Big Sky Regional Carbon Sequestration Partnership – Kevin Dome Carbon Storage

FC26-05NT42587

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Acknowledgments

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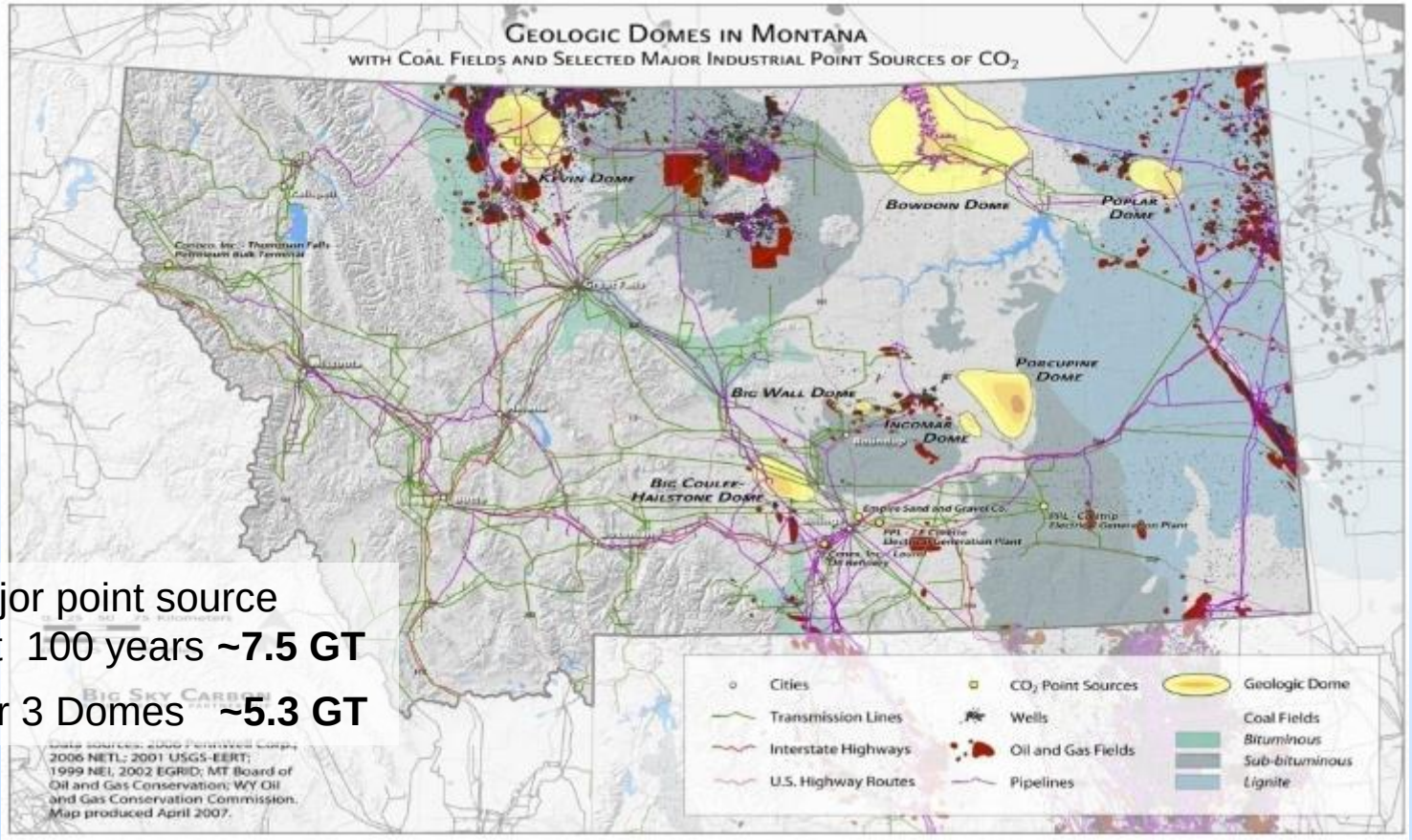
Wade Zaluski
Harry Lisabeth
Jonathan Ajo-Franklin
Tim Kneafsey
Chun Chang
Quanlin Zhou
Curt Oldenburg
Lehua Pan
Bill Carey

Domes Are Attractive Early Storage Target

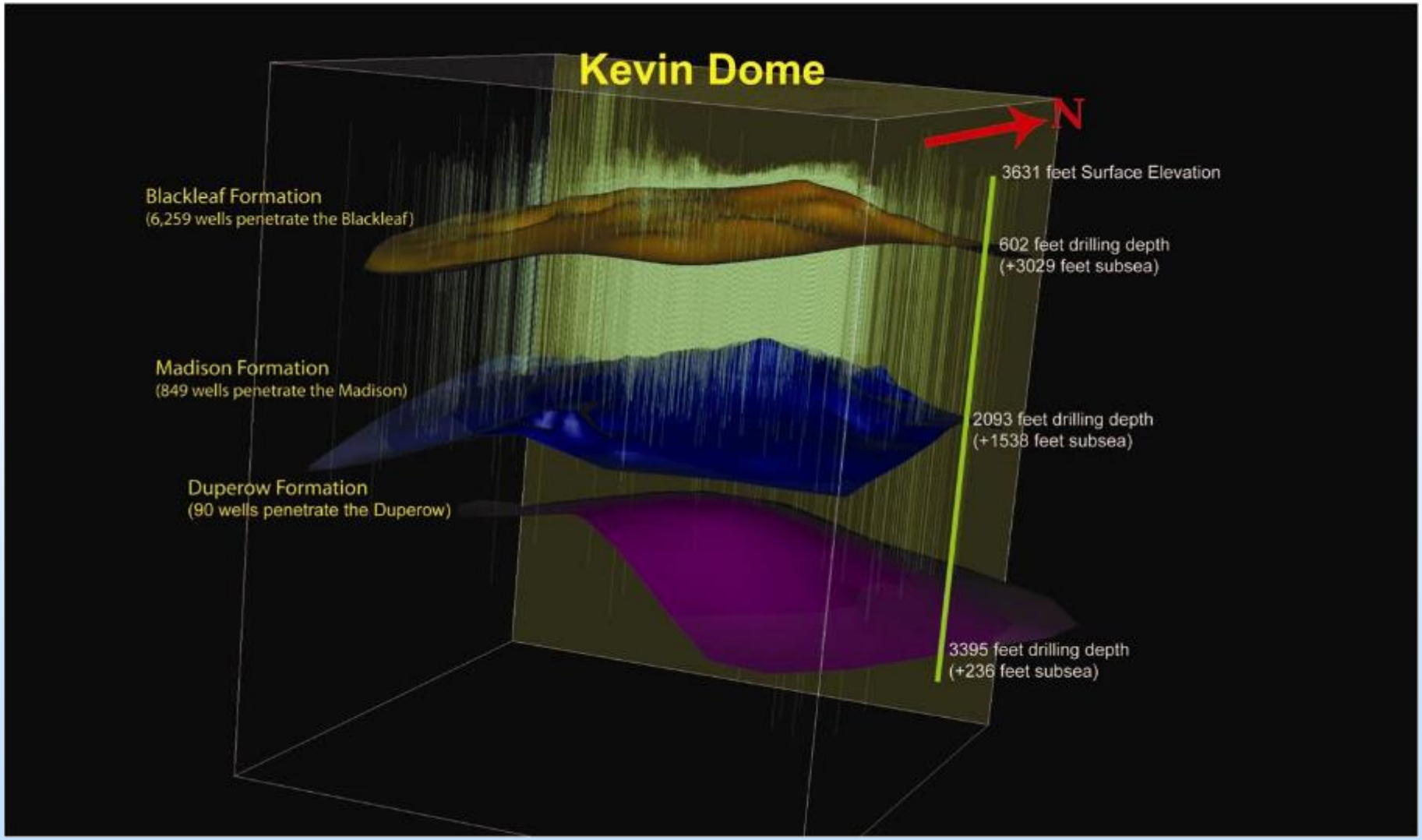


Half of the current major point source emissions for the next 100 years **~7.5 GT**

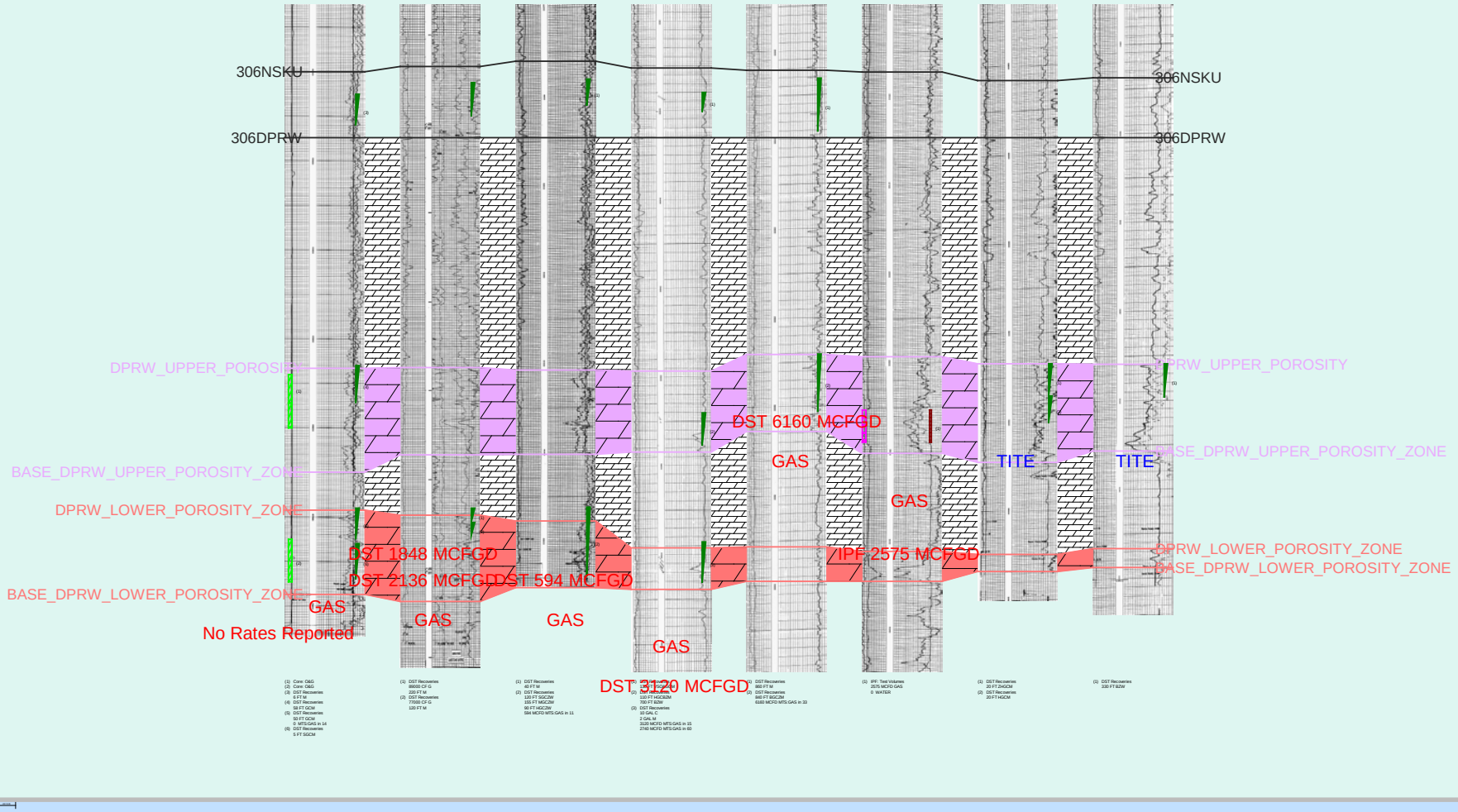
Resource Estimate for 3 Domes **~5.3 GT**

- Prevent trespass issues – buoyancy flow will take CO_2 to top of dome
- Potential use as carbon warehouse – decouple anthropogenic CO_2 rate from utilization rate

Kevin Structure Tops & Well Penetrations

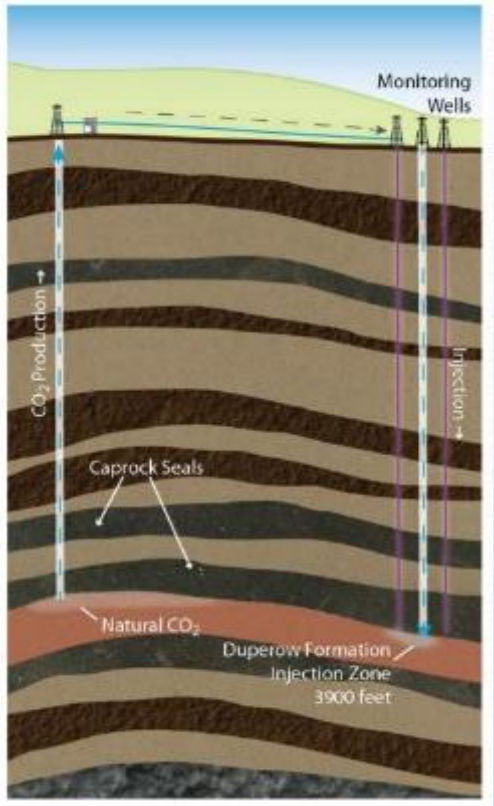


NW - SE Cross Section Kevin Dome



PETRA 11/4/2009 4:13:39 PM (Duperow_XS_11_4.CSP)

Site Characteristics – Scientific Opportunities



Natural CO_2 production

- Opportunity to study the natural accumulation and long term effects

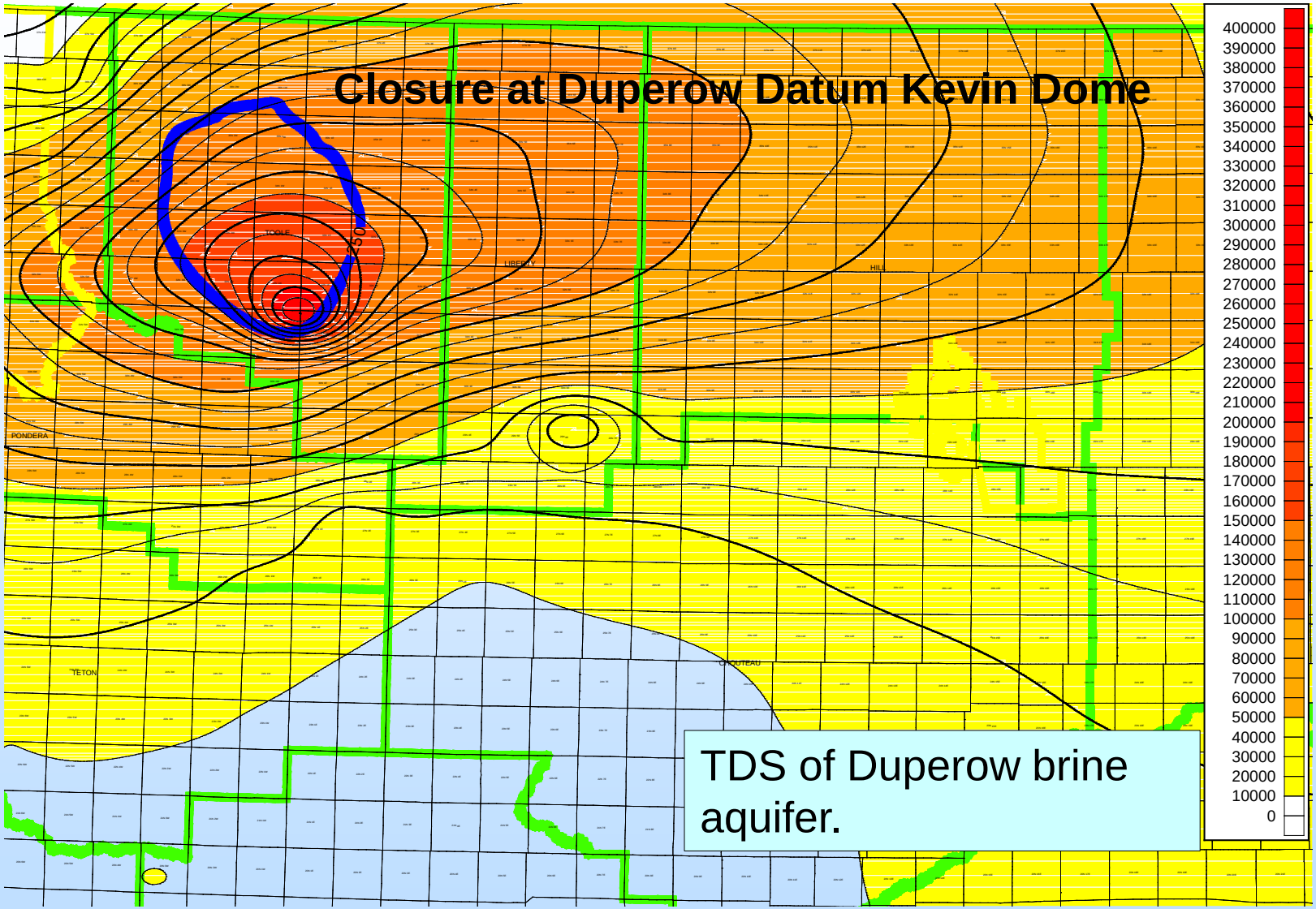
CO_2 in a reactive rock

- Opportunity to study geochemical effects on both reservoir rock (long term fate of CO_2) and caprock (storage security)
- To accomplish this, injection should be in water leg of the same formation
- Still retain engineered system learnings on injection, transport, capacity, etc.

Duperow is a fractured reservoir with very secure caprock

- Opportunity to investigate impact of fracture permeability

Regional Water Quality Data



Project Re-Scope

Project Re-scope: Maximize Learnings from Samples and Data

- Complete the core descriptive work and core flood experiments to characterize the pore and fracture geometry of the Duperow formation;
- Measure the fracture-permeability of evaporite and dolomite caprock;
- Perform laboratory measurements of seismic properties as a function of CO_2 saturation;
- Perform laboratory measurements of fracture-matrix flow to inform modeling of two-phase flow in fractured carbonate reservoir rock;
- Complete seismic processing and interpretation including use of quantitative interpretation techniques to determine if pore fluid differences in the reservoir zone can be discerned spatially without time lapse techniques;
- Apply full waveform inversion to develop a high resolution velocity model;
- Complete analysis of the geologic framework and stratigraphic architecture of the reservoir;
- Produce a final geostatic model with descriptive metadata;
- Improve phase change modeling using the production well data, assess applicability to leakage scenarios and CO_2 / EOR storage hub concept;

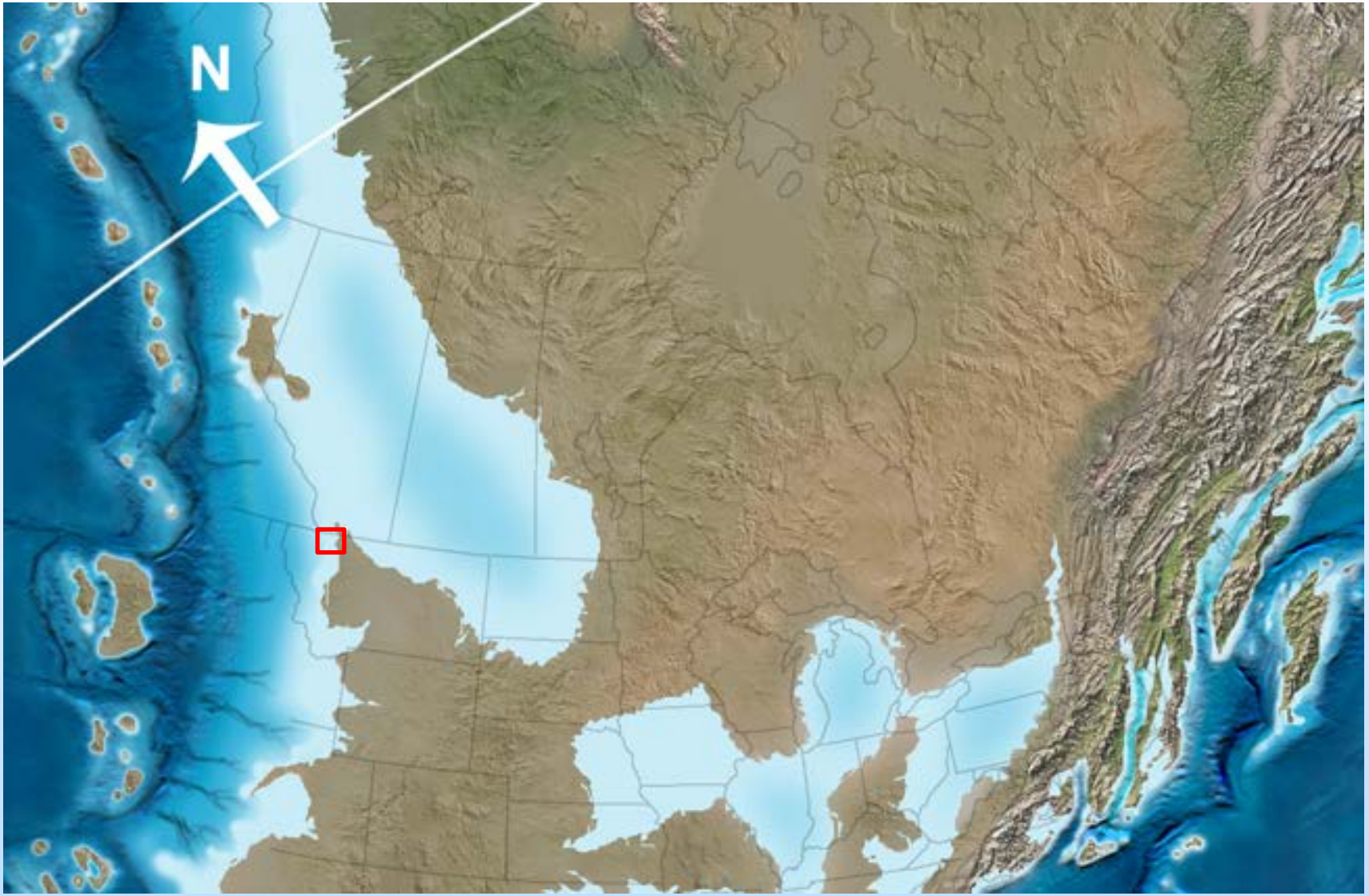
Project Re-Scope

Project Re-scope: Maximize Learnings from Samples and Data

Continued…

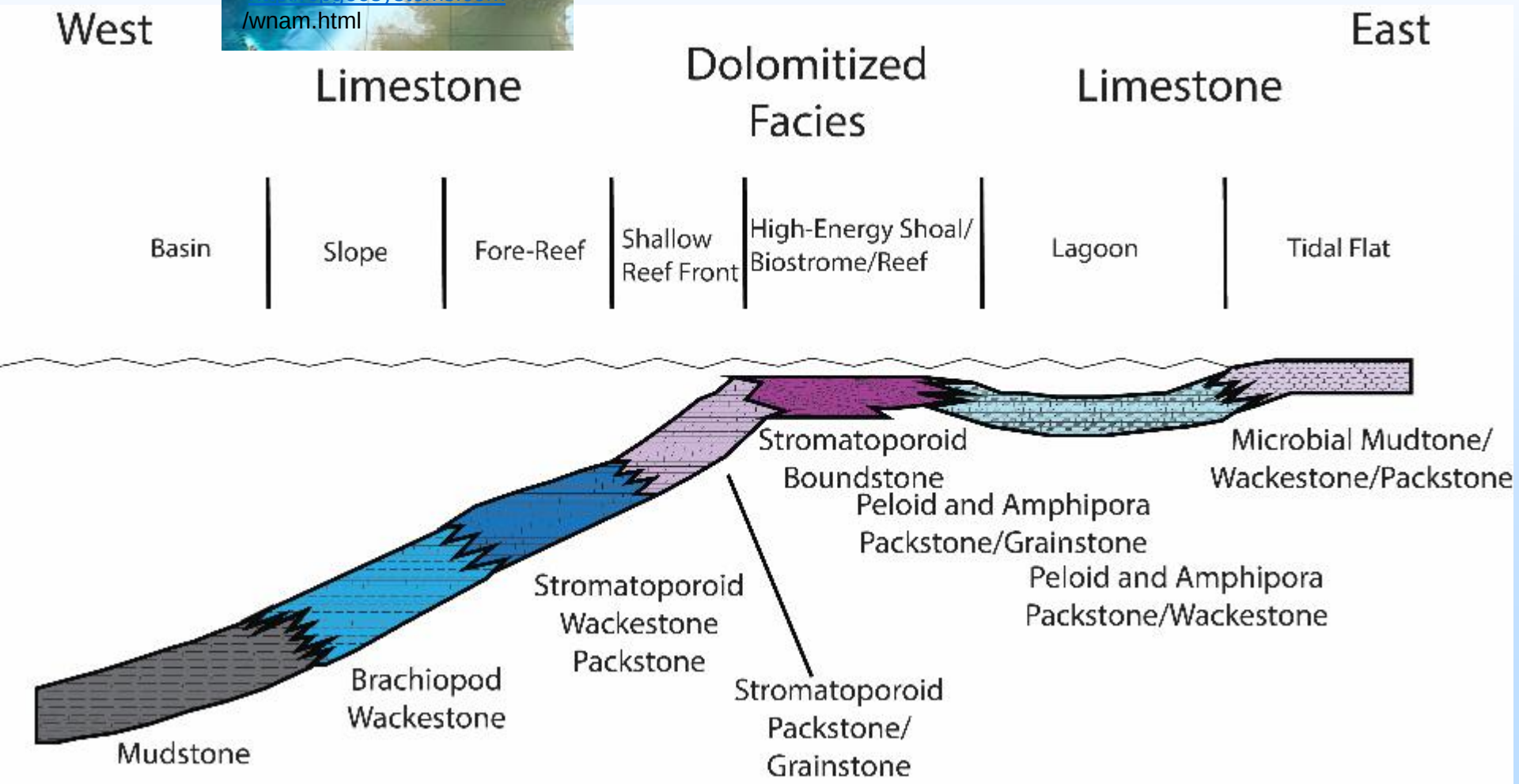
- Further develop fracture–matrix permeability interaction models incorporating data previously mentioned;
- Use the dual permeability model to refine reservoir performance for fractured carbonate reservoirs including capacity, injectivity and storage efficiency;
- Apply an integrated assessment model to Kevin Dome as a test case for NRAP tools;
- Process and analyze the surface monitoring data, assess baseline variability;
- Modify assessments of regional and national storage resources with information gained through the Kevin Dome project;
- Capture lessons learned from the permitting, risk, and management components of the Kevin Dome project through continued analyses and the development of peer-reviewed publications and web-based applications for information sharing and
- **Use the Kevin Dome project to illustrate unanticipated geologic scenarios to inform EPA's scheduled evaluation of the UIC Class VI rule.**

Middle Devonian Paleogeography

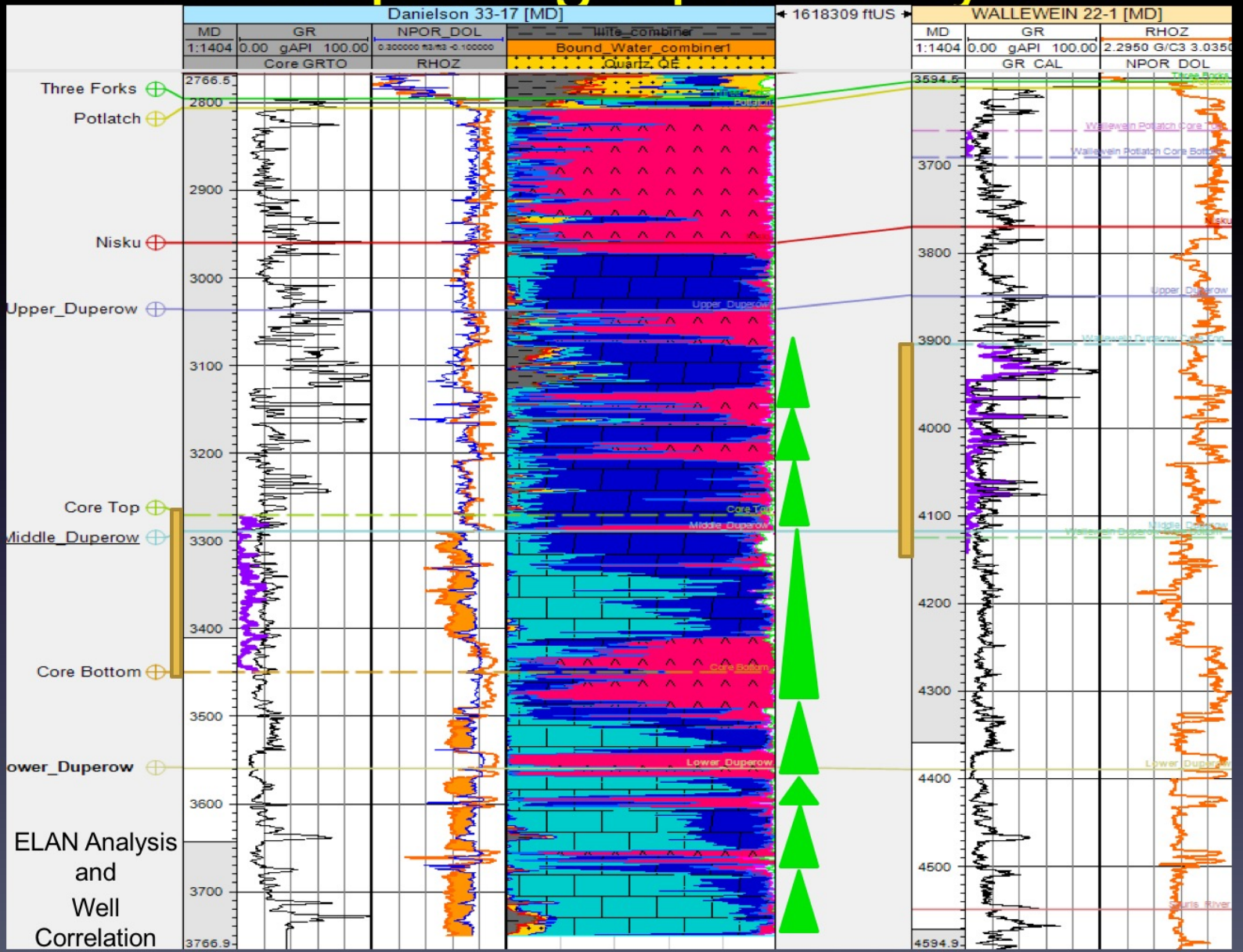


Enlarged Devonian Paleogeography – Western U.S. by Ron Blakey, http://cpgeosystems.com/wnam.ht

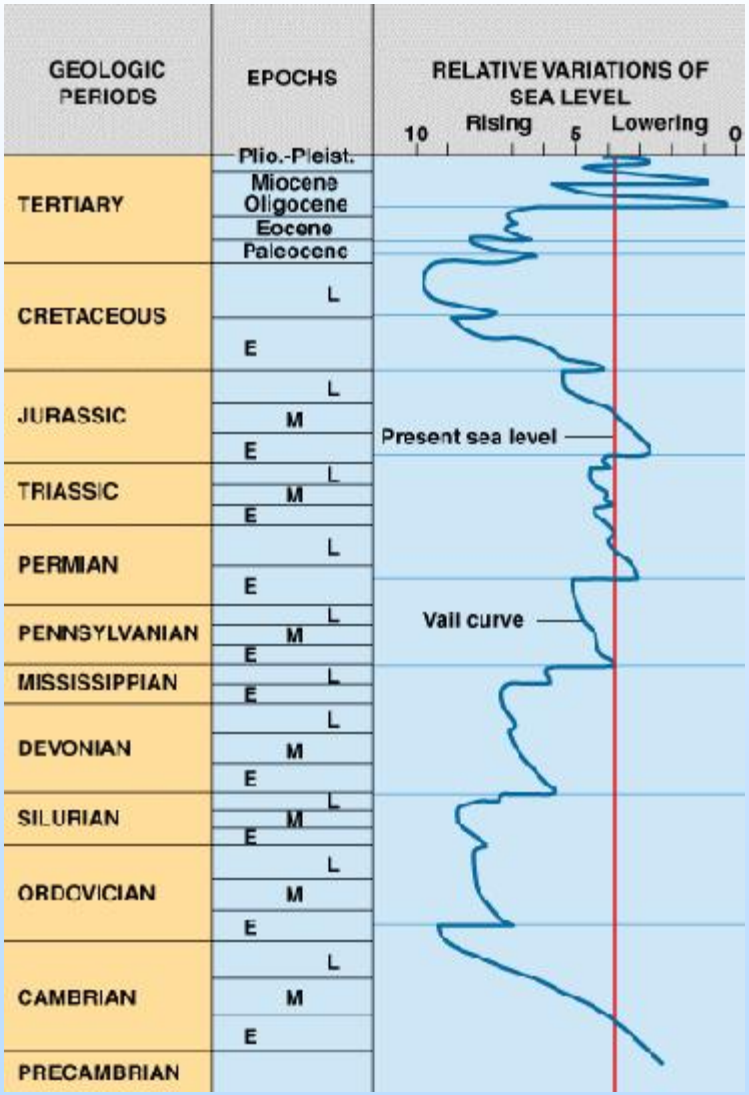
Duperow Facies Model



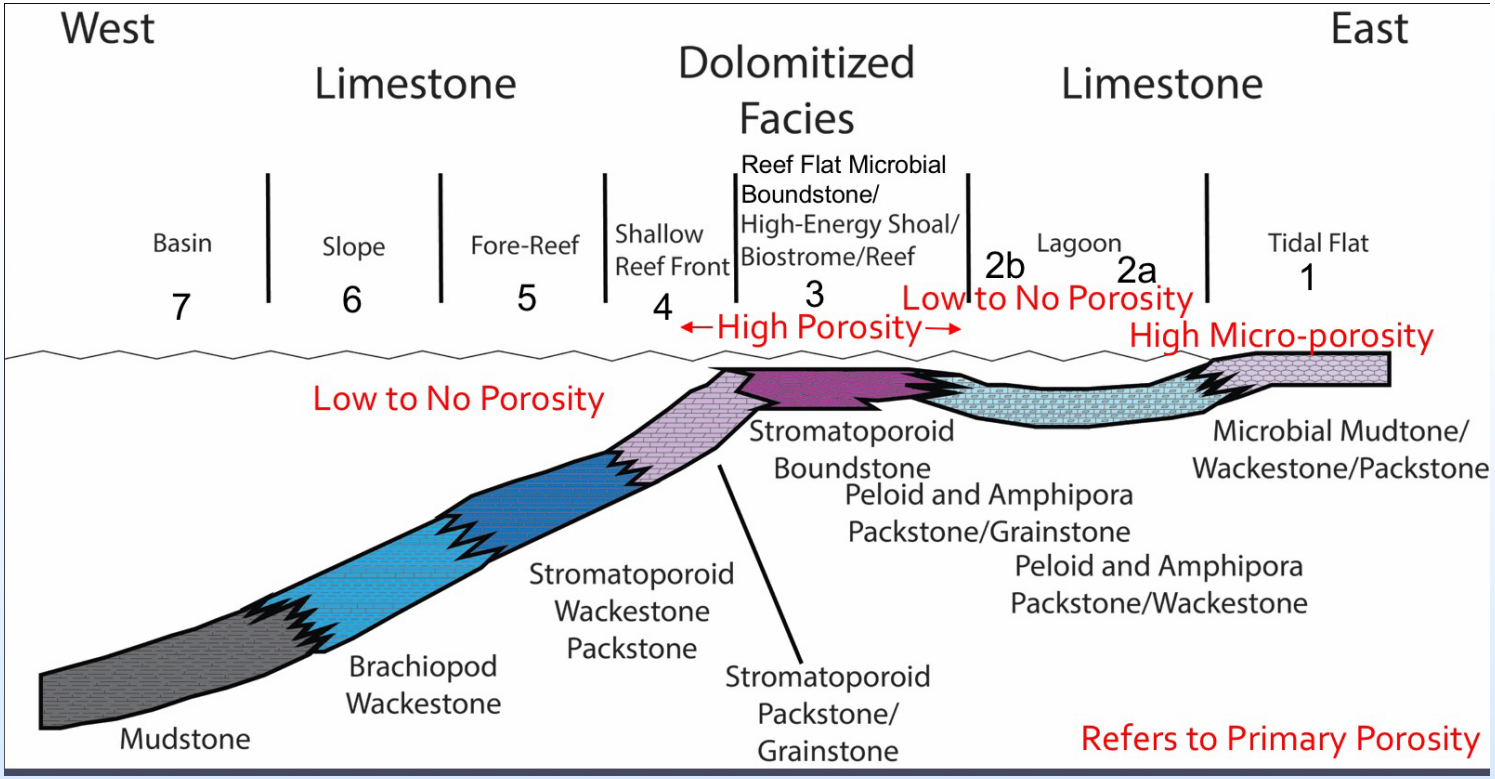
Danielson – Wallewein
8 Deepening Upward Cycles

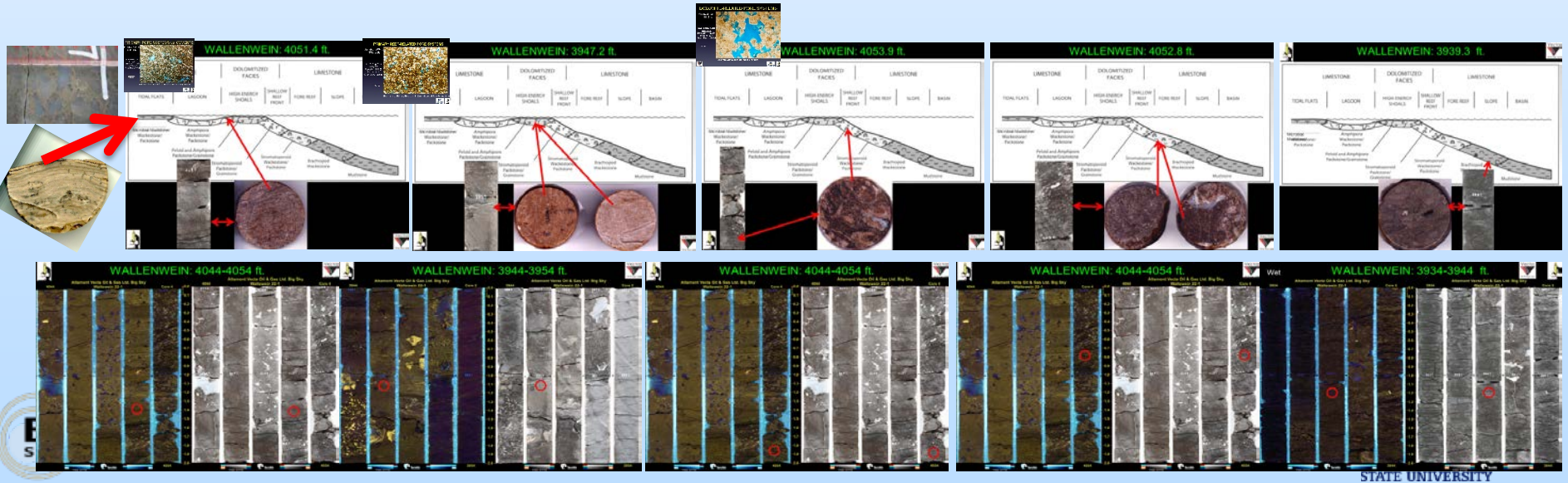


Global Sea Level Curve



Duperow Facies Model



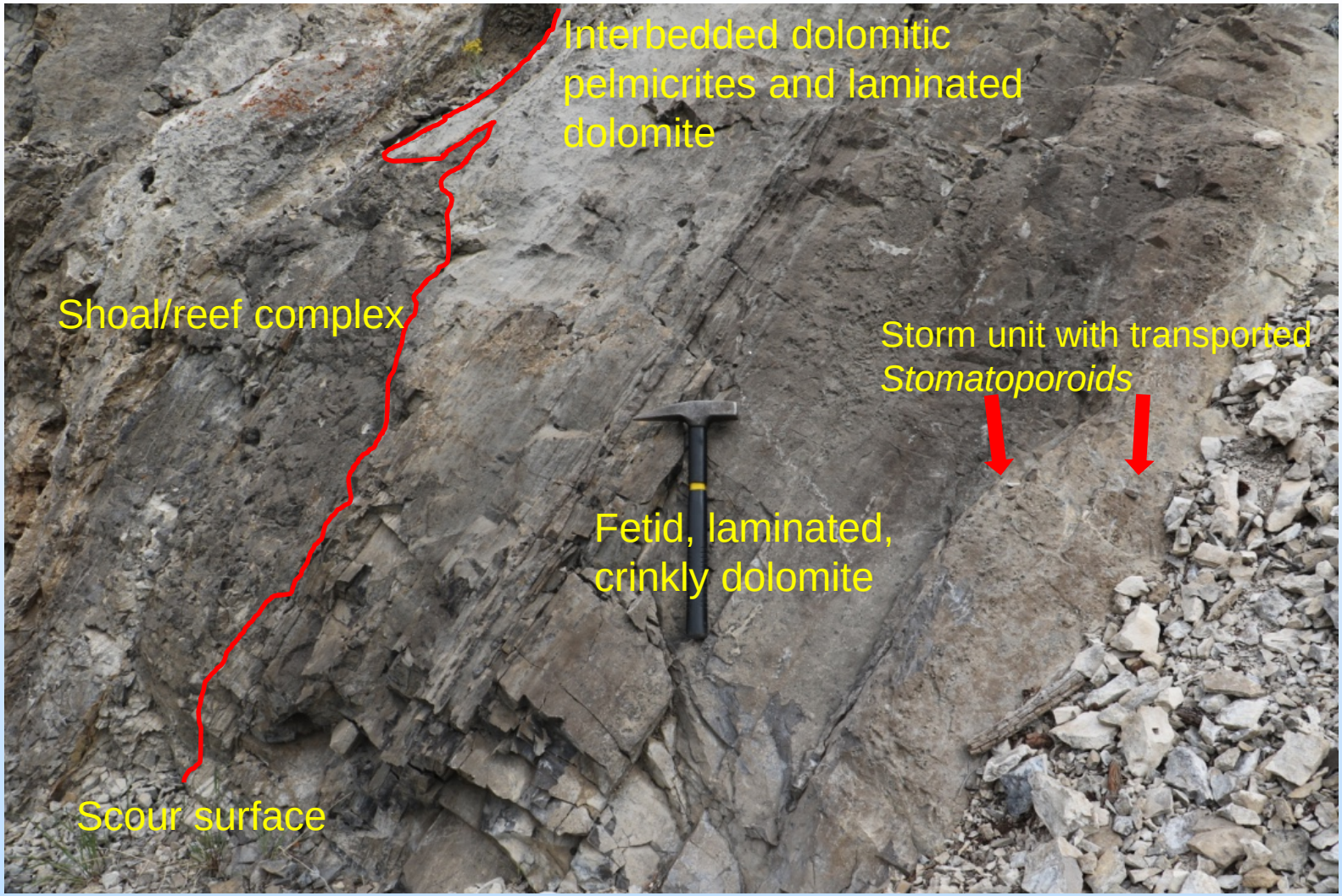


Duperow Lagoonal Facies

Laminated, organic-rich, fetid, dolomite

Inter-bedded lagoonal evaporite/laminites

Back-reef stromatoporoid heads washed into lagoon



Stromatoporoid reef topped by reef-flat “microbialites”

Reef Flat

Stromatoporoid dominated reef facies – Little Belt Mtns.

High Energy Shoal

Cross-bedded grainstones – Little Belt Mtns.

