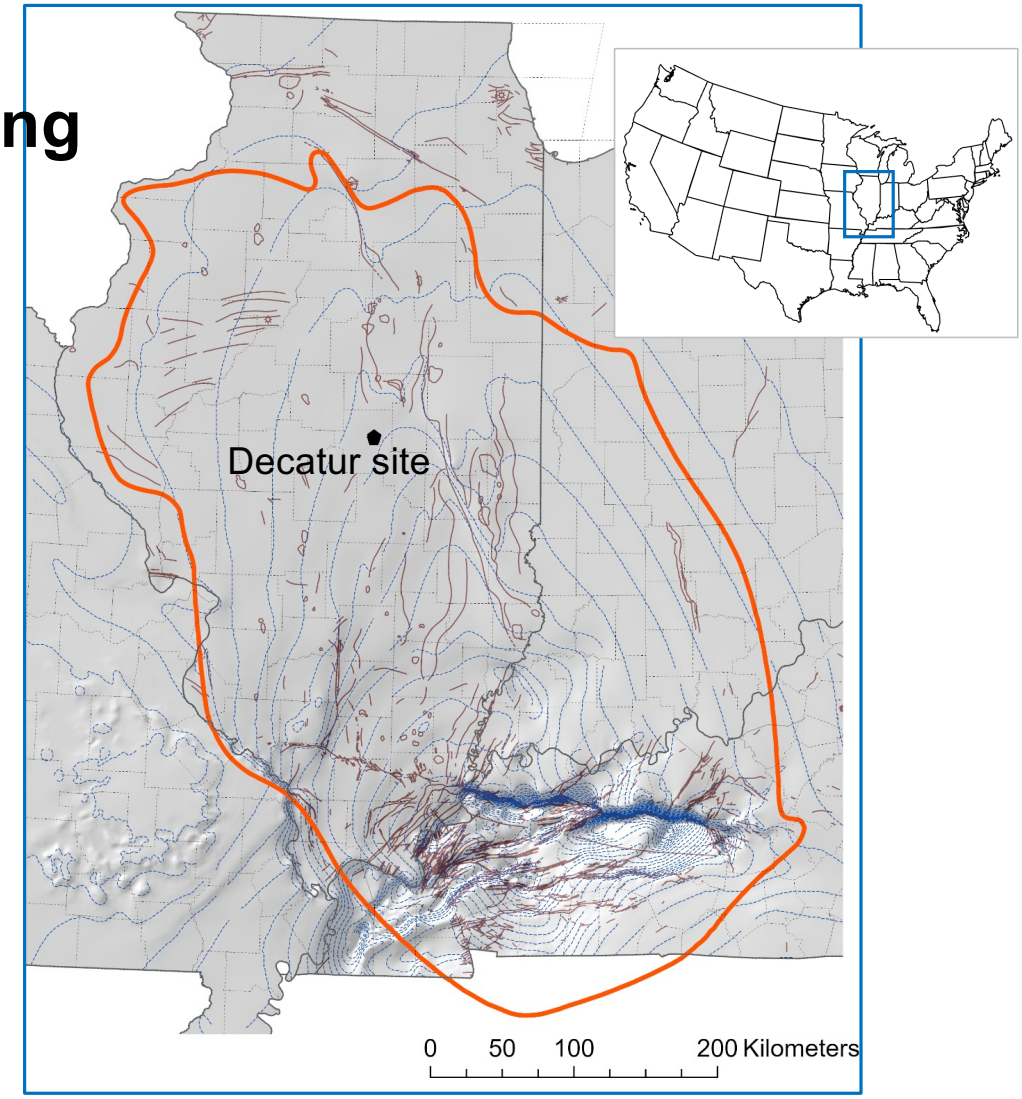
Maquoketa Shale

St. Peter Sandstone

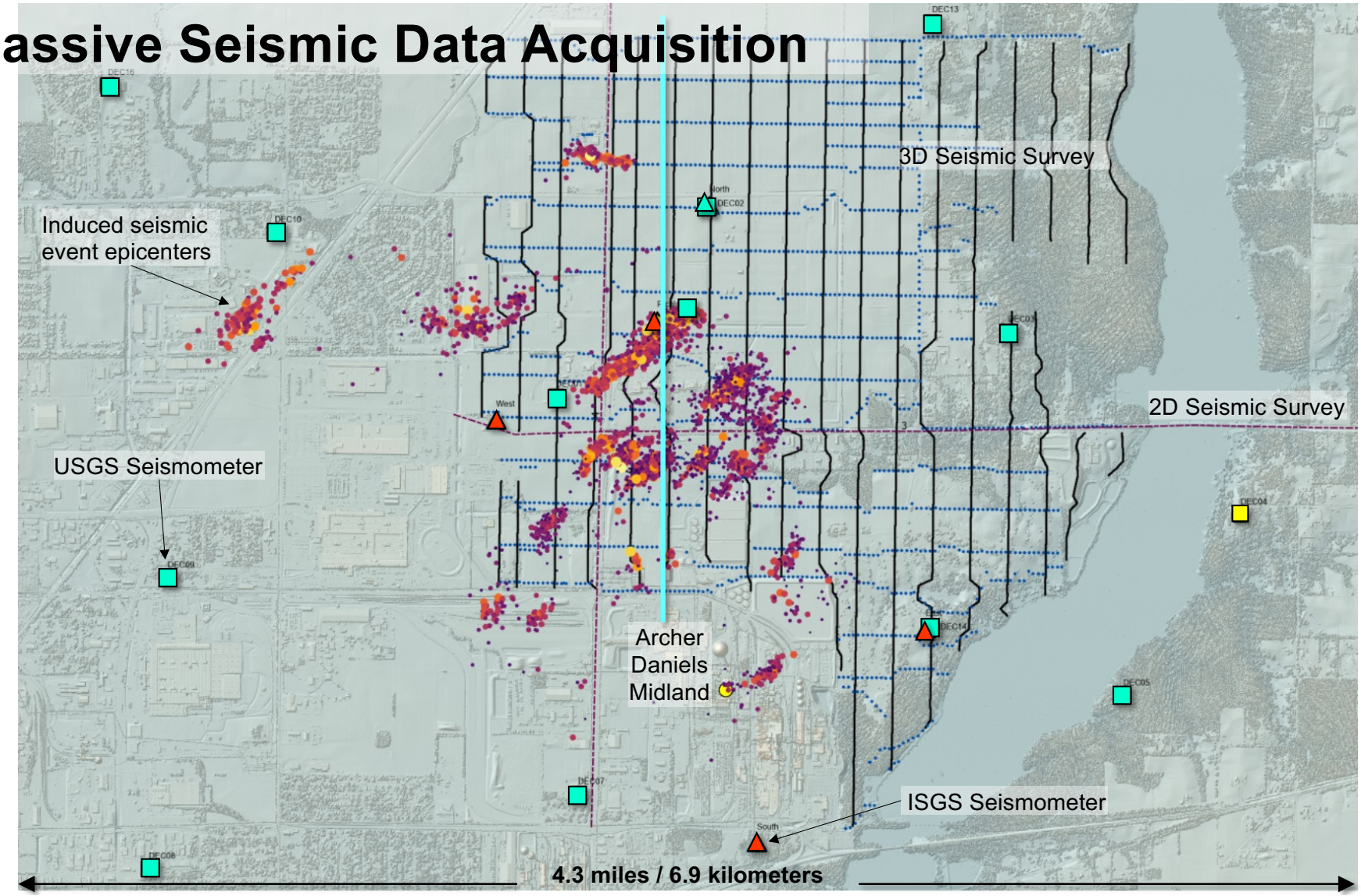
Ironton-Galesville Sandstone

Eau Claire Shale

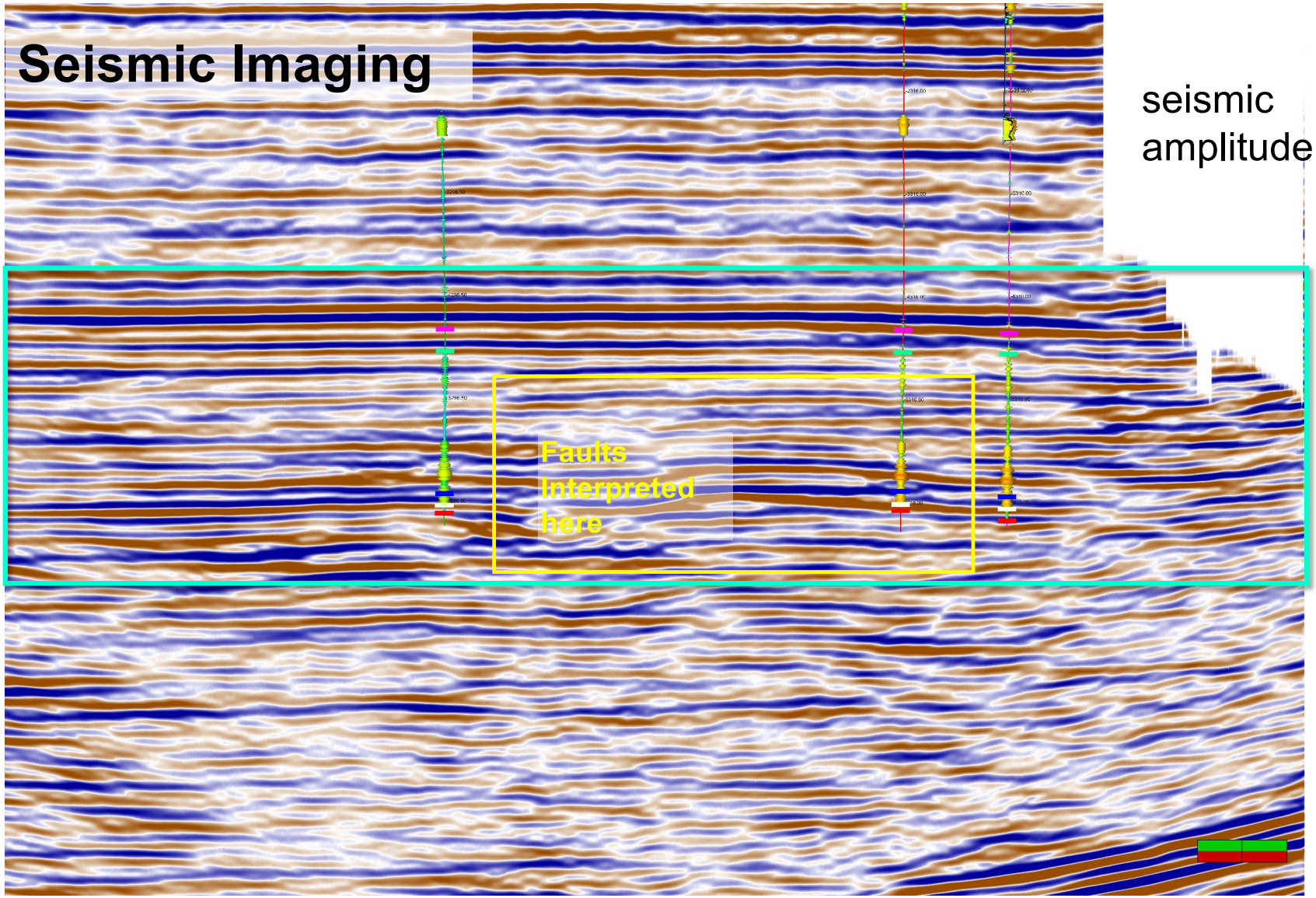
Mt. Simon Sandstone



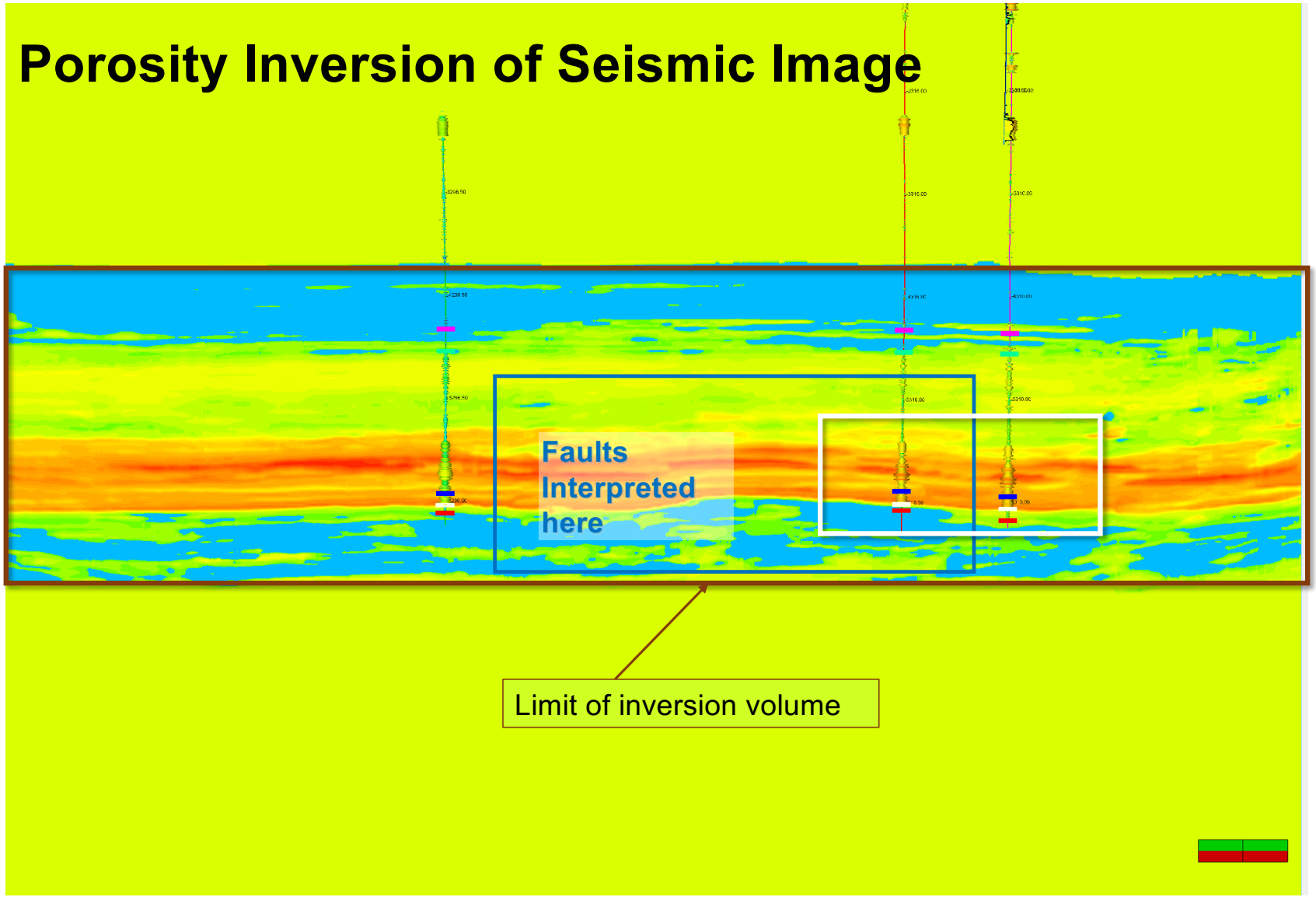
Active/Passive Seismic Data Acquisition



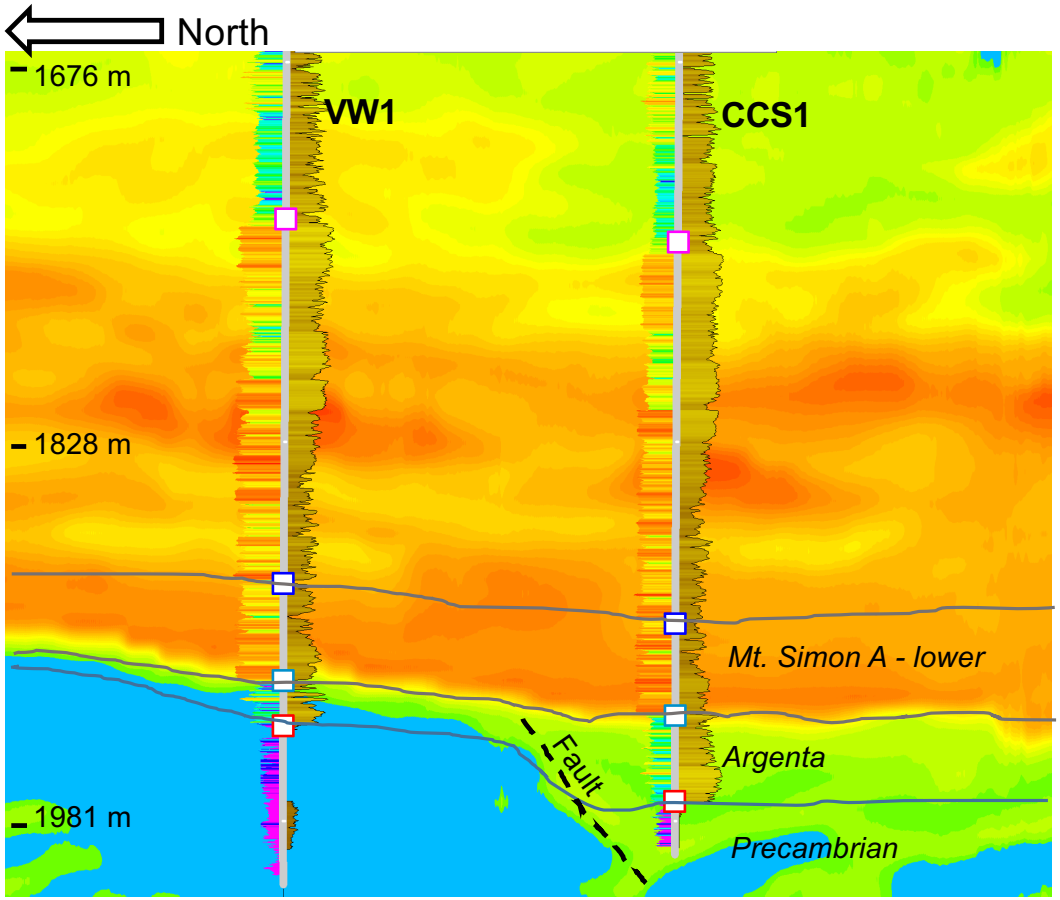
- USGS seismometer
- ISGS seismometer
- Injection and Monitoring wells
- 3D Seismic Survey
- 2D Seismic Survey


Seismic Imaging
seismic
