Big Sky Regional Carbon Sequestration Partnership – Kevin Dome Carbon Storage

FC26-05NT42587

Lee Spangler

Montana State University

U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

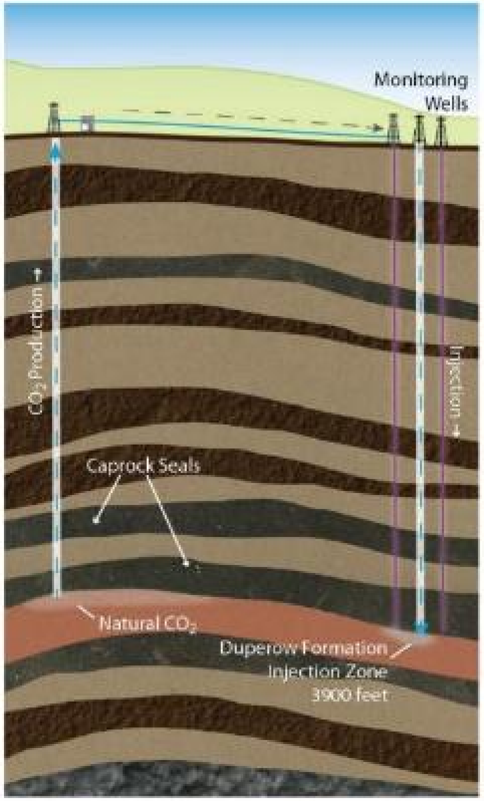
MONTANA STATE UNIVERSITY

Acknowledgments

- US Department of Energy
- Altamont Oil & Gas, Inc.
- Columbia University & Barnard College
- Idaho National Laboratory
- Los Alamos National Laboratory
- Lawrence Berkeley National Laboratory
- Schlumberger Carbon Services
- SWCA Environmental Consultants
- Vecta Oil and Gas, Ltd.
- Washington State University
- Montana State University

Dave Bowen
Colin Shaw
Omotayo Omosebi
Lianjie Huang
Minh Nguyen
Phil Stauffer
Bryan DeVault
Wade Zaluski
Harry Lisabeth
Jonathan Ajo-Franklin
Tim Kneafsey
Chun Chang
Quanlin Zhou
Curt Oldenburg
Lehua Pan
Bill Carey

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.

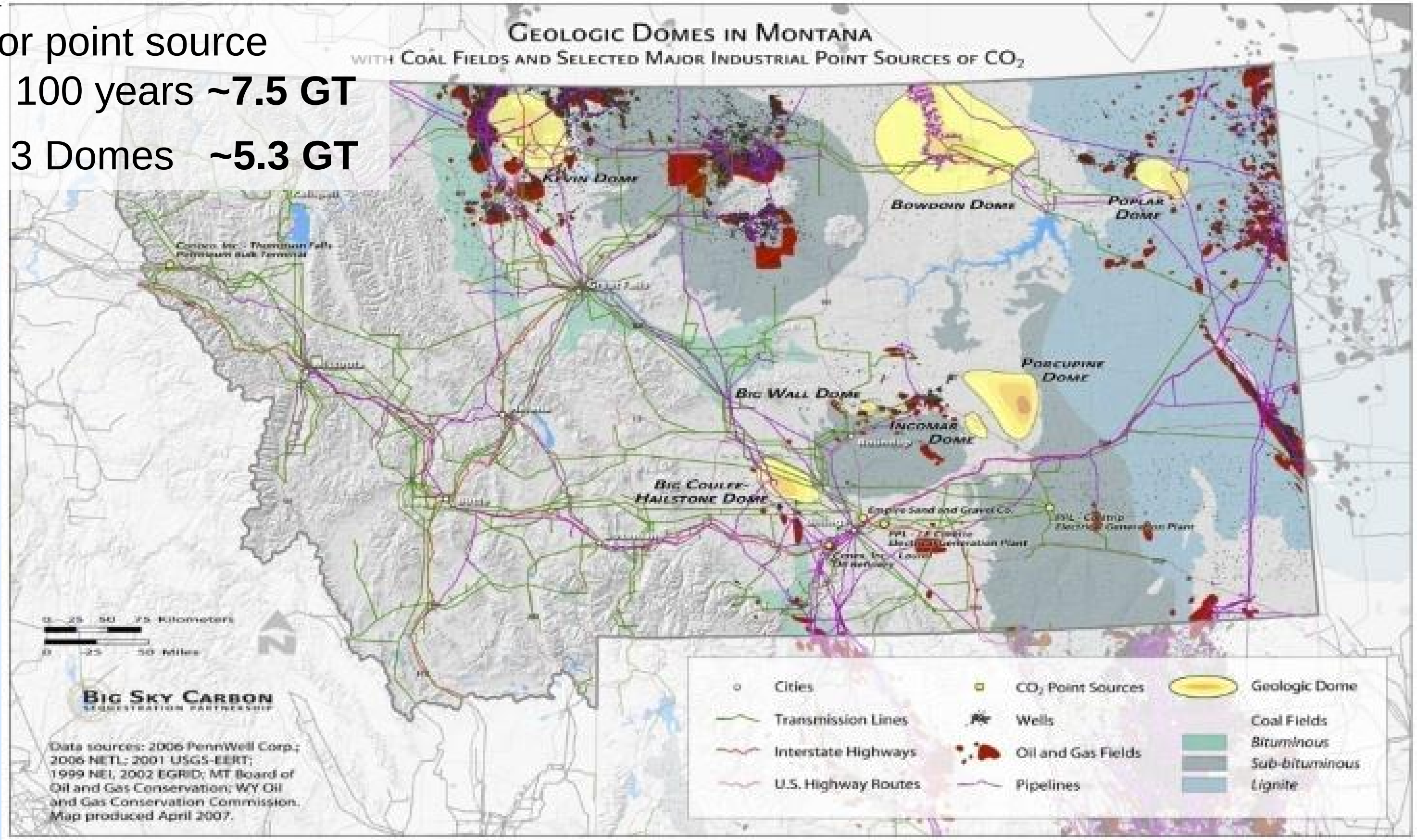
Duperow is a fractured reservoir with very secure caprock

- Opportunity to investigate impact of fracture permeability

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
- Storage Efficiency – for Kevin Dome capillary pressure can be as high as ~7 bar driving higher CO_2 saturation
- Potential use as carbon warehouse – decouple anthropogenic CO_2 rate from utilization rate

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 concepts.

Project Re-Scope

Project Re-scope: Maximize Learnings from Samples and Data

Continued…

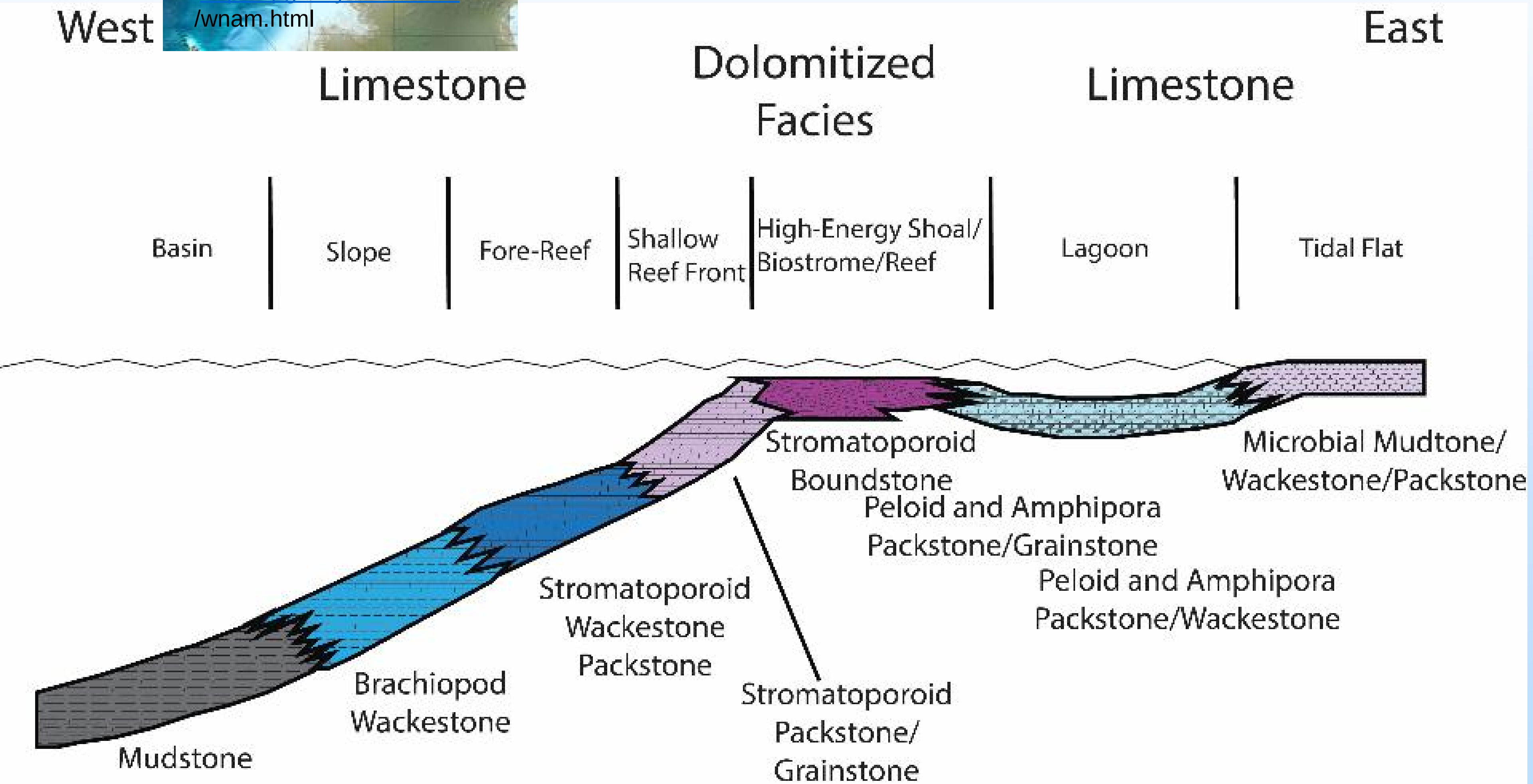
- Further develop fracture–matrix permeability interaction models incorporating data previously mentioned;
- Use the dual permeability model to refine reservoir performance for fractured carbonate reservoirs including capacity, injectivity and storage efficiency;
- Apply an integrated assessment model 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.**

Data, Samples, Models

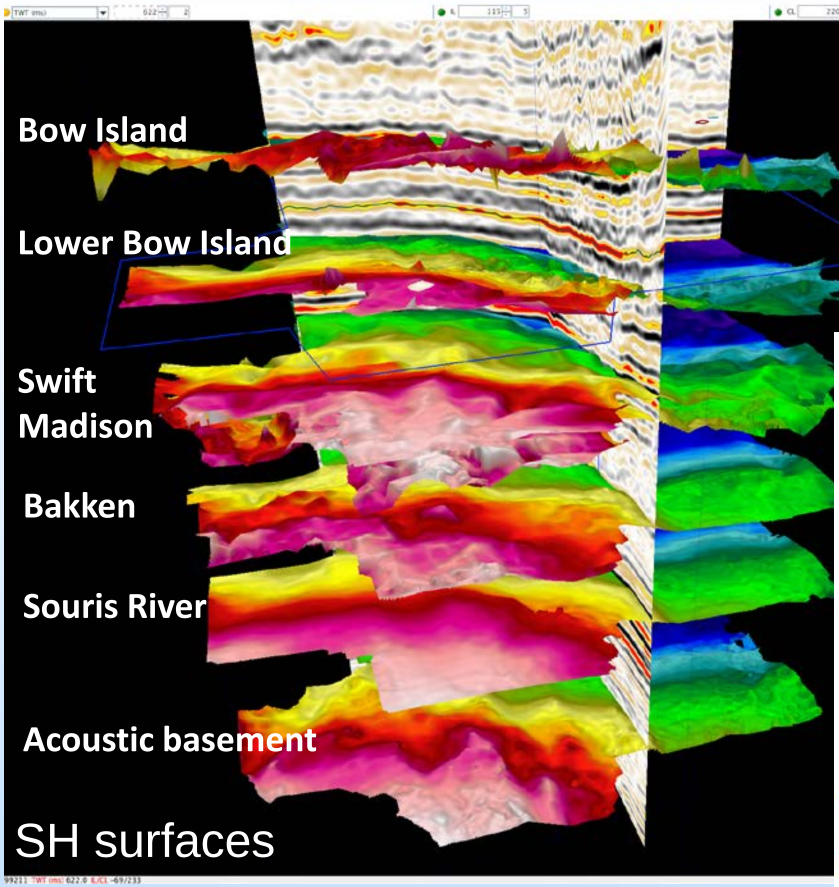
- 430 ft of carbonate core from regions both with and without CO_2 representing 7 different depositional environments
- Acquisition of core on two caprock materials, tight carbonate and anhydrite (30')
- 3D – 9C seismic data covering 32 sq. mi.
- Development of a geostatic model using Neural Nets to match well logs to facies and using p and s wave seismic to inform reservoir heterogeneity
- Geostatic model including fractures
- Dome scale geostatic model
- Model development for dual permeability systems
- Unique mechanical testing of permeability – stress relationship in caprock material

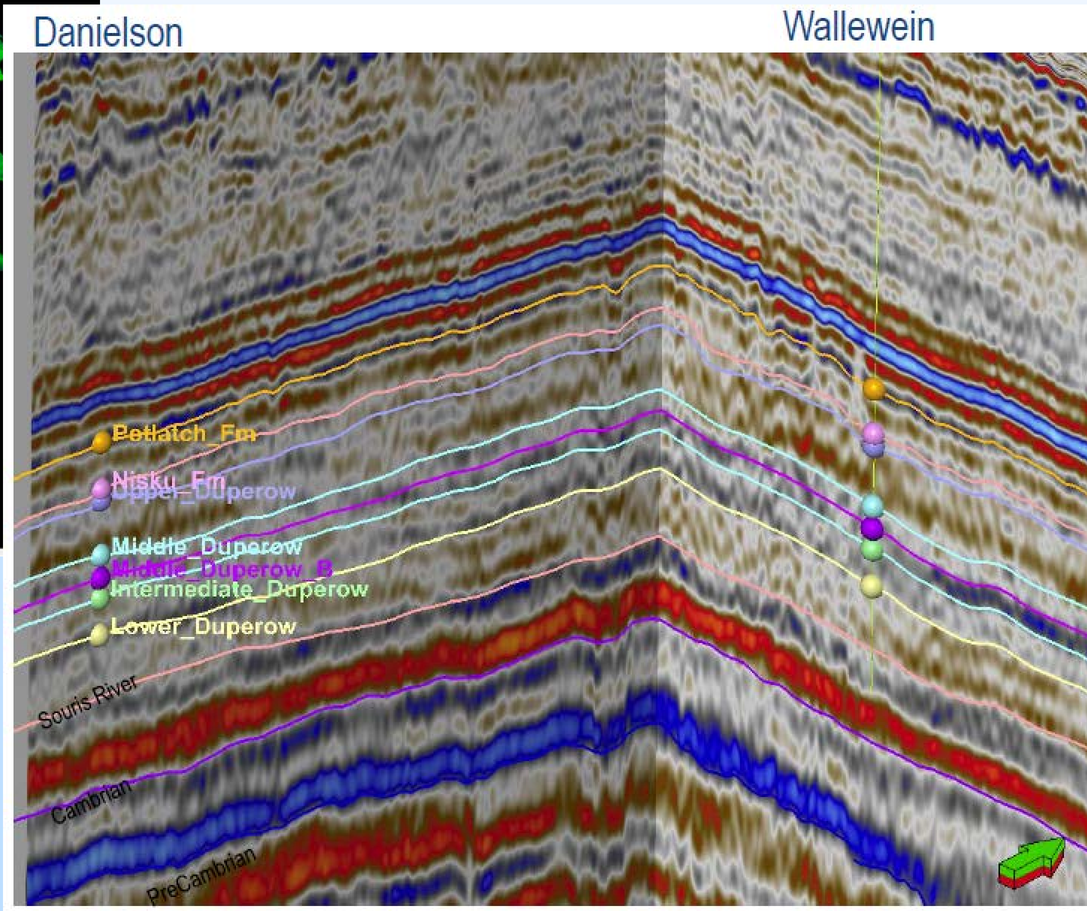
Duperow Facies Model

430 ft of carbonate core from regions both with and without CO_2 representing 7 different depositional environments plus anhydrite caprock core



Processing 3D, 9C siesmic Seismic

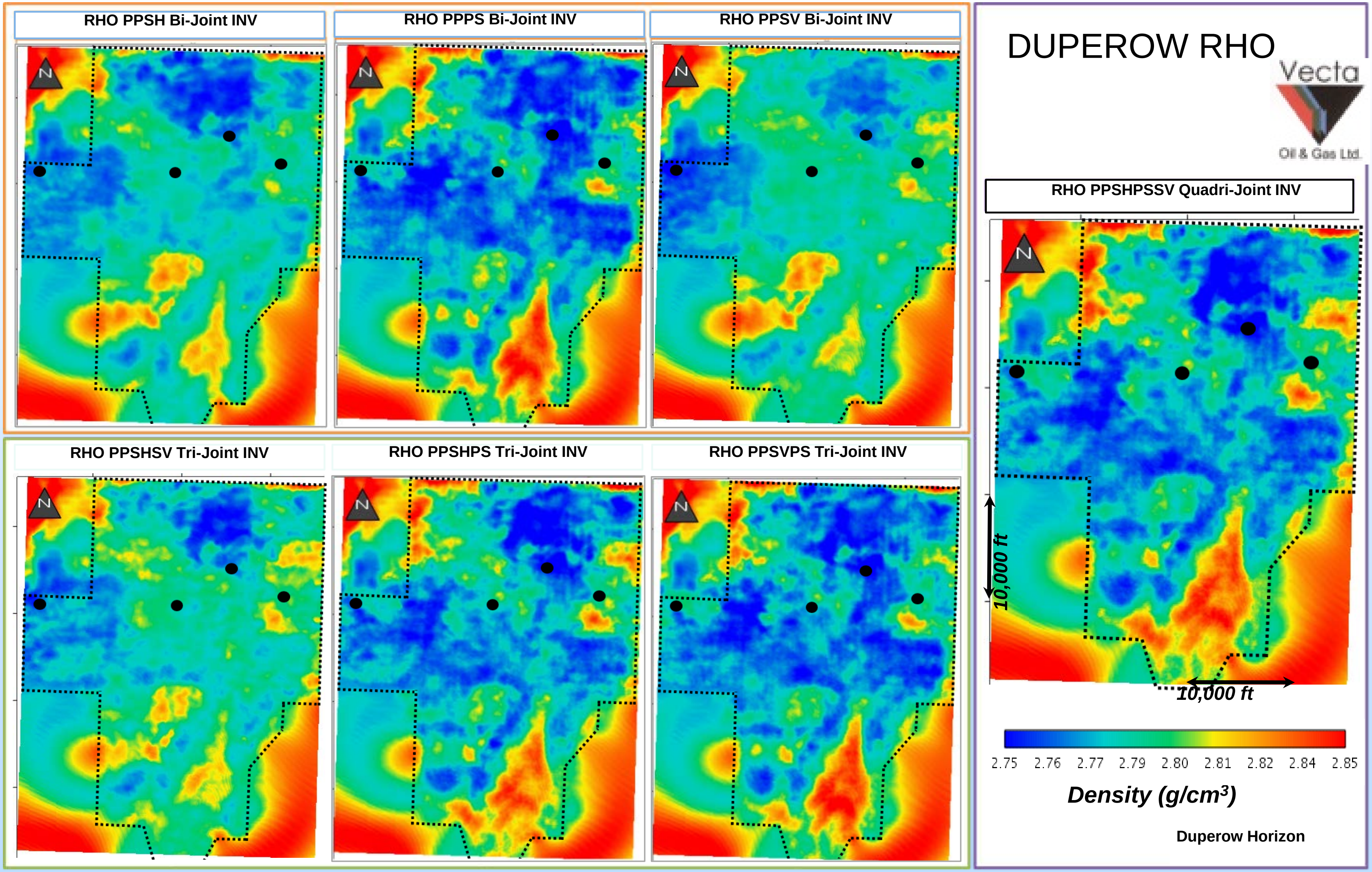




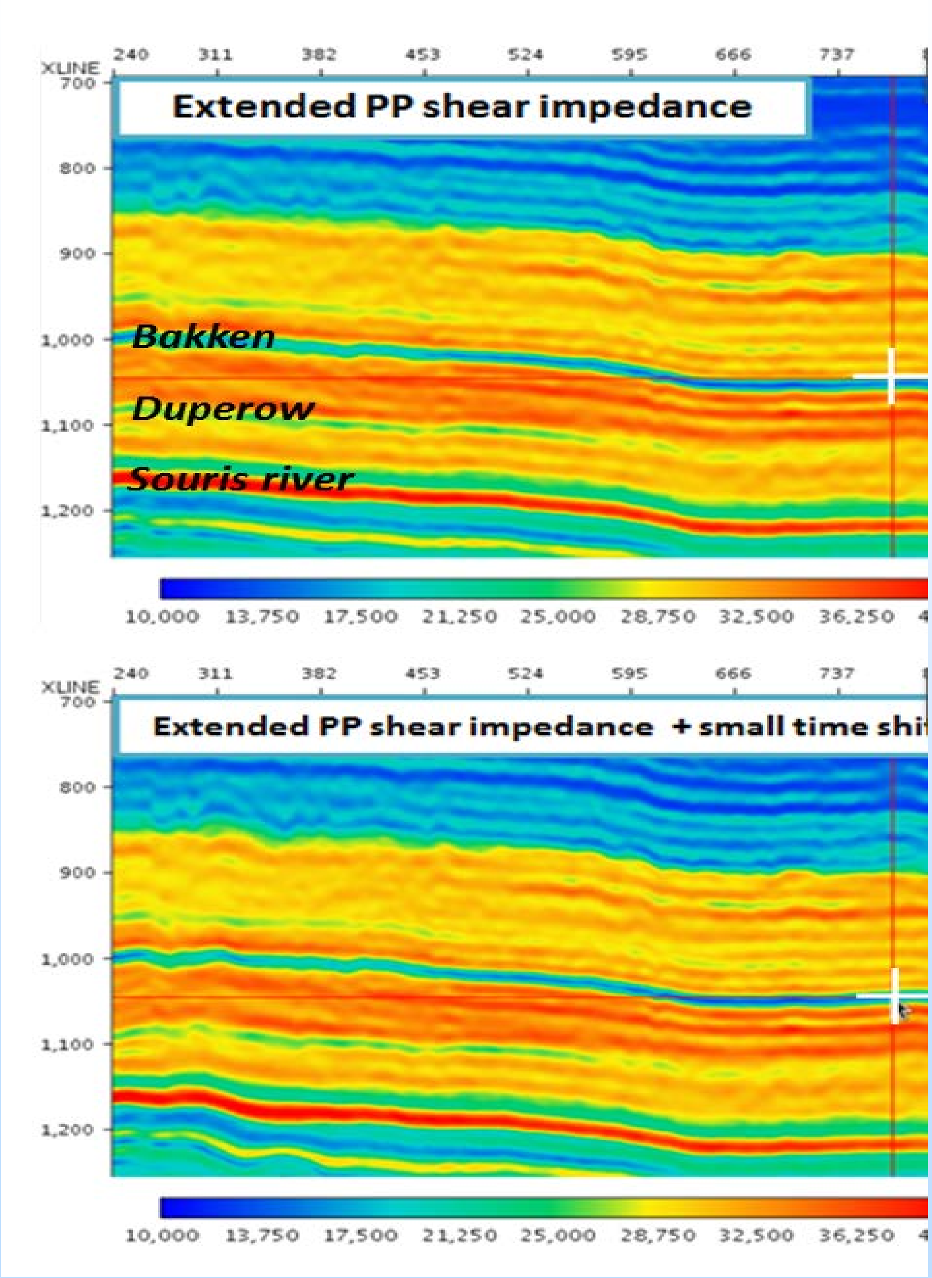
Vecta Oil & Gas Ltd.