Deepening upward cycle

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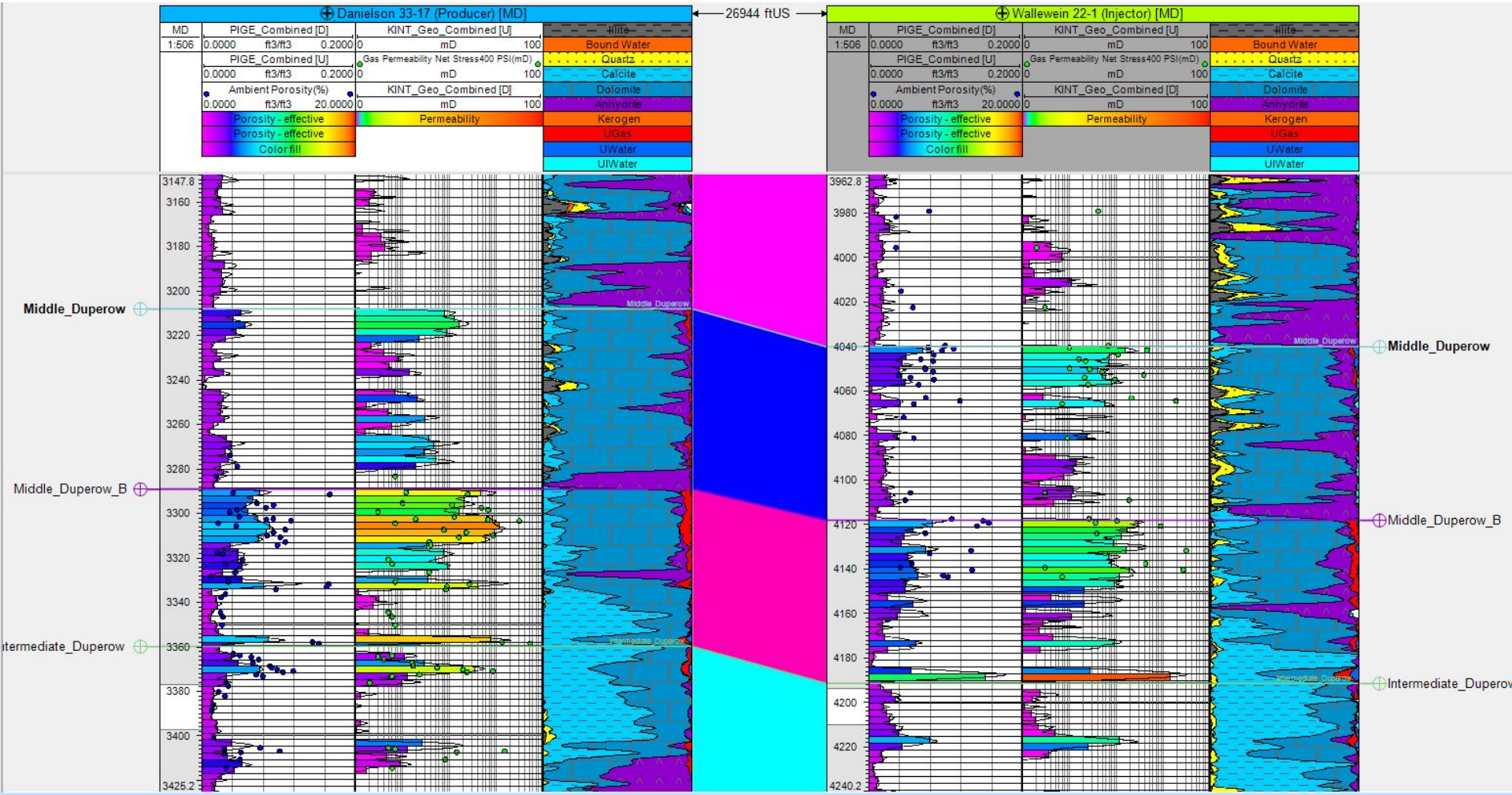
Site Characterization: ELAN Analysis and Well Correlation



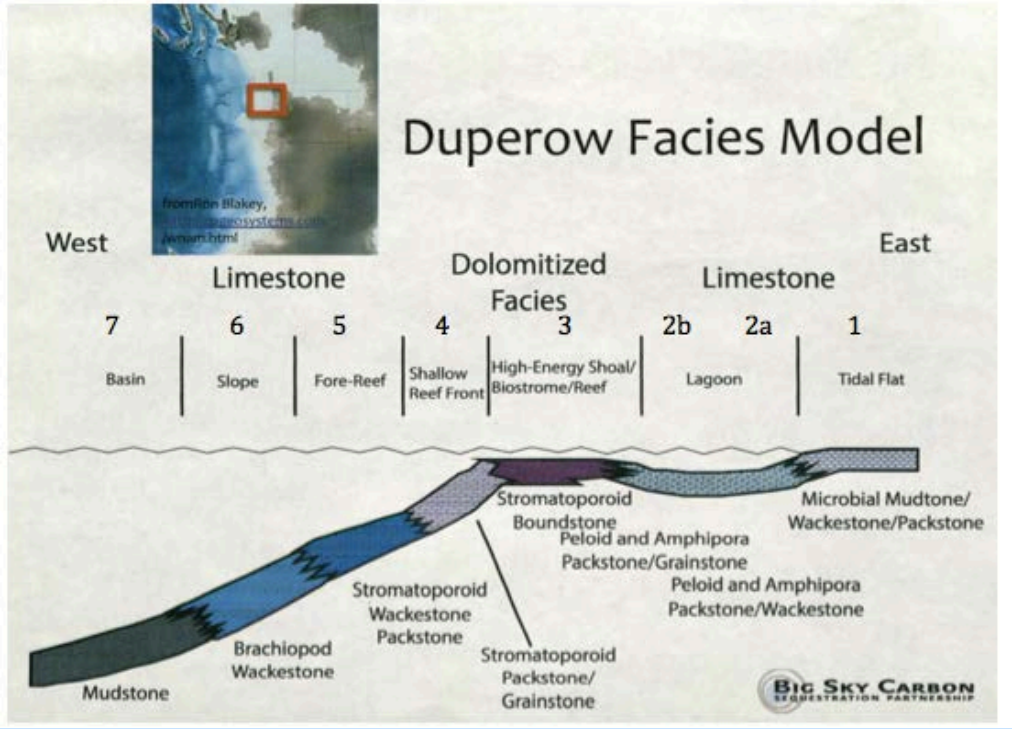
Excellent correlation for wells 12.8 km apart

Geostatic Model:Refine Model Based on Geologic Interpretation

Schlumberger Carbon Services

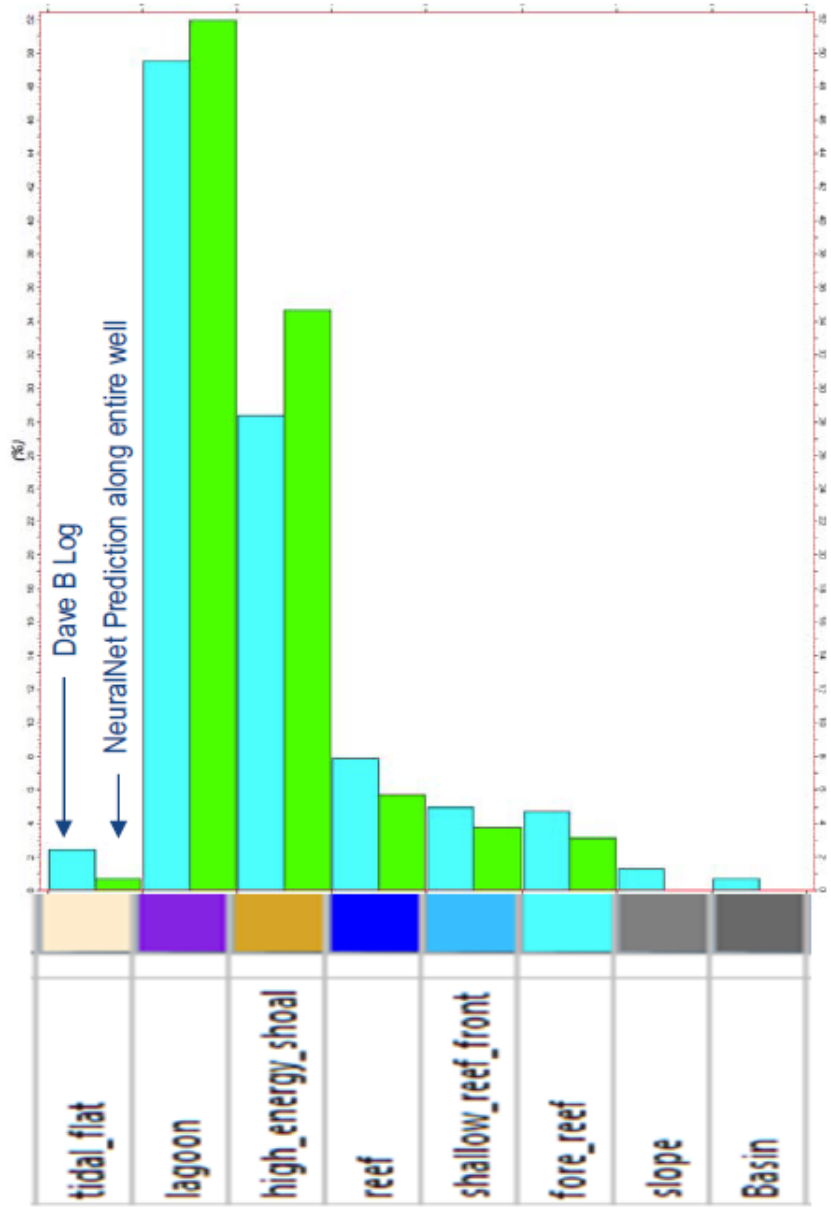
Depositional Environment

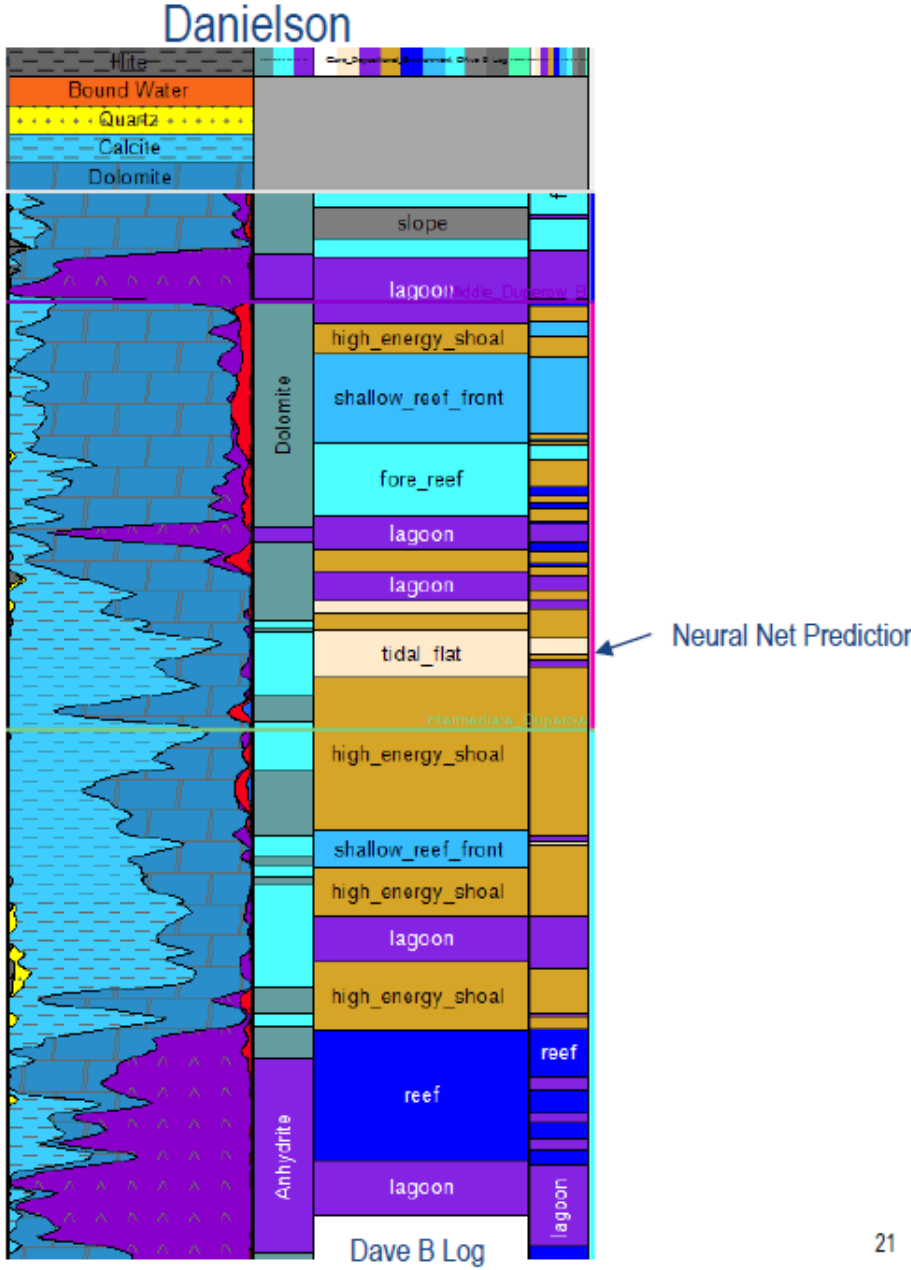
tidal_flat
lagoon
high_energy_shoal
reef
shallow_reef_front
fore_reef
slope
Basin
back_reef



Good Neural Net Match Along Core Interval

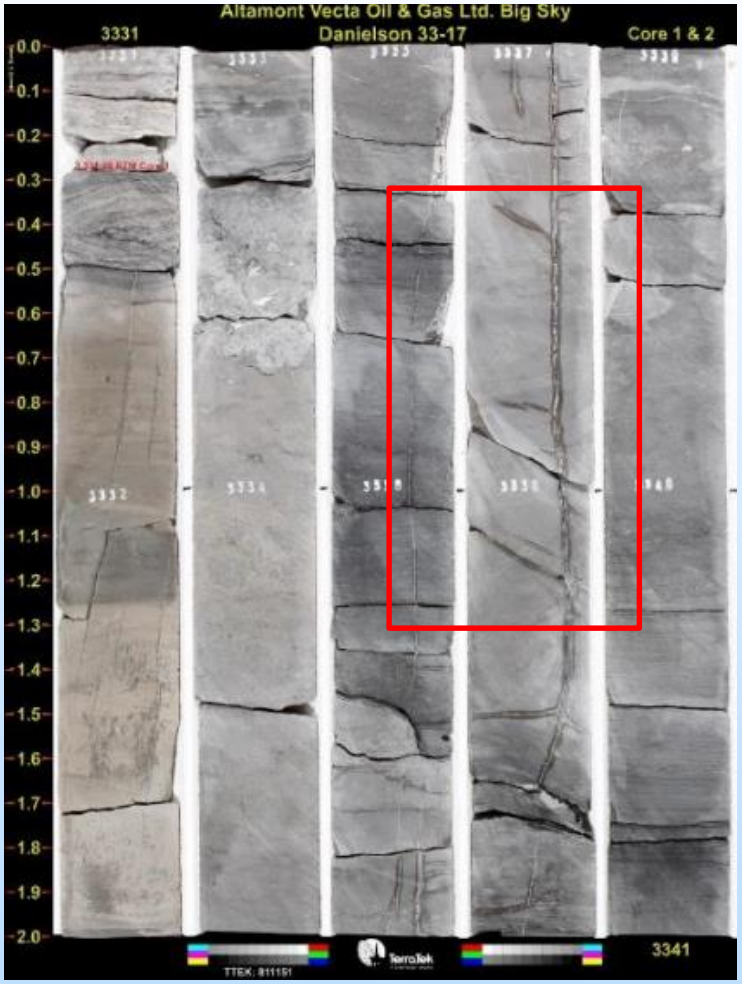
Schlumberger Carbon Services





Middle Duperow – Fractures

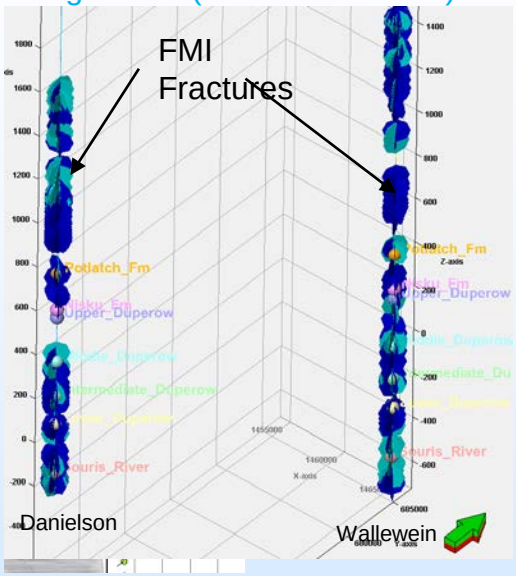
Site Characterization: Core Fracture Analysis

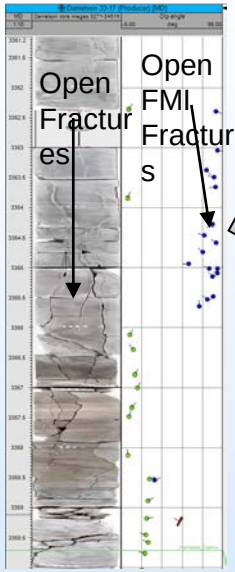


Natural Fracture Model

Inputs

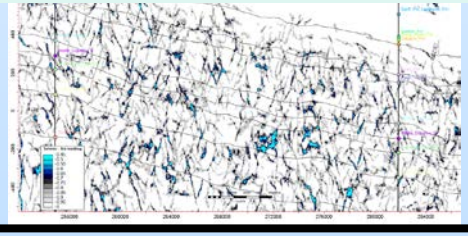
Dark Blue (Open Fractures)
Light Blue (Closed Fractures)



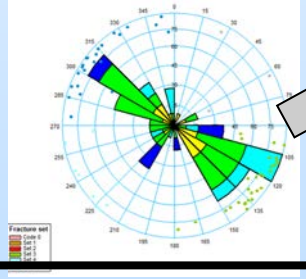


Seismic Ant Tracking Attribute

Potential fracture corridors (Light Blue)

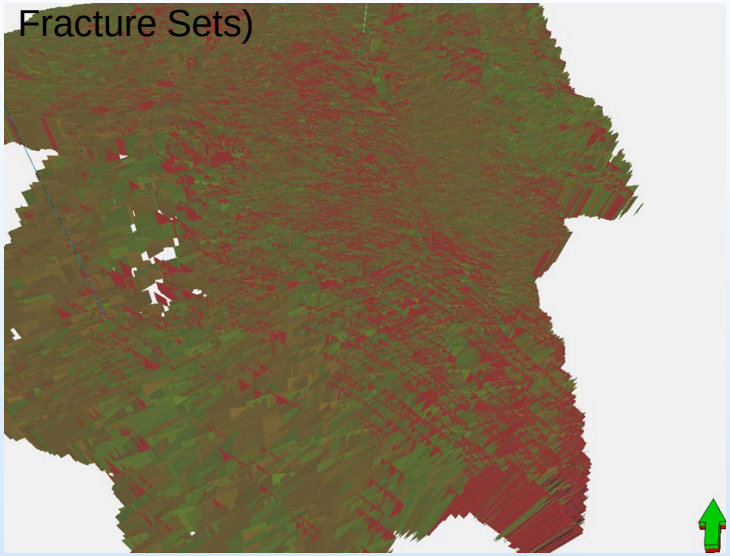


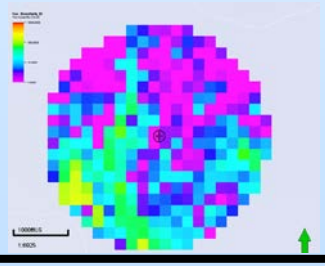
Fracture Set Stereonet



Outputs

Open natural fracture model of Middle Duperow (3 Fracture Sets)

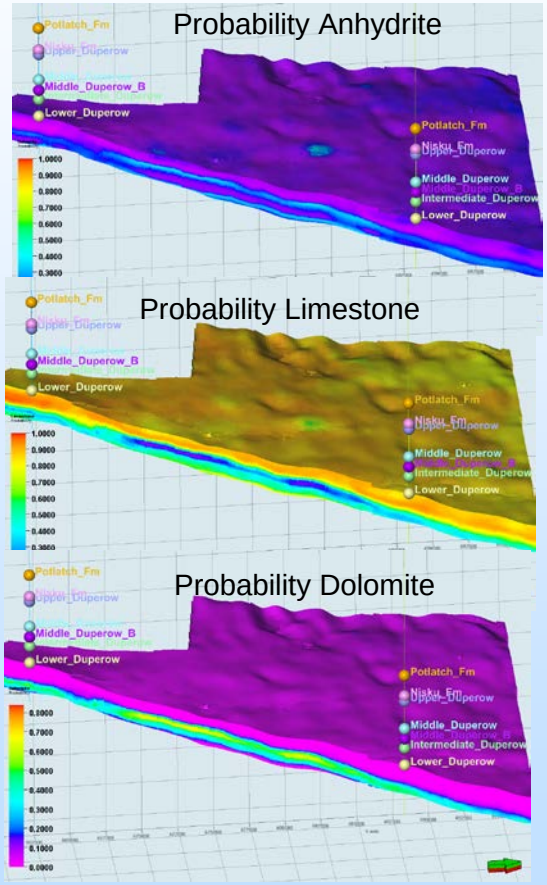


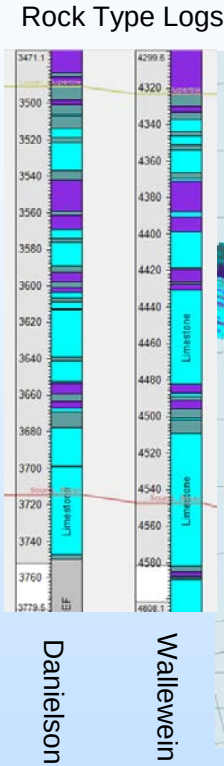


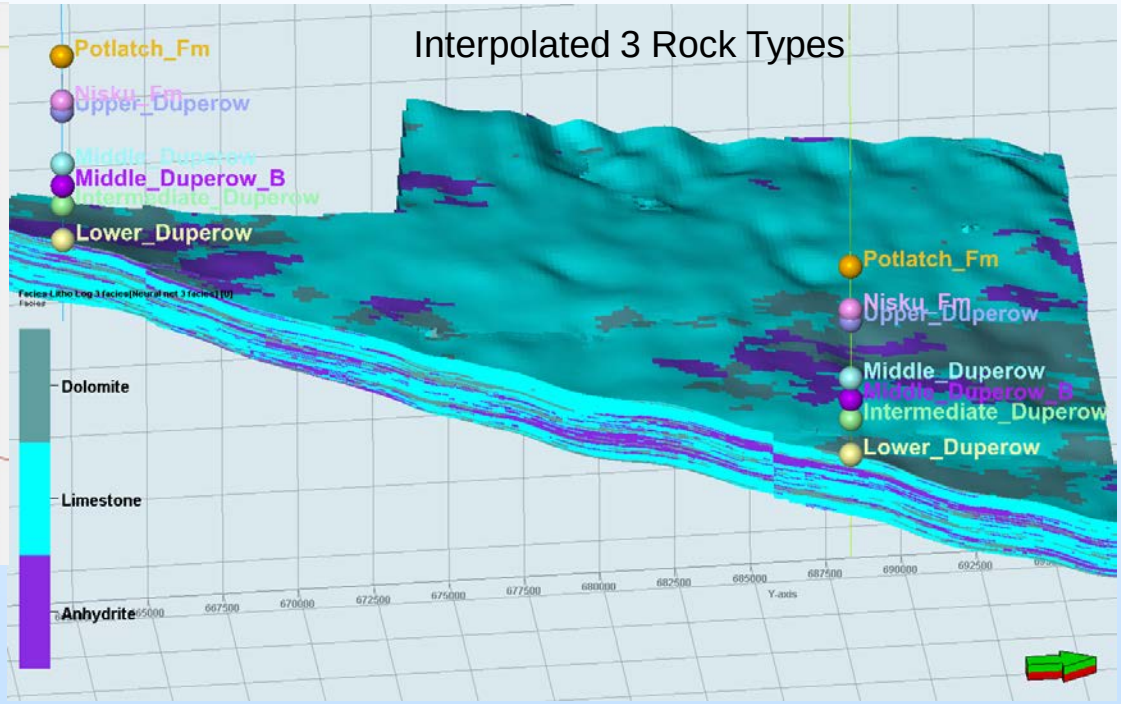
Fracture Cell
- Permeability IJK
- Porosity

Lithology Prediction Using Seismic Inversion

3D probability lithology prediction volumes as a trend for rock type interpolation

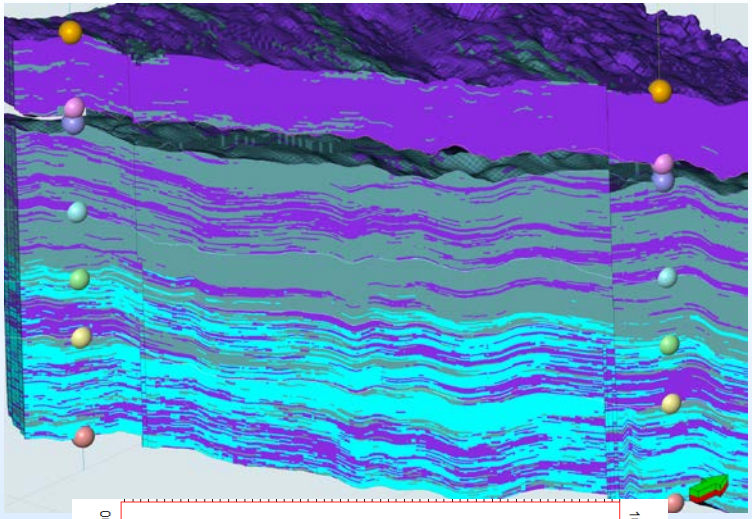




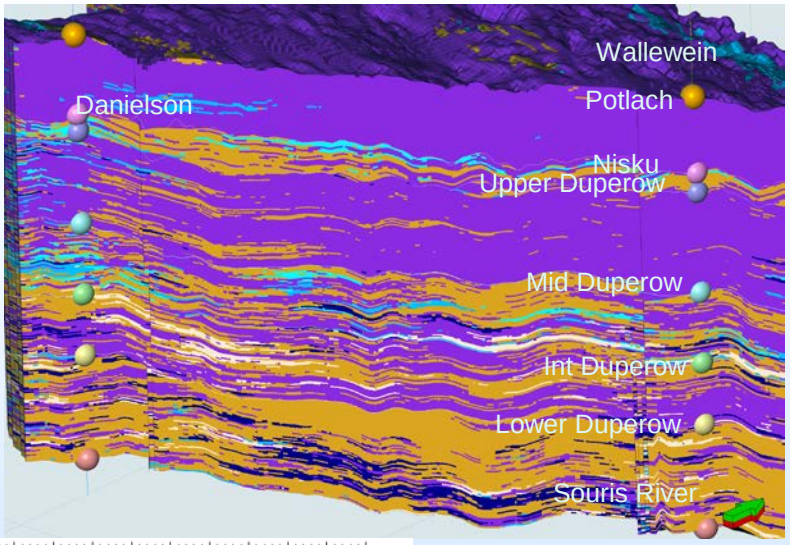


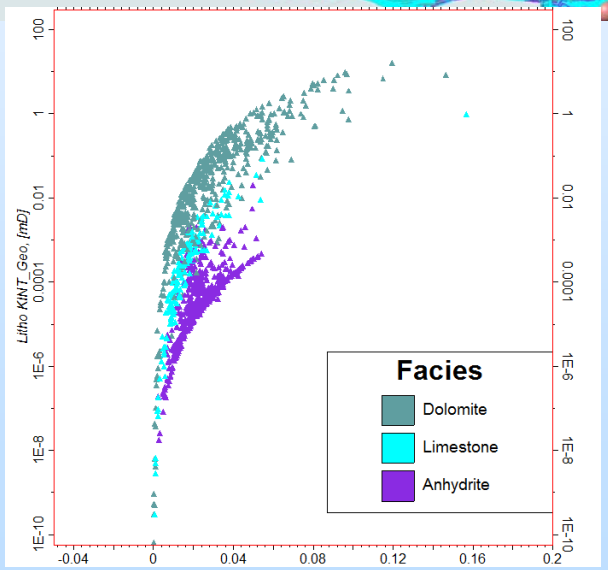
Facies, Porosity and Permeability Interpolation

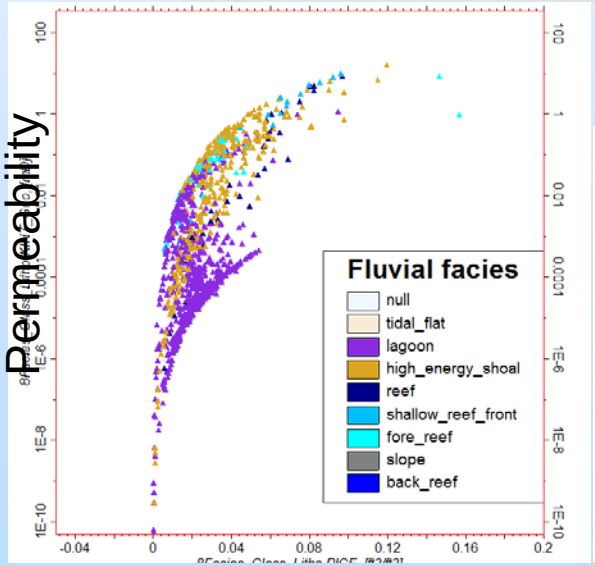
3-Rock Type



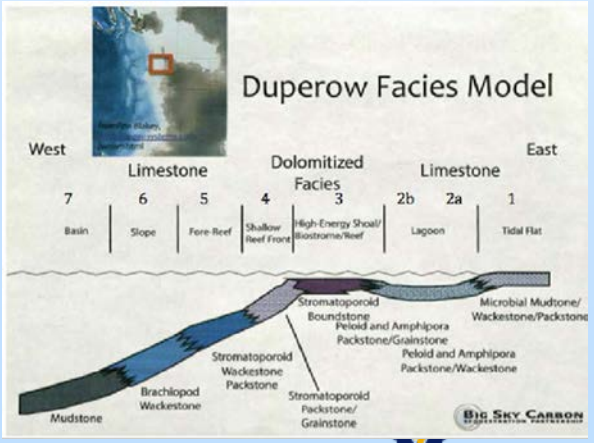
8-Rock Type







8 Rock Type model calibrated to geologist's (Dave Bowen) facies log and facies model



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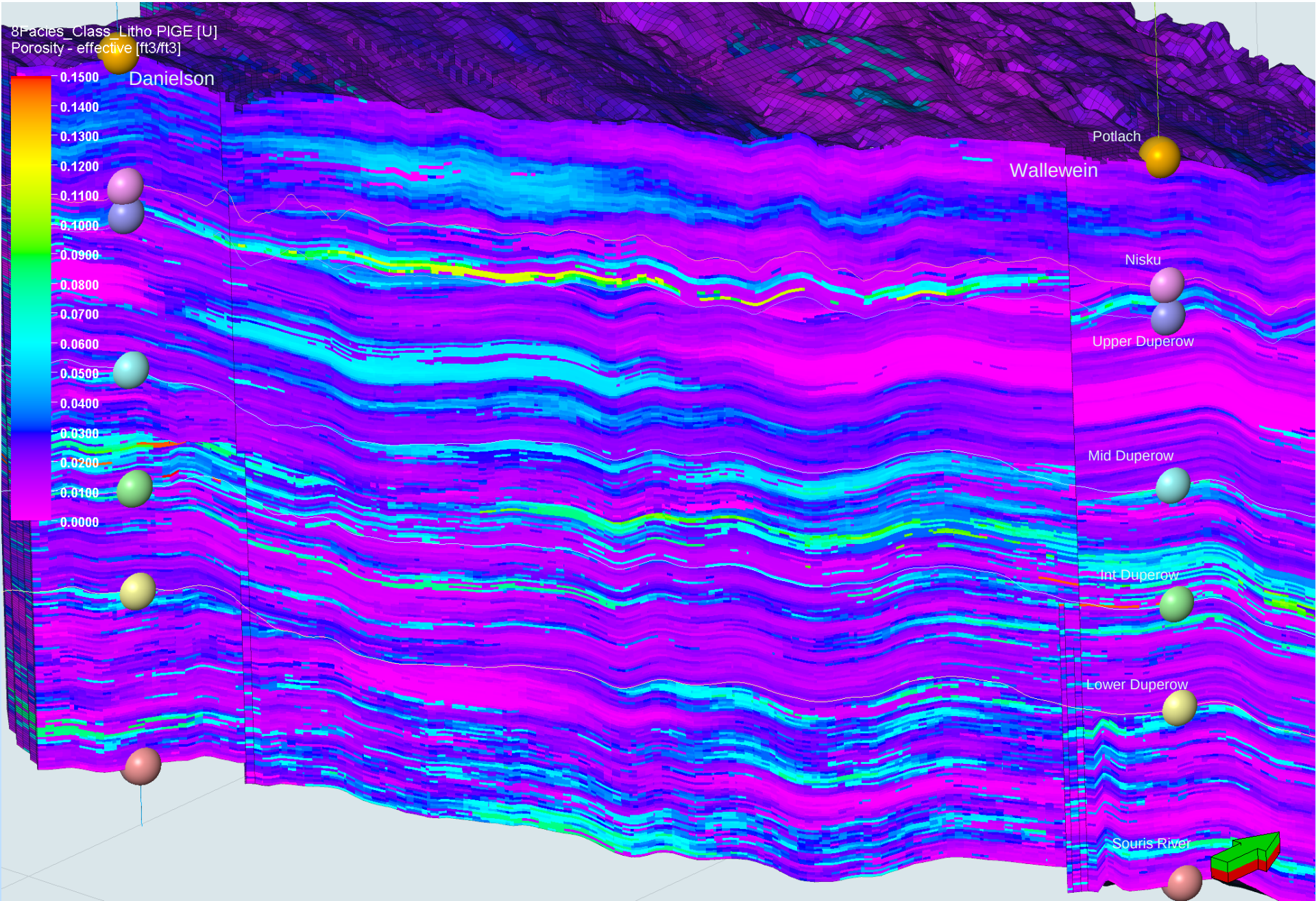
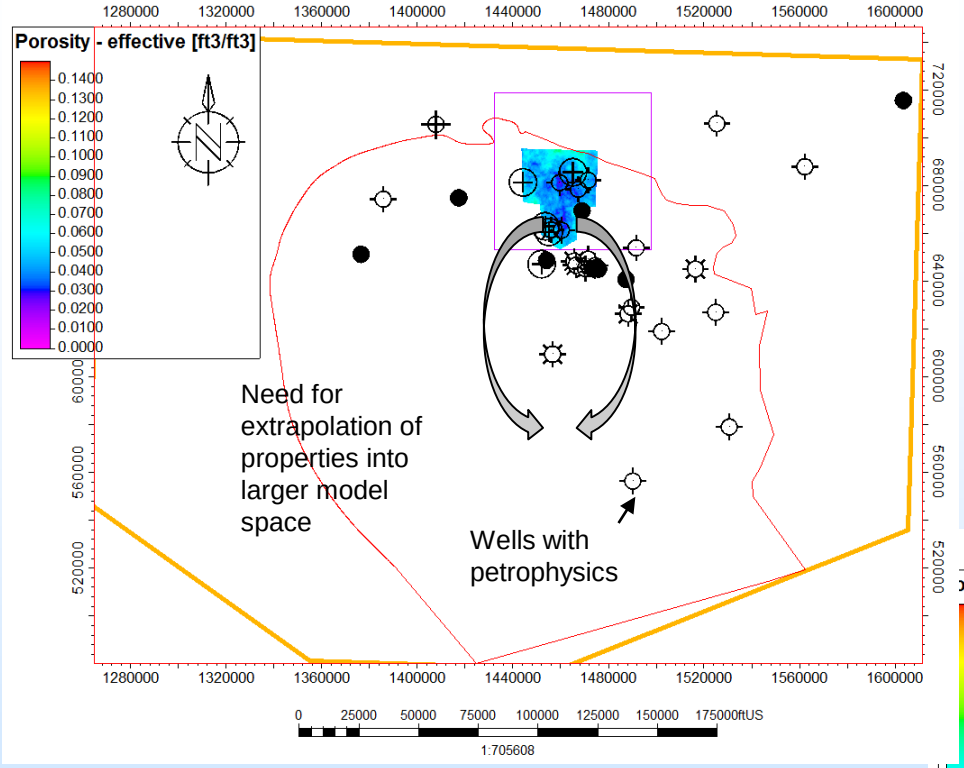
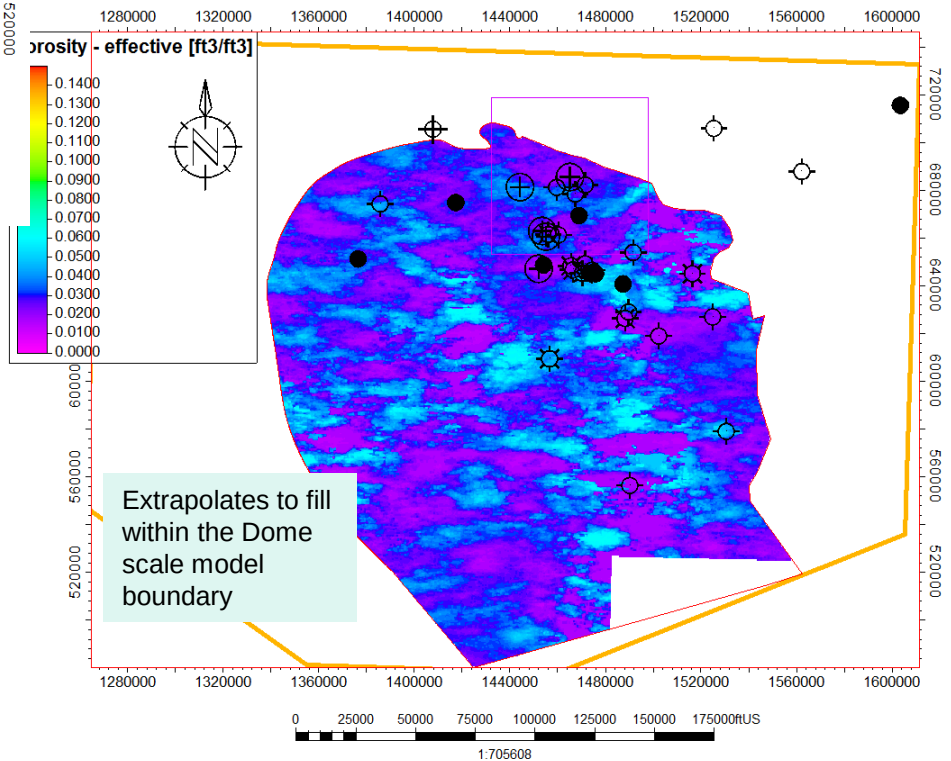
Property Interpolation (Porosity)



Dome Scale Model Property Extrapolation





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Motivation for lab seismic study

Harry Lisabeth, Jonathan Ajo Franklin

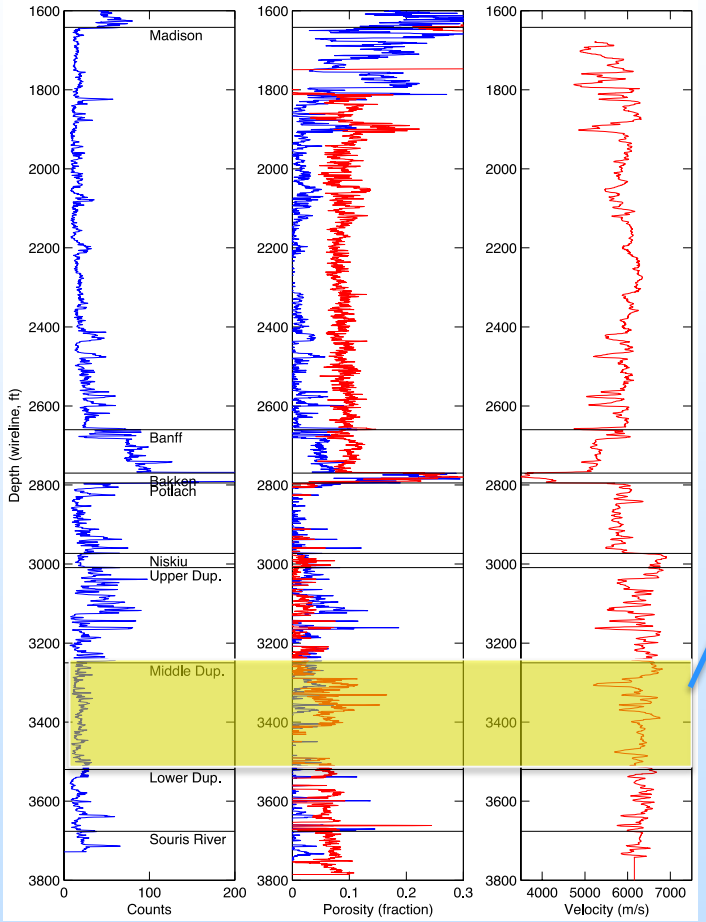
- Time-lapse (4D) seismic monitoring is one of the best tools we have to see dynamic changes in the subsurface

- Most of our understanding of changes in seismic response due to fluid replacement and stress perturbation are from studies of porous sandstones. We have much less understanding of these effects in low porosity, fractured carbonate reservoirs

- Measurements in the laboratory allow us to deconvolve complex effects of geology and gain understanding of the fundamental physics at play during fluid substitution and pressure changes

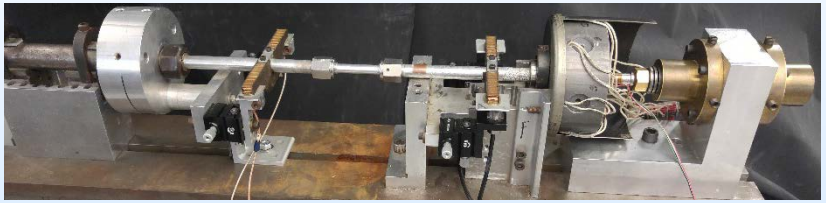
Laboratory study of structure and broadband seismic characteristics of fractured, fluid-filled reservoir material

Danielson Well (Production Pad)

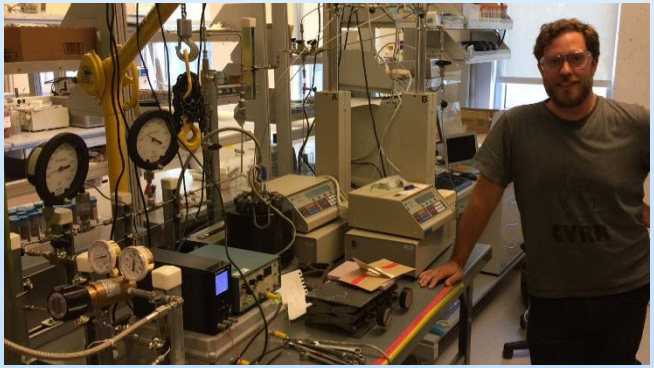


Gamma Neutron Sonic

Low frequency modulus/attenuation



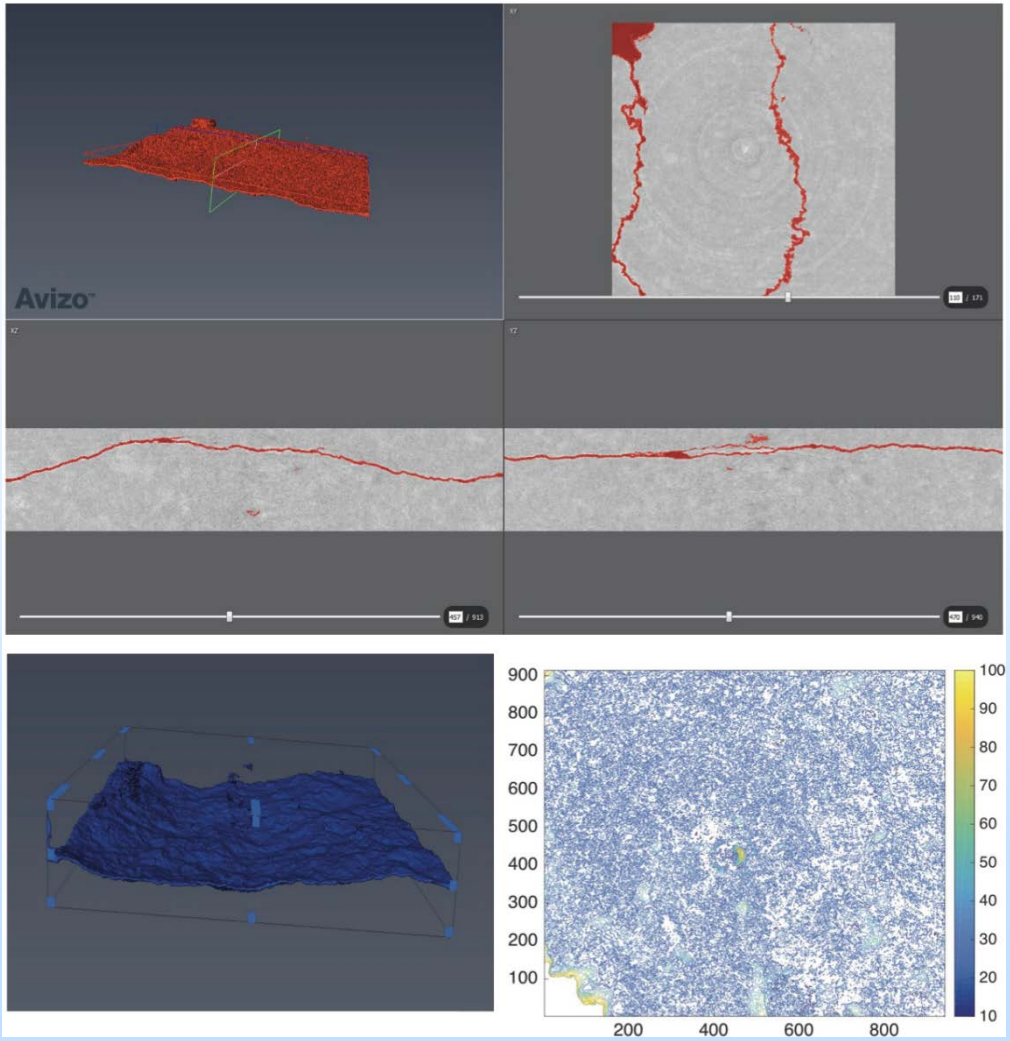
Fluid replacement/ultrasonic characterization



Synchrotron x-ray microtomography of fractured Duperow dolomite

- Fracture shows multiscale roughness, with undulations at the scale of the sample (9mm)
- Secondary fractures sub-parallel to primary fracture are evident
- At 0 pressure, aperture ranges from 10 to 100 microns
- mCT conducted to identify features of natural fractures which differ from induced tensile fractures.