amplitude
Faults
Interpreted
here

Porosity Inversion of Seismic Image



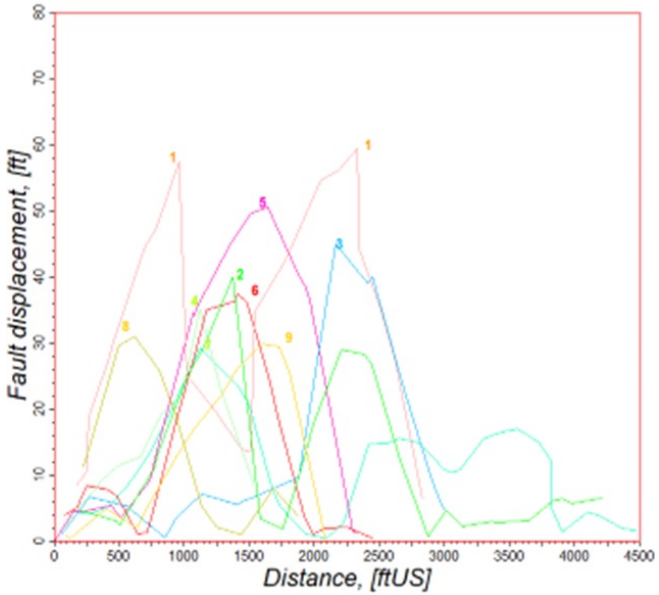
Porosity Inversion Detail - Structure



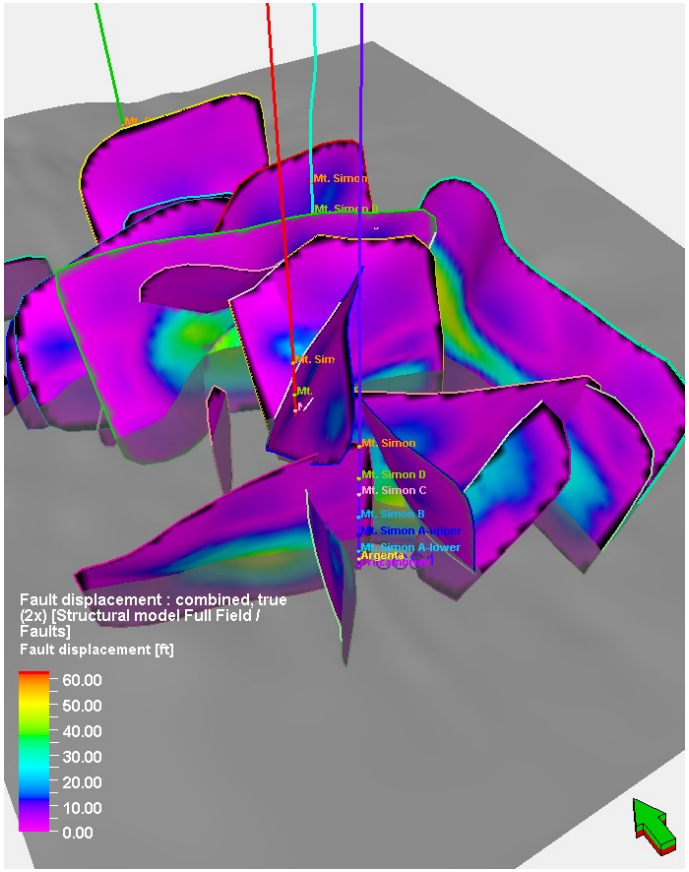
2X vertical exaggeration

Faults Interpreted from Seismic Image

- What do we need to know?
  - Whether there are faults in the reservoir – confirmed.

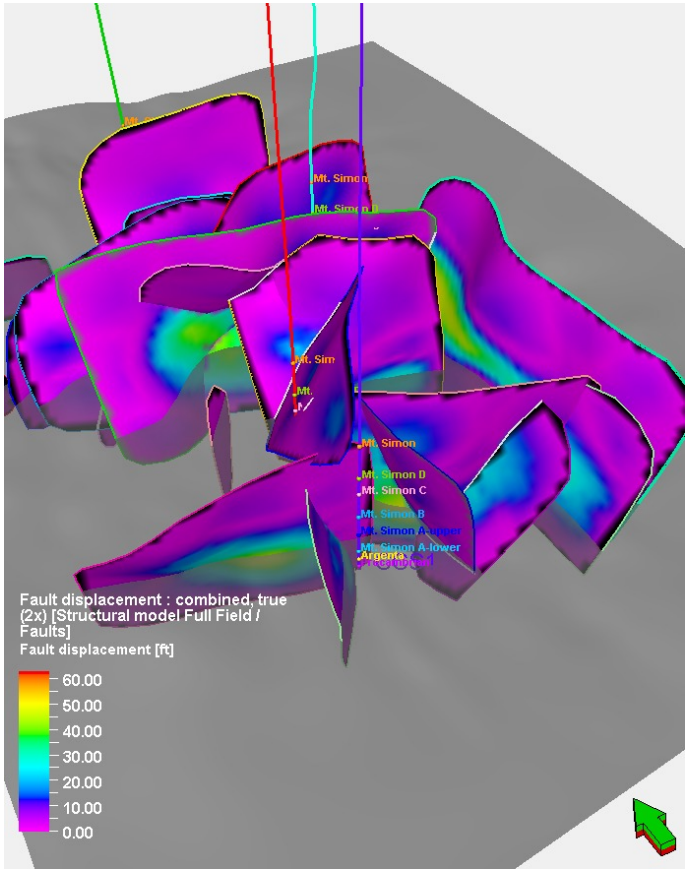


Fault displacement versus fault length for the 9 largest faults interpreted in the 3D seismic volume

