Investigating the Role of Geological Architecture on Shallow Injection in the Delaware Basin through Field Studies and Finite Element Modeling

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Center for Injection and Seismicity Research
Bureau of Economic Geology, Jackson School of Geosciences, UT Austin

BUREAU OF ECONOMIC GEOLOGY

Center for Injection and Seismicity Research

- **Center for Injection and Seismicity Research (**CISR) studies the impacts of large-scale injection on the subsurface and surface environment
- CISR applies geology, seismology, hydrogeology, geomechanics, and satellite geodesy to study how reservoirs respond dynamically to fluid injection
- CISR provides resources for stakeholders to mitigate the hazard of induced earthquakes, threats to the surface environment, and challenges to sustainable energy development

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Dr. JP Nicot[B], CISR Co-Principal Investigator, reservoir engineering, hydrogeology
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[B]UT Bureau of Economic Geology
[E]UT Department of Earth and Planetary Sciences
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[A]UT Aerospace Engineering
[P]UT Petroleum and Geosystems Engineering
[1]Ph.D. student

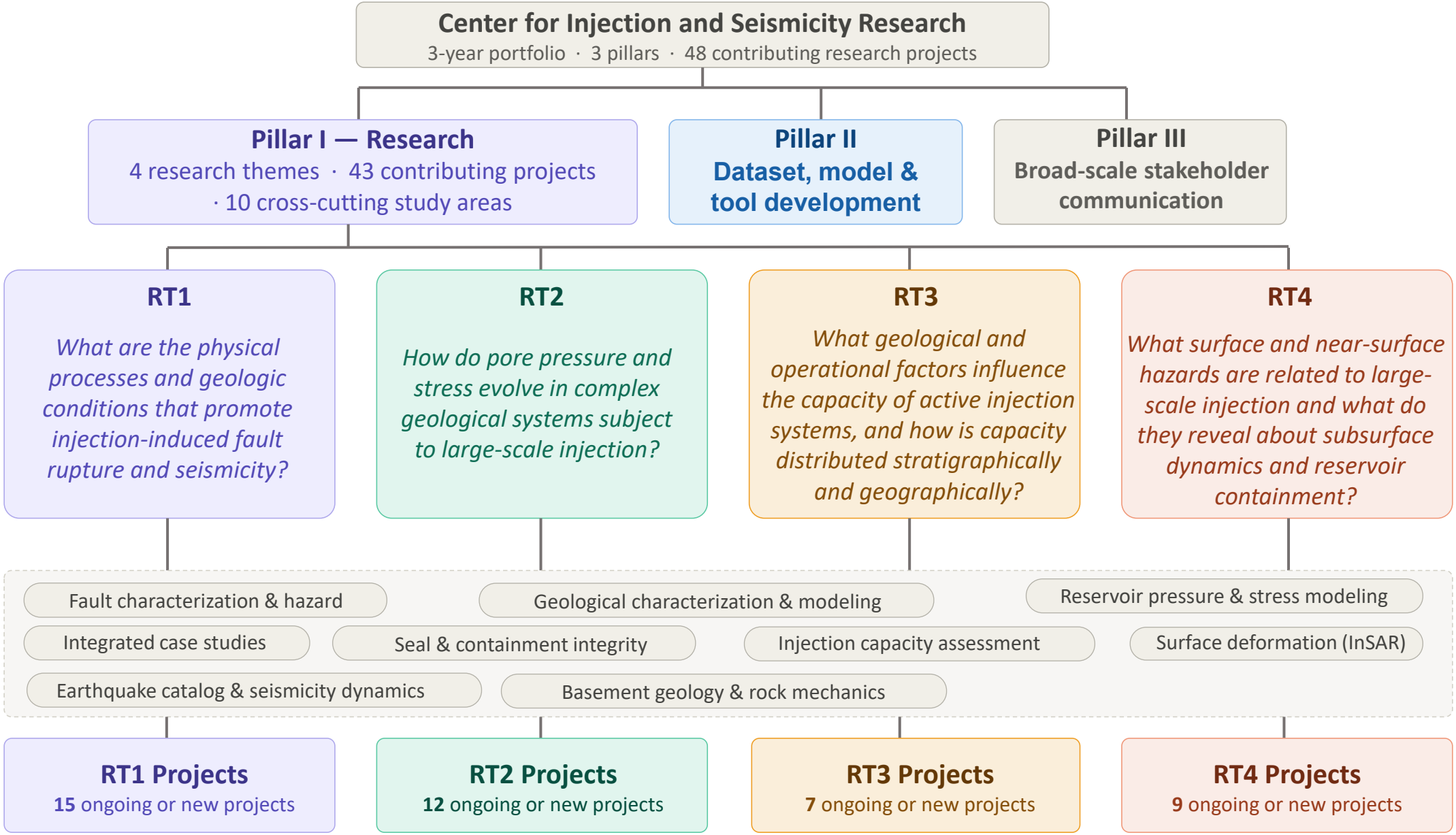
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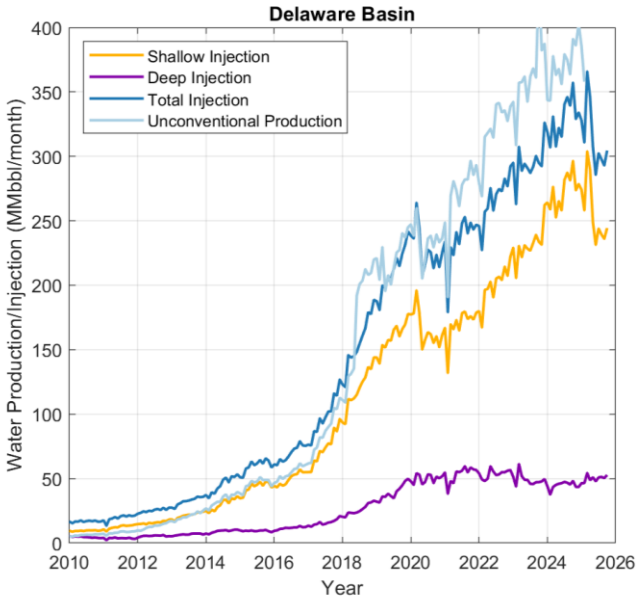
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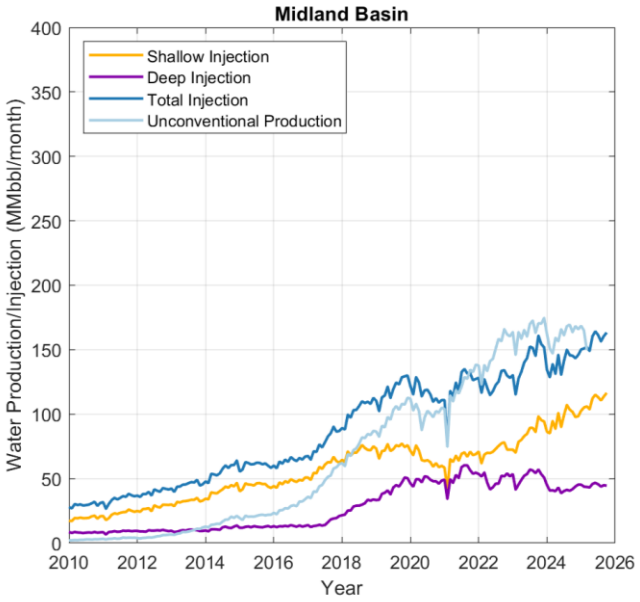


1. **Background Information**
2. Shallow Injection, Characterization and Modeling
3. New Analog Field Models

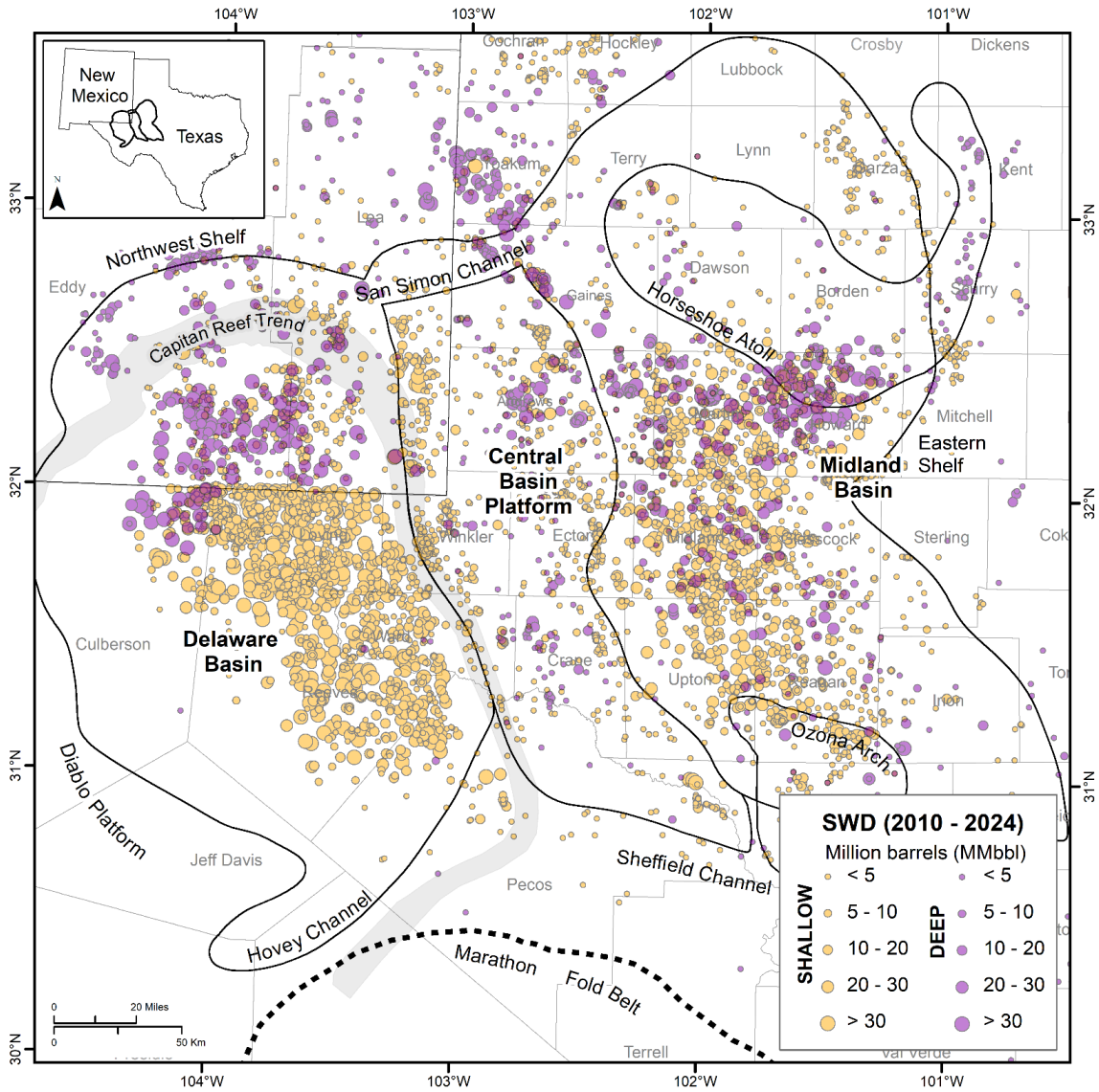
Recent Trends in Permian Basin Production and Injection

- Nearly all unconventional produced water not recycled for HF is injected for permanent disposal into strata shallower (~75% of injection) or deeper (~25%) than shale reservoirs
- Shallow injection occurring at rate of ~350 MMbbl/month, and deep at ~100 MMbbl/month, with **total daily injection of over 18 MMbbl**

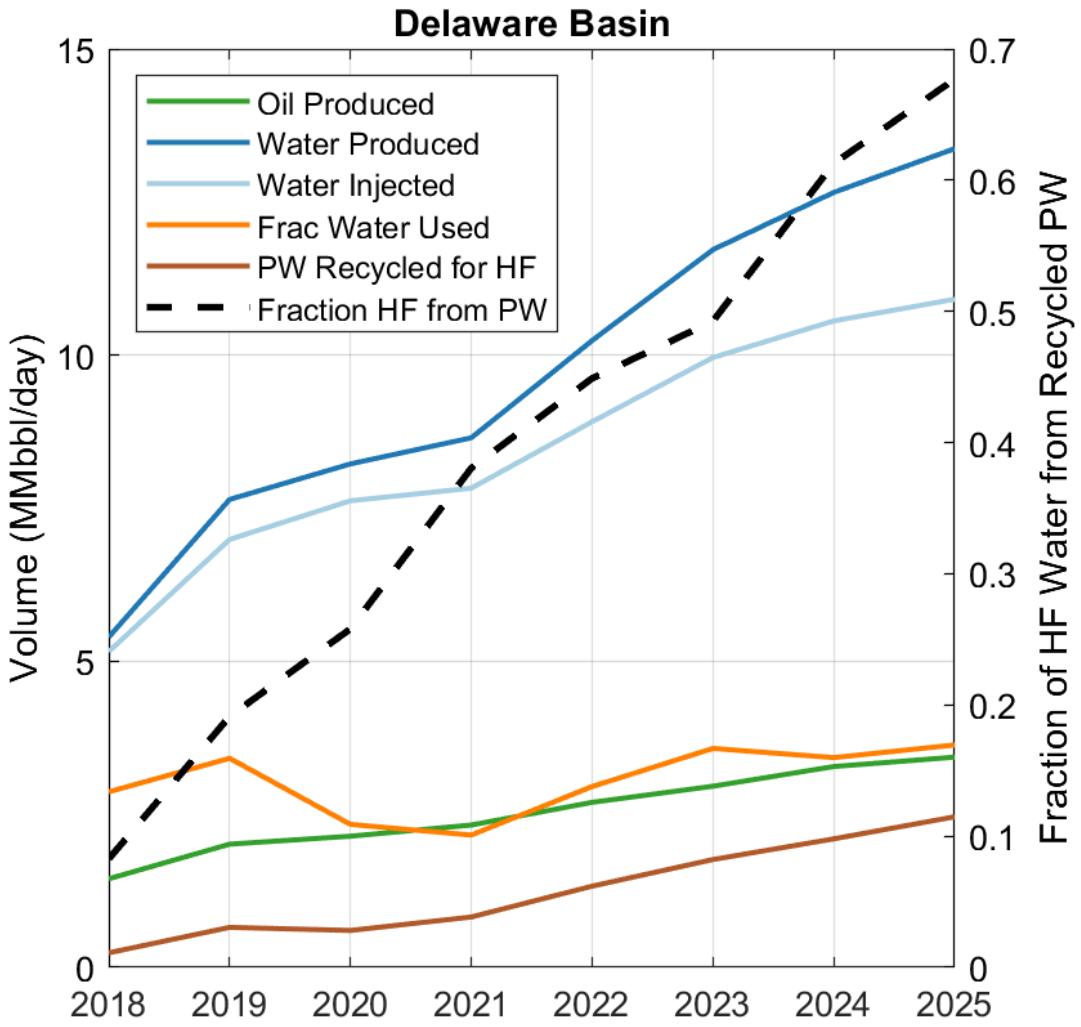


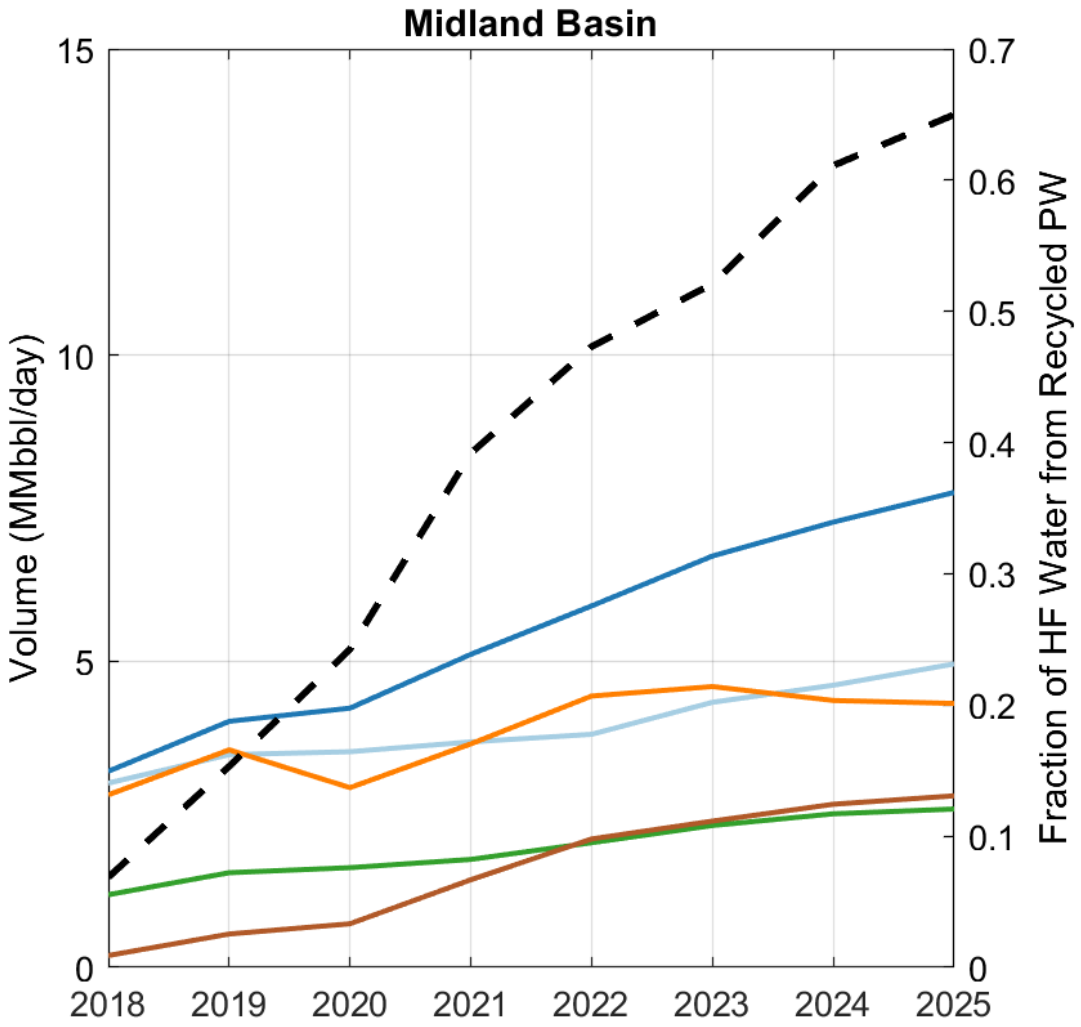


Injection data: B3 Insight



Recent Dynamics in the Permian Basin "Water Cycle"

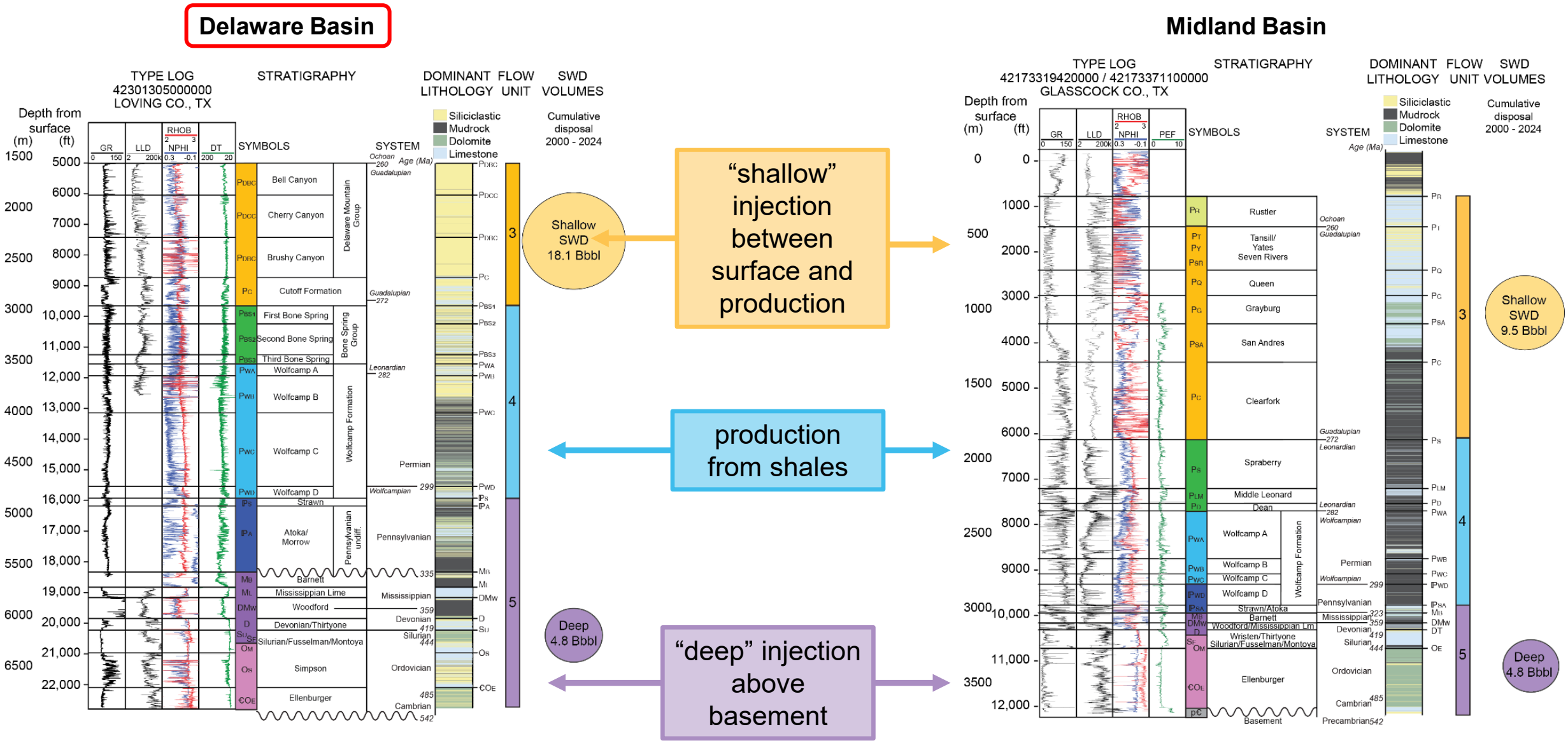




Injection data: B3 Insight

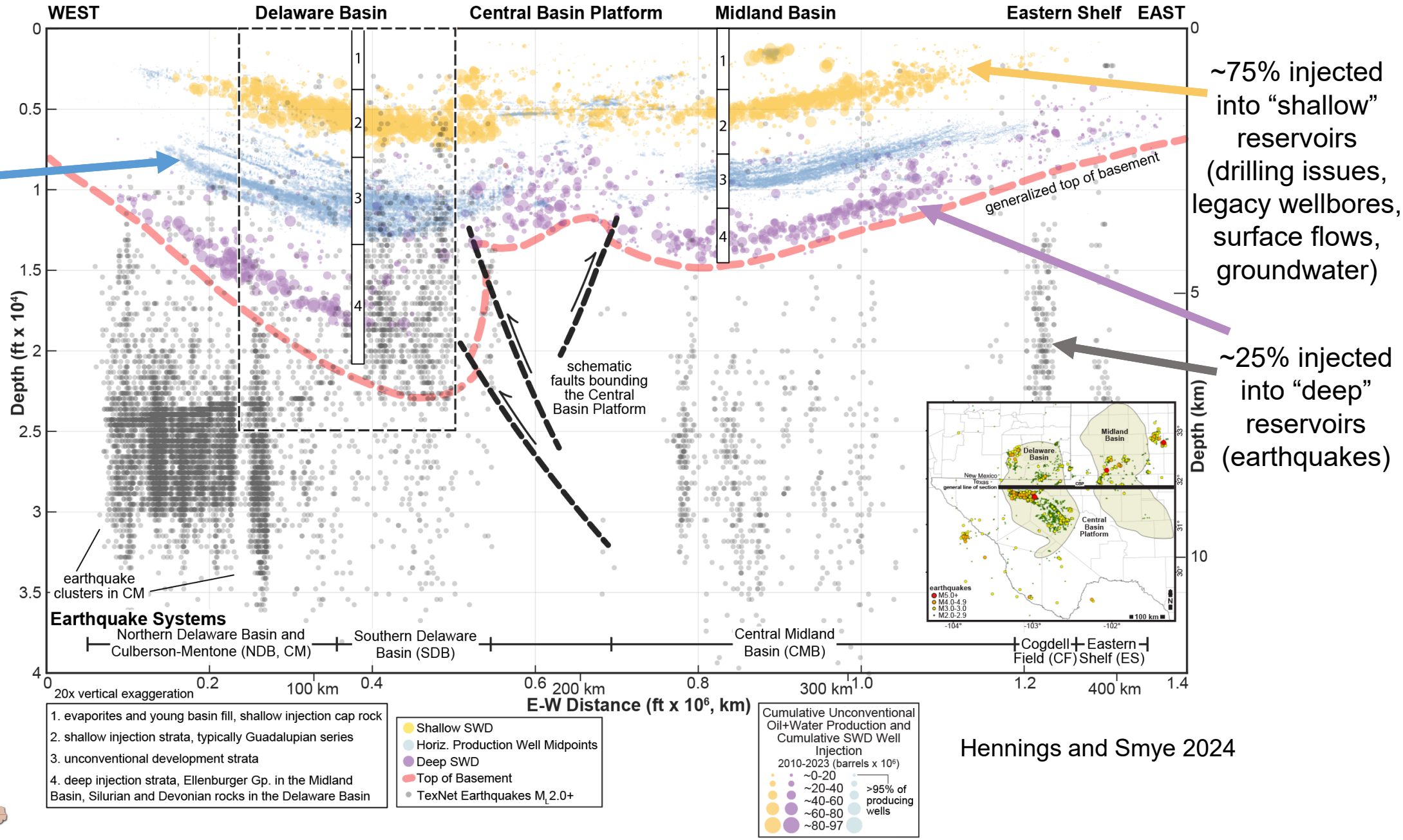
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Geology of Permian Basin Production and Injection



