CO_2 Storage and Injection Induced Seismicity

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Illinois Oil & Gas Association Annual Convention
Pre-Convention Workshop

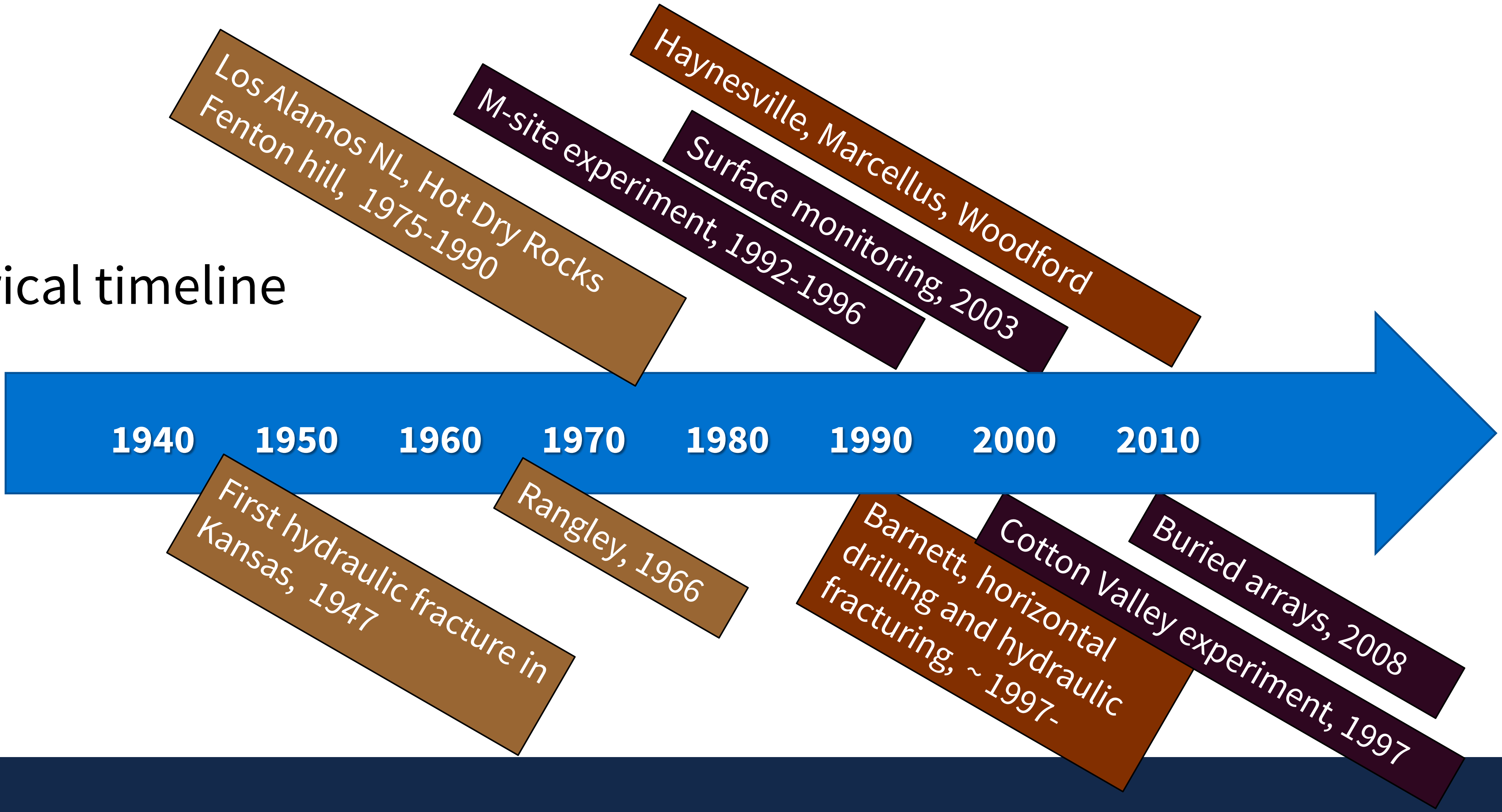
9 March 2023

Factors influencing induced seismicity

- **Hydraulic fracturing**
  - Understanding existing fractures is key
    - They can be your friend… or your enemy
- **Enhanced geothermal systems**
  - Induced seismicity likely unavoidable
  - Successful mitigation is possible
- **CCS in Illinois –**
  - Impactful reservoir heterogeneity occurs at meter scale
  - Induced seismicity in basement – similar to other locations, but
    - Small faults consistent with small seismic events
    - Hydraulic or fluid connection to basement not guaranteed
  - Large uncertainties exist for pre-injection fault identification
    - downside: not useful to identify reactivation risk
    - upside: it likely indicates lower induced seismicity risk

Hydraulic Fracturing Overview

Historical timeline



Power Generation in Enhanced Geothermal Systems

- Relevant geological and engineering issues
  - High enough temperature
  - Reservoir permeability – natural plumbing system
  - Reservoir creation
  - Induced seismicity

Additional engineering is needed for hot rocks w/o existing hydrological systems.

Creation of both permeability and reservoir is required

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USG

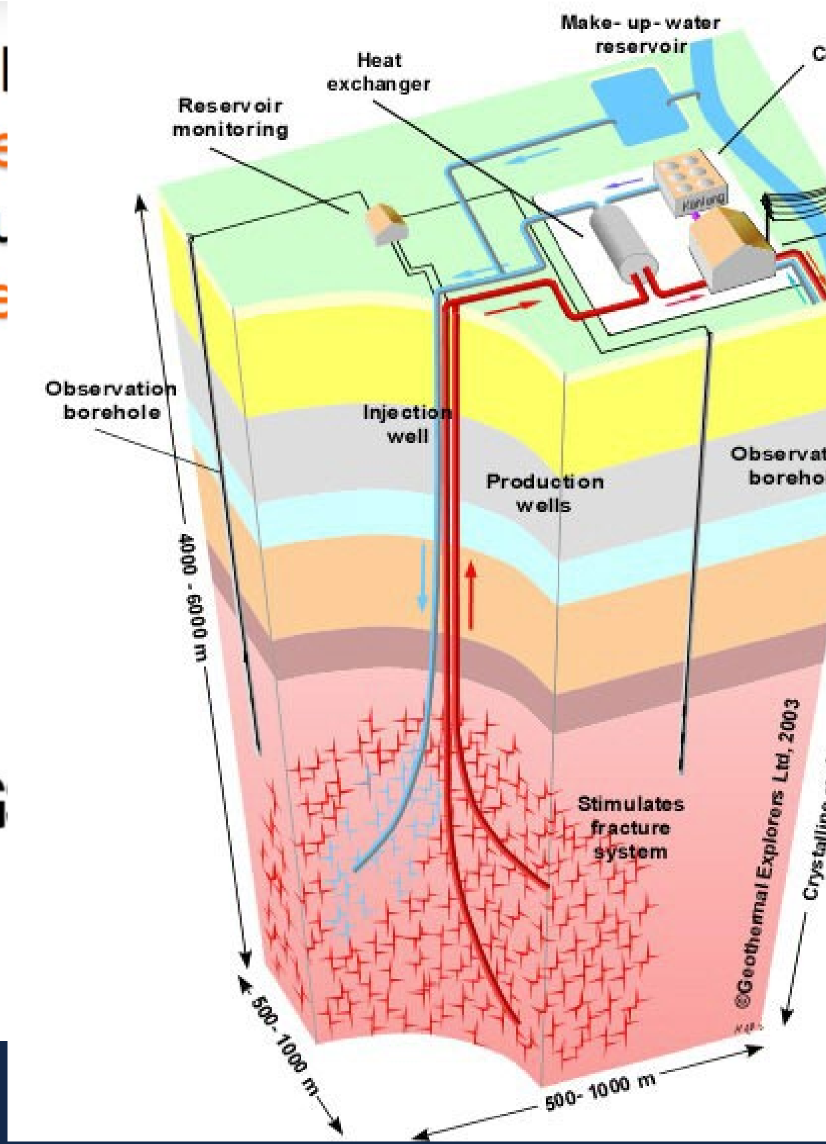
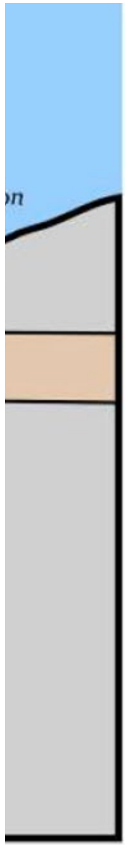
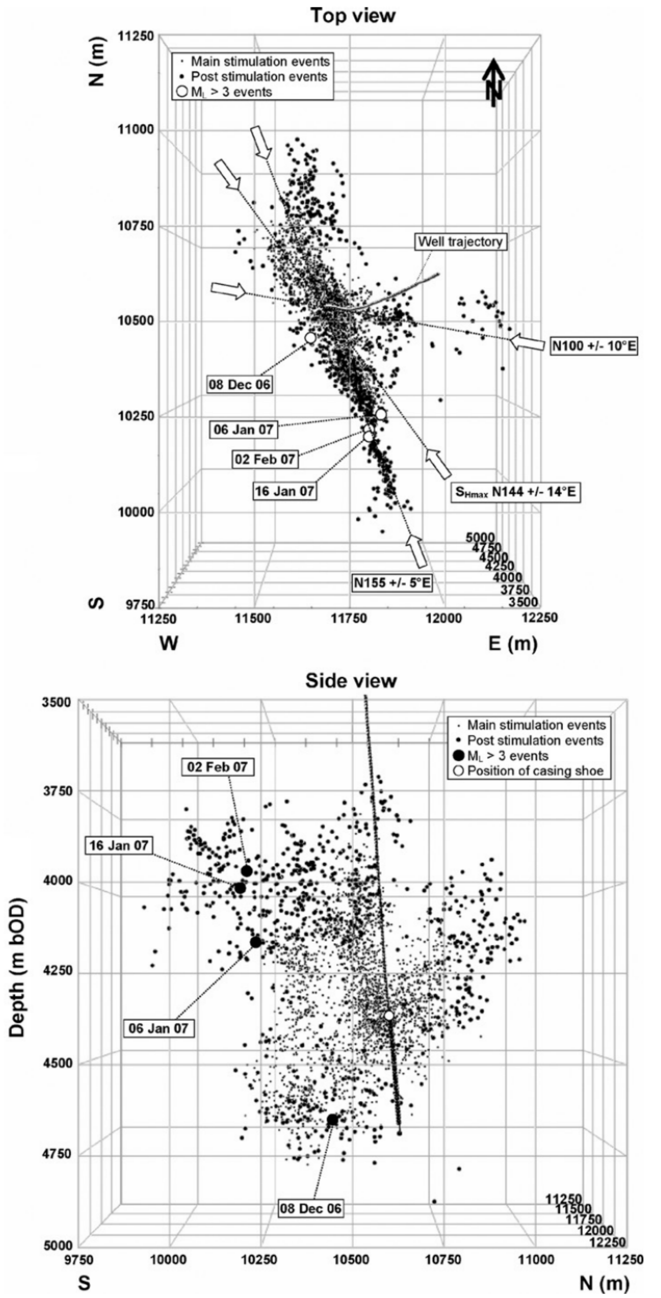