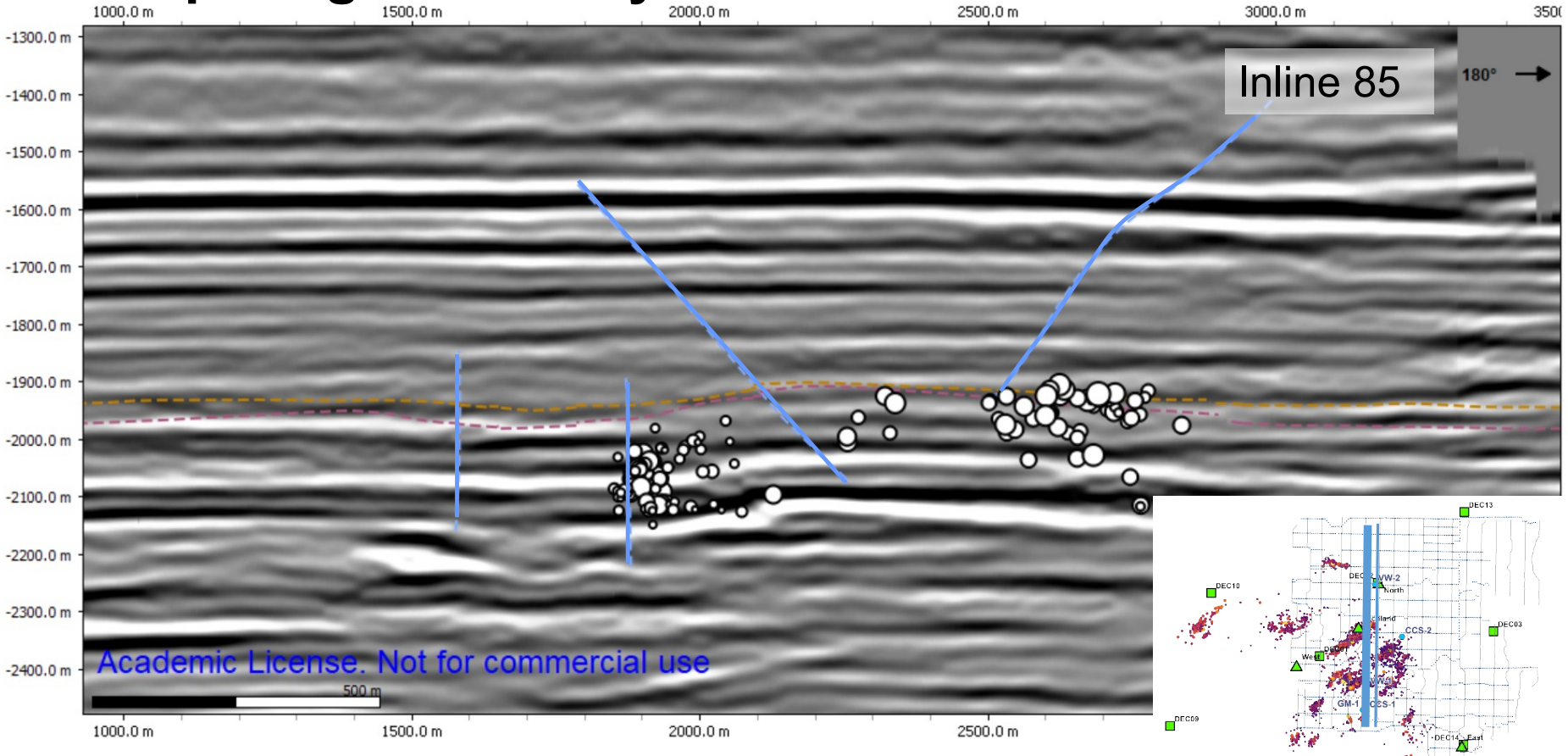


Faults Interpreted from Seismic Image

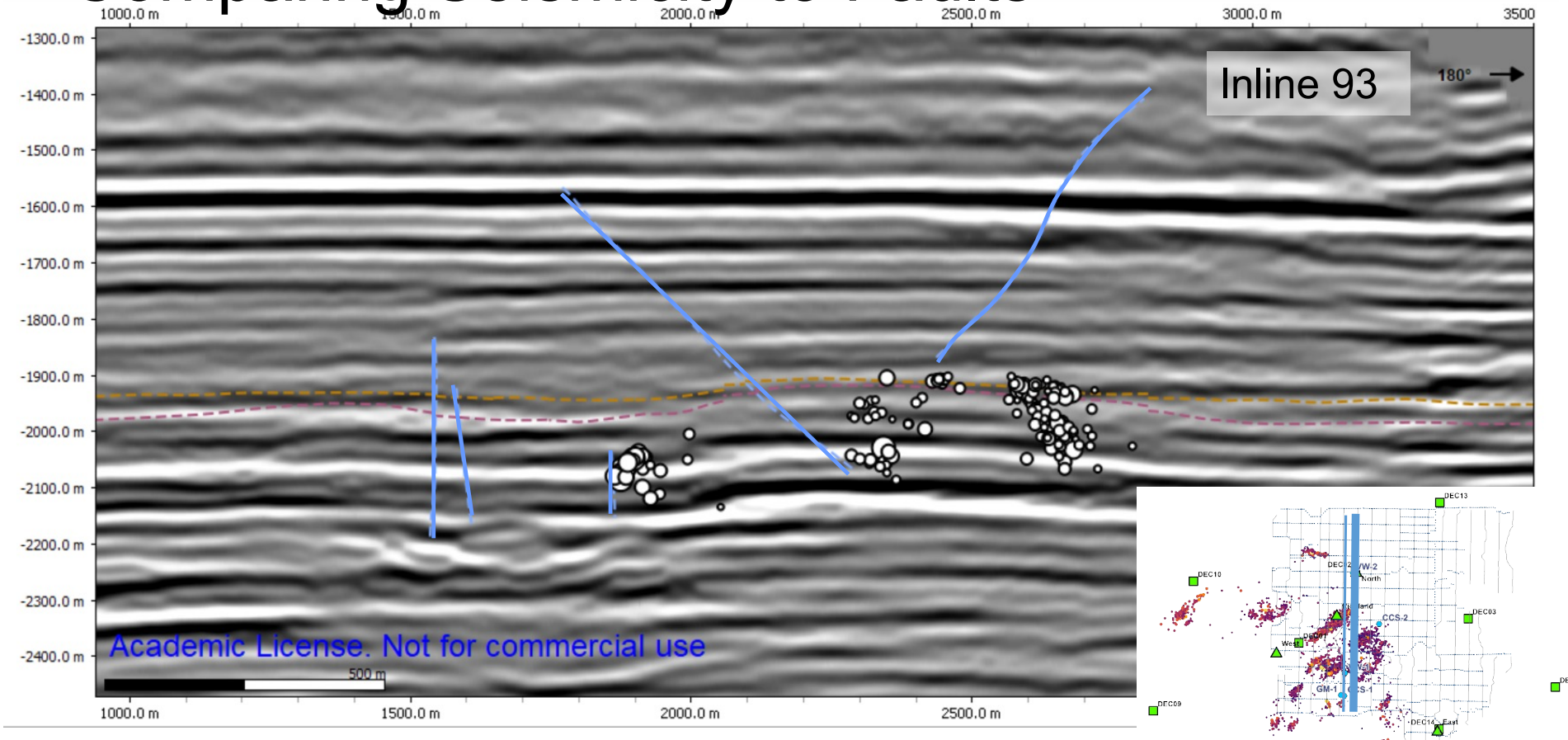
- What do we need to know?
  - Whether there are faults in the reservoir – confirmed.
- Why do we need to know it?
  - They could compromise top seal or lead to induced seismicity – also confirmed.
- What does “know” mean in this context?
  - Uncertainty related to interpretation – was compounded by seismicity.



Comparing Seismicity to Faults

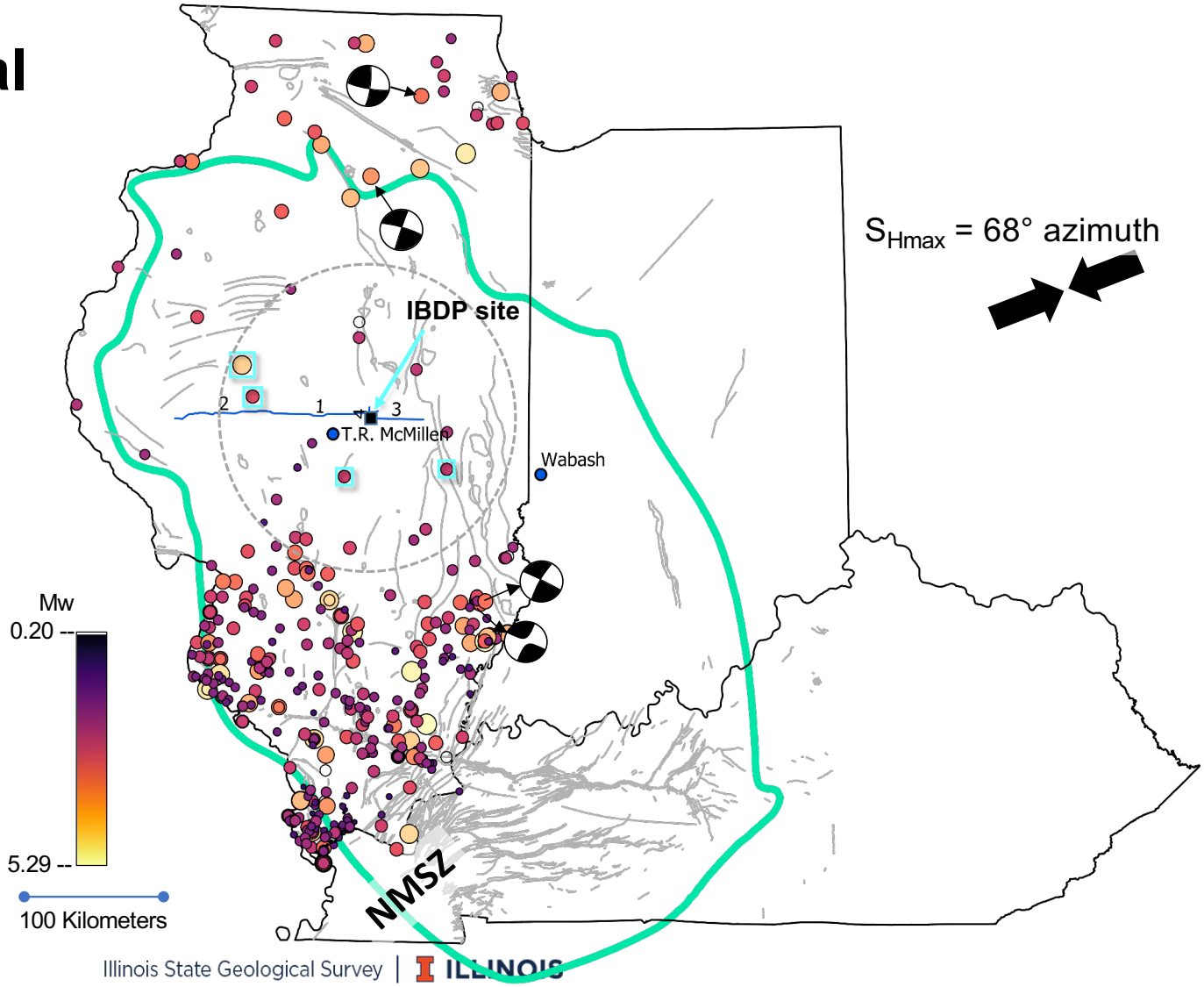


Comparing Seismicity to Faults



Historical Natural Seismicity

- Earthquakes in Illinois since 1795
- Some activity in northern Illinois
  - Moment tensors shown for 3.8 and 4.2 Mw earthquake
- Most activity is in southern part of state, where basin is deepest and has highest structural complexity
  - Moment tensors shown for Mw 5.2 EQ followed by a Mw 4.0 aftershock