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Stratigraphy of Permian Water Production and Injection



water produced with oil from shales by horizontal wells

~75% injected into “shallow” reservoirs (drilling issues, legacy wellbores, surface flows, groundwater)

~25% injected into “deep” reservoirs (earthquakes)

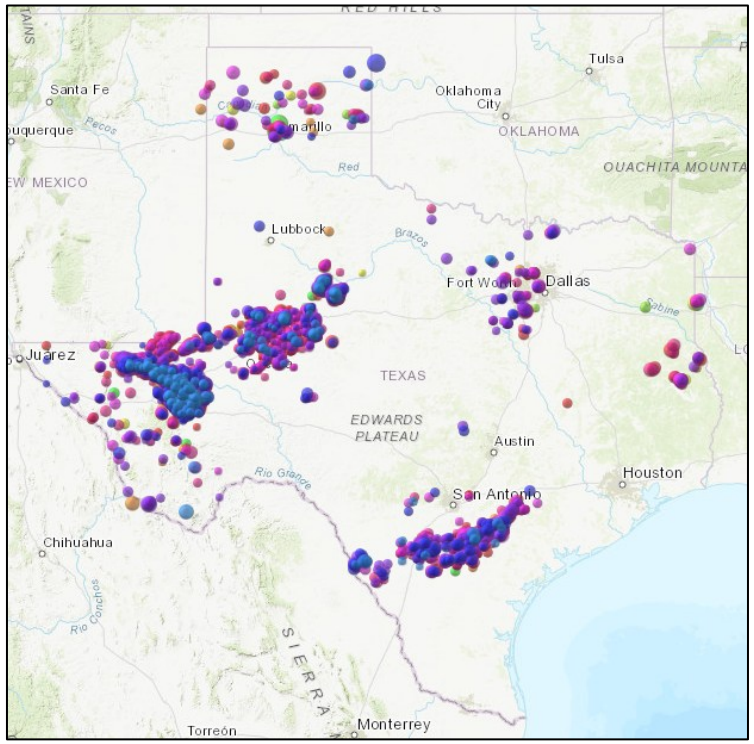
Hennings and Smye 2024

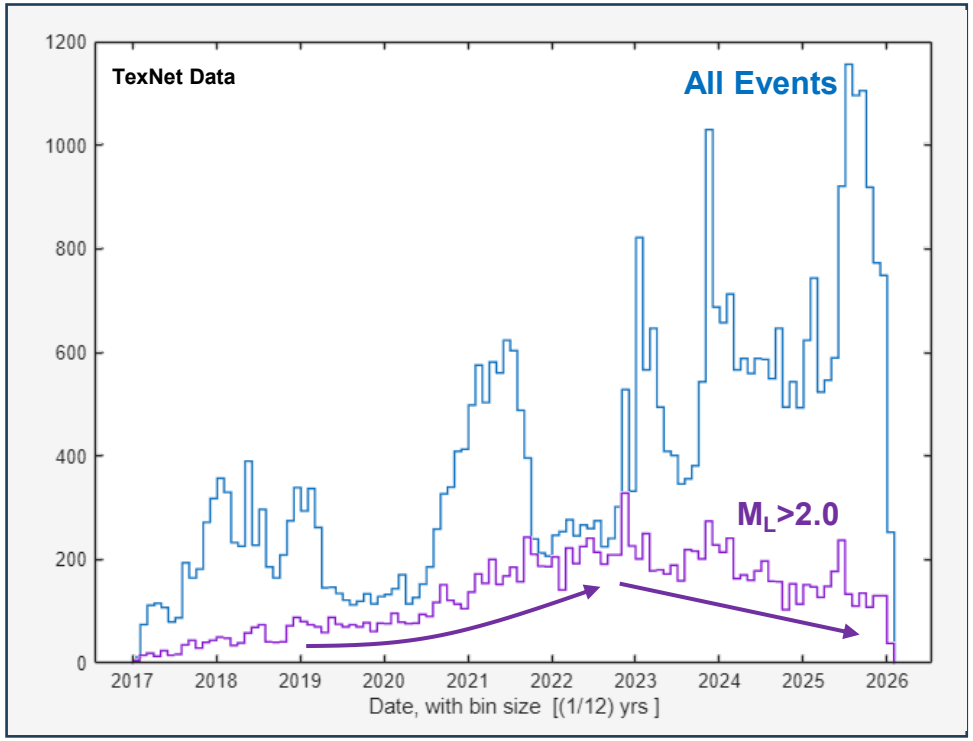
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Texas Seismicity: TexNet 2017-2026

- Operational activities throughout Texas still cause seismicity – **the Earth is a dynamic system!**
- Regulatory changes in the Permian Basin in the past few years have decreased the risk of larger earthquakes

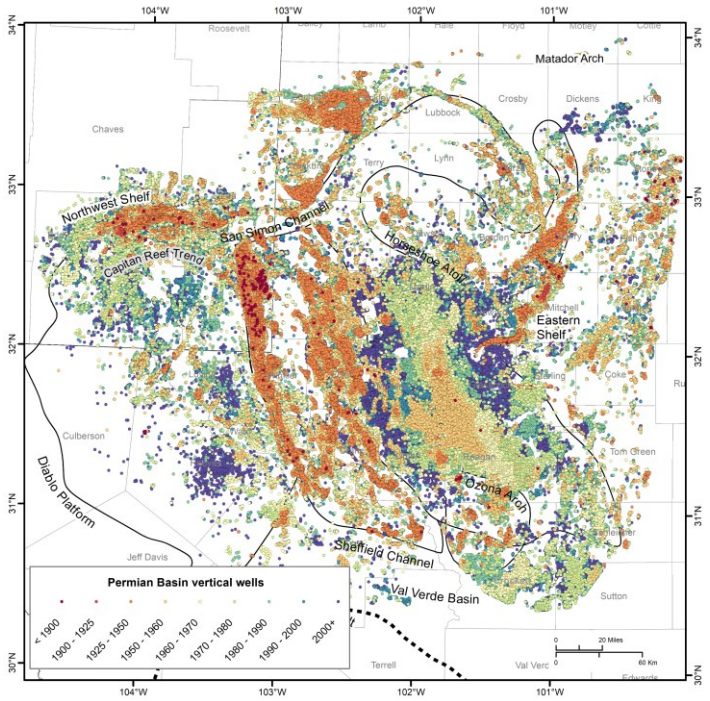
What spatiotemporal changes are observed?
How are the patterns evolving?
What causes different types of seismicity?
What matters for sustainable development?
How does seismicity relate to other hazards?

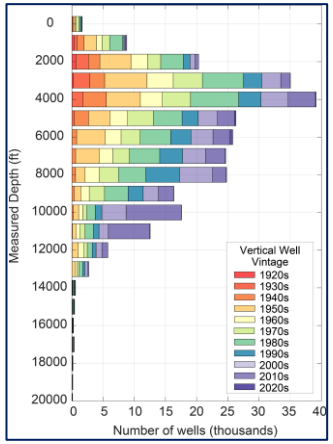




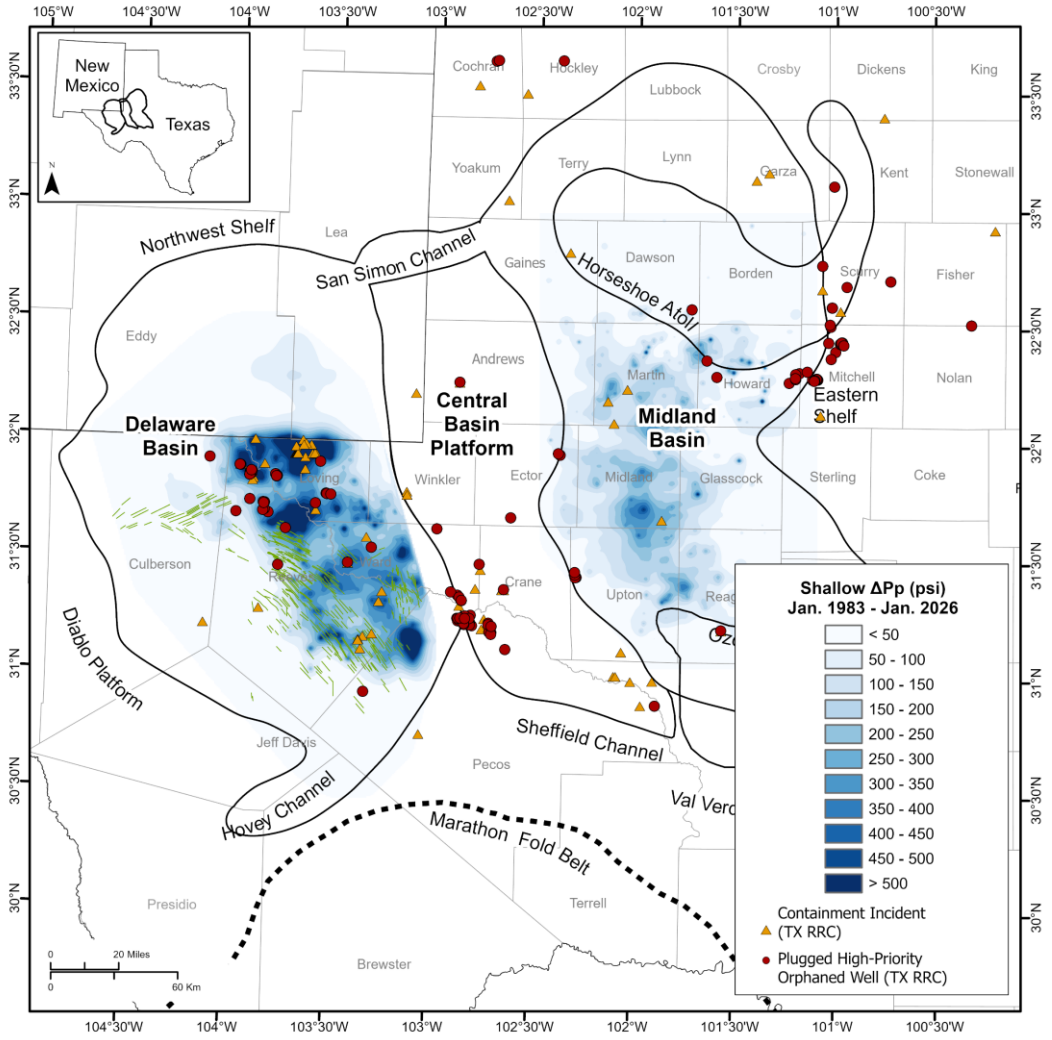
Risk: Leakage via Legacy Wells Due to ΔPp

- Over 250k legacy vertical wells in the Permian Basin region
- Frequently TD in shallow injection reservoirs
- Subset of wells orphaned and abandoned; despite increased rate of state-managed plugging, Priority 1 (leaking) wells increased from <10 per month in 2020 to 30/month in 2026

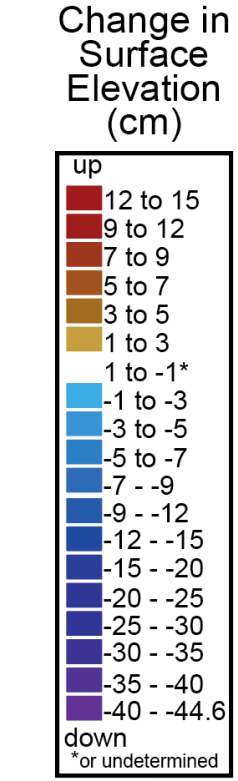


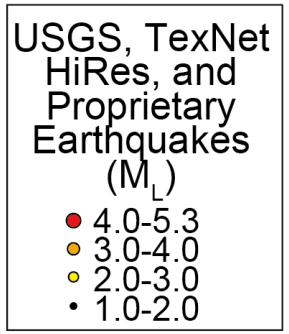


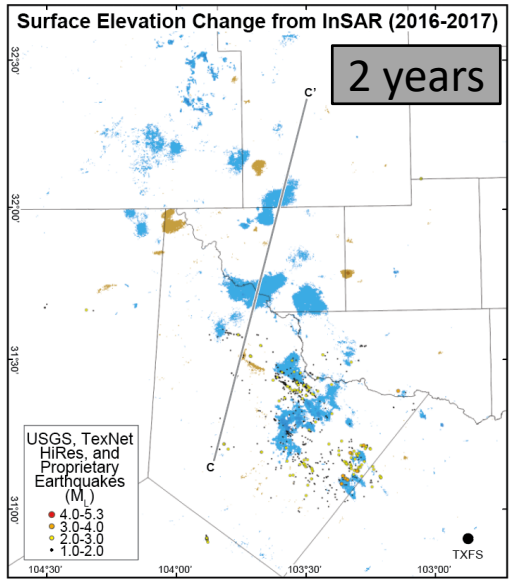
2026 shallow DPp, orphaned well flows, and preliminary SSI tracked incidents

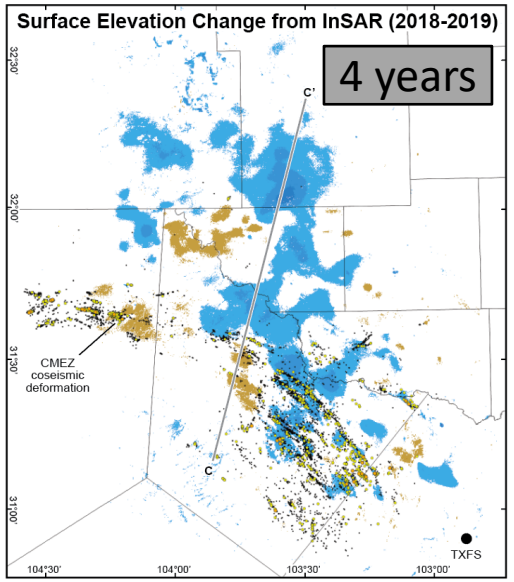


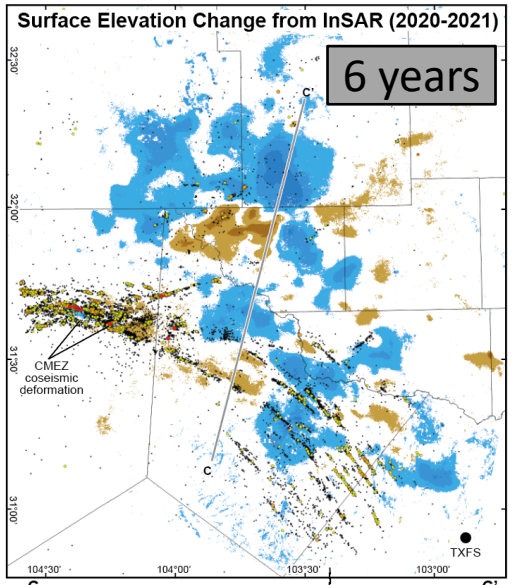
2-year cumulative InSAR surface elevation change

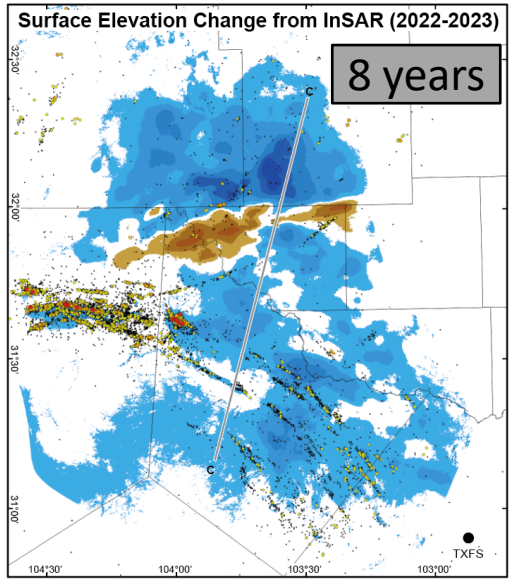


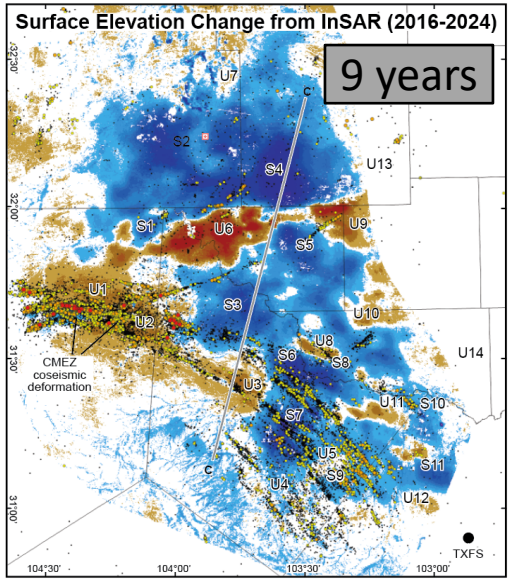


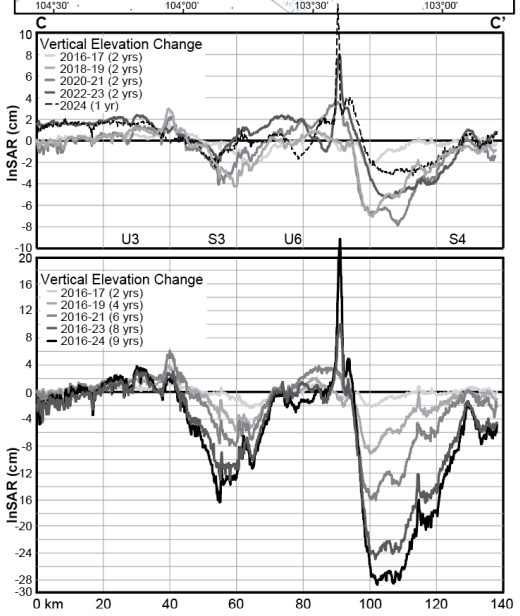








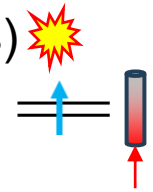




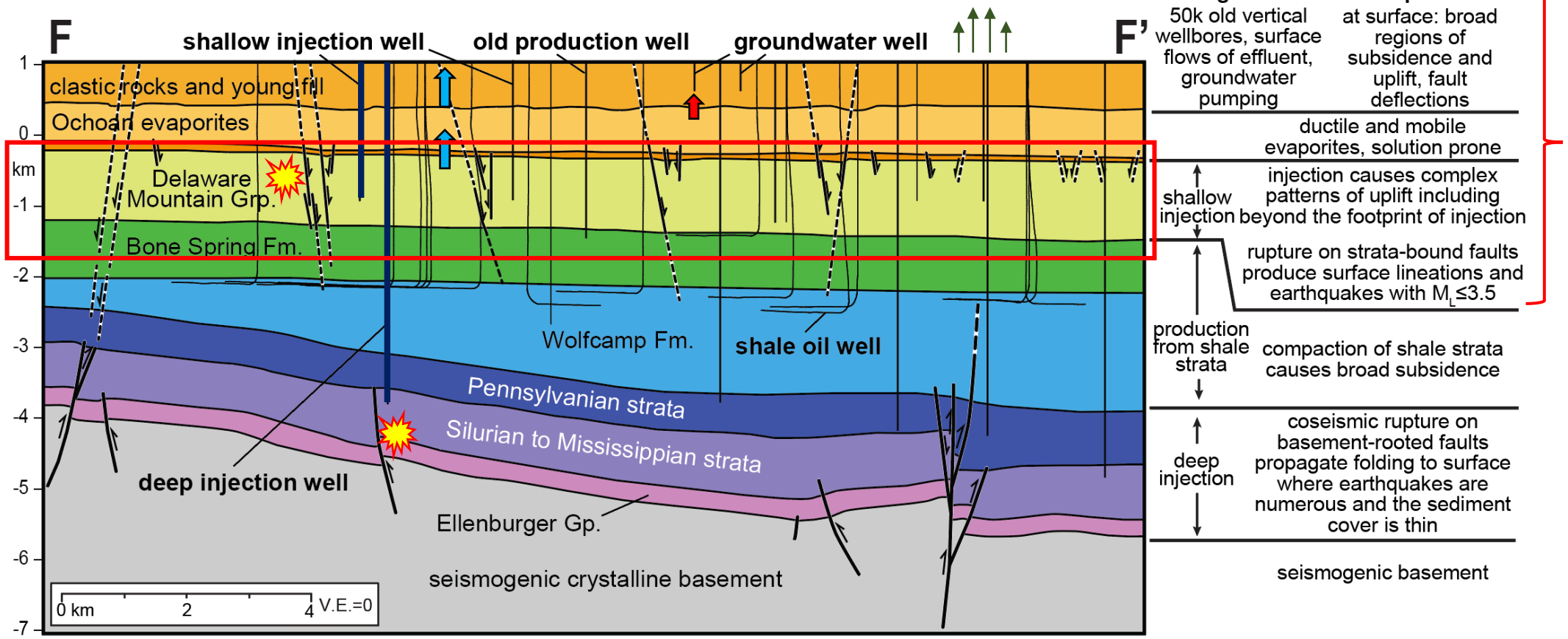
Hennings et al., 2025

Risks Related to Injection: Basement to Surface

1. Seismicity (D&S EQs)
2. Loss of Containment



- *Breached Caprock*
- *Freshwater aquifers*
- *Legacy oil wells*
- *Water wells*
- *Surface Deformation*