[Conducted at beamline 8.3.2, Advanced Light Source]



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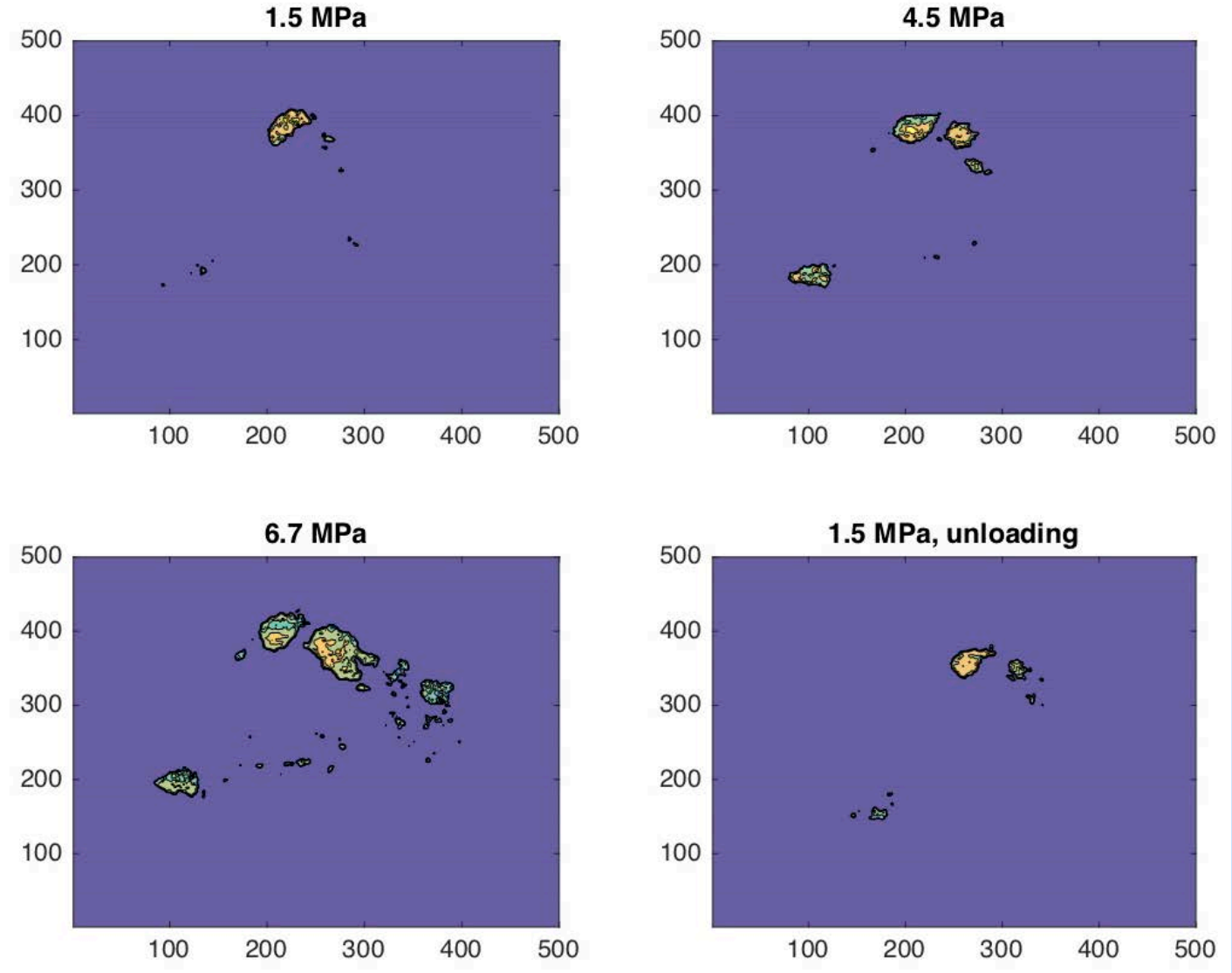
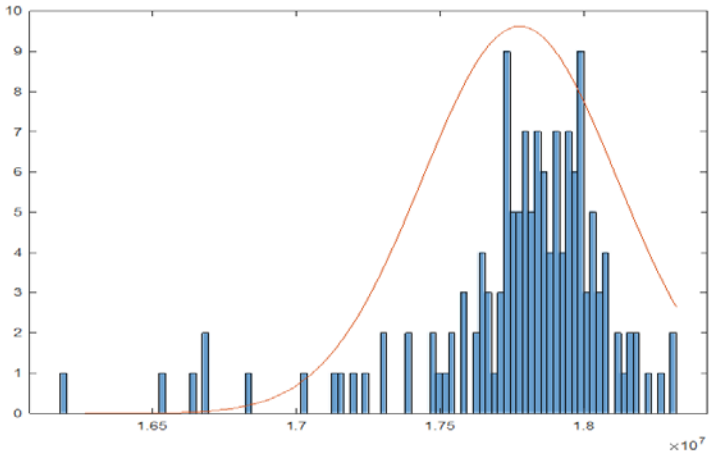
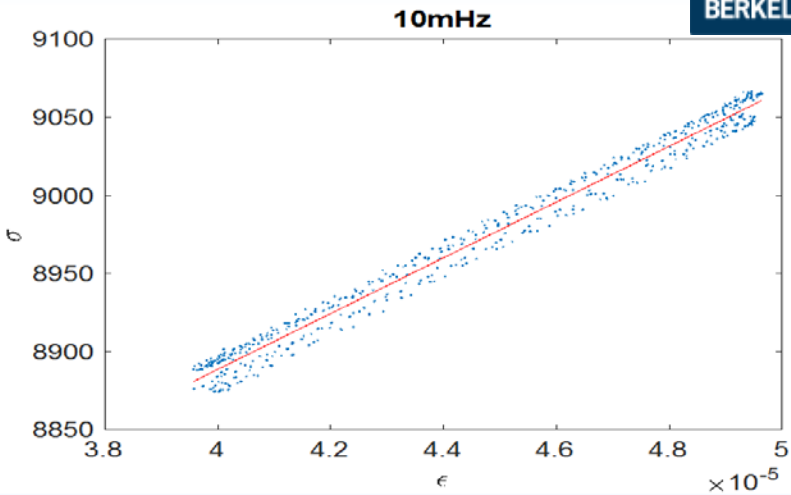
Pressure-sensitive film measurements

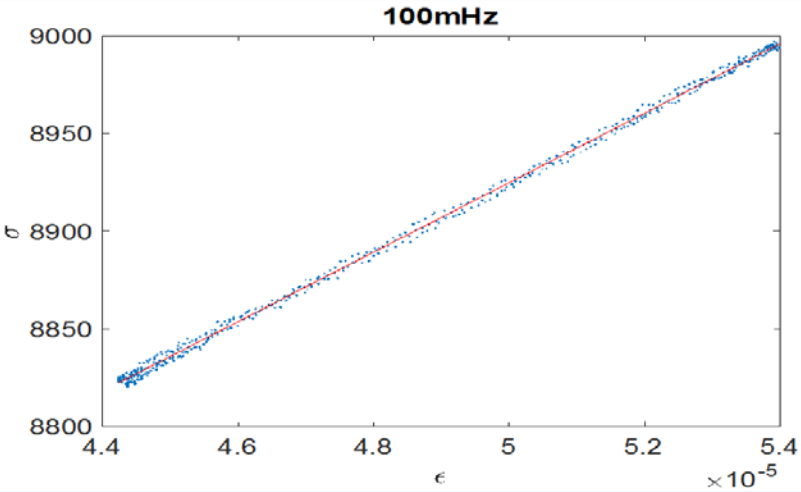


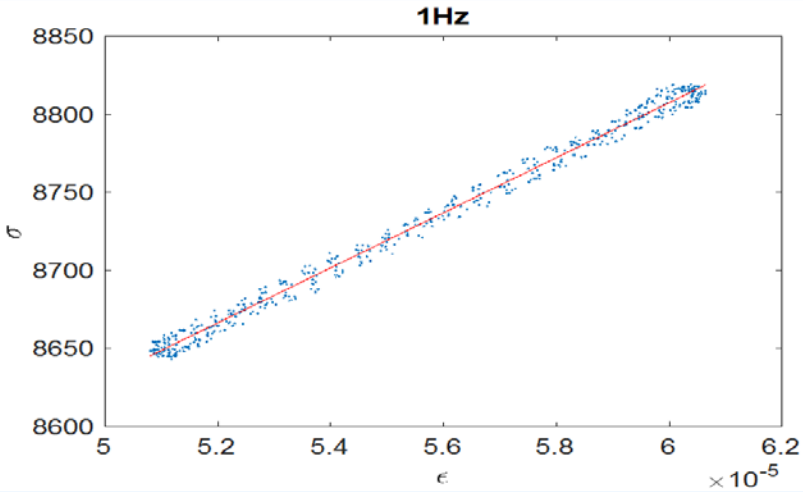
With increasing normal stress, asperities grow and local stresses are intensified

Low frequency measurements of Duperow dolomite



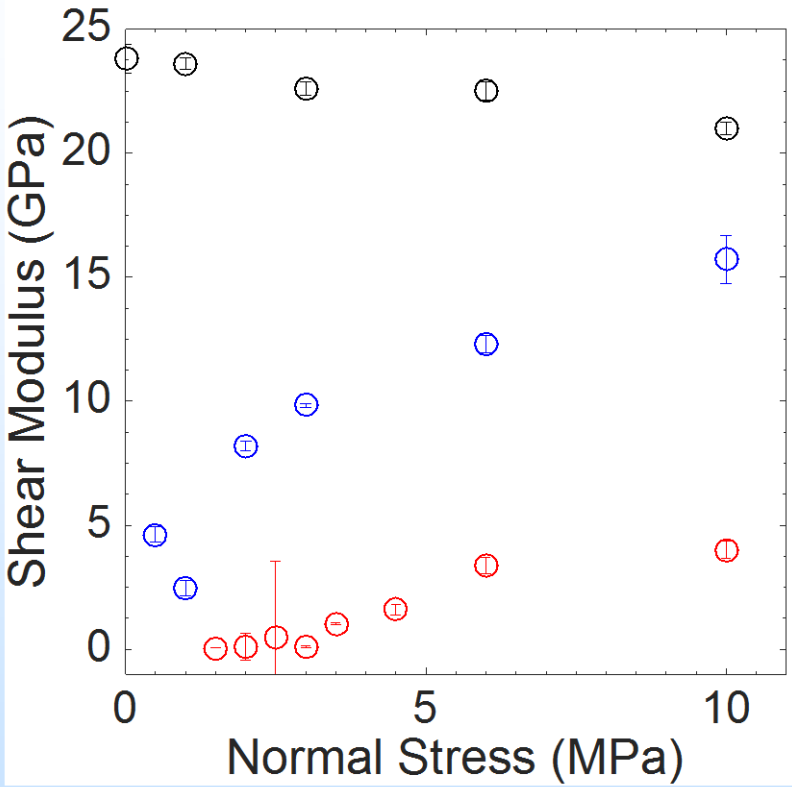


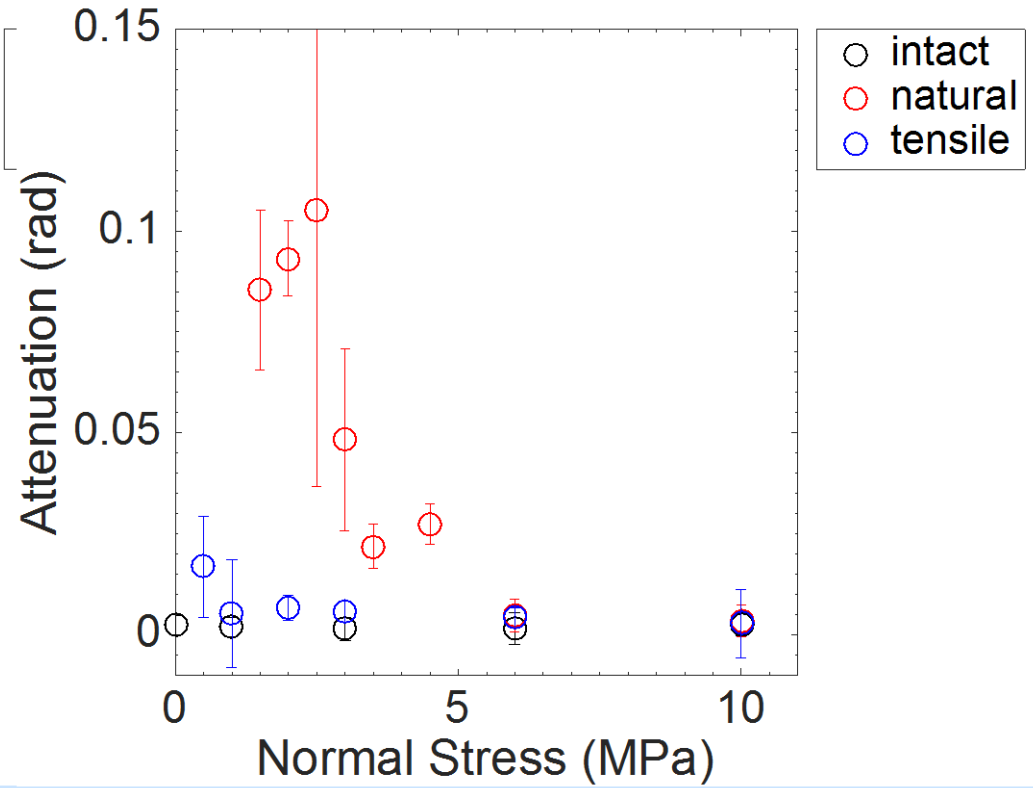




We have pushed our measurements capabilities down to 10mHz

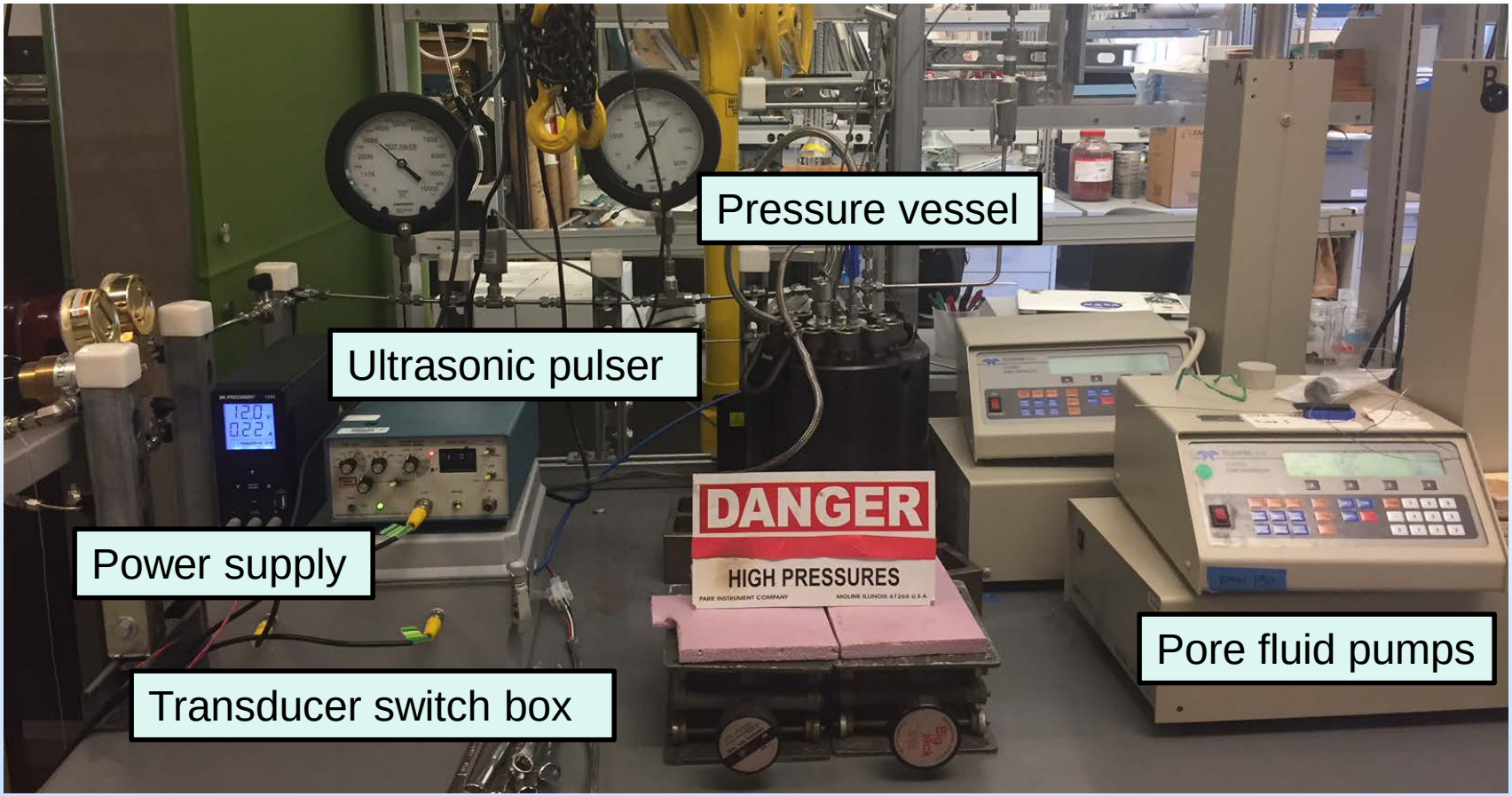
Comparison of intact, naturally fractured and tensile fractured Duperow @ 8Hz





Natural fracture has lower and less pressure dependent modulus than induced tensile fracture, and shows greater attenuation at low normal stress.

Operational high pressure, flow-through vessel with ultrasonic measurement

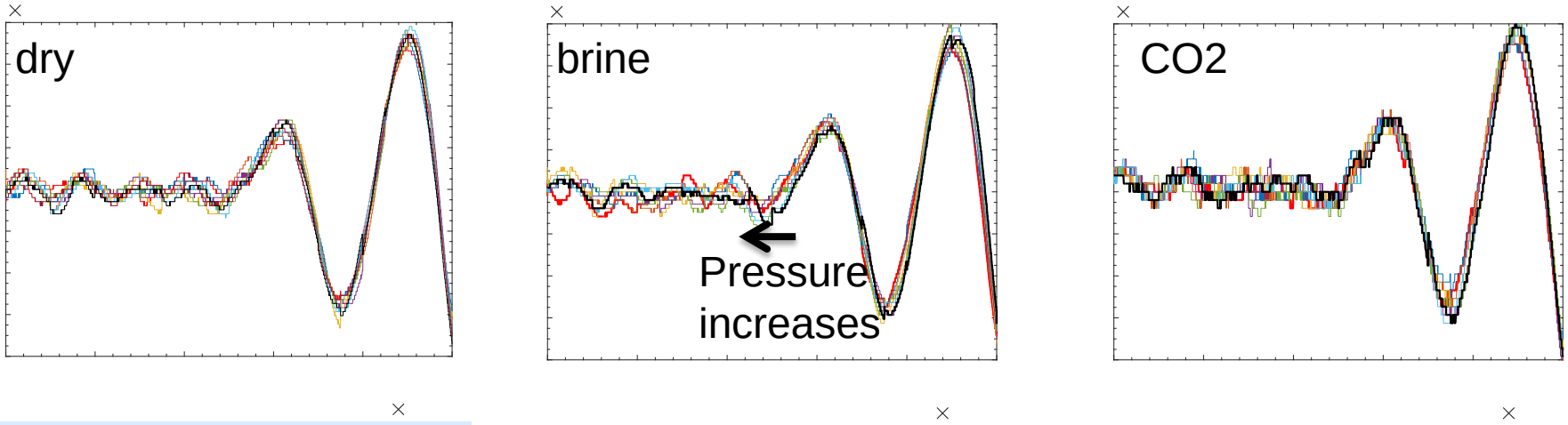


Repairs and slight redesign allows for ultrasonic characterization of fluid replacement and pressure dependence of acoustic velocities at in-situ conditions

Initial ultrasonic results, Danielson Core (~3379 ft)

P-waves

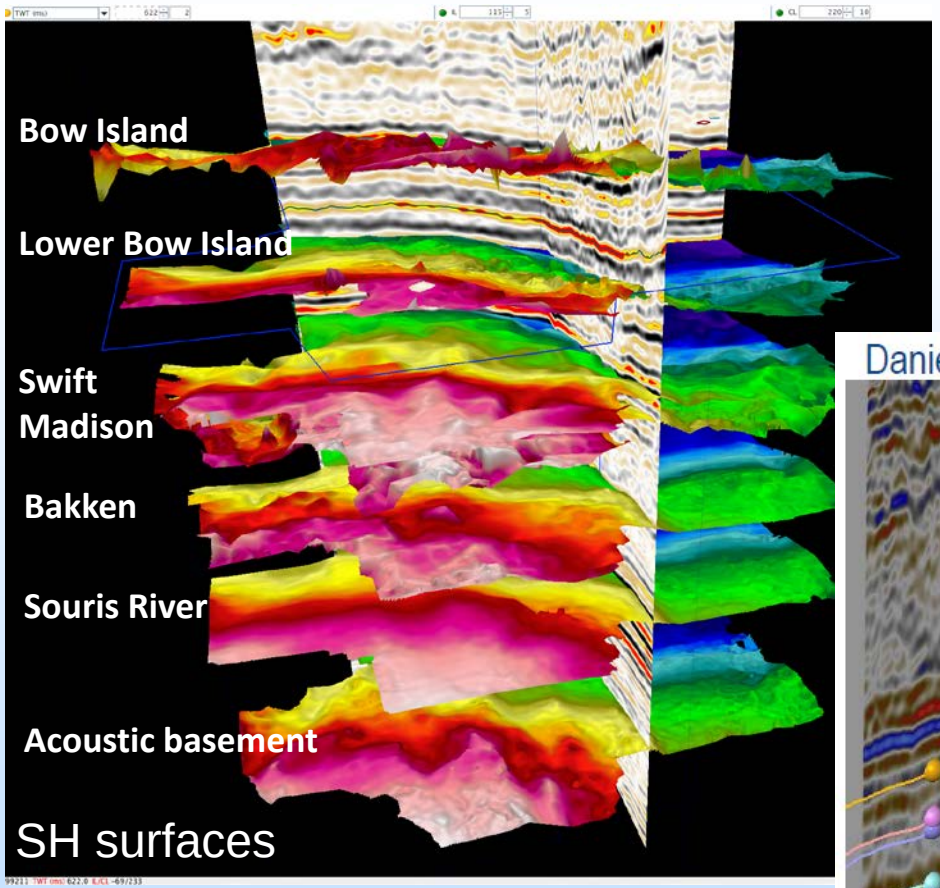
Pp = 1500 psi, Cp = 1550 – 4000 psi



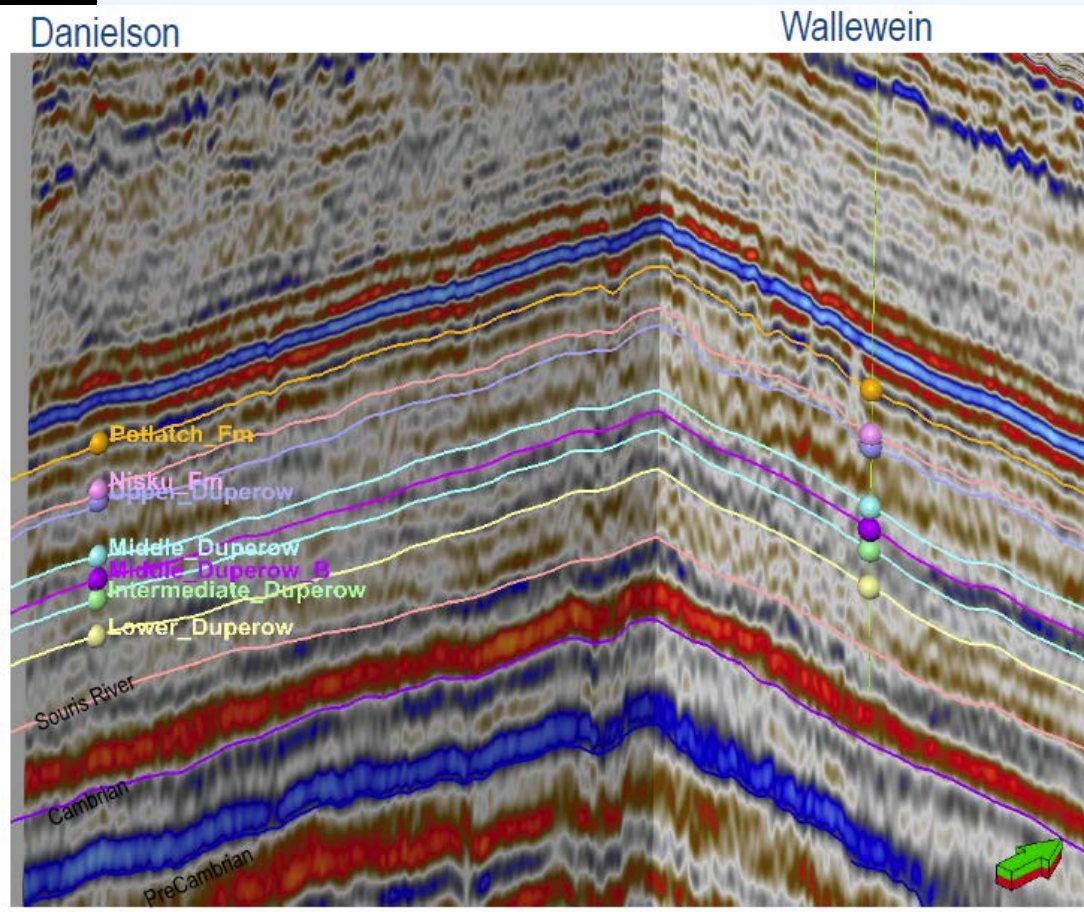
- Well-mated fracture in Duperow dolomite from Danielson well shows surprisingly little pressure dependence in the ultrasonic range; substitution of liquid CO_2 for brine reduces the pressure dependence to negligible.
- Results show smaller dependence than low F torsional shear measurements – potentially due to dominance of single stiff asperities in ultrasonic tests.
- Results show the challenge of seismic monitoring stiff formations with low porosity – fracture response may be greater at lower F and for sheared fractures.

Processing 3D, 9C siesmic Seismic

Vecta Oil & Gas Ltd.



SH surfaces



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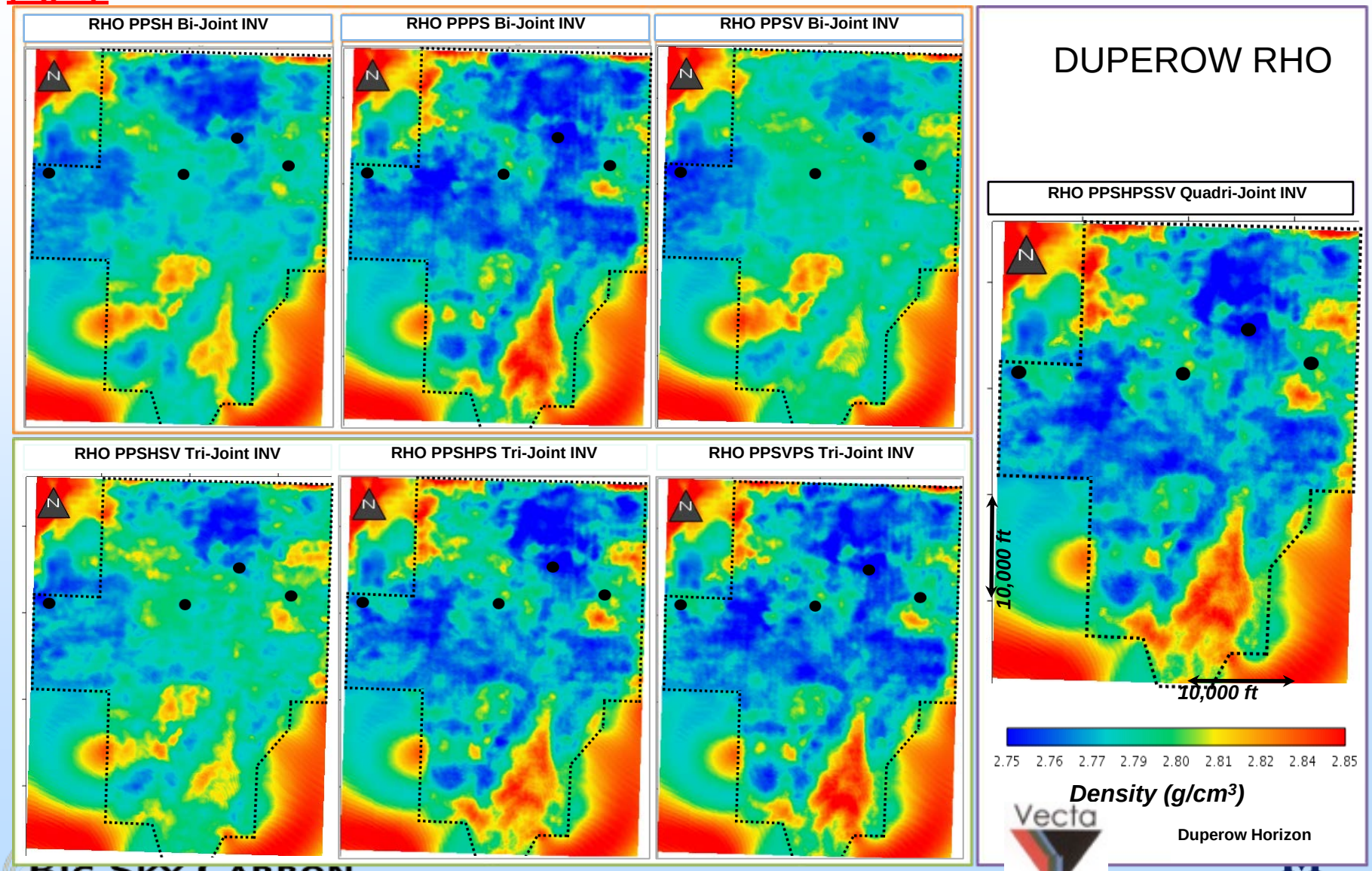
Comparison at mid-Duperow horizon of the inverted density parameter obtained with different kinds of wavefields. bi-joint inversion (3 images at the top), tri-joint (3 images at the bottom) and quadri-joint inversion (right). bi-joint *PP-PS* inversion is very similar to the final **quadri-joint inversion (right).**



Crossplot between density porosity and computed *P*-wave impedance (*IP*) from the Wallewein 22-1 well over the Middle Duperow porosity interval. Note the good correlation observed between the two quantities. The correlation coefficient between the two quantities is 0.87. Colored values are measured *IS* values.

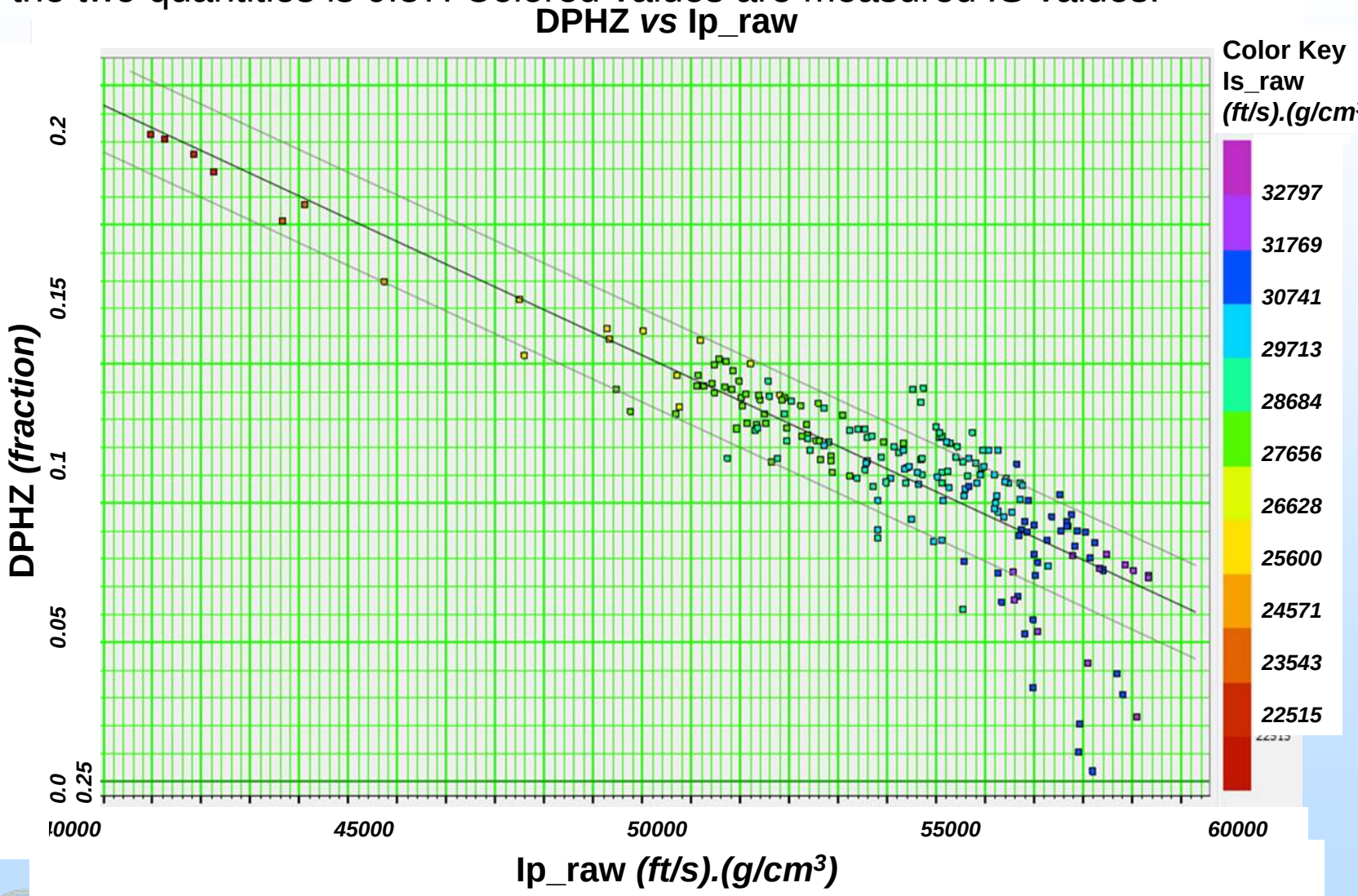
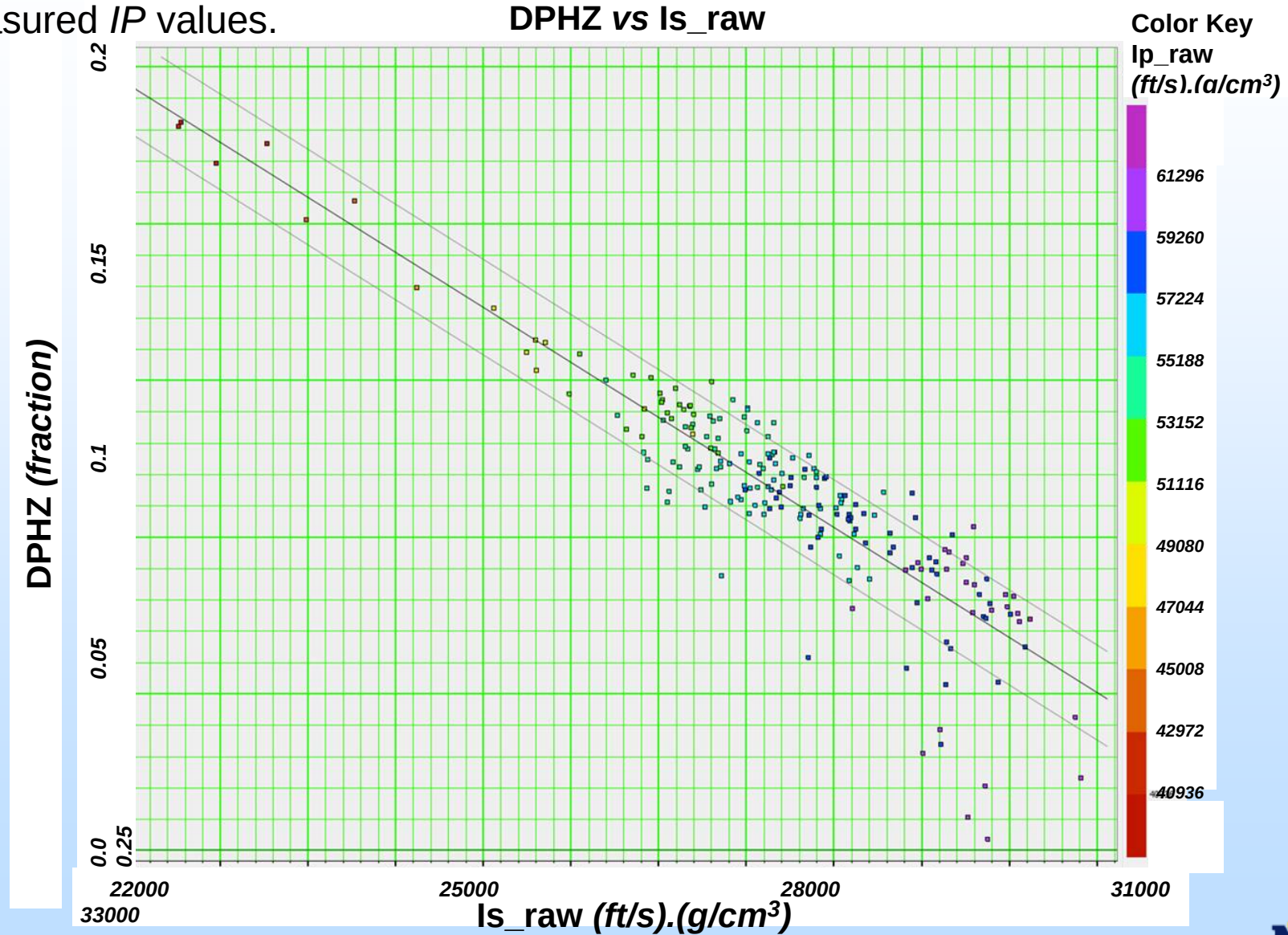


Figure 12

Crossplot of measured density porosity and *S*-wave impedance (*IS*) in Wallewein 22-1 well in mid-Duperow porosity zone. Note excellent agreement between measured two quantities with correlation coefficient of 0.89. Colored values are measured *IP* values.



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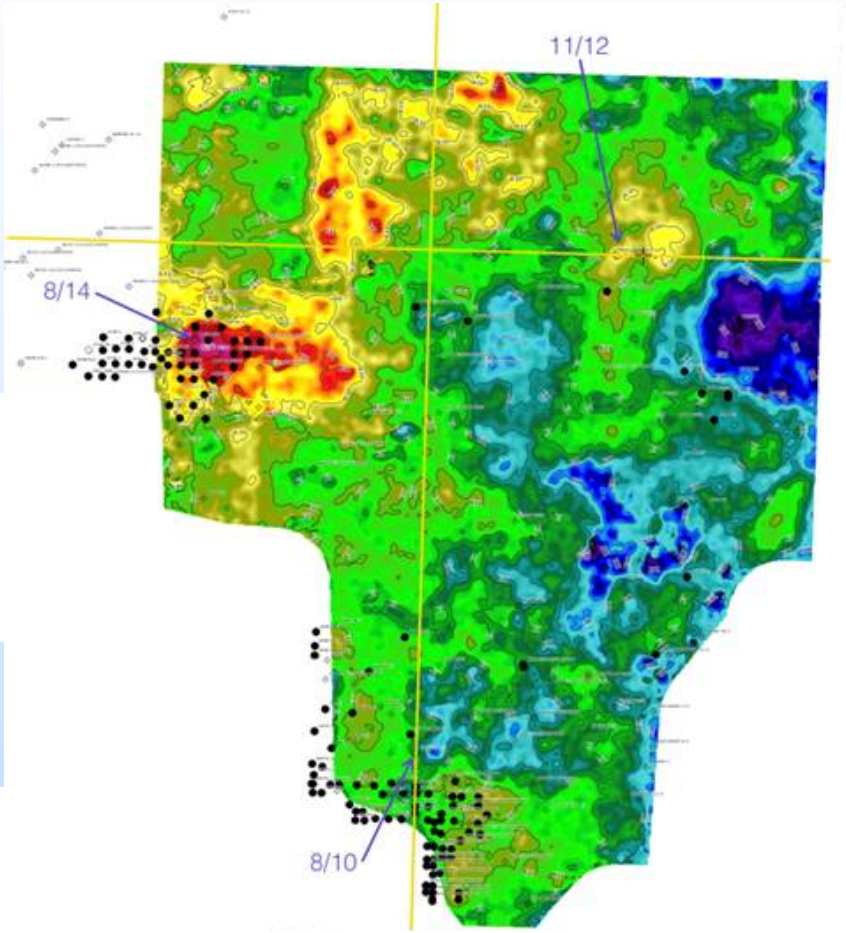
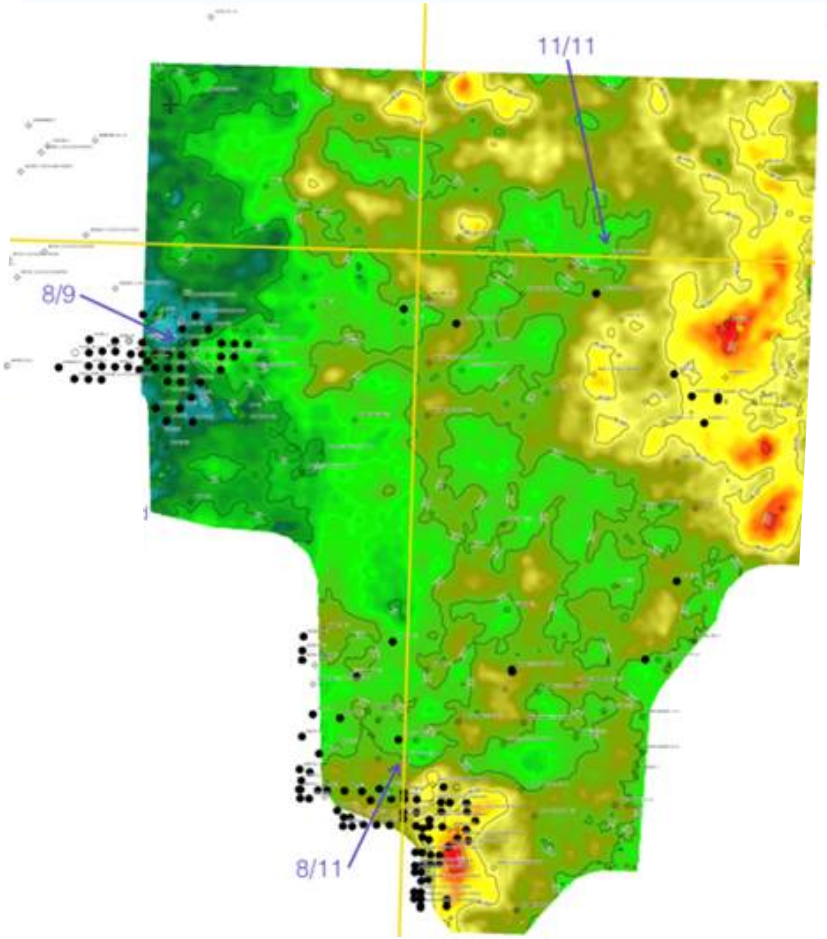
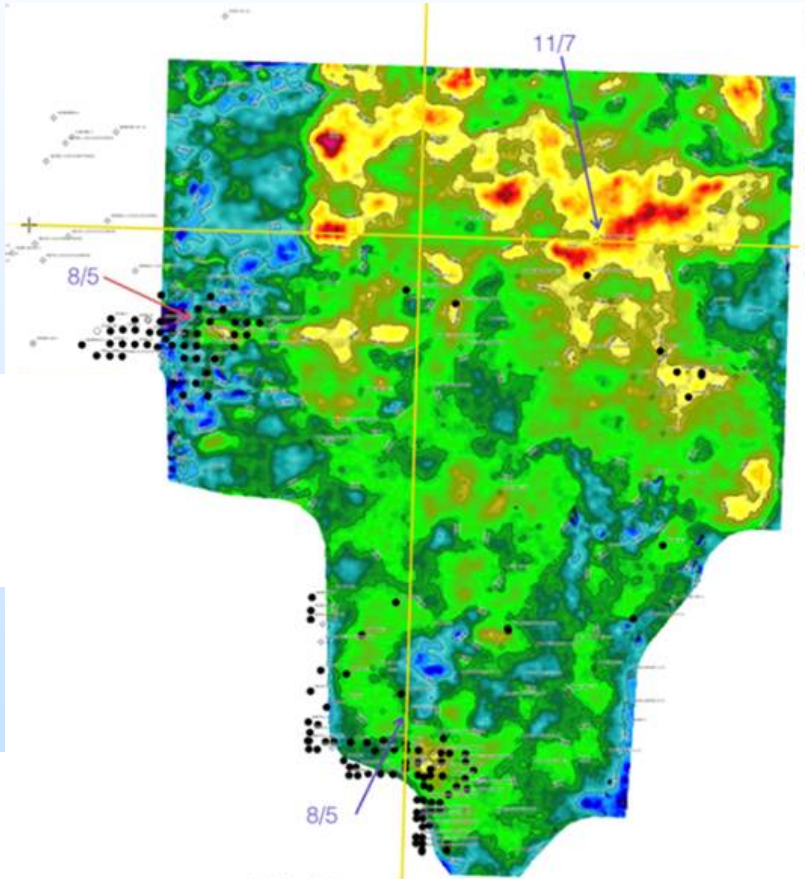
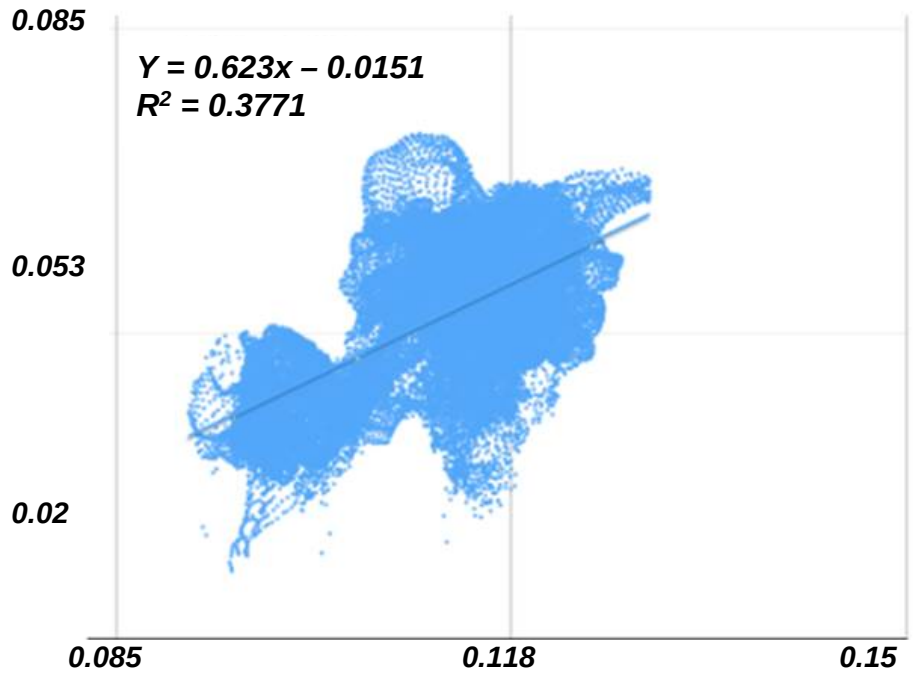
Transforms derived from porosity-impedance regressions using *IS* (left) and *IP* (right) maps for the Middle Duperow porosity zone with well locations annotated and well derived values for porosity annotated with values derived from each map at well locations.