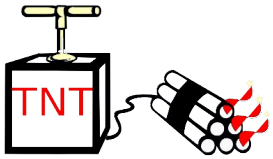


Earthquake Magnitude Reference Energies

MICROSEISMICITY

Magnitude	-3	-2	-1	0	1	2	3	4	5	6	7	8	9
Energy in joules	2	63	2000	6.3×10^4	2.0×10^6	6.3×10^7	2.0×10^9	6.3×10^{10}	2.0×10^{12}	6.3×10^{13}	2.0×10^{15}	6.3×10^{16}	2.0×10^{18}
Example using common event	1 kg dropped 20 cm	Energy in a powerful slingshot	100 kg person jumps down 2 m	Energy released by 15 grams of TNT	Typical quarry blast	Only felt nearby	Energy from 50 litres of petrol	Often felt up to 10's of miles away	Energy from 50 000 litres of petrol	3.3 Hiroshima-size A bombs		1–2 earth-quakes this size each year	Total annual energy use of UK

Table modified from British Geological Survey



Comparing to Wastewater Injection

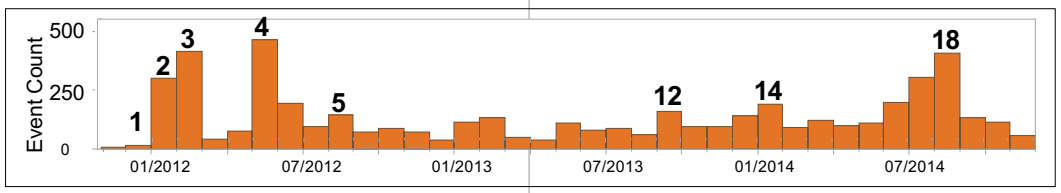
	Location	Injection rate m^3/day	Injection period	Induced seismicity	Felt seismicity
CO_2 injection	IBDP CCS1 well[1]	1123	3 years	Yes (Mw -2.1 to 1.2)	No
	IL-ICCS CCS2 well[1]	1950	3 years	Little (Mw -2 to 0.8)	No
Waste-water injection	East Texas[2]	2000	1 year or more	Yes (Mw 4.8)	Yes
	Williston Basin[3]	3300	1 month or more	Some (Mw 1.4 to 2.8)	No
	Arkansas[4]	2030	1 year or more	Yes	Yes
	S. Texas (Eagle Ford)[5]	900	Several months	Yes	Yes

[1]Williams-Stroud et al., BSSA 2020
[2]Frolich, PNAS 2012
[3]Frolich et al., SRL 2015
[4]Horton, SRL 2012
[5]Frolich and Brunt, EPSL 2013

Induced Seismicity

- USGS Seismic Stations
- ISGS Seismic Stations

- Clusters of events have temporal development
- Indicate reactivation of existing features
- Interpreted as faults, or fracture corridors



CO_2 Injection Periods at Decatur

CCS1

- November 17, 2011 – injection commenced in CCS1 well
  - Large-scale demonstration project
  - Compression capacity 1100 tonnes/day
  - Injection rate: 1000 tonnes/day
  - Volume: 1 million tonnes in 3 years (999,215 tonnes)

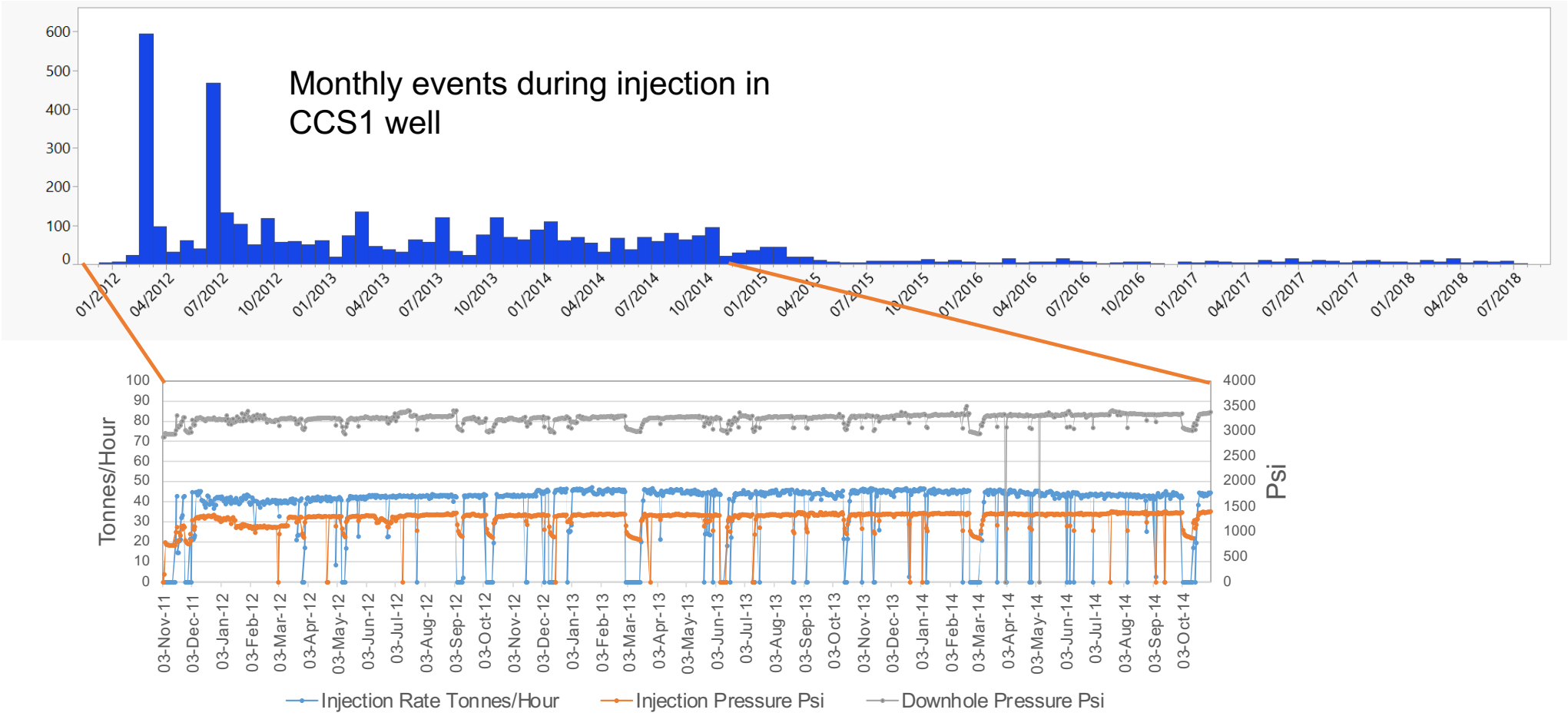
No injection

- November 26, 2014 – injection ceased in CCS1 well
  - Post injection monitoring will continue until April 2020

ICCS

- April 7, 2017 – injection commenced in CCS2 well
  - Industrial-scale demonstration project
  - Compression capacity 2200 tonnes/day
  - Injection rate: 3000 tonnes/day
  - Volume: up to 5 million tonnes in 3 years (or longer)

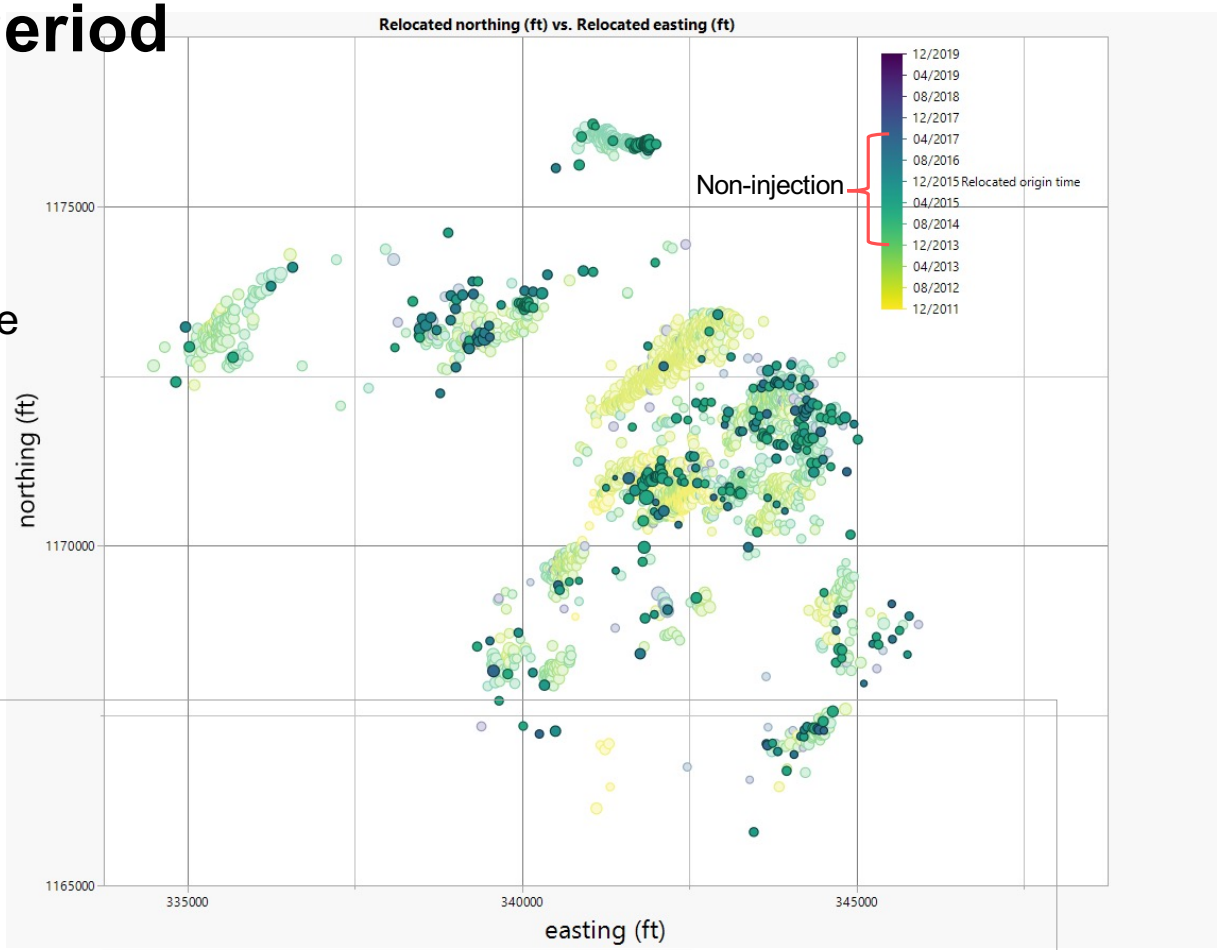
Seismicity / Pumping Rate: Poor Correlation