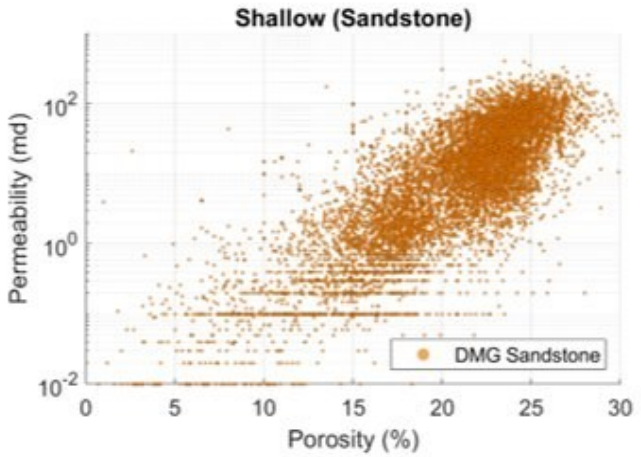


After Hennings et al. 2025

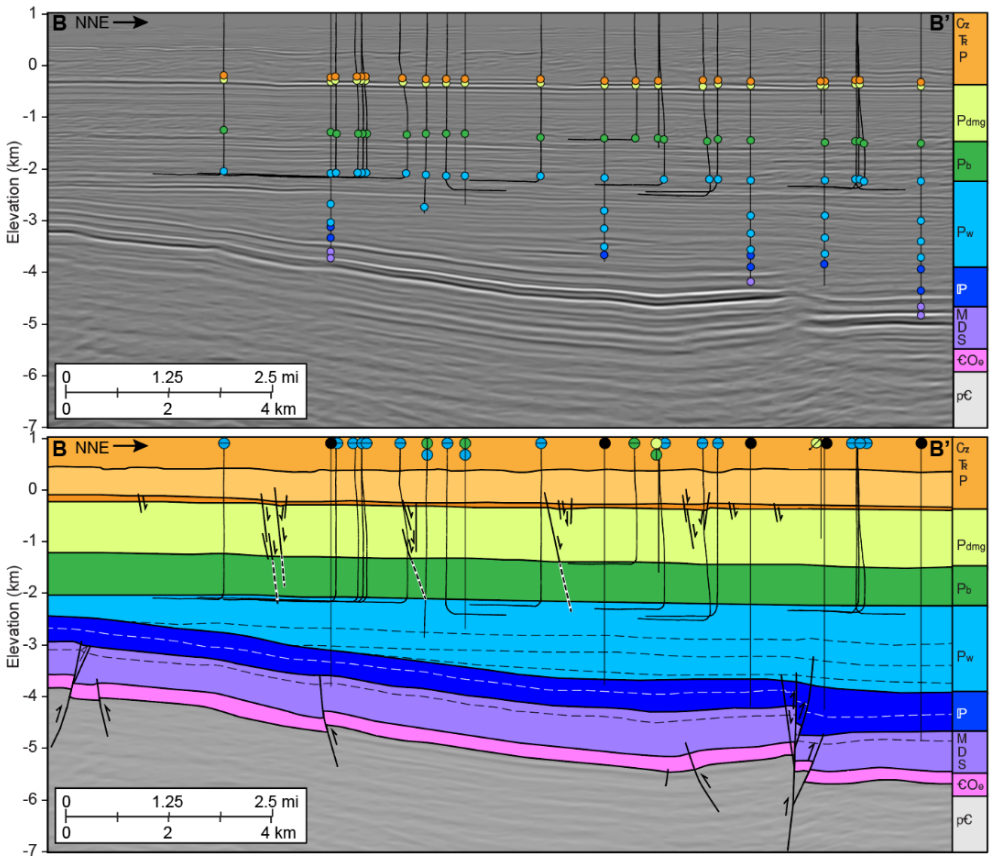
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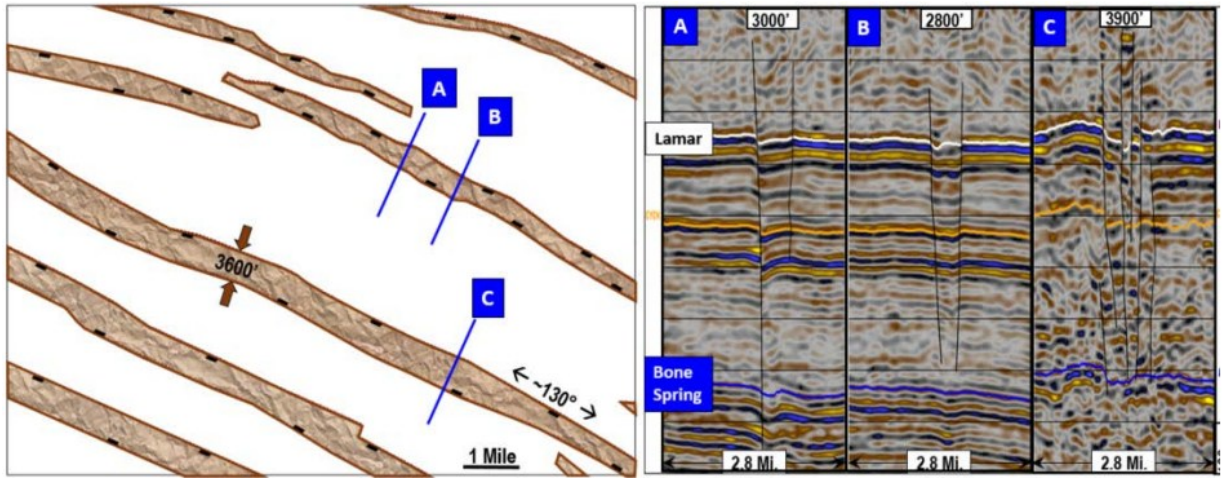
Delaware Basin DMG Shallow Injection Zone Overview

DB DMG Shallow Zone:
Deepwater sandstones with minor carbonates and siltstones, good matrix porosity and permeability, deformed by strata-bound normal faults, likely hydraulically-fractured during injection
(Smye et al. 2021)



Central Delaware Basin:
Shallow, strata-bound normal faults & oblique, segmented fault zones & inversion basement structures



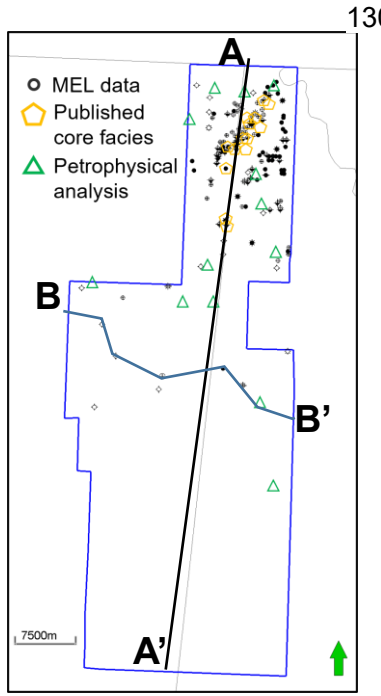


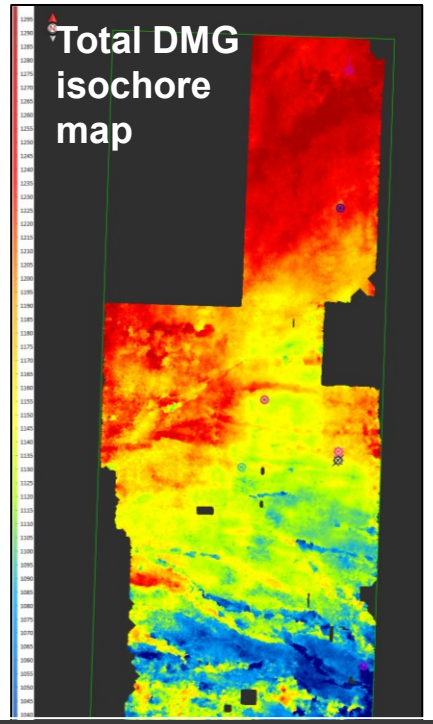
Charzynski et al. (2019)

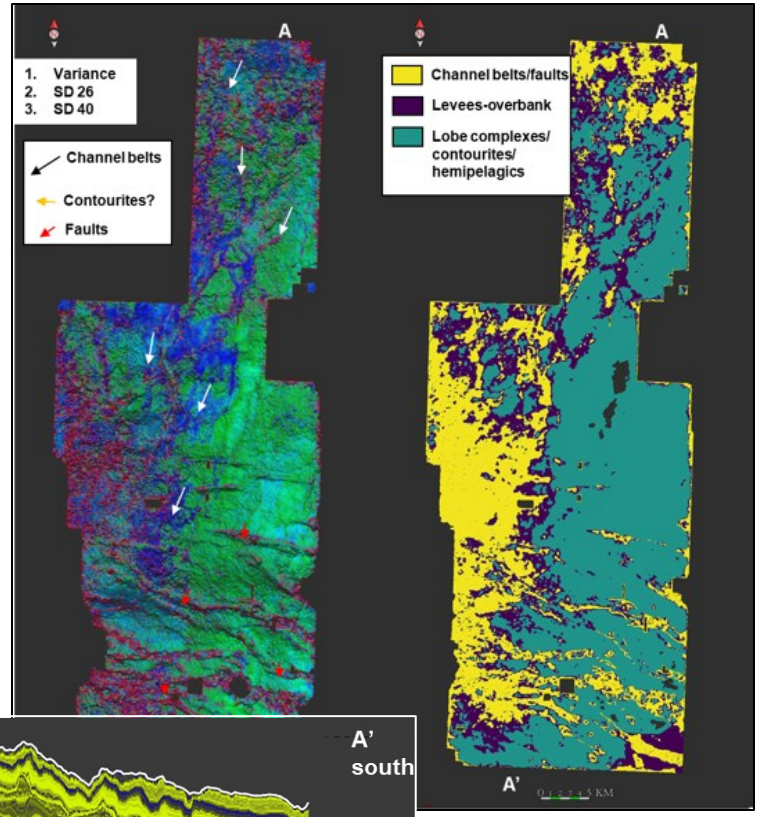
Horne et al. (2021, 2022, 2025)

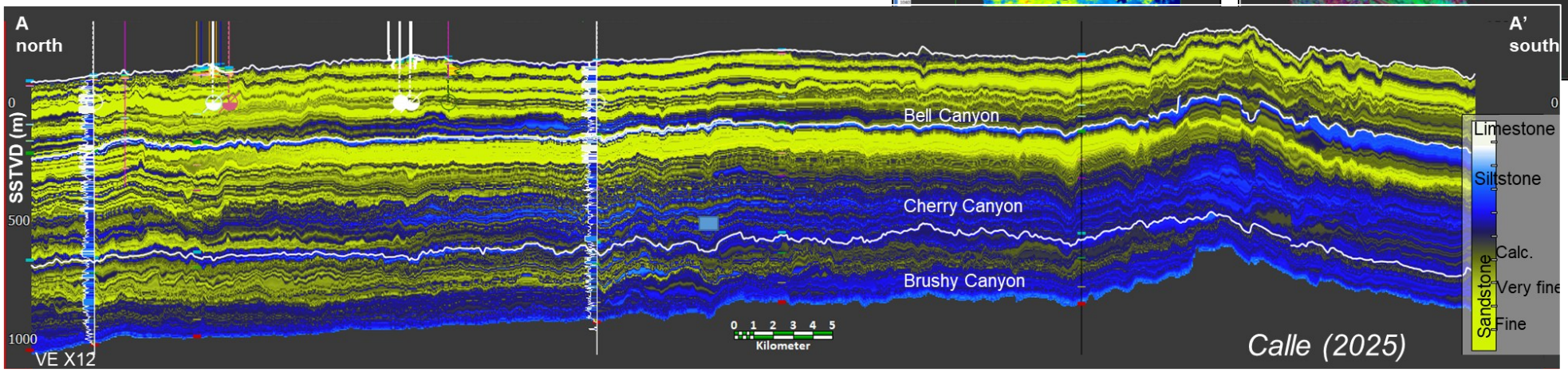
Lithofacies Distributions from Petrophysical Core Facies

- Overall DMG southward sand dispersal
- Thicker sandstone in CYCN-BLCN
- Tracking of avulsion record of basin floor fans
  - Channel belts
  - Lobe systems

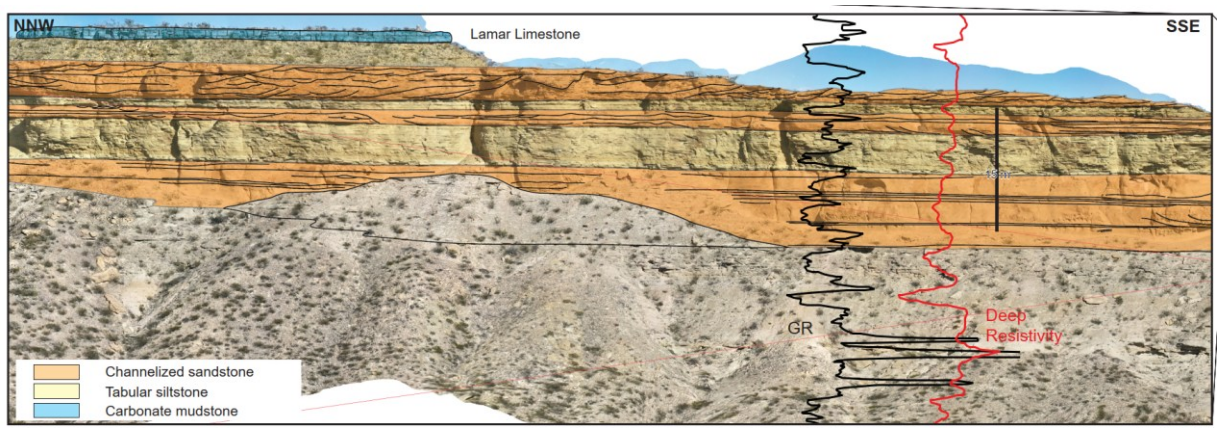




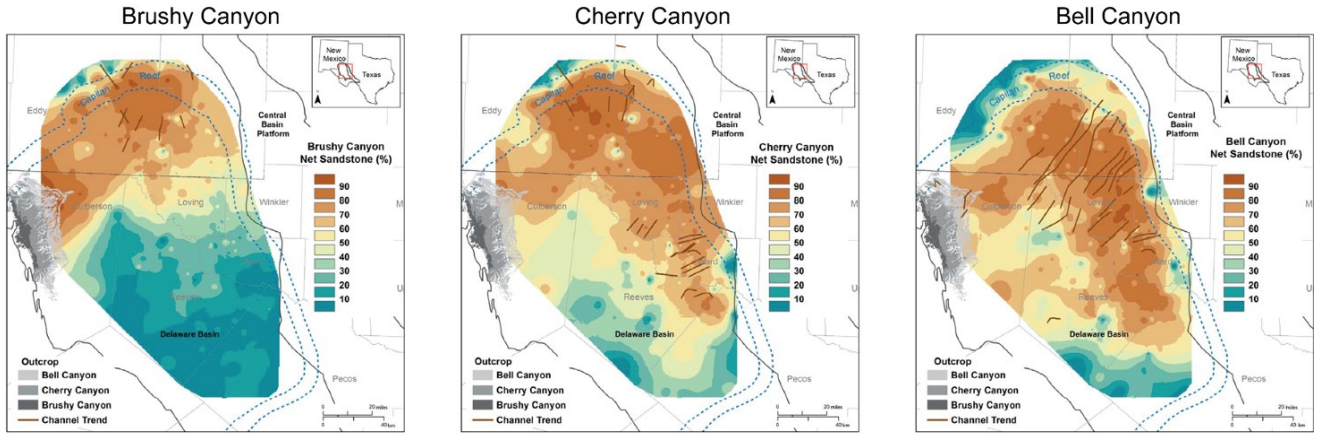




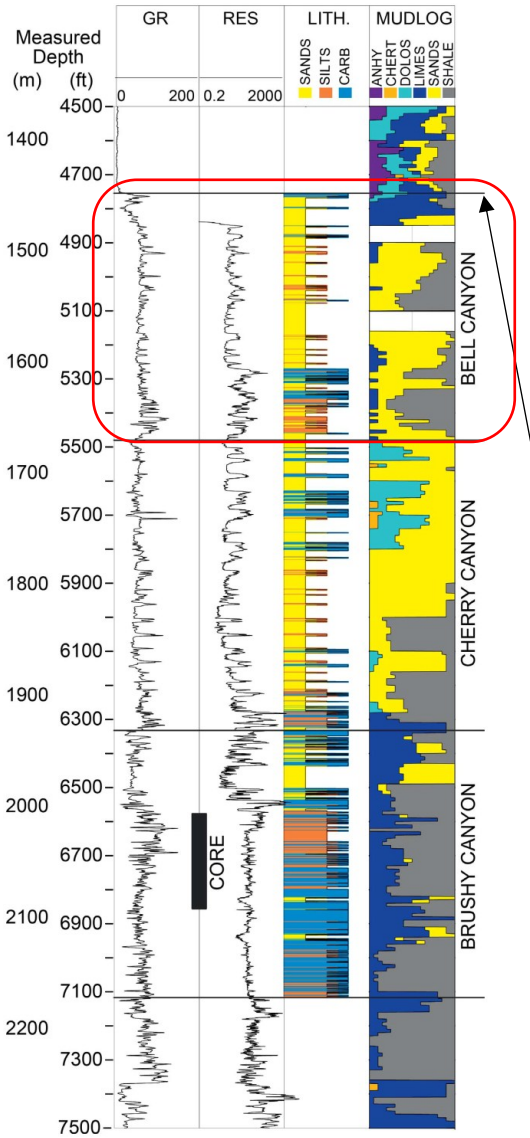
DMG Injection Zone Stratigraphy



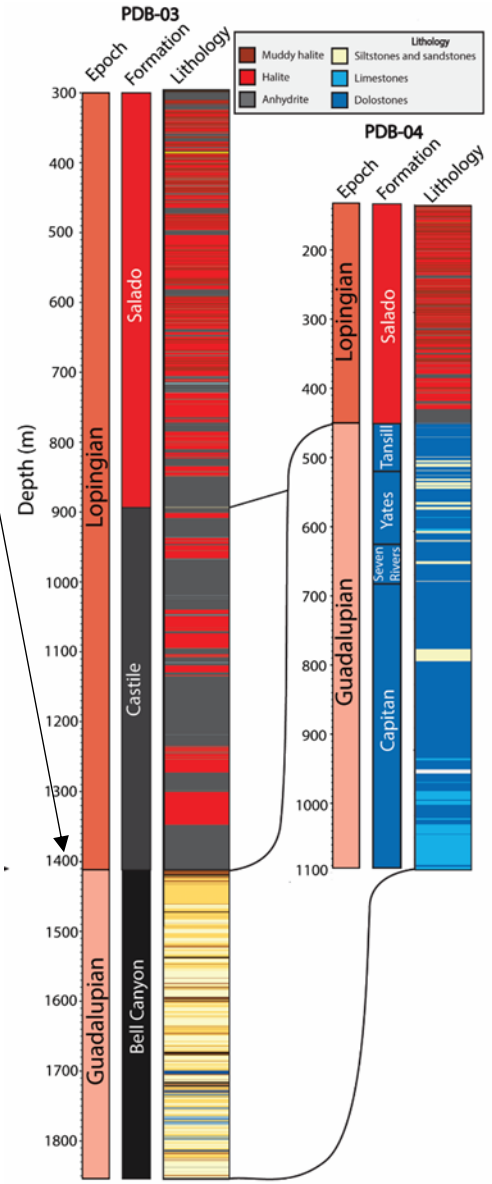
Calle et al. (2025)



Smye et al. (2021)

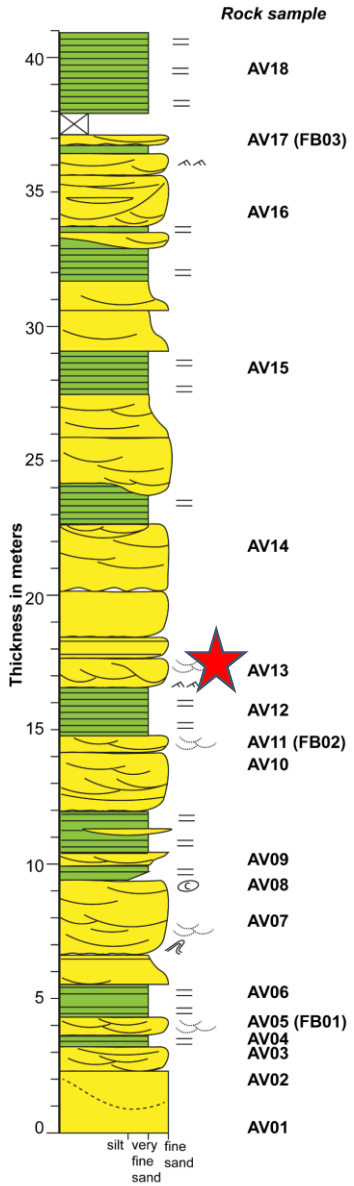


Smye et al. (2021)