Mid-Duperow porosity derived from average density values from quadri-joint inversion converted to porosity using a dolomite matrix (left) and cross plot of this map with values derived from *IP*-based regression shown in Figure 14. Note the poorer agreement with well values for the density-derived estimate but generally smaller amount of absolute variation than for that derived from the *IP* regression.

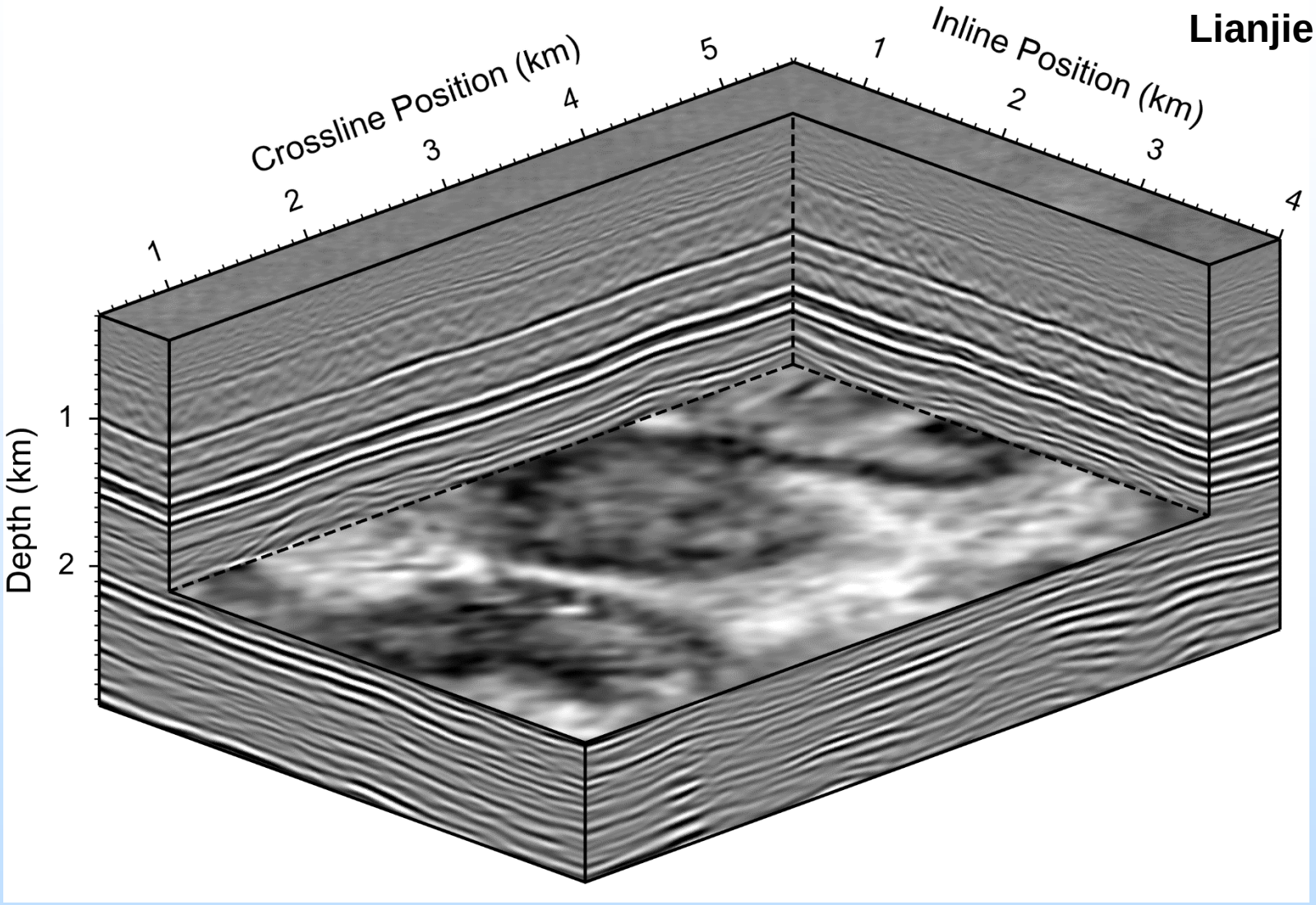




LANL's 3D Reverse-Time Migration Image of 3D Kevin Dome Seismic Data

Los Alamos NATIONAL LABORATORY

Lianjie Huang



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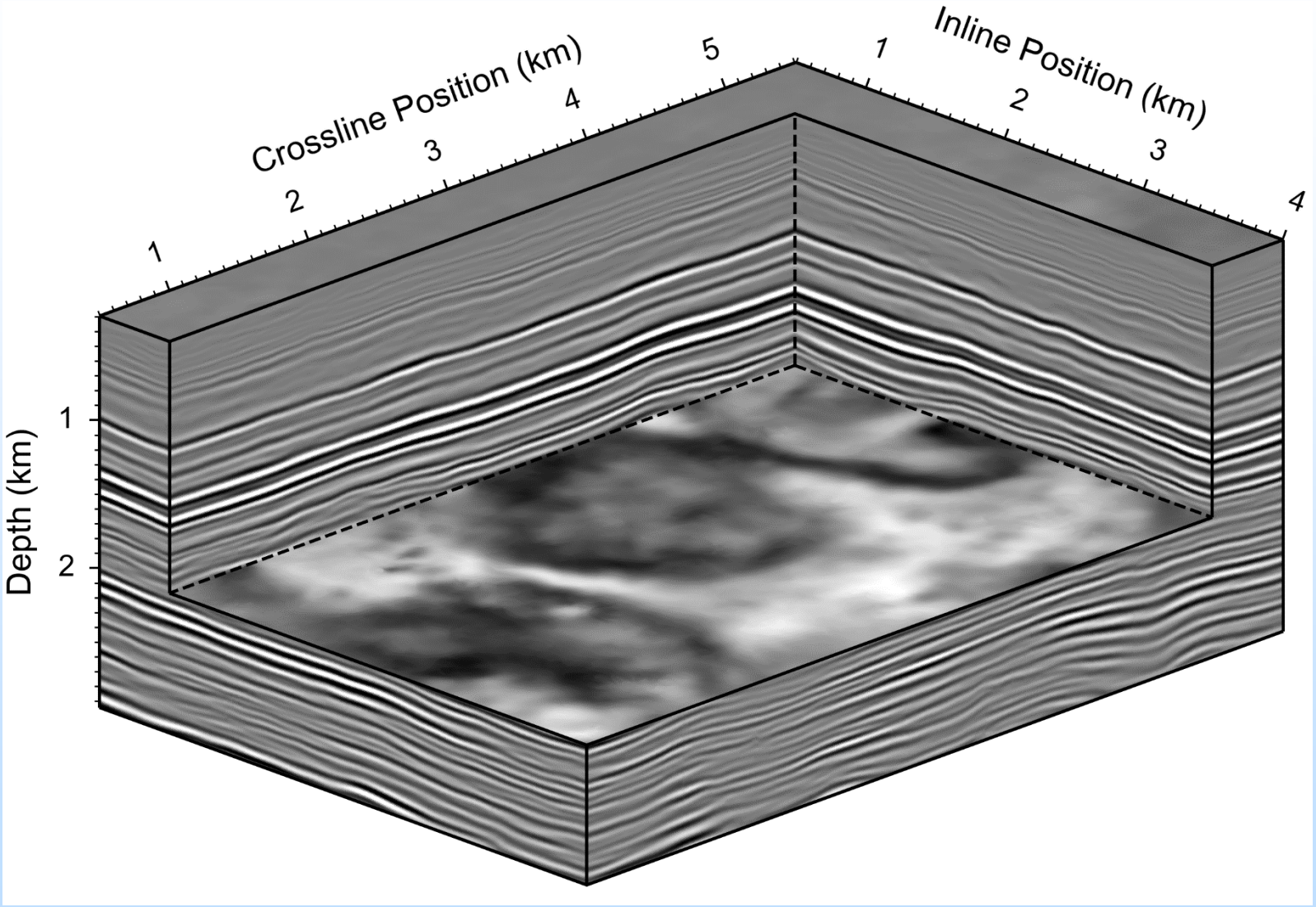
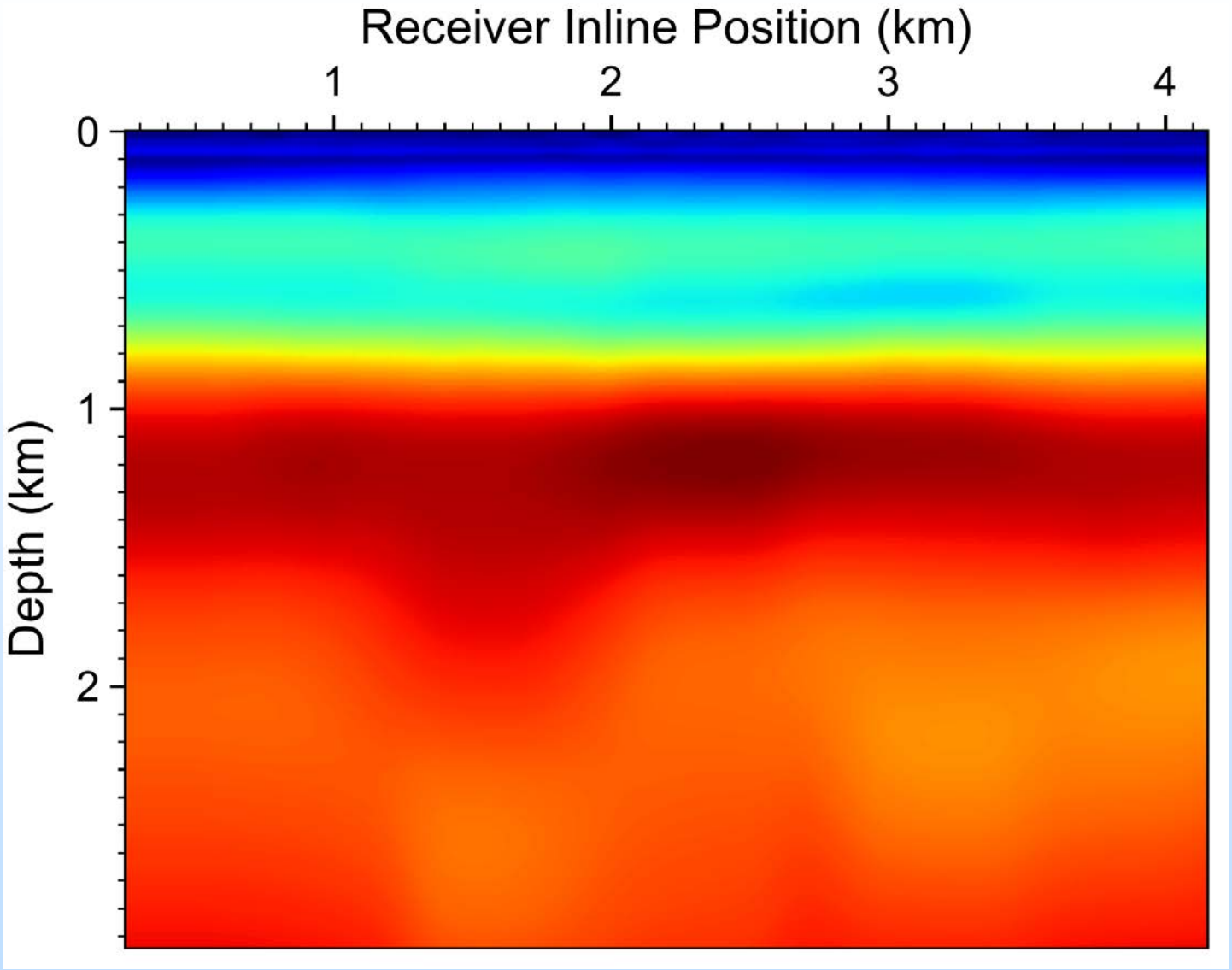
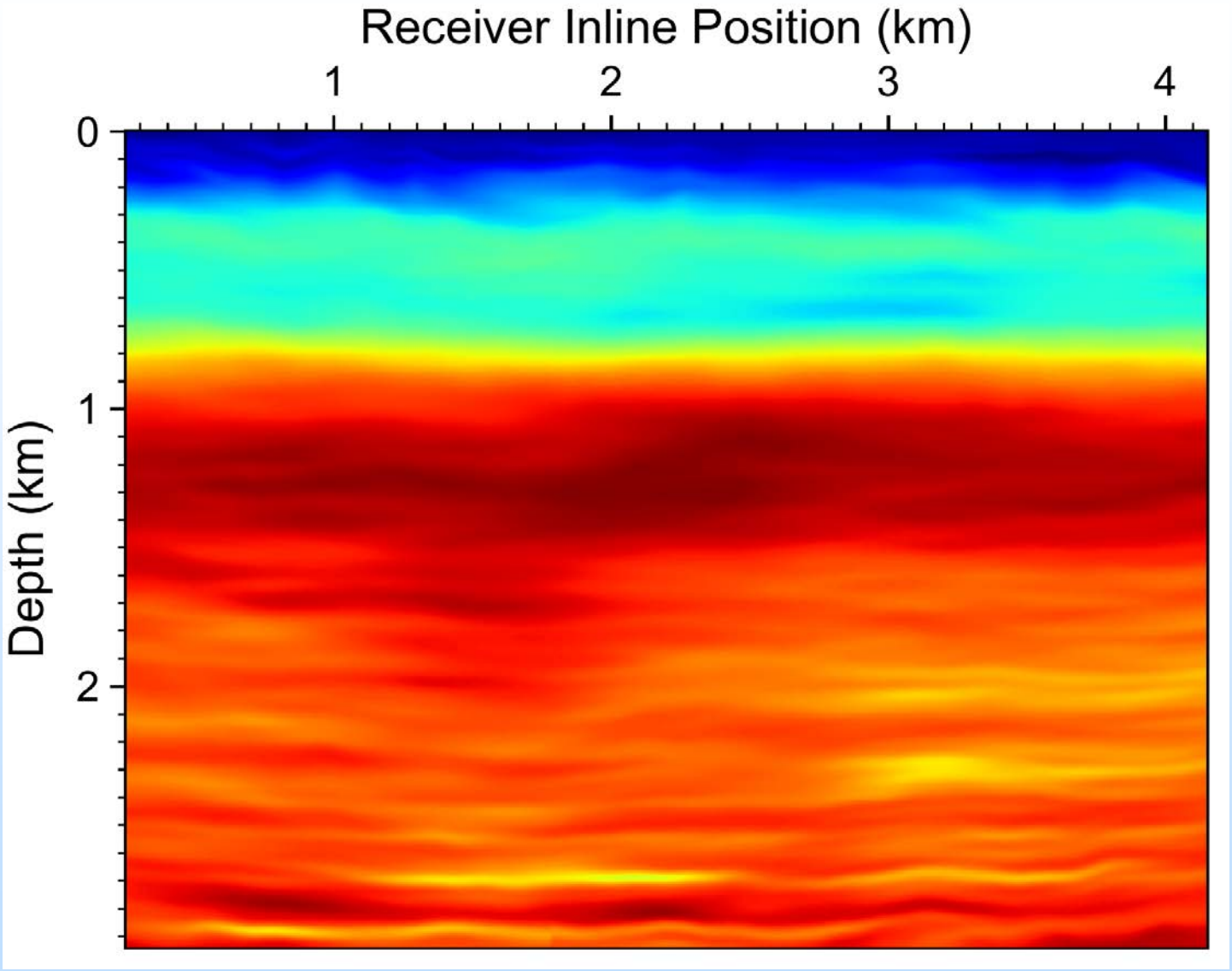
LANL's 3D Structure-Enhanced Least-Squares Reverse-Time Migration Image of 3D Kevin Dome Seismic Data (Further Improved Result)



2D slice of initial low-resolution subsurface velocity model for the Kevin Dome site



2D slice of LANL's high-resolution subsurface velocity model for the Kevin Dome site obtained using full-waveform inversion



Modeling of the Instrumented CO_2 Production Test at the Danielson 33-17 Well (Dec. 26-28, 2014)

Lehua Pan, Curtis M. Oldenburg, and Quanlin Zhou
Energy Geosciences Division
Lawrence Berkeley National Laboratory

July 26, 2018

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MONTANA STATE UNIVERSITY

Modeling of the Instrumented CO_2 Production Test at the Danielson 33-17 Well (Dec. 26-28, 2014)

Lehua Pan, Curtis M. Oldenburg, and Quanlin Zhou

- The CO_2 production test of the Danielson well in 2014 showed very low temperatures in the well and low CO_2 production rate.
- We have simulated this production test to understand the causes of low T and low productivity.
- We use TOUGH2/ECO2M.
- Existing versions of ECO2M had difficulty converging during gas-liquid phase change.
- We developed a new version of ECO2M that solves the convergence problems related to CO_2 phase change.
- TOUGH2/ECO2M retains the lower T limit of 0 ºC because the module does not simulate water ice nor hydrate formation.
- We are able to match the production test measurements if we assume a spatially variable permeability field.

Overview

- The CO_2 production test of the Danielson well in 2014 showed very low temperatures in the well and low CO_2 production rate.
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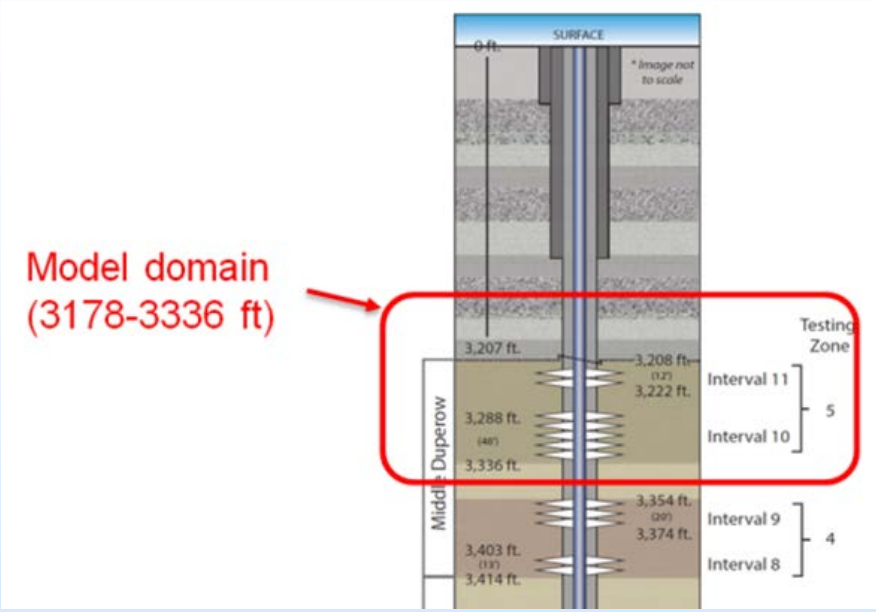
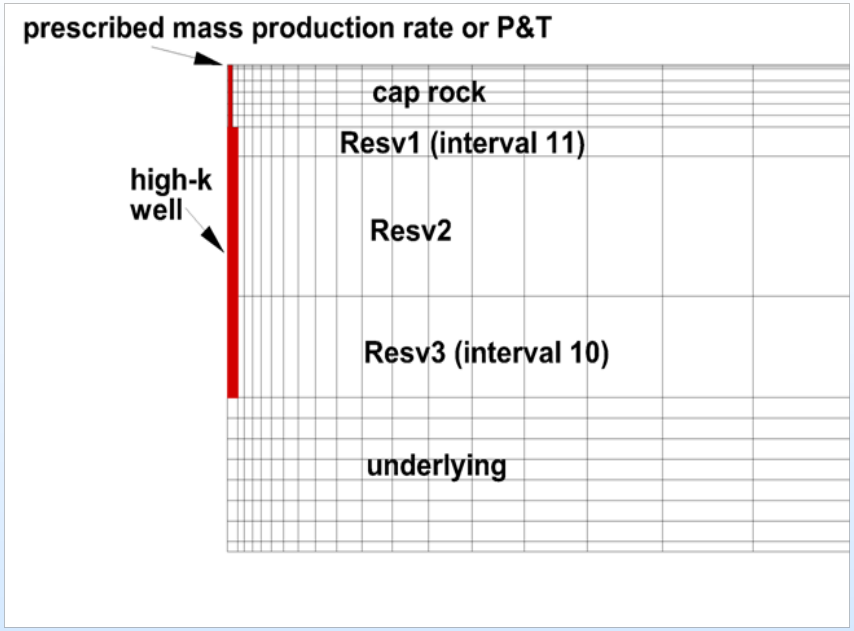
- TOUGH2/ECO2M retains the lower T limit of 0 ºC because the module does not simulate water ice nor hydrate formation.
- We are able to match the production test measurements if we assume a spatially variable permeability field.

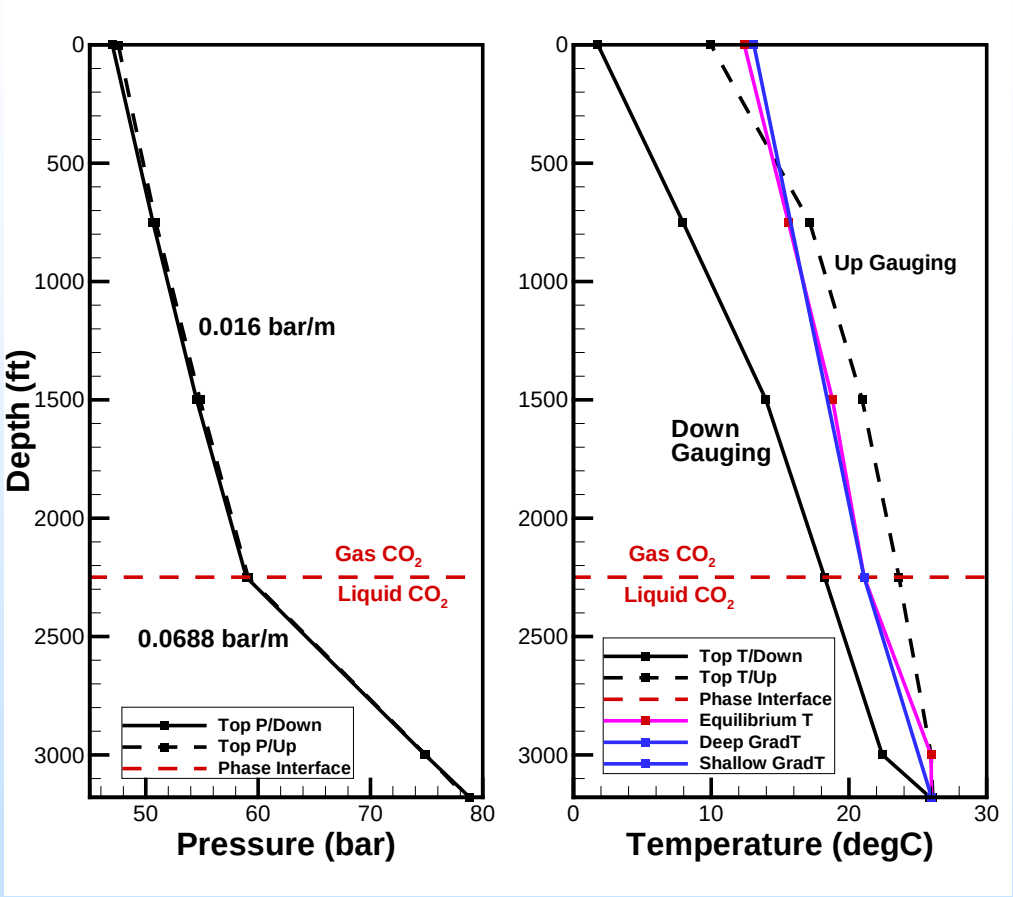
Danielson well test interval and model grid





- Radially symmetric grid (dR varies from 0.1 m near well to 100 m at R = 1 km).
- 2 7/8” tubing (ID = 0.062 m) and 5 ½” casing (ID = 0.124 m) are modeled as high-k equivalent porous media with zero capillary pressure and unit porosity.
- All boundaries are closed except for the top of the simulated well which is at the downhole gauge depth.

CO_2 is in <u>liquid</u> phase in the model domain at the start of the production test

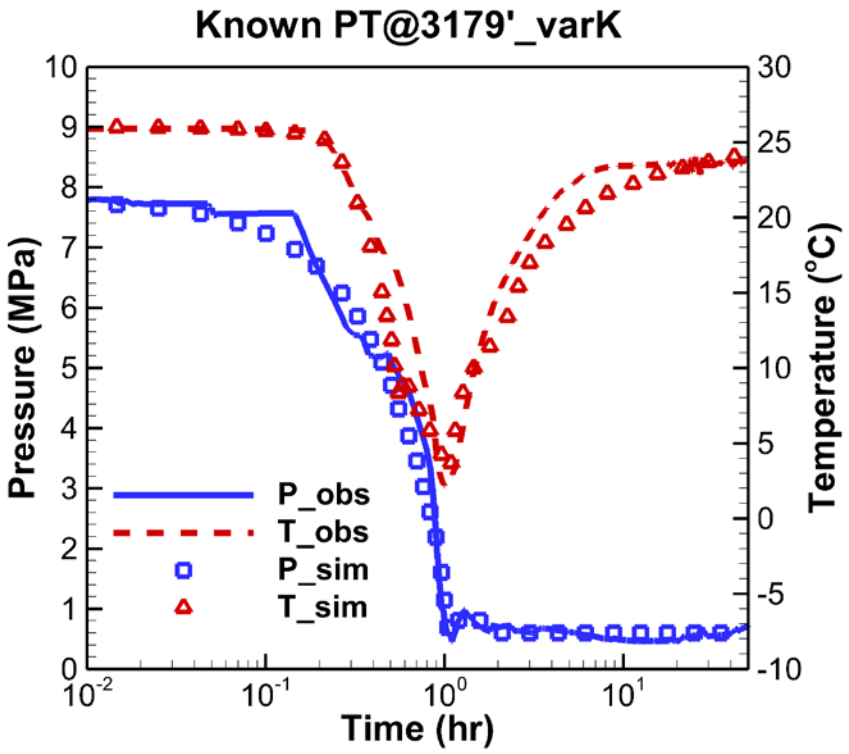


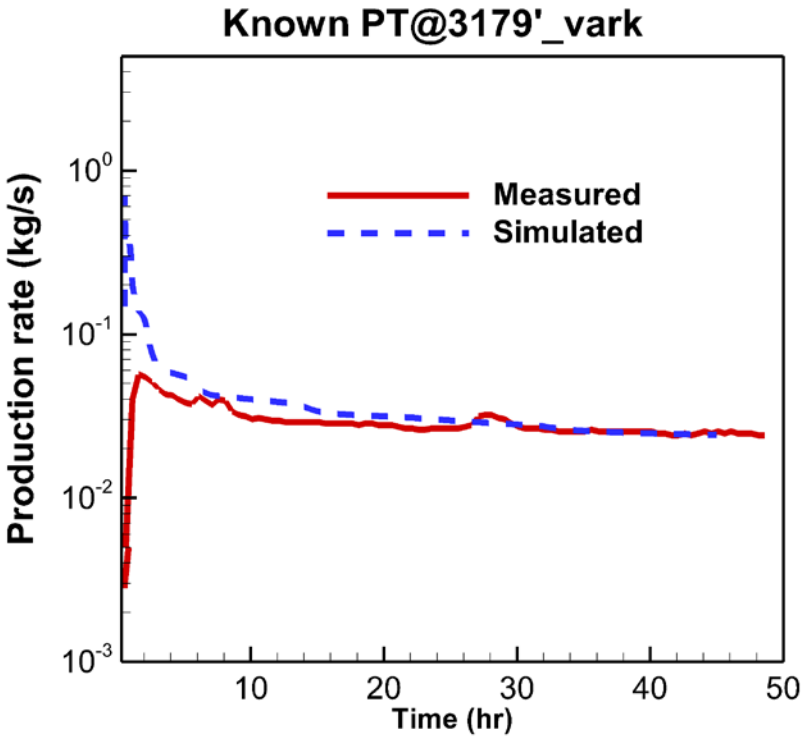
Measured P & T profiles in the entire well before and after the production test (Dec. 26-28, 2014)

- Initial reservoir conditions:
  - Water saturation: 0.2 (< residual saturation)
  - CO_2 is in liquid phase

- This is a very challenging simulation problem because CO_2 production involves expansion of liquid CO_2 during phase transition to gas which causes cooling by both depressurization and latent heat effects.

TOUGH2/ECO2M matches field results for the case of a spatially varying permeability field





Assumes the core-measured permeability only reflects a small local zone around the well (< 0.522m) which is surrounded by much lower permeability zone

Rock	k (R<0.522m) (10^{-18} m^2)	k (R>0.522m) (10^{-18} m^2)
Resv1	84.4	0.1712
Resv3	4090.0	8.296

Spatially varying permeability

The model assumes the core-measured permeability reflects a small local zone around the well (< 0.522m) that is surrounded by a much lower permeability zone

Rock	k (R<0.522m) (10^{-18} m^2)	k (R>0.522m) (10^{-18} m^2)
Resv1	84.4	0.1712
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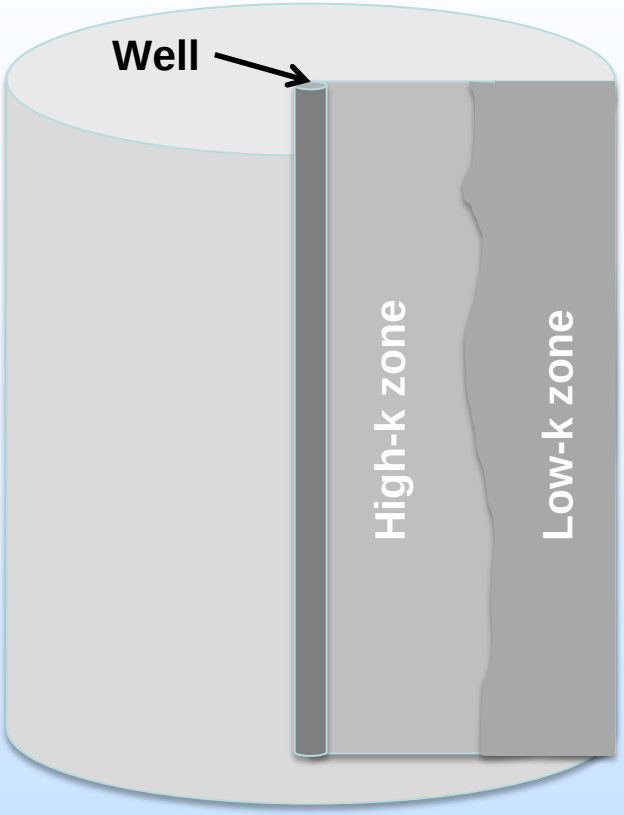
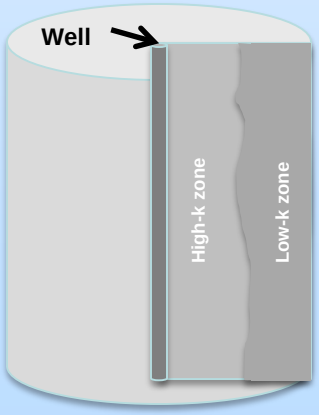


Conclusions

- The 2014 Danielson CO_2 production test is challenging to simulate because of low initial reservoir temperature and significant cooling caused by phase change and decompression.
- One way to match both production rate and temperature data is to assume a spatially varying permeability field in which the near-well region has higher permeability than the far-field region.
- Drilling can induce damage in the formation near the well that could result in such a configuration over these same length scales.
- Another source of low effective k could be formation of hydrate or water ice that plugs pore space.



Subtask R1.5

Lab measurements of fracture-matrix flow to help with modeling of two-phase flow in fractured carbonate

Chun Chang,Timothy J. Kneafsey, Quanlin Zhou

Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory

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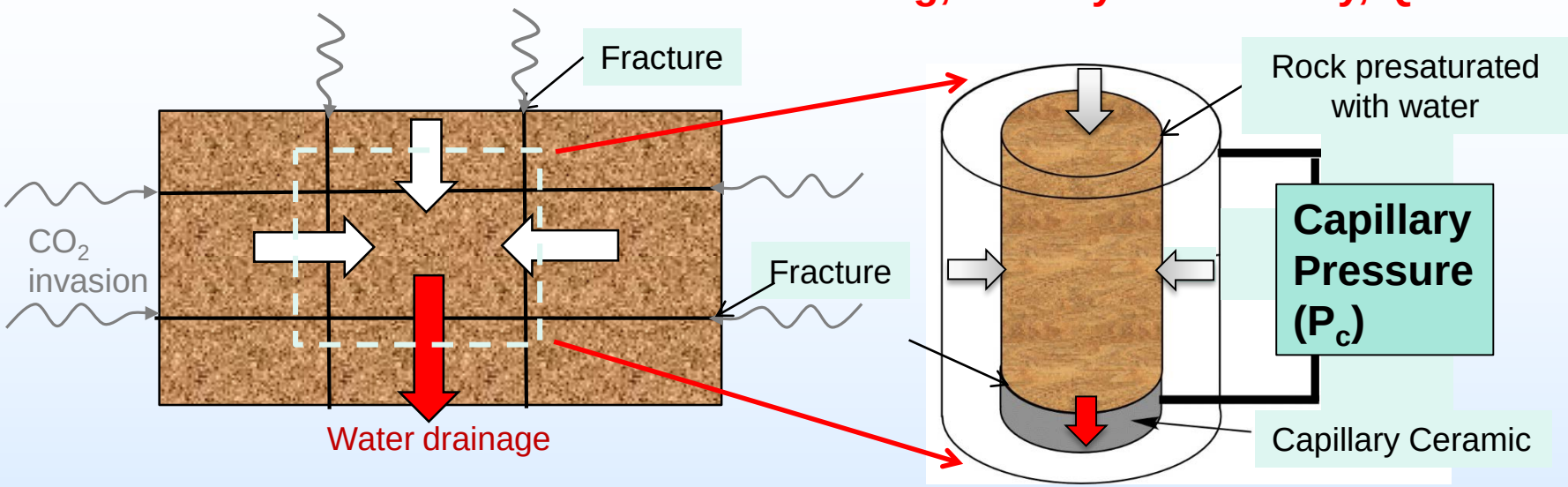
Subtask R1.5. Lab measurements of fracture-matrix flow to help with modeling of two-phase flow in fractured carbonate

Chun Chang,Timothy J. Kneafsey, Quanlin Zhou



CO_2 invasion into a fractured system and schematic of laboratory tests

Background:

To access CO_2 storage capacity in rock matrix, water must drain through fractures and matrix. Capillary continuity allows drainage across fractures to neighboring matrix blocks and requires quantification.

Laboratory flow tests were conducted to:

1. investigate the fracture-matrix interactions;
2. visualize processes showing the importance of capillary continuity to geologic carbon storage capacity.