Big Sky Carbon Sequestration Partnership

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).**



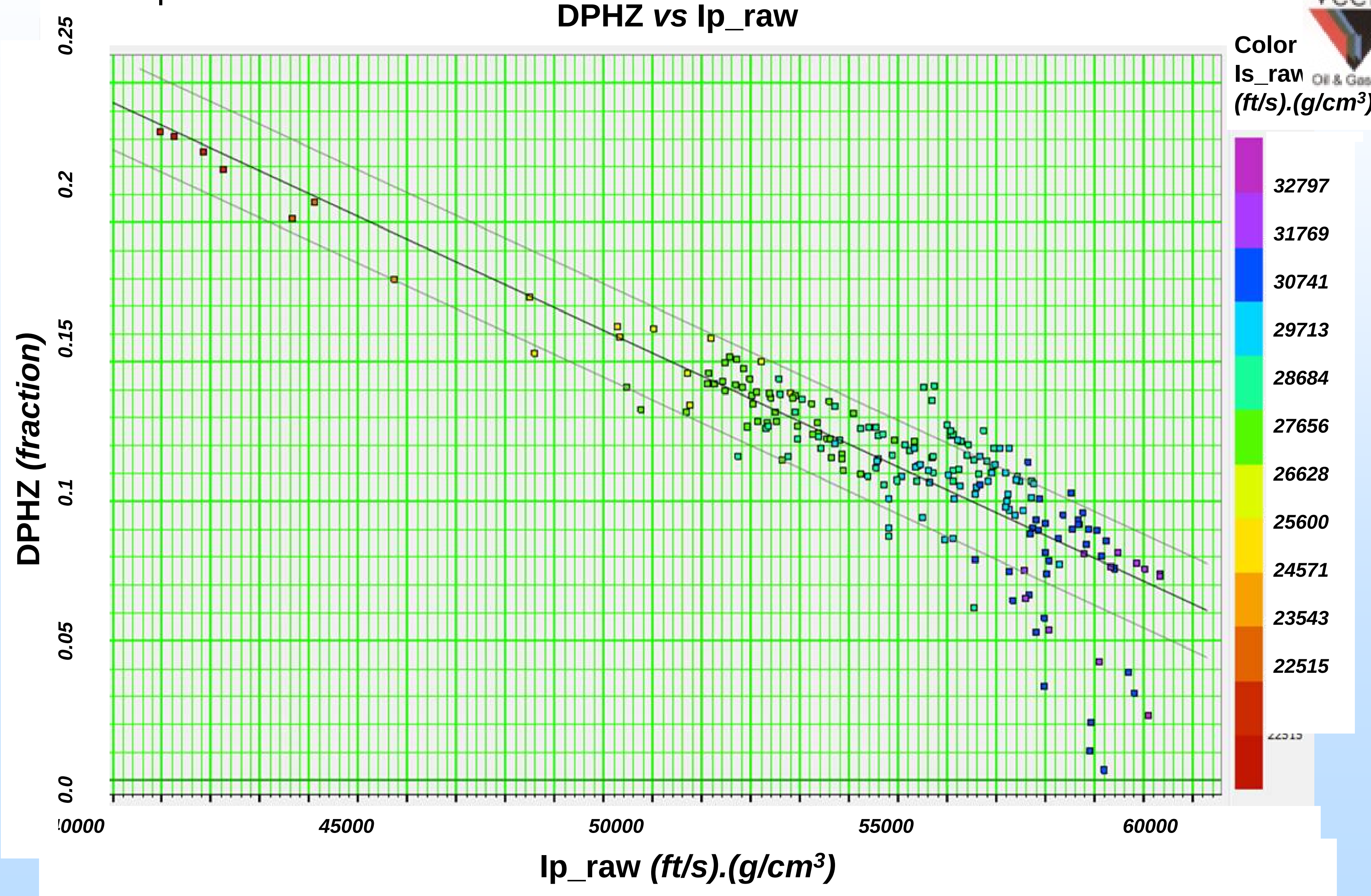
Able to image middle Duperow porosity zone



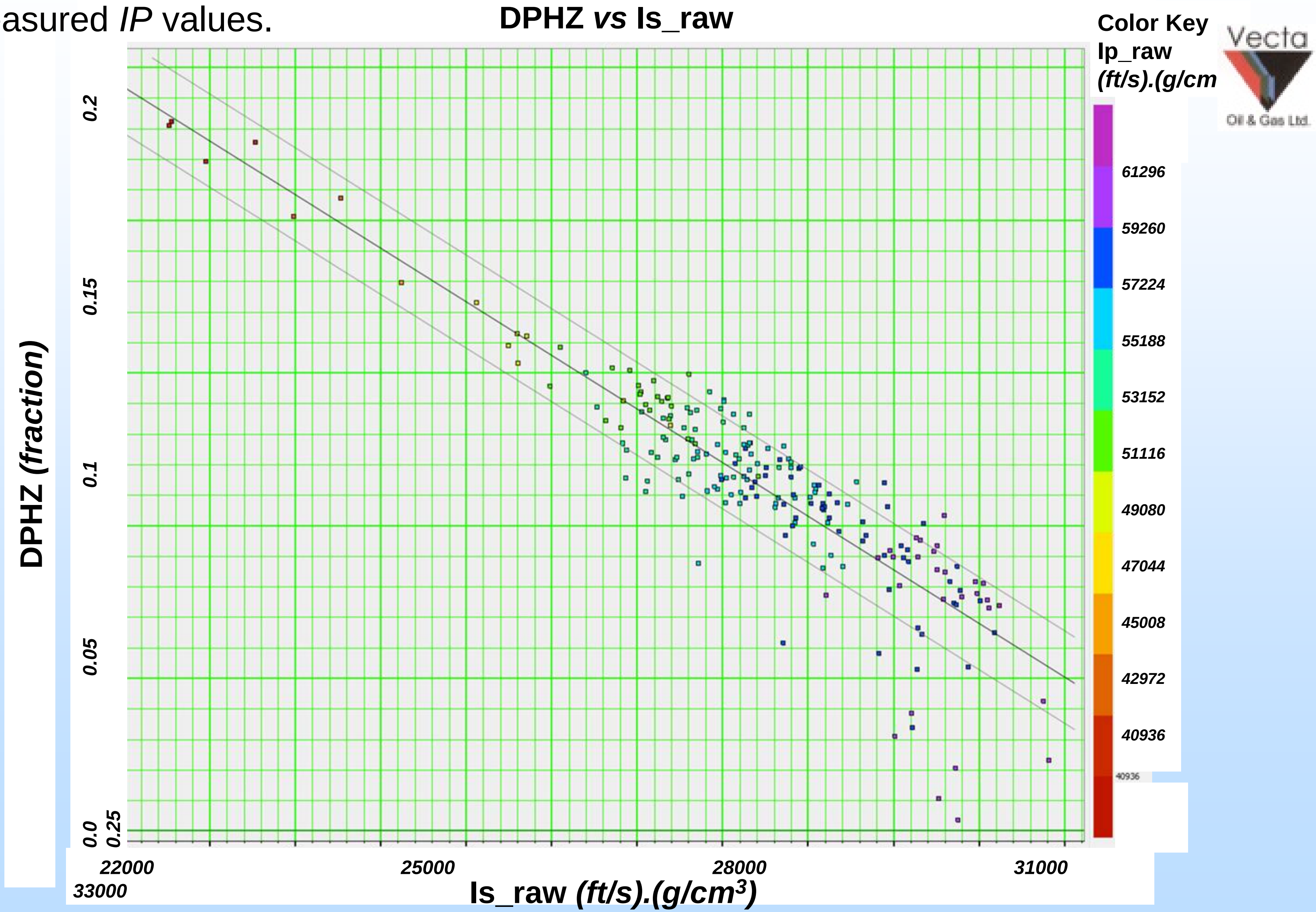
BIG SKY CARBON
SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

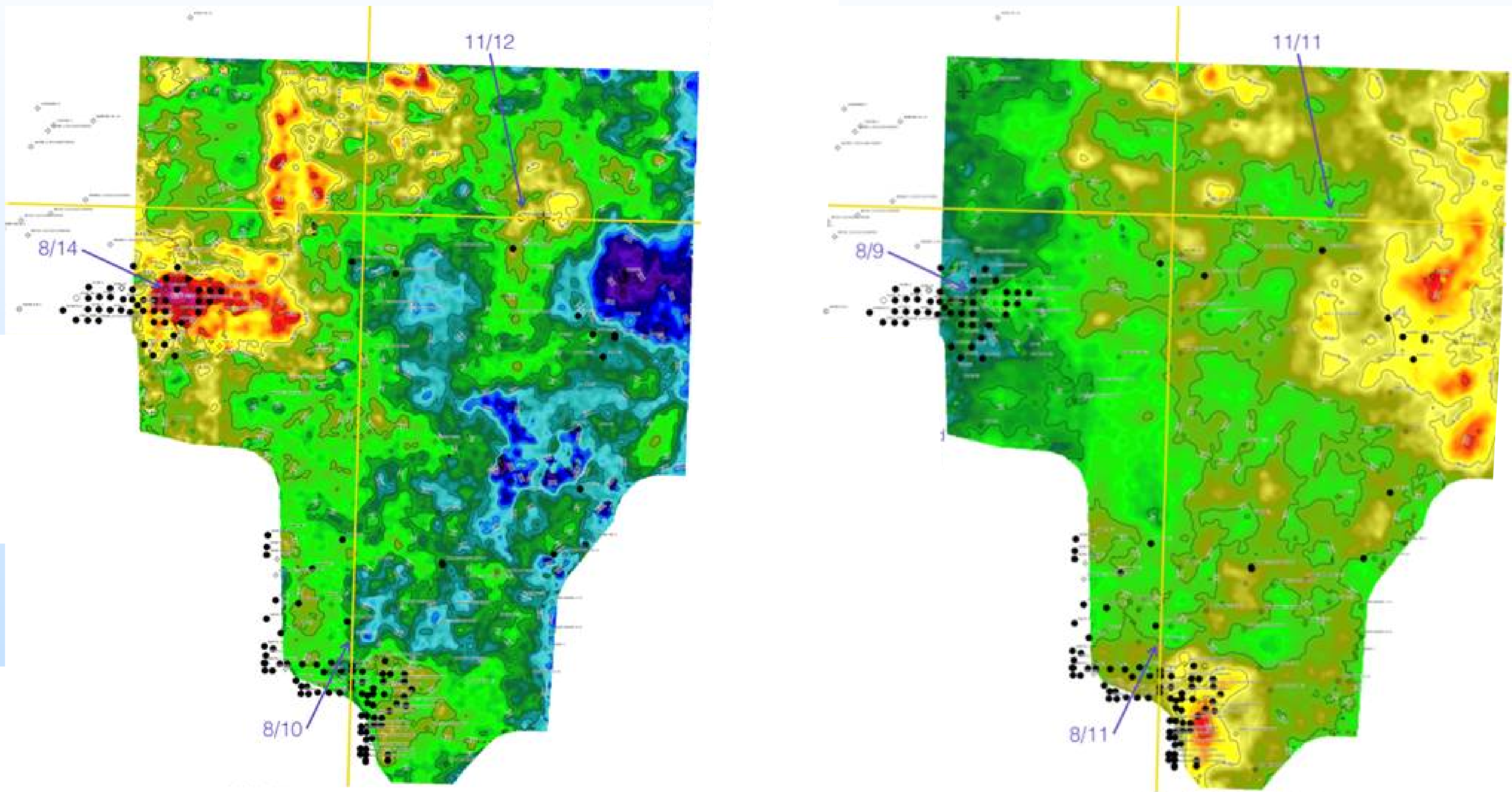
Crossplot between density porosity and computed *P*-wave impedance (*IP*) from the Wallewein 22-1 well over the Middle Duperow porosity interval. Note the good correlation observed between the two quantities. The correlation coefficient between the two quantities is 0.87. Colored values are measured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



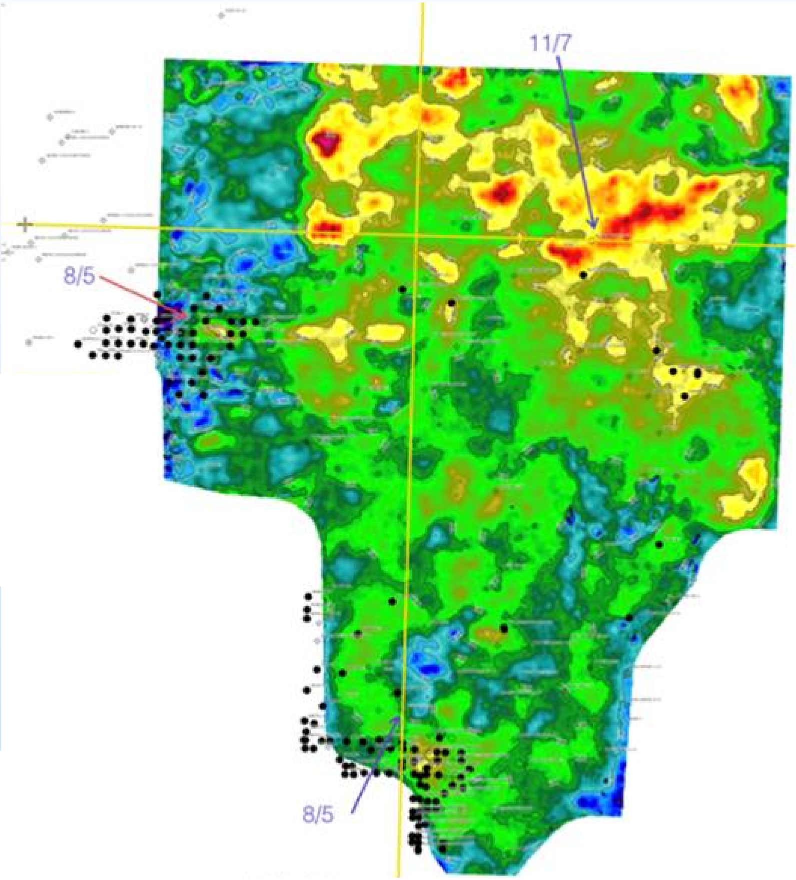
Crossplot of measured density porosity and *S*-wave impedance (*IS*) in Wallewein 22-1 well in mid-Duperow porosity zone. Note excellent agreement between measured two quantities with correlation coefficient of 0.89. Colored values are measured *IP* values.

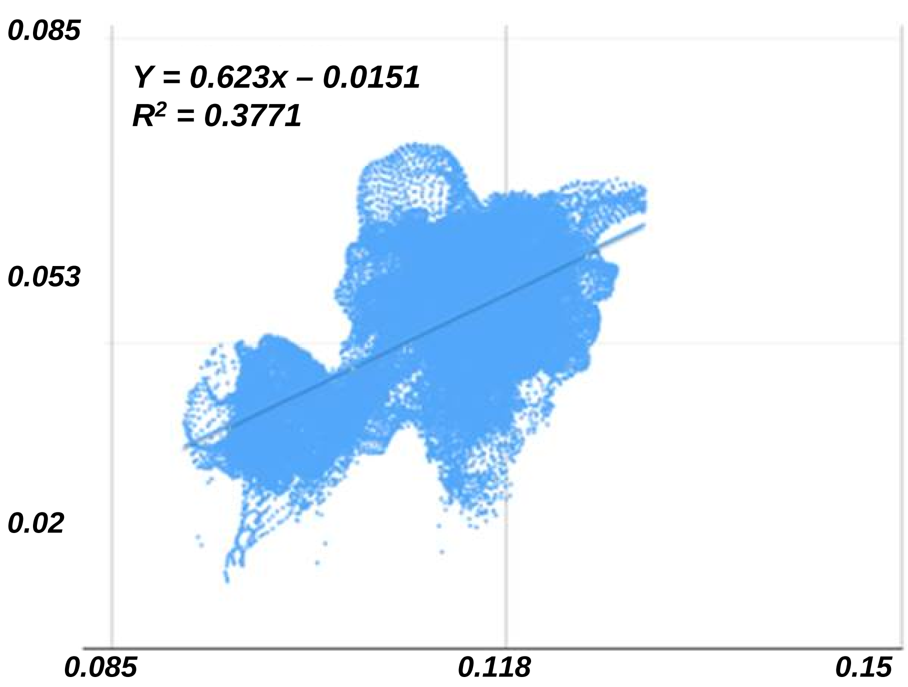


Transforms derived from porosity-impedance regressions using *IS* (left) and *IP* (right) maps for the Middle Duperow porosity zone with well locations annotated and well derived values for porosity annotated with values derived from each map at well locations.

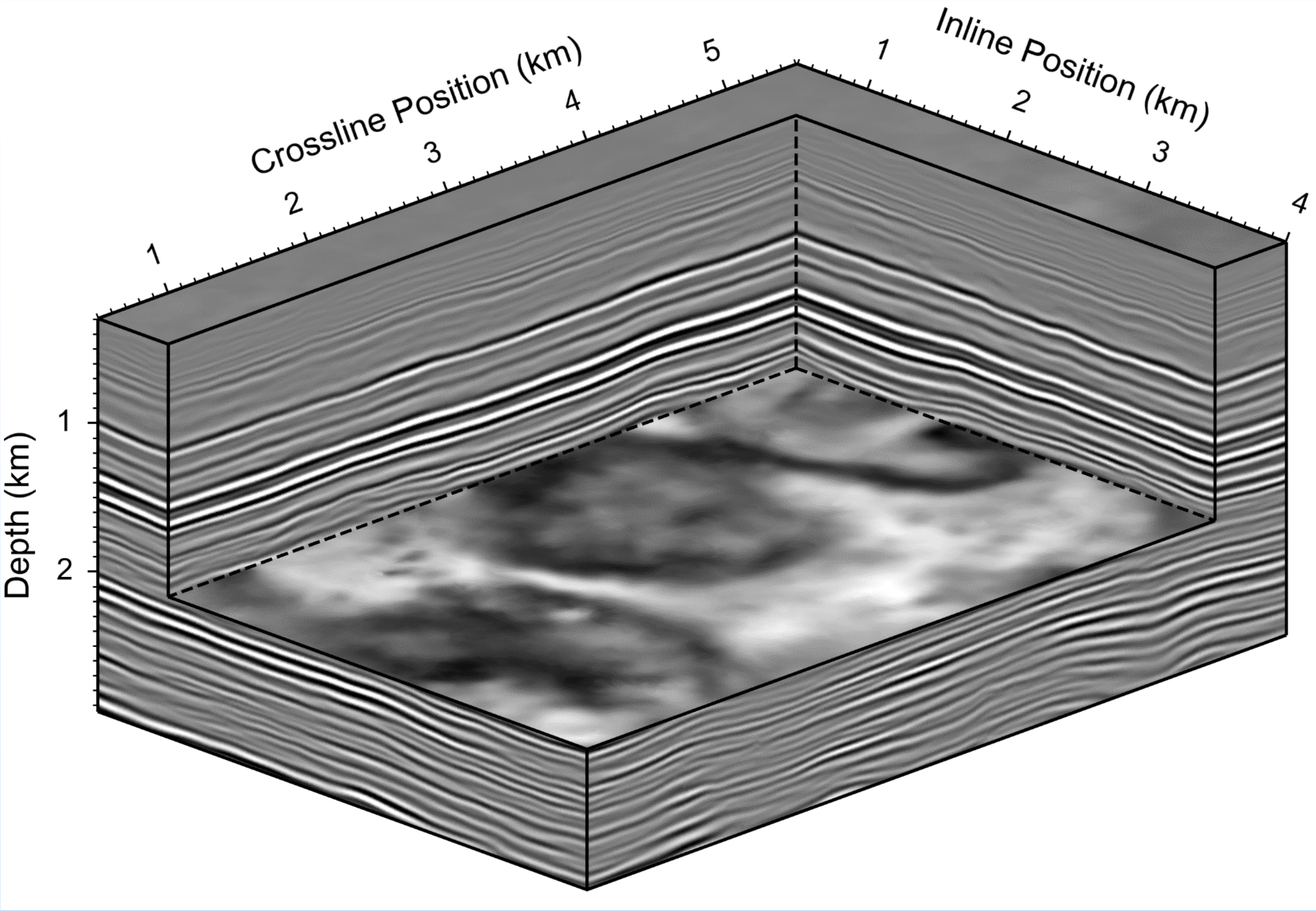


Mid-Duperow porosity derived from average density values from quadri-joint inversion converted to porosity using a dolomite matrix (left) and cross plot of this map with values derived from *IP*-based regression.