Martinez-Doñate et al. (2025)

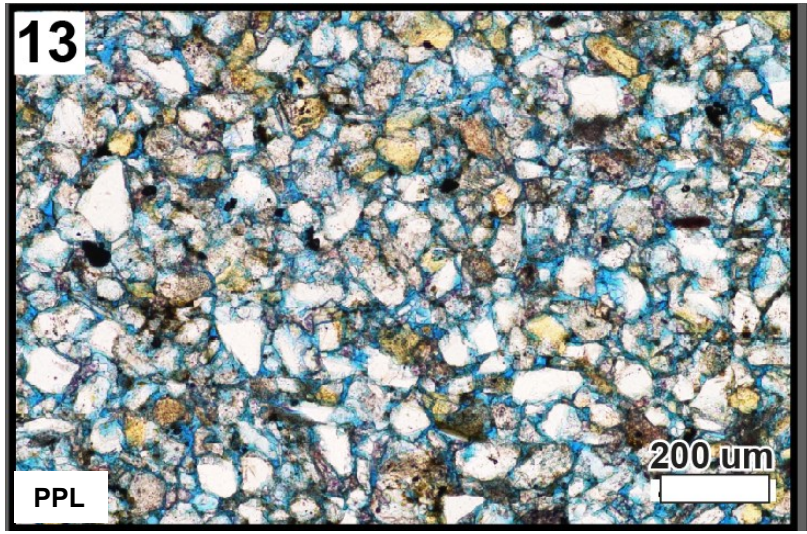
Bell Canyon Sedimentary Facies (Preliminary)

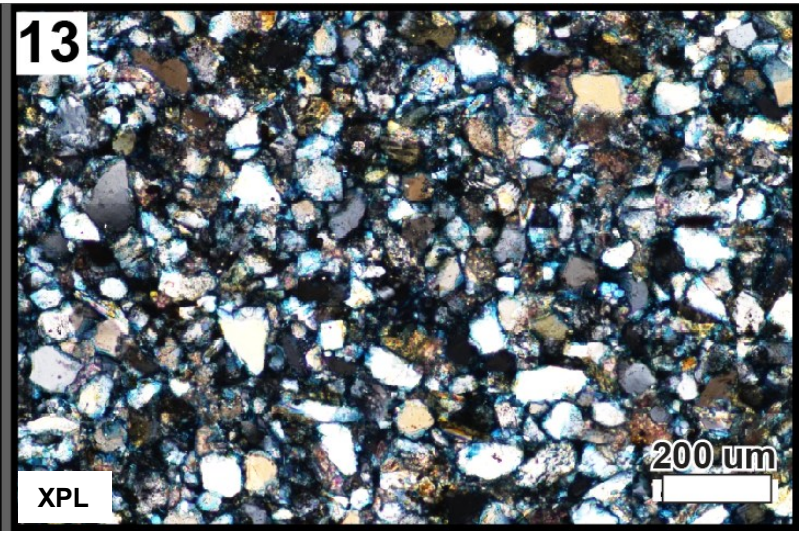


Structureless, thick-bedded sandstone



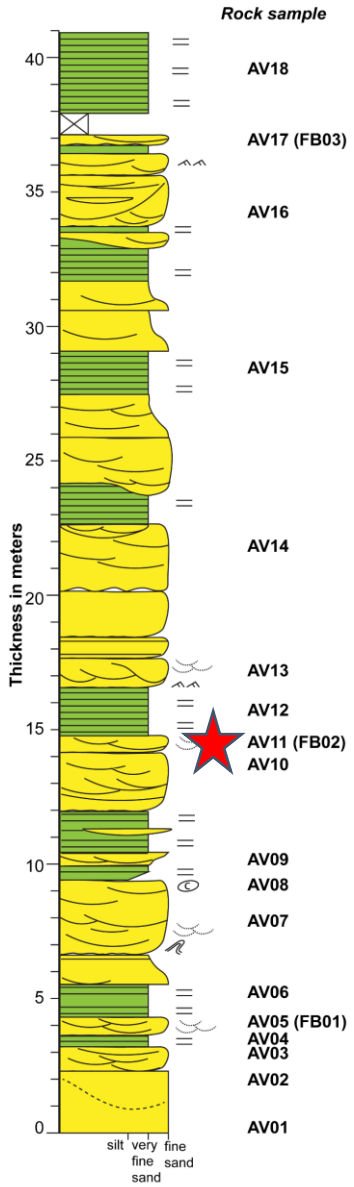
Texture	Fine to very fine-grained sandstone
	Moderately to well sorted
Composition	Quartzarenite to subarkose. Variable content of calcite cement
Thickness	0.2-1.6 m beds
Sedimentary structures	Subtle soft-sediment deformation at bases, faint trough cross-beds and elongated calcareous concretions.
Lateral continuity	>20 m. Internally beds are amalgamated and present 0.2-1.6 m erosional surfaces.





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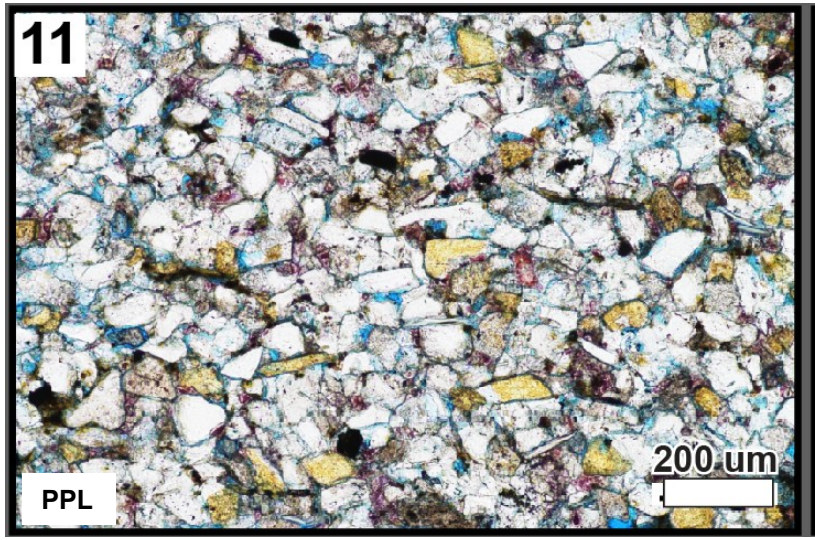
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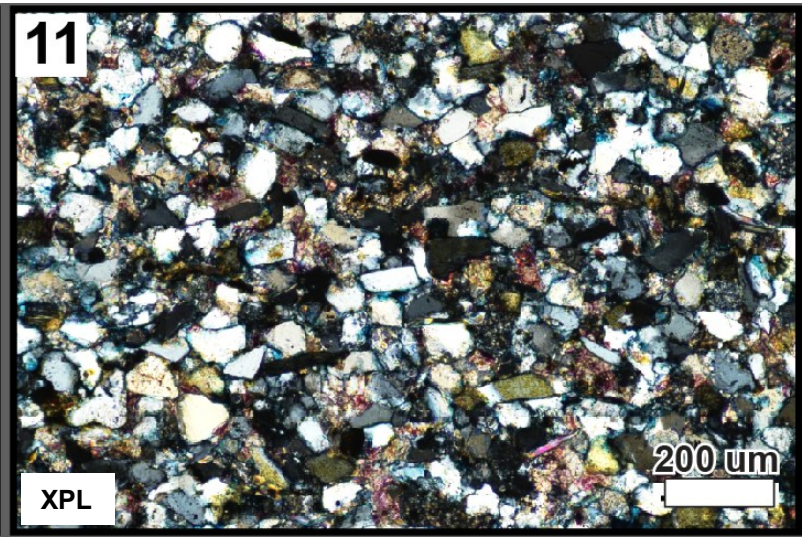


Lenticular sandstone



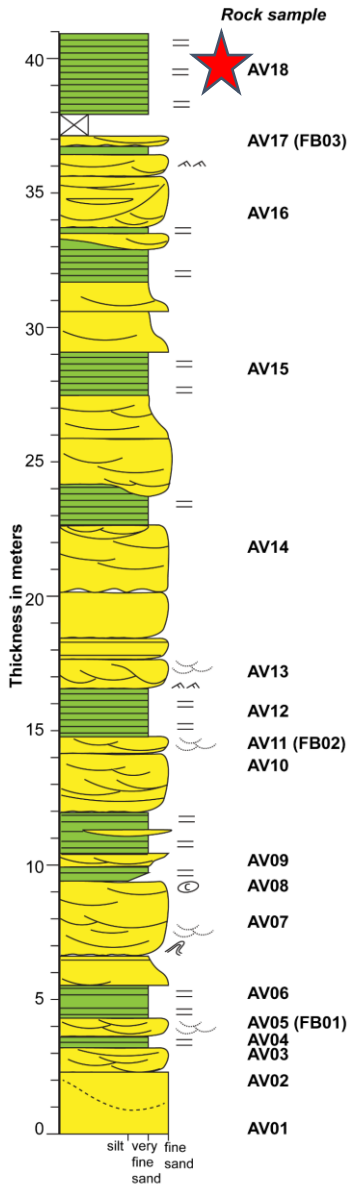
Texture	Fine-grained sandstone
	Moderately sorted
Composition	Quartzarenite to subarkose. Moderately to significant calcite cement. Variable organic matter content.
Thickness	0.2- 0.4 m lenticular beds
Sedimentary structures	Faint trough cross-bedding
Lateral continuity	>100 m



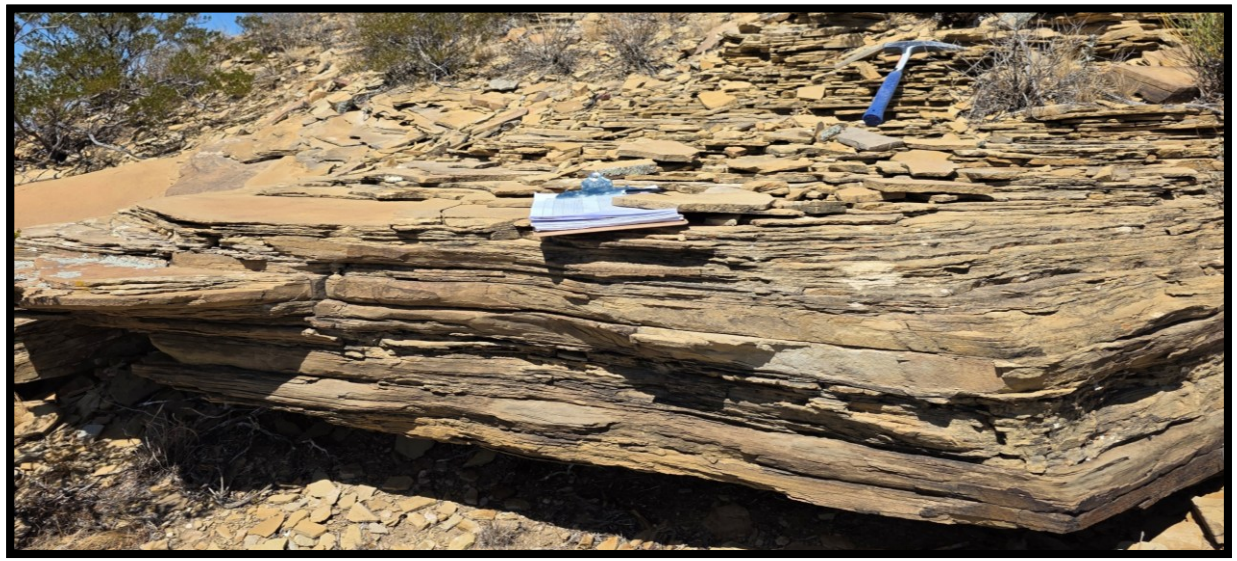


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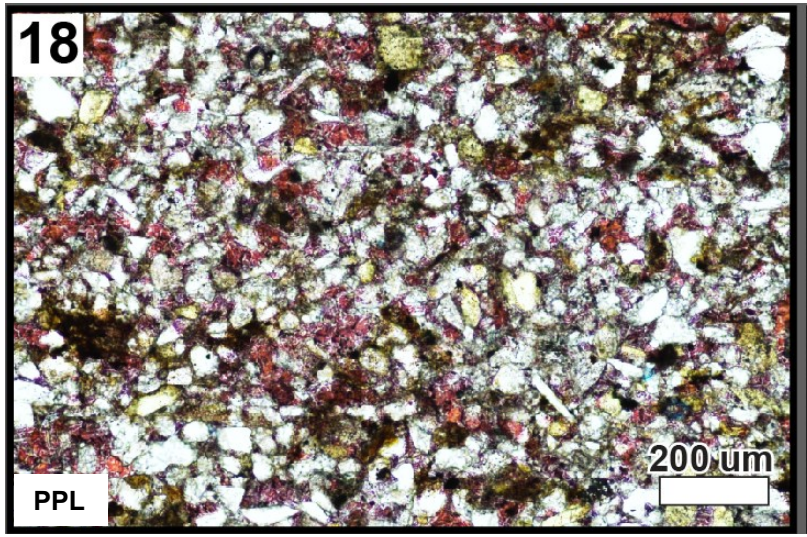
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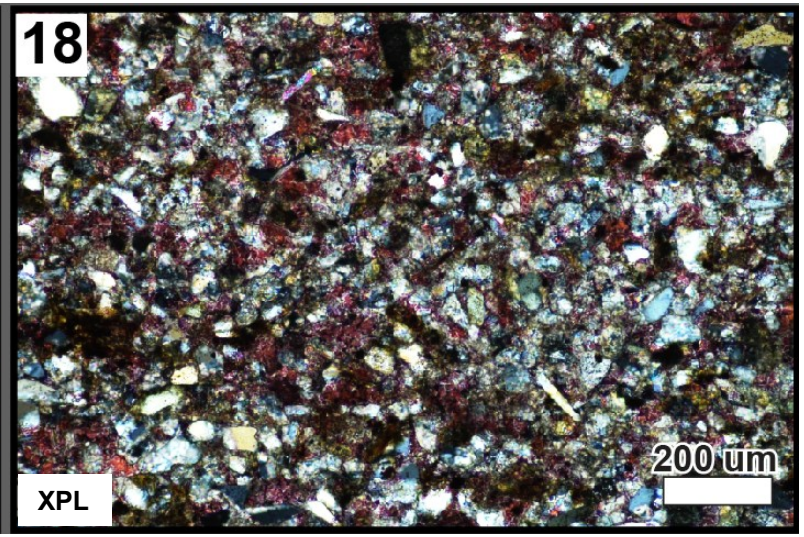


Planar laminated siltstone and sandstone



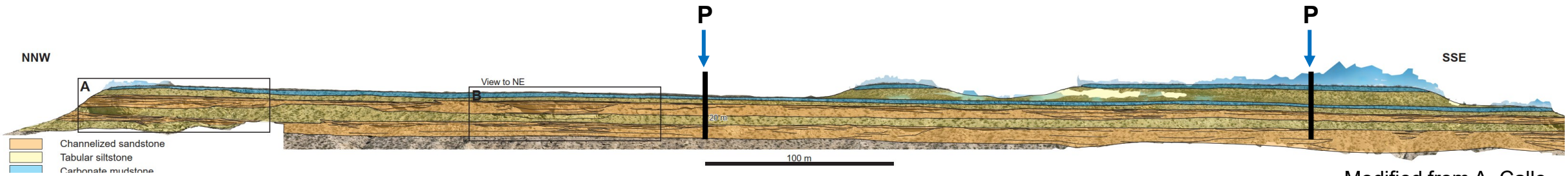
Texture	Very fine-grained sandstone and coarse siltstone
	Moderately sorted
Composition	Litharenite with clay rich matrix and organic matter. Alternating beds with significant calcite cement
Thickness	0.2-2 cm bed
	<8 cm bedsets
Sedimentary structures	Planar lamination
Lateral continuity	>50 m



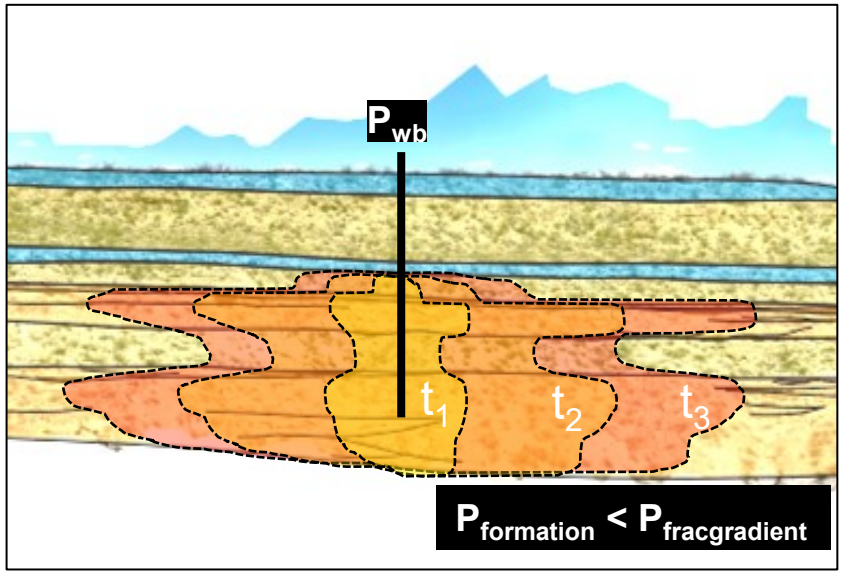


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Idealized Pressure Diffusion in a Layered Reservoir



Modified from A. Calle



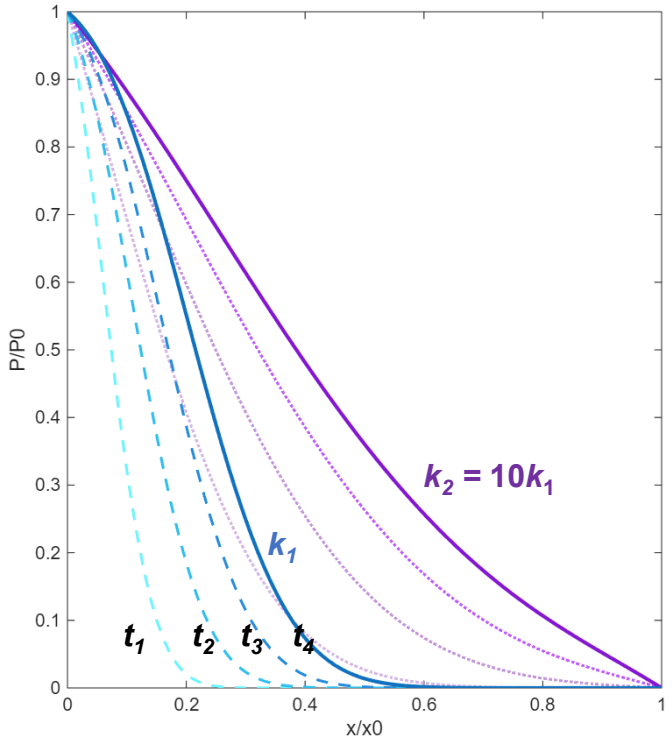
1D Pressure Diffusion:

$$\frac{\partial P}{\partial t} = c\frac{\partial^2 P}{\partial x^2}$$

c = hydraulic diffusivity

$$c = k/\mu S_s$$

k = permeability
μ = dynamic viscosity
S_s = specific storage

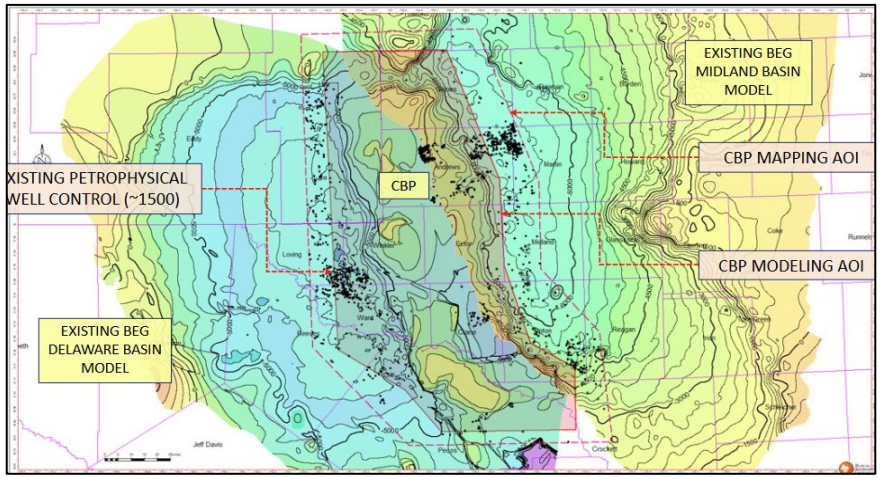


**Permitting Note - Texas RRC 6/2025:*

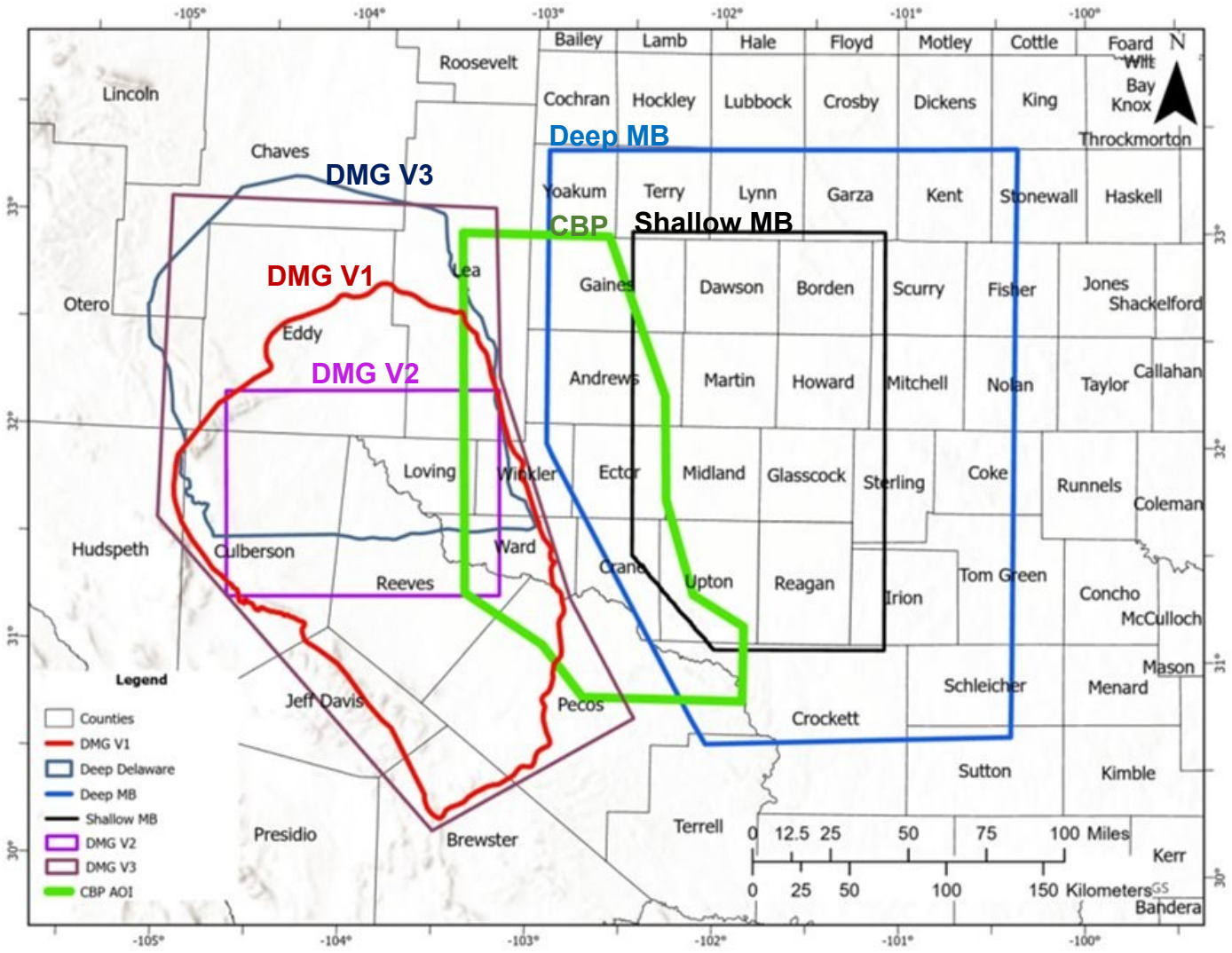
- *AOR frac gradient limit 0.25 → 0.5 mi*
- *2-mile legacy well buffer*

CISR Regional Reservoir Simulation Models

- Synthesize regional depositional trends and environments from basin-scale mapping, well control, and seismic attribute data.
- Combine core- and log-derived porosity and permeability data with injectivity permeability, compressibility, shut-in, etc. data to build robust dynamic simulation models.
- 3D static and dynamic models used for pressure evolution, injection capacity, and risking decisions.