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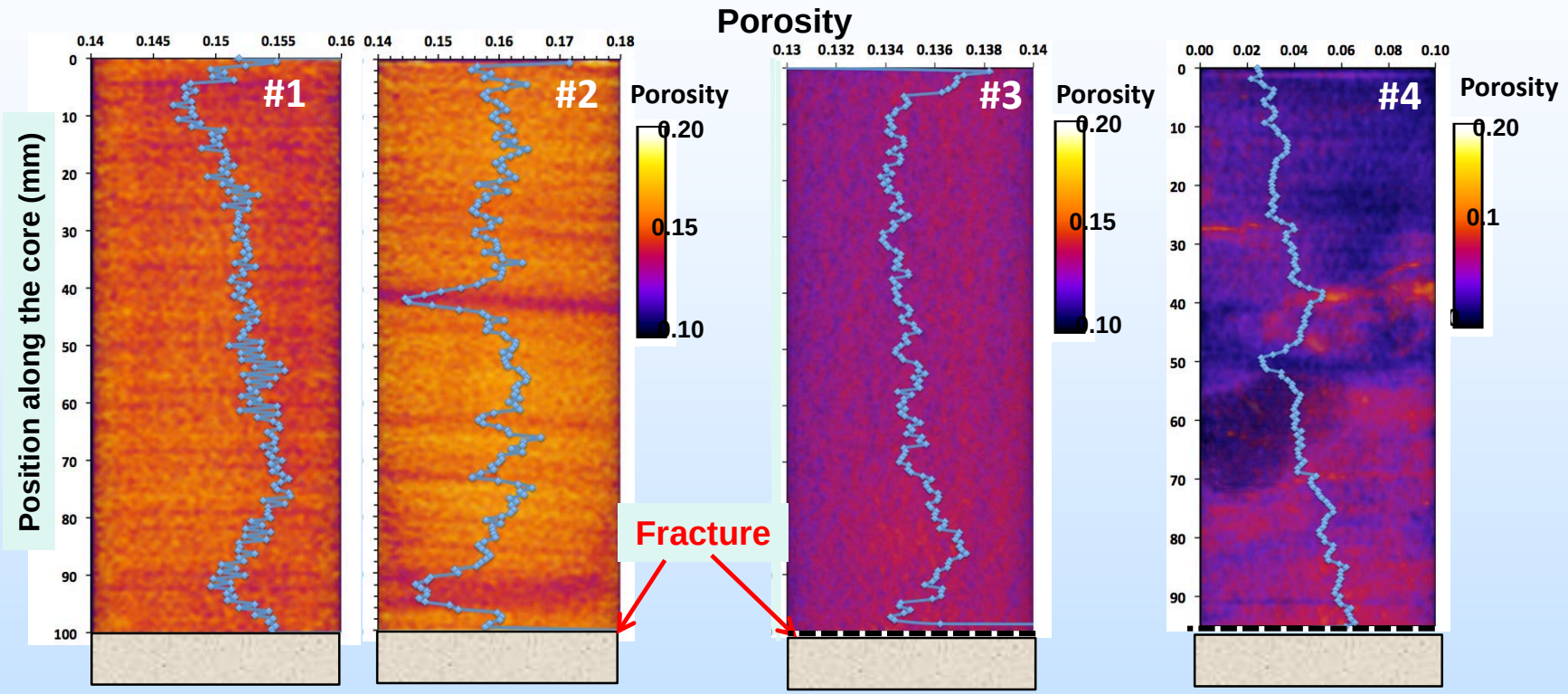
Core samples and fracture types

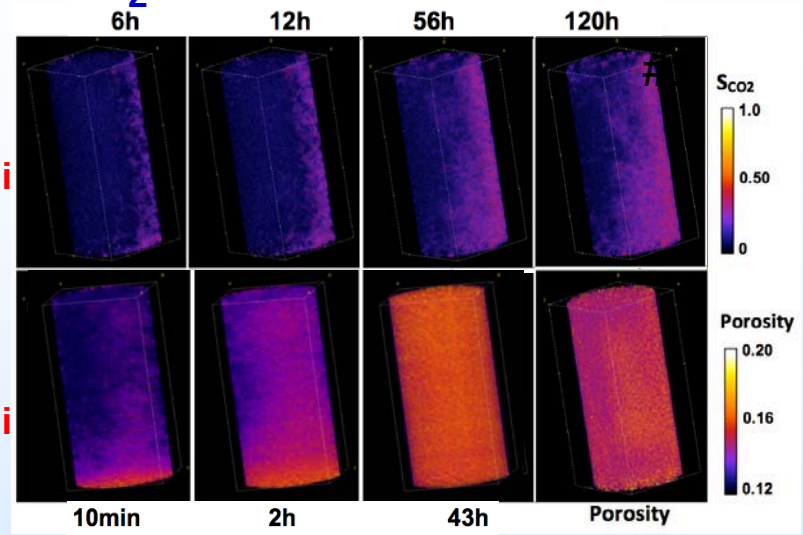
- Two types of capillary continuity of fracture
  - Good capillary continuity
  - P_c-dependent capillary continuity

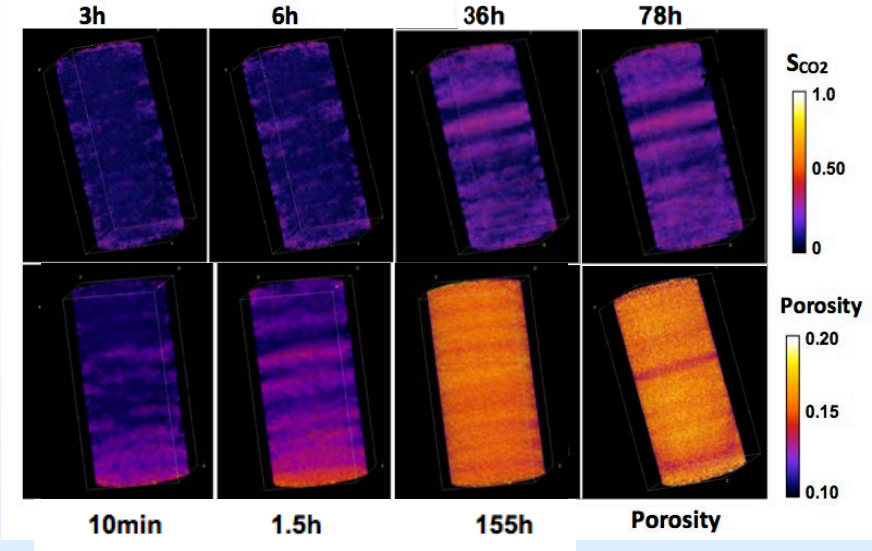


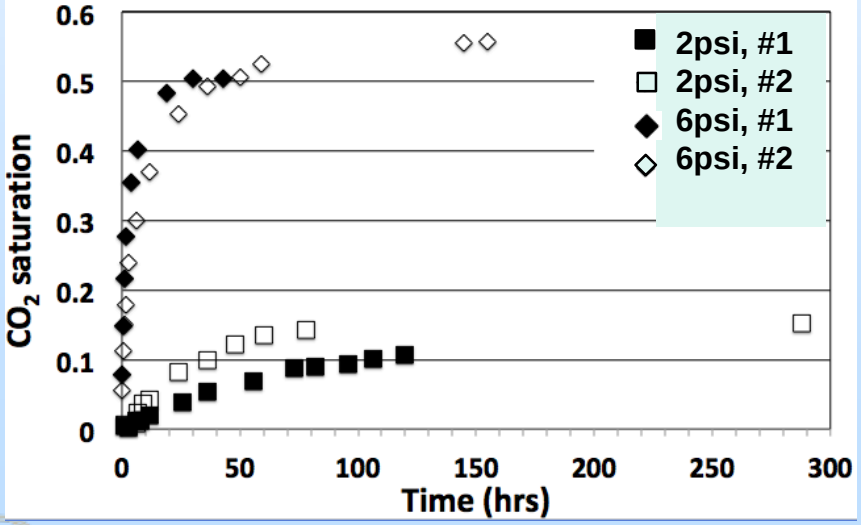
- Sample #1: Homogeneous sandstone core, Brine permeability: ~10mD, Porosity: 0.153
- Sample #2: Layered sandstone core, Brine permeability: ~10mD, Porosity: 0.158
- Sample #3:Low-permeability sandstone core, Brine permeability: ~1mD, Porosity: 0.135
- Sample #4: Heterogeneous Duperow core (Wallewein 22-1, depth: 4129 feet), Brine permeability: ~1mD, Porosity: 0.042

CO_2-water flow with good capillary continuity across fracture

❖ CO_2 distribution and saturation vs. time in rock matrix

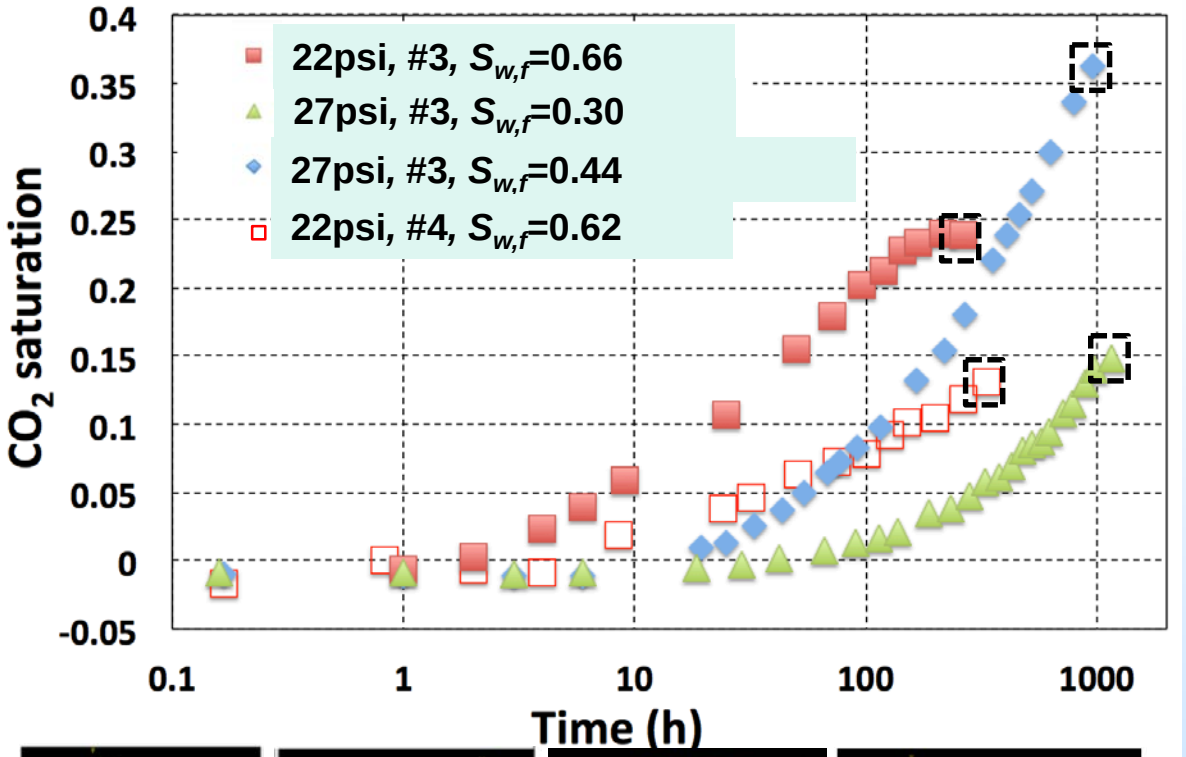


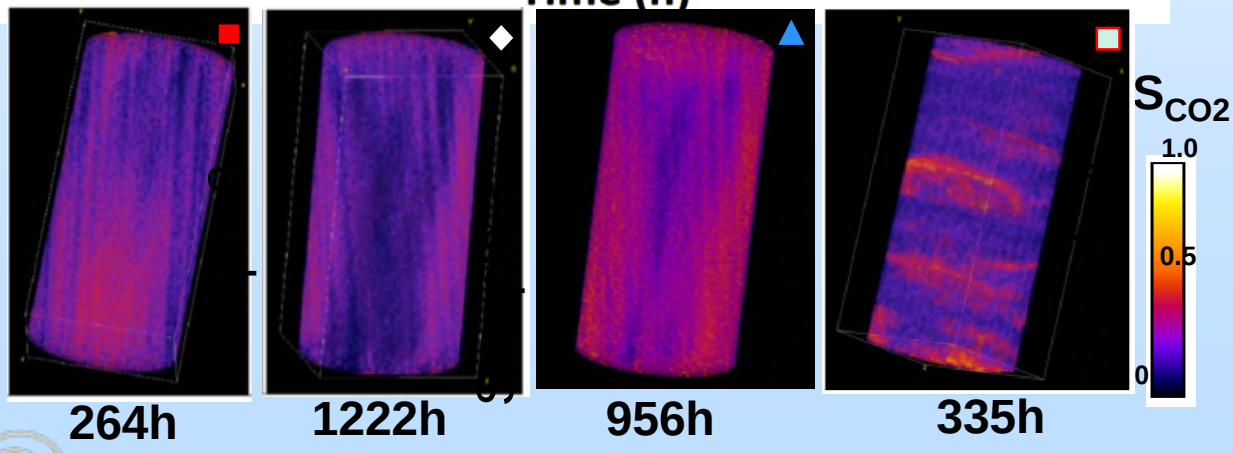




- Water saturations in fracture ($S_{w,f}$) range from 0.73 to 0.94 for both Sample #1 and #2 under P_c=2 and 6psi;
- Higher applied P_c results in higher CO_2 saturation at steady state;
- At P_c=6psi, CO_2 invasion in Sample #1 is faster than in Sample #2 (bedding perpendicular to water drainage direction).

CO_2-water flow with P_c-dependent capillary continuity of fracture





- High capillary pressure causes CO_2 to invade the fracture and lower continuity;
- Lower $S_{w,f}$ yields slower CO_2 invasion and water drainage;
- Matrix anisotropy perpendicular to water flow direction (sample #4) results in slower CO_2 invasion than in sample #3 under similar P_c and $S_{w,f}$.

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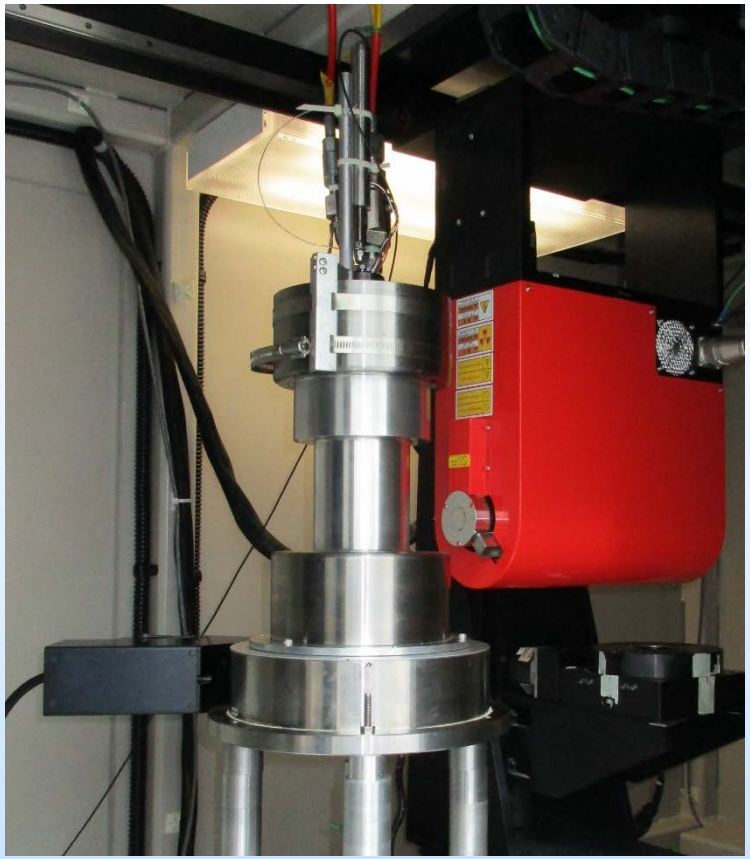
Conclusions

- The capillary continuity across fractures considerably affects the CO_2-water displacement rate and efficiency within the observed time scale;
- The capillary continuity across fractures is P_c-dependent and can be expressed in terms of fracture water saturation($S_{w,f}$);
- The displacement of water by CO_2 across a matrix-fracture system is also affected by the matrix anisotropy.

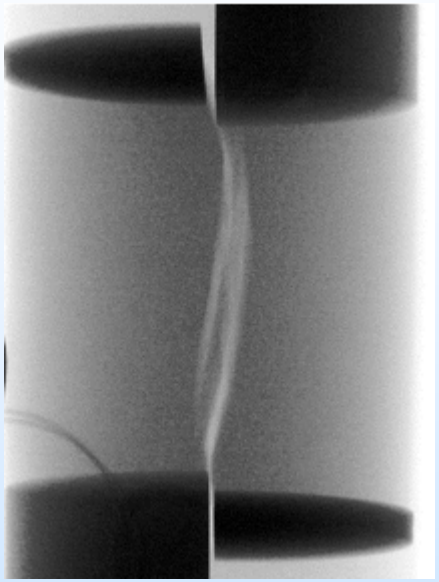
Task R1. Core Studies: Motivation

- Assess caprock geomechanical properties and suitability
- Analyze fracture-permeability relations to inform caprock damage and leakage scenarios
- Determine relationship of stress conditions and fracture reactivation on permeability
- Provide input to induced seismicity hazard assessment

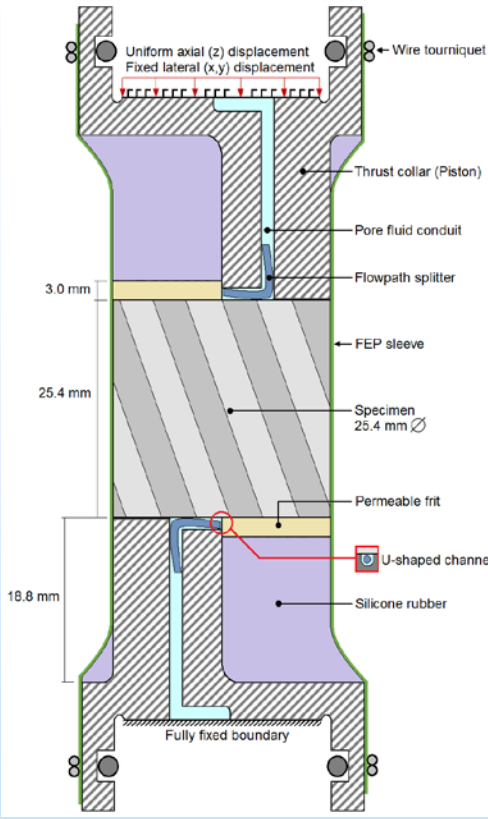
Approach: Triaxial Direct-Shear Coreflood with Simultaneous X-ray radiography/tomography



In situ radiography



Direct-shear device



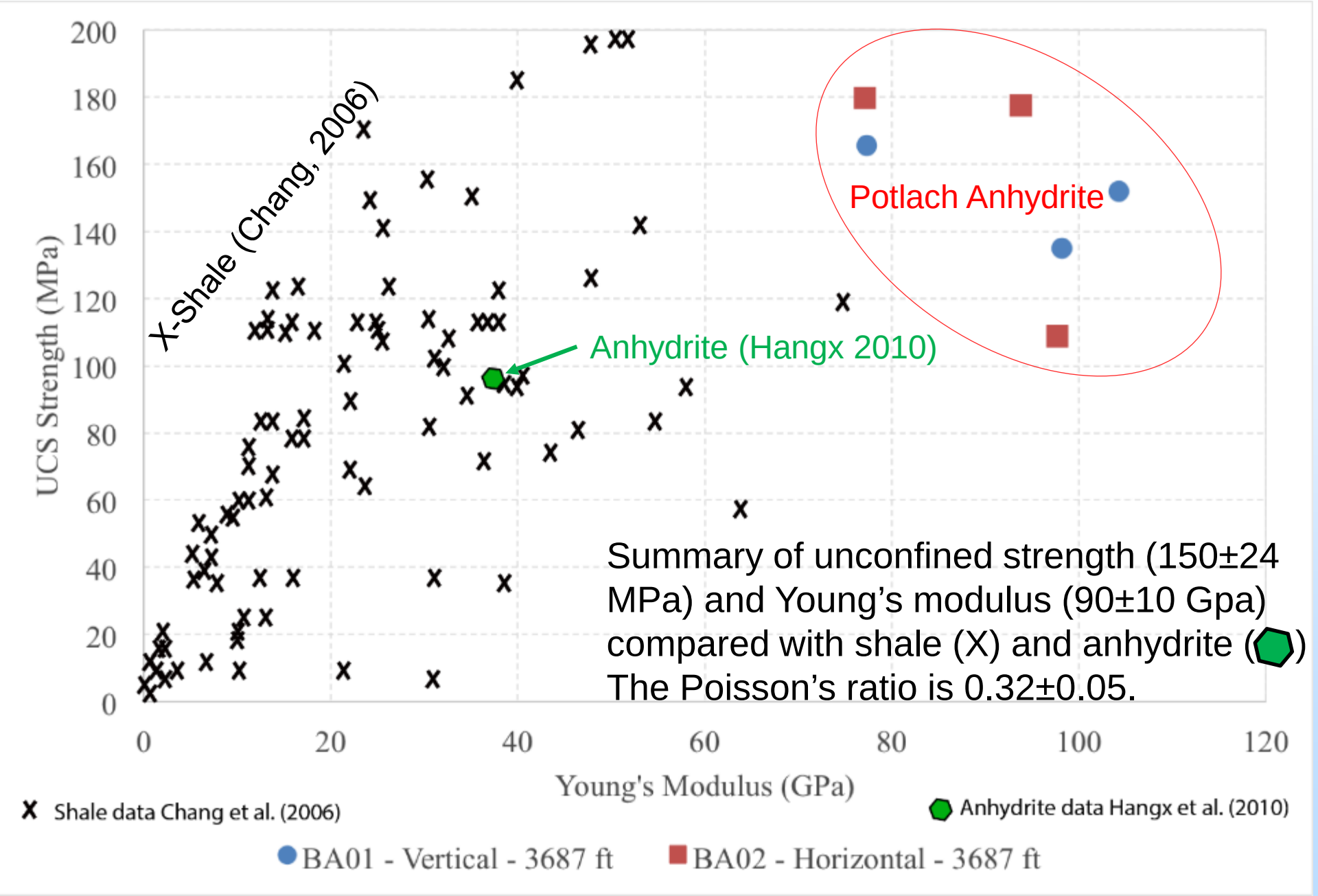
Creation of shear fractures at reservoir conditions coupled with permeability measurements and x-ray observations

Carey et al., J. Unconv. O&G Res., 2015; Frash et al. (2016) JGR; Frash et al. (2017) IJGGC

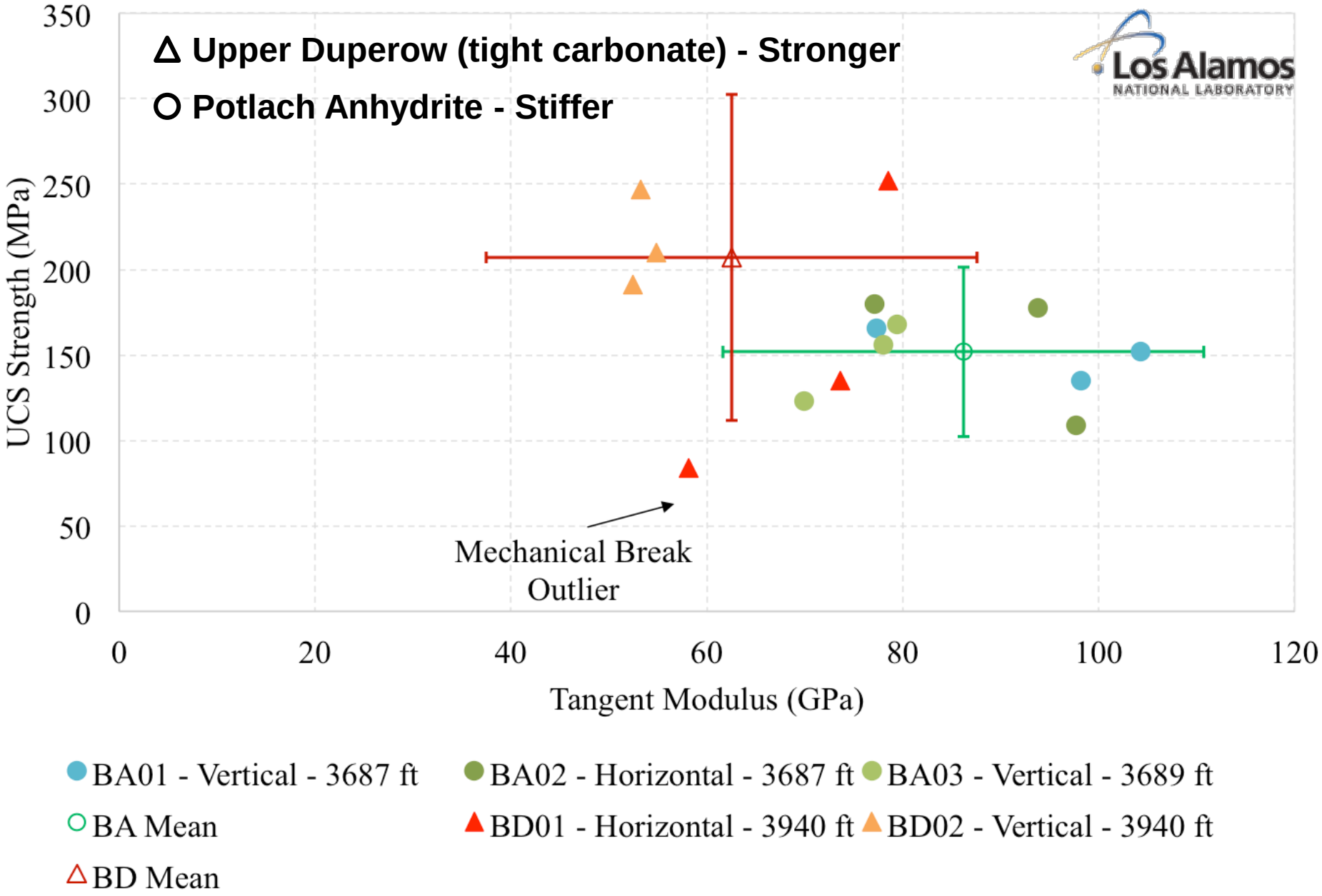
Materials

- Potlatch anhydrite—caprock at Kevin Dome, Montana
  - With minor dolomite **(Carey et al. 2017; ARMA)**
- Upper Duperow dolomite-–caprock at Kevin Dome, Montana
  - With minor anhydrite **(Frash et al. 2018; ARMA)**

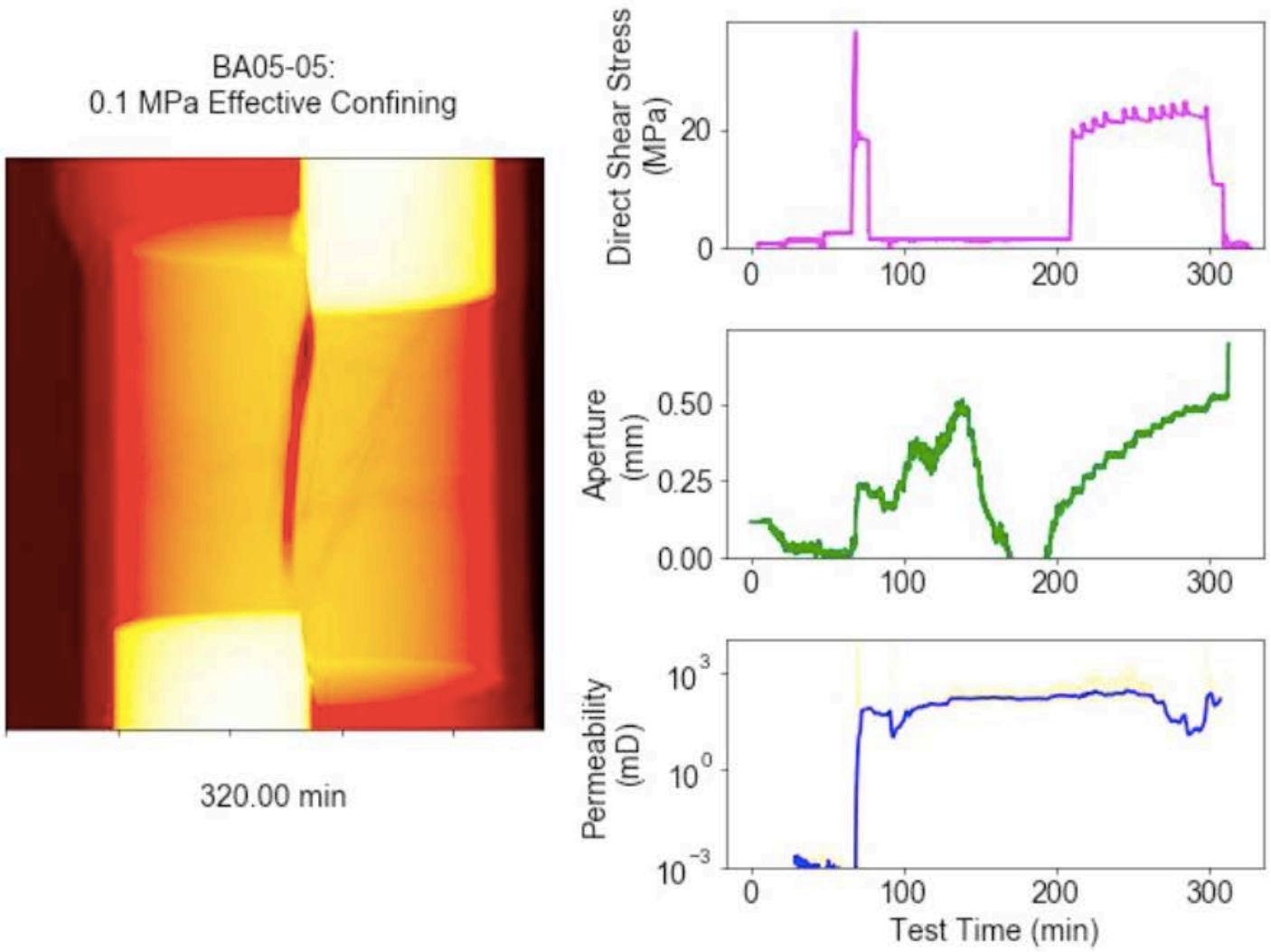
Caprock Geomechanical Tests



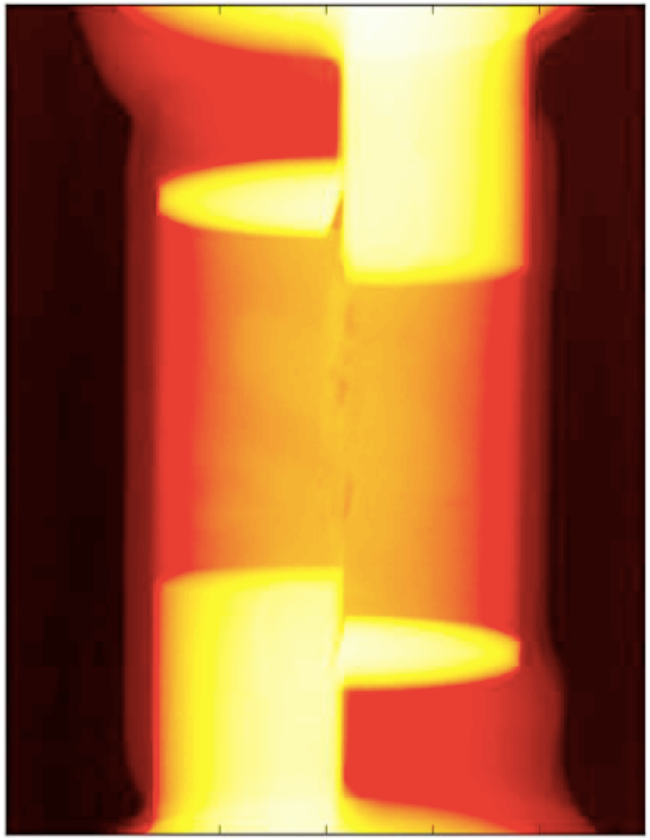
Caprock Geomechanical Analysis

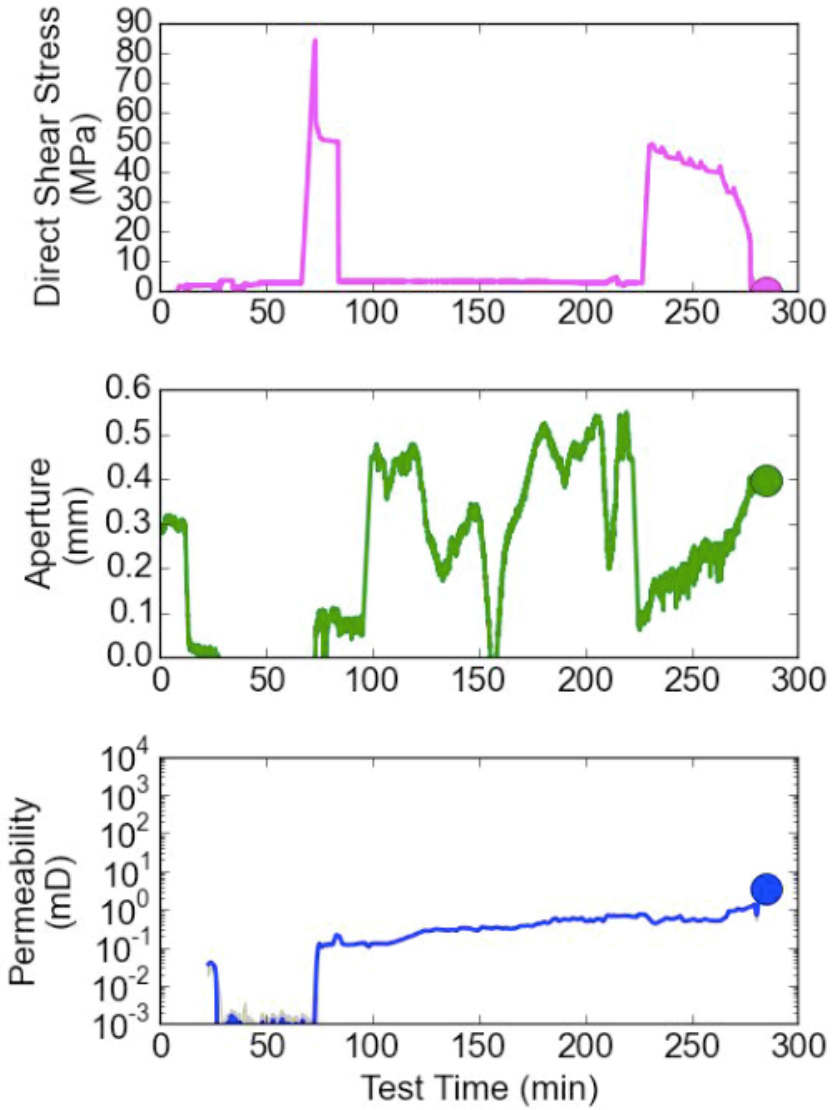


Potlatch Anhydrite at 10 MPa

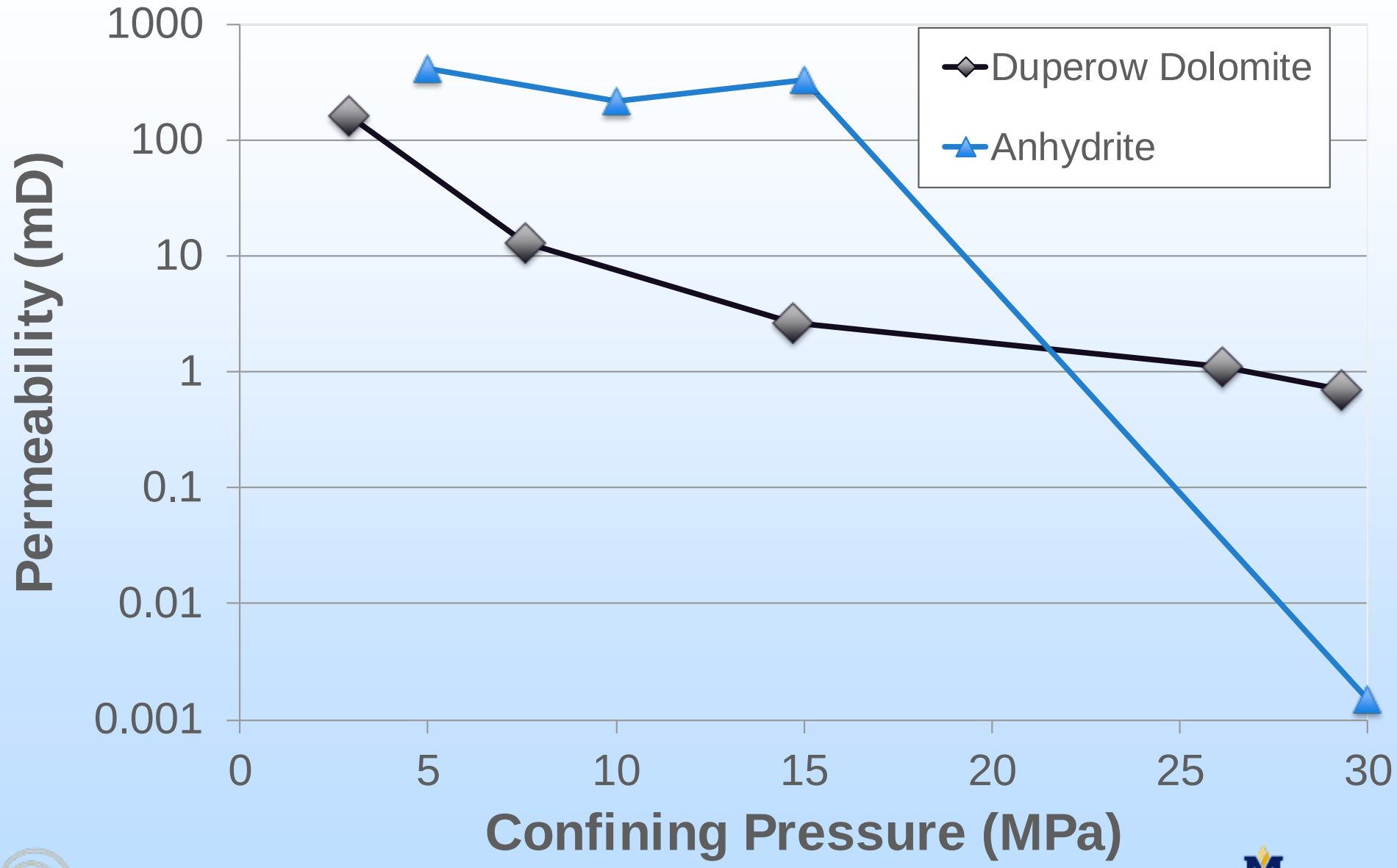


Upper Duperow Dolomite at 30 MPa





Summary Permeability-Stress Relations



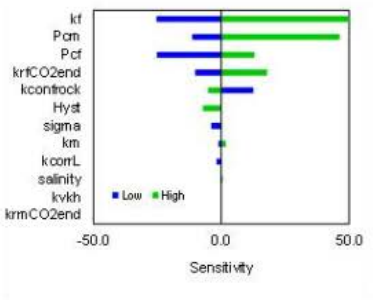
Risk Assessment – 1st paper submitted

Tsubasa Onishi, Minh Nguyen, Phil Stauffer

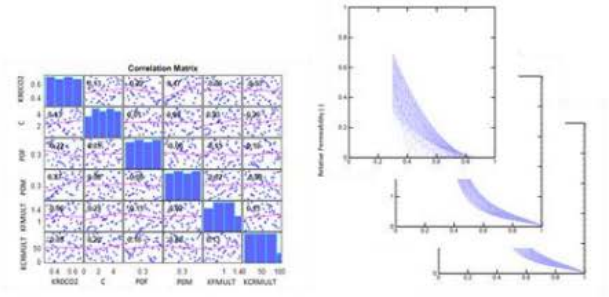
OVERVIEW

- Adopted the NRAP-IAM workflow from injection reservoir simulation to risk assessment of potential leakage
- Did not incorporate seismic interpretation into building the injection reservoir property models to characterize heterogeneity
- Focused on potential CO2/brine leakage through legacy wells

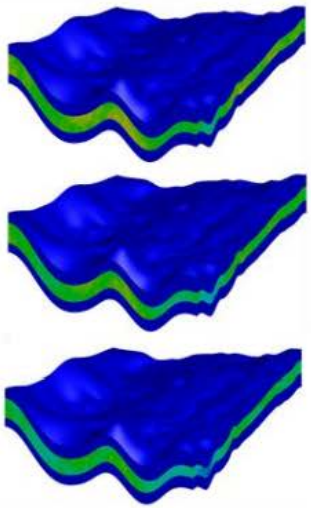
Risk Assessment – 1st paper submitted



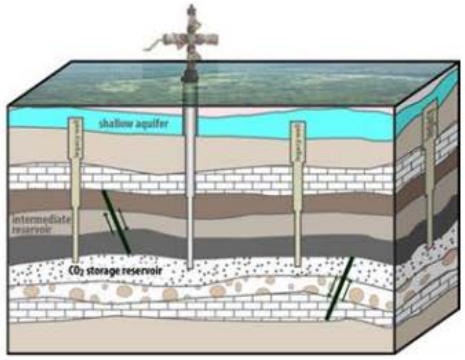
Identify Sensitive Parameters



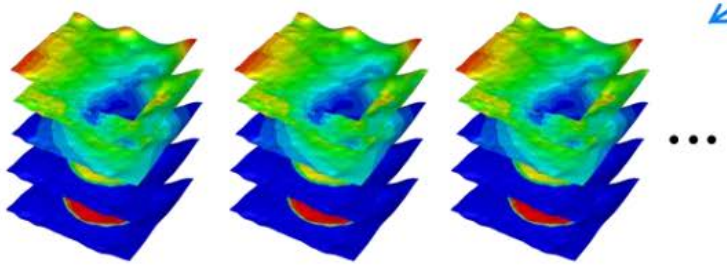
Latin Hypercube Sampling



Reservoir Simulation



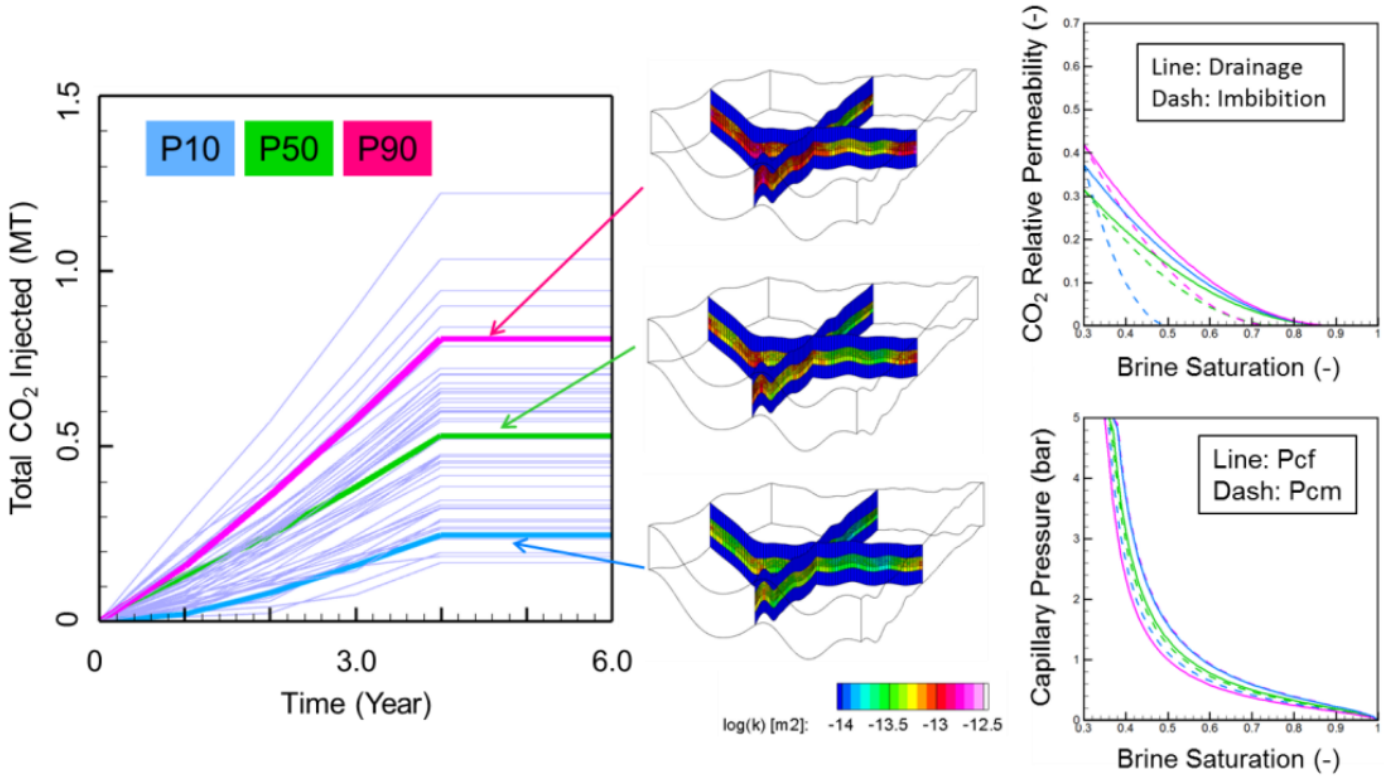
NRAP-IAM



RROM-Gen

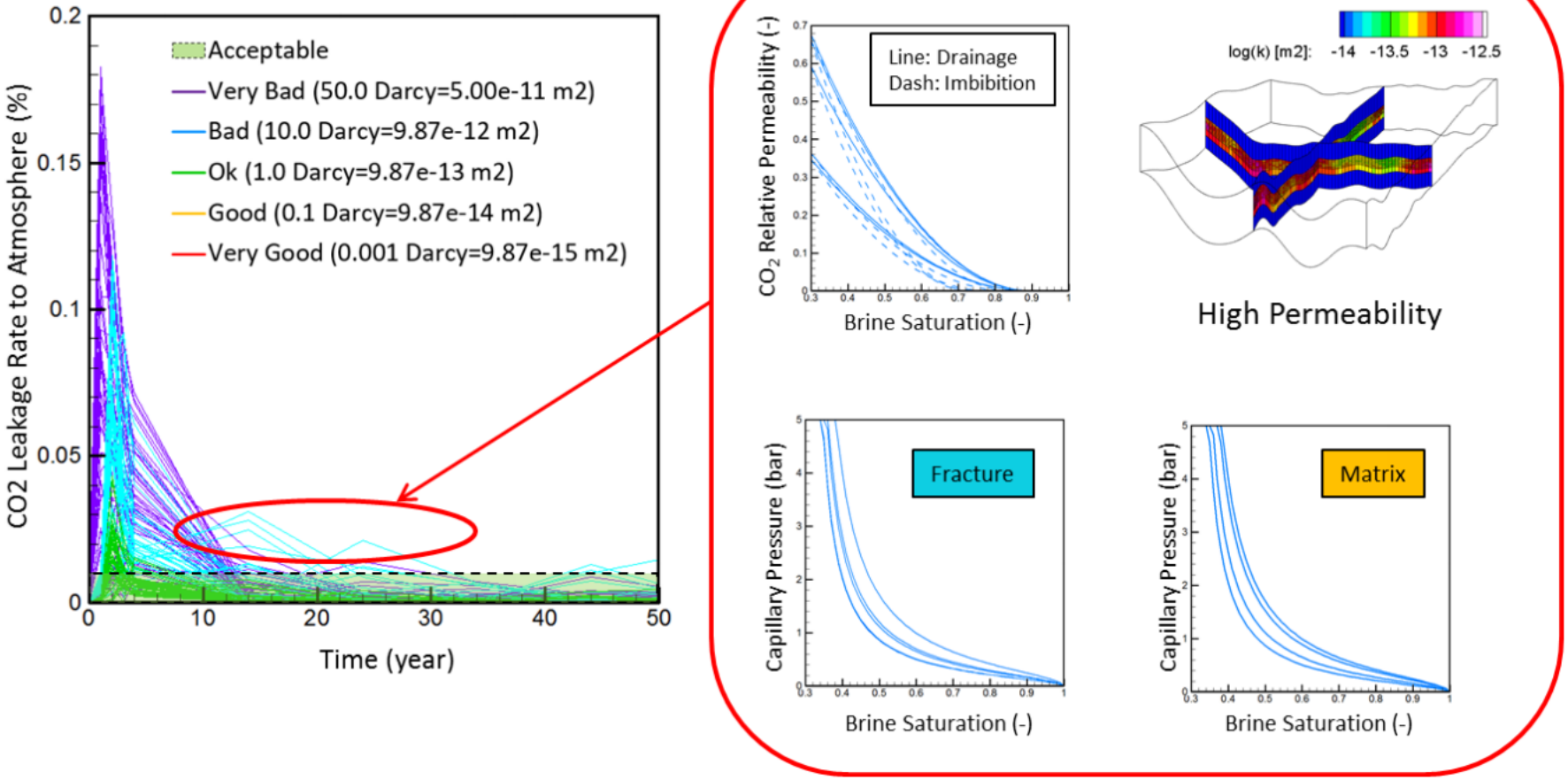
The risk assessment workflow using the reservoir simulation, RROM-Gen and NRAP-IAM

Risk Assessment – 1st paper submitted



Reservoir simulation results: total amount of CO_2 injected delineated with P10, P50 and P90 probability ranges. Different colors in right-hand figures correspond to P10, P50, and P90 in the left-hand figure.

Risk Assessment – 1st paper submitted



Reservoir simulation results including total amount of CO_2 injected and parameters for P10, P50 and P90. The dashed line shows a 0.01% leakage rate. Right-hand figures illustrate parameters of realizations that showed unacceptable leakage.

NRAP simulation results show that unless the quality of wellbore cement is extremely poor, it is unlikely that there will be CO2 leakage to the atmosphere.

Risk Assessment – 1st paper submitted

SUMMARY AND CONCLUSIONS

- The maximum total mass of injected CO2 is predicted to be lower than that of previous work due to different parameter uncertainties

- The potential amount of CO2 and brine leakage is most sensitive to values of fracture permeability, capillary pressure in both the fracture and matrix, end-point fracture CO2 relative permeability, permeability of confining rocks, and hysteresis in the CO2 relative permeability.

- Carbon storage in the Kevin Dome has little risk of CO2 leakage to the atmosphere unless the quality of the legacy wells is extremely poor.