Figure from Marone et al, GTO 2017 Peer Review, US DOE



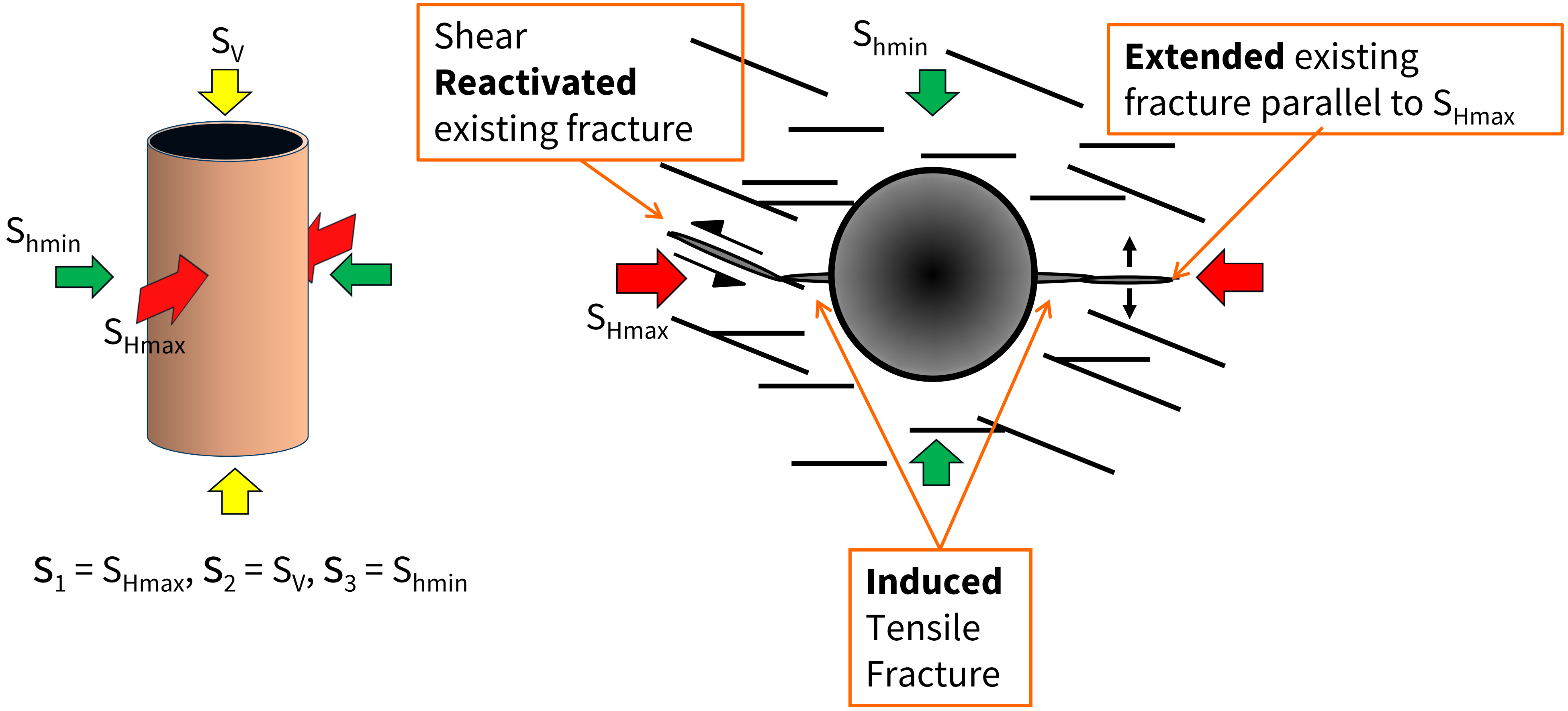
EGS and Induced Seismicity

- Development started with the Hot Dry Rock (HRD) project in late 1970s at Los Alamos National Lab
- HRD evolved into EGS (Engineered and then Enhanced Geothermal System)
- Induced seismicity magnitudes similar to oil & gas (including for oilfield water disposal)
- The **Deep Heat Mining Project** in Basel, Switzerland, induced a magnitude 3.4 event.



3D plots of induced seismicity at Basel
Figure from Häring et al, 2010, Geothermics

Failure During Frac – Impact of Existing Fractures

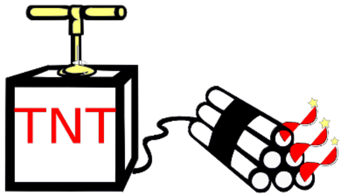


Earthquake Magnitude Reference Energies

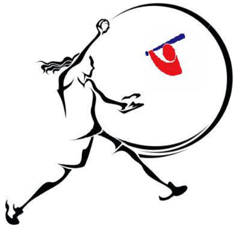
MICROSEISMICITY

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

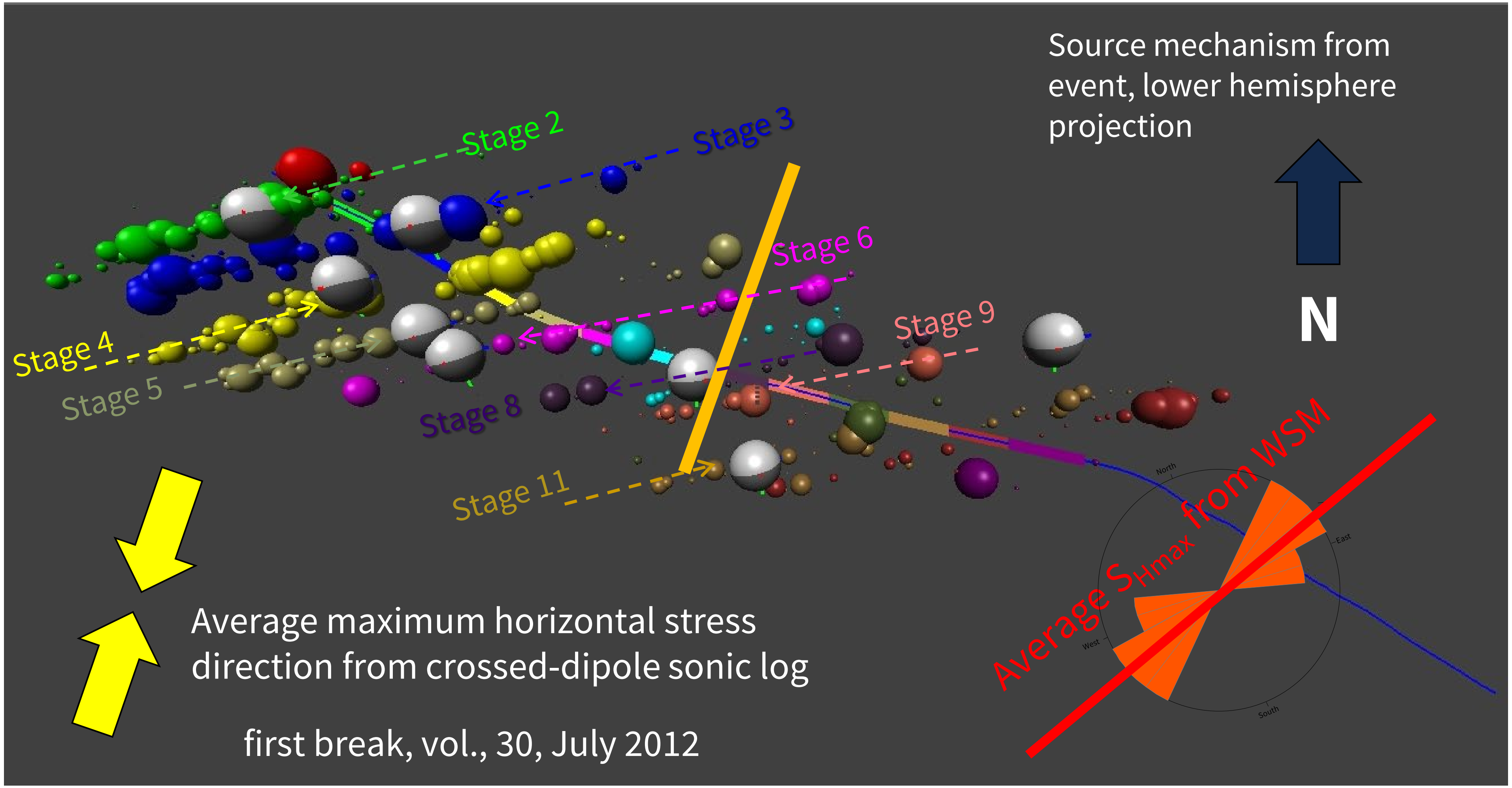


100 mph fastball
= 230 joules



M = -1.6

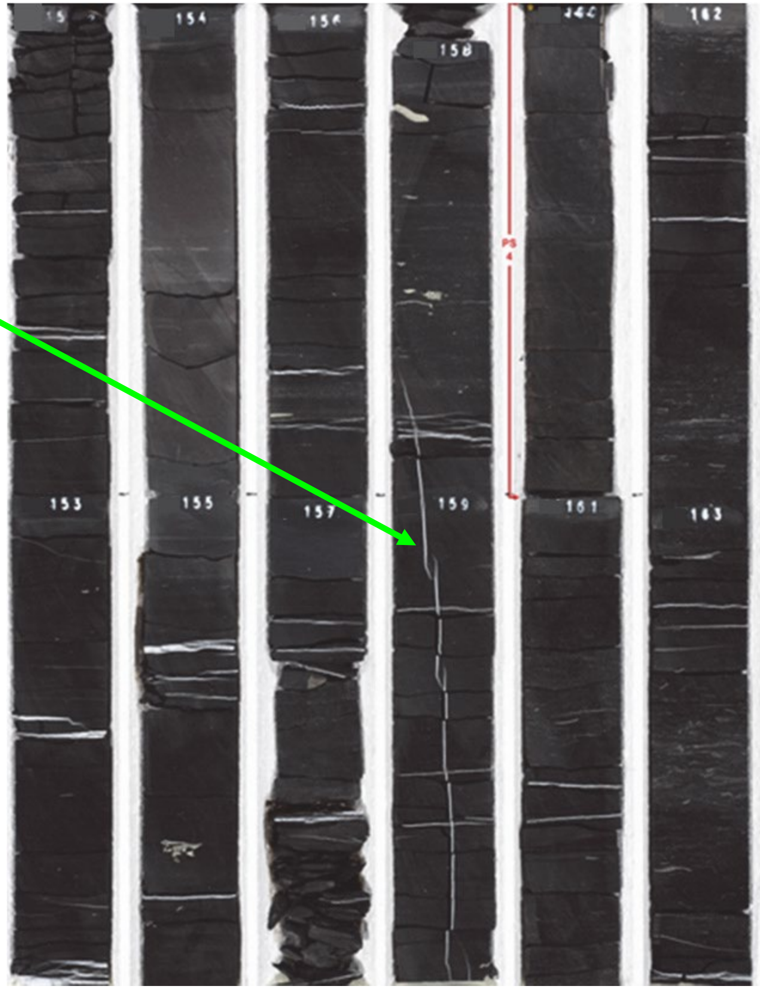
Gulf of Mexico – Stress Interpretation

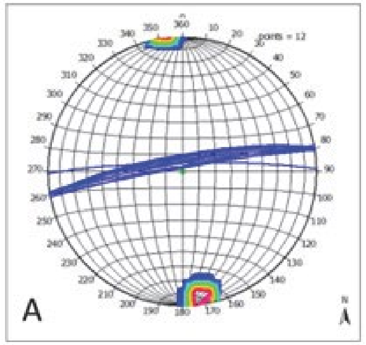


Fractures in Shale Core, Simulated HydroFrac

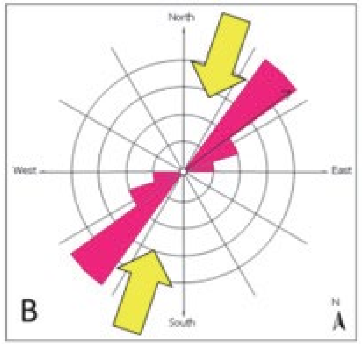
Stimulation takes advantage of existing fracture network, event cloud not parallel to maximum stress.