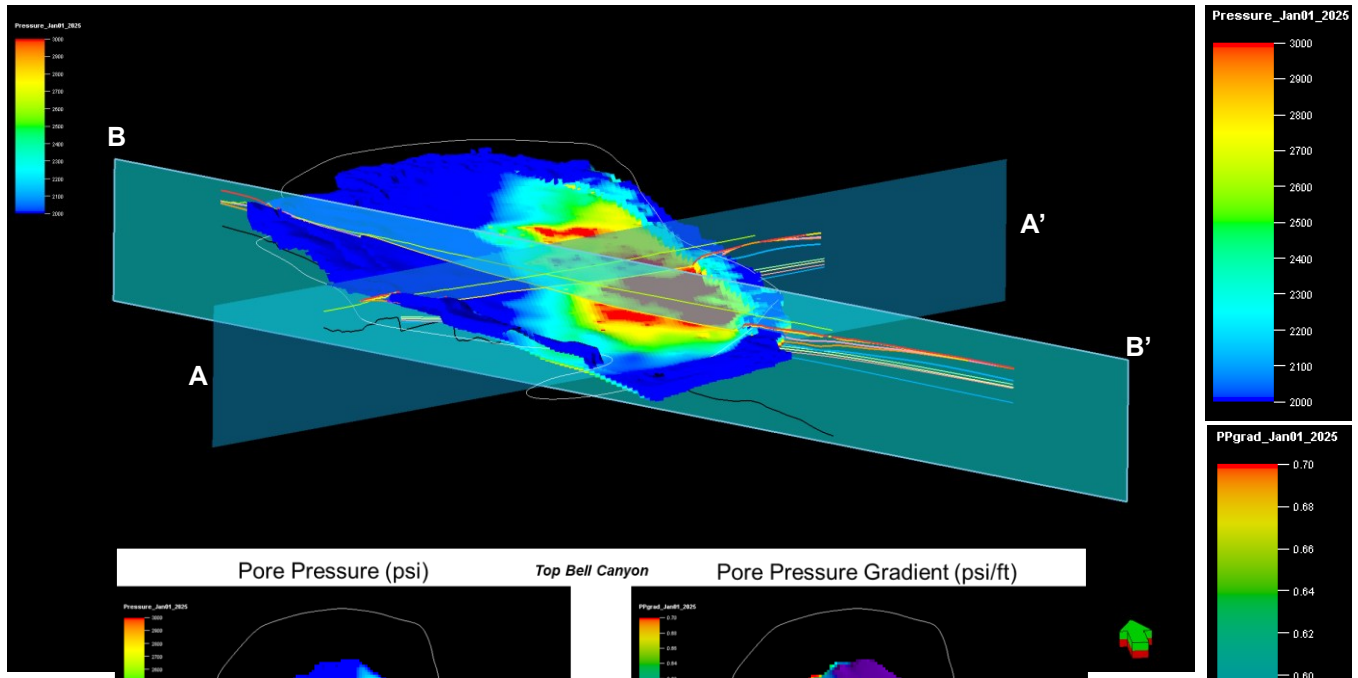


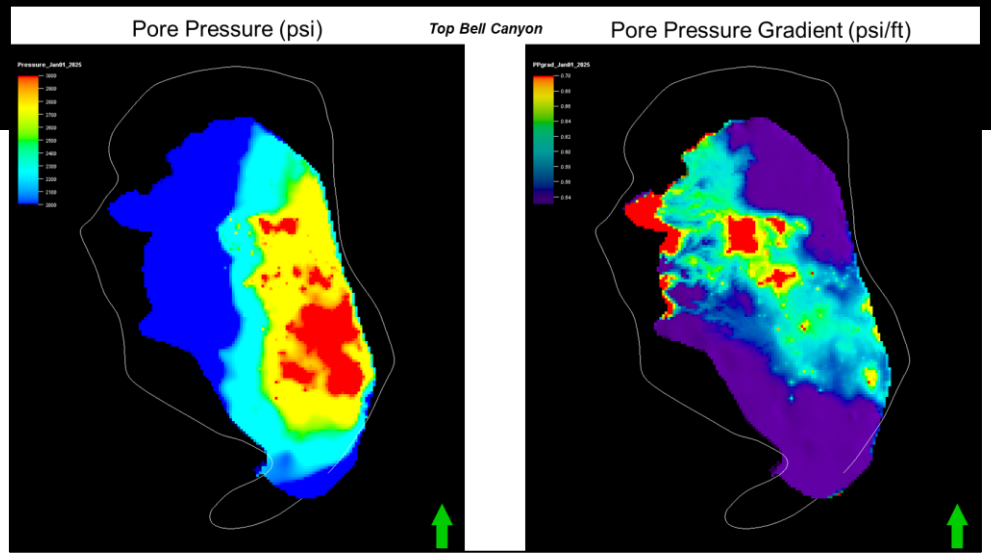
Hoffman (2026)



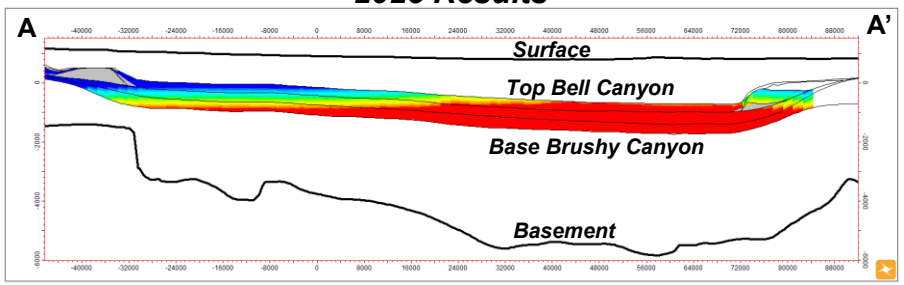
Regional Reservoir Simulation Models – DMG V1

V1 Model – Full Delaware Basin

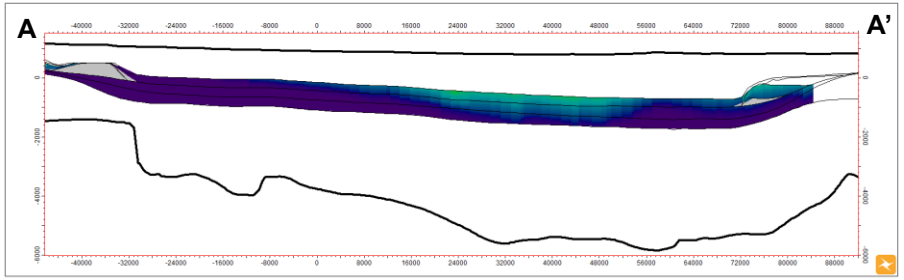




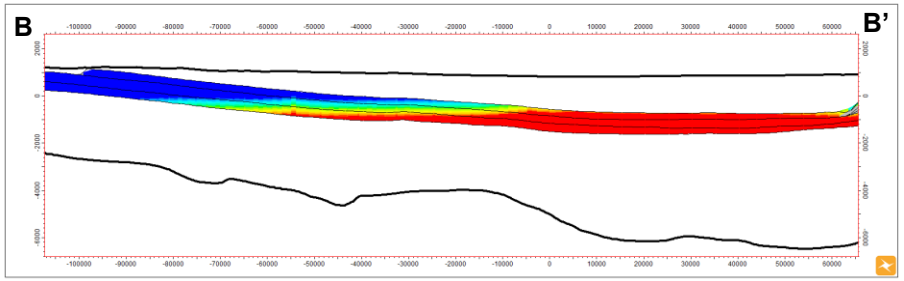
2025 Results



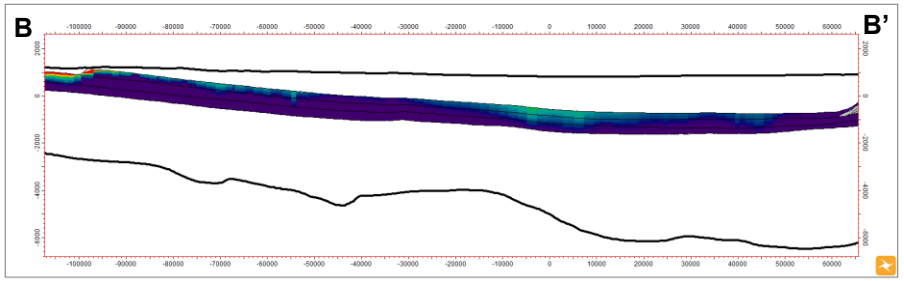
PP



PPgrad



PP



PPgrad

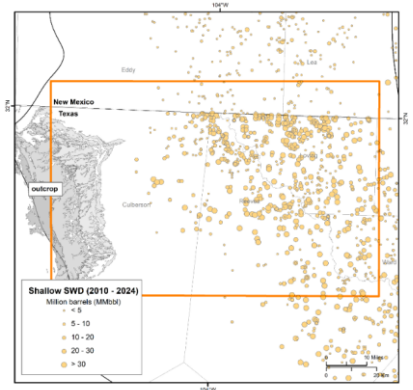
Vertical Exaggeration = 5x

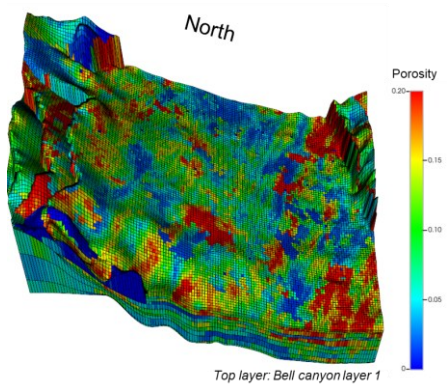
Regional Reservoir Simulation Models – DMG V2

V2 Delaware Basin DMG:

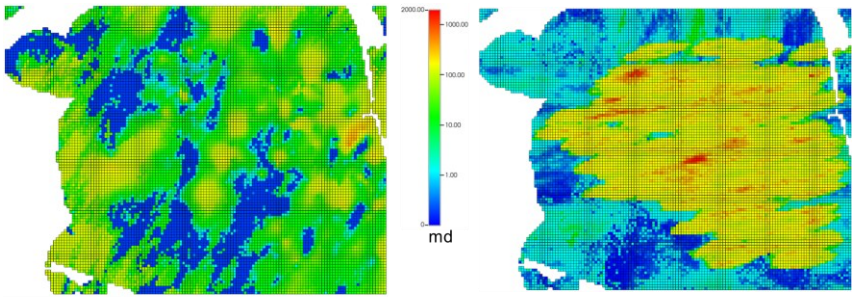
- Model dimensions: 69.8 mi × 90.5 mi (142 × 107 cells)
- Grid cell dimensions: 3280.84 ft × 3280.84 ft (1 km × 1 km)
- Cell thickness up to 509 ft with average ~300 ft
- Active cells: 143,159

Multiple Model Updates: Geology and Engineering Inputs





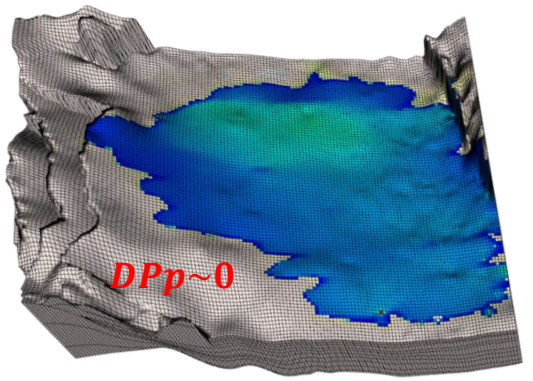
Top layer: Bell canyon layer 1



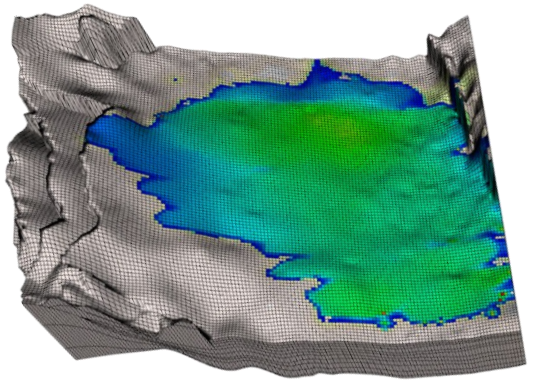
Annual Review 2024
(based mostly on facies distribution)

Q1 2025
(complex combination of injectivity and well log permeabilities

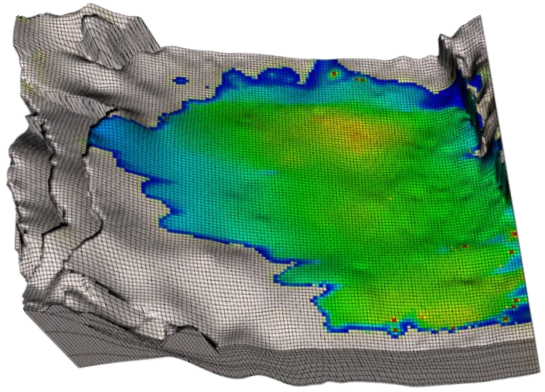
Pore pressure change 2022.1-2025.1

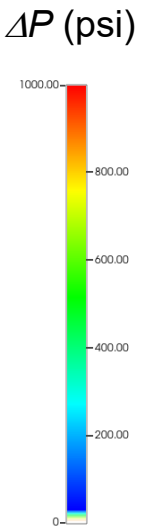


Pore pressure change 2019.1-2025.1



Pore pressure change 1983.1-2025.1



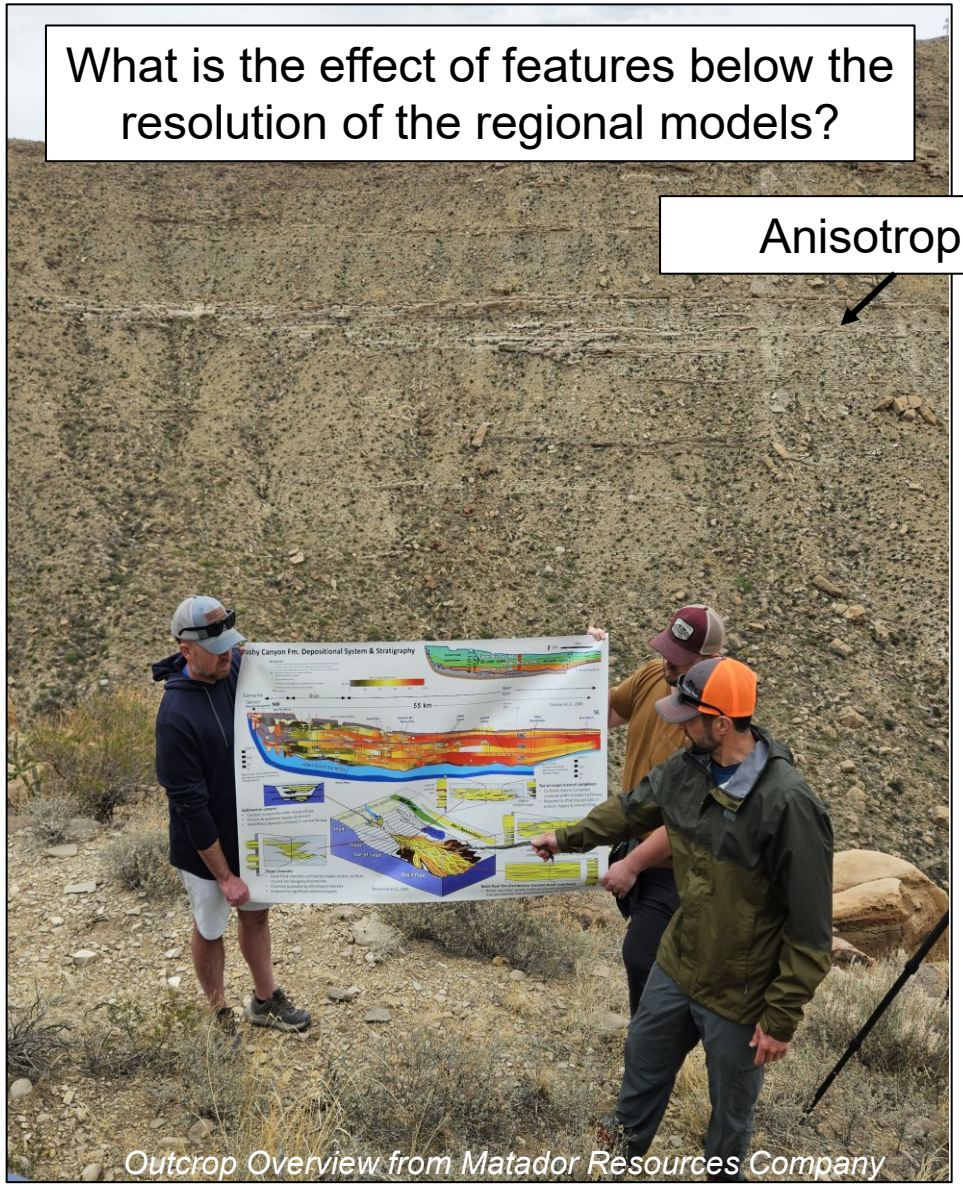




Smye et al., 2025

DMG Stratigraphy and Faults – Brushy Canyon Outcrops

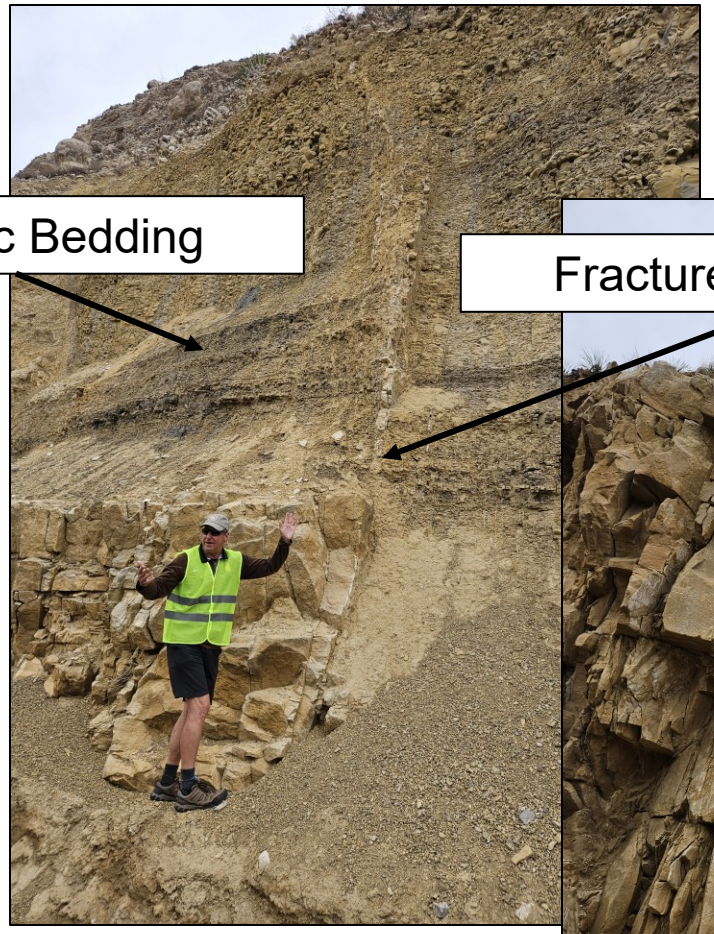
What is the effect of features below the resolution of the regional models?