Risk Assessment – 2nd paper in progress

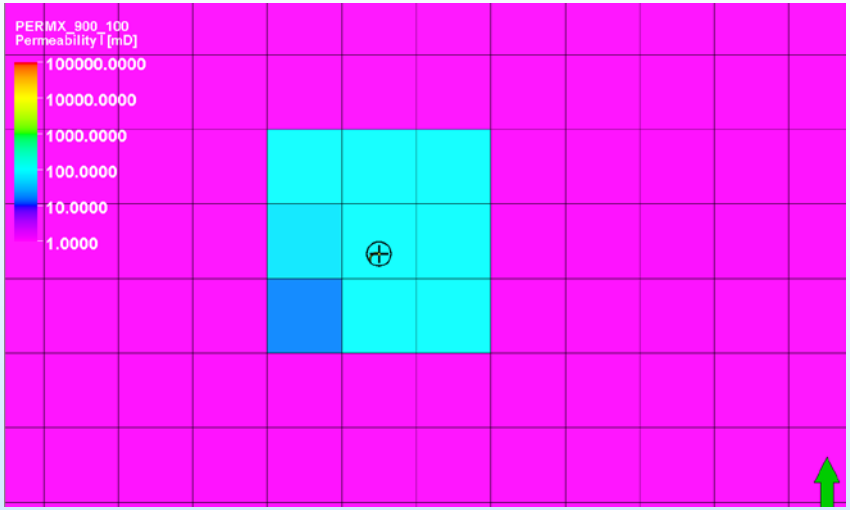
OVERVIEW

- Using seismic-driven property extrapolation to improve the injection reservoir model heterogeneity
- Incorporating a Discrete Fracture Network (DFN) model to characterize fractures in the Middle Duperow formation
- Focusing on potential leakage though hypothetical faults using NRAP-IAM

Risk Assessment – 2nd paper in progress

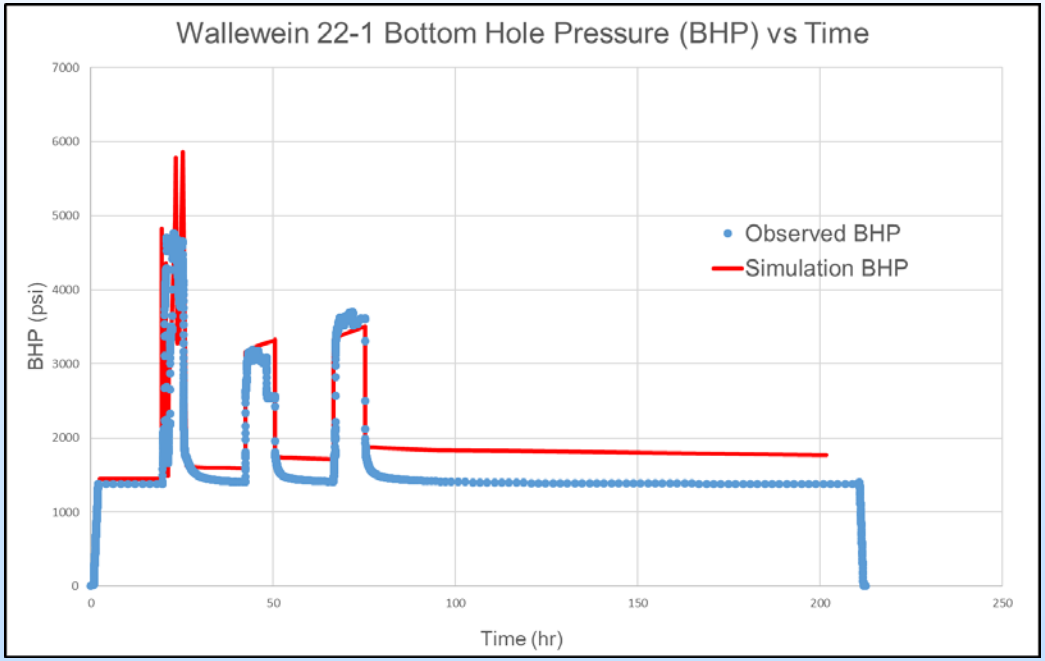
Grid Upscaling for Simulation

Cell Dimensions (ft)	Total Number of Cells	Note
200 x 200 (Original)	5,193,900	
330 x 330	1,940,449	
660 x 660	480,249	**Most Optimal**



Grid upscaling is done to ensure the overall number of grid cells is not computationally expensive for simulation. Permeability around Wallewein 22-1 is calibrated to the injection well test. Since the injection interval is smaller than the total thickness of Middle Duperow, vertical permeability is important in explaining the bottomhole pressure behavior during well test. It is more important to match the pressure behavior during the beginning of well test at Wallewein 22-1.

BHP Match with Well Test (Wallewein 22-1)



Radius around Wallewein 22-1	K Multiplier	Kv/Kh	Perforation Interval
3200	30	1	4040-4057
ft	Dimensionless	Dimensionless	ft

Risk Assessment – 2nd paper in progress

Los Alamos NATIONAL LABORATORY

PRELIMINARY RESULTS

- Well test results suggest that the radius of investigation is relatively small due to short duration and vertical permeability is important in explaining pressure response at the wellbore.

- DFN modeling shows fracture aperture and the fracture intensity have a significant impact on the calculated fracture permeability while fracture length has a relatively minor impact.

- CO2 injection simulation results indicate it is unlikely that Big Sky could meet its target of 1 million tons of CO2 stored in the Middle Duperow formation, with a lower estimated probability of success compared to previous estimates based on regional parameters.

US-EPA Class IV Requirements

Project Re-Scope: Underground Source of Drinking Water (USDW) Definition

- (40 CFR) Section 144.3 is an aquifer or part of an aquifer which:
  a. supplies any public water system, or contains a sufficient quantity of ground water to supply a public water system and currently supplies drinking water for human consumption or contains fewer than **10,000 milligrams/liter of Total Dissolved Solids (TDS)**; and
  b. is not an exempted aquifer.
- An "exempted aquifer" is part or all of an aquifer which meets the definition of a USDW but which has been exempted according to criteria in 40 CFR Section 146.4:
  1. It is mineral, hydrocarbon or geothermal energy producing, or can be demonstrated by a permit applicant as part of a permit application for a Class II or III operation to contain minerals or hydrocarbons that considering their quantity and location are expected to be commercially producible;
  2. It is situated at a depth or location which makes recovery of water for drinking water purposes economically or technologically impractical;
  3. It is so contaminated that it would be economically or technologically impractical to render that water fit for human consumption;
  4. It is located over a Class III well mining area subject to subsidence or catastrophic collapse;
  5. The total dissolved solids content of the ground water is more than 3,000 and less than 10,000 milligrams/liter and it is not reasonably expected to supply a public water system.

Not allowed under Class V, but allowed under Class IV

US-EPA Class IV Requirements

USDW under Class II, but not Class VI

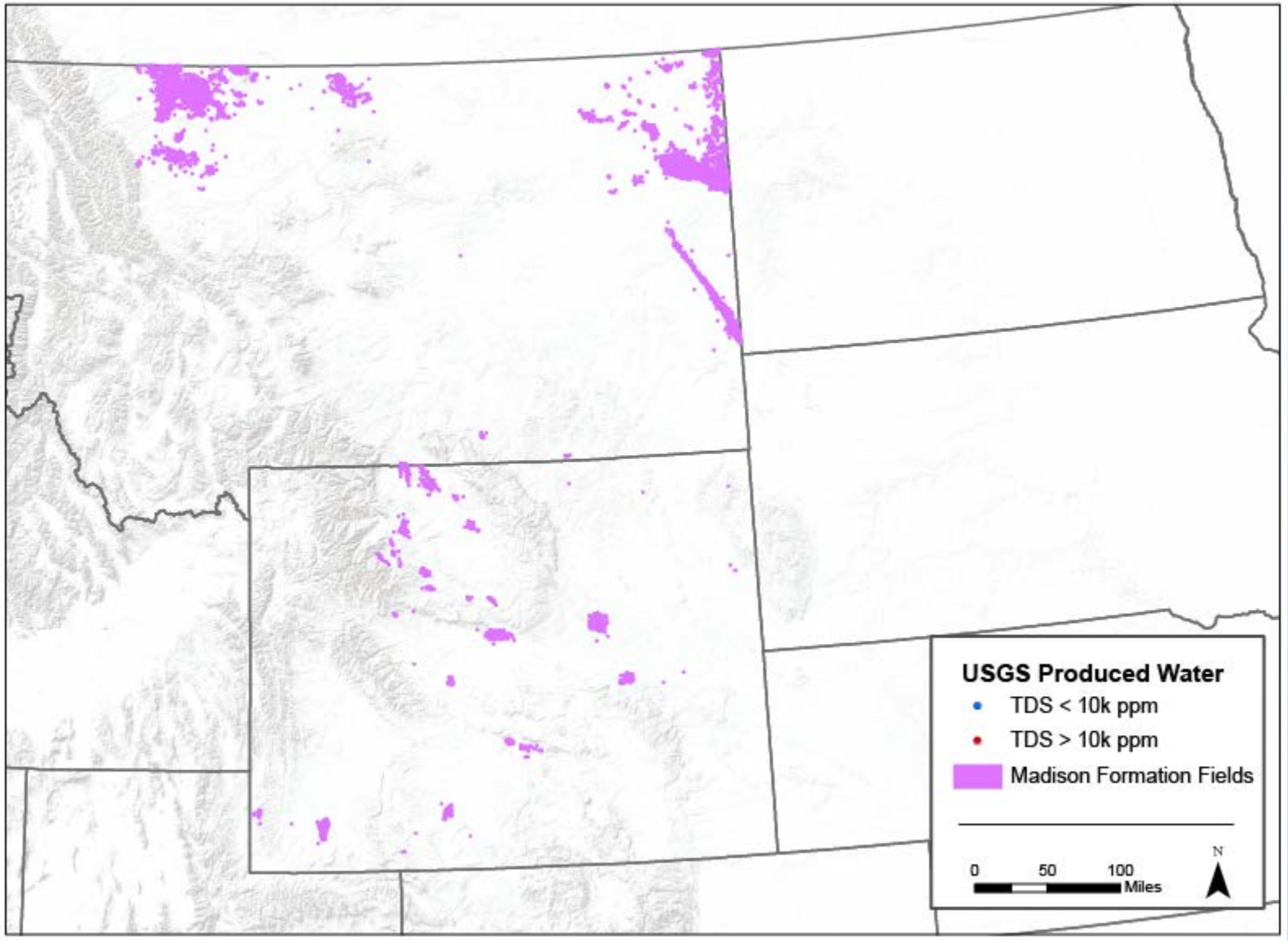
If the target reservoir (the Duperow) had high enough salinity, the lower most USDW by UIC Class VI regulations would be the Madison (~5000 ppm TDS).

The Madison is oil producing and so is NOT a USDW under Class II because of exemptions

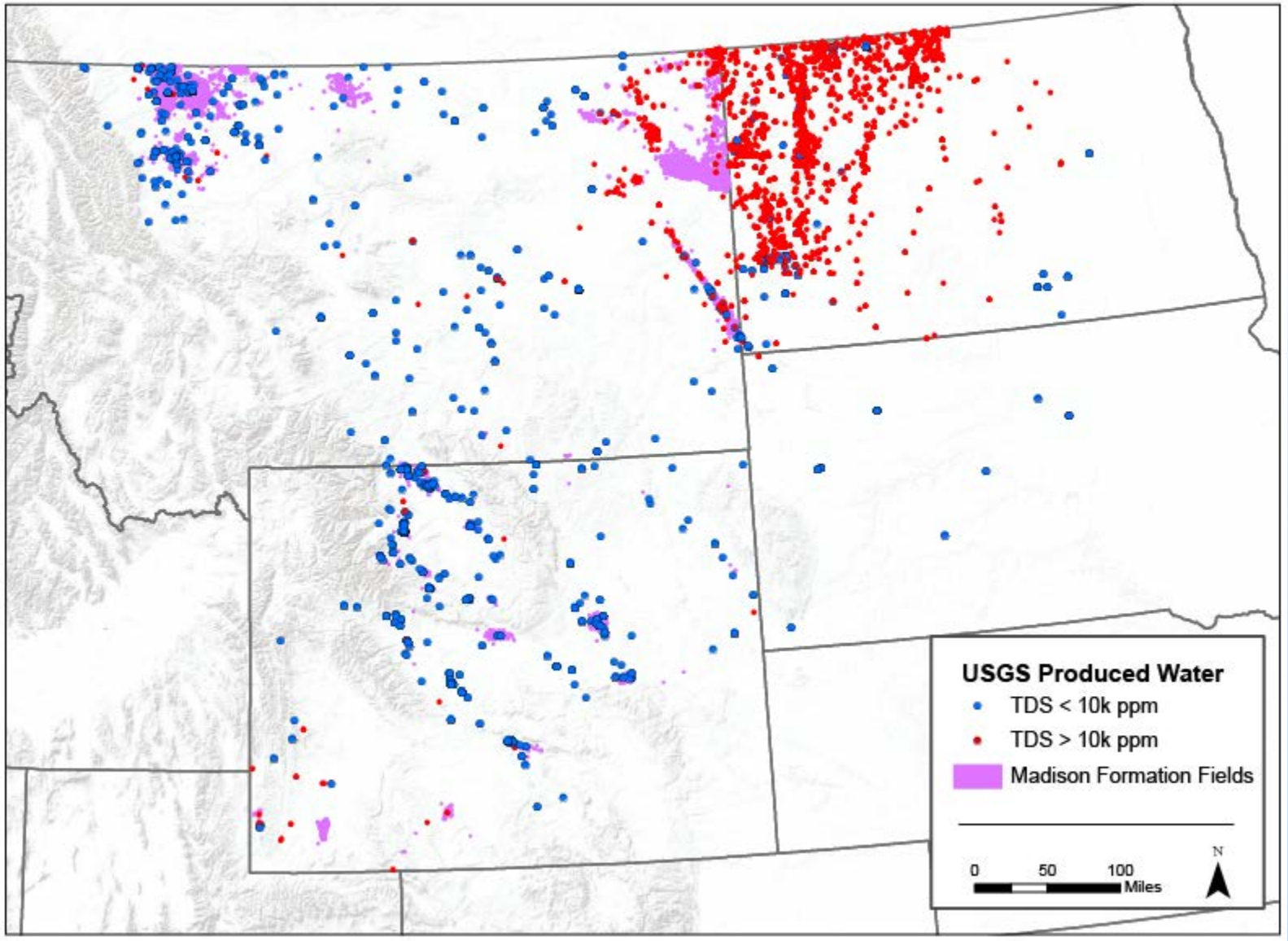
Yet to store in the Duperow beneath the Madison, the CO_2 storage project would have to treat the Madison as a USDW. This would mean:

- Setting surface casing through the Madison (which is karsted). The larger diameter borehole would likely have less integrity.
- Wastewater disposal is permitted in the Madison, yet a storage project in the Duperow would have to protect it against any reduction in water quality
- CO_2 EOR *could* be permitted in the Madison, yet a storage project in the Duperow would have to protect the Madison from CO_2 intrusion while others intentionally inject

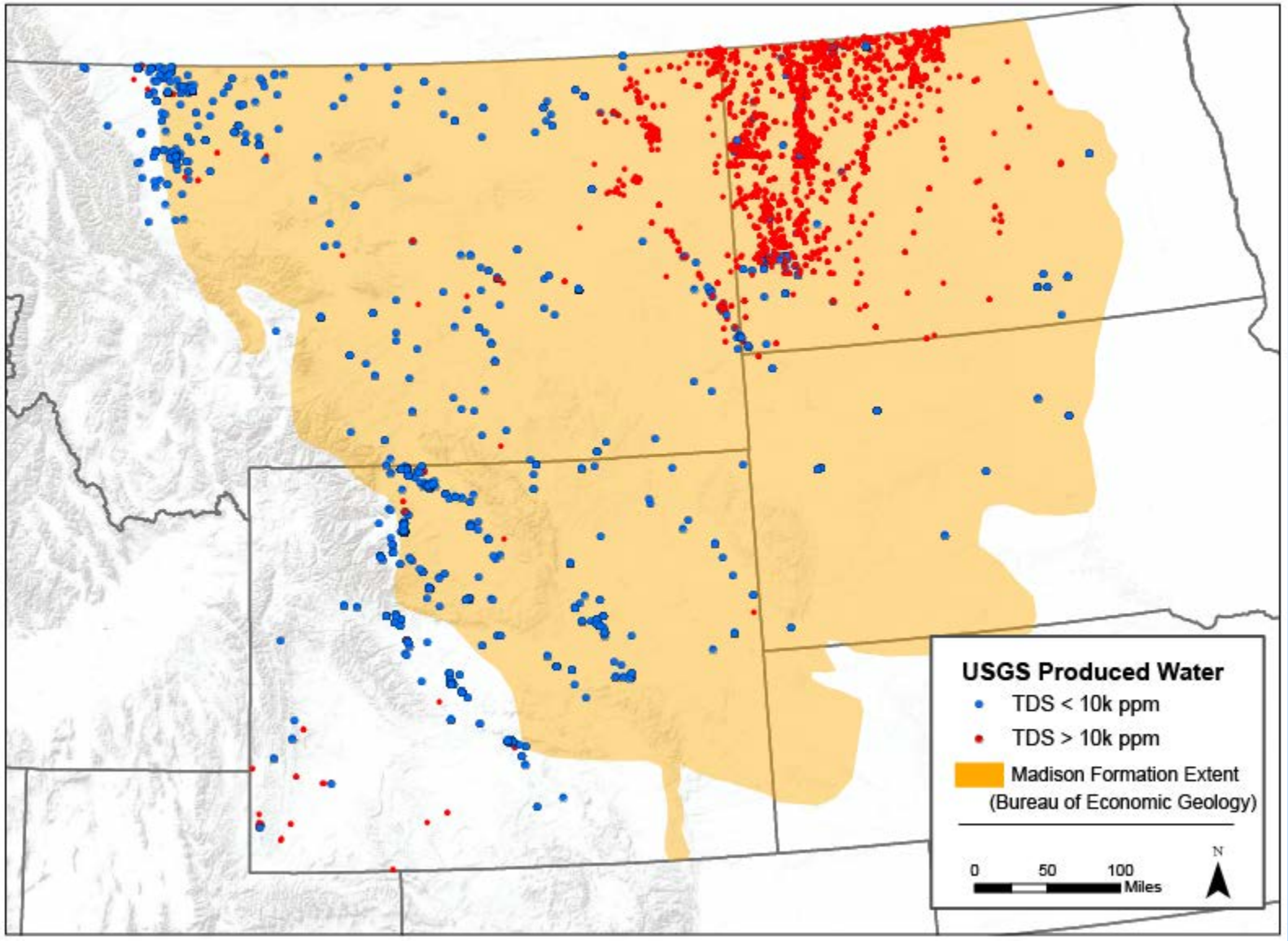
Produced Water and Madison Formation Oil & Gas Fields in and around the BSCSP Region



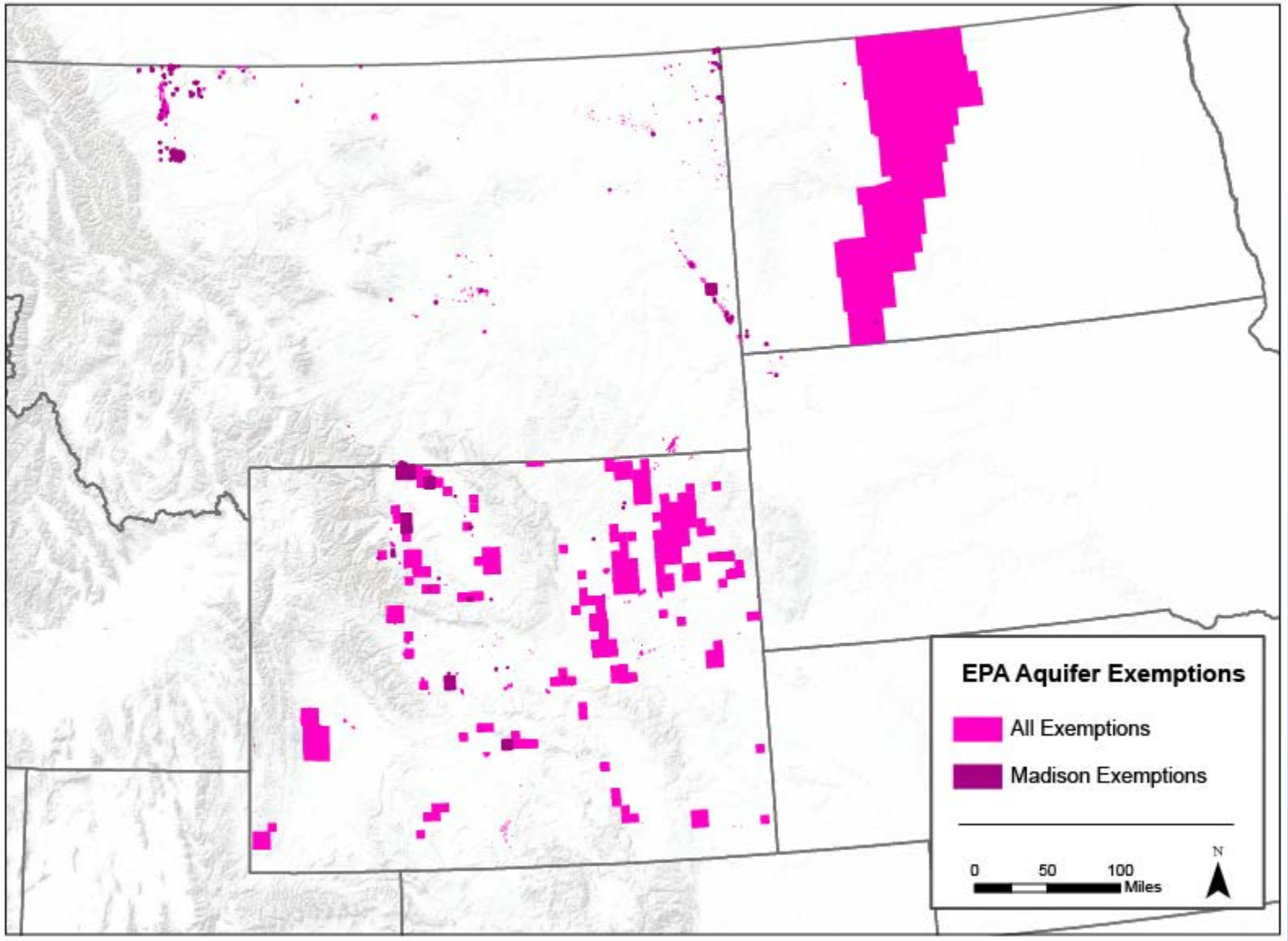
Produced Water and Madison Formation Oil & Gas Fields in and around the BSCSP Region



Produced Water and Madison Formation Continuity in and around the BSCSP Region

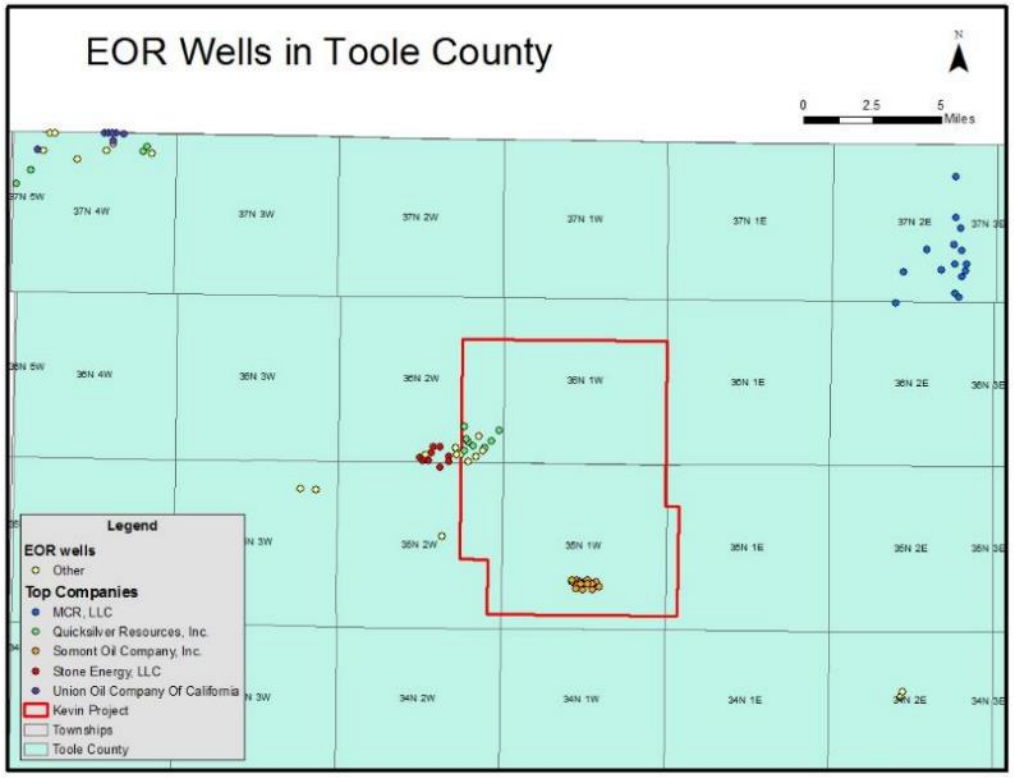


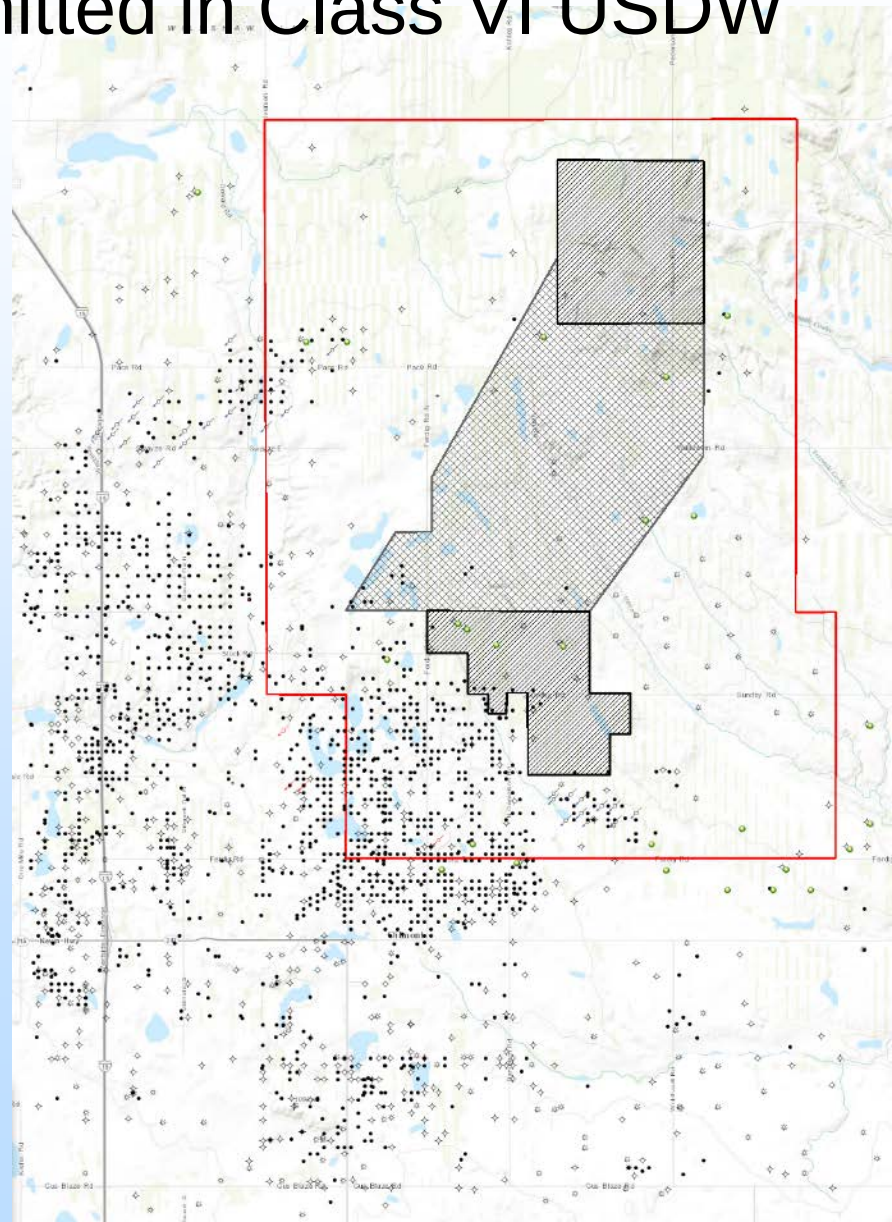
Aquifer Exemptions under EPA Safe Drinking Water Act UIC regulations



US-EPA Class IV Requirements

CO_2 EOR in Could be Permitted in Class VI USDW



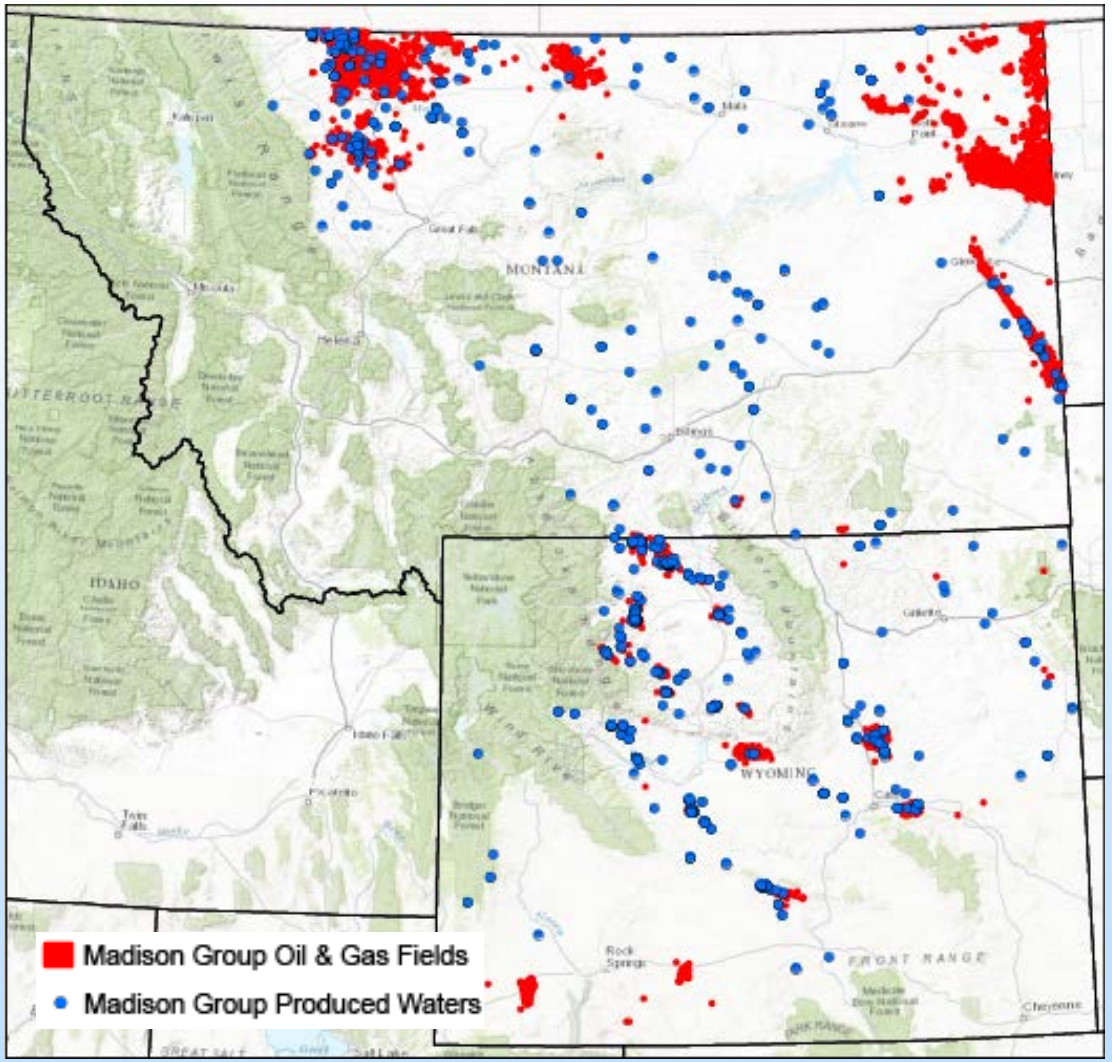


BIG SKY CARBON
SEQUESTRATION PARTNERSHIP

US-EPA Class IV Requirements

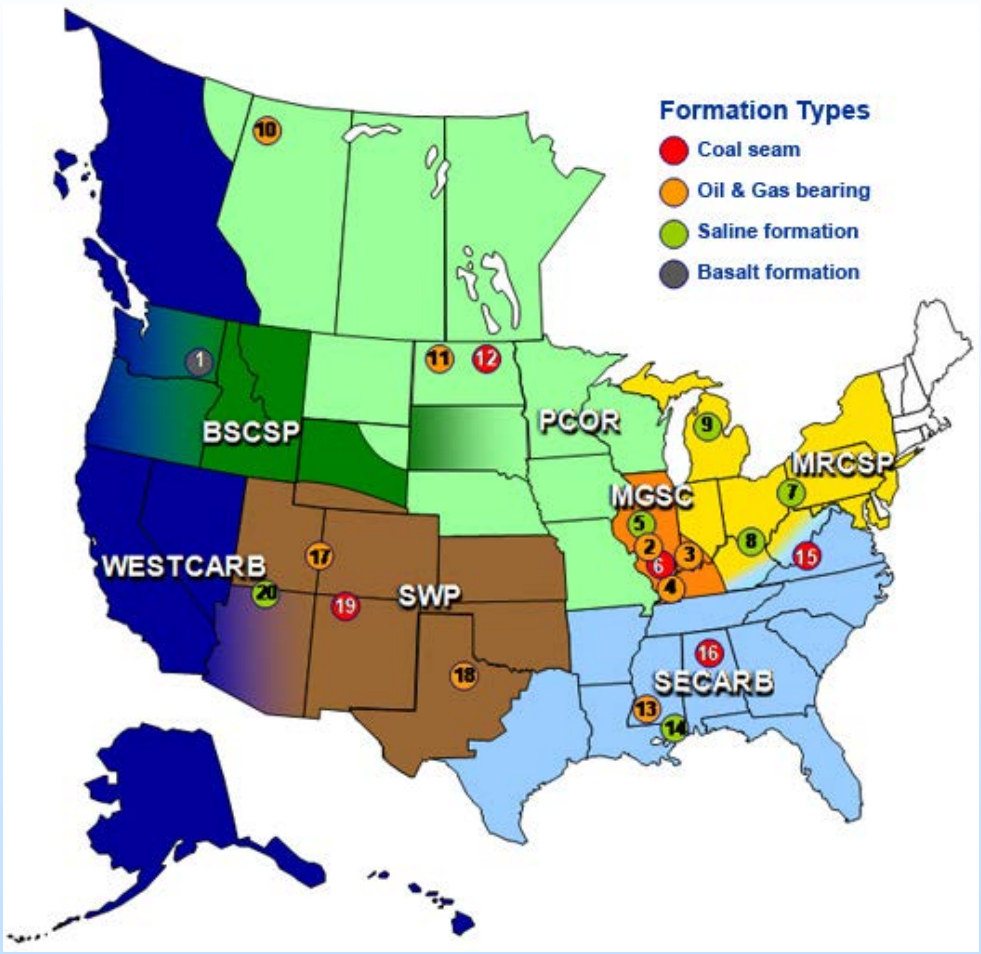
Regional Significance:

Oil fields producing from the Madison (red) and produced water sampled from Madison Group formations less than 10,000 mg/L TDS (blue)



US-EPA Class VI Impact on Research Projects

Class VI Scale and Cost:



DOE Regional Carbon Sequestration Partnership Phase II Program:

- Performed 20 injections
- 100s – 100,000 tonnes
- Wide variety of geologies
- Operated under Class V, Class II
- No extended PISC
- No Financial assurance
- Careful site characterization
- Operational monitoring

How many could have been conducted under Class VI?

Data strongly suggests Class VI requirements are overly stringent for smaller injections.

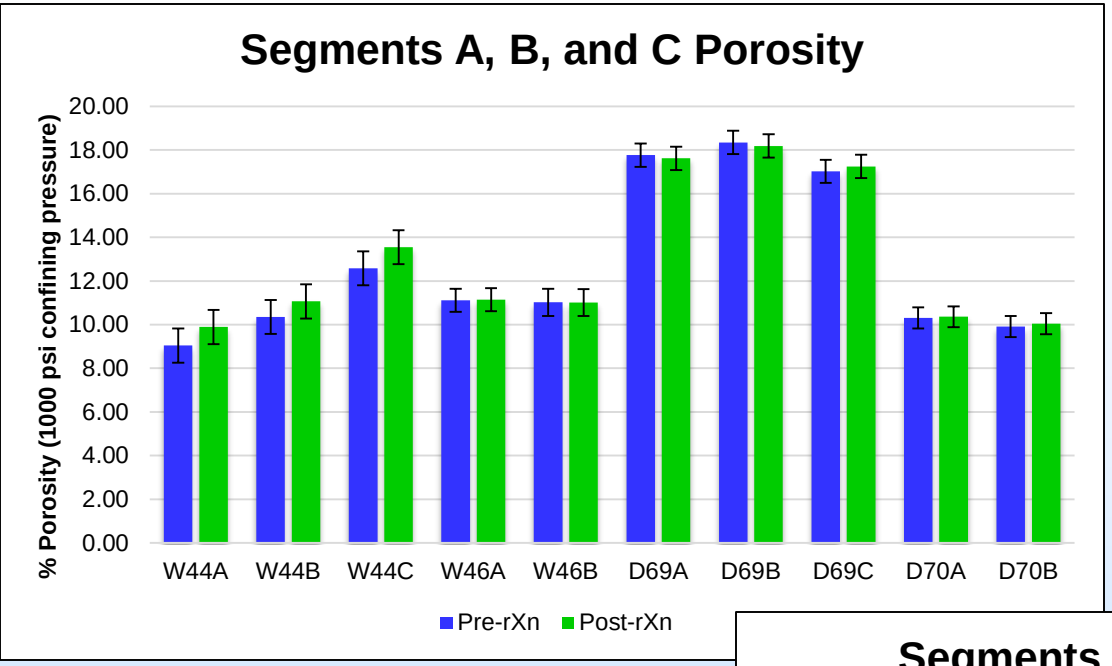
Restricts valuable research and may incentivize undesirable behavior commercially

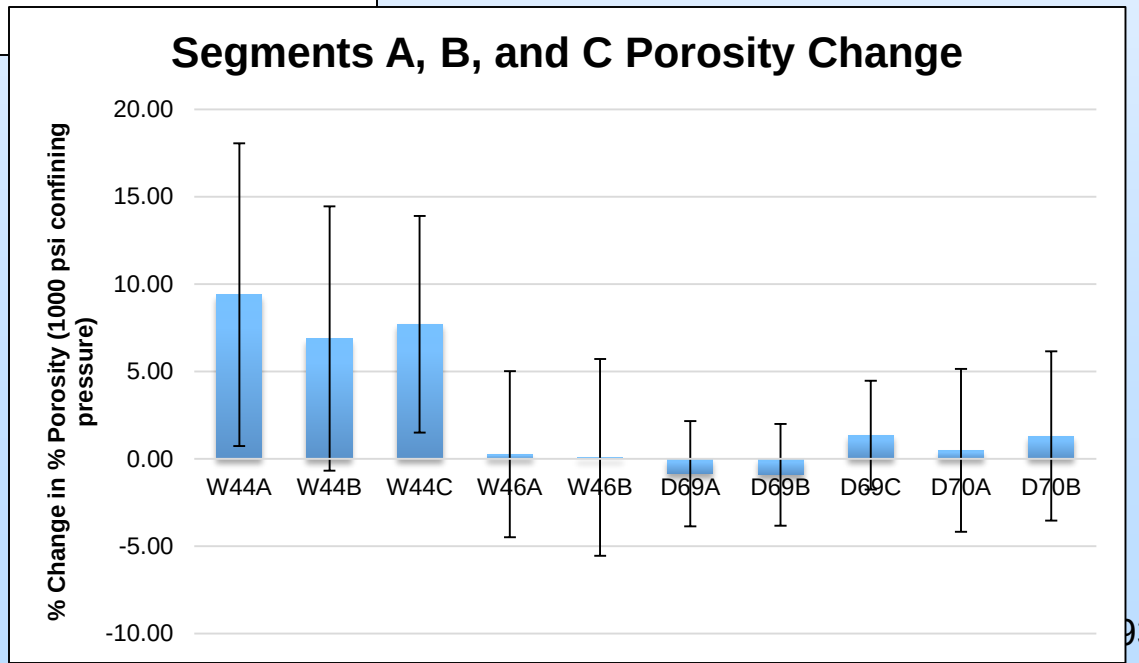
Questions?