Near-vertical fractures in core, strike oblique to maximum stress orientation.

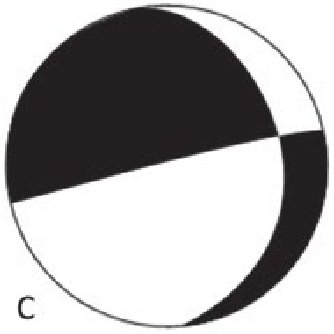




Natural fracture orientation



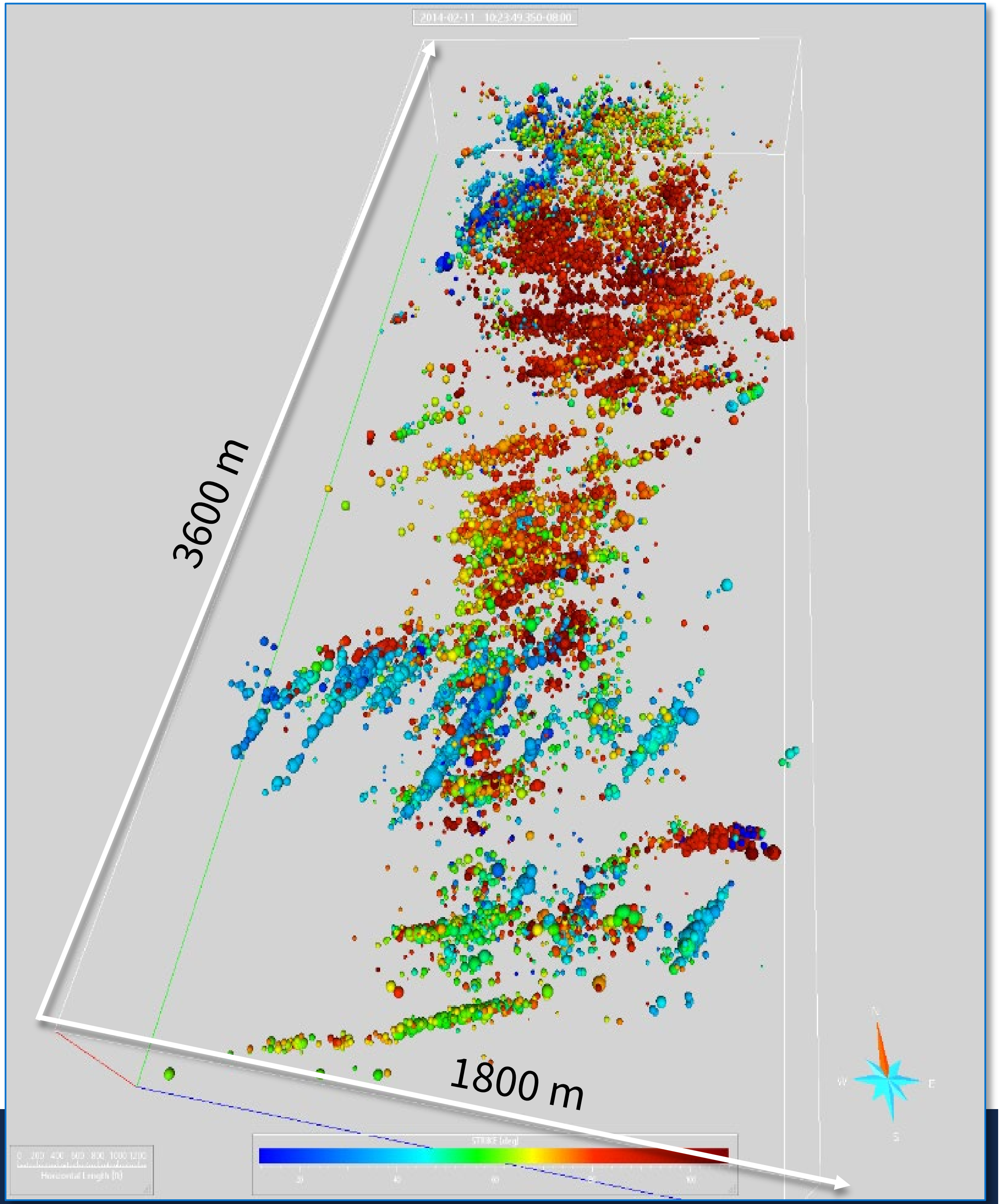
Regional and borehole stress orientations



Average source mechanism

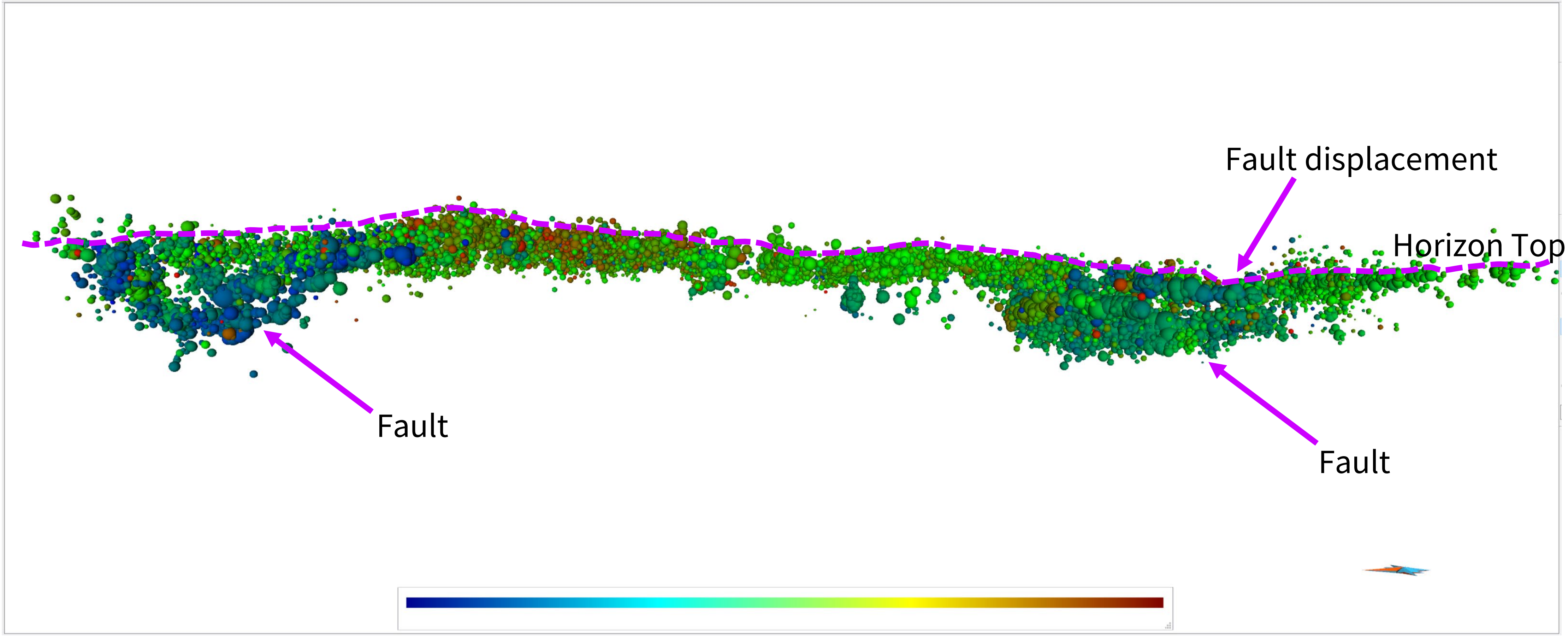
South-Central United States

- 18,506 Microseismic events located for a 5-well stimulation
- Events are sized by magnitude
  - Provides a relative size
  - Magnitude range -2.795 to 0.723
- Events are colored by strike
  - Range is 0.12º – 129º
- Full source mechanism solutions for each event
  - Includes strike, dip, rake, relative percentage of double-couple, volumetric, and CLVD components
- No wells, no horizon tops



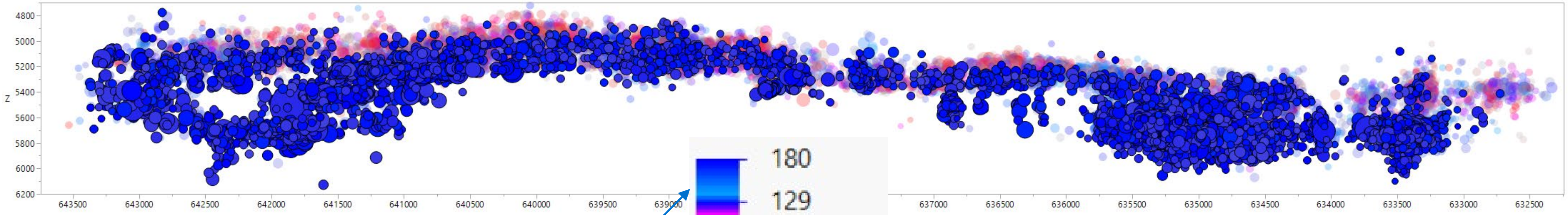
View of event cloud from the west

Possible Interpretation

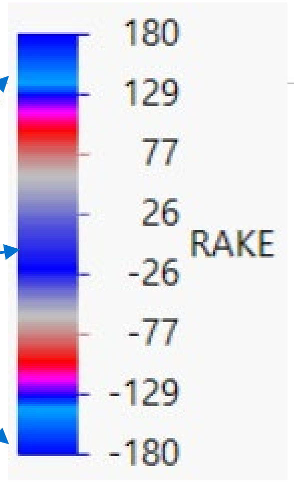


Slip Displacement Types

NORTH

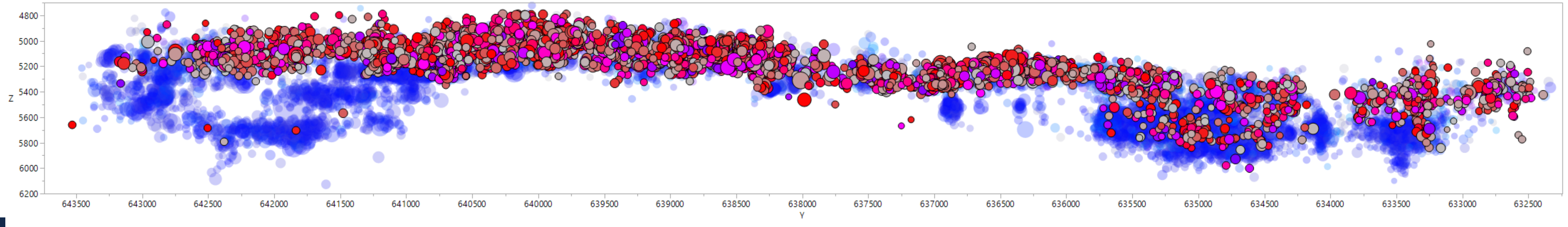


Blue events are primarily strike slip events.
Most are associated with faults, oriented oblique to S_{Hmax}