Outcrop Overview from Matador Resources Company

2026 CISR Field Trip

Anisotropic Bedding



Fractures and Faults



Photos: S. Busetti

SWD and 1D Transport, Advection/Convection and Diffusion

1D Advection-Diffusion Equation:

$$\frac{\partial u}{\partial t} = d\frac{\partial^2 u}{\partial x^2} - v\frac{\partial u}{\partial x}$$

Solute Diffusivity and Advection:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x}$$

D = diffusion coefficient
v = advection velocity

Thermal Diffusivity and Convection:

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2} - v\frac{\partial T}{\partial x}$$

$$\alpha = \frac{k}{\rho C_p}$$

α = thermal diffusivity
v = advection velocity
k = thermal conductivity
C_p = specific heat
ρ = density

Pressure Diffusivity:

$$\frac{\partial P}{\partial t} = c\frac{\partial^2 P}{\partial x^2}$$

c = pressure diffusion coefficient

Matrix (Darcy's Law):

$$q = -\frac{Ak}{\mu}\nabla p$$

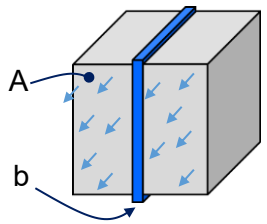
A = cross sectional area
q = volumetric flux
k = permeability
μ = viscosity
∇p = pressure drop

Fracture (Cubic Law):

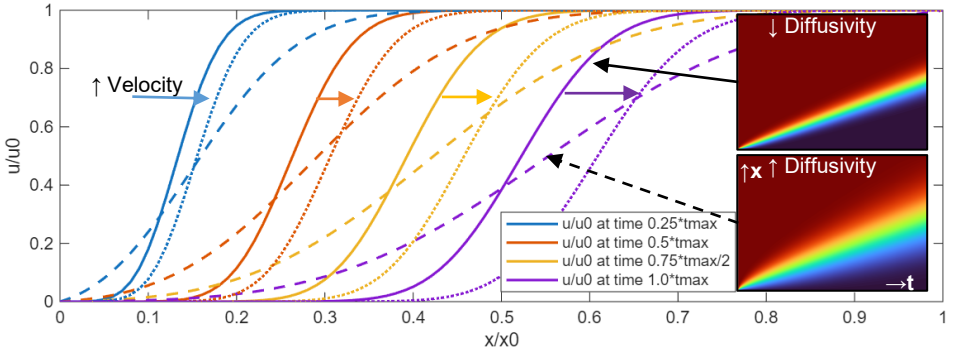
$$k_f = \frac{b^2}{12}$$

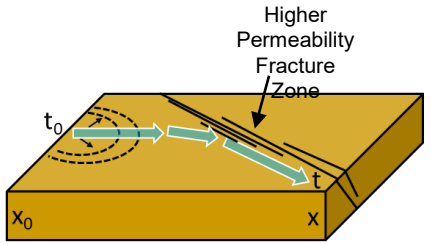
$$q = -\frac{b^3}{12\mu}\nabla p$$

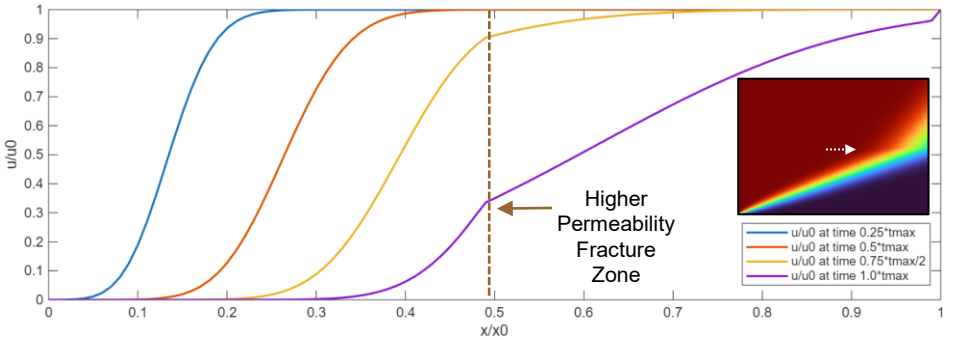
b = aperture
k_f = fracture permeability
μ = viscosity
∇p = pressure drop

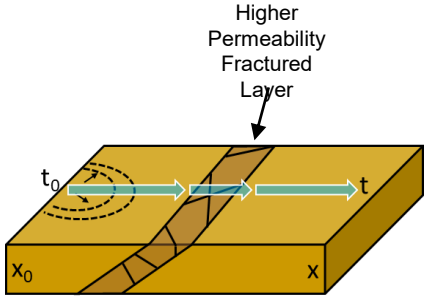


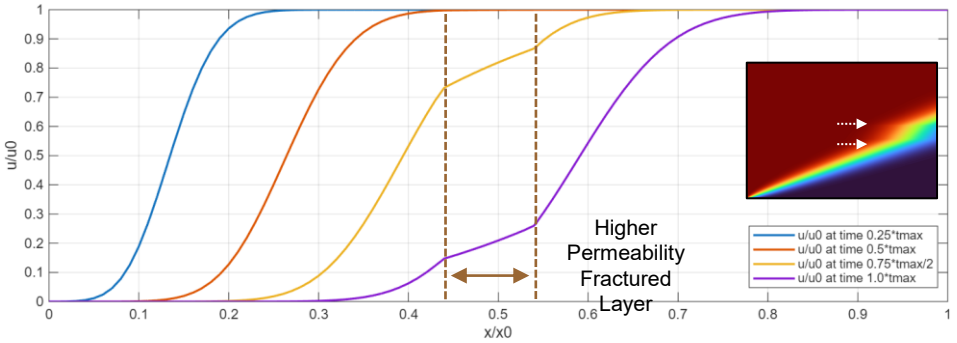








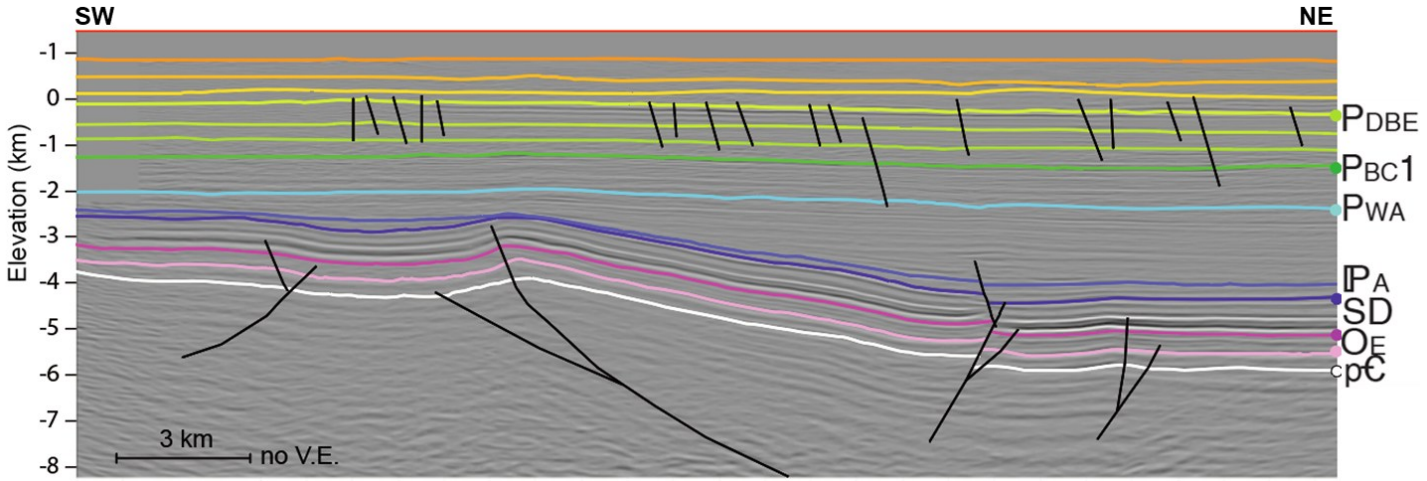


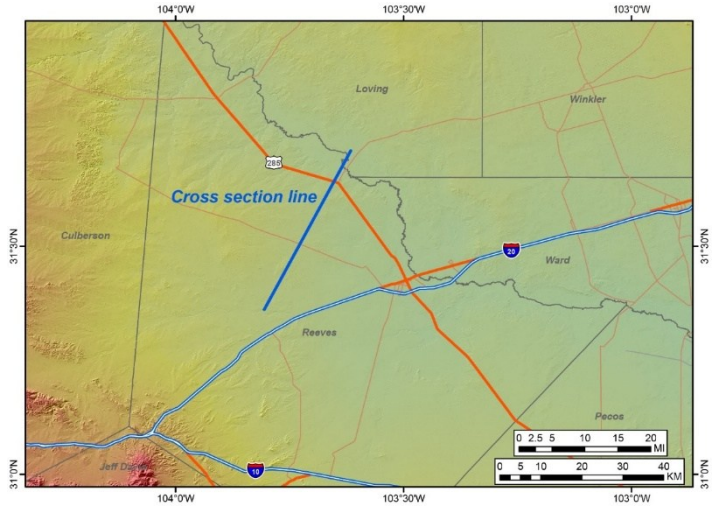


Bureau of Economic Geology CISR

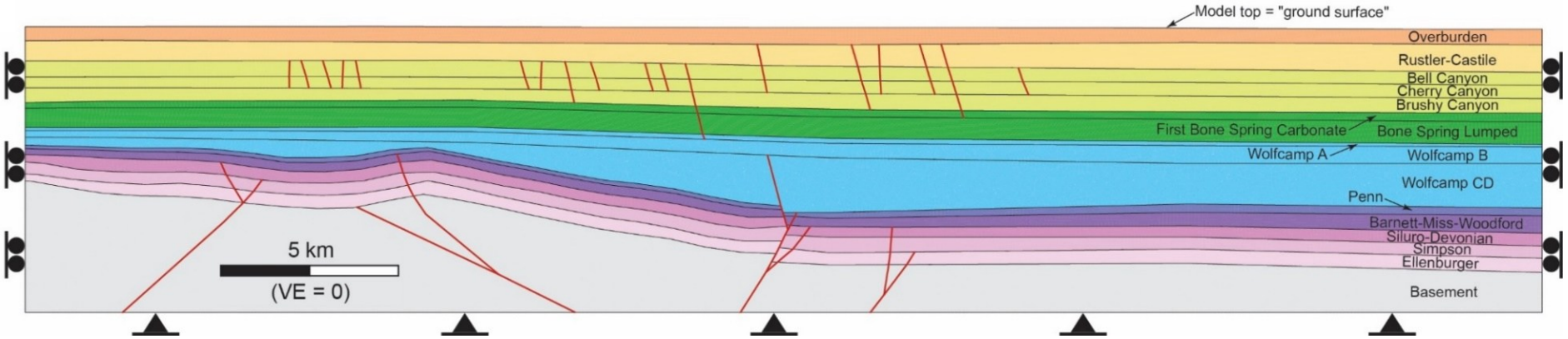
DB 2D FEM Model (After Smart et al. 2023)

- **Representative 2D seismic section as a <u>flexible FE laboratory</u> to test injection scenarios**





Seismic section by E. Horne



Base 2D FE model by K. Smart

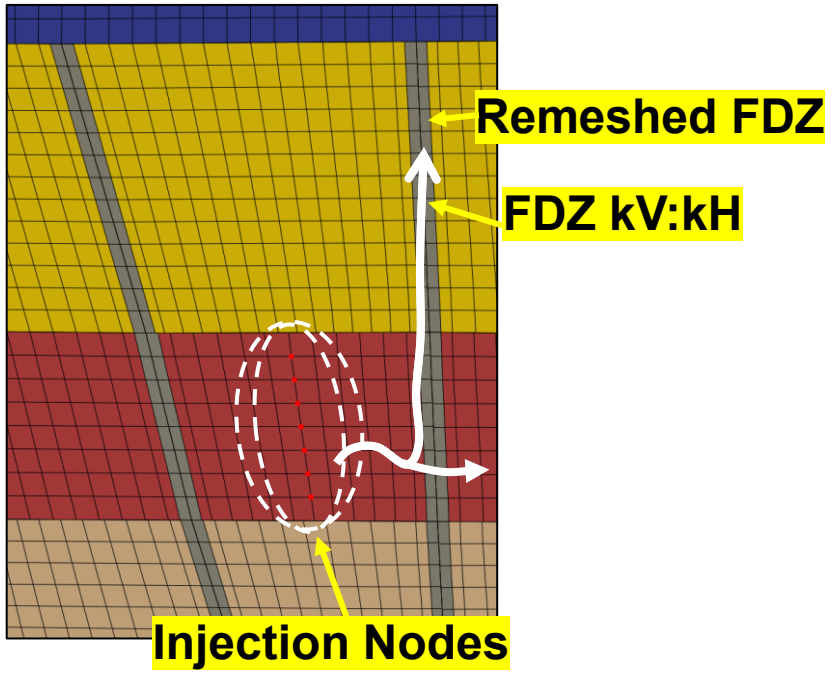
Model Modifications and Test Scenarios

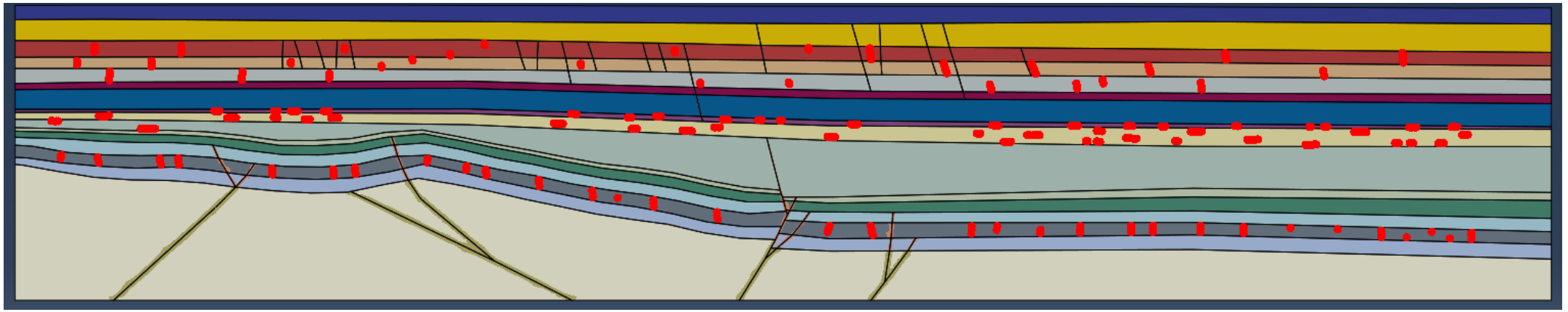
Orthotropic Permeability Modifications

Inj. PP	FDZ Perm.	Inj. Zone Perm.
0.45-0.48 psi/ft by zone 0.66 psi/ft	0.5*k⊦ = k‖	kH:kV = 0.1
	1* k⊦:k‖ = 0.05	kH:kV = 1
	10* k⊦:k‖ = 0.05	kH:kV = 0.1 or 1 (far/close faults)
	100* k⊦:k‖ = 0.05	

	k11	k22	k33	Void Ratio
1	7.25E-12	1.45E-11	1.45E-11	0.010101
2	7.5E-11	1.5E-10	1.5E-10	0.0204082
3	2.95E-10	5.89E-10	5.89E-10	0.0309278
4	7.75E-10	1.55E-09	1.55E-09	0.0416667
5	1.65E-09	3.29E-09	3.29E-09	0.0526316
6	3.05E-09	6.09E-09	6.09E-09	0.0638298

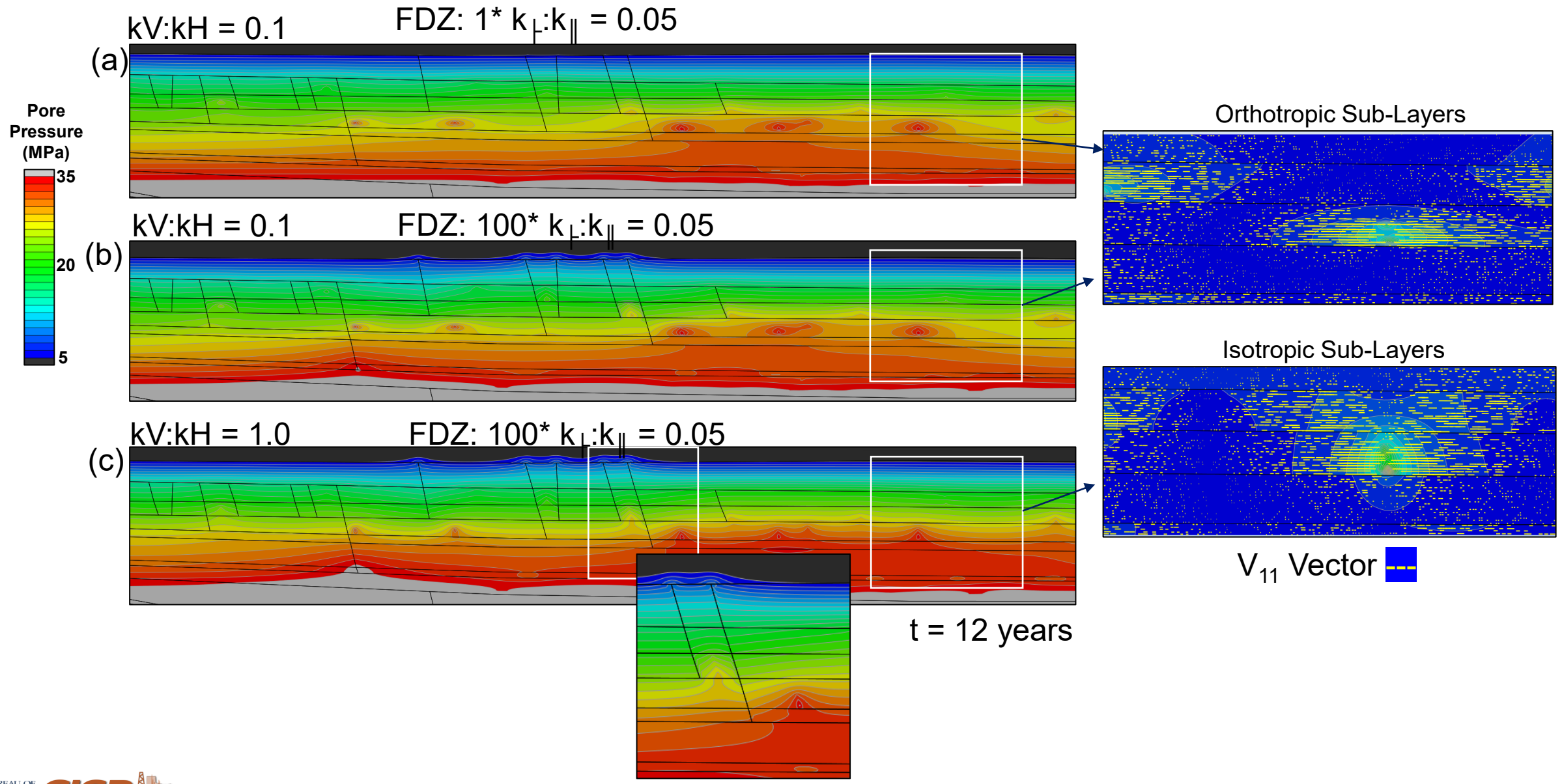
*(*hydraulic conductivity and void ratio)*





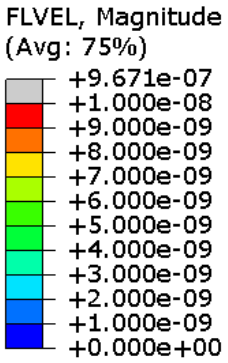
(Injection/Depletion)