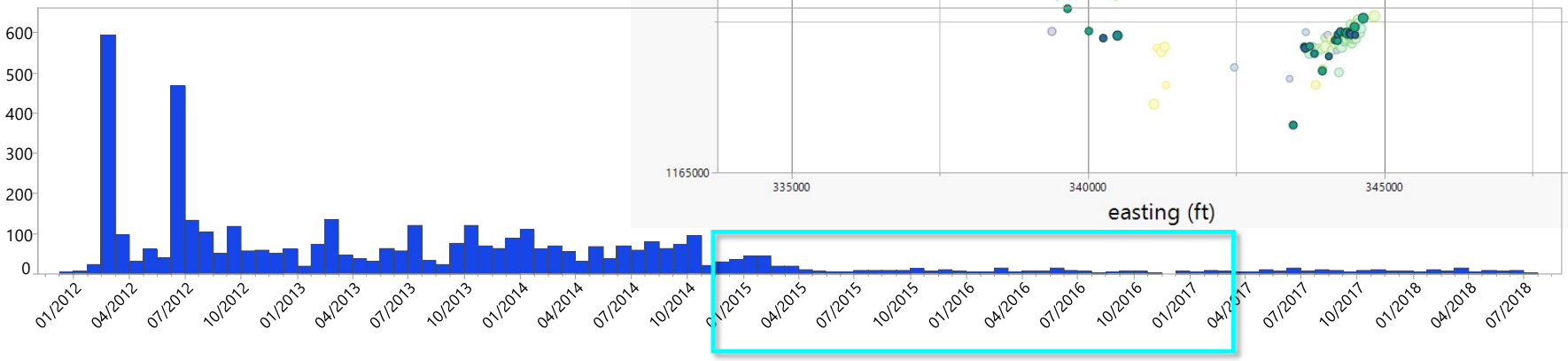


Interim Non-injection Period

Slight increase in seismicity after injection stopped

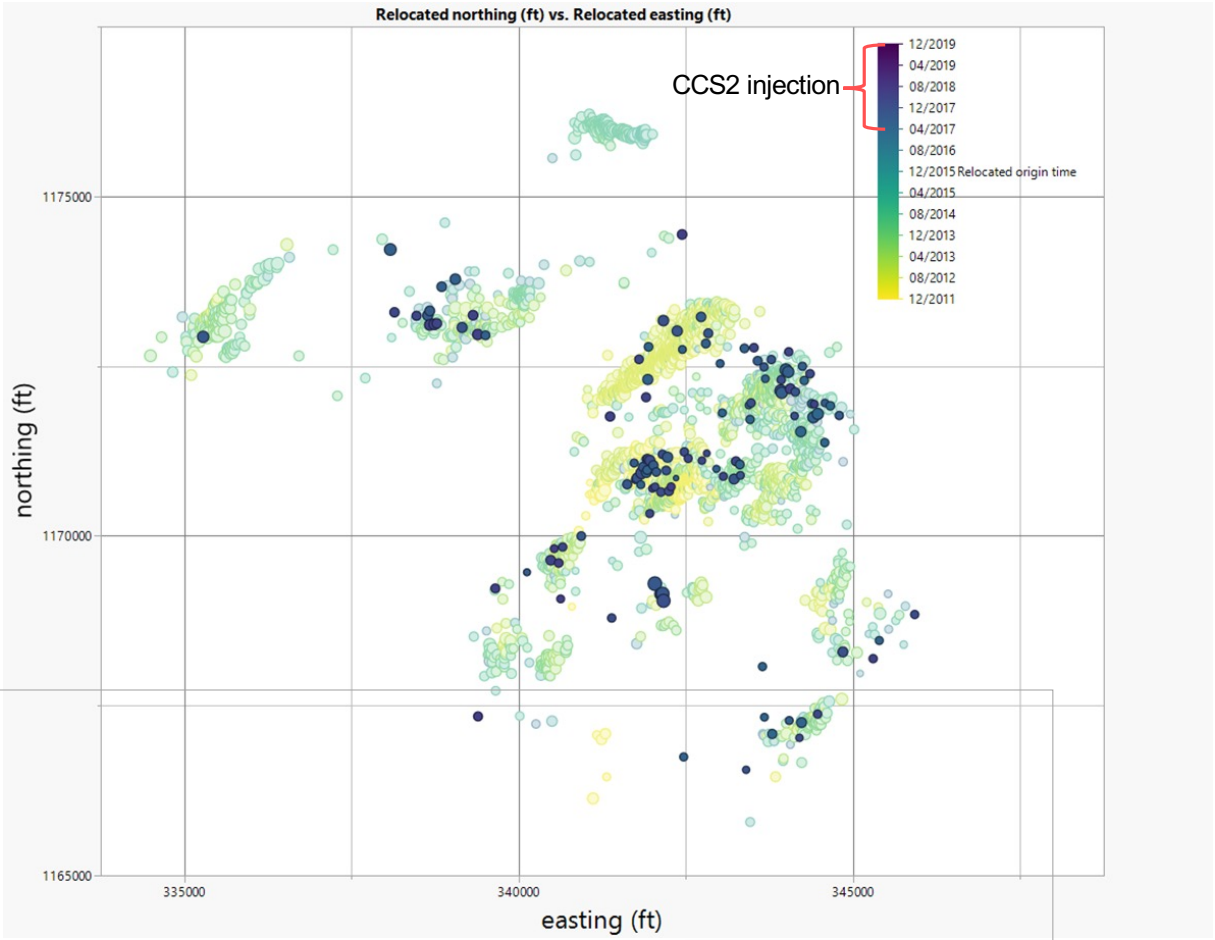
Microseismicity subsides to a much lower level, <10 events/month average

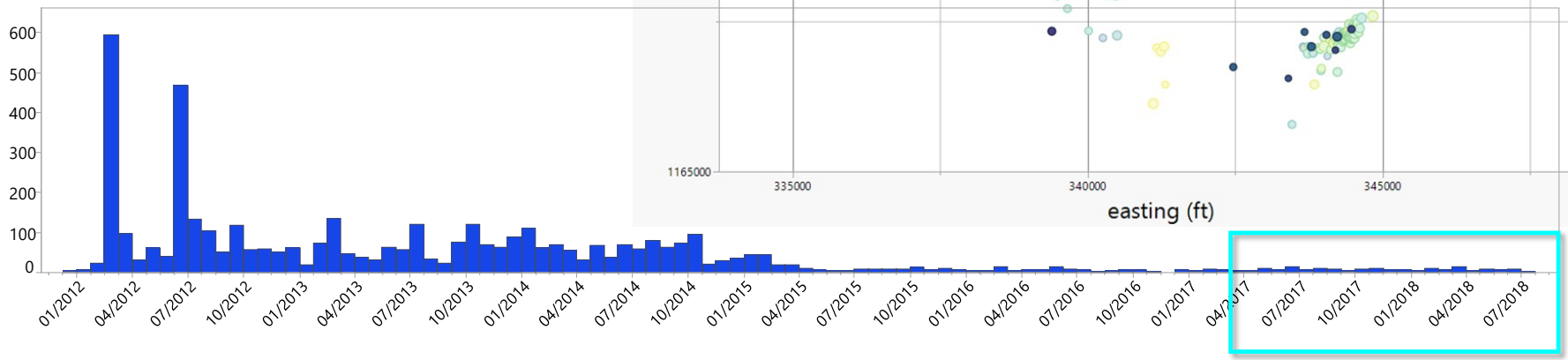




Injection in 2nd Well

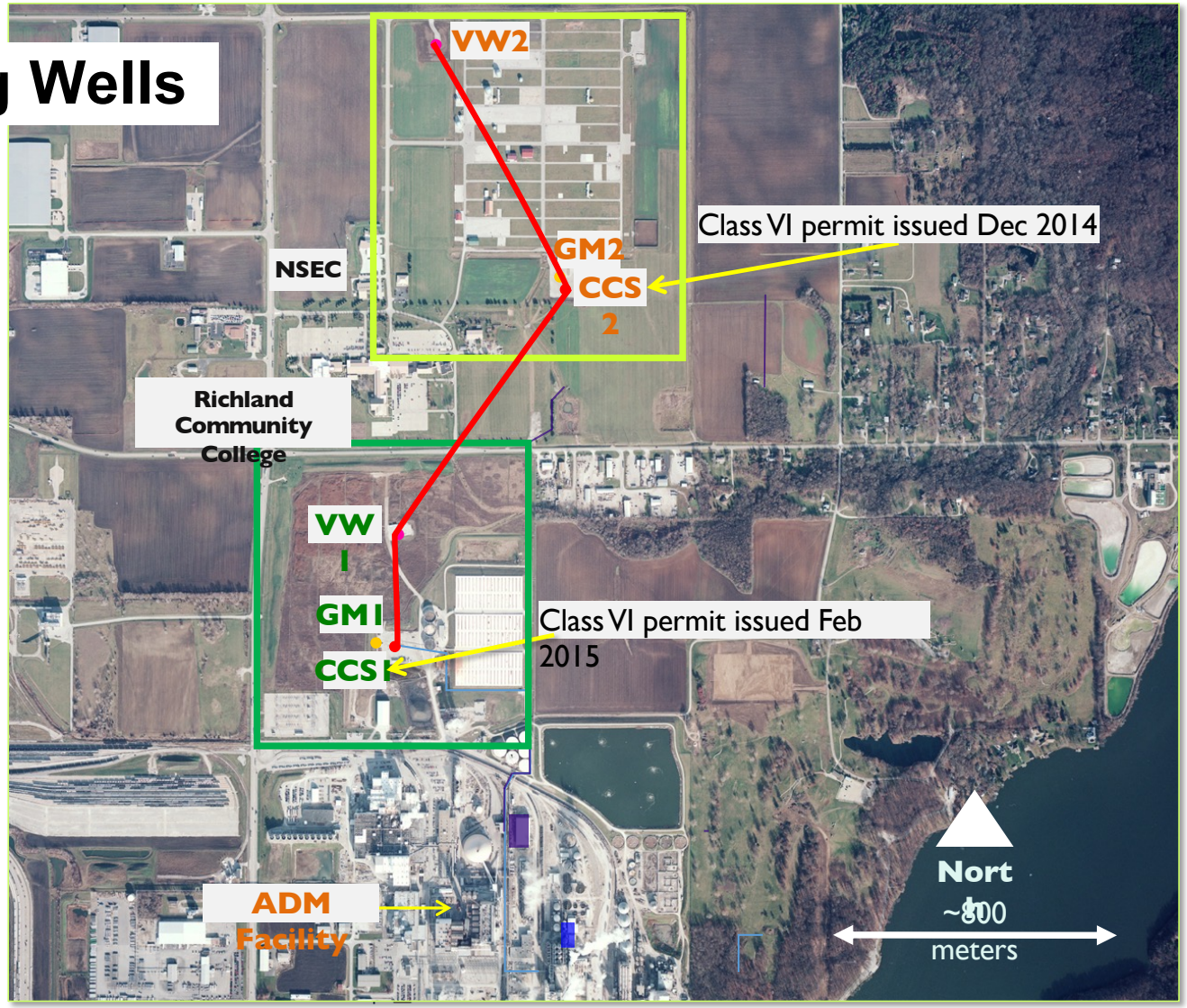
- No apparent increase of events with new injection
- CCS2 injection rate is 1.7x CCS1 injection rate
- Microseismicity continues to average ~10 events/month





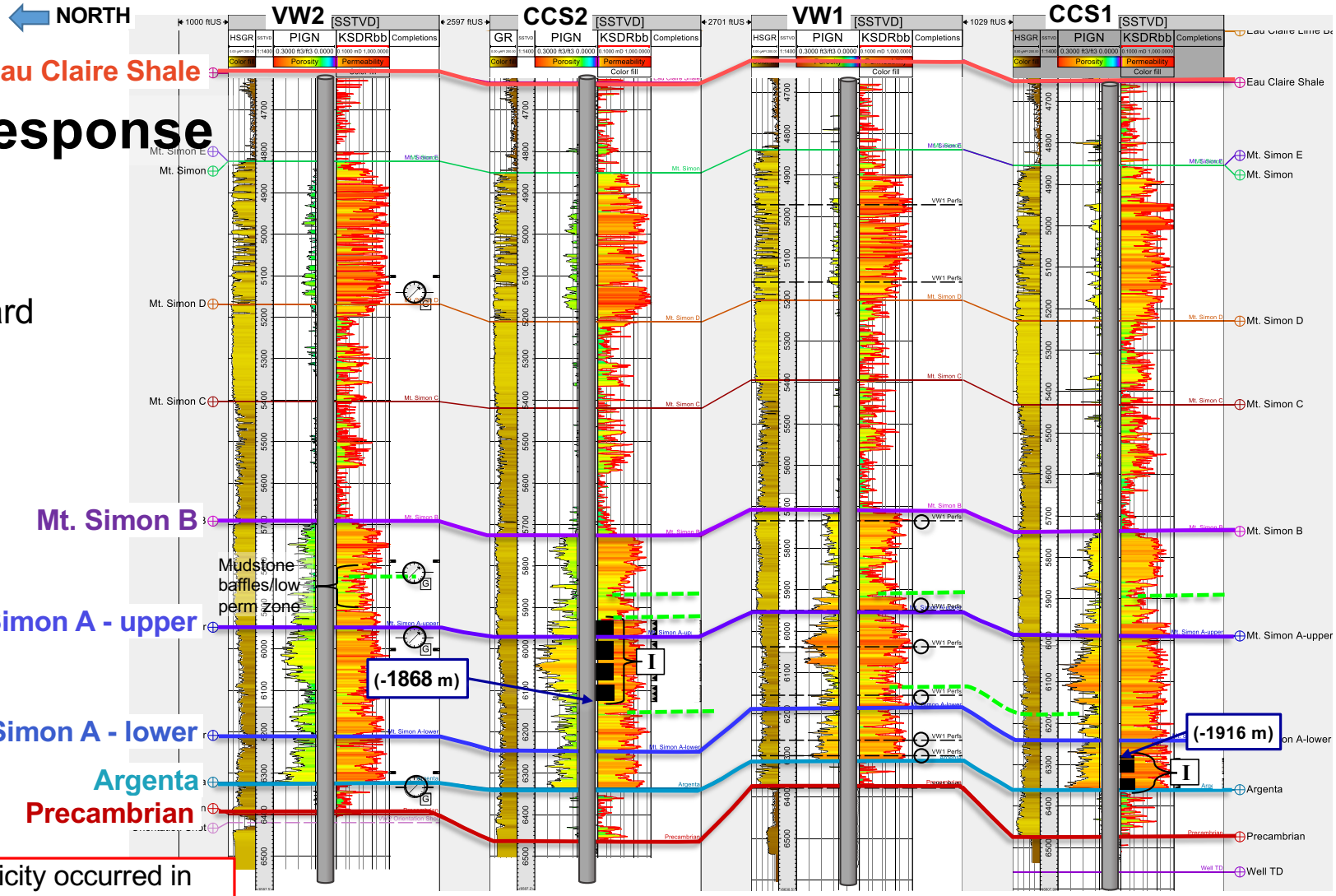
Deep Monitoring Wells

- Injection wells
  - CCS1 and CCS2
  - ~1100 m apart
- Geophysical monitoring wells
  - GM1 (31 geophones for VSP and microseismic)
  - GM2 (3 deep geophones for microseismic)
- Verification wells measuring temperature and pressure
  - VW1 and VW2