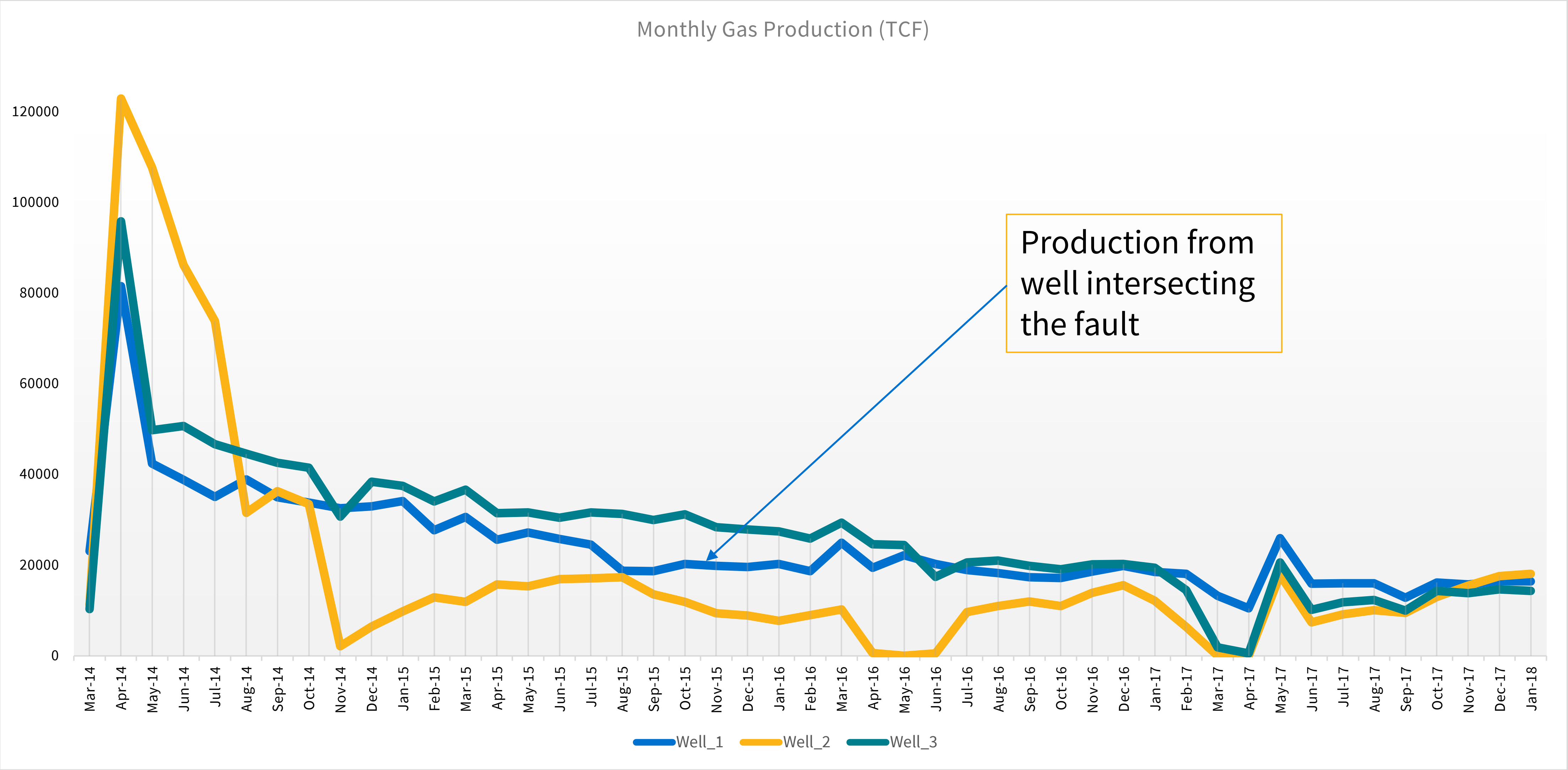


Red and gray events are primarily dip slip events
Fracture planes are primarily parallel to S_{Hmax}

NORTH



Well Production Behavior



Fluid Injection Rate Influence on Induced Seismicity

Rocky Mountains Arsenal waste fluid injections, Rangely, CO USA, 1966

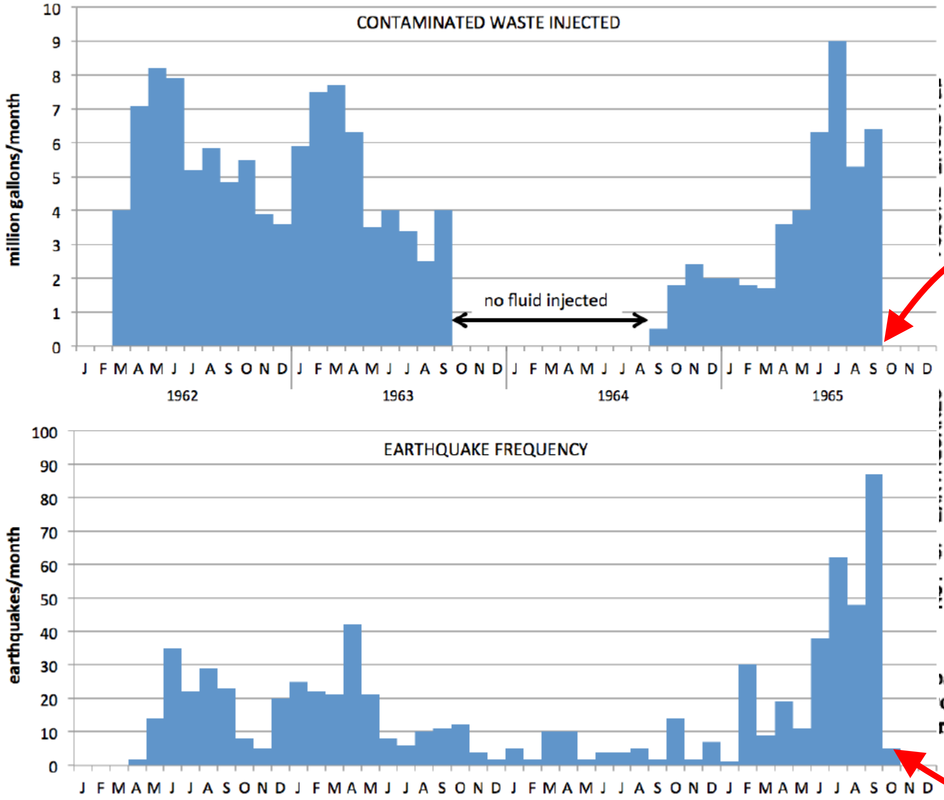
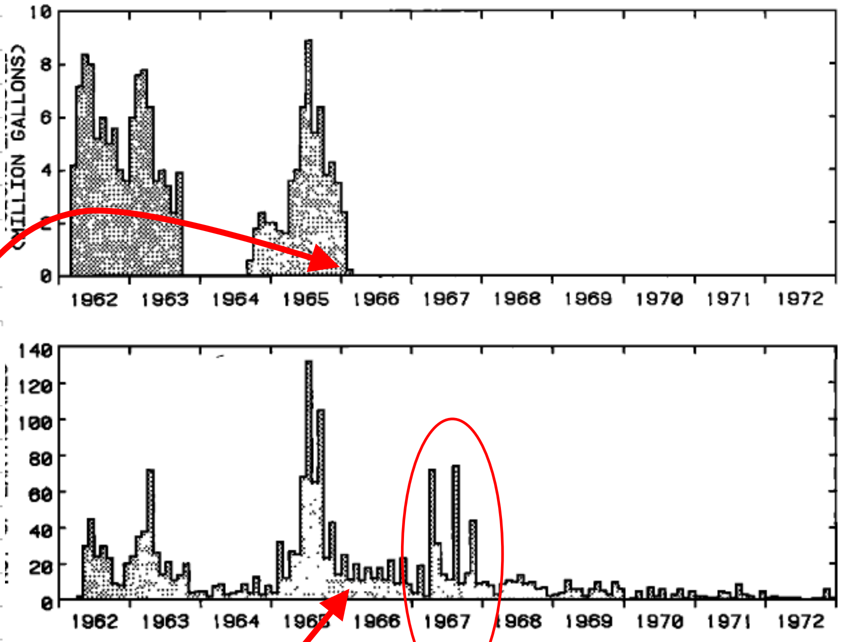


Figure Histograms showing relation between volume of waste injected into the Rocky Mountain Arsenal well and earthquake frequency. SOURCES: Adapted from Evans (1966); Healy et al. (1968); McClain (1970); Hsieh and Bredehoeft (1981).

HSIEH AND BREDEHOEFT: DENVER EARTHQUAKES



›arison of fluid injected and the frequency of earthquakes at the Rocky Mountain Arsenal. Upper graph ›olume of fluid waste injected in the disposal well. Lower graph shows number of earthquakes per month. ›rrelation for the period 1962–1966 was first noted by *Evans* [1966].

Hsieh and Bredehoeft, JGR, 1981.

CCUS at Decatur, Illinois

CCUS at Decatur, Illinois

- 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
- Completed conceptual site model and history matching

Illinois Industrial CCS Project

- 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

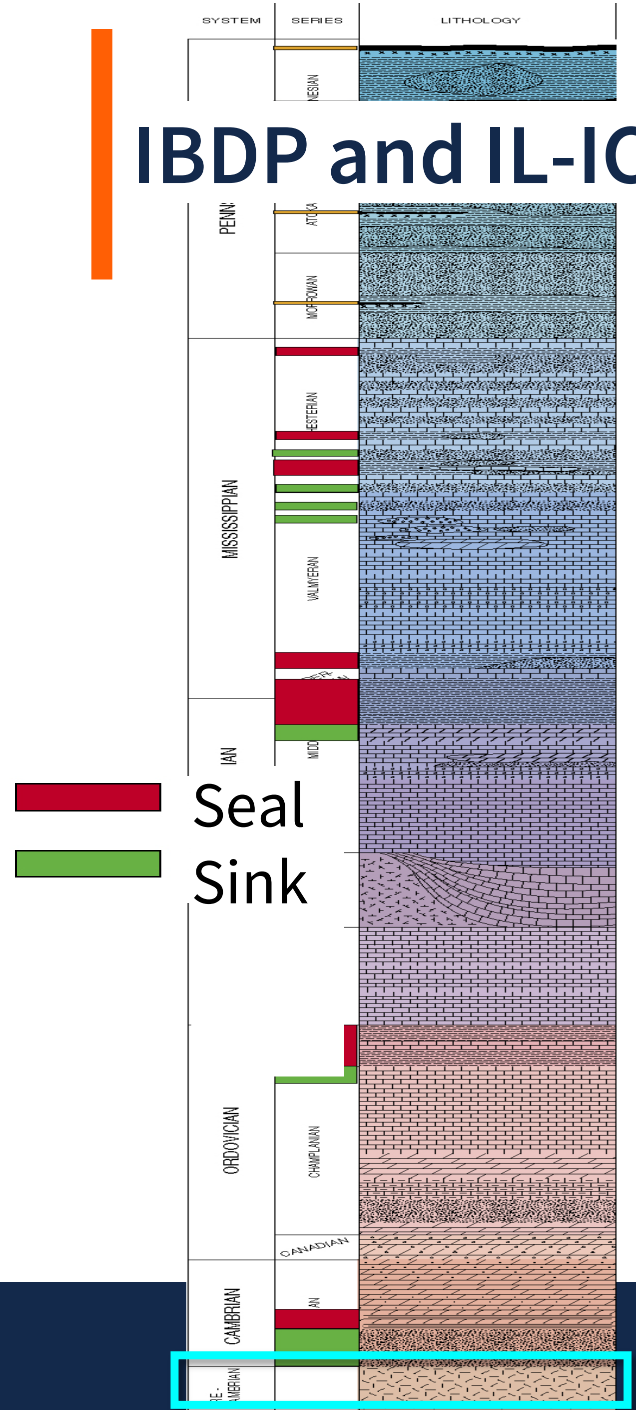
Contribution:

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

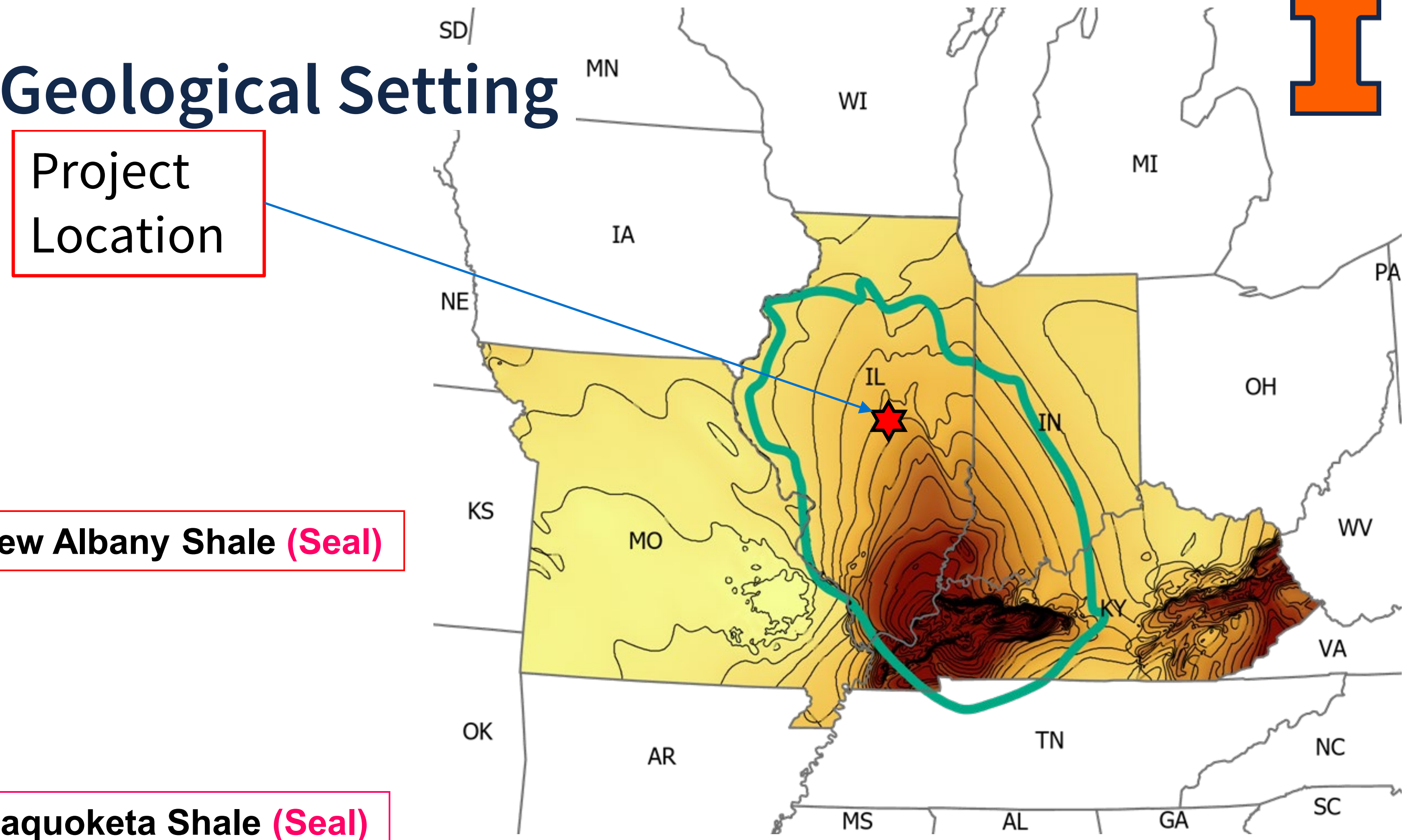
Status:

- Injection Began April 7, 2017
- Optimization of capture process
- >2,000,000 (as of June 2021)

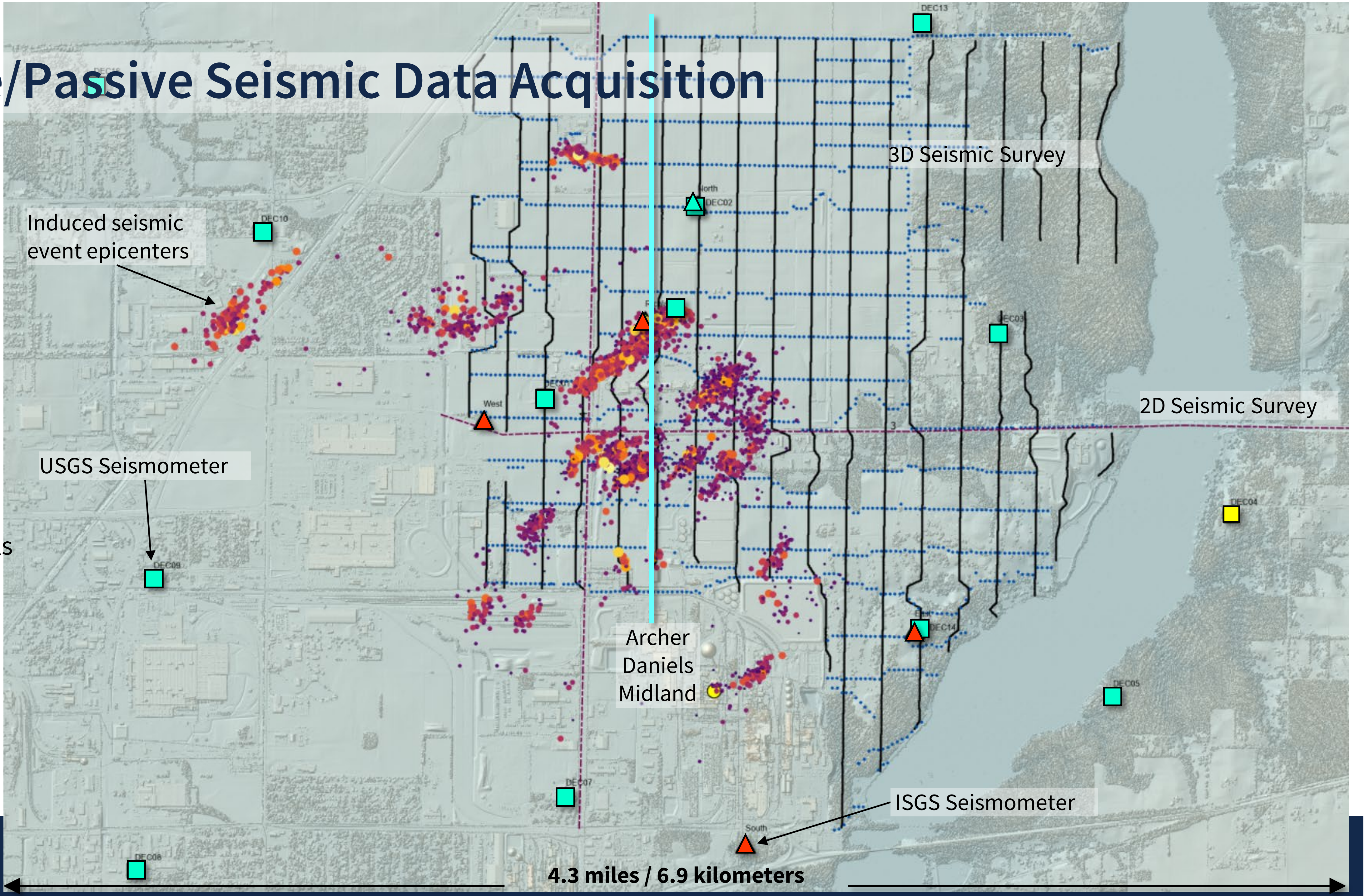
IBDP and IL-ICCS Geological Setting



- **New Albany Shale (Seal)**
- **Maquoketa Shale (Seal)**
- St. Peter Sandstone (Sink)
- Ironton-Galesville Sandstone (Sink)
- **Eau Claire Shale (Seal)**
- Mt. Simon Sandstone (Sink)