Results: Pore Pressure Due to Layering



Results: Fault Flow Restriction/Bypass & PP Profile

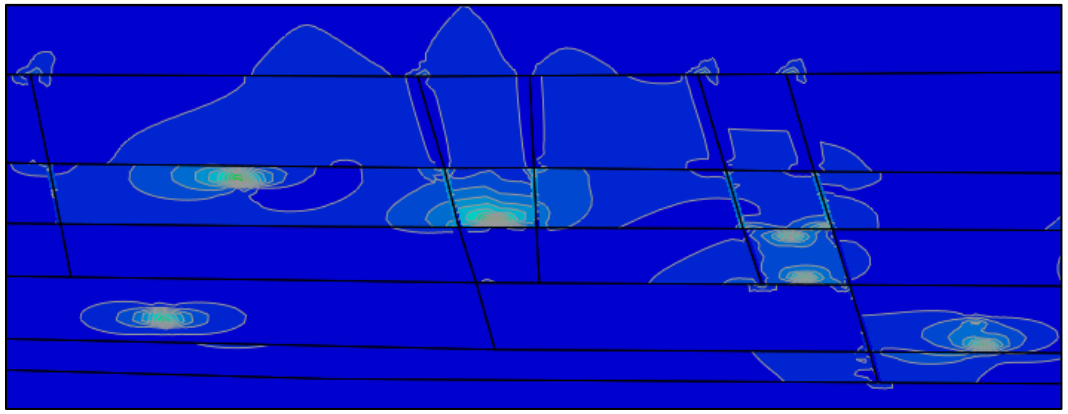
m/s

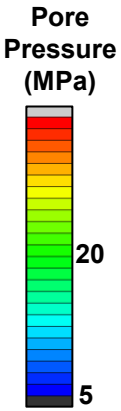


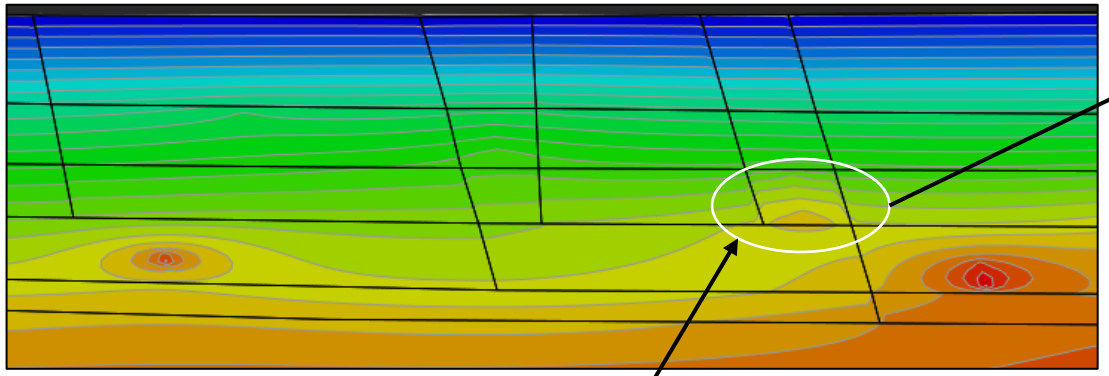
~0.03-0.3 m/yr

kV:kH = 0.1

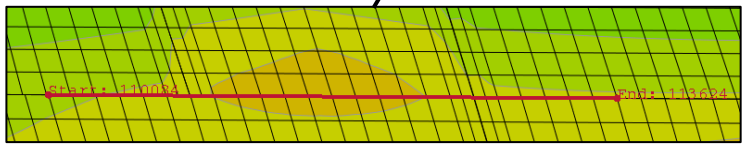
FDZ: 0.5* $k_{\perp}=k_{\parallel}$



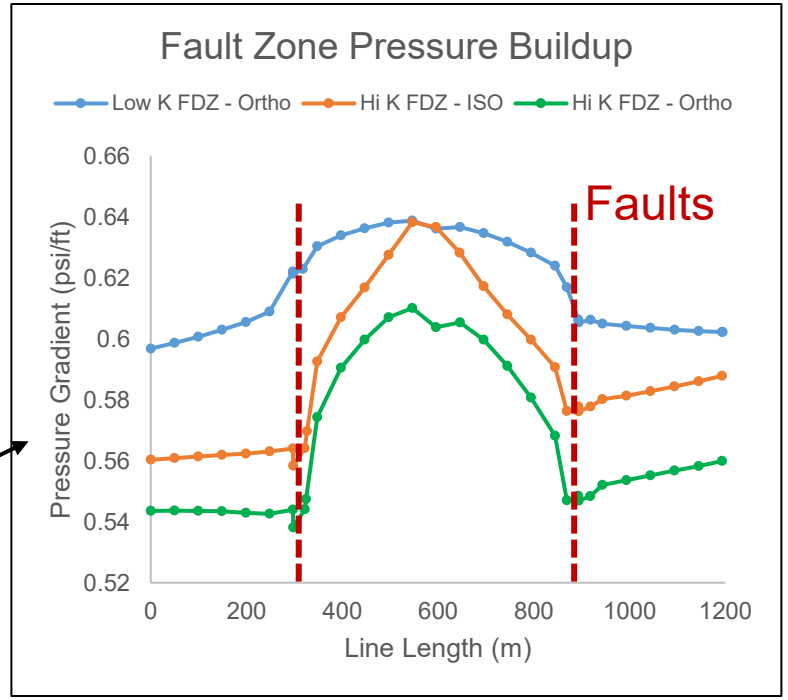




Top Brushy Canyon

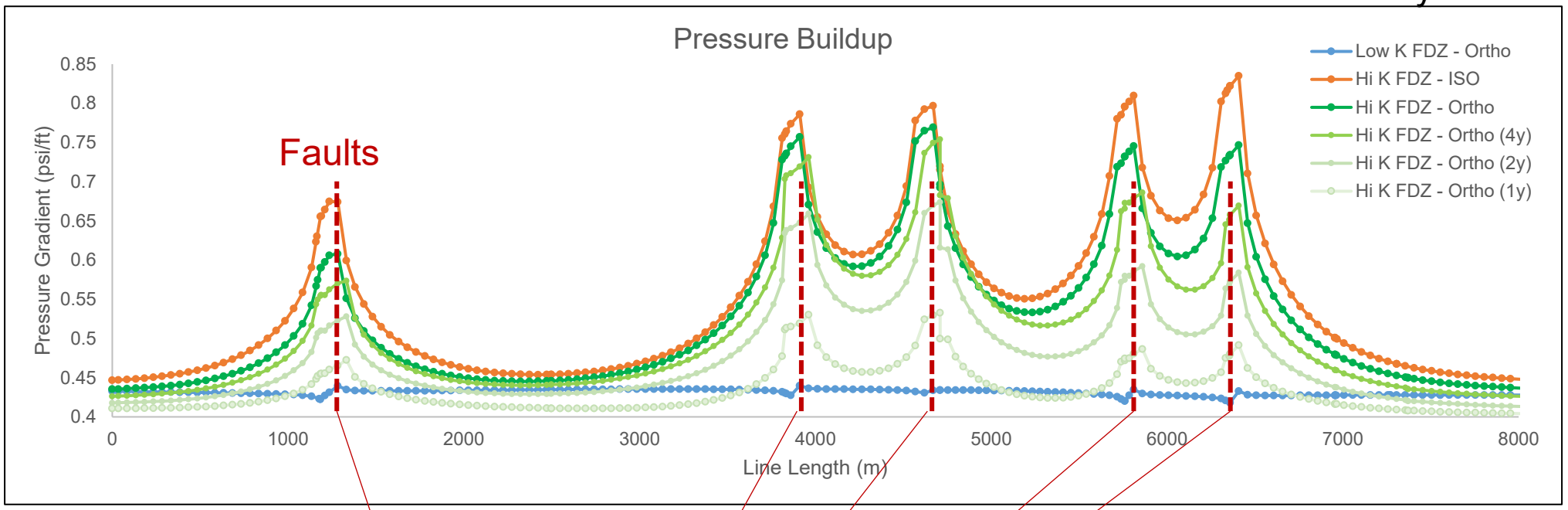


t = 12 years

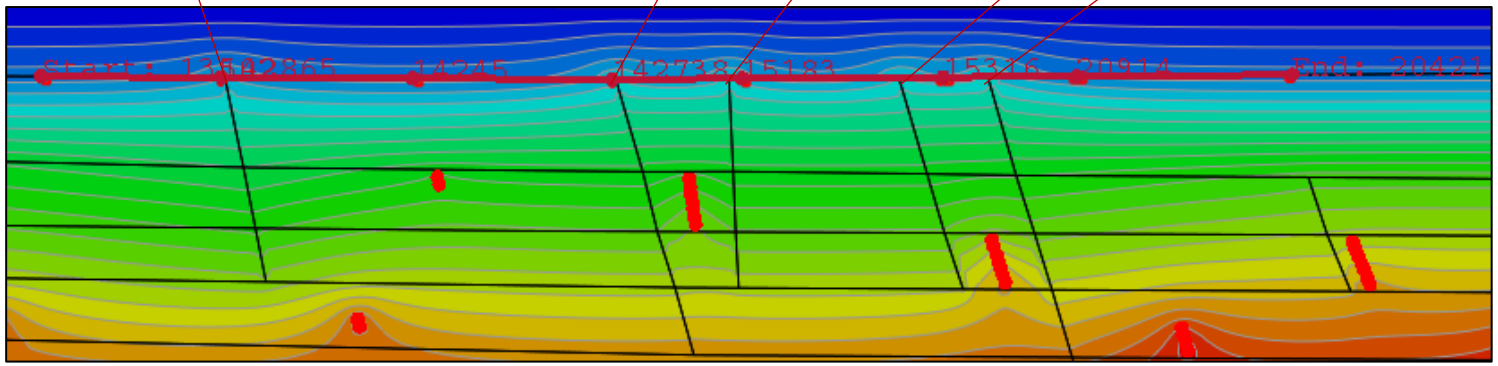


Results: Fault Tip Pressure Migration

t = 12 years



Top Bell Canyon

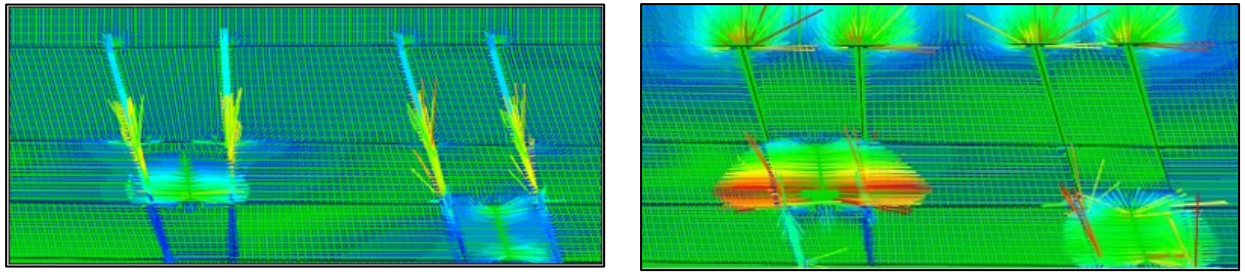


Summary and Next Steps

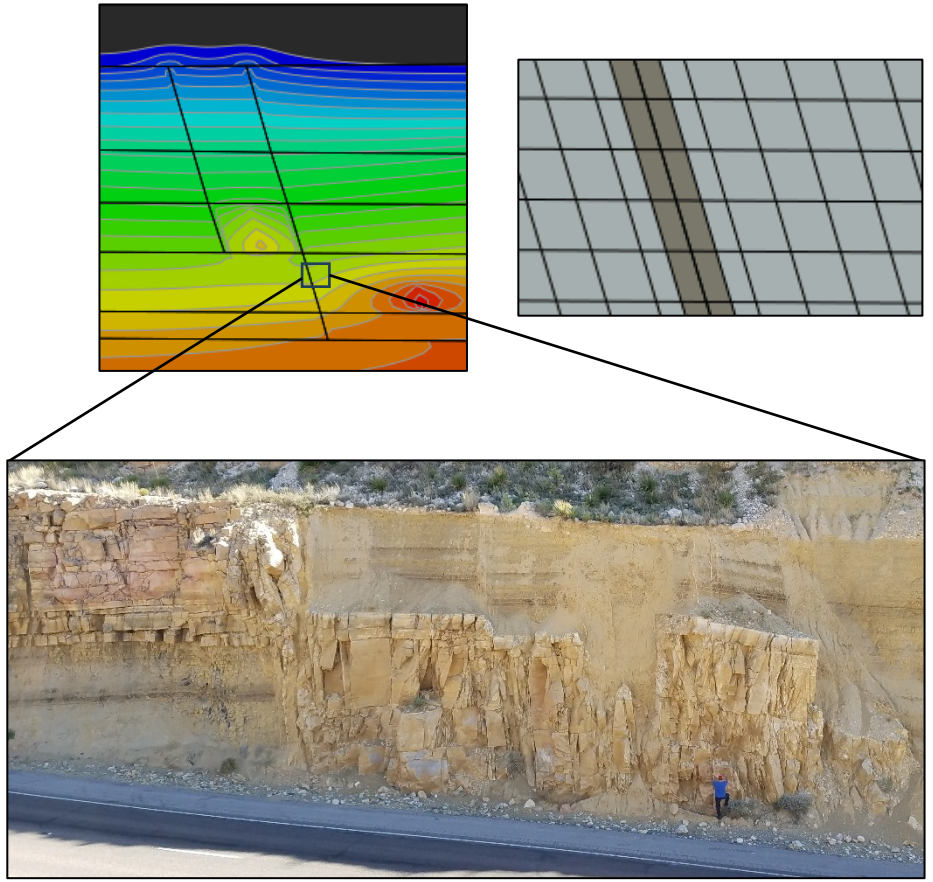
- **Questions that can be answered with seismic scale conceptual models:**

- Faults can channelize and redirect flow and facilitate out-of-zone pressure migration in areas where fault parallel flow exceeds injection zone flow.

- Flow restricting fault zones and stratigraphic flow barriers act to restrict lateral flow and amplify pressure buildup adjacent to faults:
  - *could play a role in the generation of earthquakes*
  - *may contribute to containment issues in areas where pressure capacity is exceeded.*



Flow at 1-10km scale



Several more mechanistic questions require higher resolution models…

1. Background Information
2. Shallow Injection, Characterization and Modeling
3. **New Analog Field Models**

DMG Structural Fabric – Bell Canyon Faults and Fractures

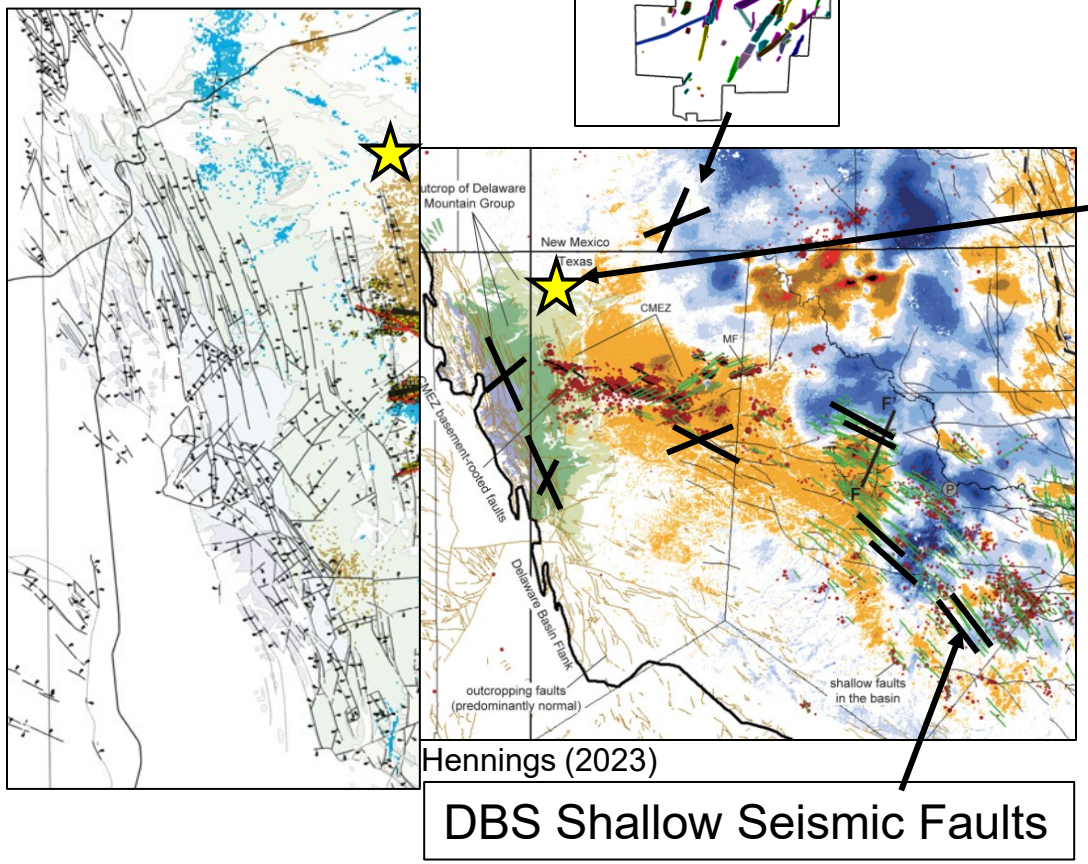
How does structural fabric affect flow and pressure migration?



DMG DBN/NM Shallow Seismic Faults

Horne (2022)

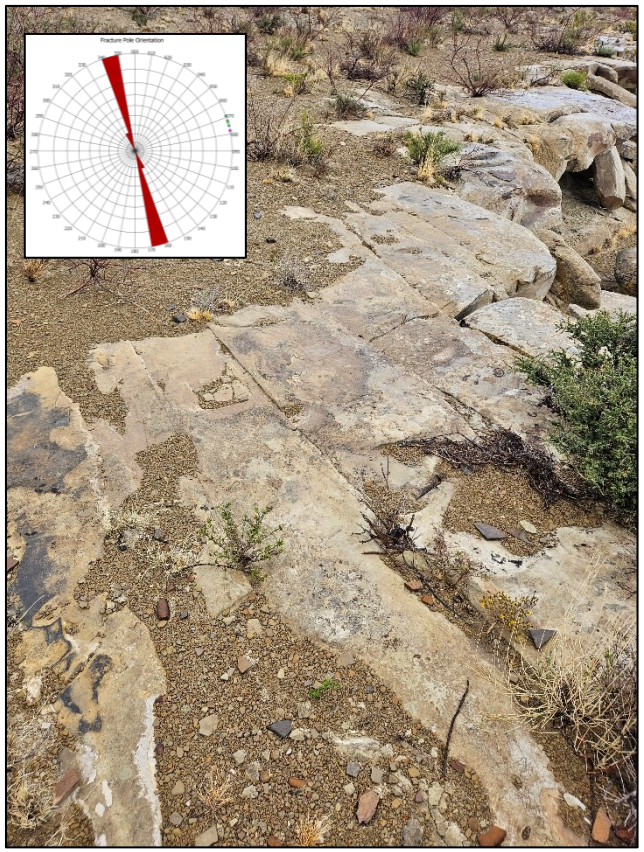
Bell Canyon Shear Fractures and Faults in Outcrop



Hennings (2023)

DBS Shallow Seismic Faults

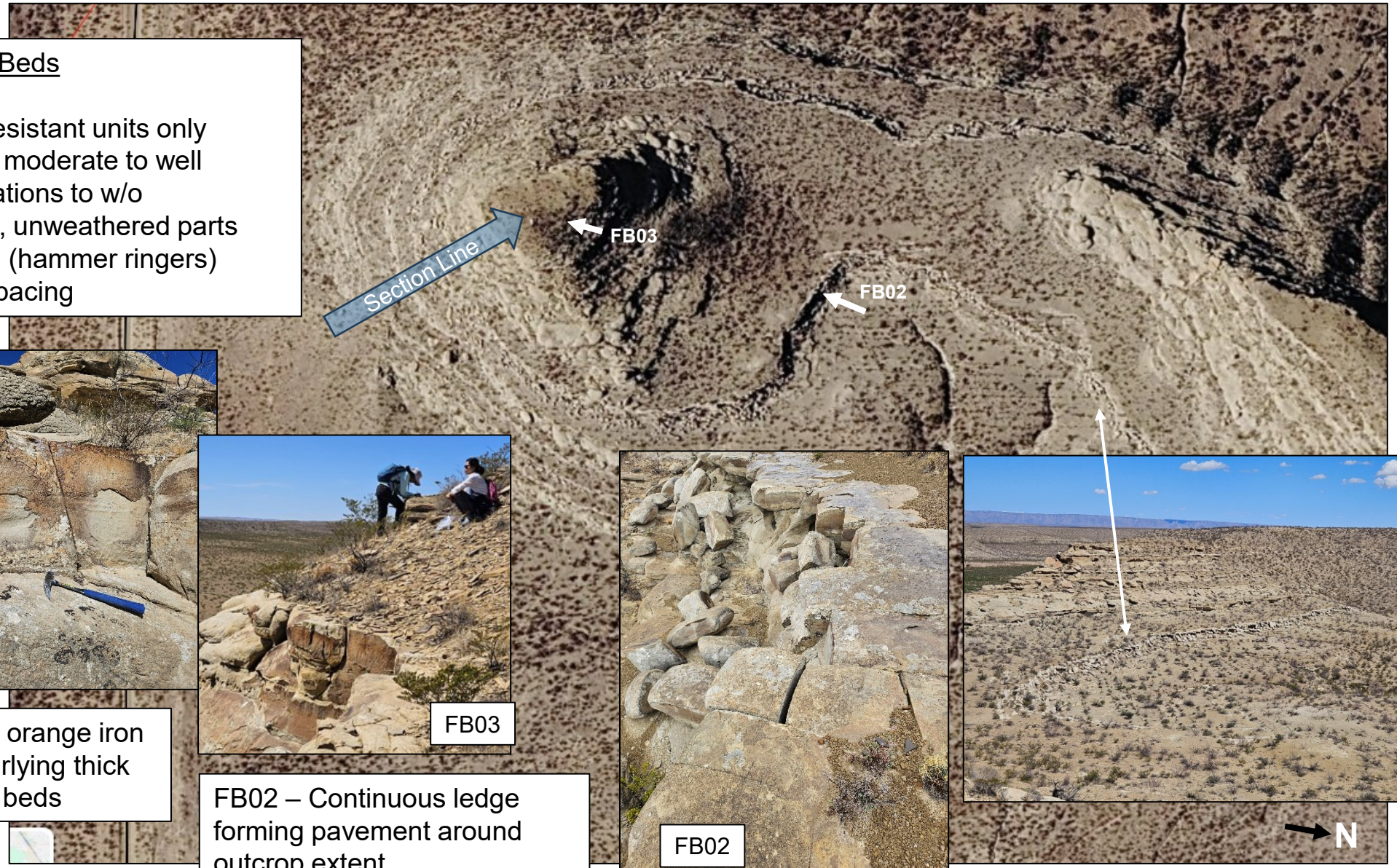




Photos: S. Busetti

Bell Canyon Outcrop → 3D Reservoir Model (Preliminary)

Well Cemented Fracture Beds
- FB01,FB02, FB03
- In 3+ ledge-forming resistant units only
- Grey, fine sandstone, moderate to well cemented, fine laminations to w/o depositional structure, unweathered parts very brittle and strong (hammer ringers)
- Systematic fracture spacing





FB03 – Topmost, orange iron staining from overlying thick planar laminated beds

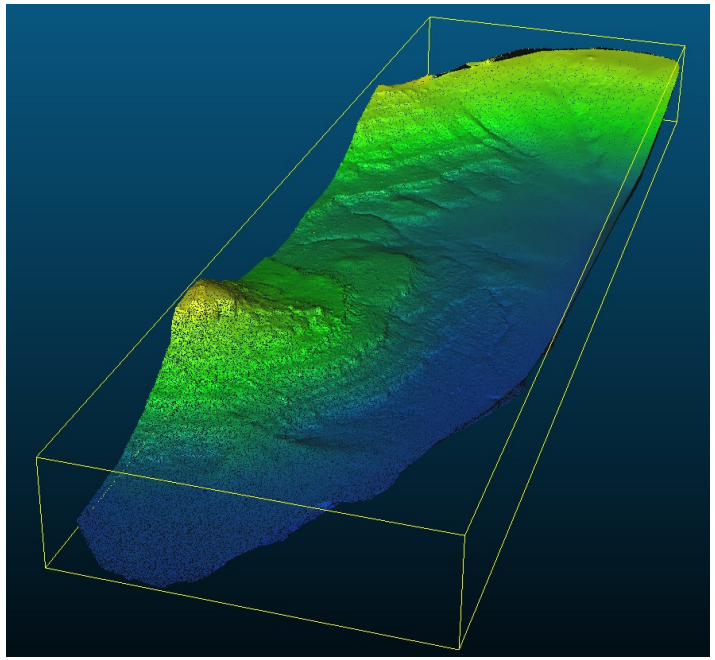
FB02 – Continuous ledge forming pavement around outcrop extent