Reservoir Response

Mudstone baffle at 1883 SSTVD may have inhibited upward migration of CO_2



○ Pressure gauge

Mudstone baffle

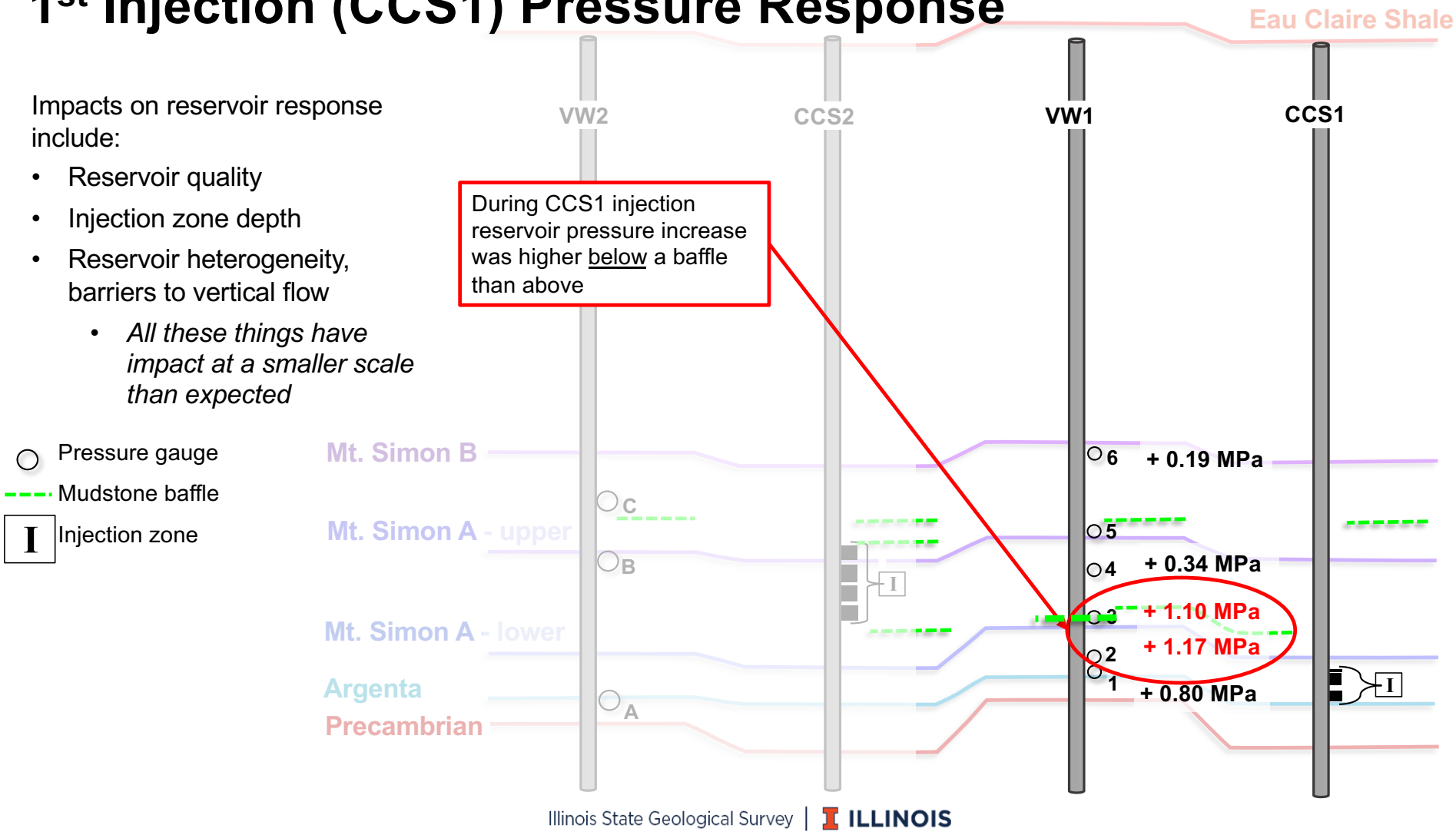
I Injection zone

90% of the induced seismicity occurred in the Precambrian basement.

1st Injection (CCS1) Pressure Response

Impacts on reservoir response include:

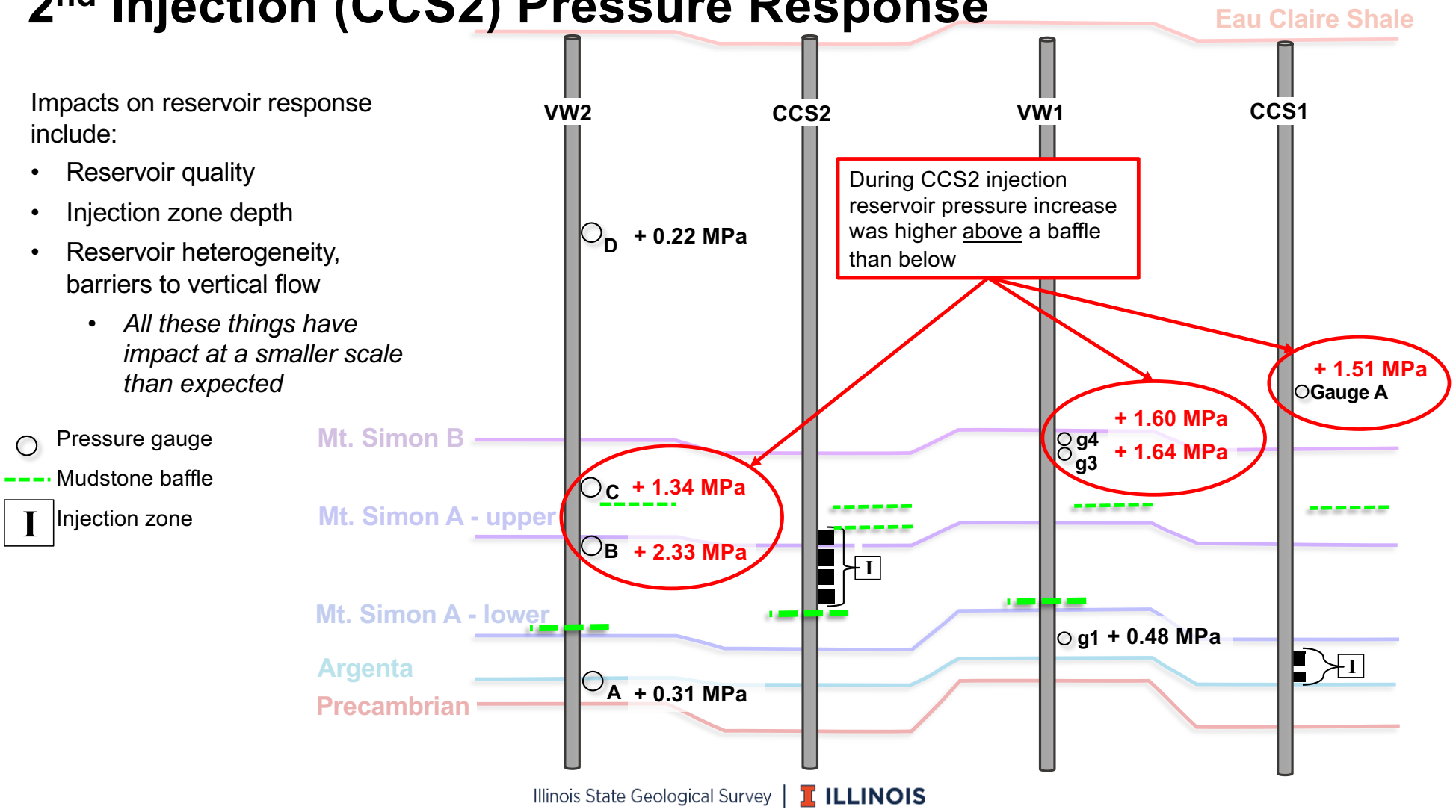
- Reservoir quality
- Injection zone depth
- Reservoir heterogeneity, barriers to vertical flow
  - *All these things have impact at a smaller scale than expected*



2nd Injection (CCS2) Pressure Response

Impacts on reservoir response include:

- Reservoir quality
- Injection zone depth
- Reservoir heterogeneity, barriers to vertical flow
  - *All these things have impact at a smaller scale than expected*

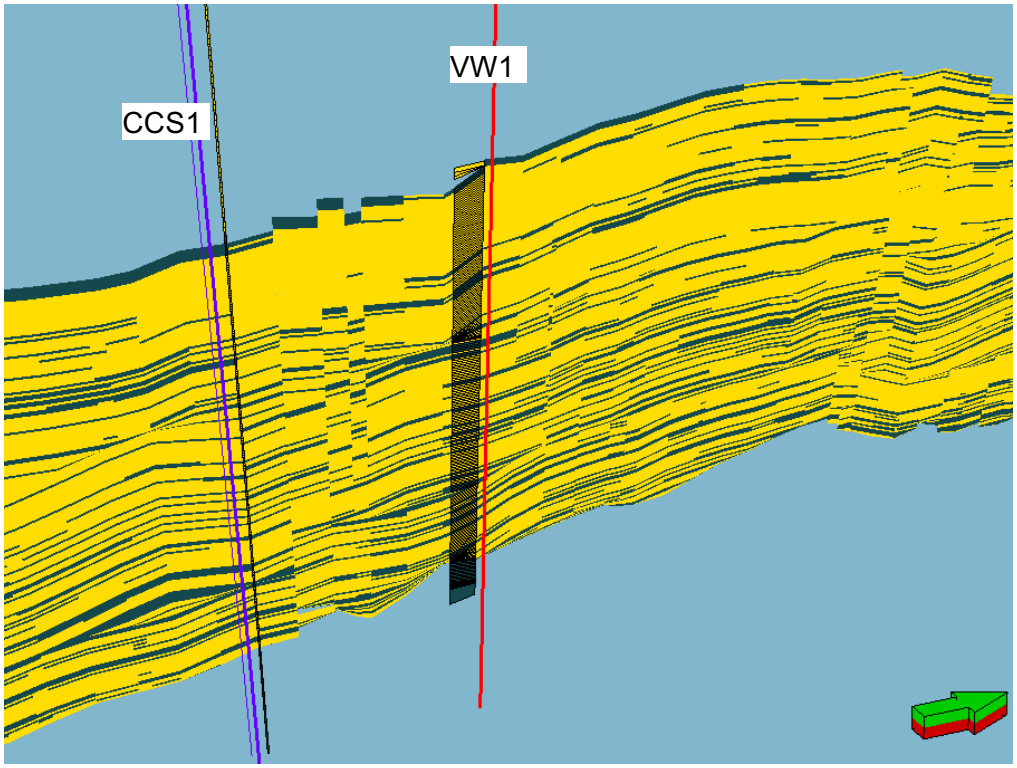


Geologic Modeling – Baffle Facies

Impacts on reservoir response include:

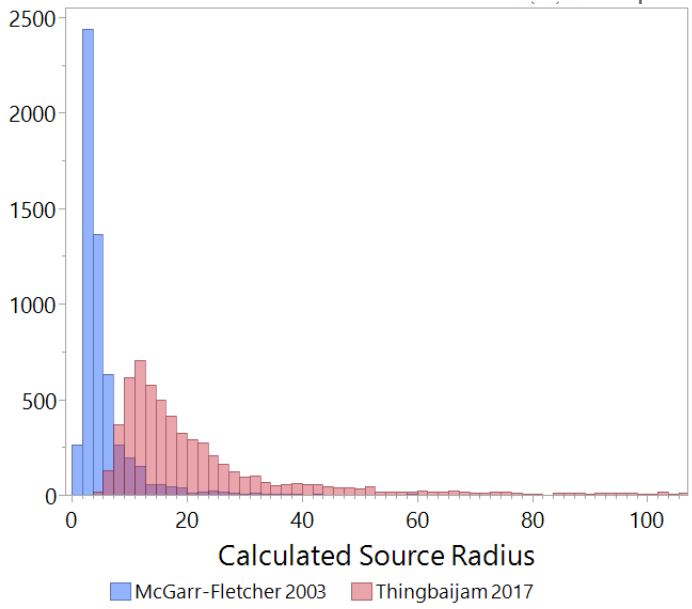
- Reservoir quality
- Injection zone depth
- Reservoir heterogeneity, barriers to vertical flow

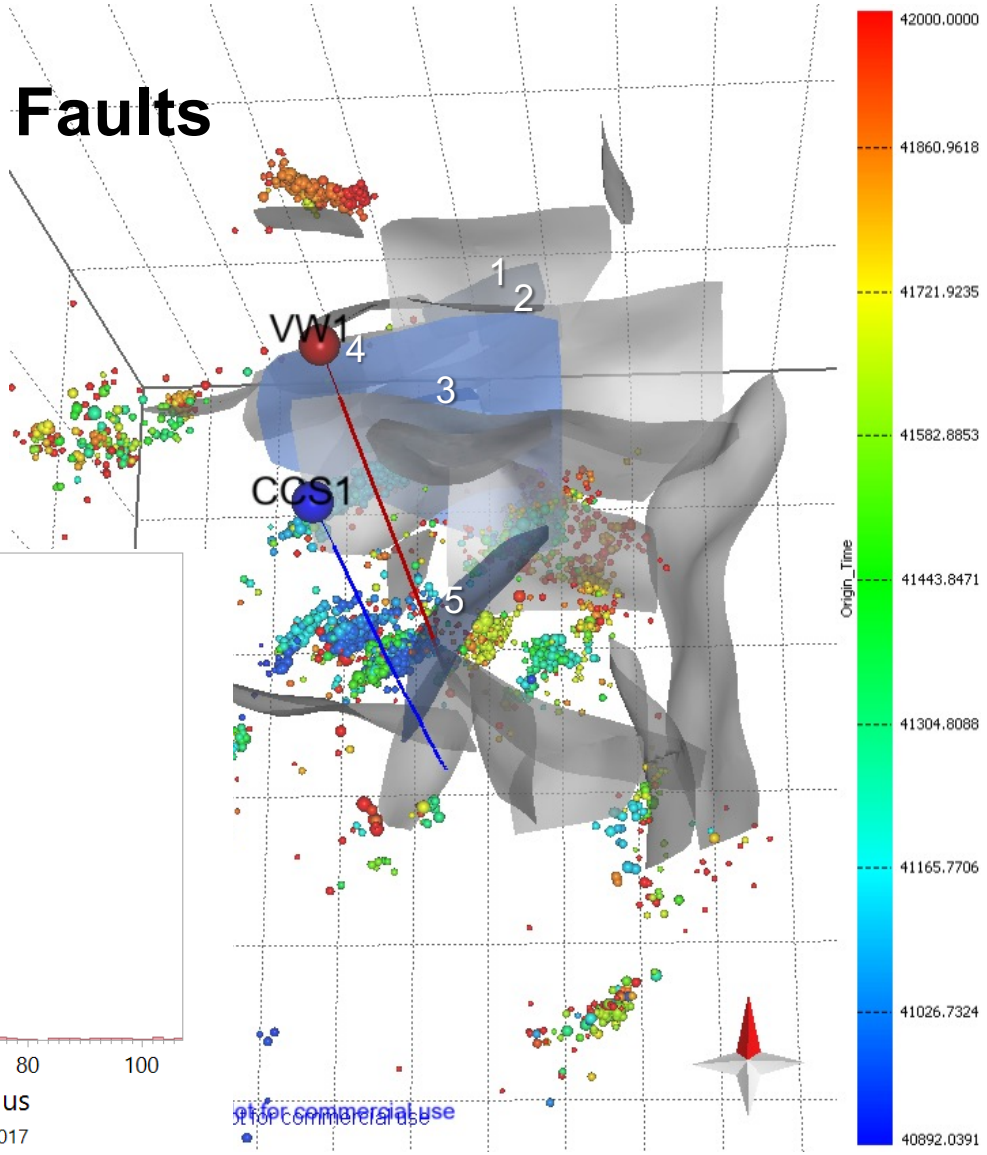
- The baffle facies improved the history matching, accounting for strong vertical flow anisotropy.
- Low-permeability layers were matched to the well depth, but stochastically distributed in the reservoir between wells.



Events and Faults

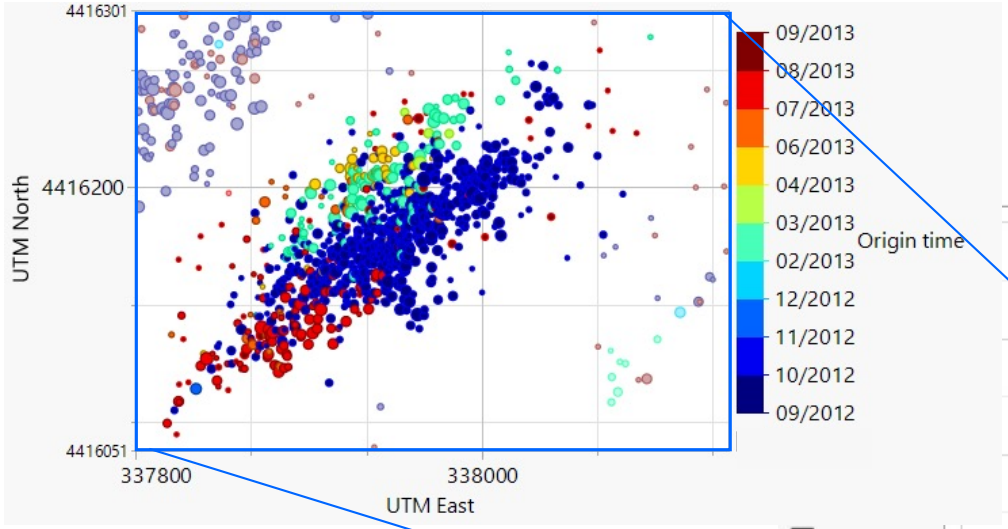
- High confidence interpreted faults shown in blue
- Poor spatial correlation of faults with event cluster locations

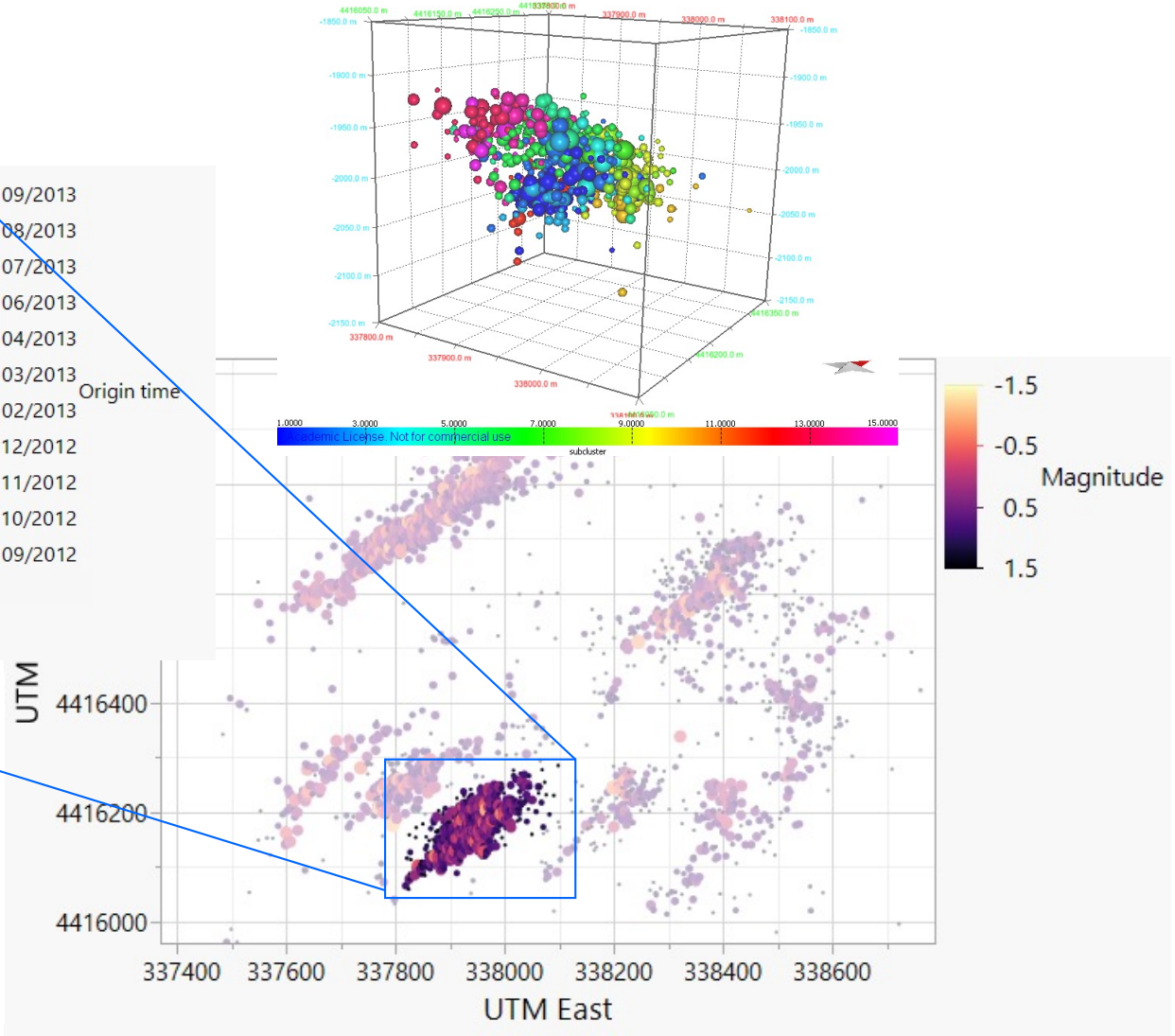




- Events are sized by magnitude, colored by time
- Blue events are the earliest – most of the clusters formed in the first few months of injection