Core Flood Experiments

	Sample ID	Avg. pressure (psi)	Temperature (°C)	Brine/DI	Duration of N_2 exposure (days)	Duration of CO_2 exposure (days)
Set 1	D69A	1400	60	Brine	5	28
	D69B	1400	60	Brine	5	28
	D69C	1400	60	Brine	33	0
	W44A	1400	60	Brine	5	28
	W44B	1400	60	Brine	5	28
	W44C	1400	60	Brine	33	0
	W46A	1400	60	Brine	5	28
	W46B	1400	60	Brine	5	28
	W46C	1400	60	Brine	33	0
Set 2	D70A	1400	60	DI	5	28
	D70B	1400	60	DI	5	28
	D70C	1400	60	DI	5+28 (not consecutive)	0
	D68A	1400	60	Brine	5	0

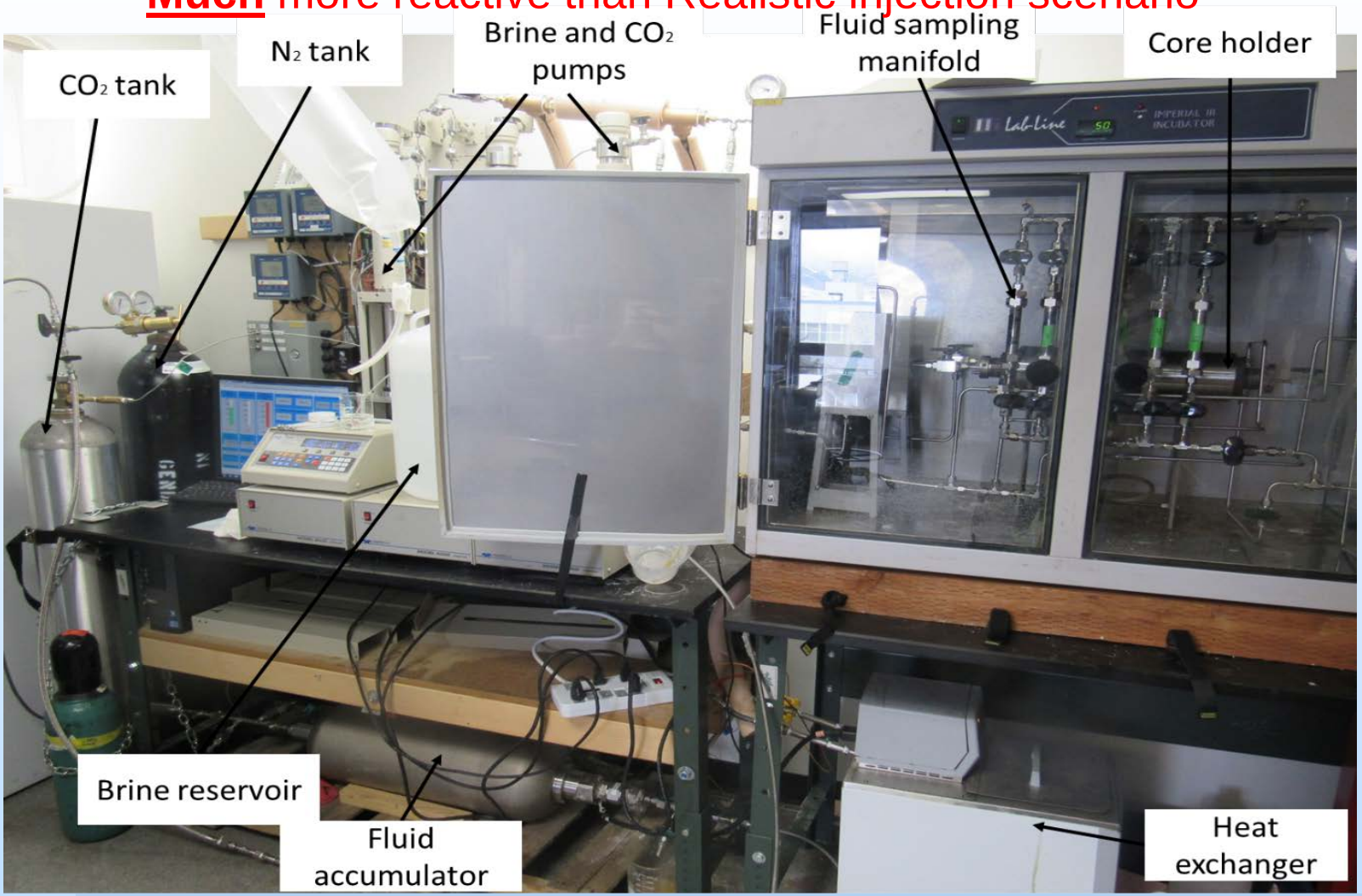
Core Flood Experiments





Methods: CO_2 Core Flow Experiment

Much more reactive than Realistic injection scenario

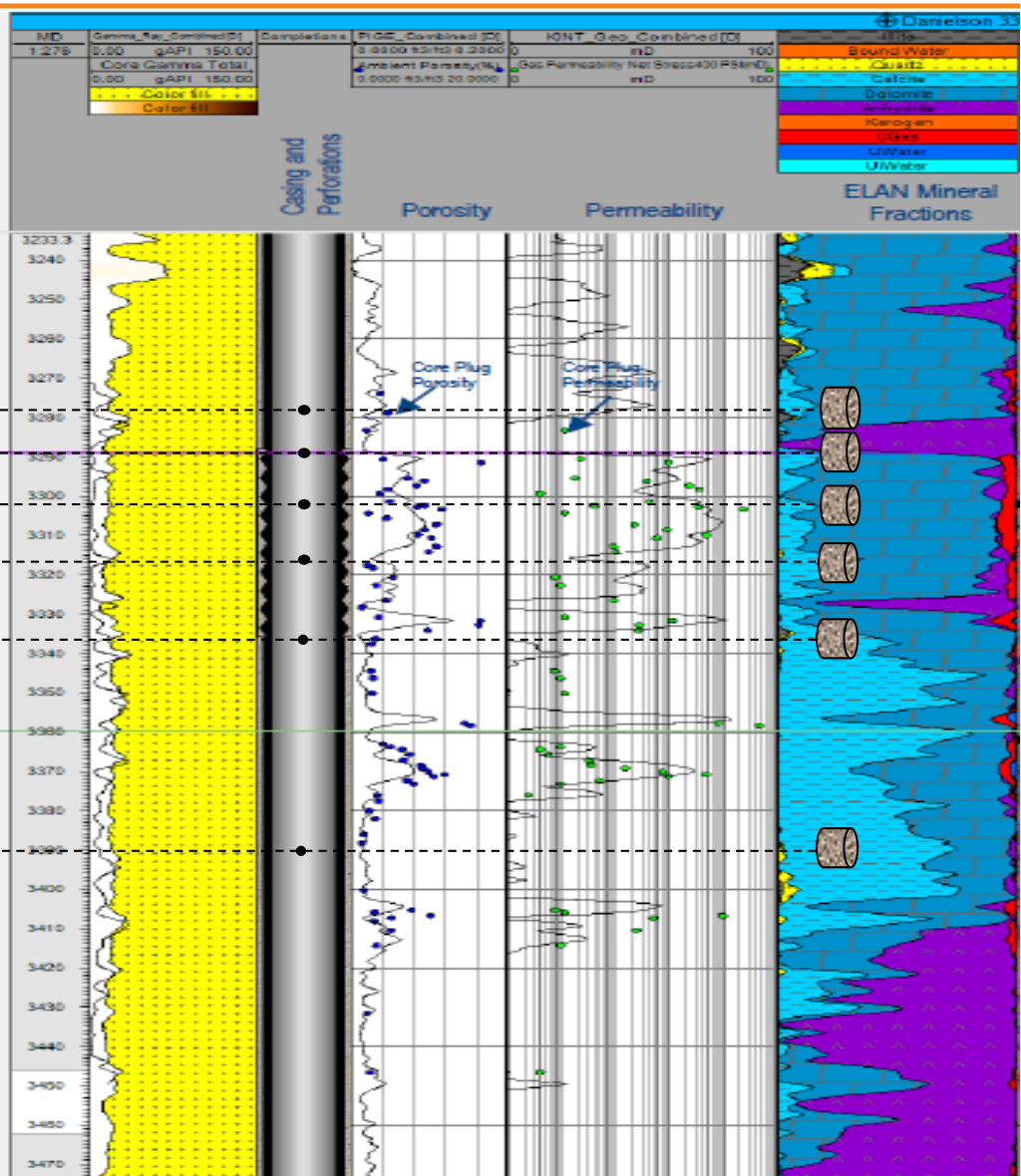


- **Injection pressure: ~ 1,300 psi**
- **Temperature: 50˚C (122˚F)**
- **Test period: 3 days of pure brine flow + 14 days of brine/scCO2 flow**

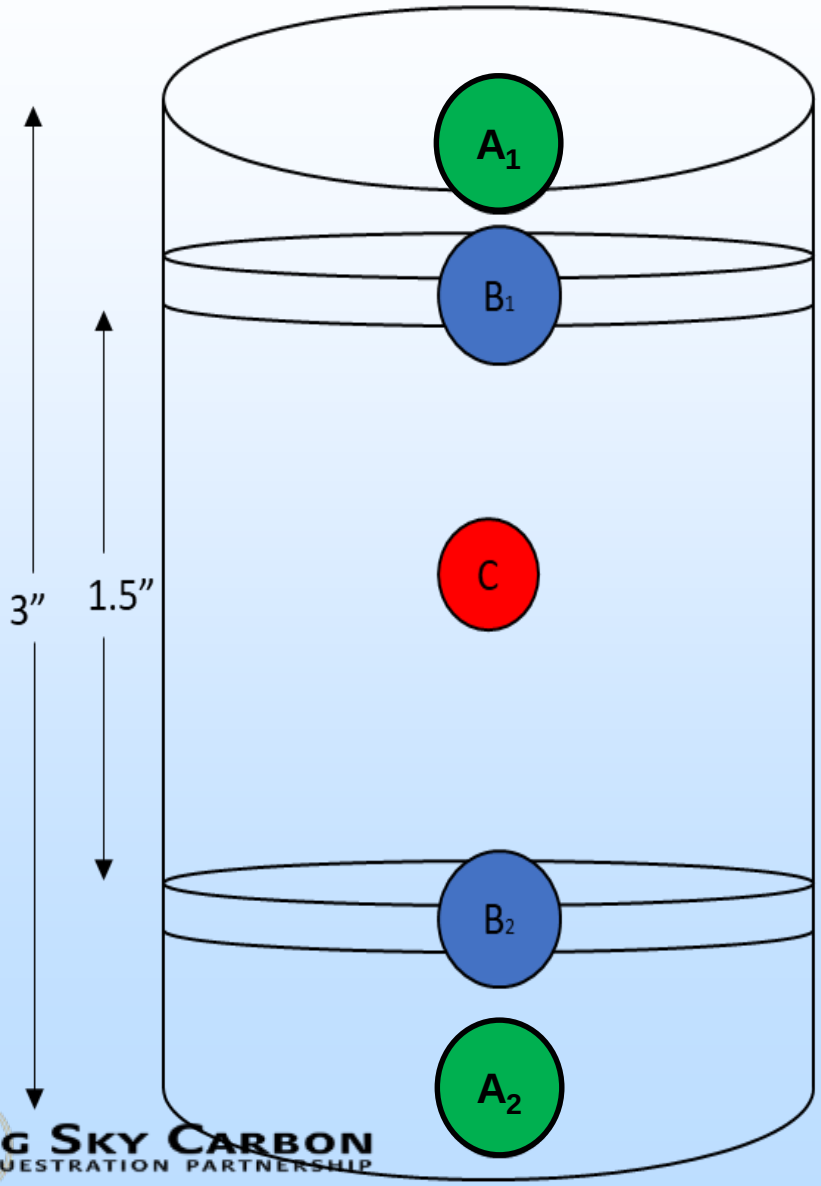
Core Flow: Sampling

Danielson Core Interval (3271-3451 ft MD)

	Depth (ft)
1. Lagoon	3292.1’
2. High Energy Shoal	3294.1’
3. Shallow Reef front	3307.2’
4. Fore Reef	3322.9’
5. Tidal Flat	3349.0’
6. Reef	3410.7’



Core Flow Methods: Sub-Sampling



Characterization Method

-XRD
-XRF
-N_2 adsorption

-SEM-BSE-EDX
-Raman
-Thin section

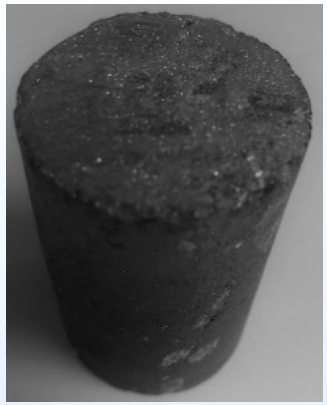
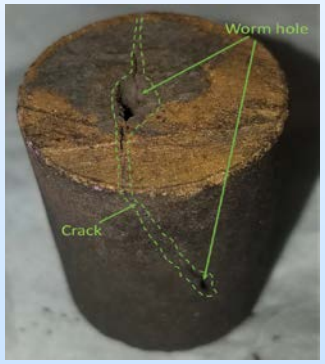
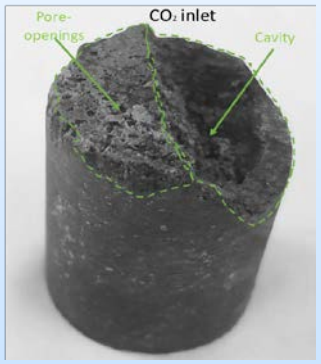
-Gas ϕ and k
-Micro-CT scan
-NMR (Water ϕ and k)
-Strength

Flow Through CO_2 Challenge

-SEM-BSE-EDX
-Raman
-Thin section

-XRD
-XRF
-N_2 adsorption

Experimental Results

	High Energy Shoal	Reef	Lagoon
Before CO_2 Challenge			
After CO_2 Challenge			

High Energy Shoal:

Massive crack and see-through wormhole are visible on the sample, indicating that the presence of $scCO_2$ initiates chemical reactions leading to mineral dissolution

Reef:

Severe erosion of the sample and pore opening provide physical evidence of significant changes in pore structure and connectivity

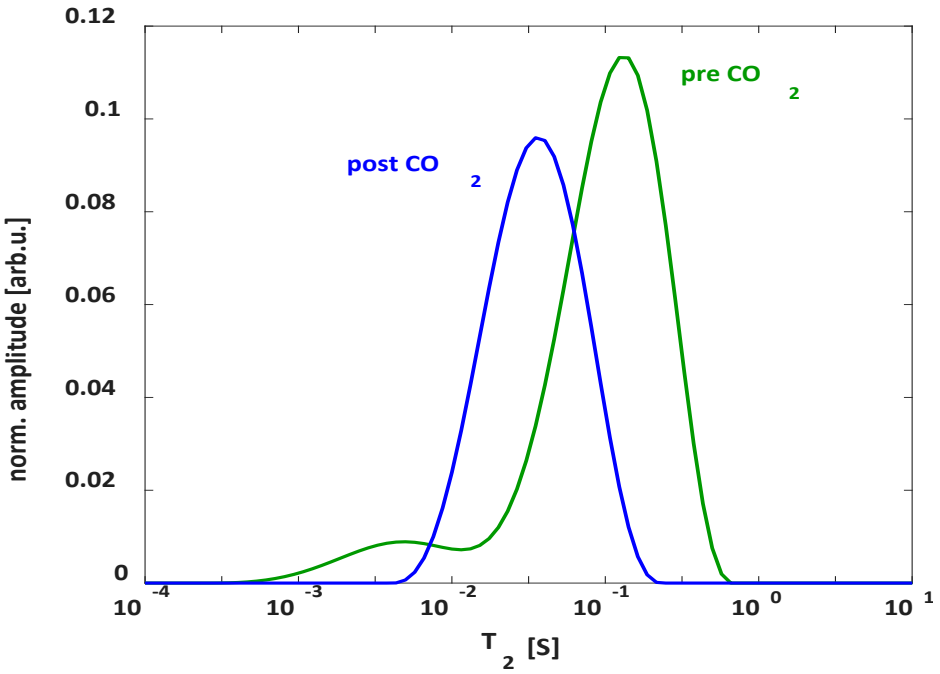
Lagoon:

Physical structure remains the same, just some discolorations

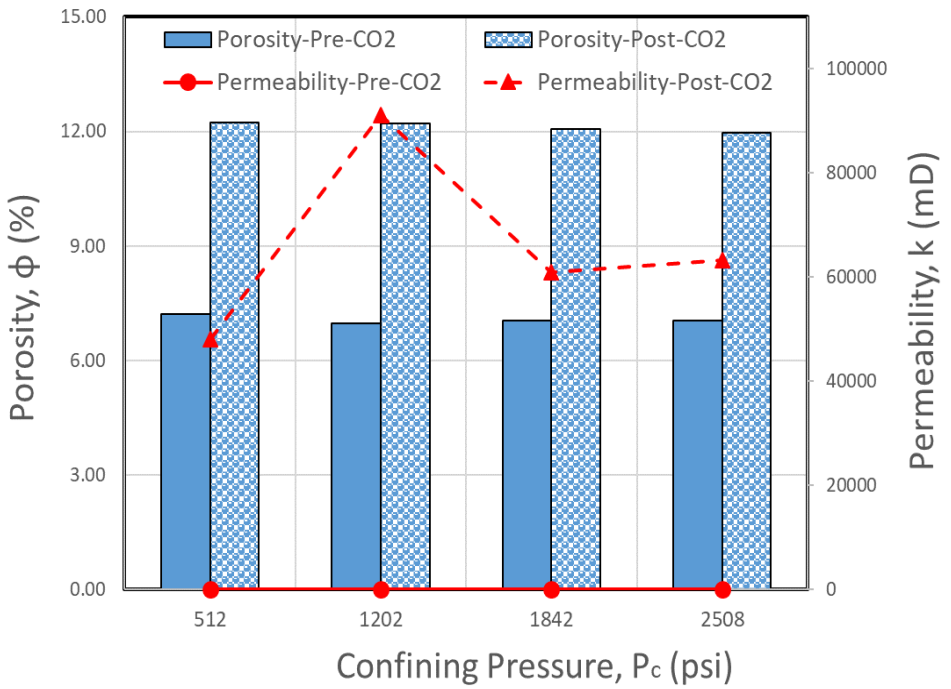
Much more reactive than Realistic injection scenario

NMR: High Energy Shoal

NMR: Fully-saturated core



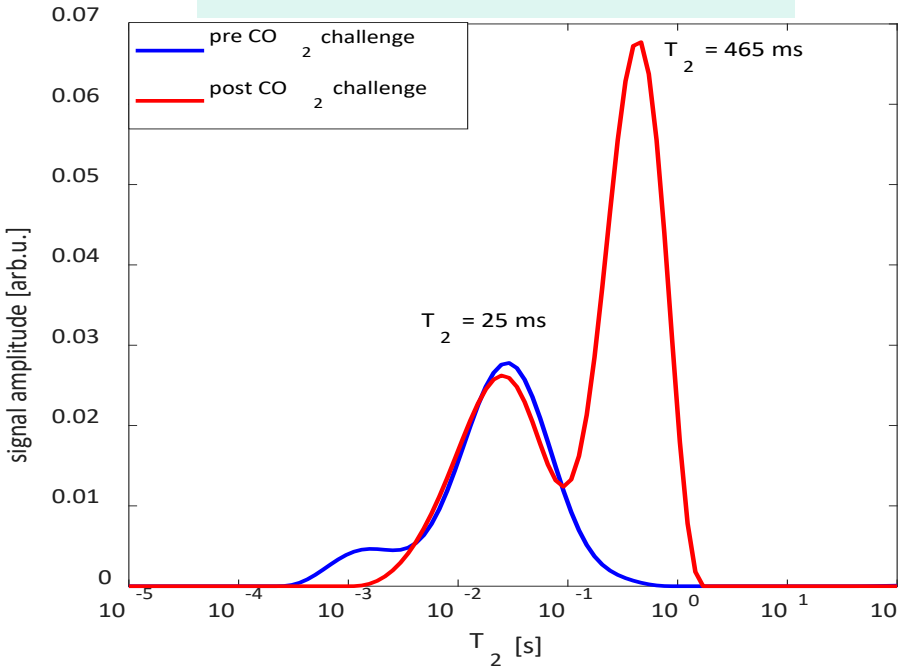
Gas Porosity/Permeability: Dried core



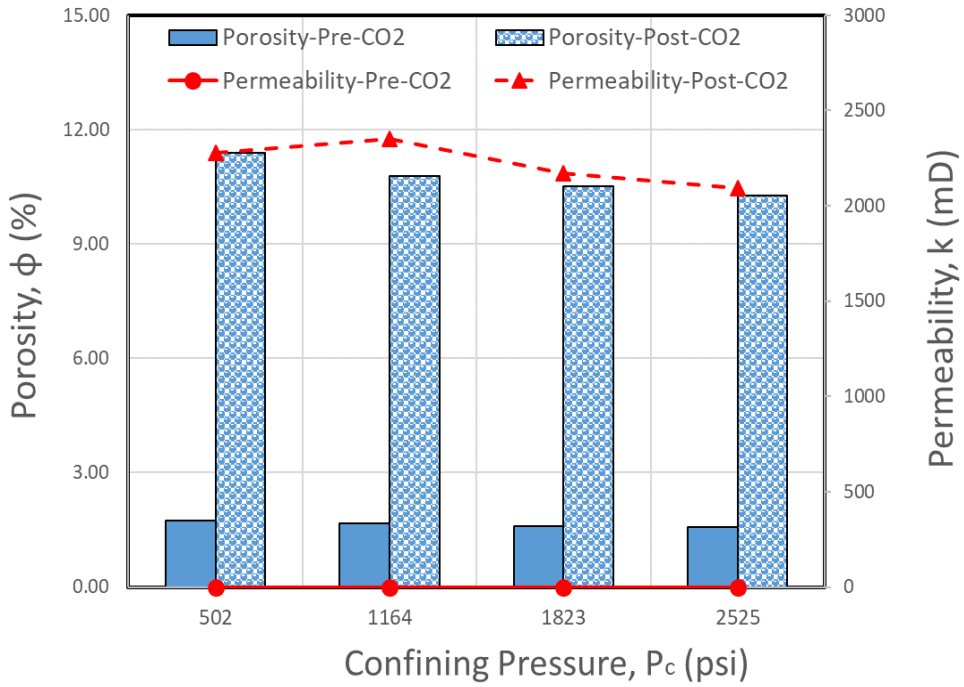
- A shift towards shorter T_2 times indicating either a decrease in the pore size distribution or a change in the mineral composition on the surface of the pores.
- Decrease in pore size distribution is unlikely after a CO_2 challenge unless new mineral is precipitated or CO_2 is trapped in the pores, causing less water to enter the core resulting in an apparent smaller pore size distribution.
- A change in the mineral composition of the surface will affect the surface relaxivity, ρ, and could potentially cause the shift to shorter T_2 times.
- *Gas φ/k*: Significant increase is due to mineral dissolution

NMR: Reef

NMR: Fully-saturated core



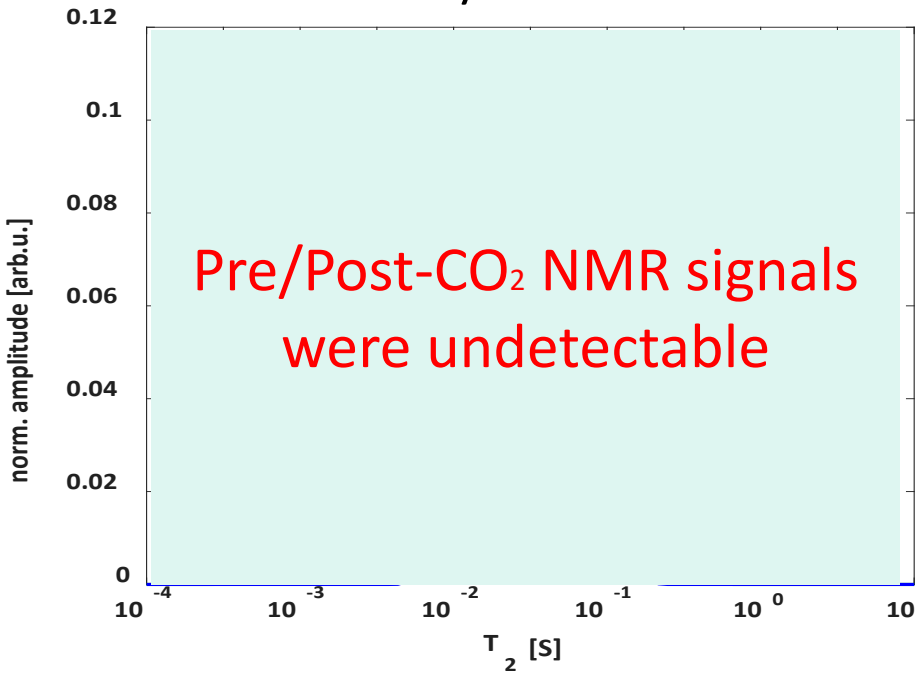
Gas Porosity/Permeability: Dried core



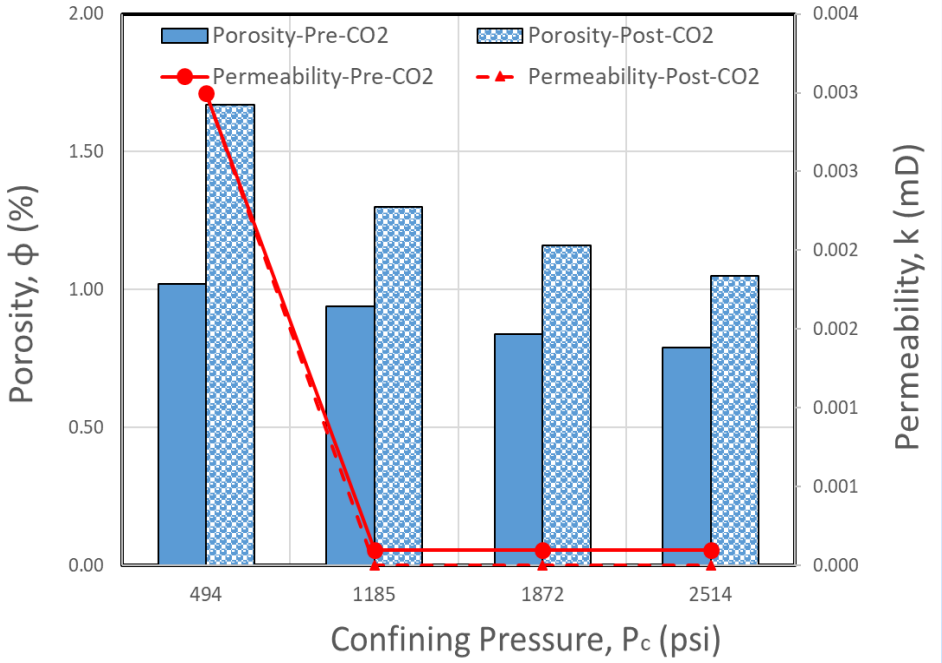
- Shorter T_2 population disappears after CO_2 challenge.
- No significant shift is observed for the longer T_2 population.
- New T_2 population appears after CO_2 challenge, indicates that the CO_2 challenge has potentially created larger void spaces within the core.
- *Gas φ/k*: Significant increase is due to mineral dissolution

NMR: Lagoon

NMR: Fully-saturated core



Gas Porosity/Permeability: Dried core



- NMR signal is undetectable before and after CO_2 experiment because the pores were inaccessible
- No significant change in porosity and permeability

NMR Porosities (%)

Sample ID	Pre-CO_2 Challenge				Post-CO_2 Challenge				Remark
	Fully saturated	1st centrifuge (3,000 g)	2nd centrifuge (6,000 g)	3rd centrifuge (10,000 g)	Fully saturated	1st centrifuge (3,000 g)	2nd centrifuge (6,000 g)	3rd centrifuge (10,000 g)	
High Energy Shoal (HES 1)	10.6	--	6.2	5.4	7.6	--	--	5.4	
Shallow Reef Front (SR 1)	8.8	4.4	--	3.8	--	--	--	--	Core was destroyed during CO_2 experiment
Shallow Reef Front (SR 2)	5.3	3.8	--	2.9	**	**	--	--	Replacement core for SR 1
Fore Reef (FR 1)	4.2	3.6	--	3.0	***	***	--	--	
Reef (R 1)	2.5	2.0	--	--	9.0	7.6	--	--	
Tidal Flat (T 1)	1.6	1.4	--	--	*	*	--	--	
Lagoon (EL 2)	No NMR Signal				No NMR Signal				

-- No NMR data

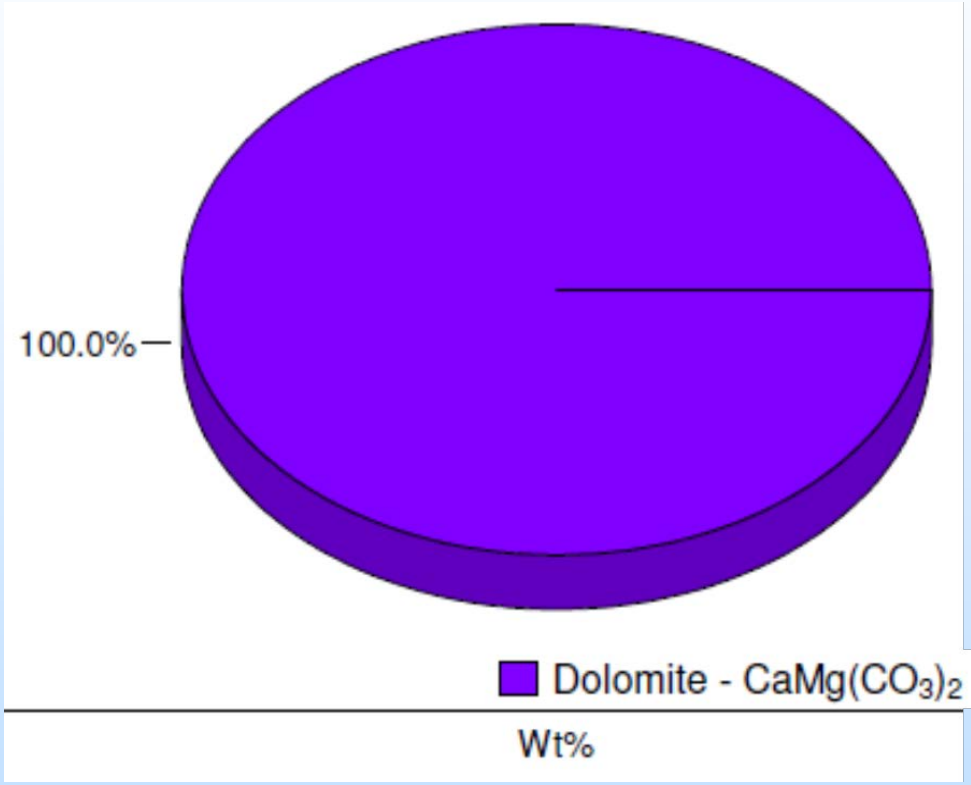
** CO_2 experiment is ongoing

* NMR experiment is ongoing

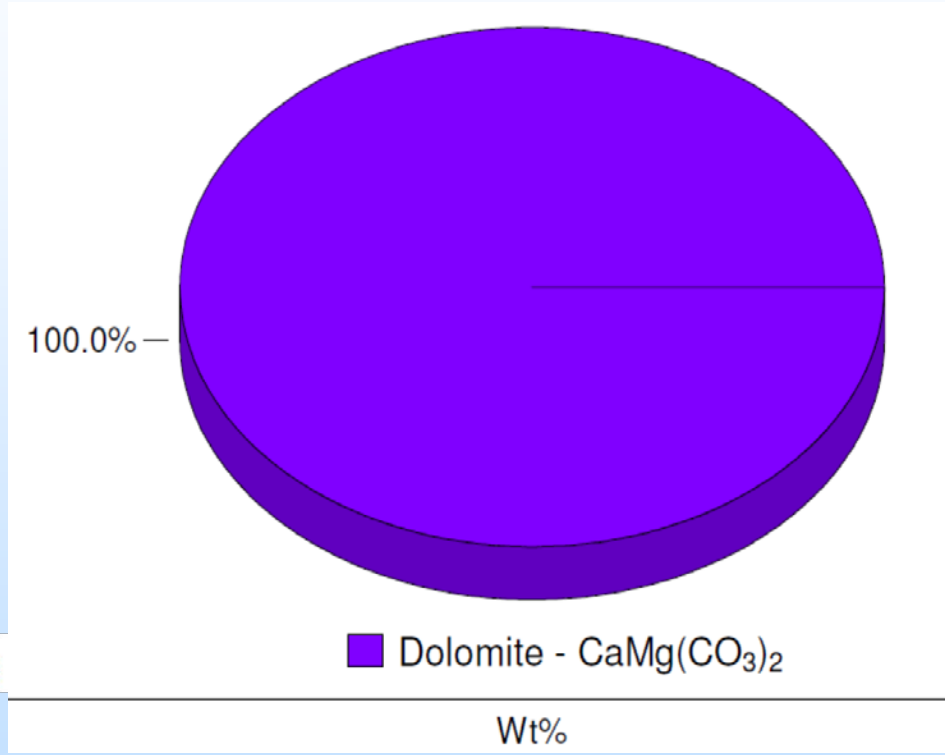
*** Planned CO_2 experiment

XRD Mineralogy: High Energy Shoal

Pre-CO_2



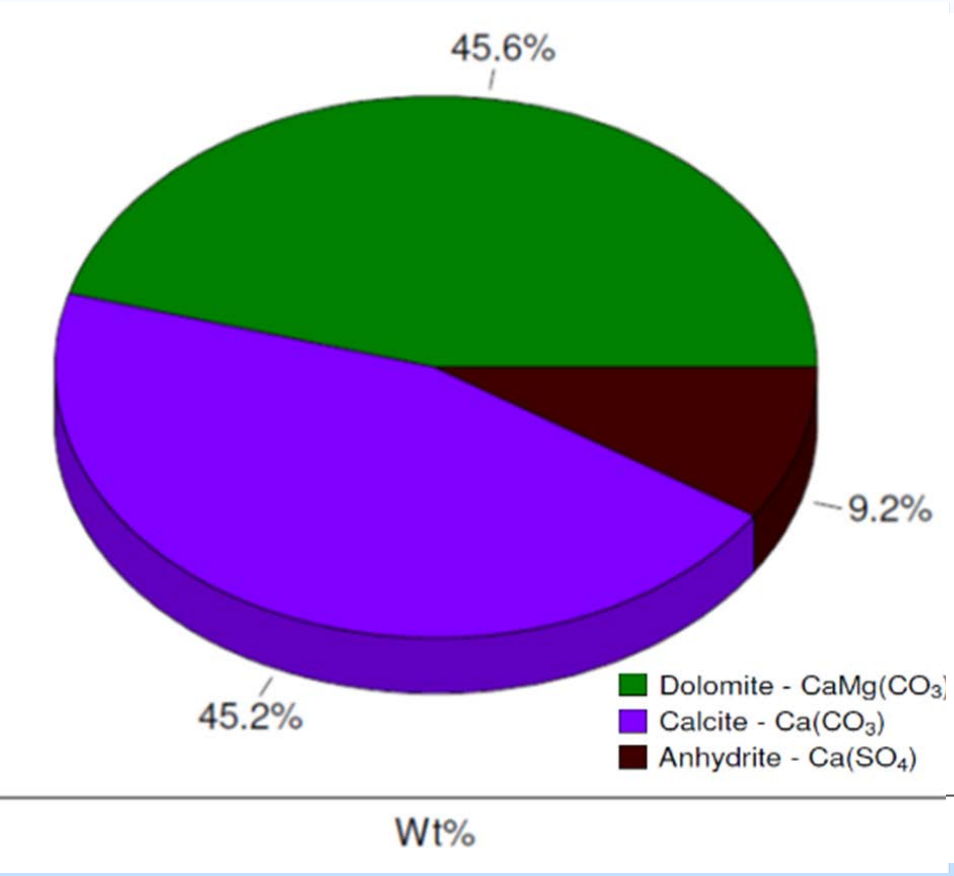
Post-CO_2



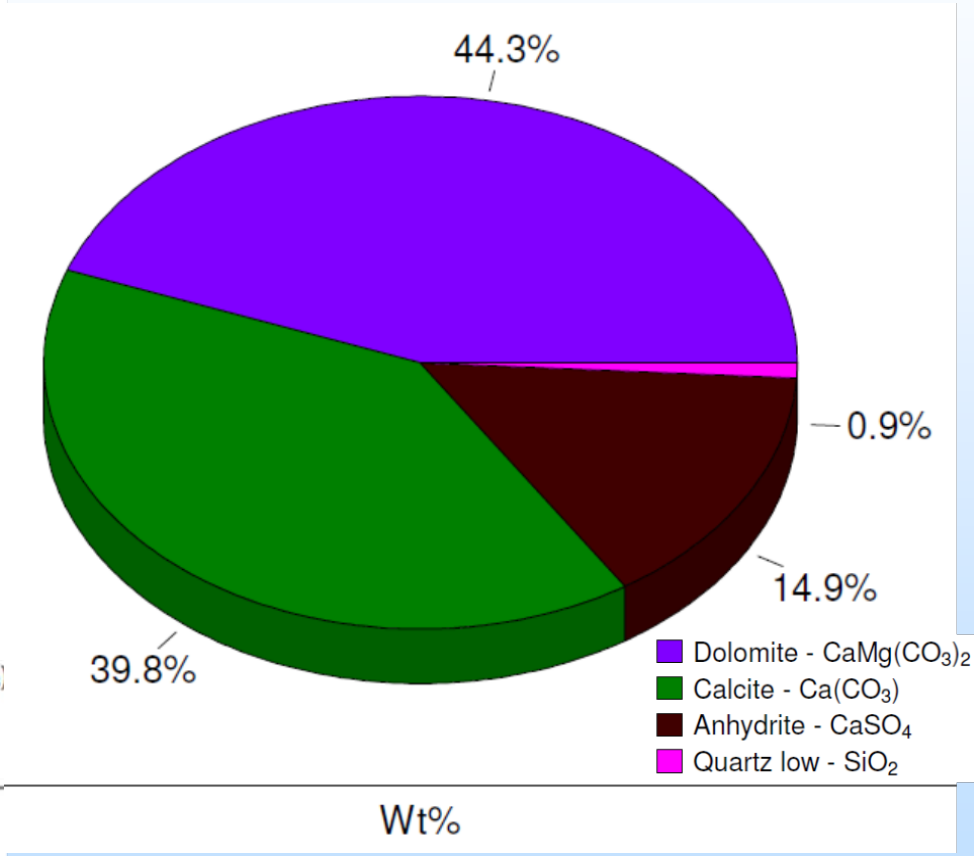
- No significant change in mineralogy

XRD Mineralogy: Reef

Pre-CO_2



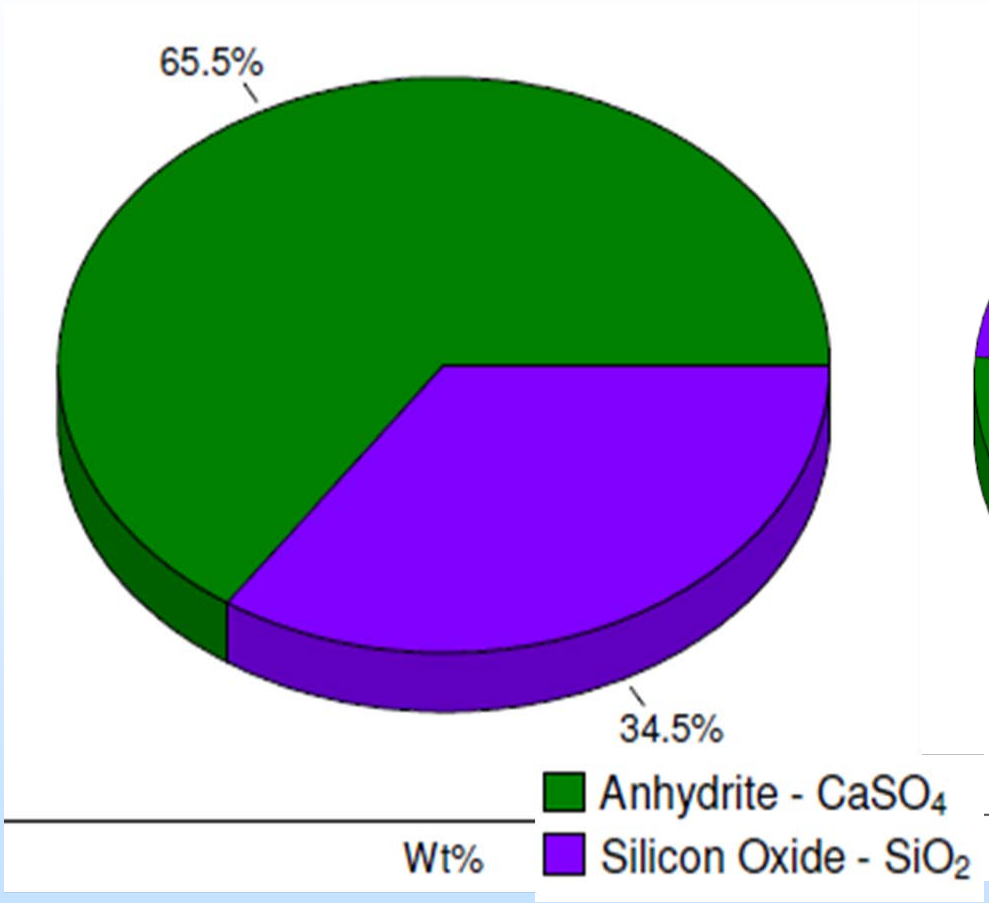
Post-CO_2



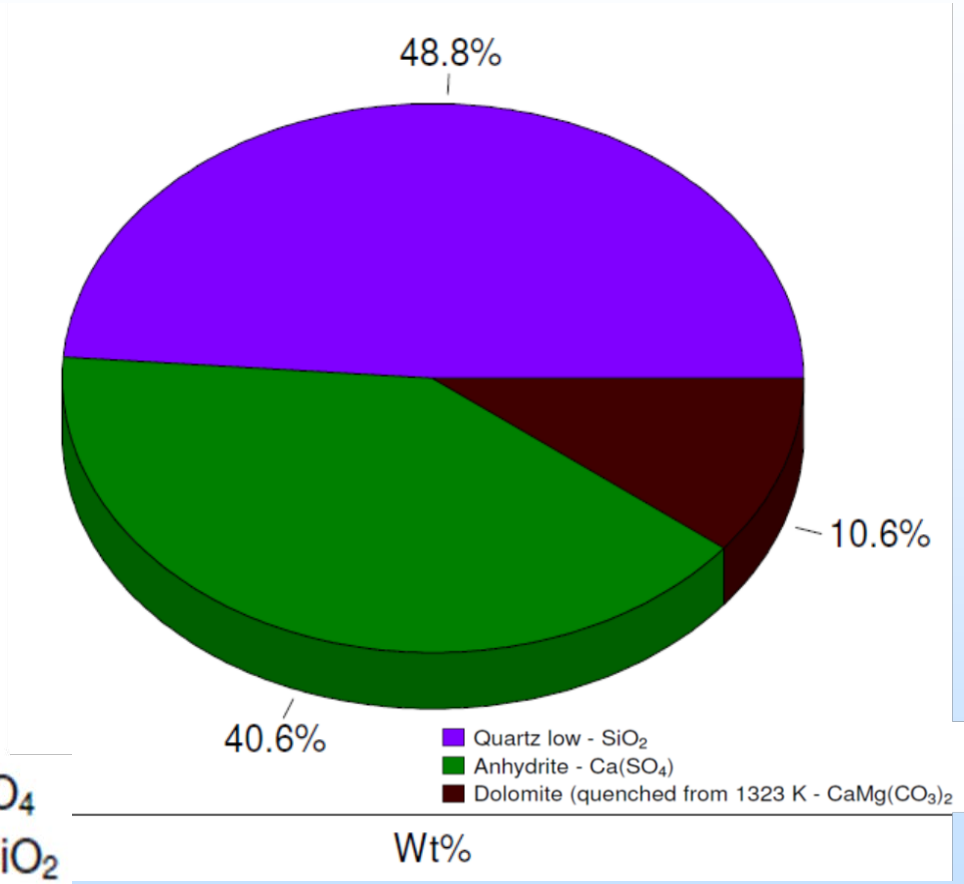
- No significant change in mineralogy

XRD Mineralogy: Lagoon

Pre-CO_2



Post-CO_2



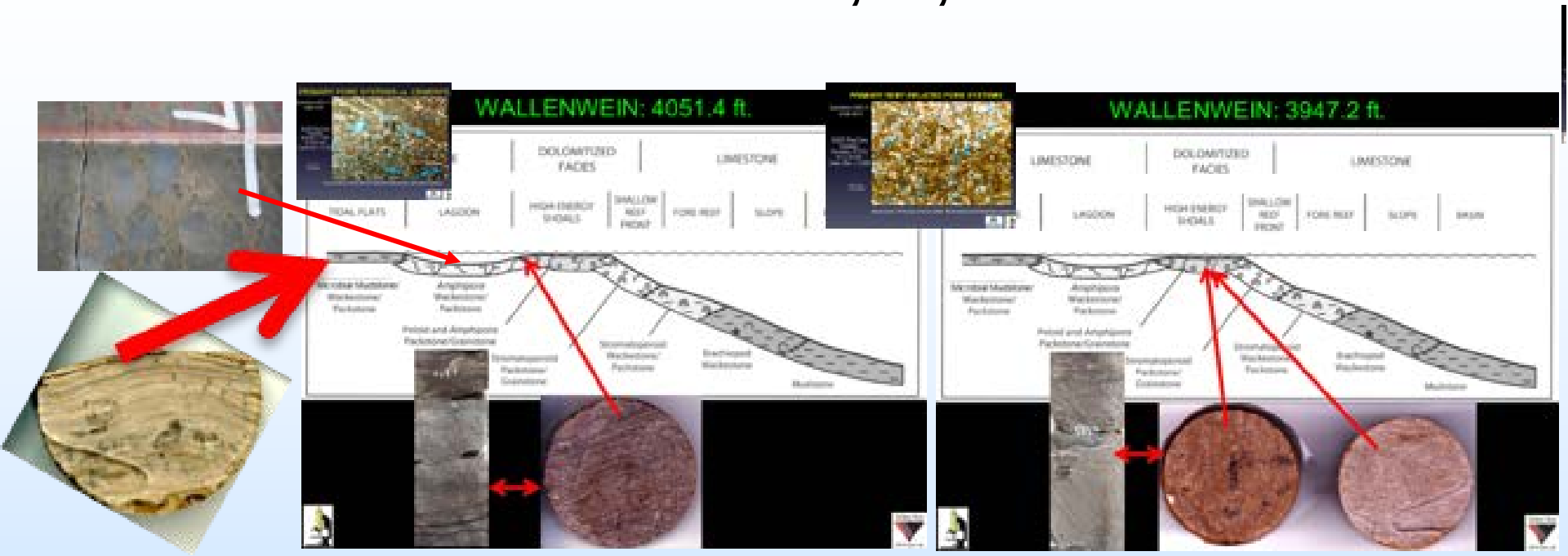
- Dolomite in the post-CO_2 core is likely present before the test as the well log shows

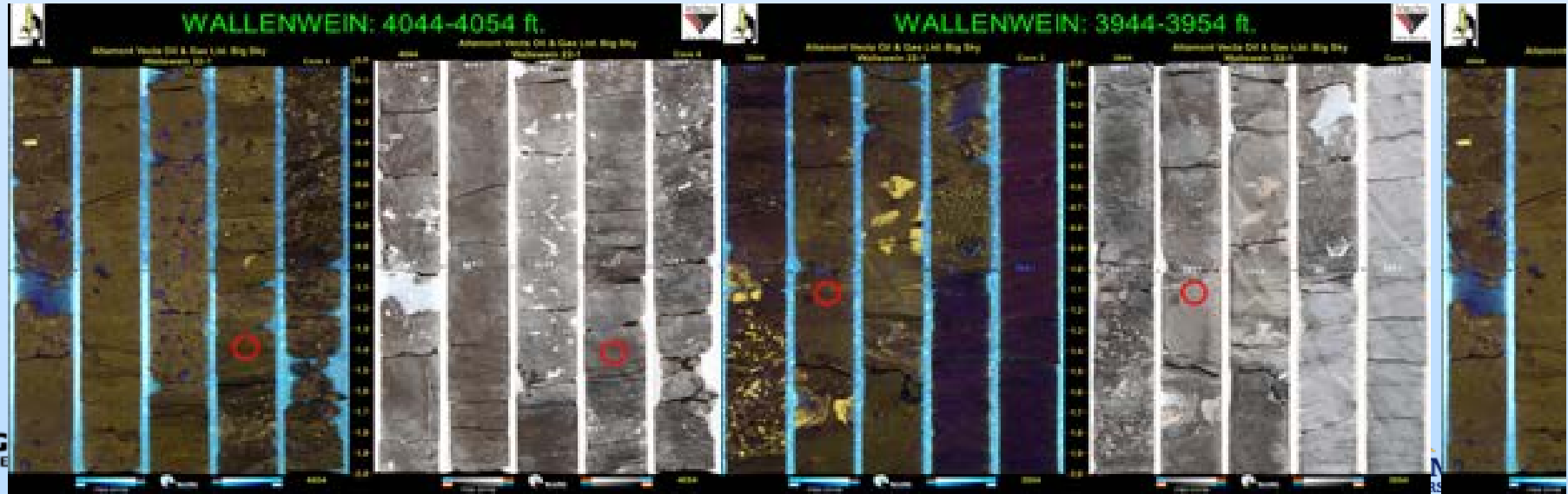
Summary

- High energy shoal, reef, and lagoon rock samples respond differently to supercritical CO_2.
- Rapid dissolution occurs predominantly in the reef and high energy shoal rock cores primarily because carbonates are susceptible to dissolution in the presence of CO_2.
- In addition to mineralogy, severity of the dissolution process is largely influenced by the transport properties of the rock.
- Lagoon rock sample is the most resistant to CO_2 invasion mainly because it's pores are inaccessible, thus ensuring it's integrity as a caprock.