Bureau of Economic Geology CISR

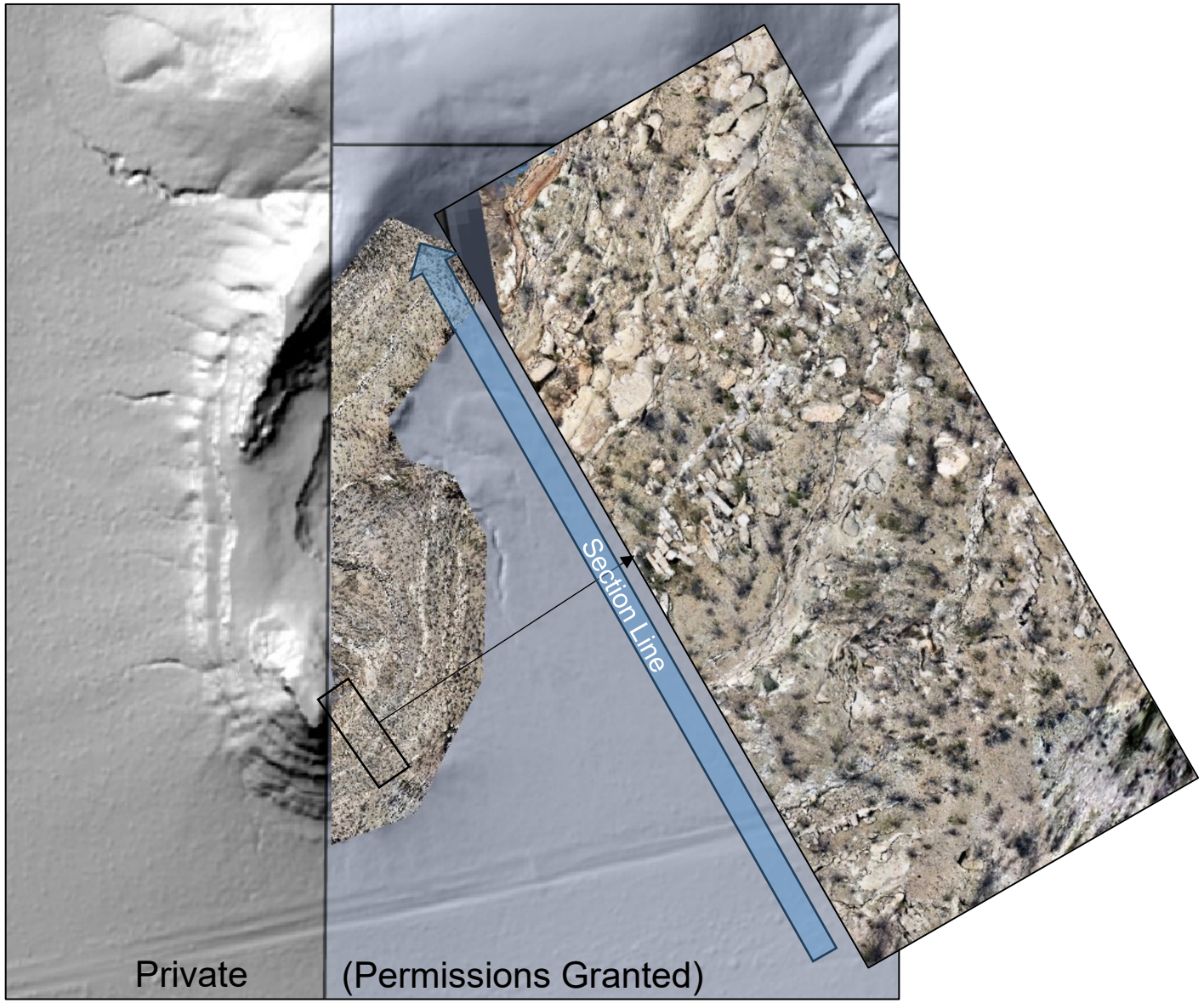
Bell Canyon Outcrop → 3D Reservoir Model (Preliminary)

Mechanical Stratigraphy Simulation Model

- Stratigraphic measured section
- Thin sections for each main layer
- 3D drone photogrammetry
  - Bedding contacts
  - Fracture stratigraphy
  - Fracture orientations
  - High resolution DEM



Drone Image Overlain on USGS 1m DEM

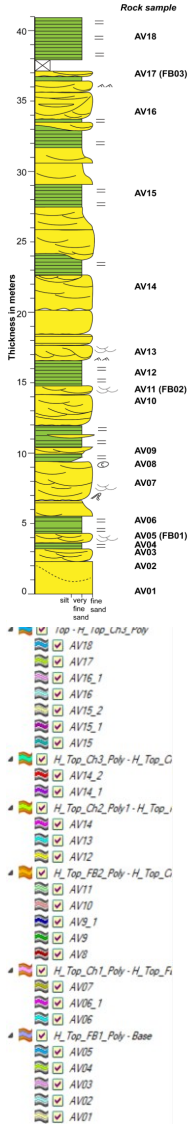


Bell Canyon Outcrop → 3D Reservoir Model (Preliminary)

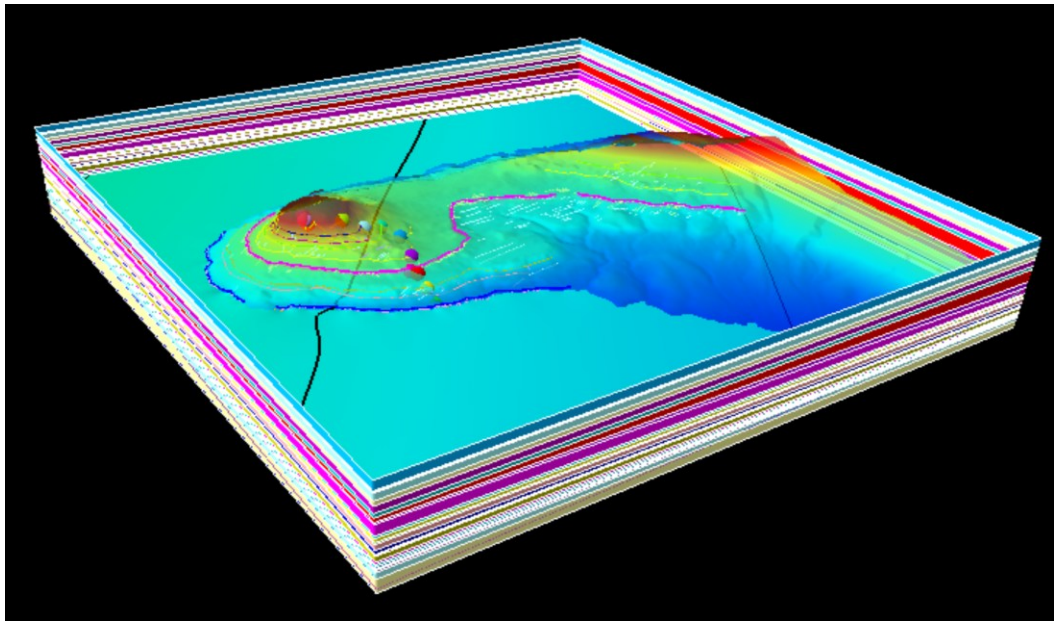
3D Digital Outcrop Model

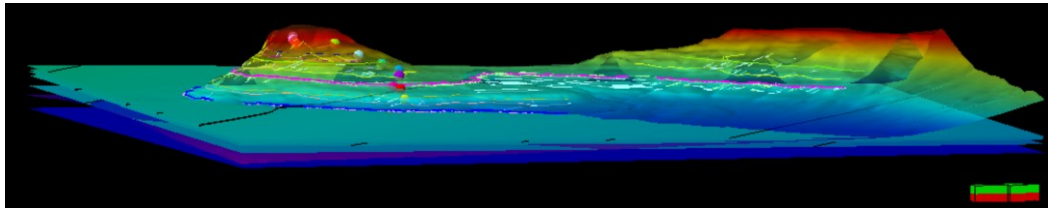






3D Geomodel

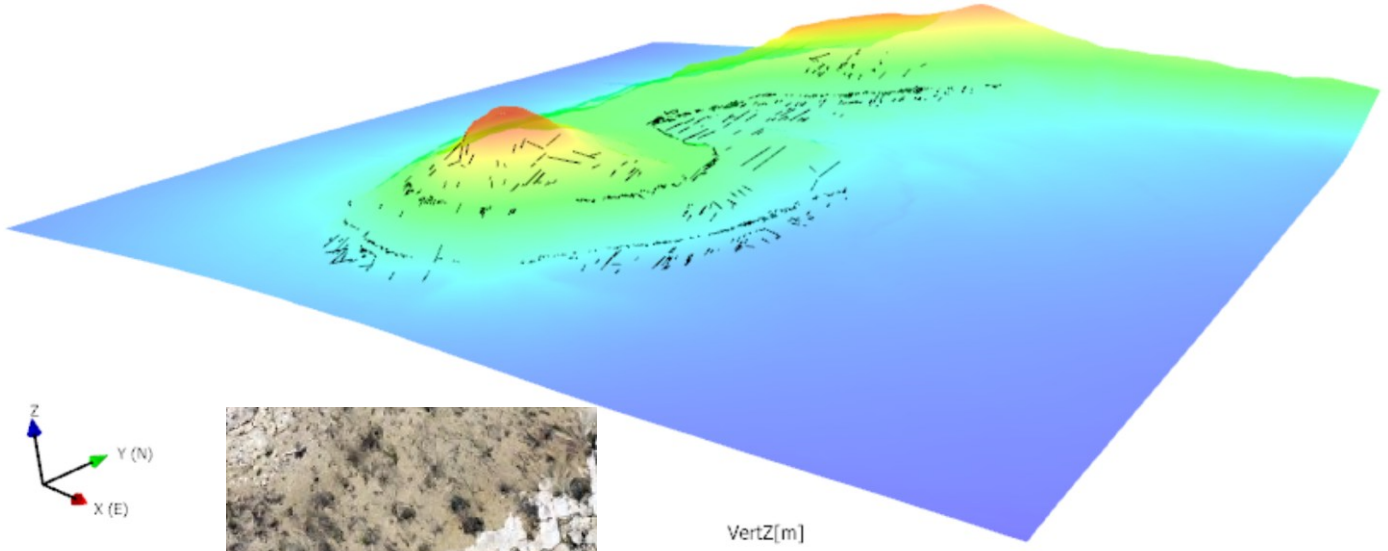




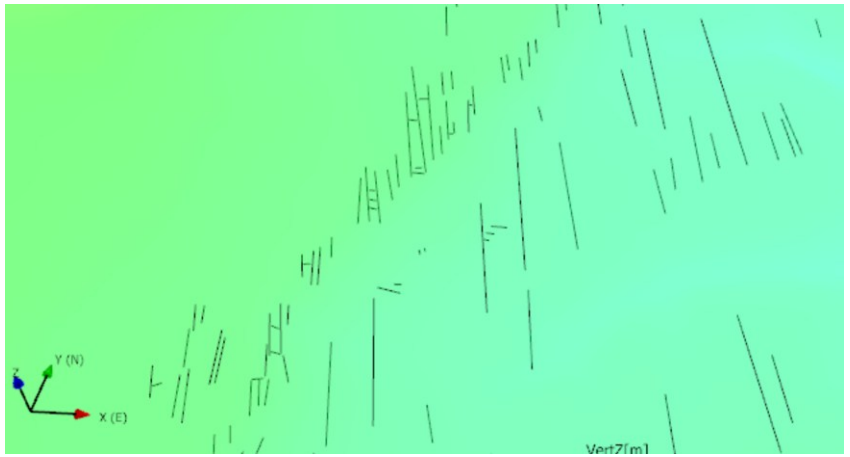
400m x 400m x 50m
1m lateral grid resolution
25 layers/zones

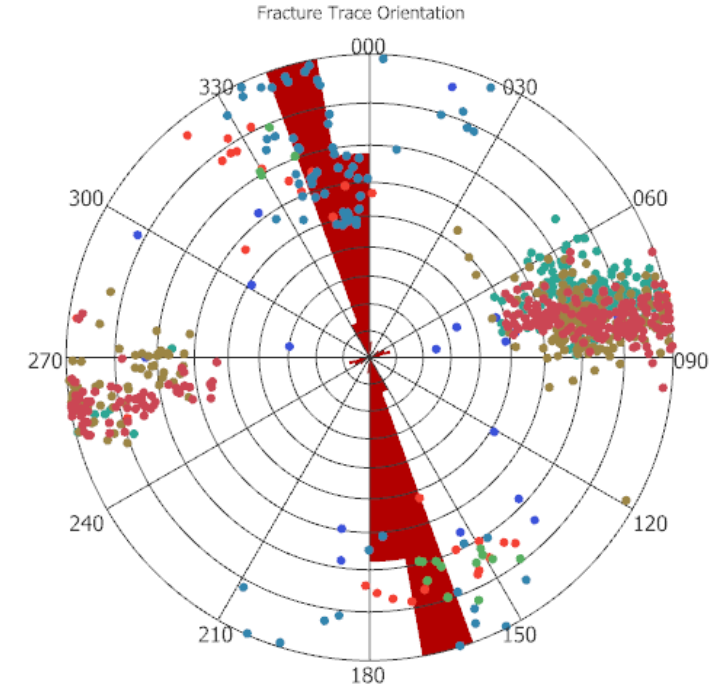
Bell Canyon Outcrop → 3D Fracture Interpretation

Aerial Photo Interpreted Fracture Traces on 3D Model





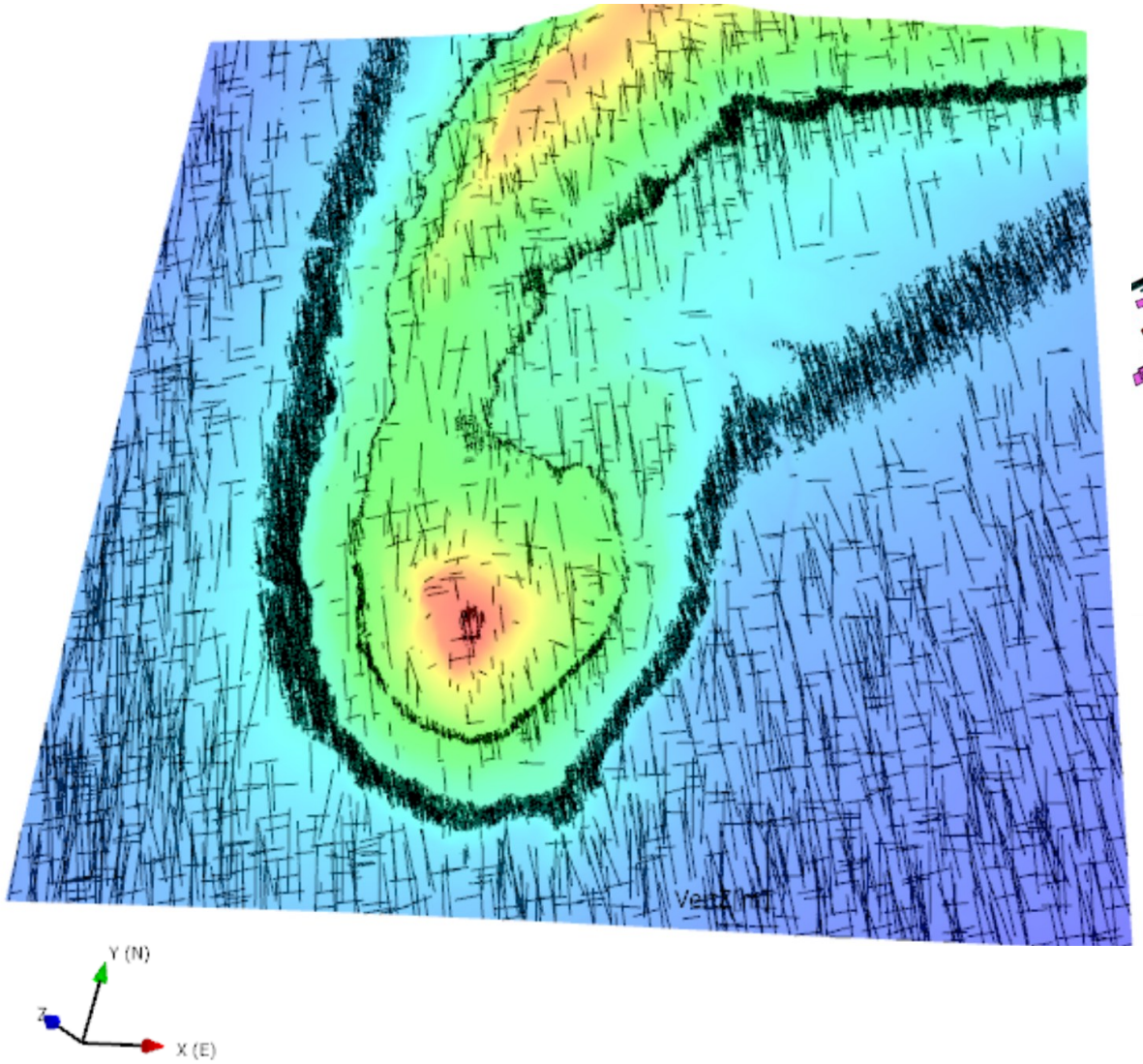




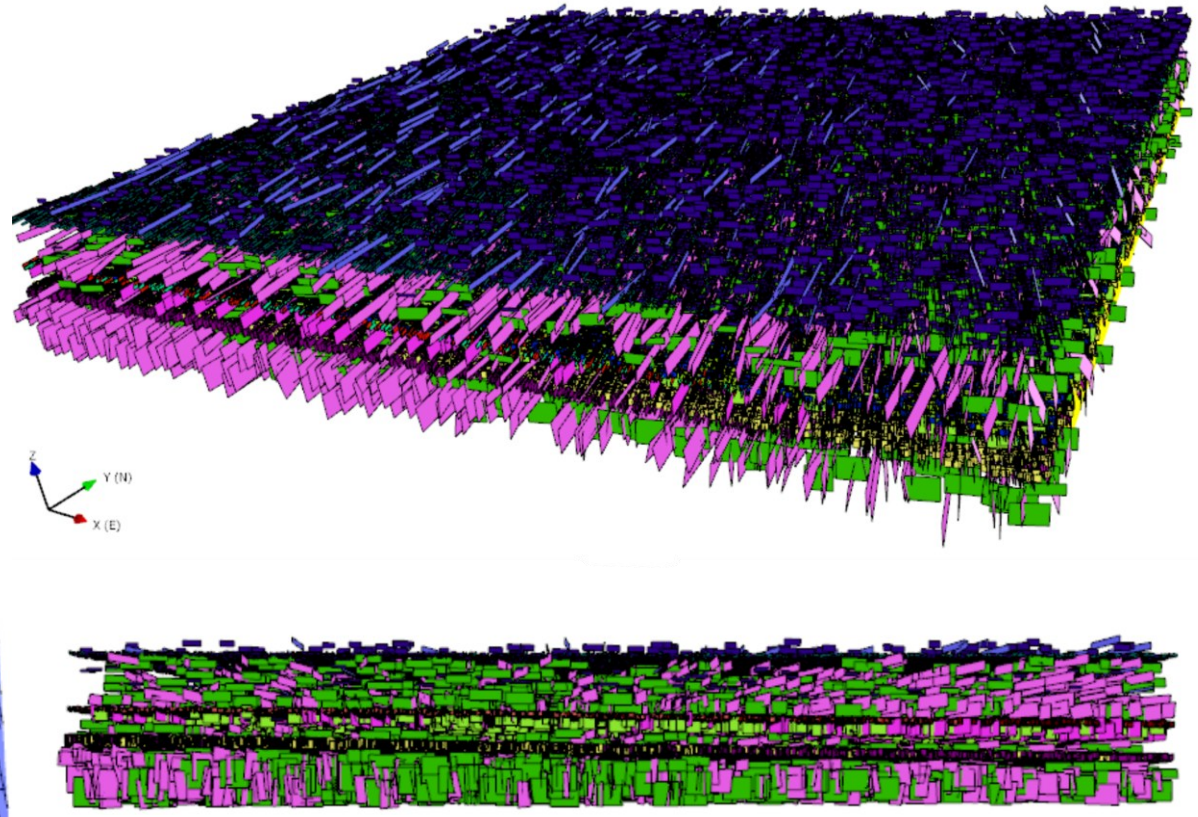


Bell Canyon Outcrop → 3D Fracture Model (Preliminary)

Surface Trace Outcrop Model



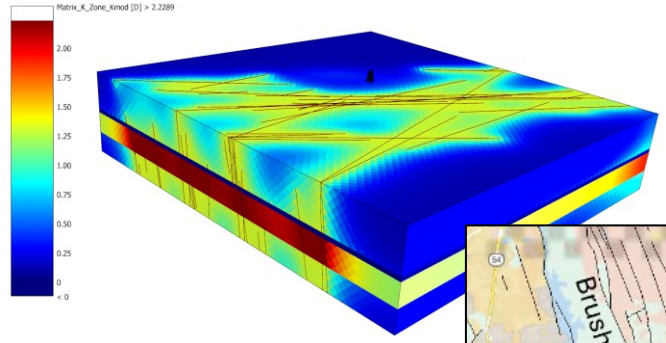
3D Conditioned DFN Model

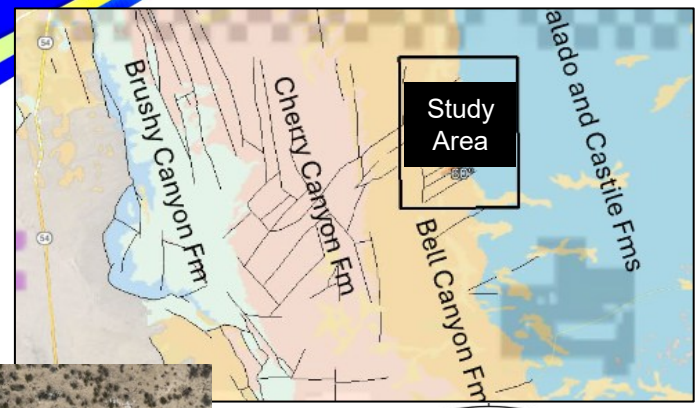


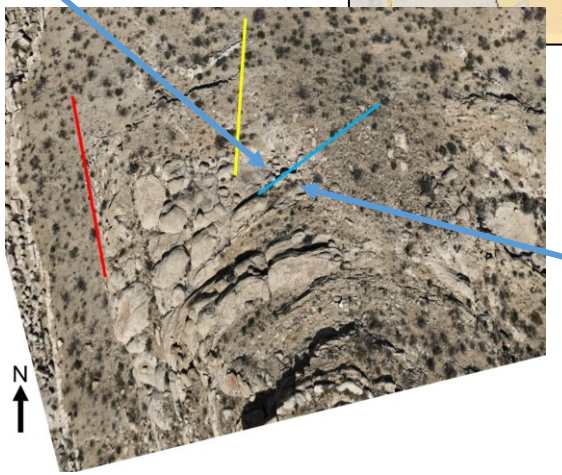
Ongoing 3D Reservoir Model Applications – Next Steps

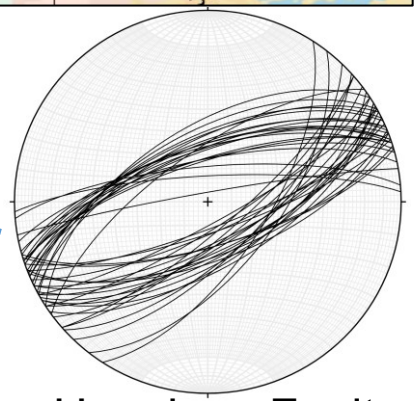
- Condition 3D outcrop model matrix to thin section porosity and subsurface poro-perm relations
- Synthesize previous outcrop work (Hennings and others) and macro-faults
- Single vs dual porosity behaviors
- Injectivity and diffusivity conditioning
- Evaluate grid upscaling effects
- Explore mechanistic conditions for anisotropic or fracture-assisted fault activation, pressure compartmentalization, and out-of-zone flow

Hypothetical Fault Zone Enhancement
(or maybe flow barriers?)









Hennings Faults

CISR's Ongoing Basement to Surface Research

1. Water production and injection trends
2. Earthquake rates and association with deep and shallow injection
3. Fault characterization across the Permian Basin
4. Updated basement horizon mapping
5. DMG and top seal (Castile and Salado Fm. evaporites) characterization
6. Shallow pore pressure increase and impact to legacy wells
   - Injection capacity (pore pressure change)
   - Available pore space (fill capacity)
   - Updates to simulation models (facies, stratigraphy, fractures, faults, etc.)
7. InSAR monitoring on injection uplift and production subsidence