3D Structure-Enhanced Least-Squares Reverse-Time Migration Image of 3D Kevin Dome Seismic Data

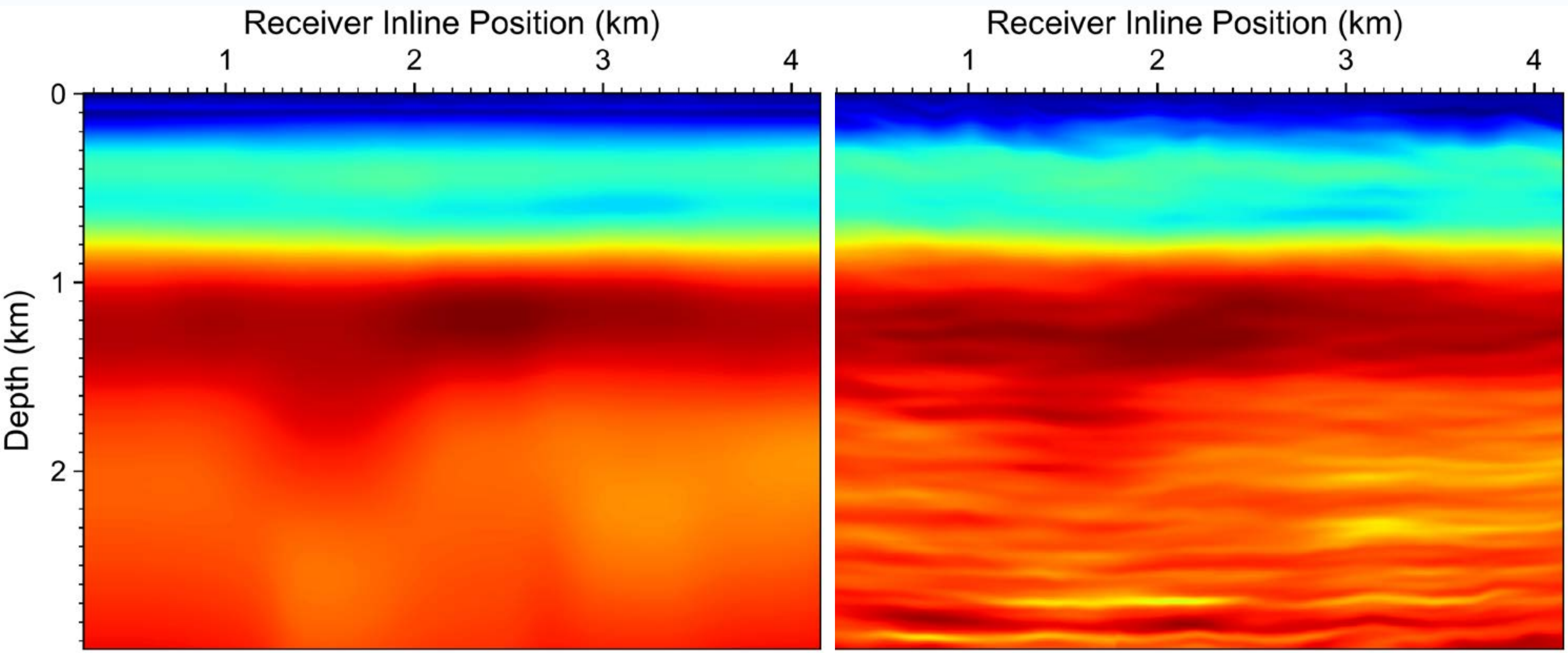


Los Alamos NATIONAL LABORATORY

Big Sky Carbon Sequestration Partnership

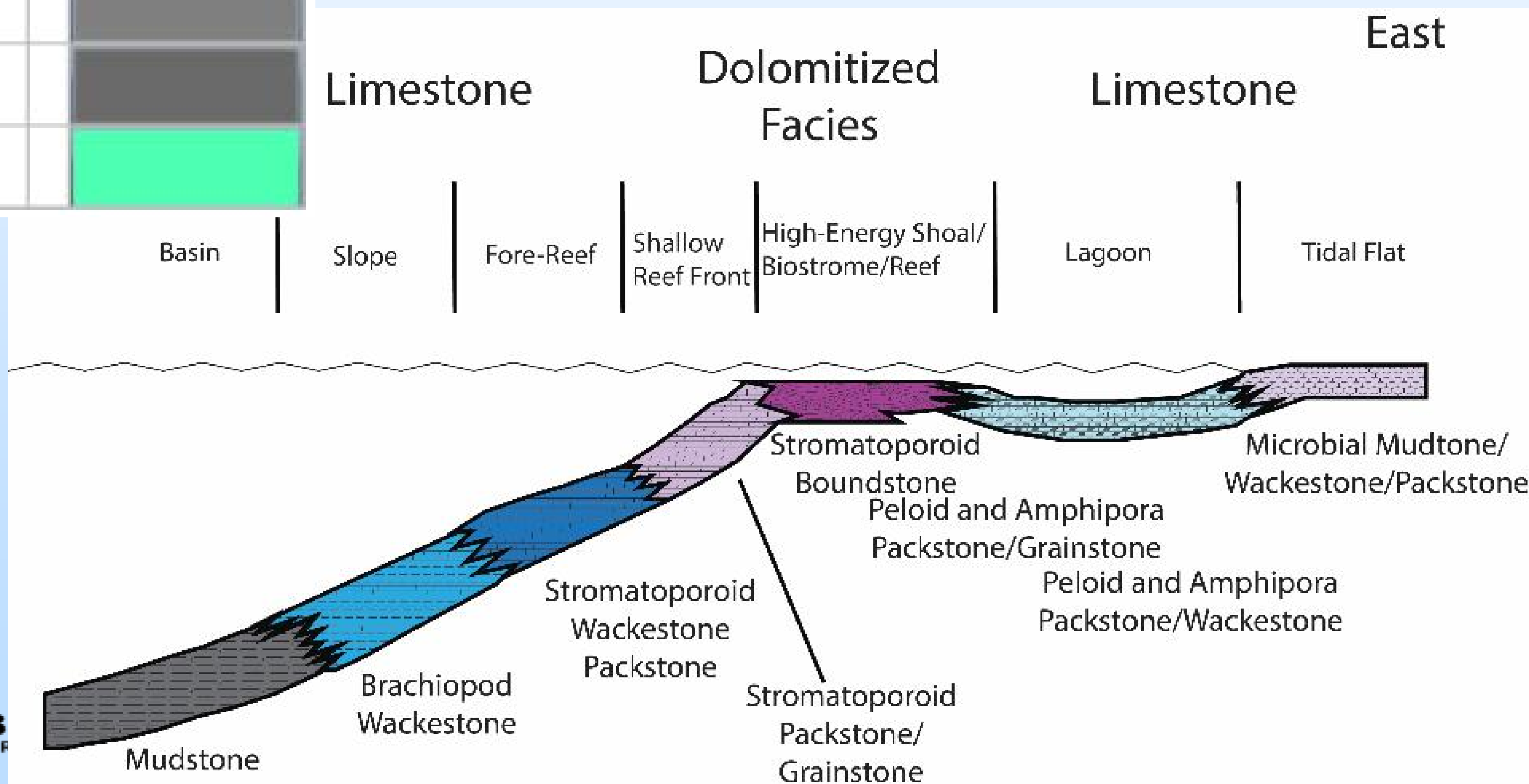
Montana State University

Improved high-resolution subsurface velocity model for the Kevin Dome site obtained using full-waveform inversion



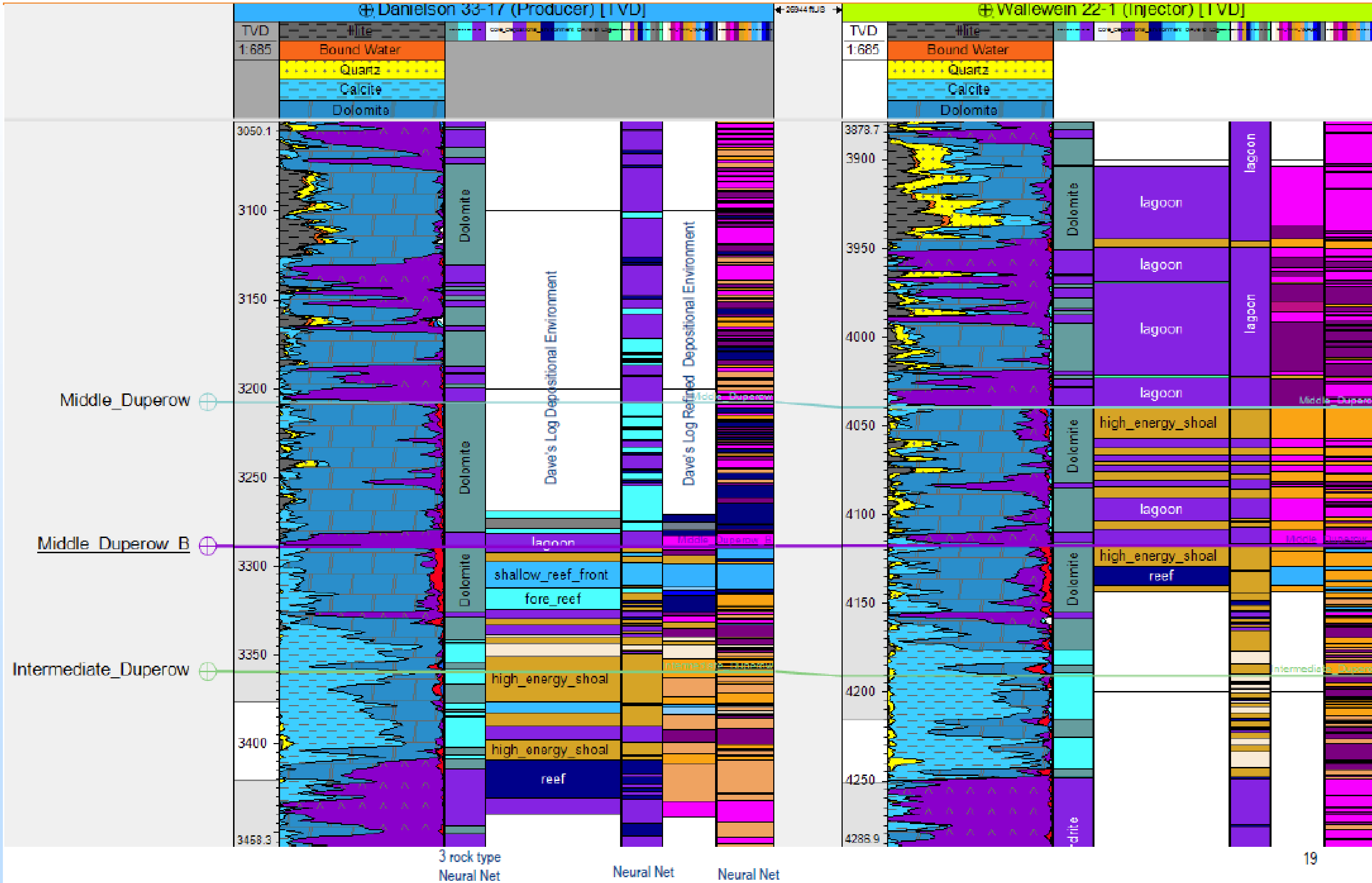
Refine Model Based on Geologic Interpretation

tidal_flat
lagoon
high_energy_shoal
reef
shallow_reef_front
fore_reef
slope
Basin
back_reef



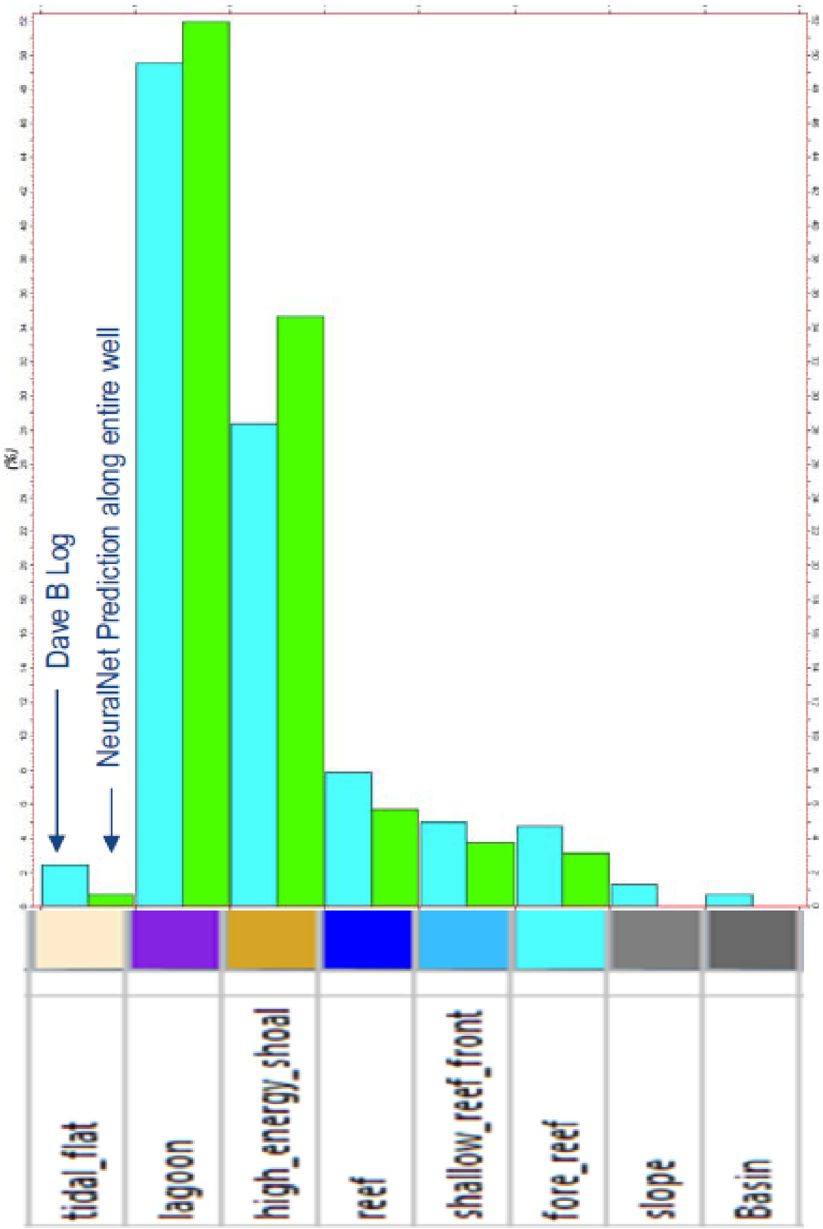
Neural Net Depositional Env. Predictions

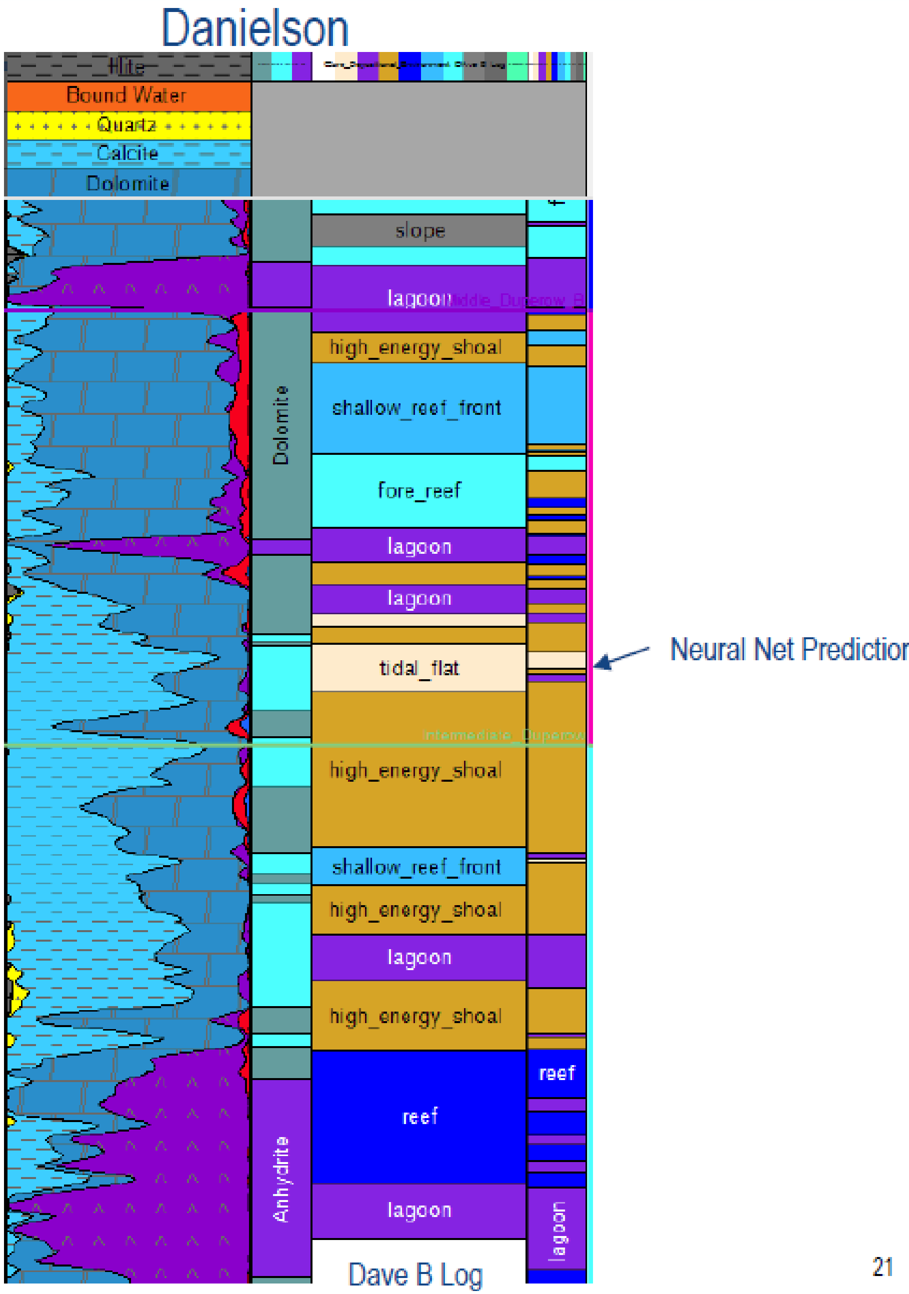
Schlumberger Carbon Services



Good Neural Net Match Along Core Interval

Schlumberger Carbon Services

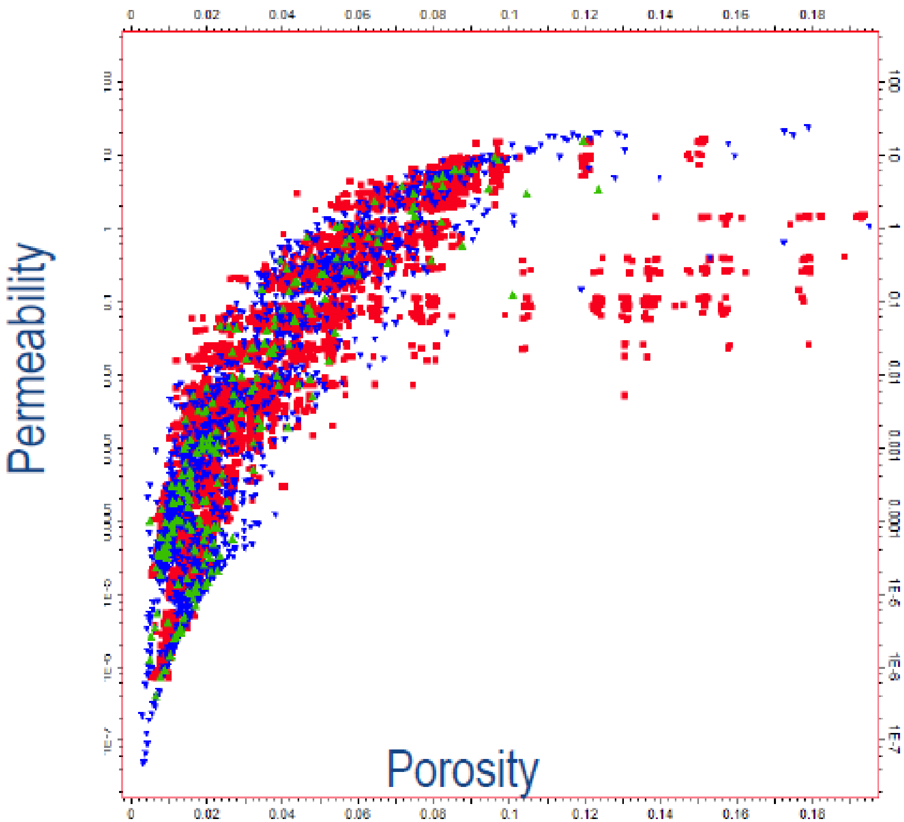


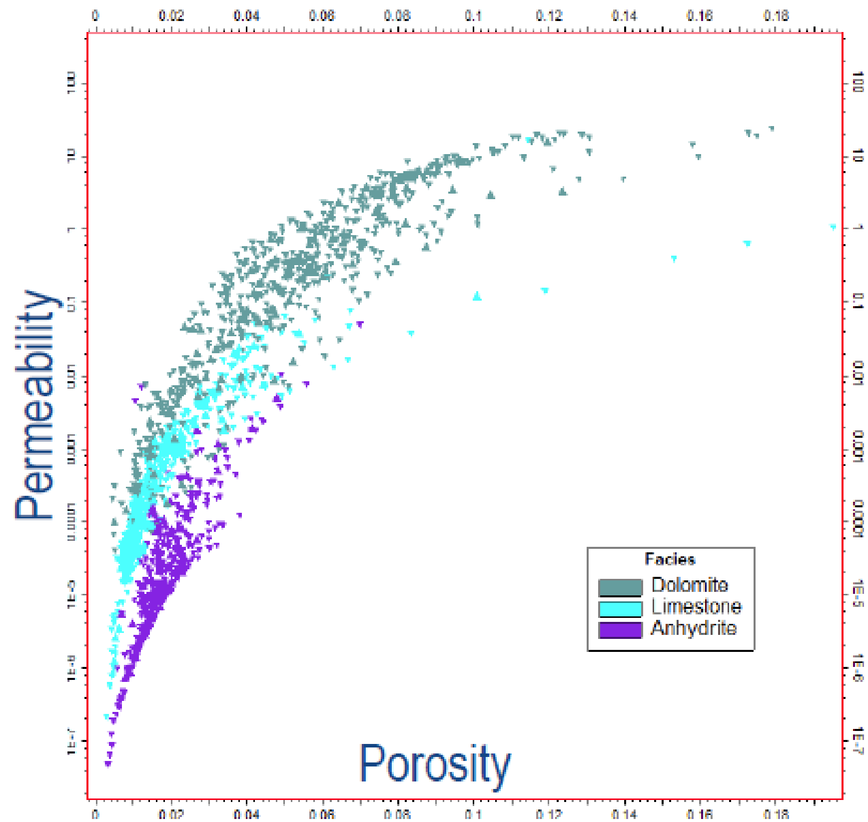


Porosity & Permeability Modeling Within Rock Types

Schlumberger Carbon Services

(Mid Duperow B and Intermediate Duperow)





Consistency between Well logs (blue), upscaled cells (green) and the interpolated property (red).

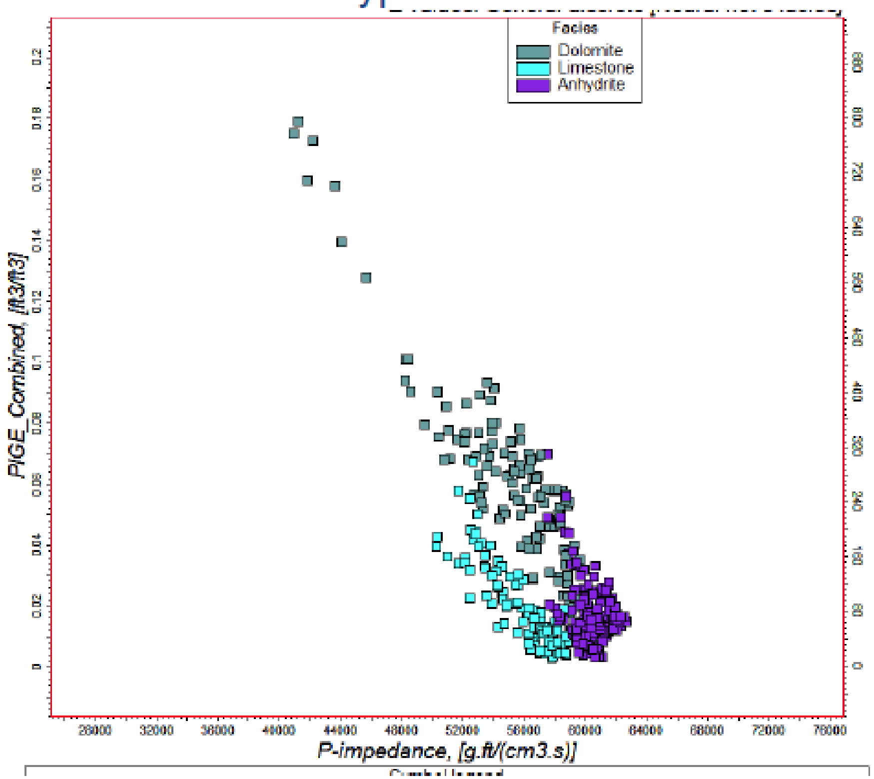
Note the separate porosity/permeability relationships for the 3 rock types