Presentation Outline

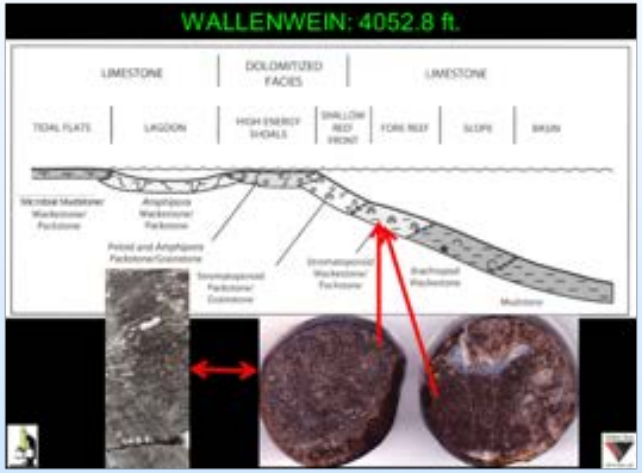
Facies 1, 2, 3

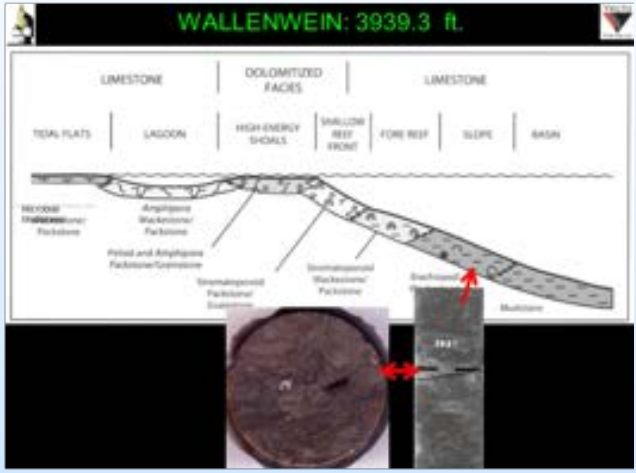

WALLENWEIN: 4051.4 ft.
WALLENWEIN: 3947.2 ft.
DOLOMITIZED FACIES
LIMESTONE
TIDAL FLATS
LAGOON
HIGH ENERGY SHOALS
SHALLOW REEF FRONT
FORE REEF
SLOPE
BASIN

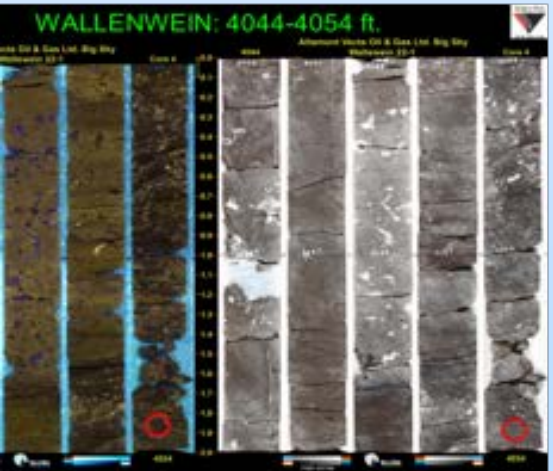

WALLENWEIN: 4044-4054 ft.
WALLENWEIN: 3944-3954 ft.

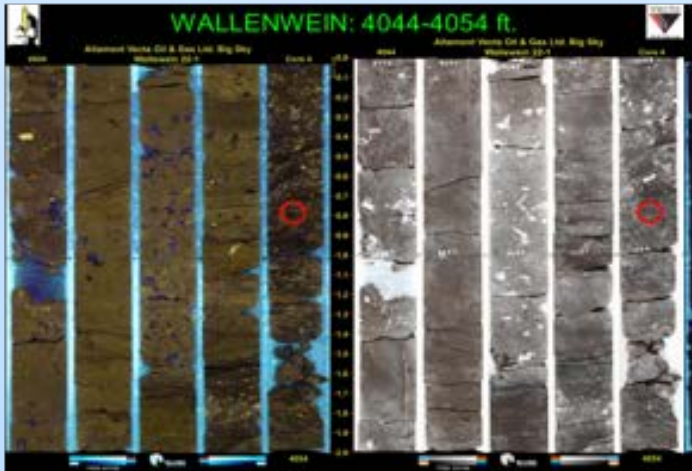
Facies 4, 5, 6

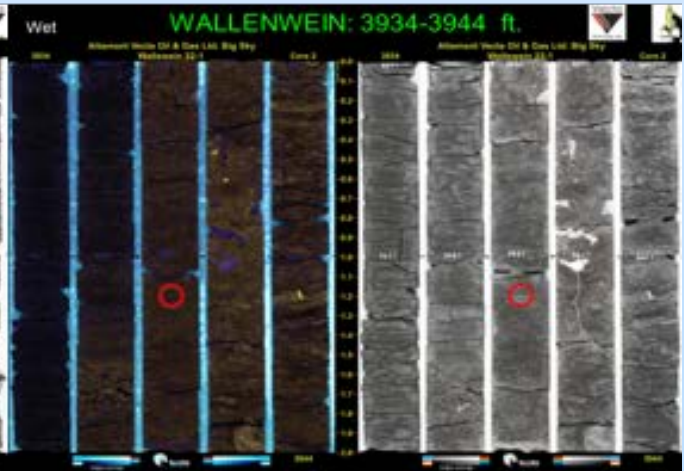
WALLENWEIN: 4053.9 ft.
LIMESTONE
DOLOMITIZED FACIES
LIMESTONE
TIDAL FLATS
LAGOON
HIGH ENERGY SHOALS
SHALLOW REEF FRONT
FORE REEF
SLOPE
BASIN


WALLENWEIN: 4052.8 ft.
LIMESTONE
DOLOMITIZED FACIES
LIMESTONE
TIDAL FLATS
LAGOON
HIGH ENERGY SHOALS
SHALLOW REEF FRONT
FORE REEF
SLOPE
BASIN


WALLENWEIN: 3939.3 ft.
LIMESTONE
DOLOMITIZED FACIES
LIMESTONE
TIDAL FLATS
LAGOON
HIGH ENERGY SHOALS
FORE REEF
SLOPE
BASIN

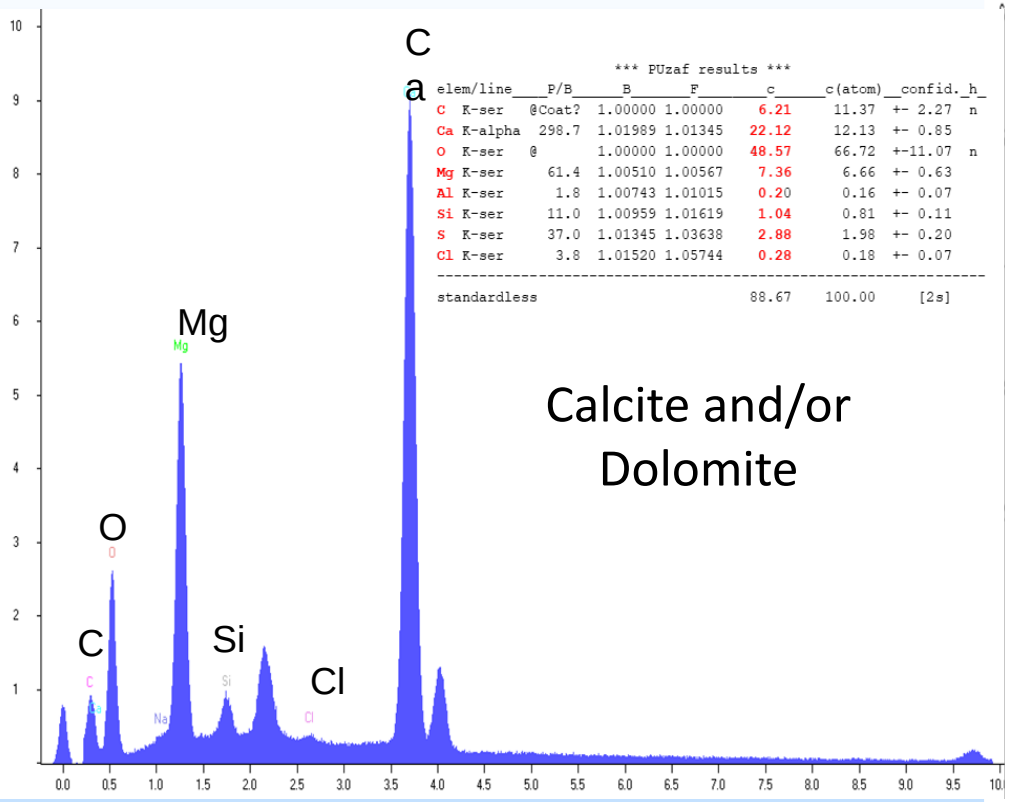

WALLENWEIN: 4044-4054 ft.


WALLENWEIN: 4044-4054 ft.

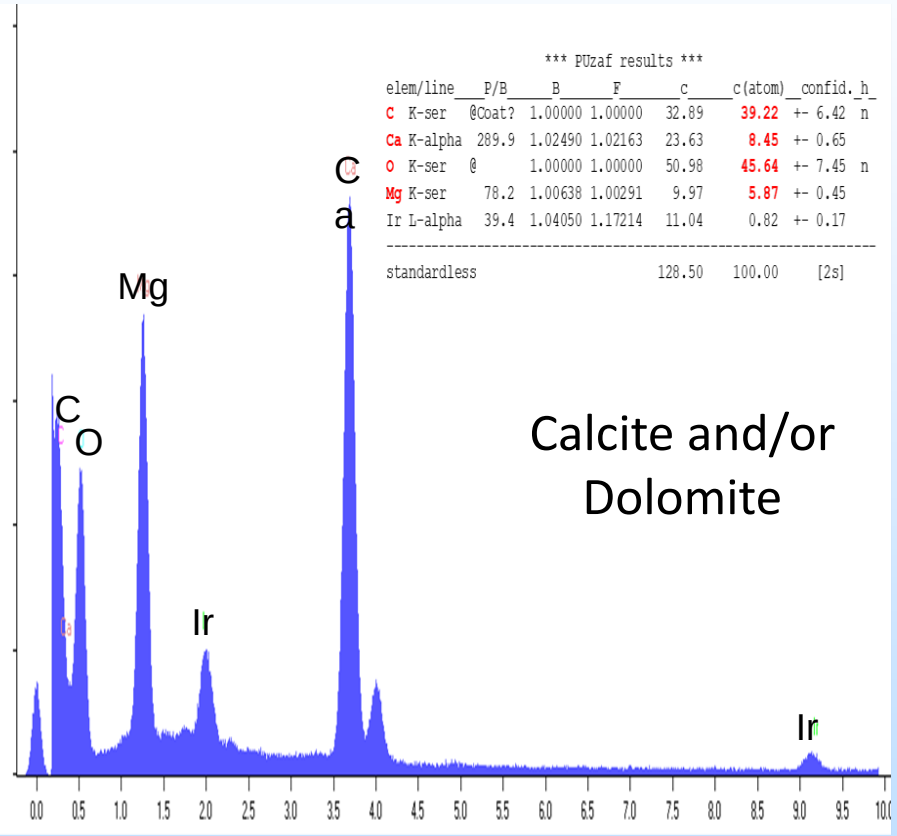

Wet
WALLENWEIN: 3934-3944 ft.

EDX Elemental Composition : High Energy Shoal

Pre-CO_2

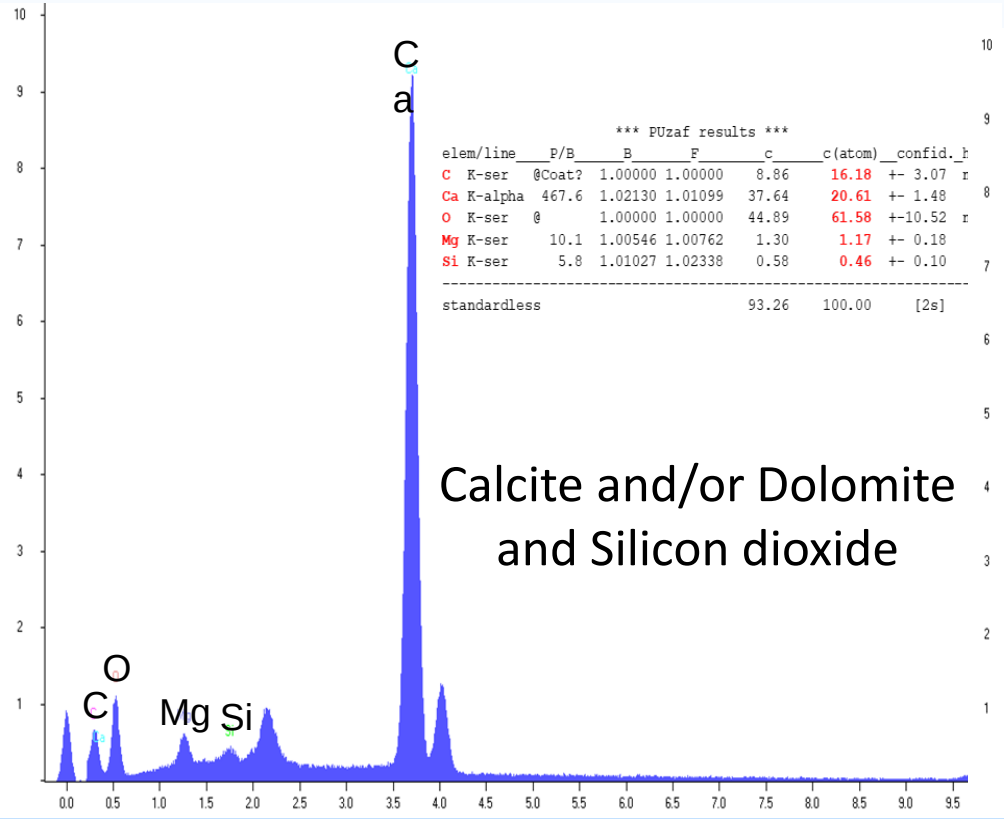


Post-CO_2



EDX Elemental Composition : Reef

Pre-CO_2

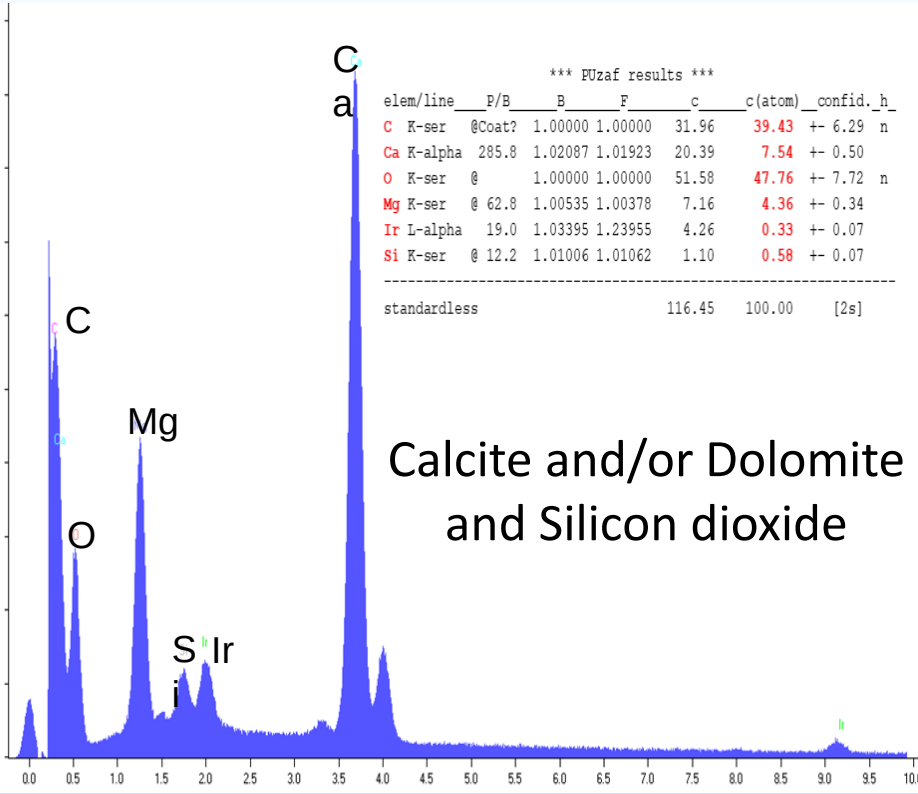


*** PUzaf results ***

elem/line	P/B	B	F	c	c(atom)	confid.	h
C K-ser	@Coat?	1.00000	1.00000	8.86	16.18	+- 3.07	r
Ca K-alpha	467.6	1.02130	1.01099	37.64	20.61	+- 1.48	
O K-ser	@	1.00000	1.00000	44.89	61.58	+-10.52	r
Mg K-ser	10.1	1.00546	1.00762	1.30	1.17	+- 0.18	
Si K-ser	5.8	1.01027	1.02338	0.58	0.46	+- 0.10	
standardless				93.26	100.00	[2s]	

Calcite and/or Dolomite and Silicon dioxide

Post-CO_2



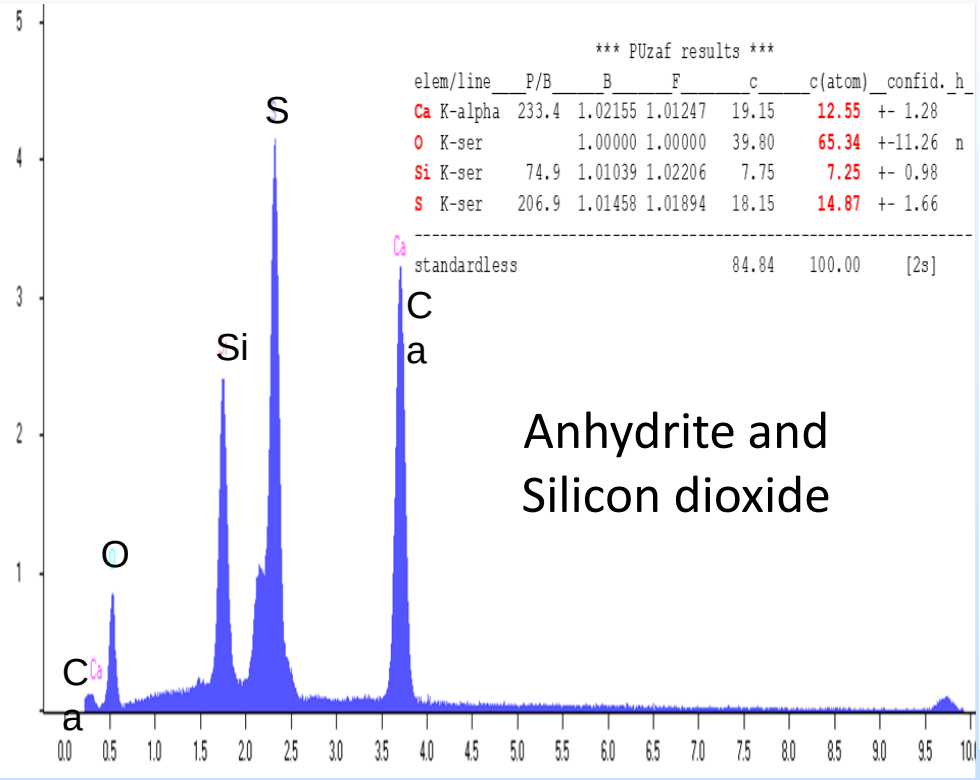
*** PUzaf results ***

elem/line	P/B	B	F	c	c(atom)	confid.	h
C K-ser	@Coat?	1.00000	1.00000	31.96	39.43	+- 6.29	n
Ca K-alpha	285.8	1.02087	1.01923	20.39	7.54	+- 0.50	
O K-ser	@	1.00000	1.00000	51.58	47.76	+- 7.72	n
Mg K-ser	@ 62.8	1.00535	1.00378	7.16	4.36	+- 0.34	
Ir L-alpha	19.0	1.03395	1.23955	4.26	0.33	+- 0.07	
Si K-ser	@ 12.2	1.01006	1.01062	1.10	0.58	+- 0.07	
standardless				116.45	100.00	[2s]	

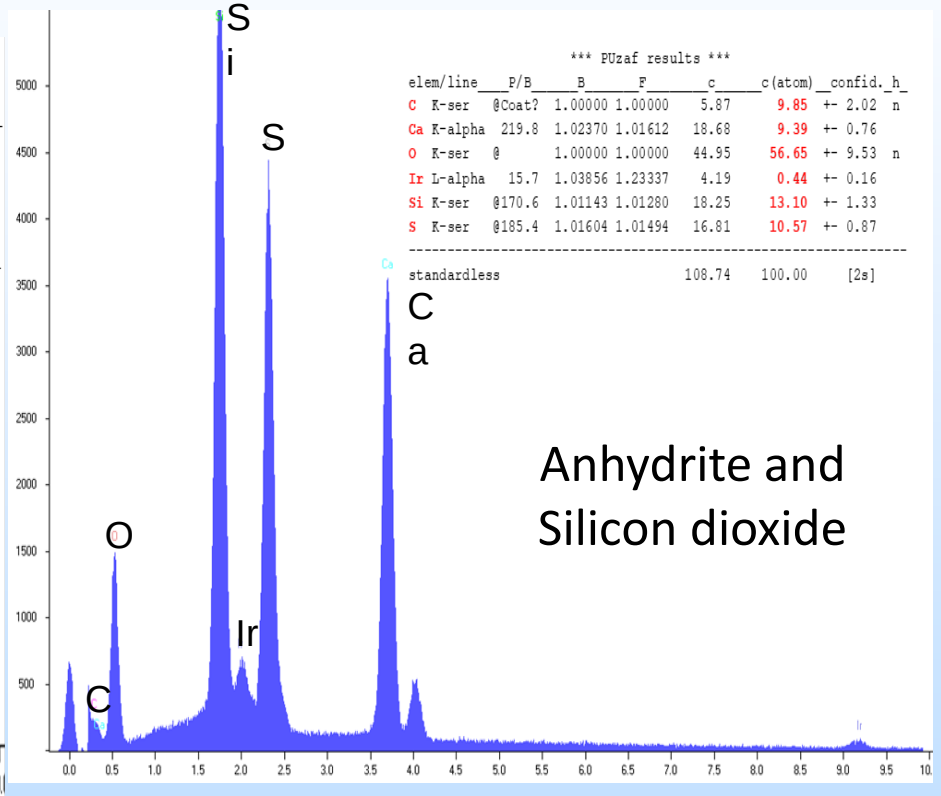
Calcite and/or Dolomite and Silicon dioxide

EDX Elemental Composition : Lagoon

Pre-CO_2



Post-CO_2



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Technical Status

- Prepare as many technical status slides as needed, but recognize the limits of the allocated presentation time.
- Use these slides to logically walk through the project. Focus on telling the story of your project and highlighting the key points as described in the Presentation Guidelines.
- Include specific information to show how your project is advancing the state-of-the-art; be as quantitative as possible in describing improvements in the performance of your technology compared to the state-of-the-art.

Accomplishments to Date

- Bullet List of Accomplishments (see Presentation Guidelines for examples).
- Multiple slides can be used if needed.

Lessons Learned

- Research gaps/challenges.
- Unanticipated research difficulties.
- Technical disappointments.
- Changes that should be made next time.
- Multiple slides can be used if needed.

Synergy Opportunities

- Discuss how collaboration among projects could have a synergistic effect on advancing the technologies described during the session in which you are presenting.

Project Summary

- Key Findings.
- Next Steps.

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Identify the program goals being addressed.

- Insert project benefits statement.
  - See Presentation Guidelines for an example.

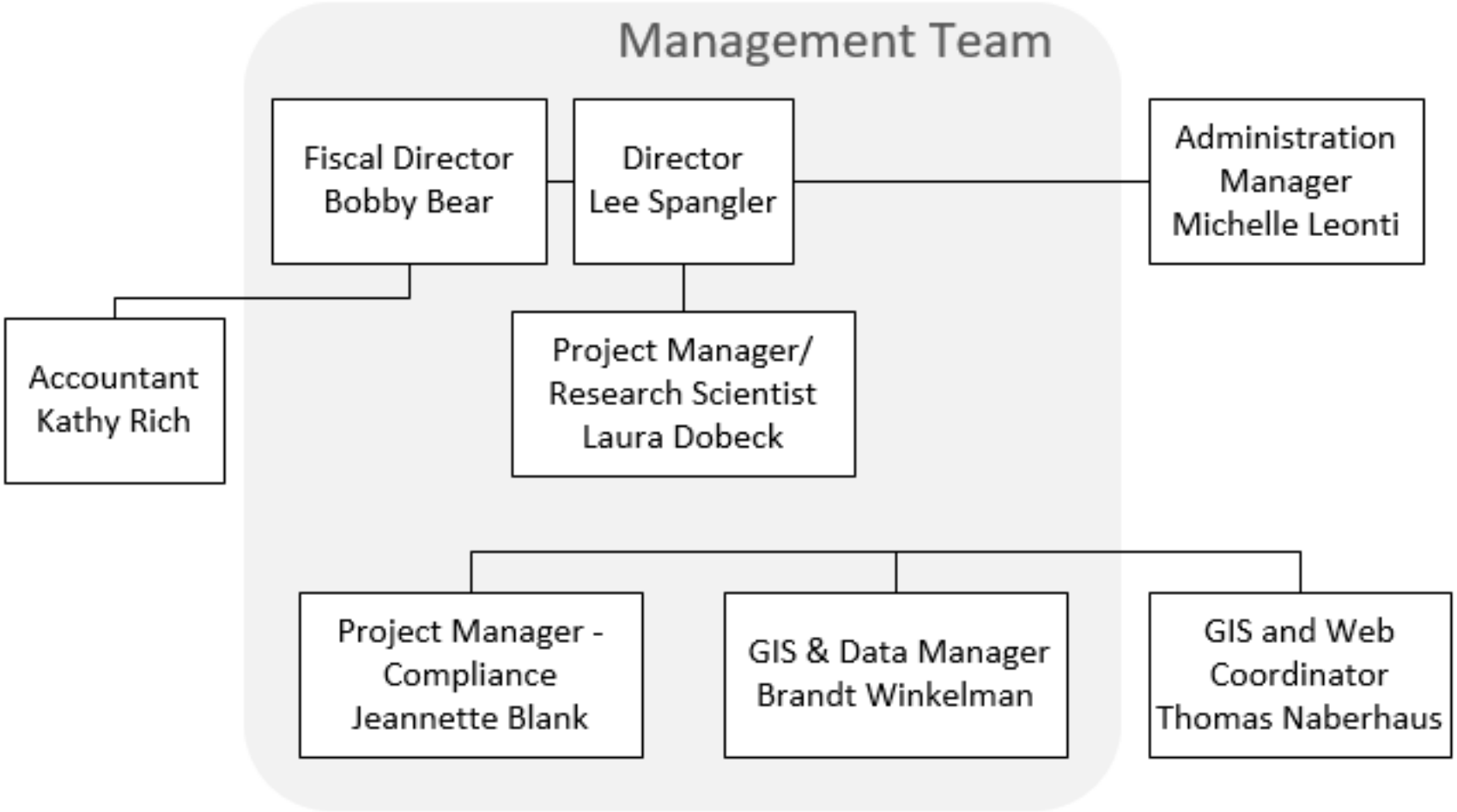
Project Overview

- Describe the project goals and objectives in the Statement of Project Objectives.

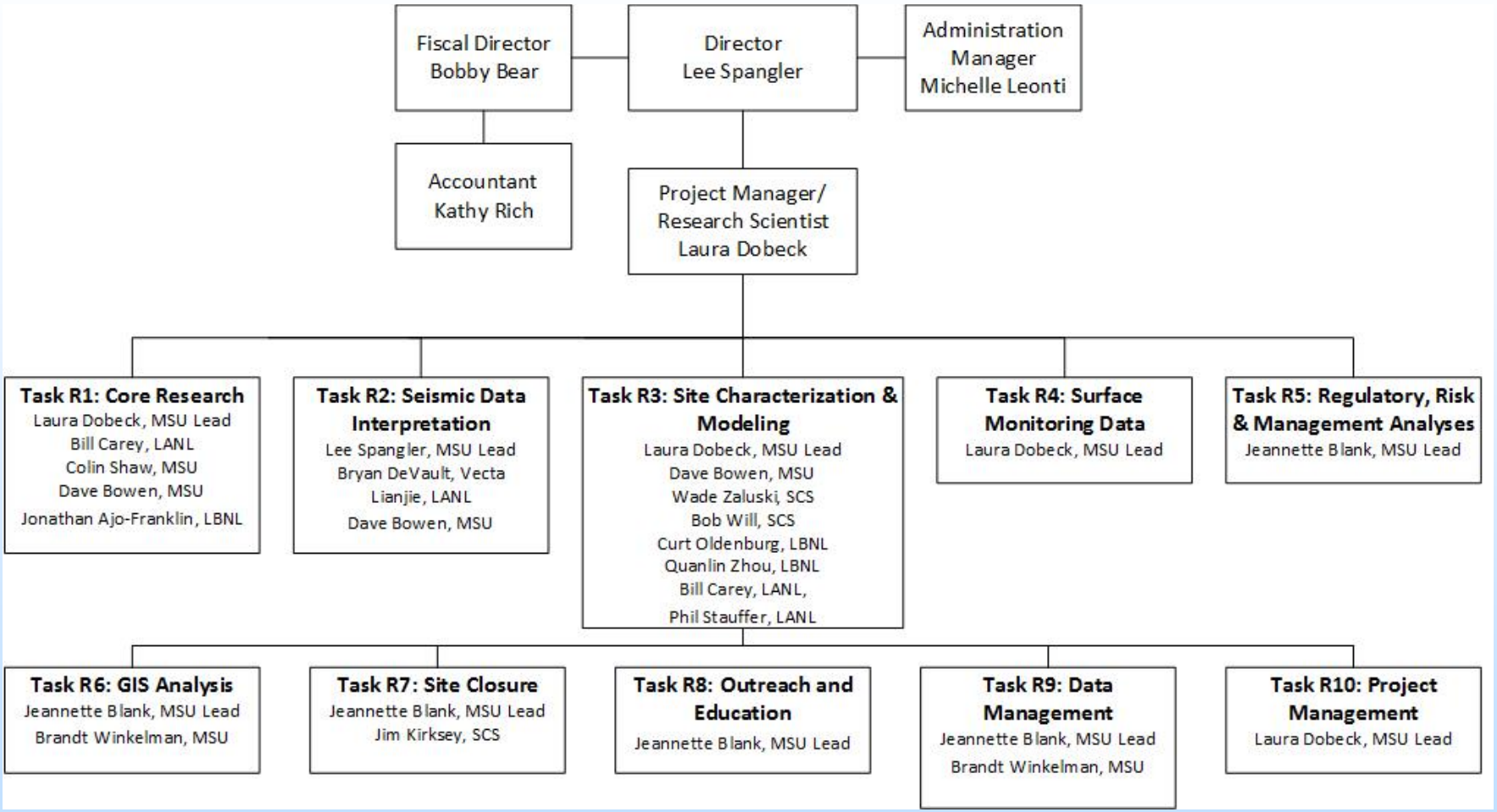
Goals and Objectives

  - How the project goals and objectives relate to the program goals and objectives.
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.

Organization Chart

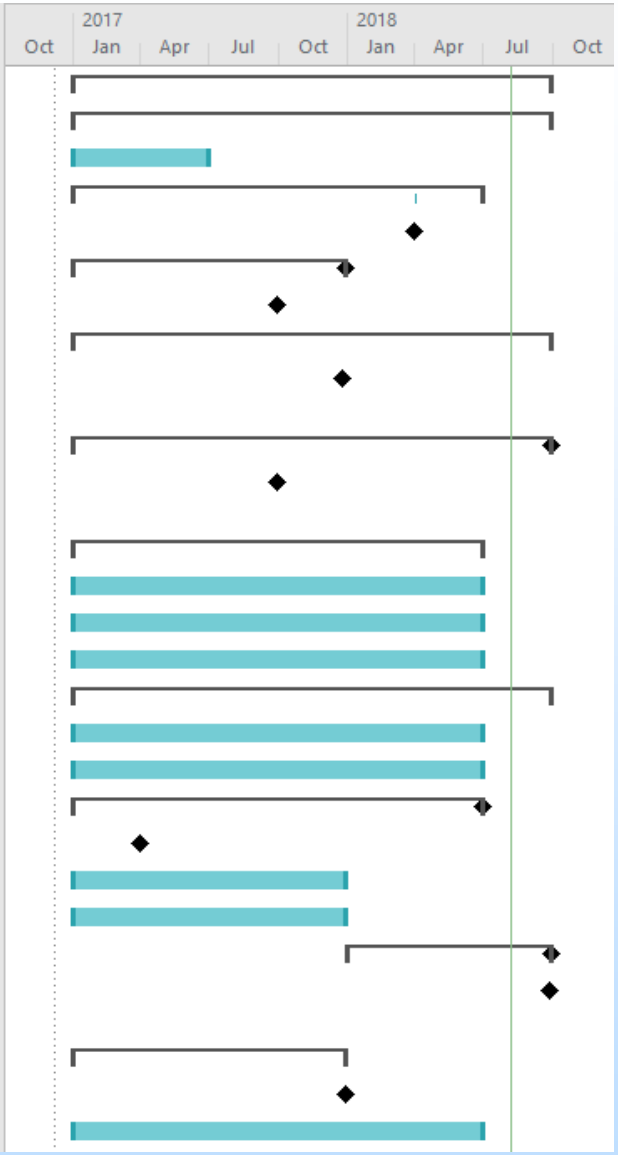


Organization Chart



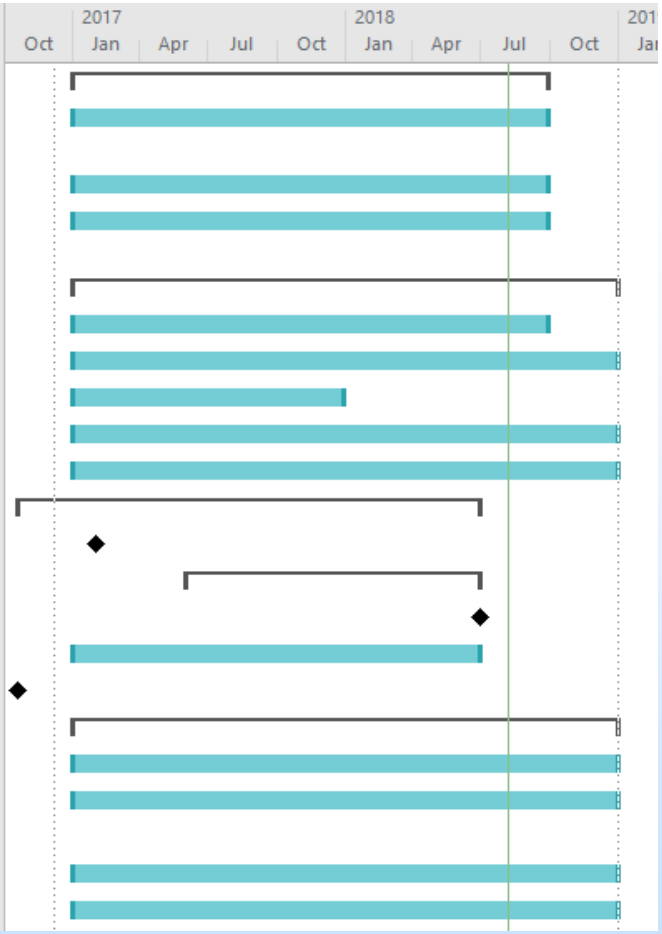
Gantt Chart

Task Name	Start	Finish
Tasks R1-R4 Completion of Research: Core, Seismic, Modeling, MVA	**Mon 1/2/17**	**Fri 9/28/18**
Task R1. Core Research	**Mon 1/2/17**	**Fri 9/28/18**
R1.1 Characterization of Duperow fractures	Mon 1/2/17	Fri 6/30/17
R1.2 Laboratory Core Flood Studies	**Mon 1/2/17**	**Fri 6/29/18**
M: Completion of core flood NMR	Fri 3/30/18	Fri 3/30/18
R1.3 Fracture permeability of caprock	**Mon 1/2/17**	**Fri 12/29/17**
M: Completion of caprock fracture-permeability measurements	Fri 9/29/17	Fri 9/29/17
R1.4 Core seismic properties	**Mon 1/2/17**	**Fri 9/28/18**
M: Completion of initial stress-dependent seismic property measurements of fractured Duperow samples and submission of manuscript	Tue 12/26/17	Tue 12/26/17
R1.5 Lab measurements of fracture-matrix flow	**Mon 1/2/17**	**Fri 9/28/18**
M: Design calculations, sensitivity, and scale effects of fracture-matrix interaction and preparation of lab experiments (draft report)	Sat 9/30/17	Sat 9/30/17
Task R2. Seismic Data Interpretation	**Mon 1/2/17**	**Fri 6/29/18**
R2.1 Seismic processing and interpretation	Mon 1/2/17	Fri 6/29/18
R2.2 High-resolution 3D velocity model building	Mon 1/2/17	Fri 6/29/18
R2.3 Geophysical Characterization of Kevin Dome	Mon 1/2/17	Fri 6/29/18
Task R3. Site Characterization and Modeling	**Mon 1/2/17**	**Fri 9/28/18**
R3.1 Geologic framework of Kevin Dome	Mon 1/2/17	Fri 6/29/18
R3.2 Stratigraphic architecture and reservoir characterization	Mon 1/2/17	Fri 6/29/18
R3.3 Geostatic modeling	**Mon 1/2/17**	**Fri 6/29/18**
M: Distribution of revised geostatic model to partners	Fri 3/31/17	Fri 3/31/17
R3.4 Liquid-gas CO2 phase transition modeling	Mon 1/2/17	Fri 12/29/17
R3.5 Fractured carbonate systems modeling	Mon 1/2/17	Fri 12/29/17
R3.6 Large-scale modeling and storage capacity estimate for Kevin Dome	**Mon 1/1/18**	**Fri 9/28/18**
M: Completion of large-scale modeling and storage capacity estimate for the Kevin Dome	Fri 9/28/18	Fri 9/28/18
R3.7 Application of an Integrated Assessment Model	**Mon 1/2/17**	**Fri 12/29/17**
M: Complete NRAP-IAM- calculations	Fri 12/29/17	Fri 12/29/17
Task R4. Processing and Analyzing Surface Monitoring Data	Mon 1/2/17	Fri 6/29/18



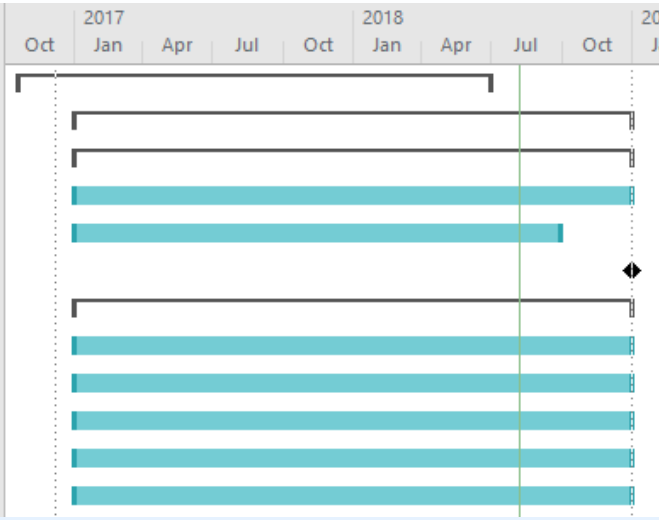
Gantt Chart

Task Name	Start	Finish
Task R5. Regulatory, Risk, and Management Analyses	**Mon 1/2/17**	**Fri 9/28/18**
R5.1 Documenting Lessons Learned from BSCSP's Permitting and Regulatory Program	Mon 1/2/17	Fri 9/28/18
R5.2 Documenting Lessons Learned from BSCSP's Risk Management Program	Mon 1/2/17	Fri 9/28/18
R5.3 Documenting Lessons Learned from BSCSP's Management Strategies for Large-Scale Field Activities	Mon 1/2/17	Fri 9/28/18
Task R6. GIS for Regional, National, and Project-Level Analysis	**Mon 1/2/17**	**Mon 12/31/18**
R6.1 Regional Characterization for CCS	Mon 1/2/17	Fri 9/28/18
R6.2 National GIS Working Group	Mon 1/2/17	Mon 12/31/18
R6.3 Analysis of National Storage Resources and EPA Class VI Regulations	Mon 1/2/17	Fri 12/29/17
R6.4 Geospatial Cyberinfrastructure	Mon 1/2/17	Mon 12/31/18
R6.5 GIS Support for Project Activities	Mon 1/2/17	Mon 12/31/18
Task R7. Site Closure	**Thu 10/20/16**	**Fri 6/29/18**
R7.1 Wallewein Well	Mon 1/2/17	Tue 1/31/17
R7.2 Danielson Well	**Thu 6/1/17**	**Fri 6/29/18**
M: Site closure or transfer of the Danielson 33-17 Well	Fri 6/29/18	Fri 6/29/18
R7.3 Landowner Communications	Mon 1/2/17	Fri 6/29/18
M: Final documentation of the Wallewein well site closure	Thu 10/20/16	Thu 10/20/16
Task R8. Outreach and Education	**Mon 1/2/17**	**Mon 12/31/18**
R8.1 Maintain Website	Mon 1/2/17	Mon 12/31/18
R8.2 Outreach Materials	Mon 1/2/17	Mon 12/31/18
R8.3 Annual Meetings		
R8.4 National Outreach Working Group	Mon 1/2/17	Mon 12/31/18
R8.5 Collaborative Opportunities and Information Exchange	Mon 1/2/17	Mon 12/31/18



Gantt Chart

Task Name	Start	Finish
Task R7. Site Closure	**Thu 10/20/16**	**Fri 6/29/18**
Task R8. Outreach and Education	**Mon 1/2/17**	**Mon 12/31/18**
Task R9. Data Management	**Mon 1/2/17**	**Mon 12/31/18**
R9.1 Data Management Electronic Resources	Mon 1/2/17	Mon 12/31/18
R9.2 Management of Geologic Samples	Mon 1/2/17	Fri 9/28/18
M: Complete data preparation for archival	Mon 12/31/18	Mon 12/31/18
Task R10. Project Management	**Mon 1/2/17**	**Mon 12/31/18**
R10.1 Reporting and publications	Mon 1/2/17	Mon 12/31/18
R10.2 Risk Activities	Mon 1/2/17	Mon 12/31/18
R10.3 Energy development opportunities	Mon 1/2/17	Mon 12/31/18
R10.4 Final Project Report and Technical Briefing	Mon 1/2/17	Mon 12/31/18
R10.5 Project and Budget Management	Mon 1/2/17	Mon 12/31/18



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Onishi, T., Nguyen, M., Carey, J.W., Will, R., Zaluski, W., Bowen, D.W., DeVault, B., Duguid, A., Zhou, Q., Fairweather, S., Spangler, L. and Stauffer, P., Potential CO2 and brine leakage through wellbore pathways for geologic CO2 sequestration using the National Risk Assessment Partnership tools: Application to the Big Sky Regional Partnership. International Journal of Greenhouse Gas Control, 2018. In Review

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Saltiel, S., Bonner, B.P., Mittal, T., Delbridge, B. and Ajo-Franklin, J.B., Experimental evidence for dynamic friction on rock fractures from frequency-dependent nonlinear hysteresis and harmonic generation. Journal of Geophysical Research: Solid Earth, 2017. 122(7): p.4982-4999 DOI: 10.1002/2017JB014219.

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Yoshida, N., Levine, J.S. and Stauffer, P.H., Investigation of uncertainty in CO2 reservoir models: A sensitivityanalysis of relative permeability parameter values. International Journal of Greenhouse Gas Control, 2016. 2016(49): p. 161-178 DOI: 10.1002/ghg.1607.

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