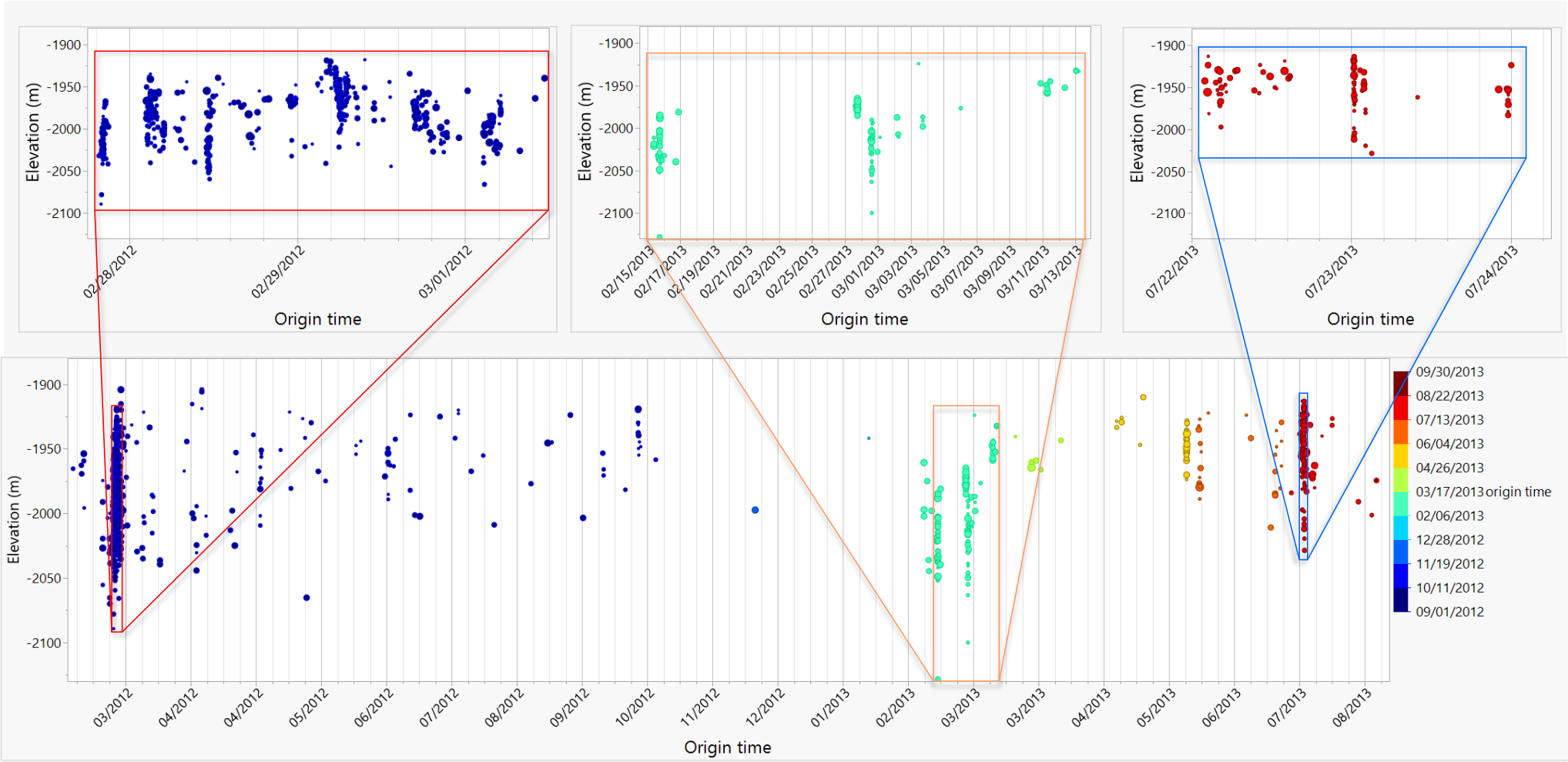
Cluster D3 Bursts



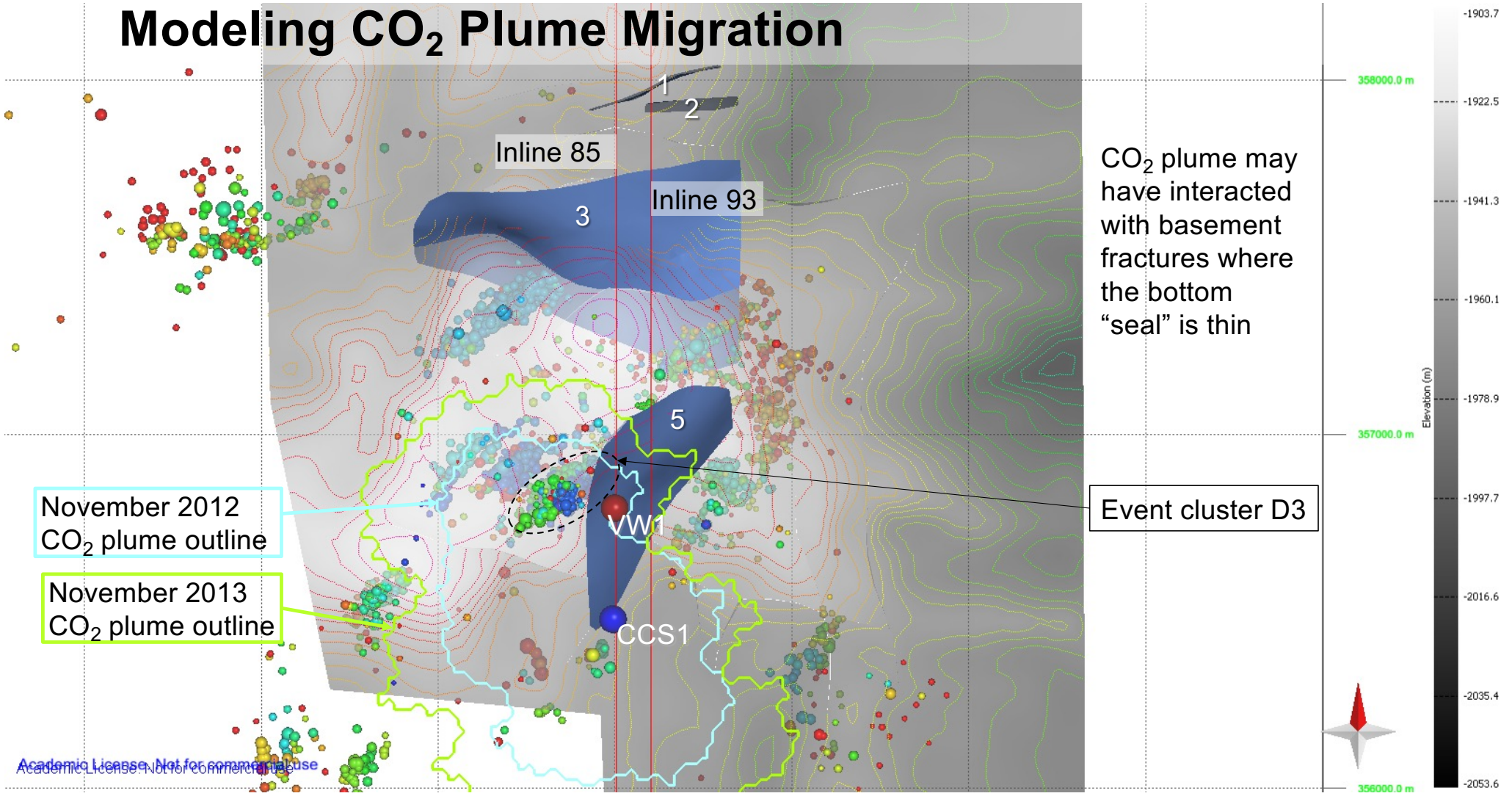


- Temporal busts of activity suggest separate fracture/fault planes
- Events are colored by time ~1 month per discrete color
- At least 4 bursts are highlighted
- Each burst can be fit to a plane

15 Temporal Bursts in Cluster D3



Modeling CO_2 Plume Migration



Conclusions

- Faults were identified in the reservoir, originally with high uncertainty
- No top seal leak risk was identified, but induced seismicity occurred
  - not on the faults that were identified before injection, but uncertainty of some faults was decreased by integration with induced seismicity
- Detailed analysis of the induced seismicity revealed
  - Smaller features within the clusters
  - Probable fracture corridors in the basement
- Geomechanical testing and observed failure in the reservoir aren't consistent
  - Geochemical interactions may play a bigger role than originally thought

Acknowledgments

- The Illinois Basin – Decatur Project was funded by the U.S. Department of Energy (DOE)
- Understanding the data continues to improve through collaborations, including
  - The MRCI (Midwest Regional Carbon Initiative), a collaboration between multiple state geological surveys and academic institutions and industry, funded by DOE
  - Illinois Storage Corridor CarbonSAFE projects in other Illinois Basin locations
- Petroleum Experts donated the MOVE structural modeling and analysis software used in this study, and Schlumberger Petrel was used to build the static model from the fault interpretation

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Illinois State Geological Survey

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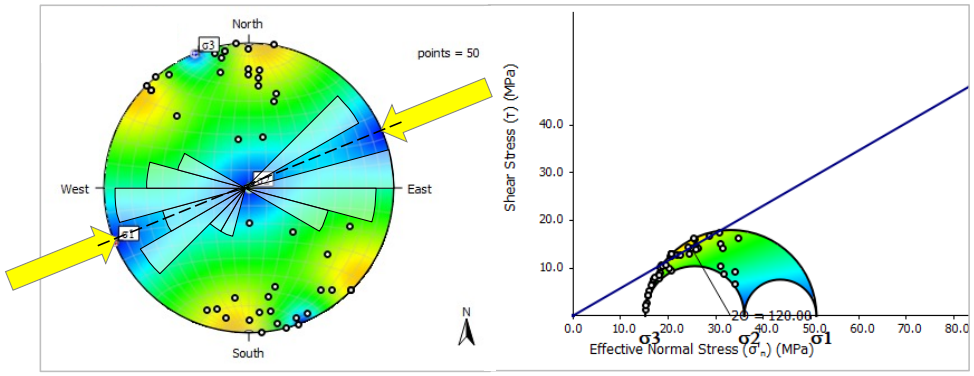
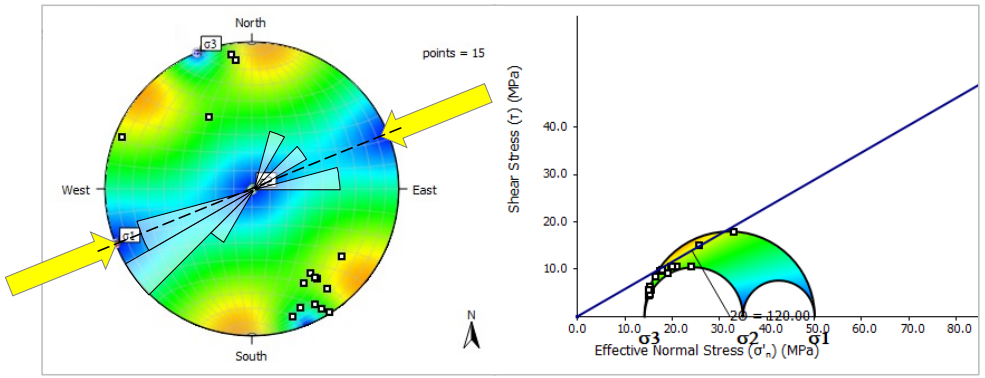
Failure Analysis

- Cluster D3 formed mostly prior to installation of surface seismic monitoring network
- Source mechanism failure planes consistent with burst best-fit plane orientations
- Observed failure planes are much weaker than expected by Mohr-Coulomb criteria
  - lab friction angle = 42°, all planes fail if friction angle is 12°





Subsurface injection – comparisons and issues

Wastewater disposal

- Volumes injected
  - 800 - 2000 m^3/day
- Associated induced seismicity
  - Felt events, Mw 5.7 in OK
- Groundwater contamination
  - Dispersal and dilution enough
  - Water-rock interaction
- Pore space needed to maintain injection without contaminating gw and causing earthquakes
  - ?
- Reservoir pressure increases linearly with H_2O injection

Carbon sequestration

- Volumes injected
  - CCS1 average 800 m^3/day
  - CCS2 average 1900 m^3/day
- No felt events
  - All detected events < Mw 2*
- Leak containment
  - Is top seal integrity sufficient?
  - Does microseismicity compromise topseal via faults?
- Reservoir pressure increase with CO_2 injection influenced by[1]:
  - $scCO_2$ behaves like gas
  - Dissolution
  - Water saturated with CO_2 denser than brine
  - Water-CO_2-rock interaction
  -
  -

[1]Vilarrasa and Carrera, PNAS 2015