Porosity vs. P-Impedance

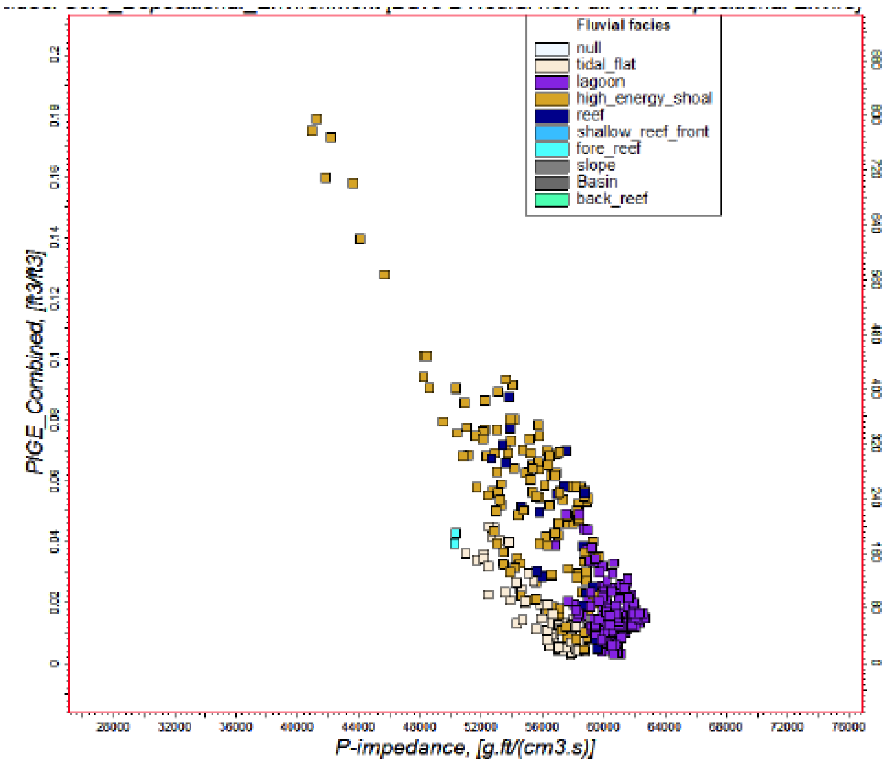
Schlumberger Carbon Services

Porosity

3 Rock Type

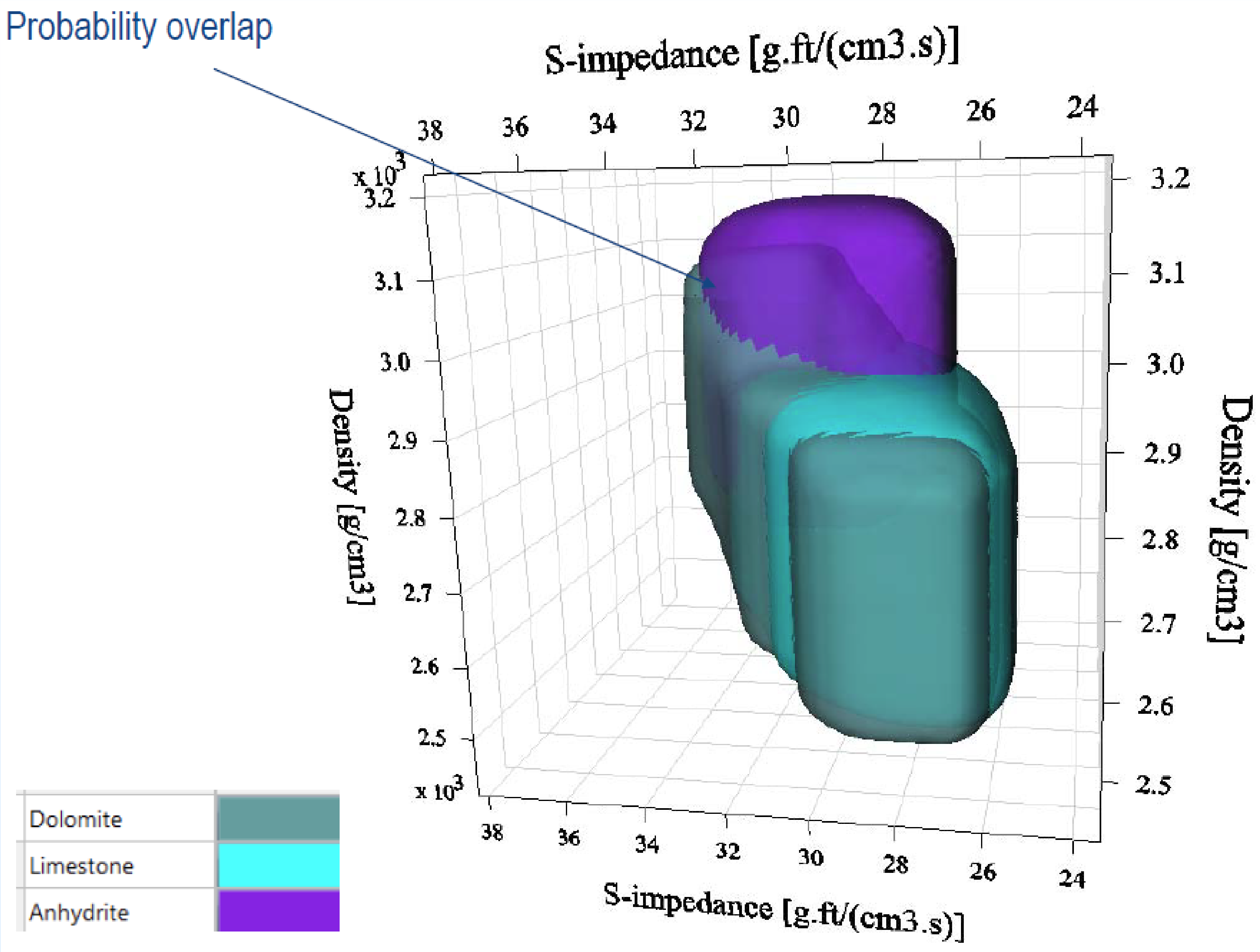


Dave Bowen's Depositional Environment



Use Multi-Component Seismic to Model Heterogeneity

Schlumberger Carbon Services

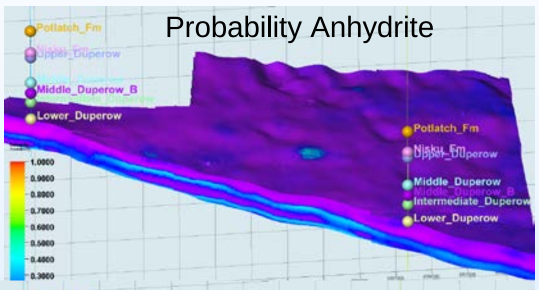


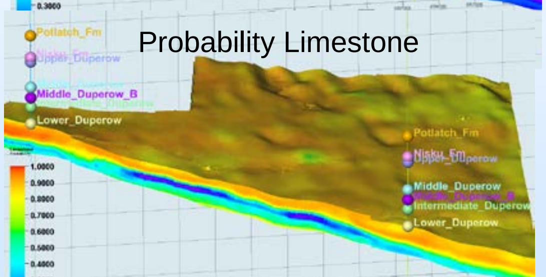
Big Sky Carbon Sequestration Partnership

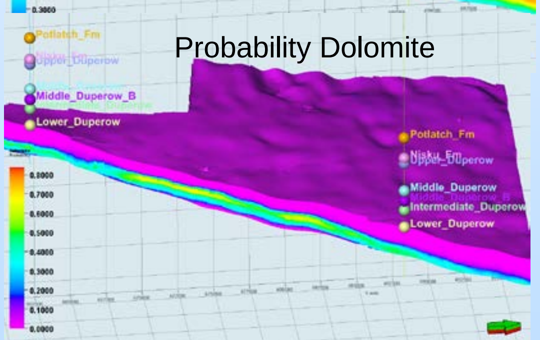
Montana State University

Lithology Prediction Using Seismic Inversion

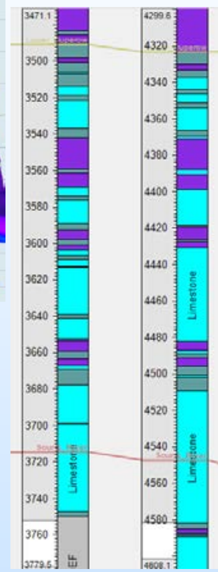
3D probability lithology prediction volumes as a trend for rock type interpolation





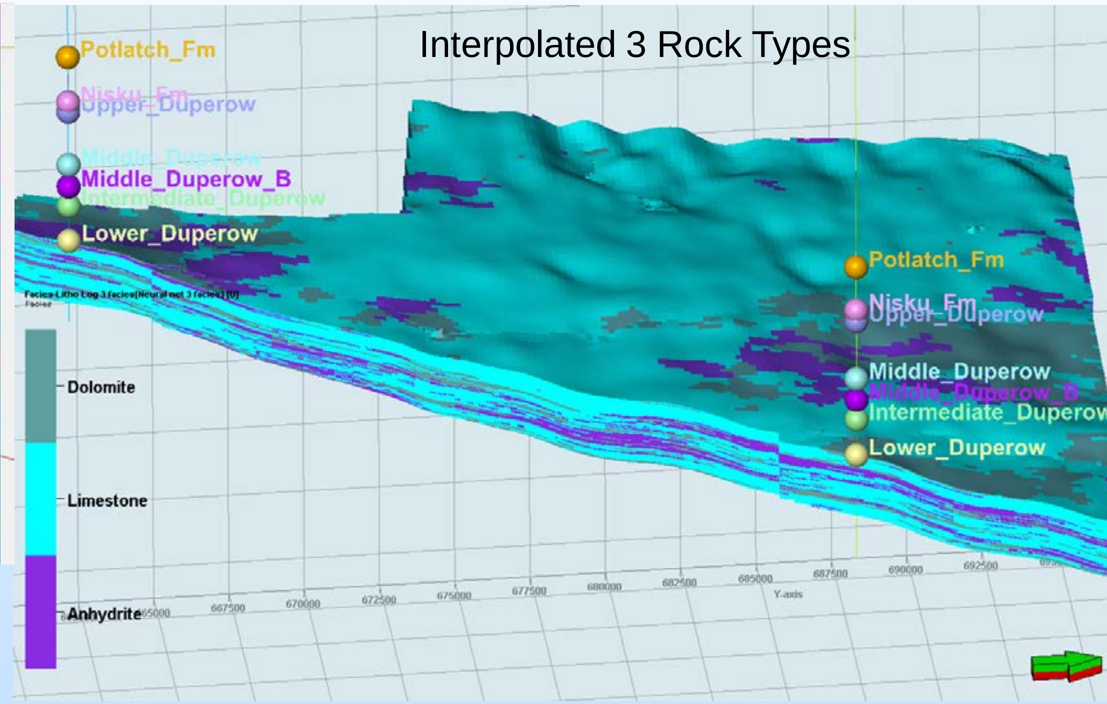


Rock Type Logs



Danielson

Wallewein

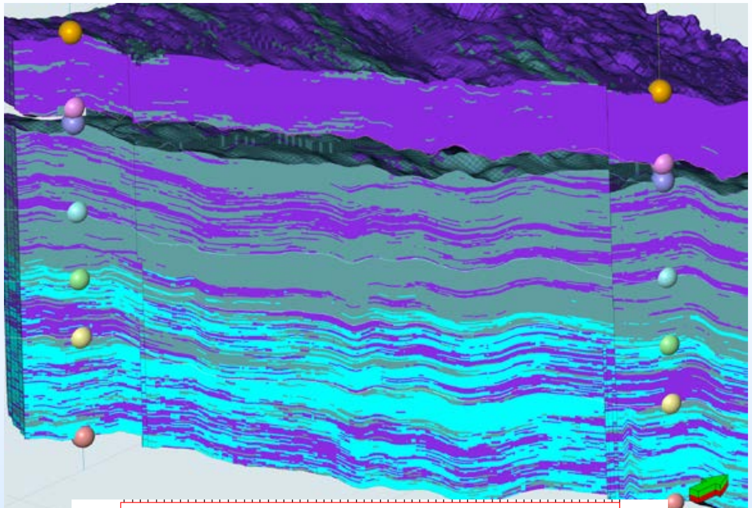


BIG SKY CARBON SEQUESTRATION PARTNERSHIP

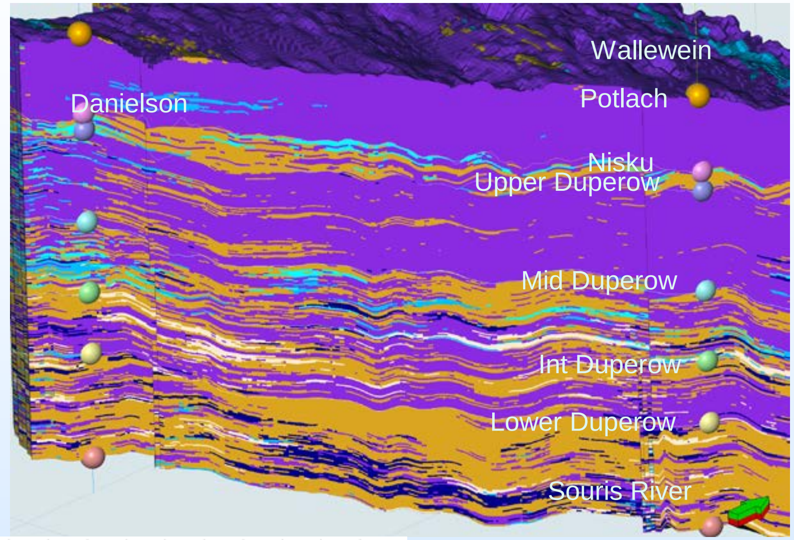
MONTANA STATE UNIVERSITY

Facies, Porosity and Permeability Interpolation

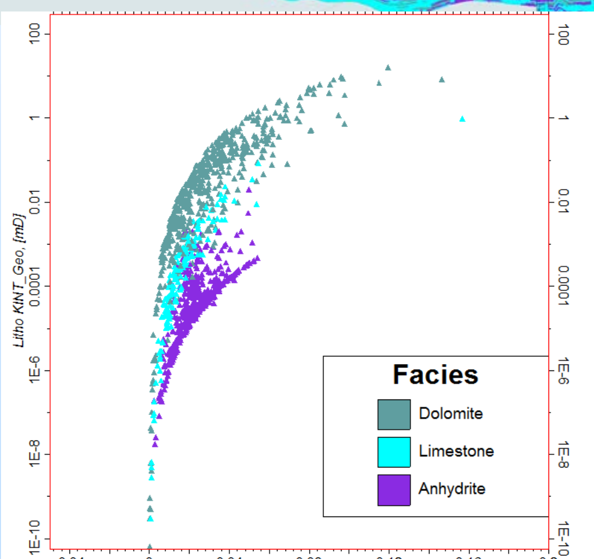
3-Rock Type



8-Rock Type

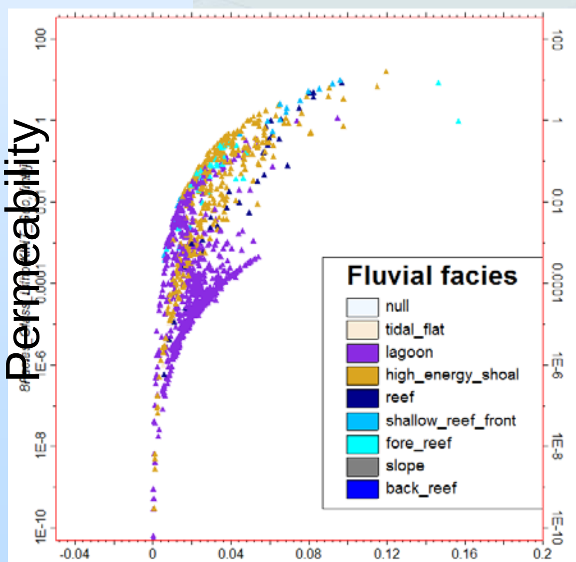


Permeability



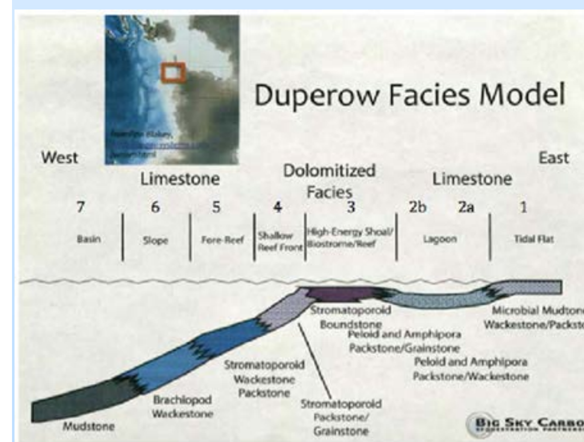
Porosity

Permeability



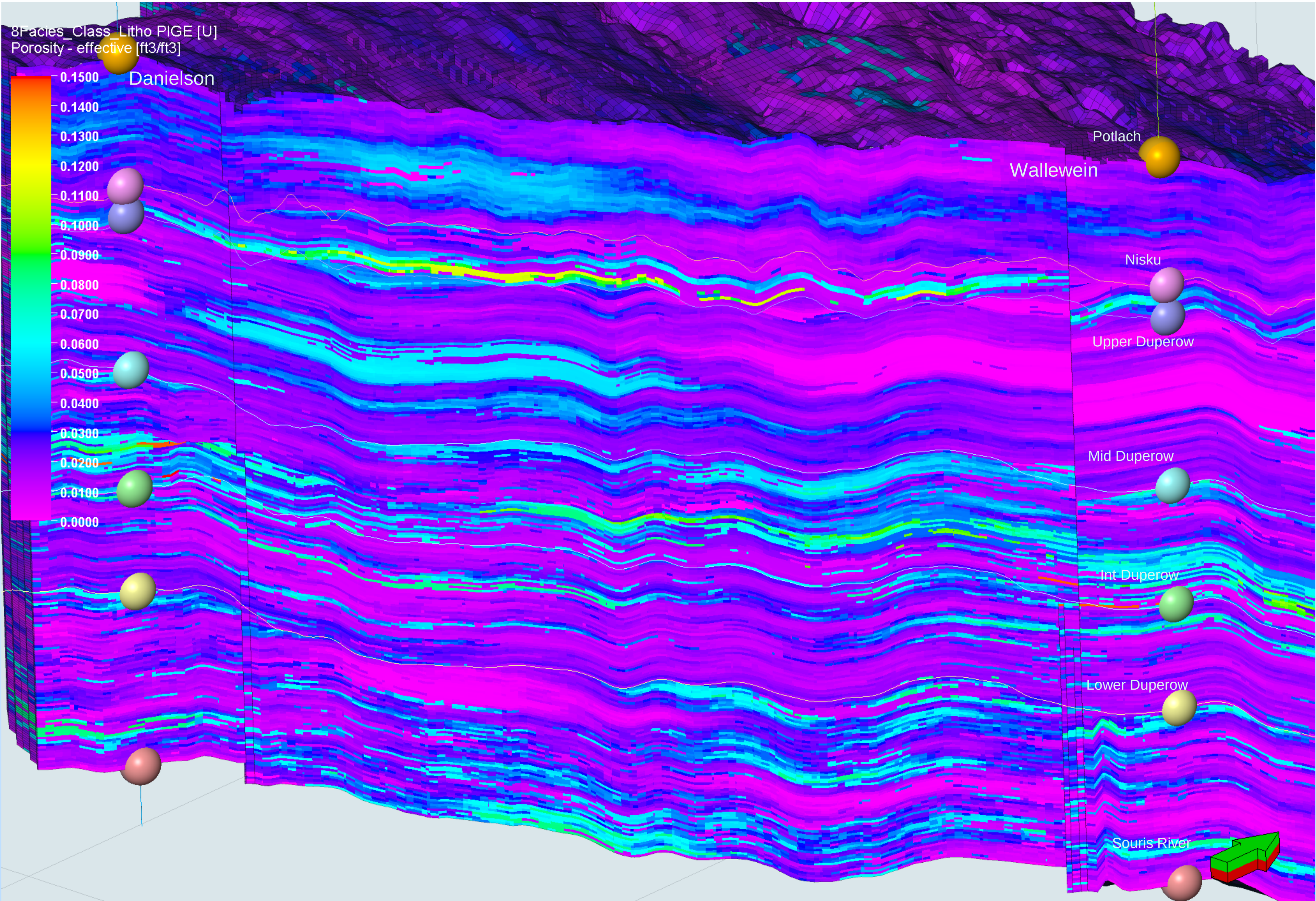
Porosity

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

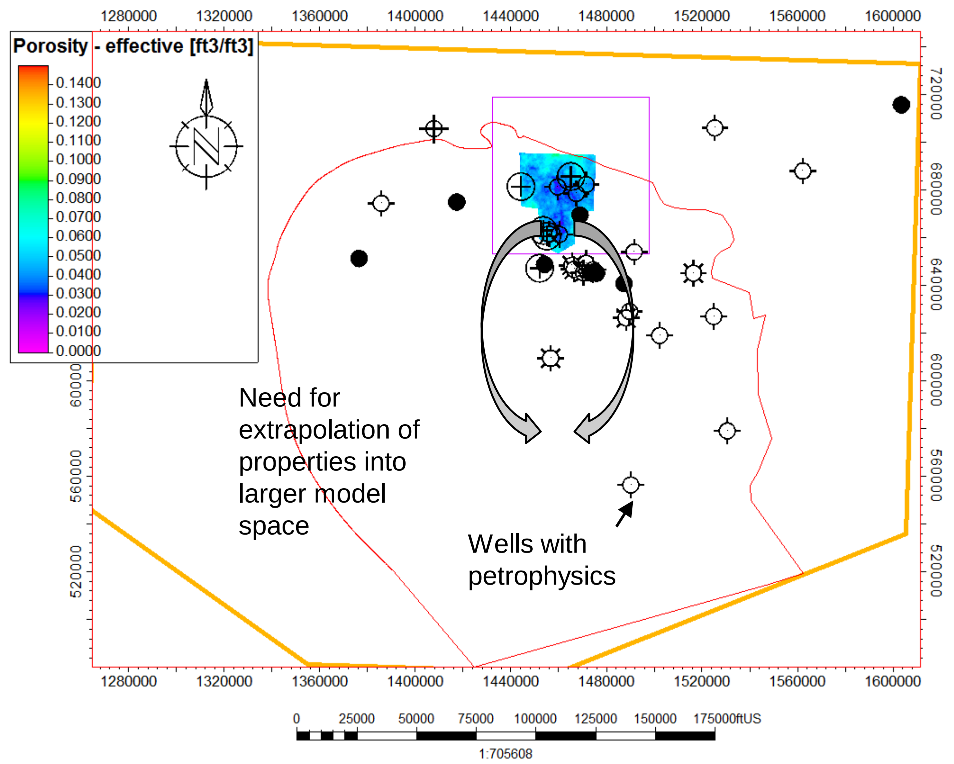


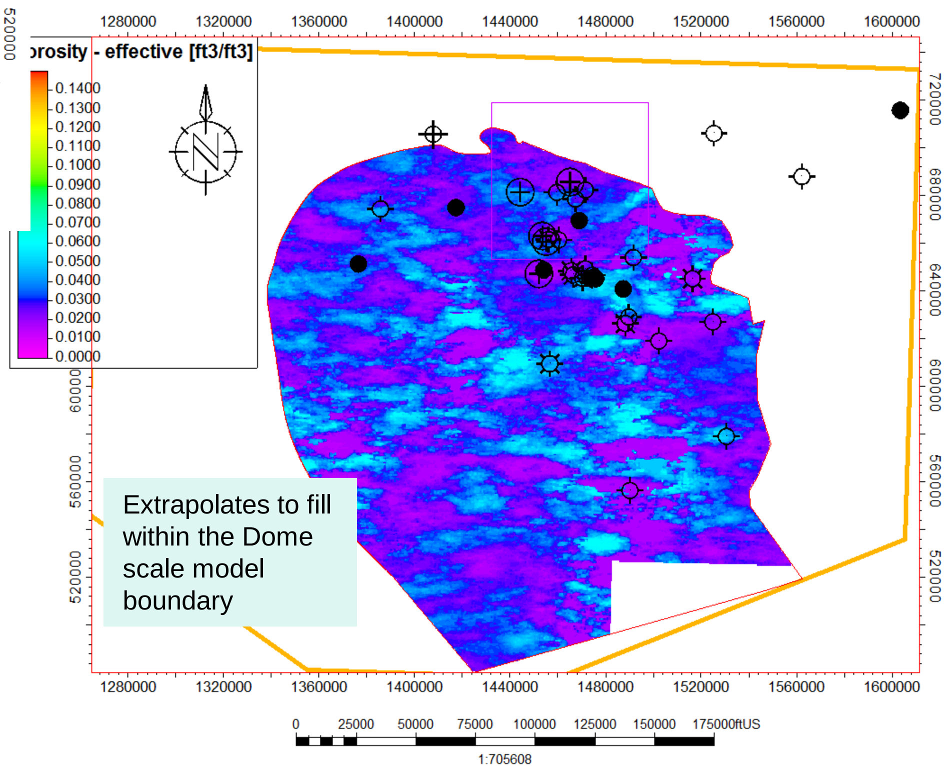
BIG SKY CARBON SEQUESTRATION PARTNERSHIP
MONTANA STATE UNIVERSITY

Property Interpolation (Porosity)