Active/Passive Seismic Data Acquisition



USGS seismometer

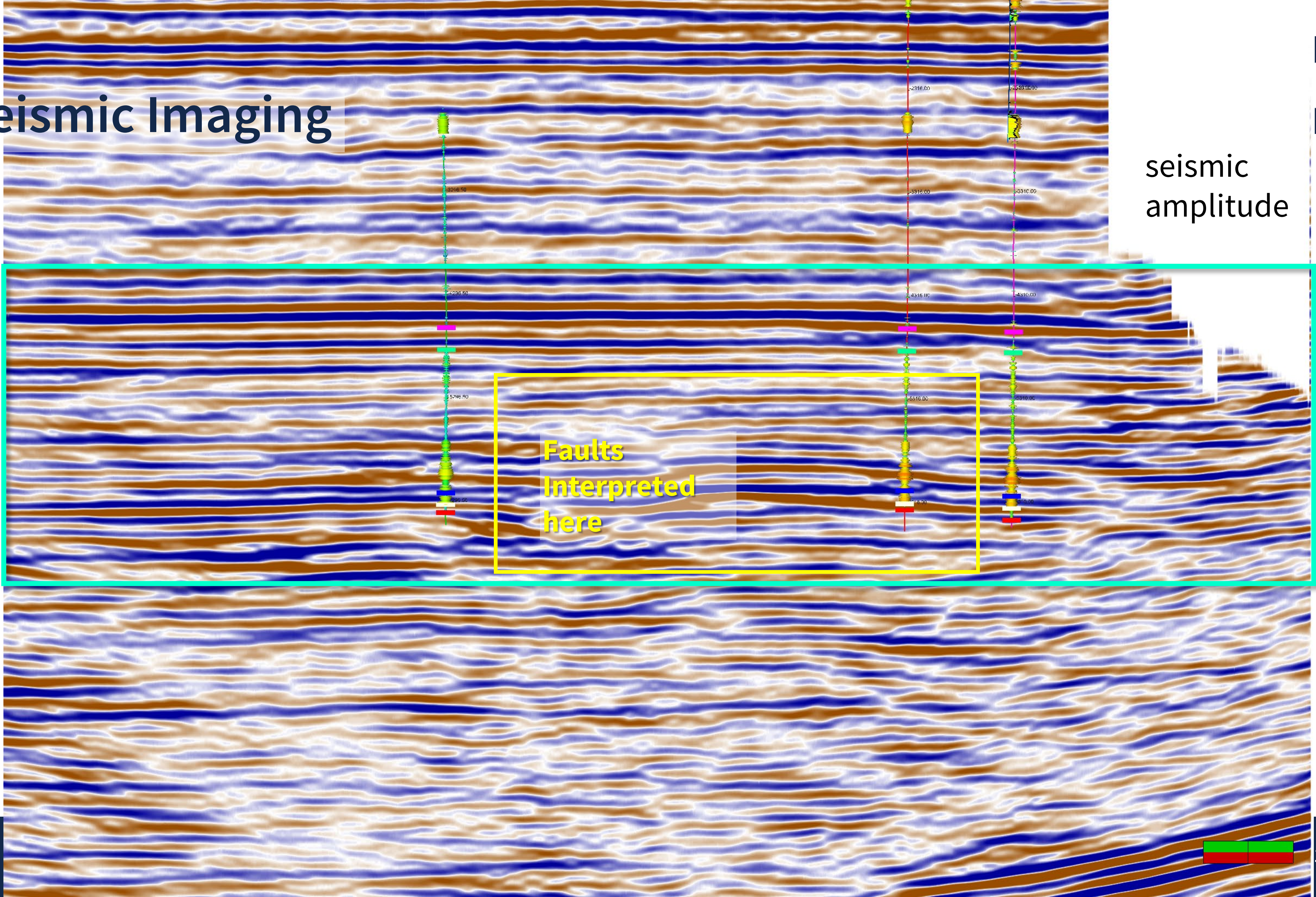
ISGS seismometer

Injection and Monitoring wells

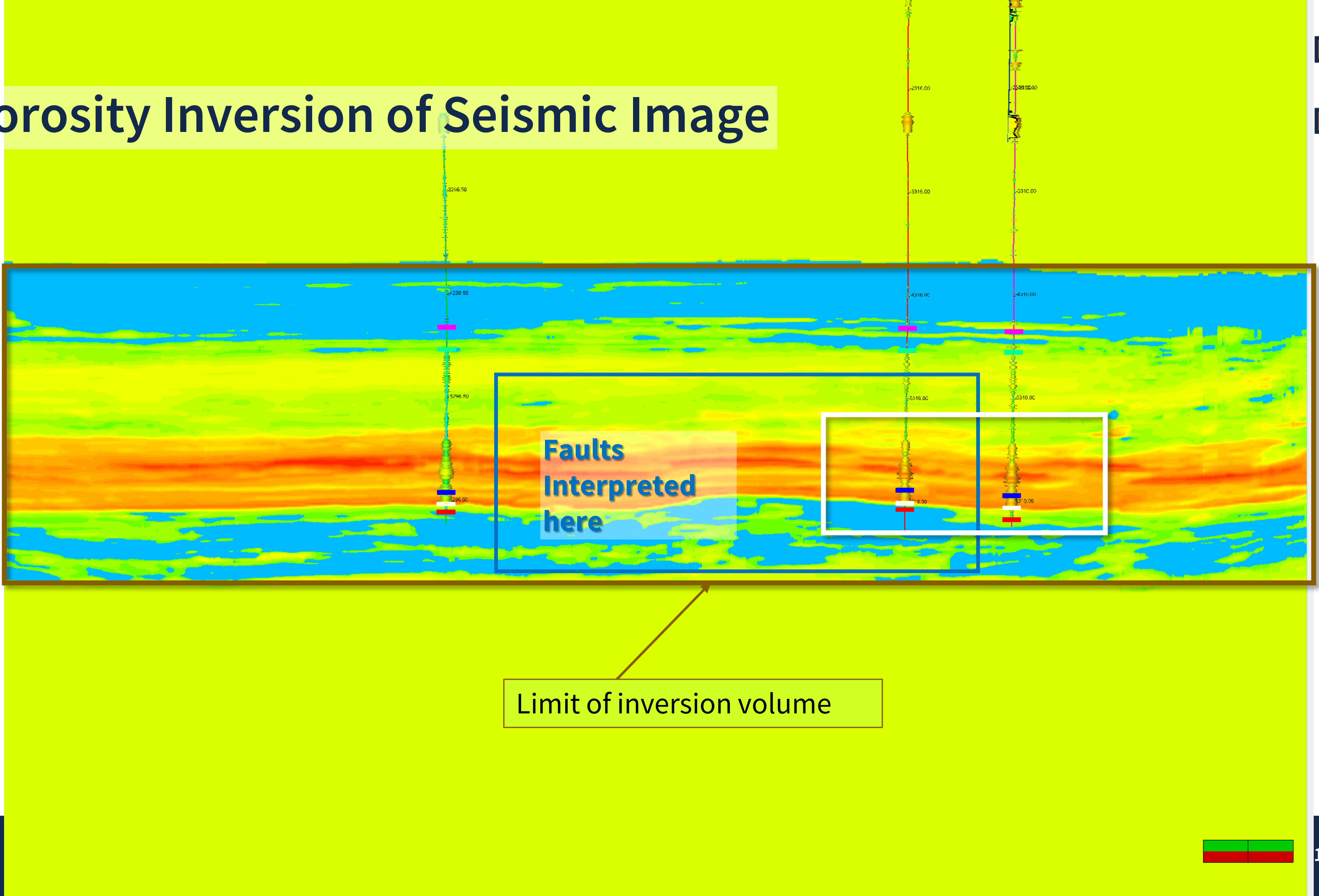
3D Seismic Survey

2D Seismic Survey

Seismic Imaging

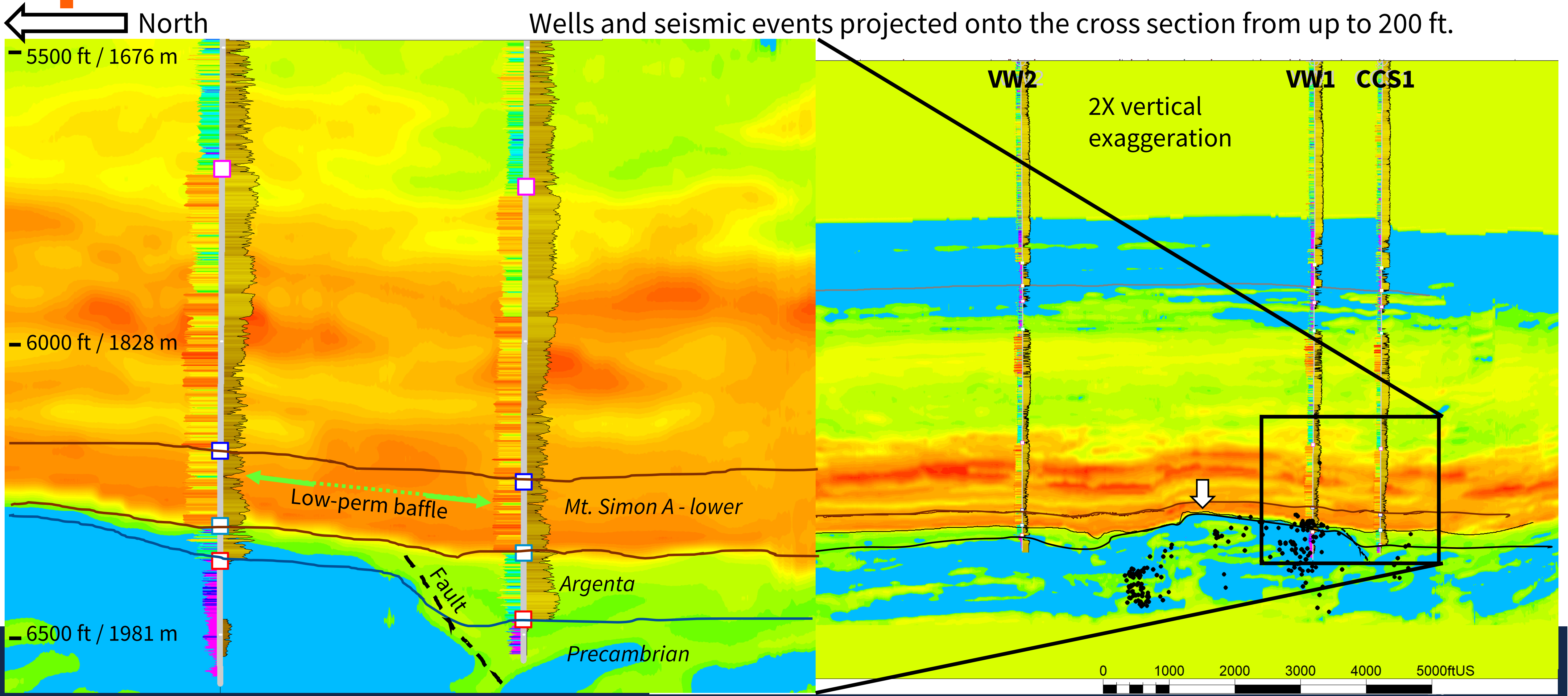


Porosity Inversion of Seismic Image



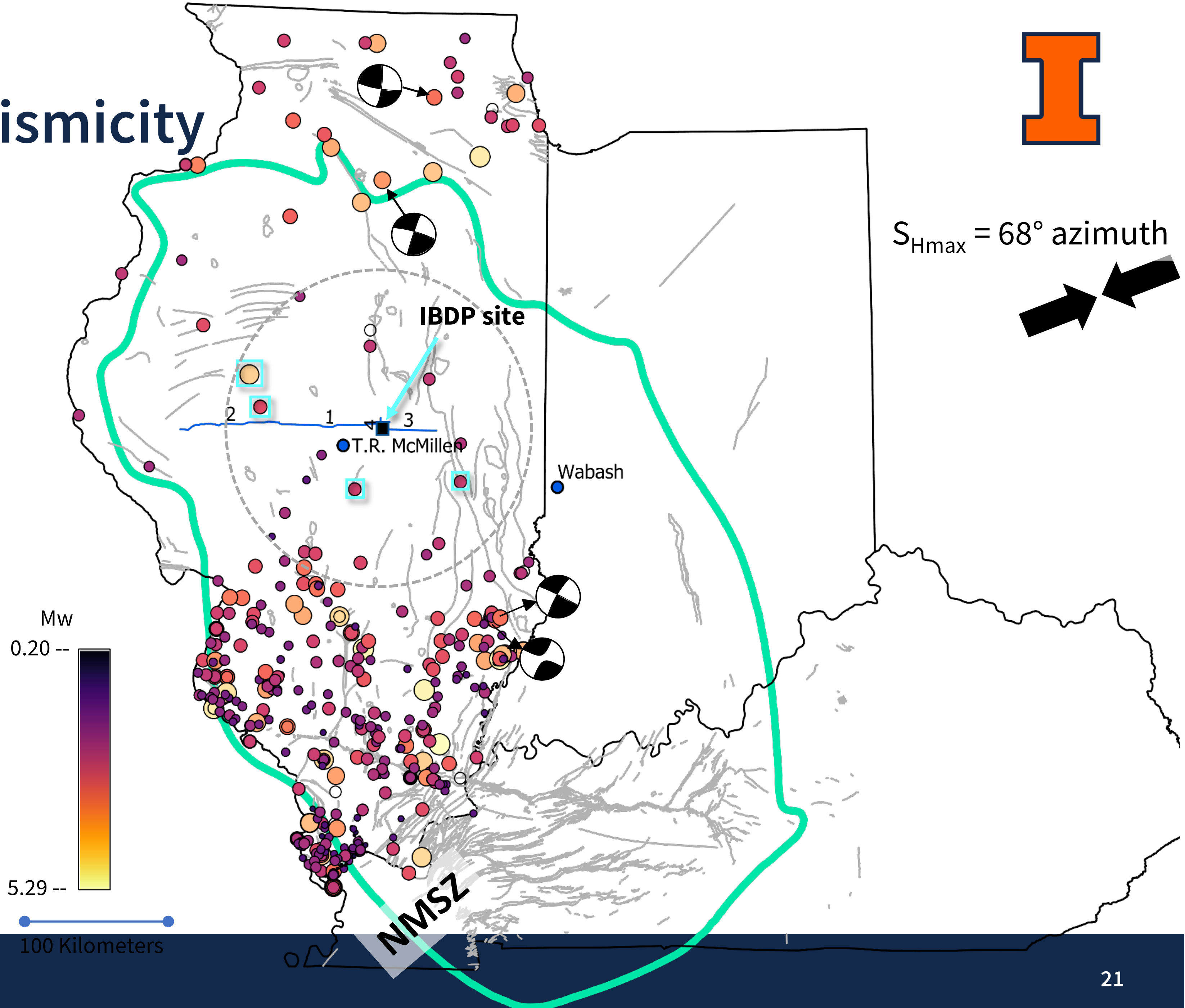
Fault Interpretation on Porosity Inversion