Dome Scale Model Property Extrapolation

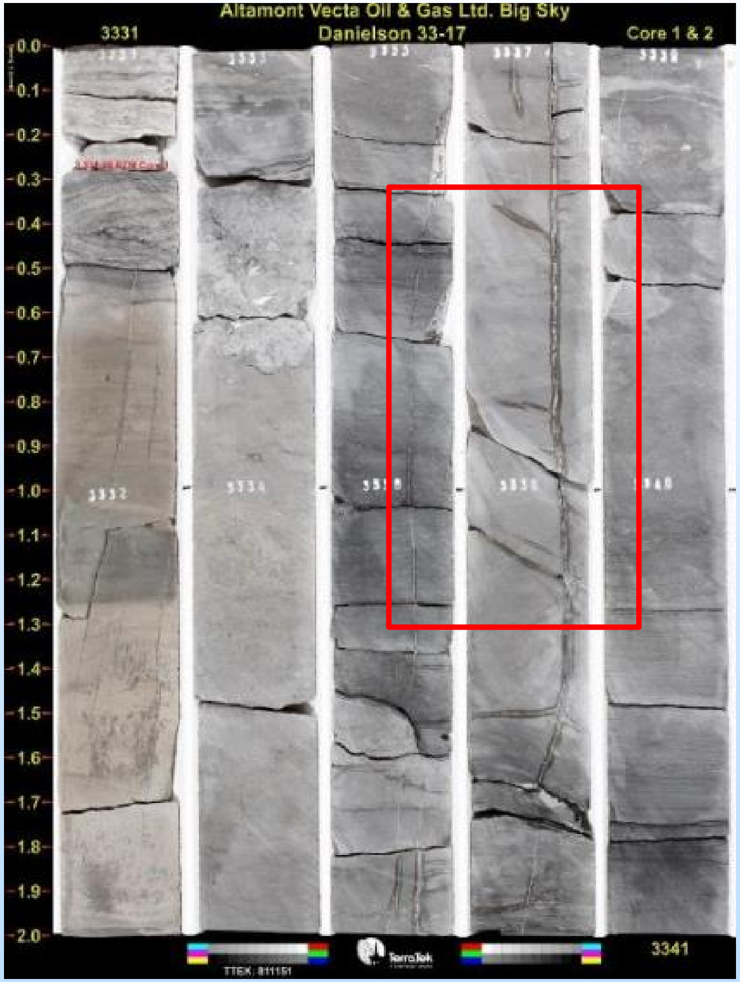




Big Sky Carbon Sequestration Partnership

Middle Duperow – Fractures

Site Characterization: Core Fracture Analysis

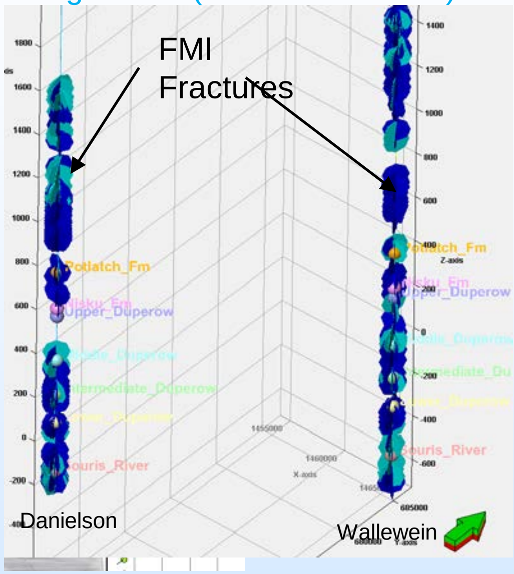


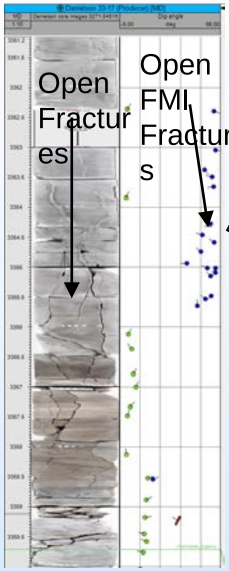
Natural Fracture Model

Inputs

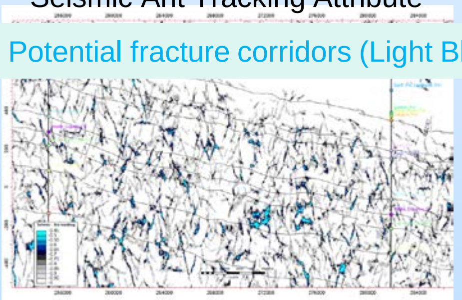
Dark Blue (Open Fractures)

Light Blue (Closed Fractures)

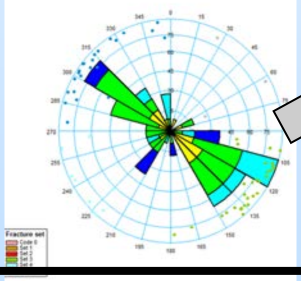




Seismic Ant Tracking Attribute

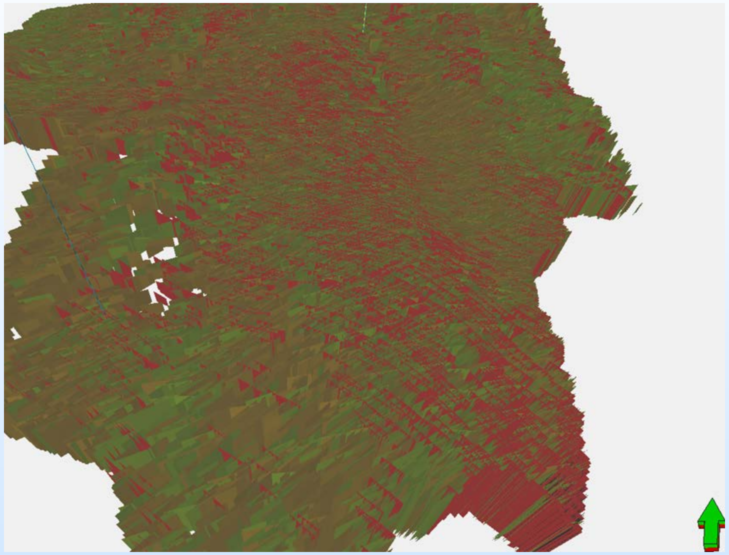


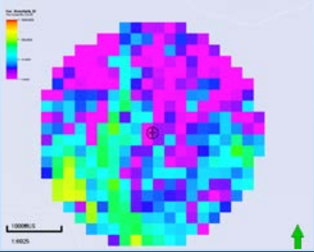
Fracture Set Stereonet



Outputs

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

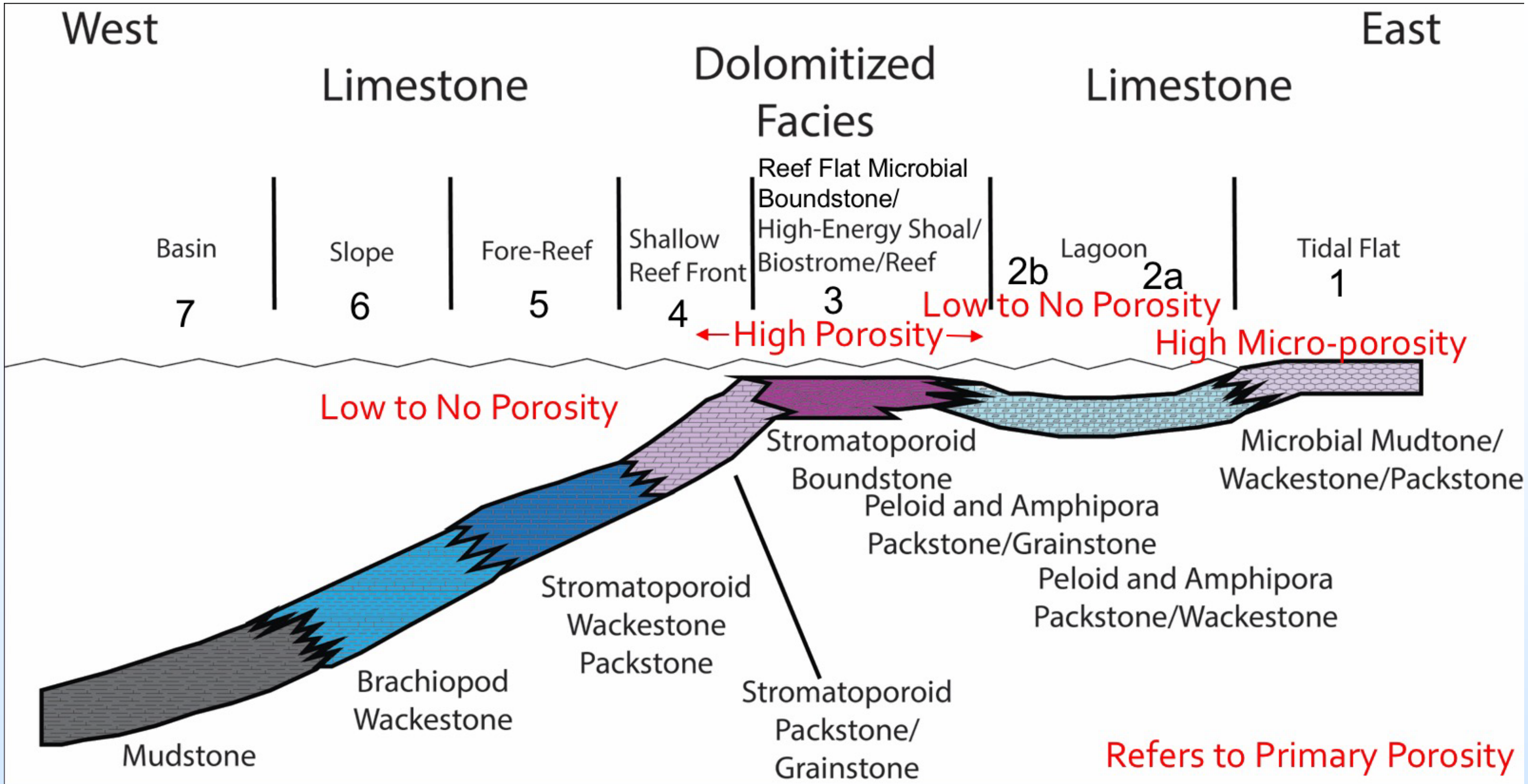


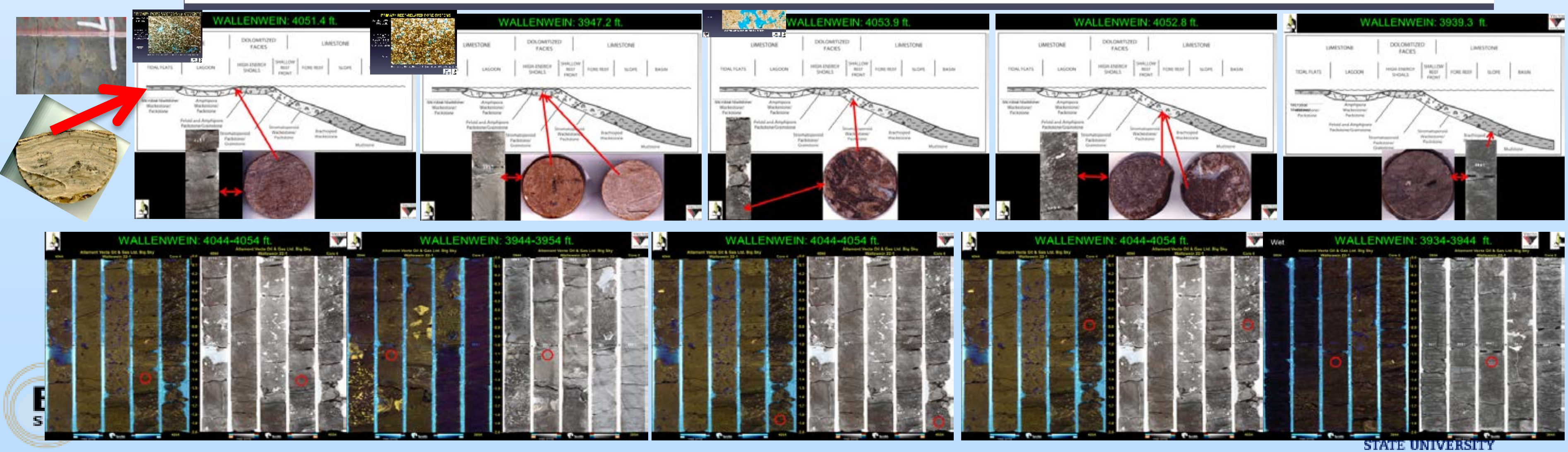


Fracture Cell

- Permeability IJK
- Porosity

Duperow Facies Model





STATE UNIVERSITY

BSCSP Core Viewer Database   Home

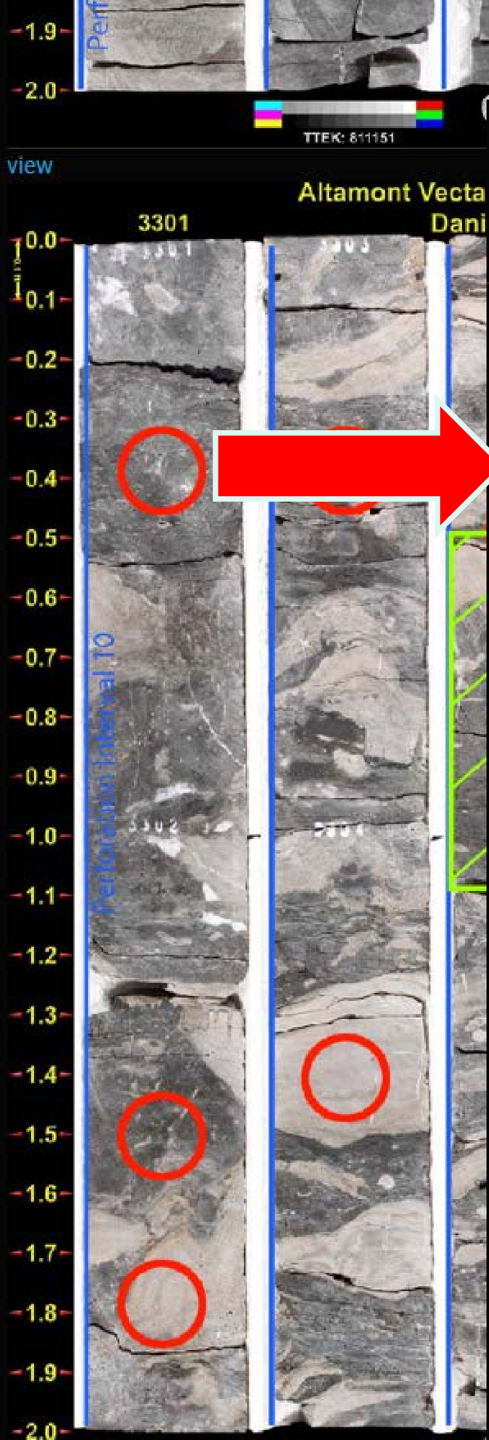
Welcome to the Kevin Dome Core Database

Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

Welcome to the Kevin Dome Core Database

This database has been designed to assist partners with core data viewing. Information can be downloaded in several formats, and requests for samples and thin sections may be submitted to MSU. All data on this site is made available for BSCSP partner use only. If you intend to use this data for any publication, please contact brandt.winkelman@montana.edu. Given the number of researchers working on these samples, notification ensures the use of the most current data and helps coordinate research activities.



BSCSP Core Viewer Database   Home

24243_3301_44_B

Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

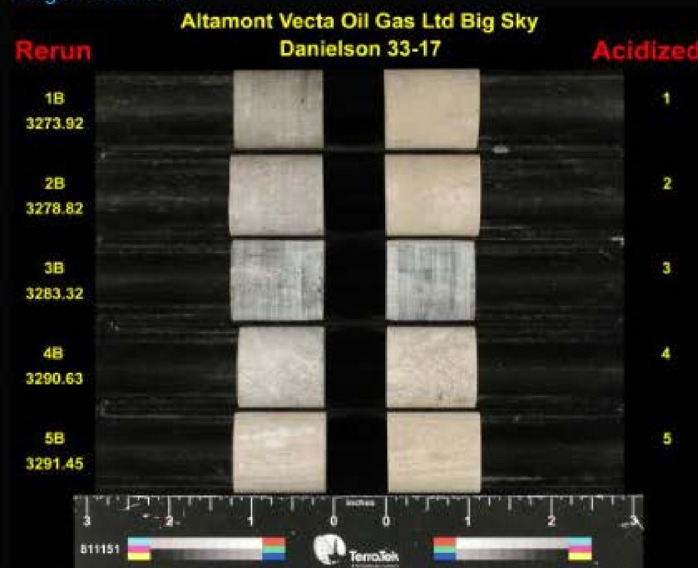
Sample ID: 24243_3301_44_B
Plug ID: 11B
Well: Danielson 33-17
Sample Depth (ft): 3301.440
Sample Length (cm): 2.832
Sample Diameter (cm): 2.517
Bulk Density (g/cc): 2.742
Dry Bulk Density (g/cc): 2.733
Grain Density (g/cc): 2.873
Ambient Porosity (%): 4.860
Saturation (Water % PV): 14.710
Saturation (Oil % PV) : 4.330
Lithology: anhy dol, dk gy & wh, xl & f-m gr, sl/ vgy, frac
Sample Plug Image
Plug Photos 11-15
Sample Slab Image
D 3301 - 3311

Plug Photos

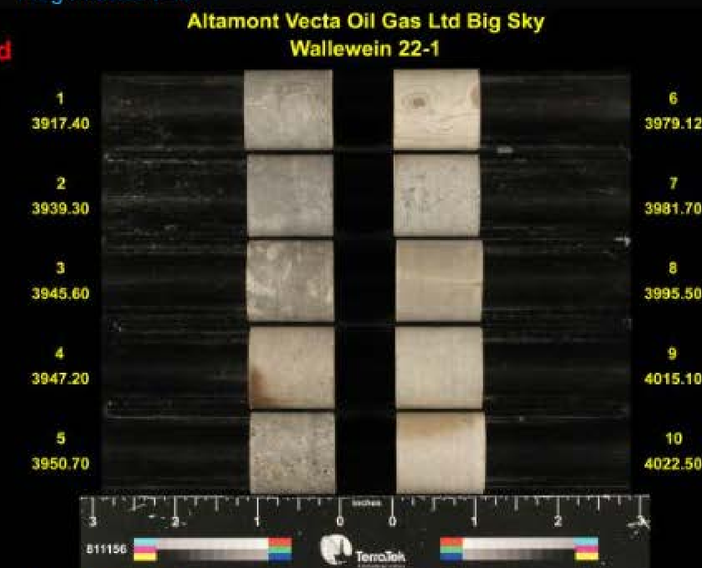
Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

Plug Photos 1 - 5



Plug Photos 1-10



Plug Photos 1-10

Plug Photos 11-15

Core Routine Analysis

Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

Well - Any - Apply

Plug ID	Sample ID	Well	Ambient Porosity (%)	Bulk Density (g/cc)	Dry Bulk Density (g/cc)	Gas Permeability Net Stress 400 PSI (mD)	Grain Density (g/cc)	Lithology	Sample Depth (ft)	Sample Diameter (cm)
1	24242_3917_40_A	Wallewein 22-1	2.71	2.794	2.791	0.01	2.869	dol, gy, xl, sl/ anhy	3917.400	2.540
1B	24242_3917_40_B	Wallewein 22-1							3917.400	
2	24242_3939_30_A	Wallewein 22-1	3.43	2.786	2.778	<0.01	2.876	dol, dk gy-gy, f gr, sl/ lam	3939.300	2.539
2B	24242_3939_30_B	Wallewein 22-1							3939.300	
3	24242_3945_60_A	Wallewein 22-1	1.79	2.808	2.807	<0.01	2.858	dol, gy & lt gy, xl, sl/ vgy	3945.600	2.540
3B	24242_3945_60_B	Wallewein 22-1							3945.600	
4	24242_3947_20_A	Wallewein 22-1	4.37	2.746	2.744	0.02	2.869	dol, gy-brn, f gr, anhy	3947.200	2.541

BSCSP Core Viewer Database   Home

Core Sample Tracker

Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

Displaying 1 - 208 of 208

Sample Status - Any -   Sample Location   Apply

Core Sample Ref	Sample Delivered	Sample Location	Sample Status	CCA	Sample Analyses
24243_3365_75_B	2014-10-31	LBNL	Intact	43B	Thin Sections (Eby);#Porosity (TerraTek);#Permeability (TerraTek);#Bulk Density (TerraTek);#Grain Density (TerraTek);#Oil and Water Saturation (TerraTek);#Ultrasonic (LBNL);#MicroCT (LBNL)
24243_3405_87_B	2014-10-31	LBNL	Intact	60B	Thin Sections (Eby);#Porosity (TerraTek);#Permeability (TerraTek);#Bulk Density (TerraTek);#Grain Density (TerraTek);#Oil and Water Saturation (TerraTek);#Ultrasonic (LBNL);#MicroCT (LBNL)
24242_4119_30_B	2014-10-31	LBNL	Intact	34B	Thin Sections (Eby);#Porosity (TerraTek);#Permeability (TerraTek);#Bulk Density (TerraTek);#Grain Density (TerraTek);#Oil and Water Saturation (TerraTek);#Ultrasonic (LBNL);#MicroCT (LBNL)
24242_4139_30_B	2014-10-31	LBNL	Intact	40B	Thin Sections (Eby);#Porosity (TerraTek);#Permeability (TerraTek);#Bulk Density (TerraTek);#Grain Density (TerraTek);#Oil and Water Saturation (TerraTek);#Ultrasonic (LBNL);#MicroCT (LBNL)

40B Thin Sections (Eby);#Porosity (TerraTek);#Permeability (TerraTek);#Bulk Density (TerraTek);#Grain Density (TerraTek);#Oil and Water Saturation (TerraTek);#Ultrasonic (LBNL);#MicroCT (LBNL)

BSCSP Core Viewer Database   Home

Wells

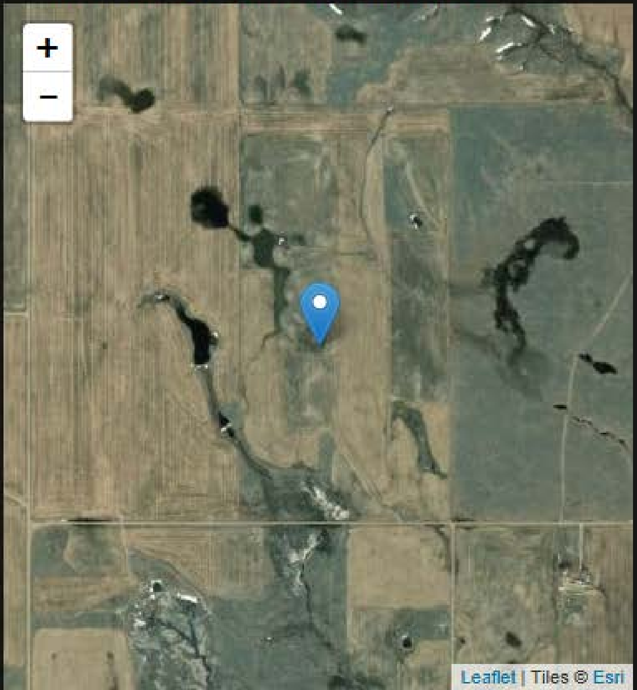
Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image
- View Plug Images
- Routine Analysis Table
- Sample Tracker
- Wells

Danielson 33-17

Well ID: Danielson3317
Type: Production
Elevation: 3566.00
KB: 3577.00
TD: 3800.00
Spud Date: Mon, 05/05/2014 - 01:00

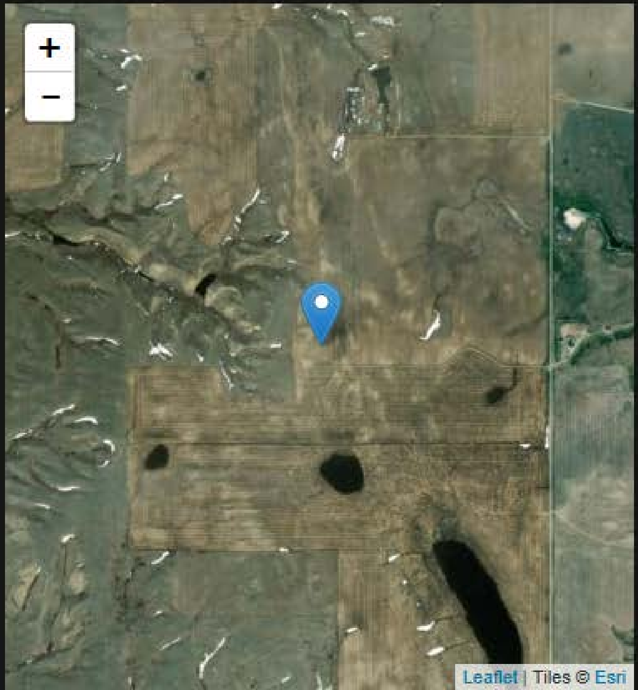
Danielson33-17_811151_CCA_Rerun_FinalResults_rev09172014.pdf   305.47 KB

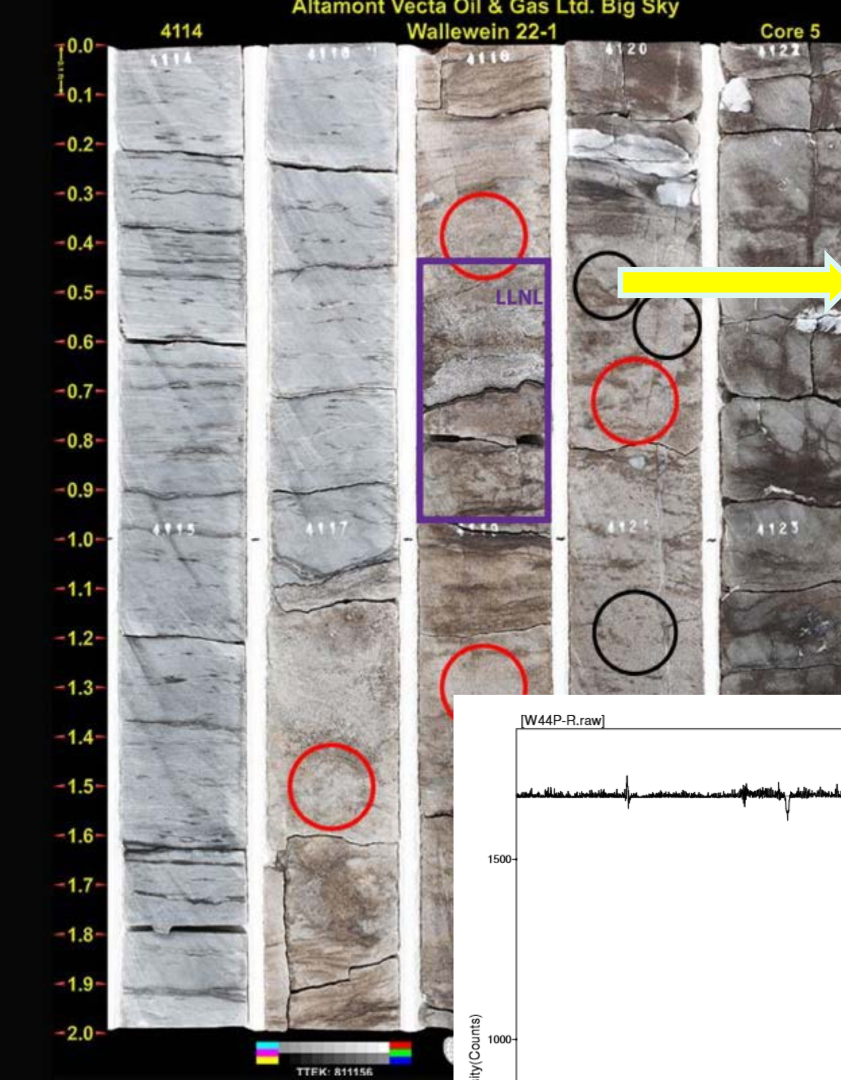


Wallewein 22-1

Well ID: Wallewein221
Type: Monitoring Geochemical
Elevation: 3963.00
KB: 3974.00
TD: 4700.00
Spud Date: Mon, 05/19/2014 - 01:00

Wallewein22-1_811156_CCA_FinalResults.pdf   260.37 KB



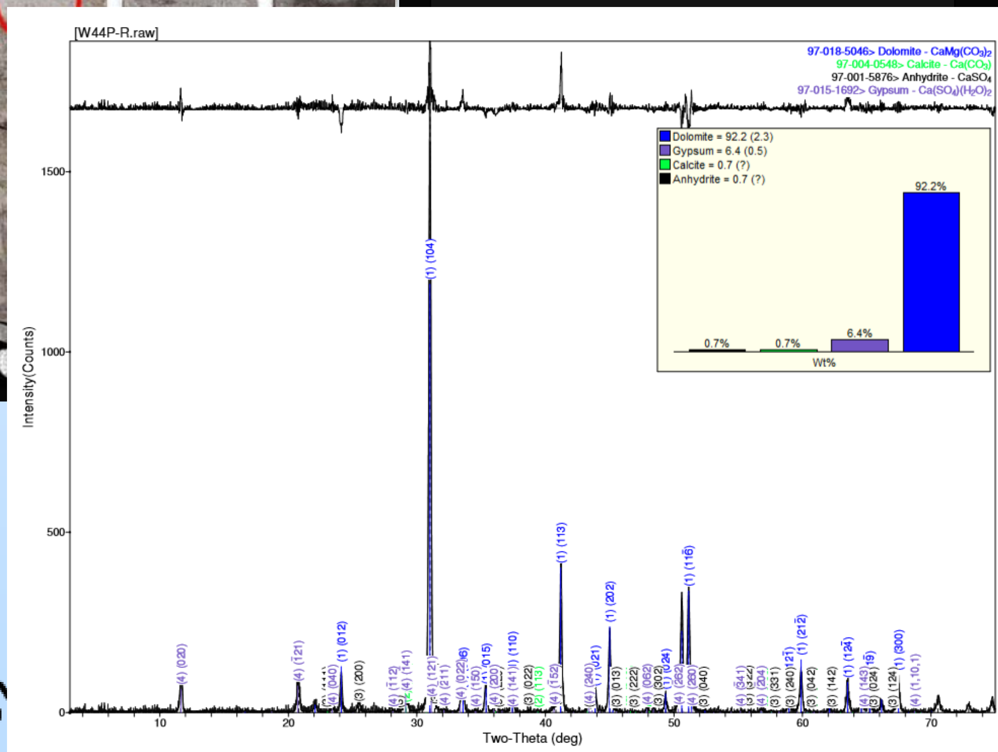


24242_4120_50_A

Core Viewer Menu

- Core Viewer Home
- Select Plugs from Slab Image

Sample Location
MSU Earth Sciences
Sample Status
Intact
Sample Delivered
Mon, 11/03/2014 - 12:00
Sample Analyses
XRD (MSU)
Attachments
24242_4120_50_A_XRD_W44P-R.pdf



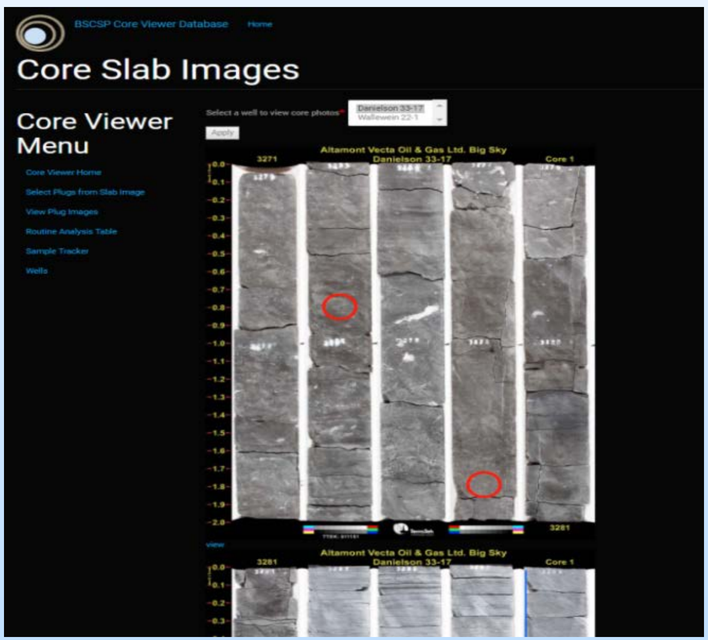
BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

RokBase

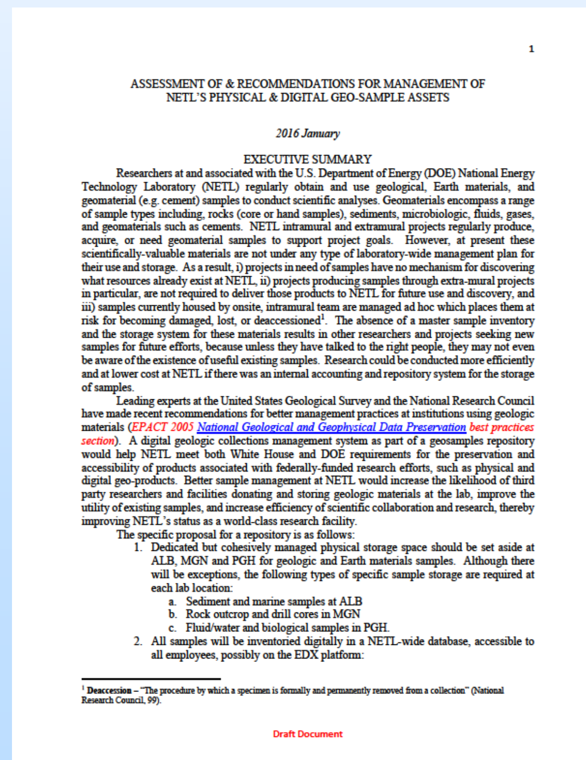
MSU-ERI's CoreViewer Application

https://core.bigskyco2.org



NETL Geostash Whitepaper January 2016

Assessment of & Recommendations for Management of NETL'S Physical & Digital Geo-Sample Assets



1

ASSESSMENT OF & RECOMMENDATIONS FOR MANAGEMENT OF NETL'S PHYSICAL & DIGITAL GEO-SAMPLE ASSETS

2016 January

EXECUTIVE SUMMARY

Researchers at and associated with the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) regularly obtain and use geological, Earth materials, and geomaterial (e.g. cement) samples to conduct scientific analyses. Geomaterials encompass a range of sample types including, rocks (core or hand samples), sediments, microbiologic, fluids, gases, and geomaterials such as cements. NETL intramural and extramural projects regularly produce, acquire, or need geomaterial samples to support project goals. However, at present these scientifically-valuable materials are not under any type of laboratory-wide management plan for their use and storage. As a result, i) projects in need of samples have no mechanism for discovering what resources already exist at NETL, ii) projects producing samples through extra-mural projects in particular, are not required to deliver those products to NETL for future use and discovery, and iii) samples currently housed by onsite, intramural team are managed ad hoc which places them at risk for becoming damaged, lost, or deaccessioned[1]. The absence of a master sample inventory and the storage system for these materials results in other researchers and projects seeking new samples for future efforts, because unless they have talked to the right people, they may not even be aware of the existence of useful existing samples. Research could be conducted more efficiently and at lower cost at NETL if there was an internal accounting and repository system for the storage of samples.

Leading experts at the United States Geological Survey and the National Research Council have made recent recommendations for better management practices at institutions using geologic materials (*EPACT 2005 National Geological and Geophysical Data Preservation best practices section*). A digital geologic collections management system as part of a geosamples repository would help NETL meet both White House and DOE requirements for the preservation and accessibility of products associated with federally-funded research efforts, such as physical and digital geo-products. Better sample management at NETL would increase the likelihood of third party researchers and facilities donating and storing geologic materials at the lab, improve the utility of existing samples, and increase efficiency of scientific collaboration and research, thereby improving NETL's status as a world-class research facility.

The specific proposal for a repository is as follows:

1. Dedicated but cohesively managed physical storage space should be set aside at ALB, MGN and PGH for geologic and Earth materials samples. Although there will be exceptions, the following types of specific sample storage are required at each lab location:
   a. Sediment and marine samples at ALB
   b. Rock outcrop and drill cores in MGN
   c. Fluid/water and biological samples in PGH.
2. All samples will be inventoried digitally in a NETL-wide database, accessible to all employees, possibly on the EDX platform:

[1] **Deaccession** – "The procedure by which a specimen is formally and permanently removed from a collection" (National Research Council, 99).

Draft Document

Similarity of Purpose and Implementation

CoreViewer was developed to store data and images, as well as to provide visualizations for well core data that was produced by the Big Sky Carbon Sequestration Partnership. The system is implemented in the Drupal content management system and provides a data model to store data about earth materials.

Drupal™

From the Geostash Paper: "The open source database system, Drupal is recommended … and should be integrated into the Energy Data eXchange (EDX) for use by researchers. The EDX development team can write a custom database system with Drupal … that has a user-friendly interface for researchers to search for, request, and upload metadata for geoscience collections."

Features

- Migration tool for data ingest
- Forms for manual data creation and edits
- Filterable display of Rok sets
  - [ex] View a table of attributes from all samples with a parent relationship to the Danielson Well Slab Rok
- Data export tool
  - [ex] Download all fields for a set of Roks into a csv file
- Tracking location of physical samples
  - [ex] fields provided for storing current location, coordinates, address, institution

RokBase   Home   Log in

Danielson Well Slab

Submitted by thomas on Wed, 05/15/2019 - 15:32

Material: Rock core
Classification: Shale
Geological Unit: Madison
Field Name: Kevin Sunburst

Geologic Age: Devonian
Age (min): 358 mya
Age (max): 419 mya
Formation Thickness: 540 m

Description

In 2014, BSCSP drilled two characterization wells in the project area. These wells provided additional detailed site specific geologic information. The first well was drilled to a depth of 3,800 feet and the second well was drilled to 4,696 feet. As the wells were drilled, on-site geologist collected rock cuttings from every 10 feet. Gas and fluid samples were also collected and analyzed during the drilling process.

The next step was the coring process, which involved cutting and removing long cylinders of rock from the well hole. These "cores" are being tested and studied for their geologic properties and chemical composition. Cores were removed using 60 foot core barrels and protected in aluminum sleeves. In total, BSCSP cored 180 continuous feet in the first well and 240 feet in the second well. These segments provide researchers rock samples from the upper Duperow formation (which contains solid caprock), as well as samples from the middle Duperow formation, where the rock is more porous and contains CO2. The sleeves were then carefully packaged and transported to labs for initial measurement, testing and archiving procedures. Later, the core will be divided into samples of various sizes and shared with team partners for a wide range of testing and analysis.

Collection Method
When the logging was complete, the drill team cased the well by inserting and connecting pipe one joint at a time down the length of the hole. The well was then cemented through a two-stage cement process, first cementing the lower section (from 4,700 feet deep to 2,390 feet), followed by the upper section (from 2,390 feet to the surface). Work on the monitoring well was wrapped up successfully on the evening of May 30th, and the drilling rig was moved off the site.

Collection Method Description
After the drilling of the main hole for the monitoring well was finished, the team began the logging process, which allows collection of a wide range of data from the underground layers exposed by the open hole. Logging involves

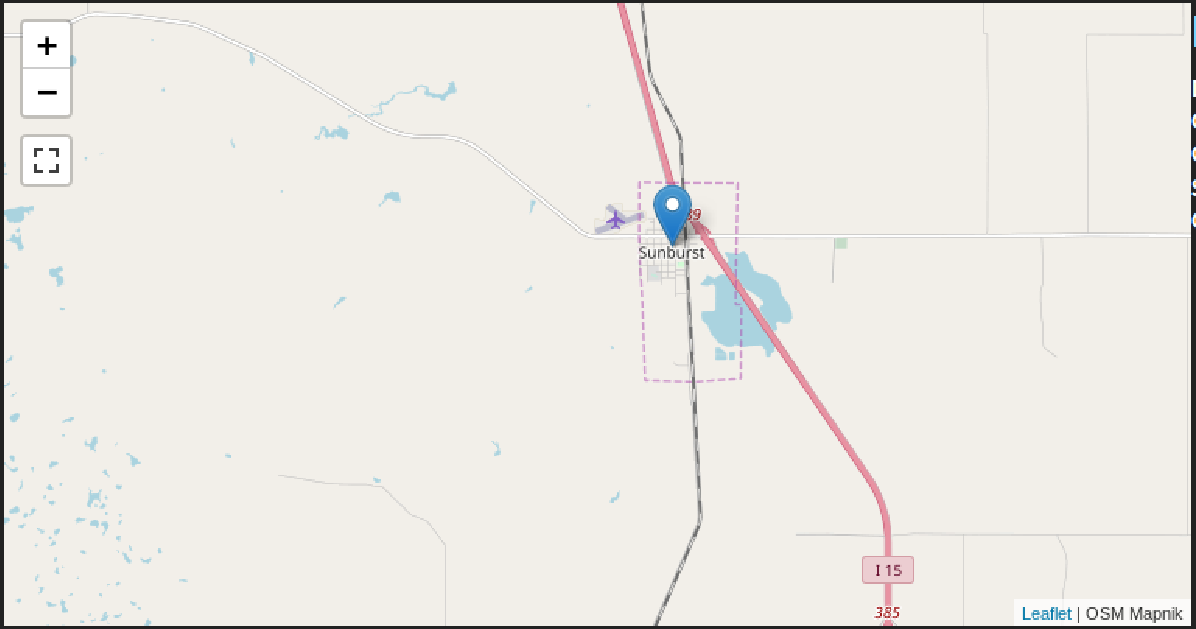
Children

Danielson 24243_3283_32_B
Danielson 24243_3278_82_B
Danielson 24243_3273_92_B

Purpose

In the laboratory, routine core analyses were performed for 110 core plugs from both wells. The analyses included bulk density, dry bulk density, grain density, ambient porosity, water and oil saturations, gas permeability, and lithological descriptions. Additionally, six plugs were chosen for X-ray diffraction analysis to determine whole rock mineralogy and help interpret the other results. Further work for the creation of thin sections and petrographic analysis is currently underway. Together, the logging and coring process provides important characterization details, such as the depth and lithology (rock type) of each formation, the porosity and permeability of rocks, the size and connectivity of rock pores, the existence of fractures, and other geologic properties. This information will in turn, guide drilling, injection, and monitoring activities throughout the life of the project.

Original Location

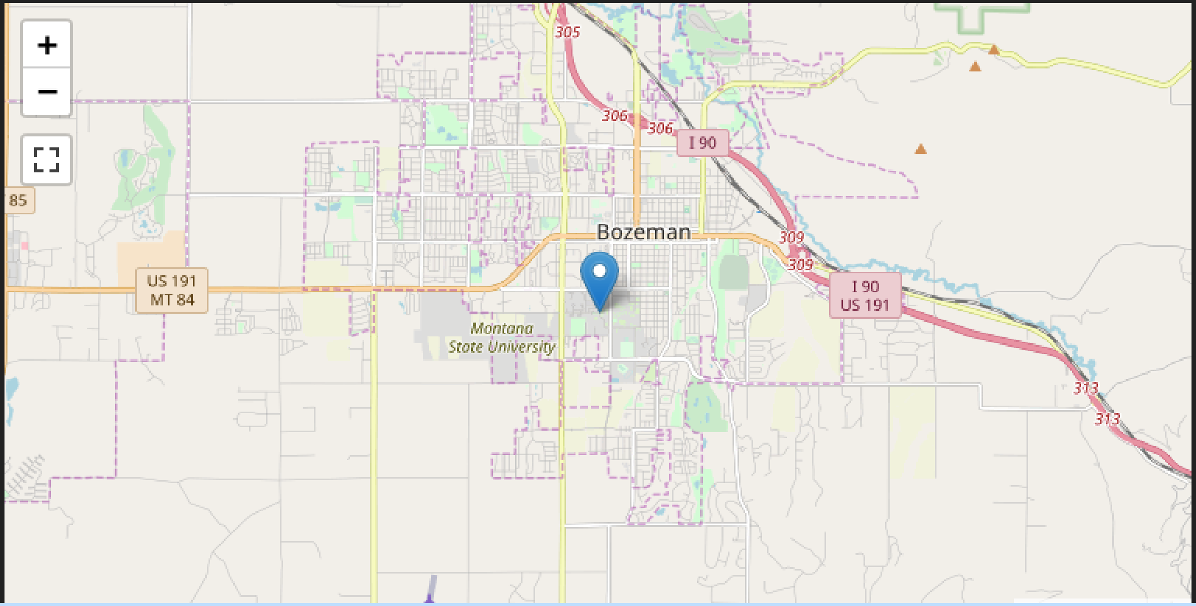


Kevin Dome, MT

Details

Depth: 3,451.00
City: Sunburst
County: Toole
State/Province: MT
Country: United States

Current Location



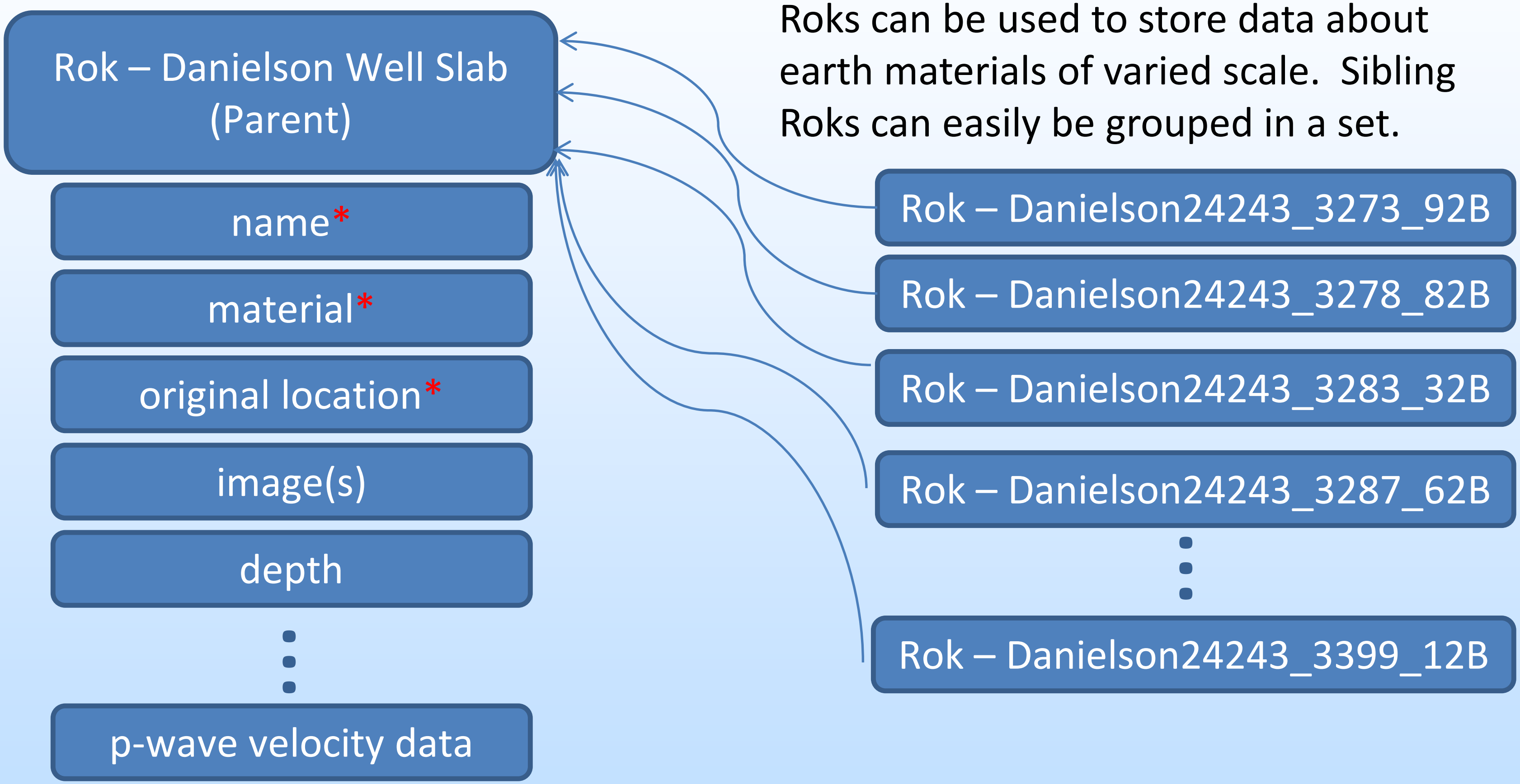
Data Model

- Minimum set of required fields with many optional fields
  - Required: name*, material*, original location*
  - Optional: image(s), depth, field name, collection method, … , medical CT scans, p-wave velocity data, …
- Support for file attachments of various types.
  - [ex] xls, pdf, doc, csv, …
- Relationship to additional content types provides ability to store data directly in the database
  - [ex] Routine analysis from core viewer has been supported with this method
  - Fields are stored in a separate data container that refers to a sample Rok
- Parent entity reference to implement hierarchy
  - [ex] Display a view of all roks with the same parent = all core samples from the same slab

RokBase Data Model

Hierarchy – Roks maintain a relationship to parent Rok

Roks can be used to store data about earth materials of varied scale. Sibling Roks can easily be grouped in a set.