Wells and seismic events projected onto the cross section from up to 200 ft.



Historical Natural Seismicity

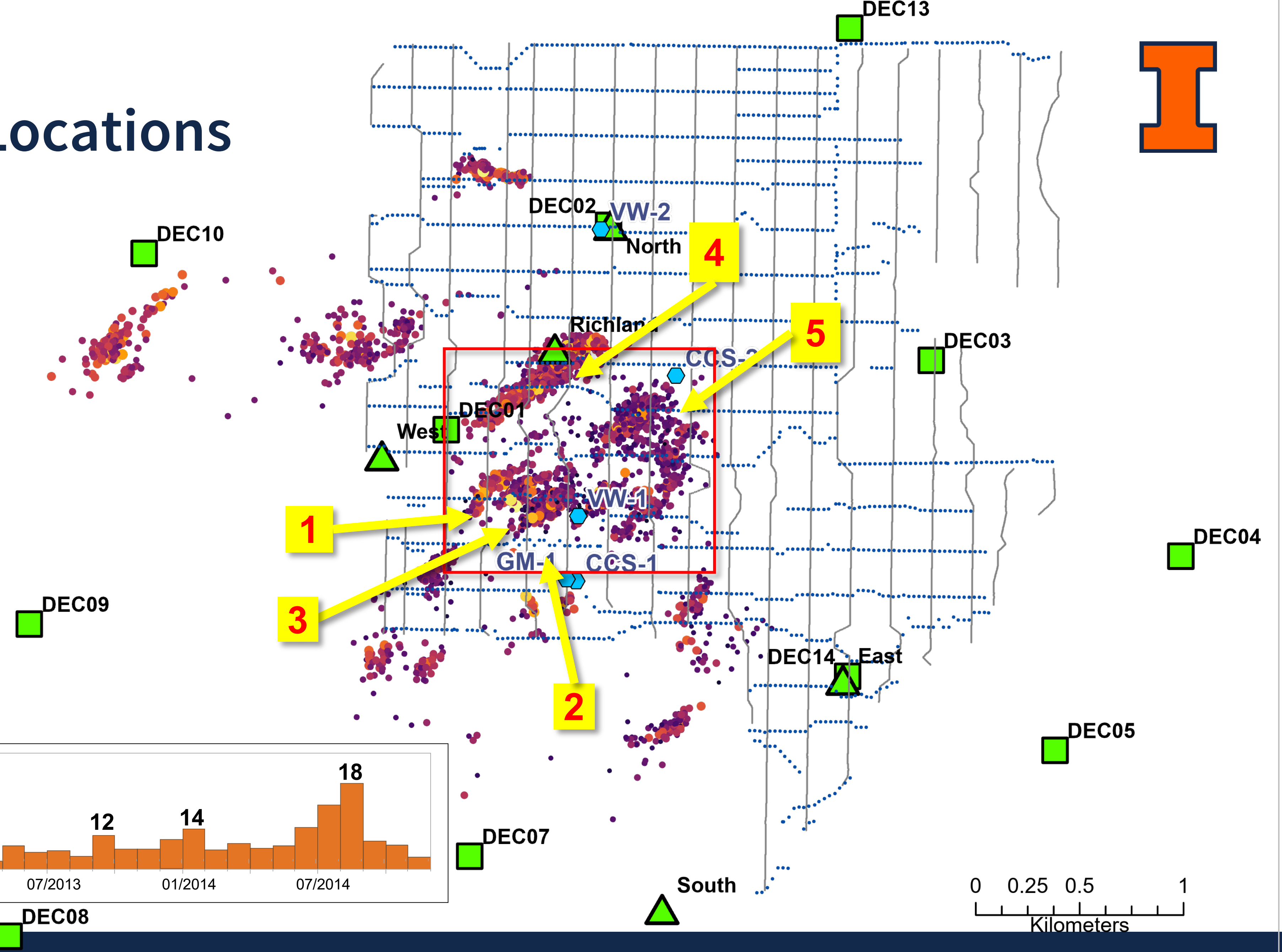
- Earthquakes in Illinois since 1795
- Some activity in northern Illinois
  - Moment tensors shown for 3.8 and 4.2 Mw earthquake
- Most activity is in southern part of state, where basin is deepest and has highest structural complexity
  - Moment tensors shown for Mw 5.2 EQ followed by a Mw 4.0 aftershock

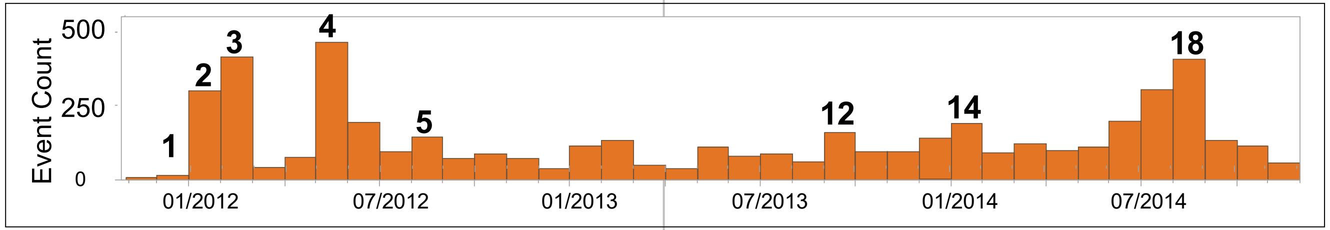


Induced Event Locations

- USGS Seismic Stations
- ISGS Seismic Stations

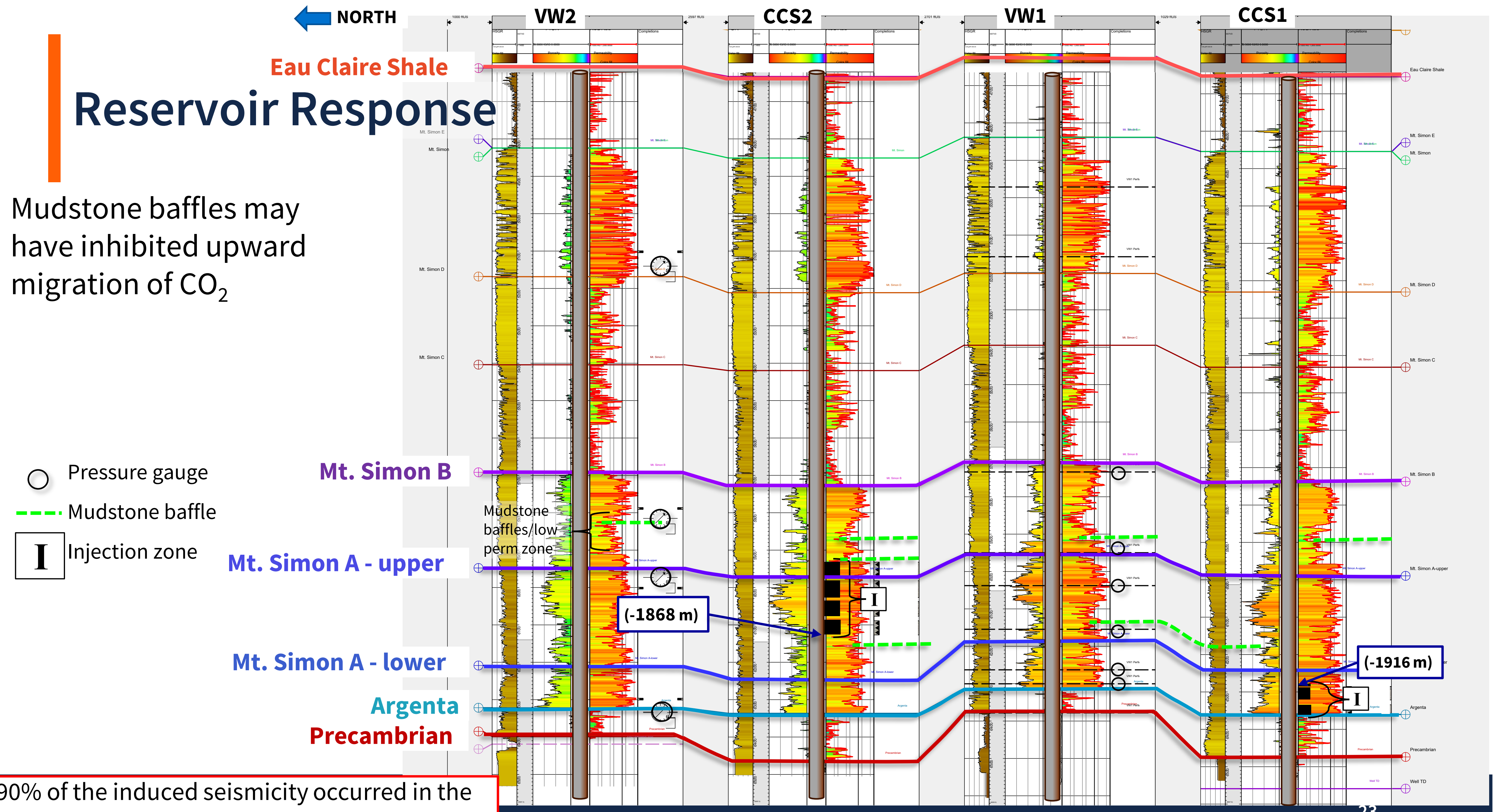
- Clusters of events have temporal development
- Indicate reactivation of existing features
- Interpreted as faults, or fracture corridors