Subtask R1.5

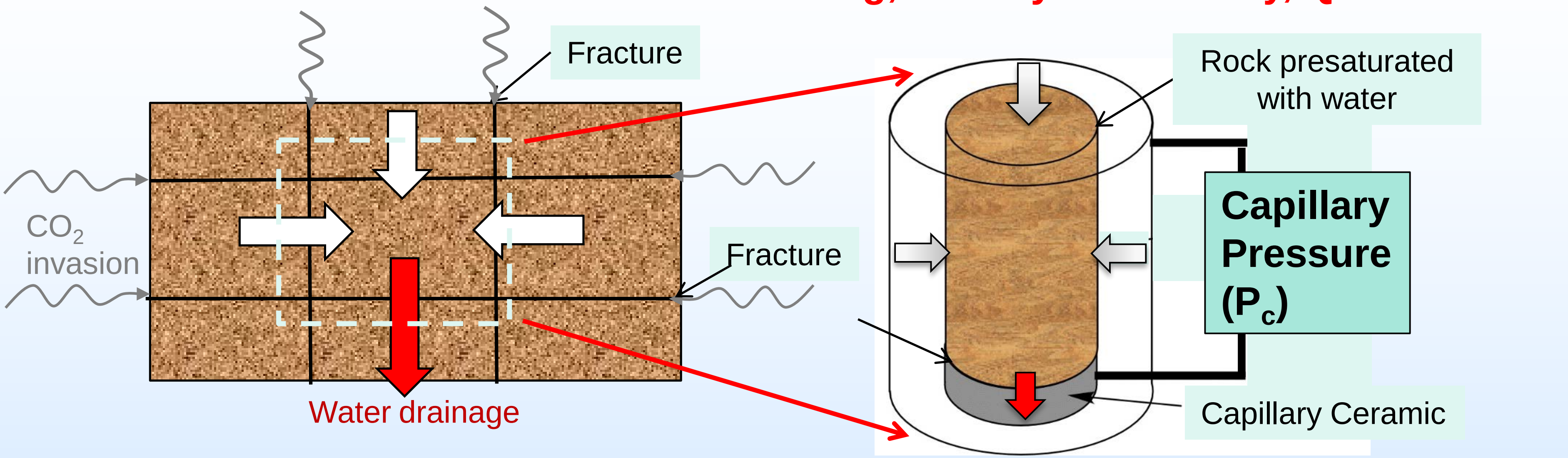
Lab measurements of fracture-matrix flow to help with modeling of two-phase flow in fractured carbonate

Chun Chang,Timothy J. Kneafsey, Quanlin Zhou

Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory

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.

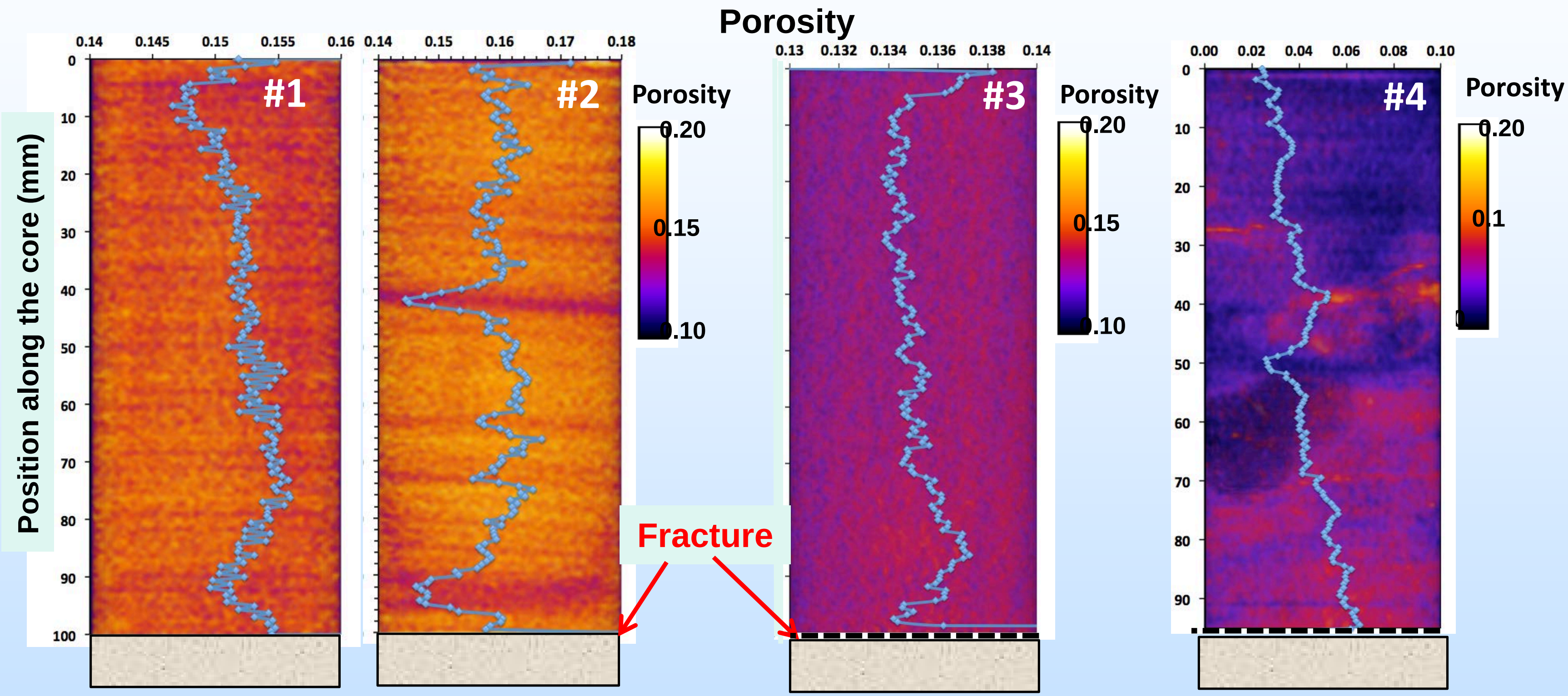
Laboratory flow tests were conducted to:

1. investigate the fracture-matrix interactions;

2. visualize processes showing the importance of capillary continuity to geologic carbon storage capacity.

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

Berkeley Lab

Big Sky Carbon Sequestration Partnership

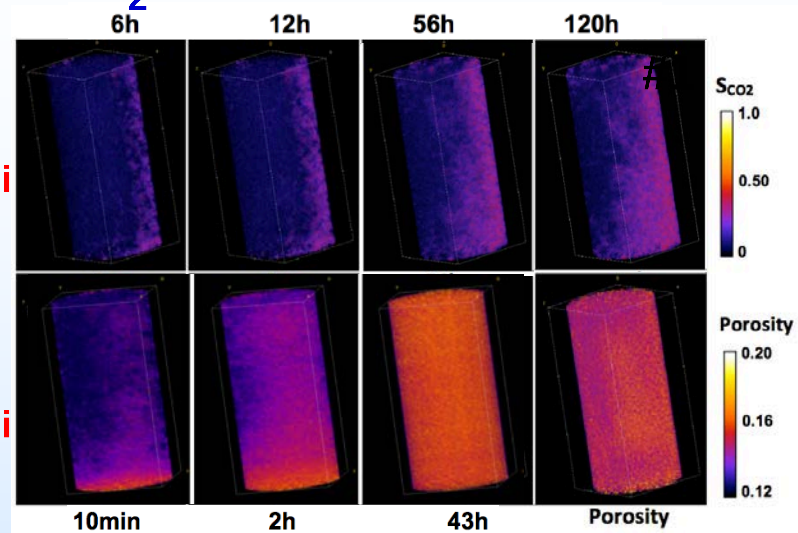
Montana State University

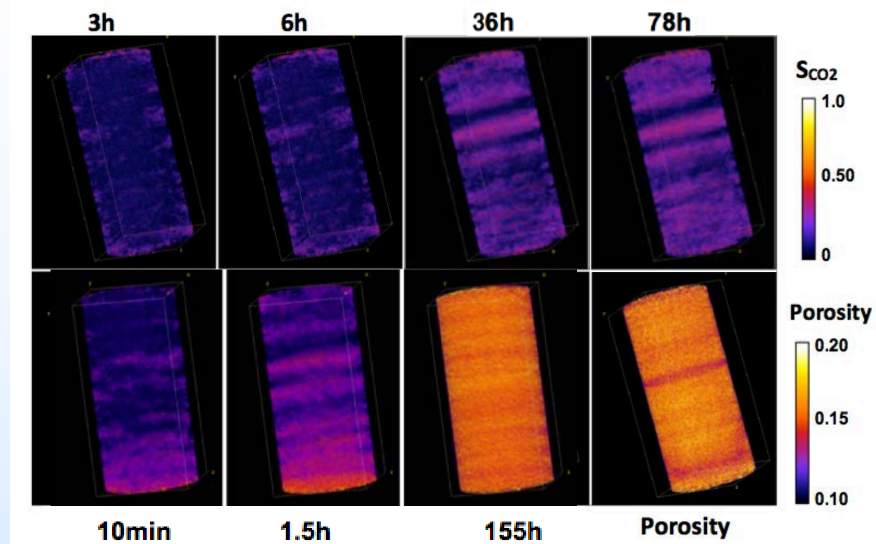
CO_2-water flow with good capillary continuity across fracture

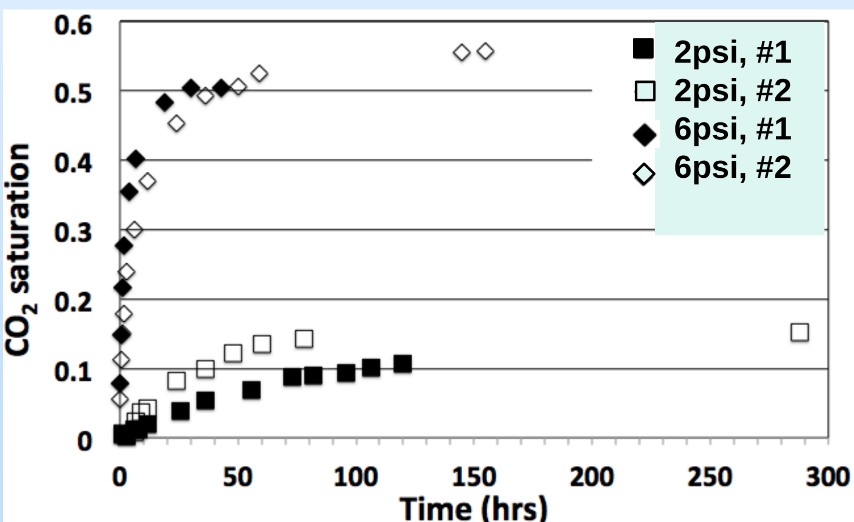
❖ CO_2 distribution and saturation vs. time in rock matrix

P_c= 2 psi

P_c= 6 psi







- 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).

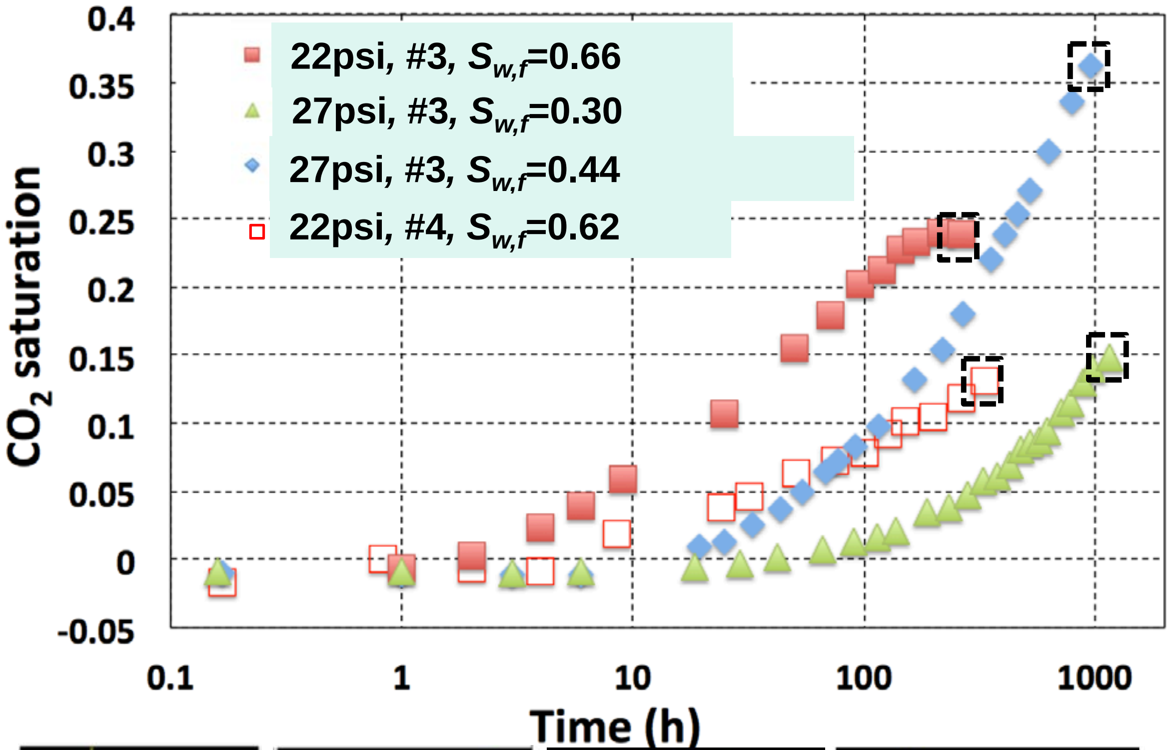
Berkeley Lab

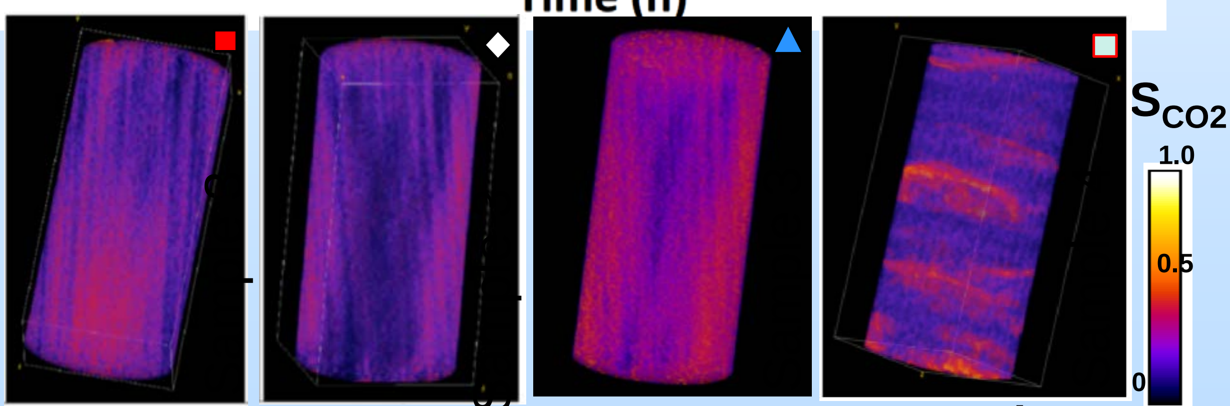
Big Sky Carbon Sequestration Partnership

Montana State University

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

BERKELEY LAB





- 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 $S_{w,f}$.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

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.

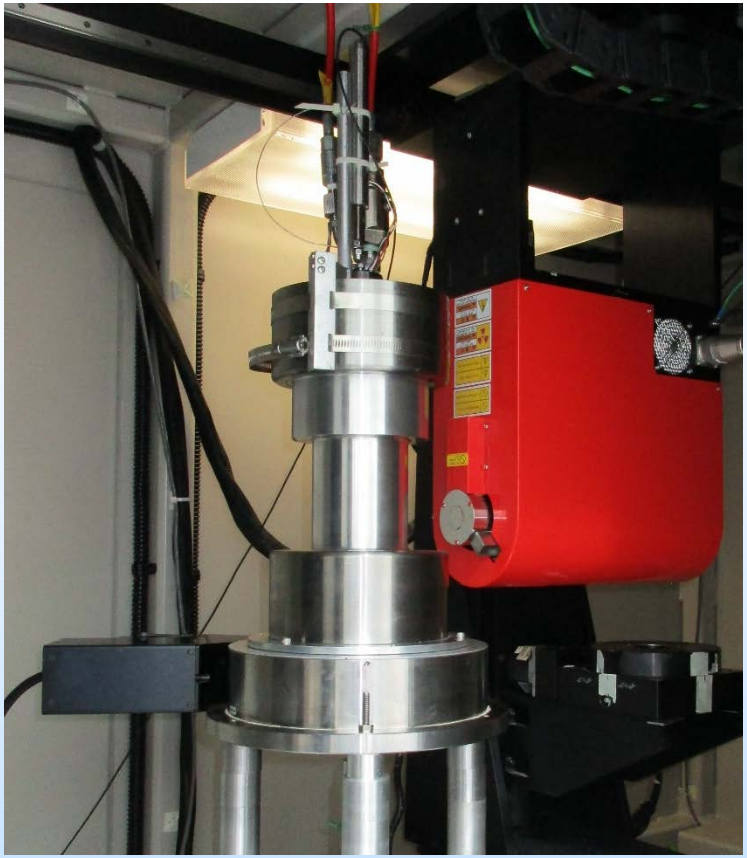
Task R1. Core Studies: Motivation

Los Alamos NATIONAL LABORATORY

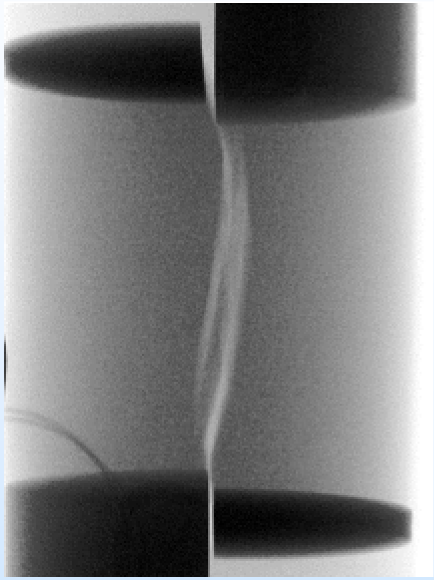
Bill Carey

- 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

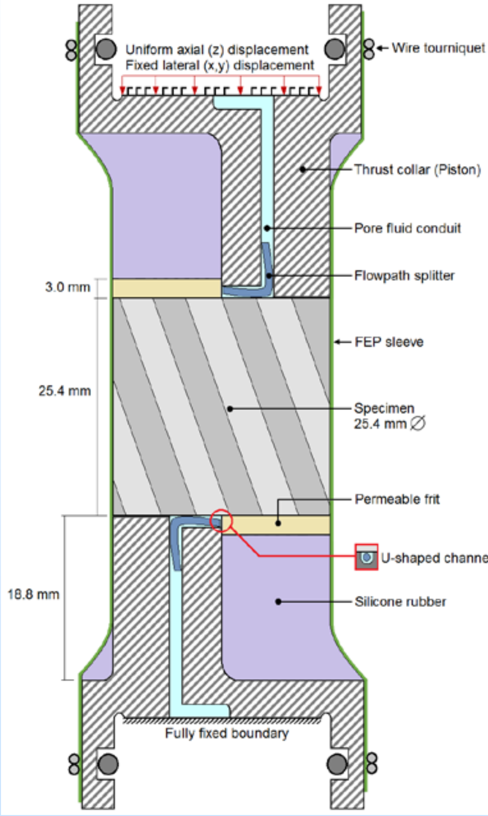
Approach: Triaxial Direct-Shear Coreflood with Simultaneous X-ray radiography/tomography



In situ radiography



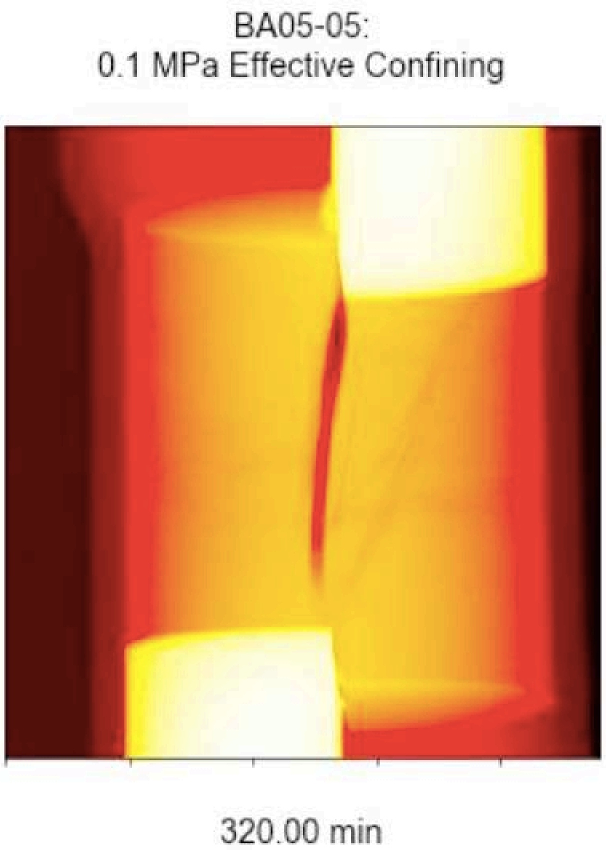
Direct-shear device

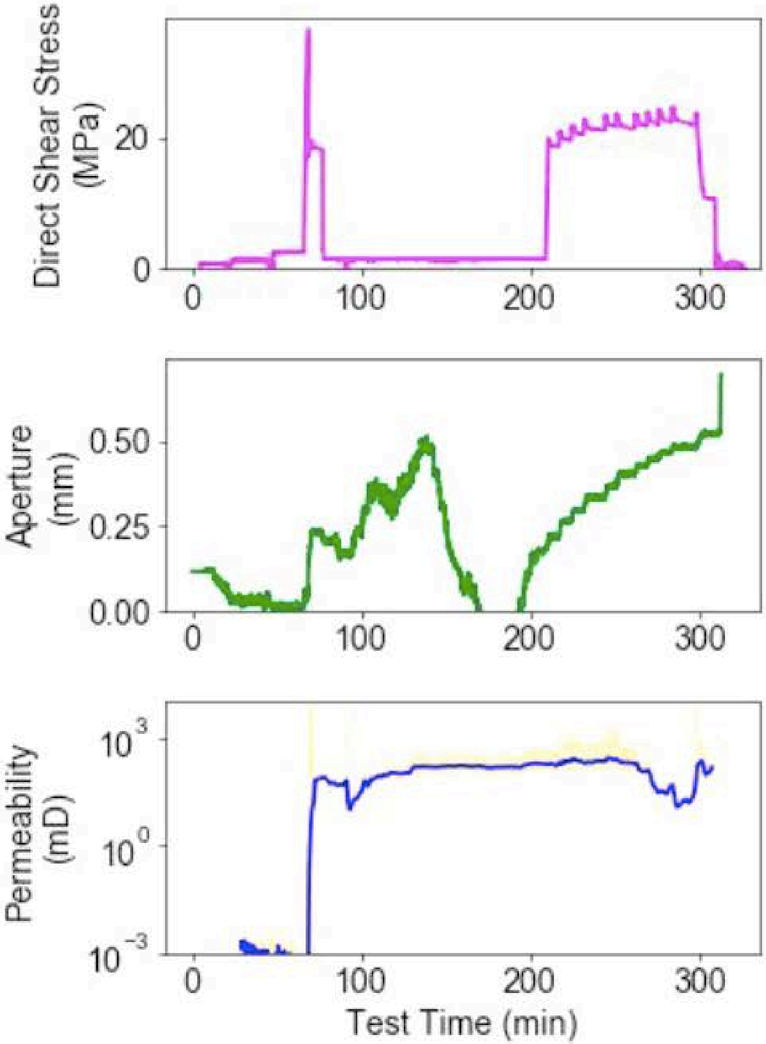


Creation of shear fractures at reservoir conditions coupled with permeability measurements and x-ray observations