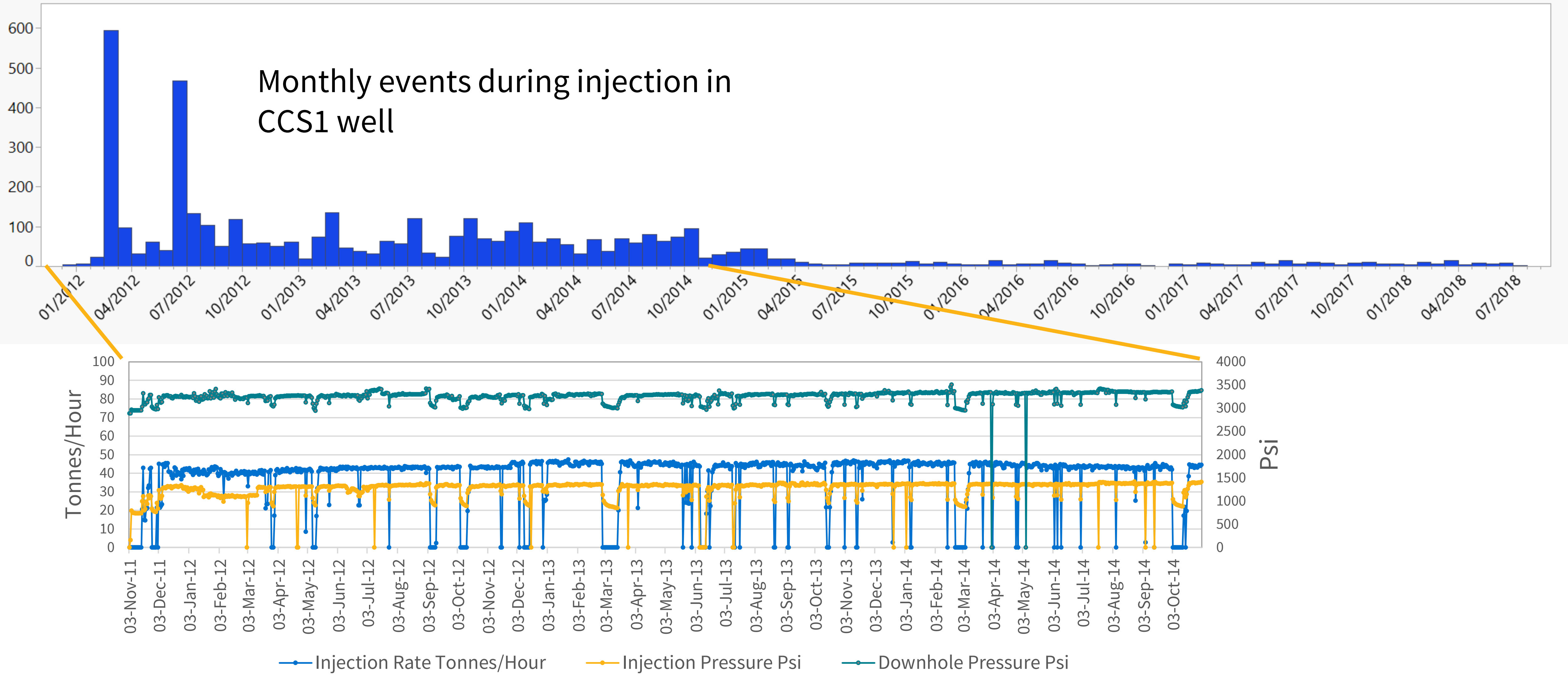
Reservoir Response

Mudstone baffles may have inhibited upward migration of CO_2



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

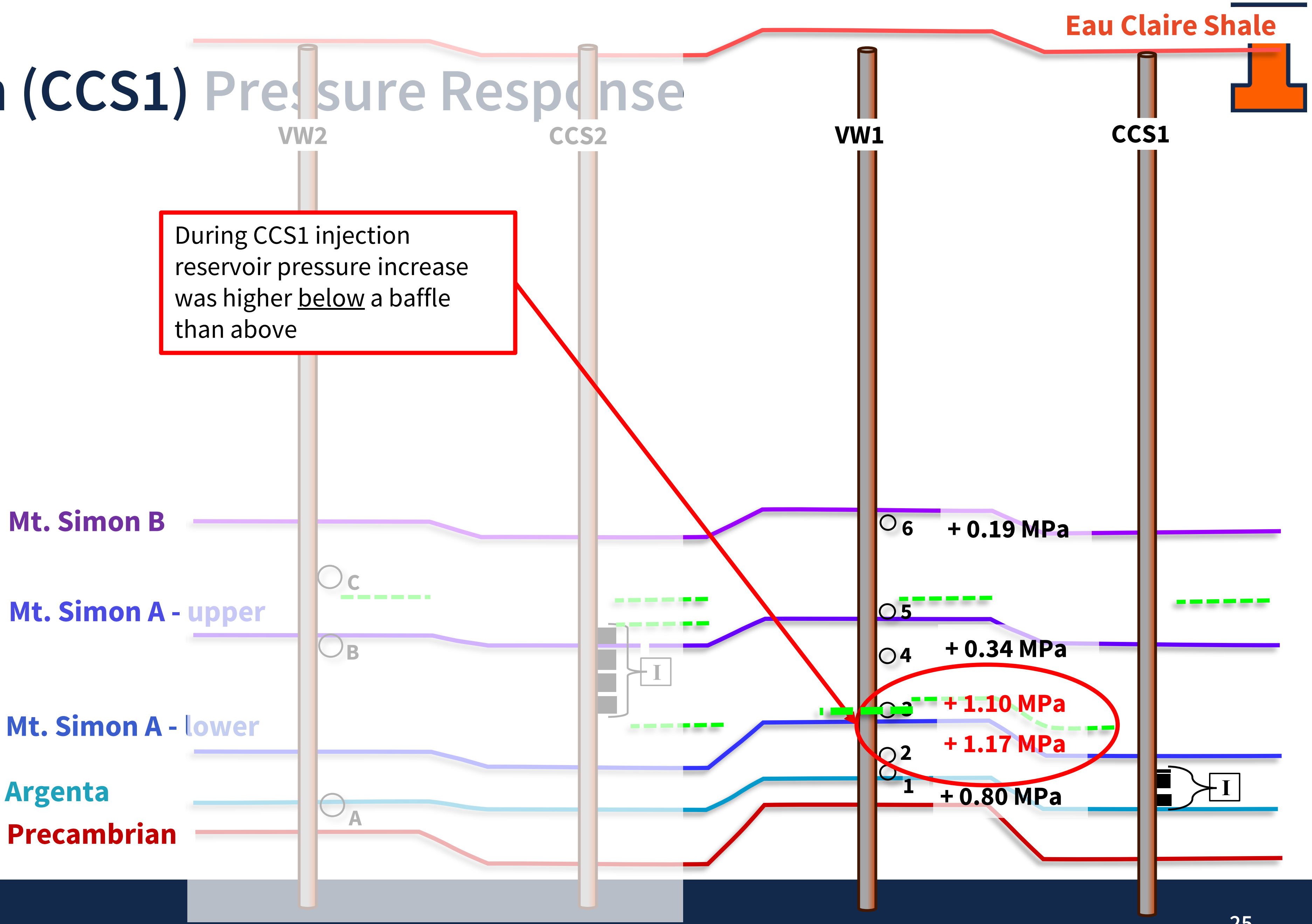
Seismicity / Pumping Rate: Poor Correlation



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:

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- Injection zone depth
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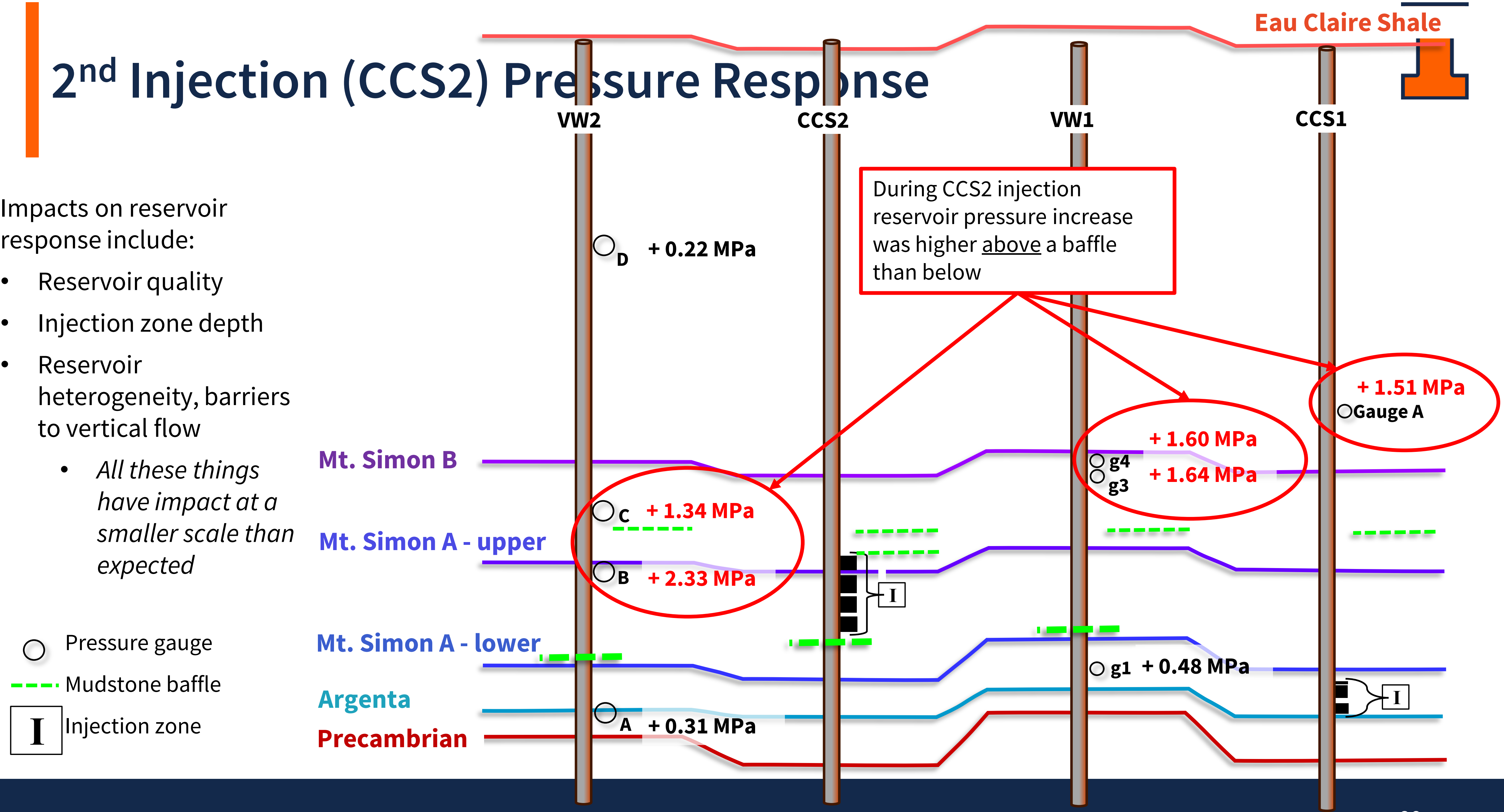

Comparing to Wastewater Injection

	Location	Injection rate m^3/day	Injection period	Induced seismicity	Felt seismicity
$scCO_2$ 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

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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

THANK YOU!