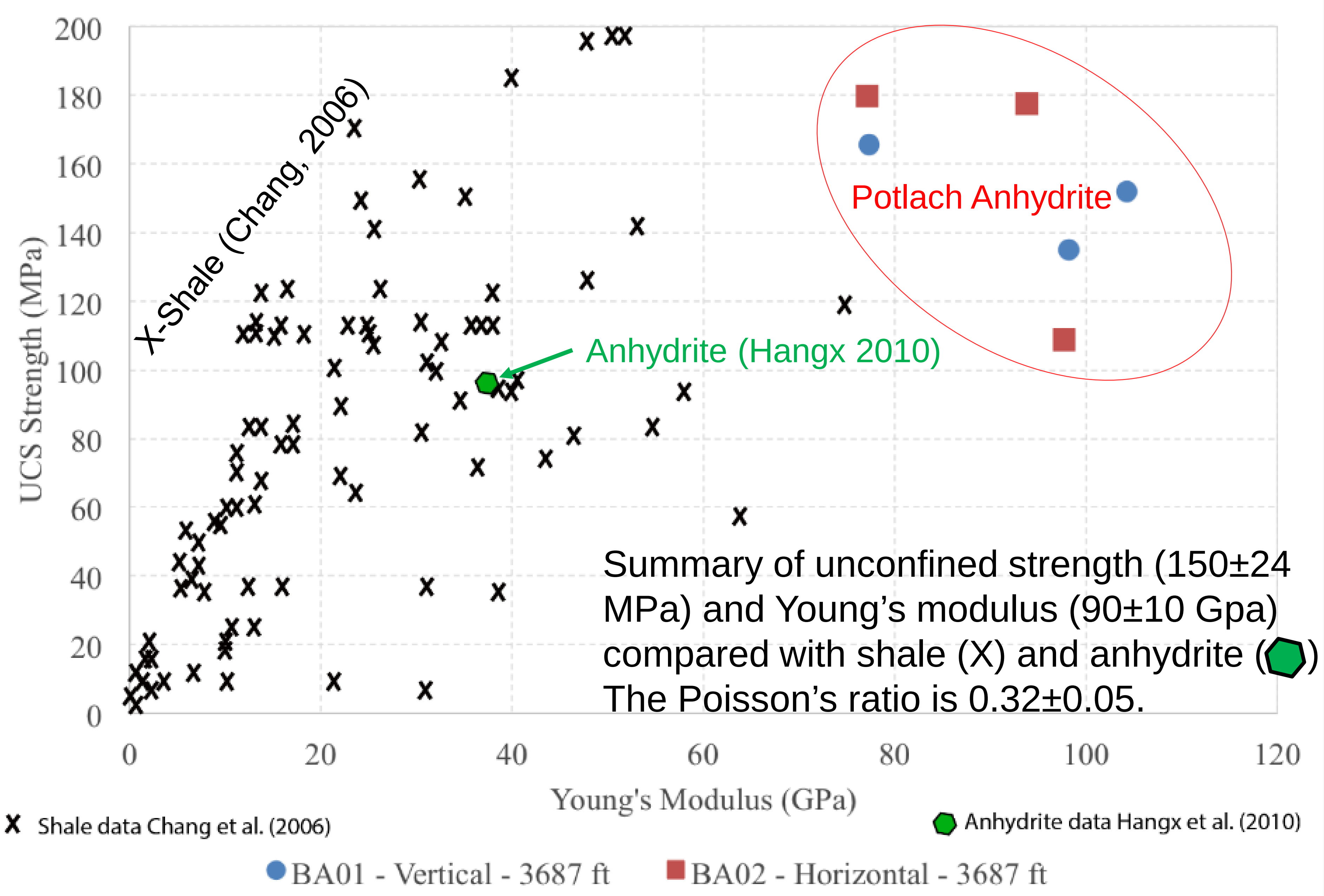
Carey et al., J. Unconv. O&G Res., 2015; Frash et al. (2016) JGR; Frash et al. (2017) IJGGC

Potlatch Anhydrite at 10 MPa



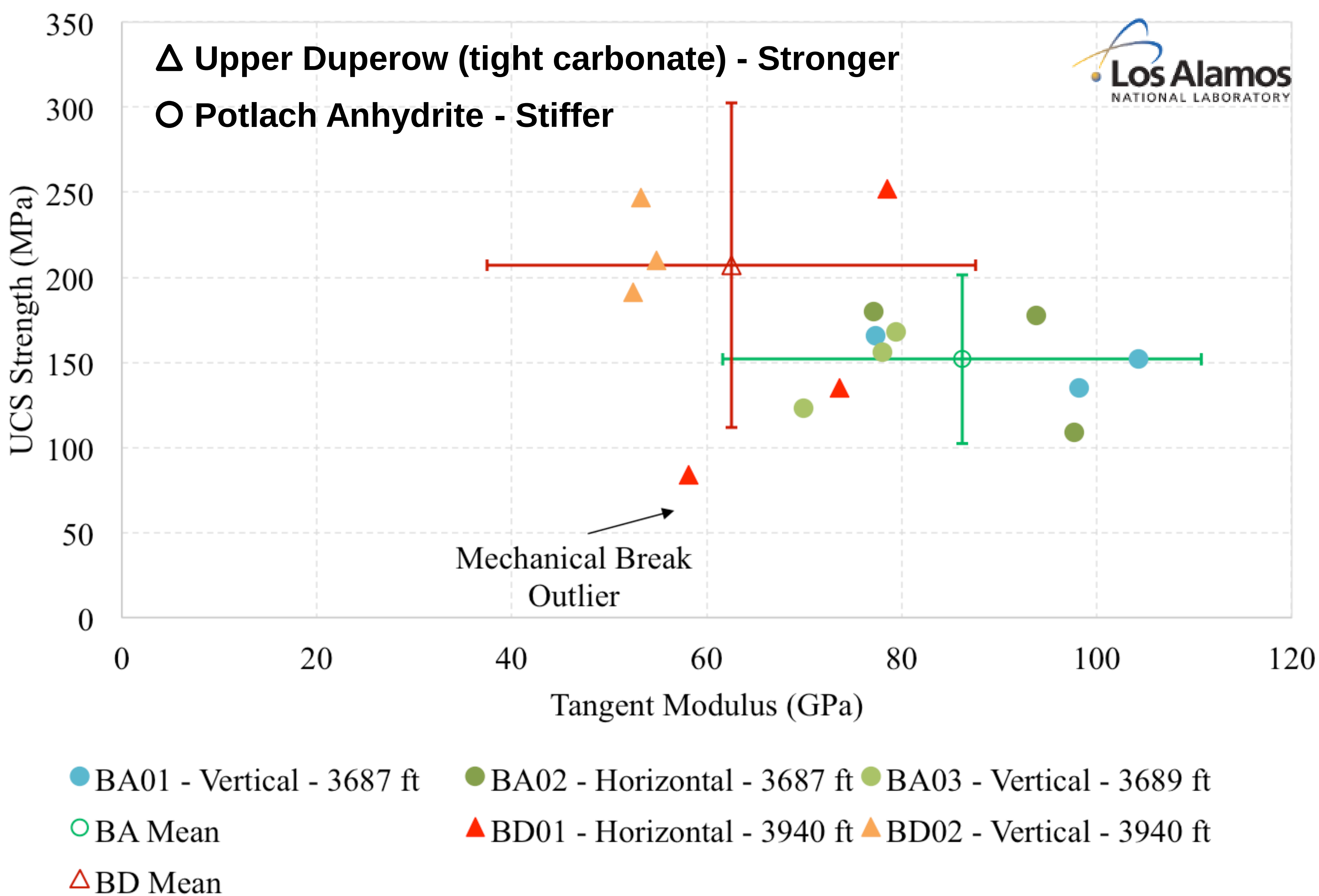


Caprock Geomechanical Tests

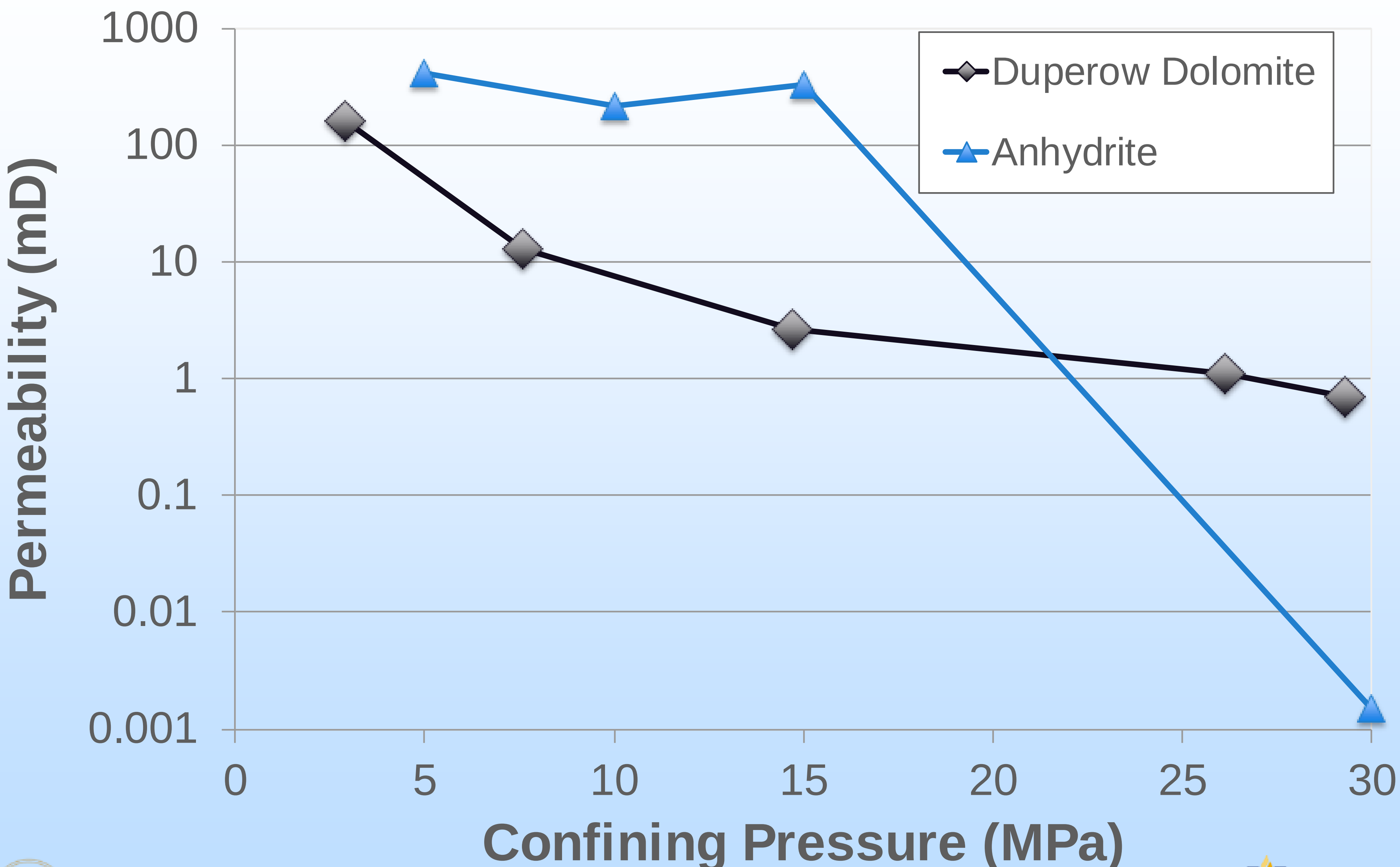


Summary of unconfined strength (150±24 MPa) and Young's modulus (90±10 Gpa) compared with shale (X) and anhydrite ( )
The Poisson's ratio is 0.32±0.05.

Caprock Geomechanical Analysis



Summary Permeability-Stress Relations



Motivation for lab seismic study

Harry Lisabeth, Jonathan Ajo Franklin

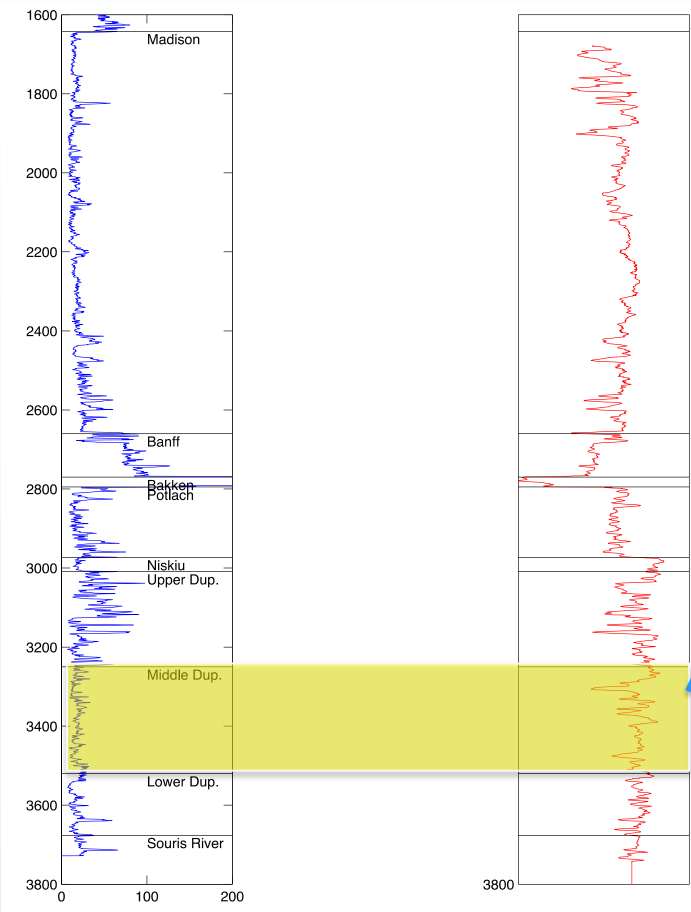
- Time-lapse (4D) seismic monitoring is one of the best tools we have to see dynamic changes in the subsurface

- 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

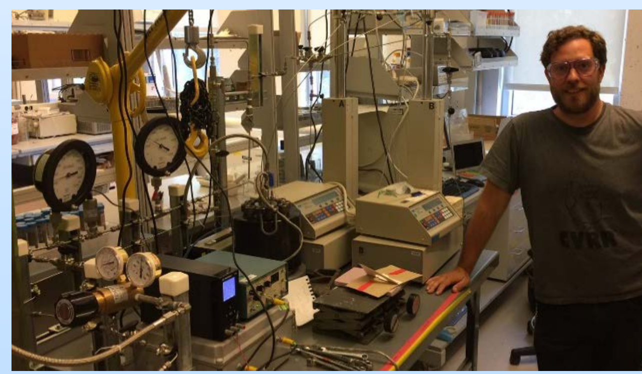
Danielson Well (Production Pad)



Gamma Neutron Sonic

Low frequency modulus/attenuation

Fluid replacement/ultrasonic characterization



BIG SKY CARBON SEQUESTRATION PARTNERSHIP

BERKELEY LAB

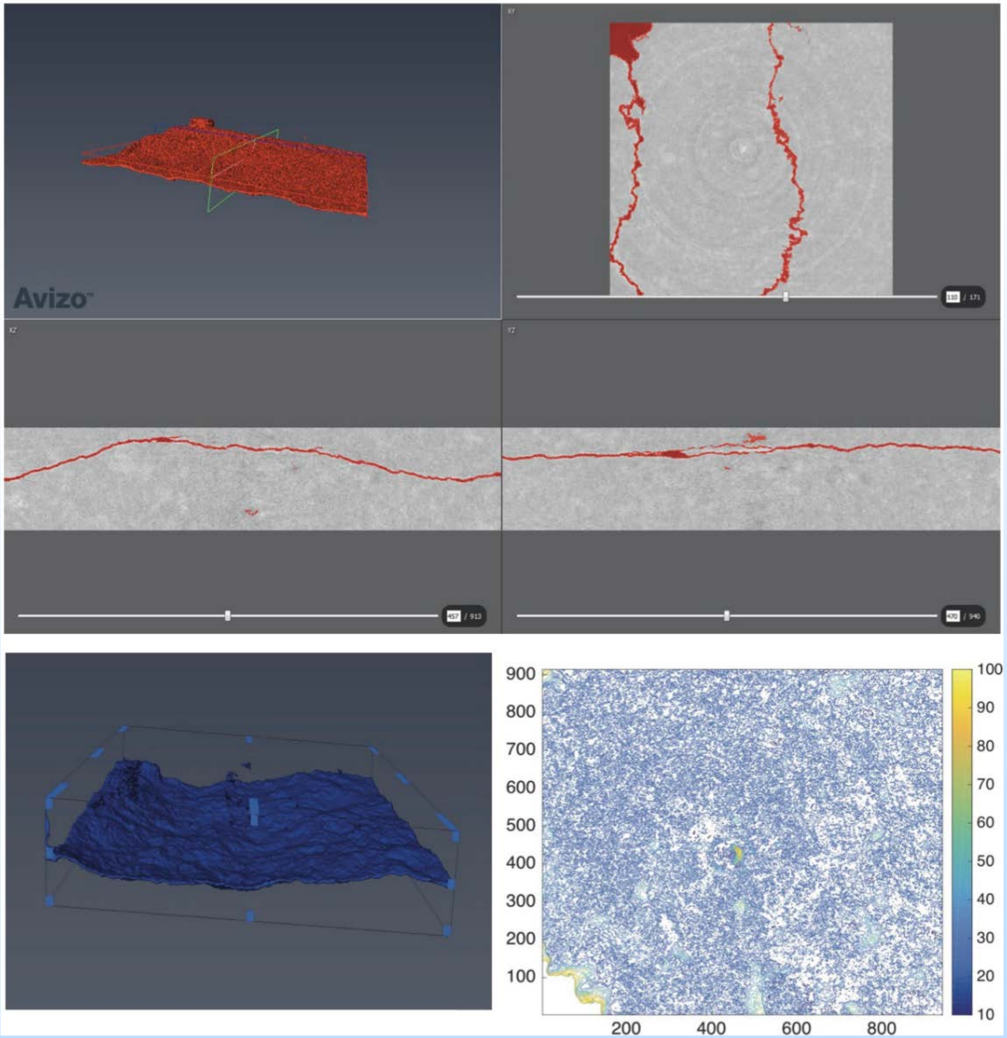
MONTANA STATE UNIVERSITY

Synchrotron x-ray microtomography of fractured Duperow dolomite

BERKELEY LAB

- 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.

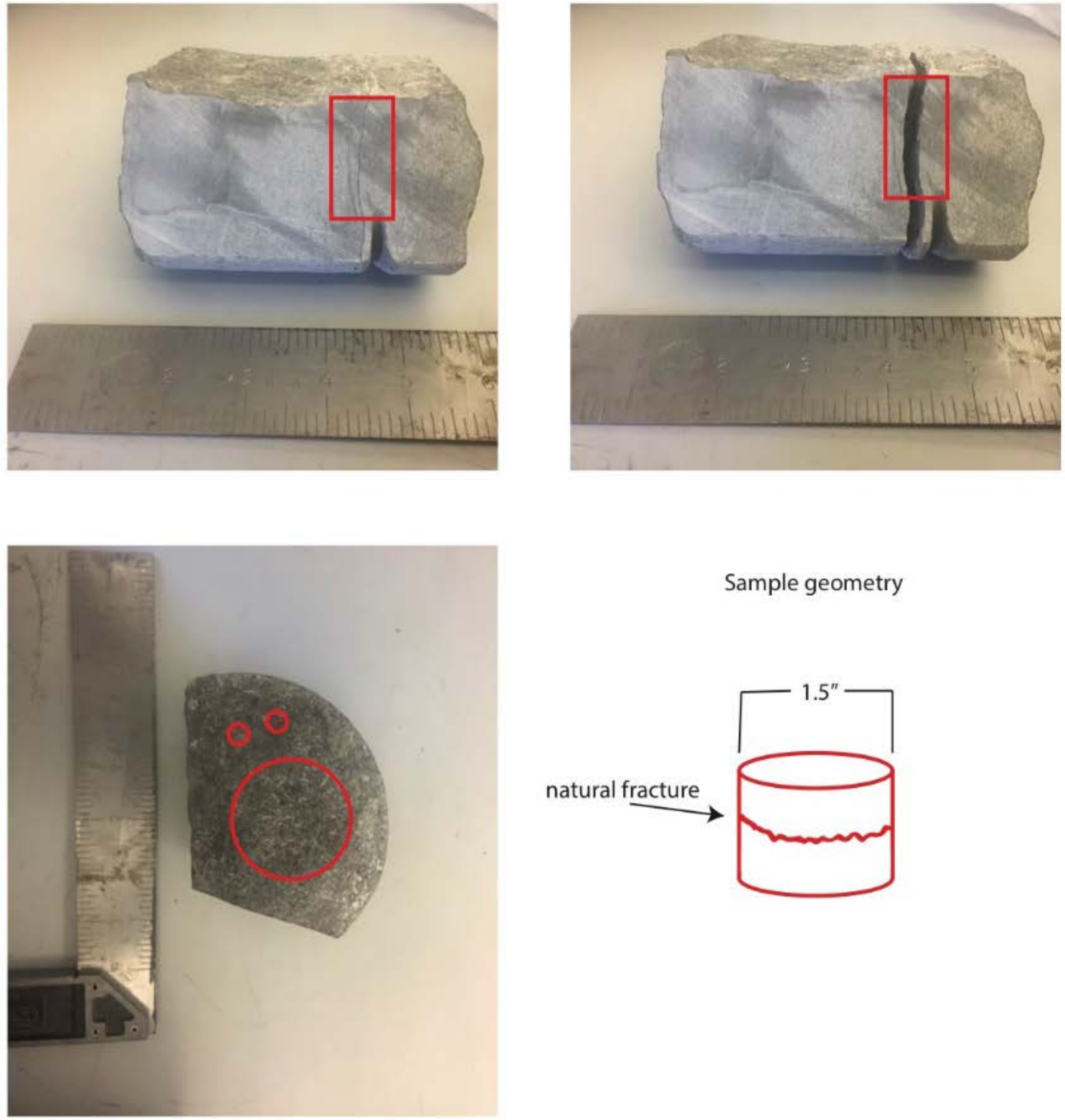
[Conducted at beamline 8.3.2, Advanced Light Source]



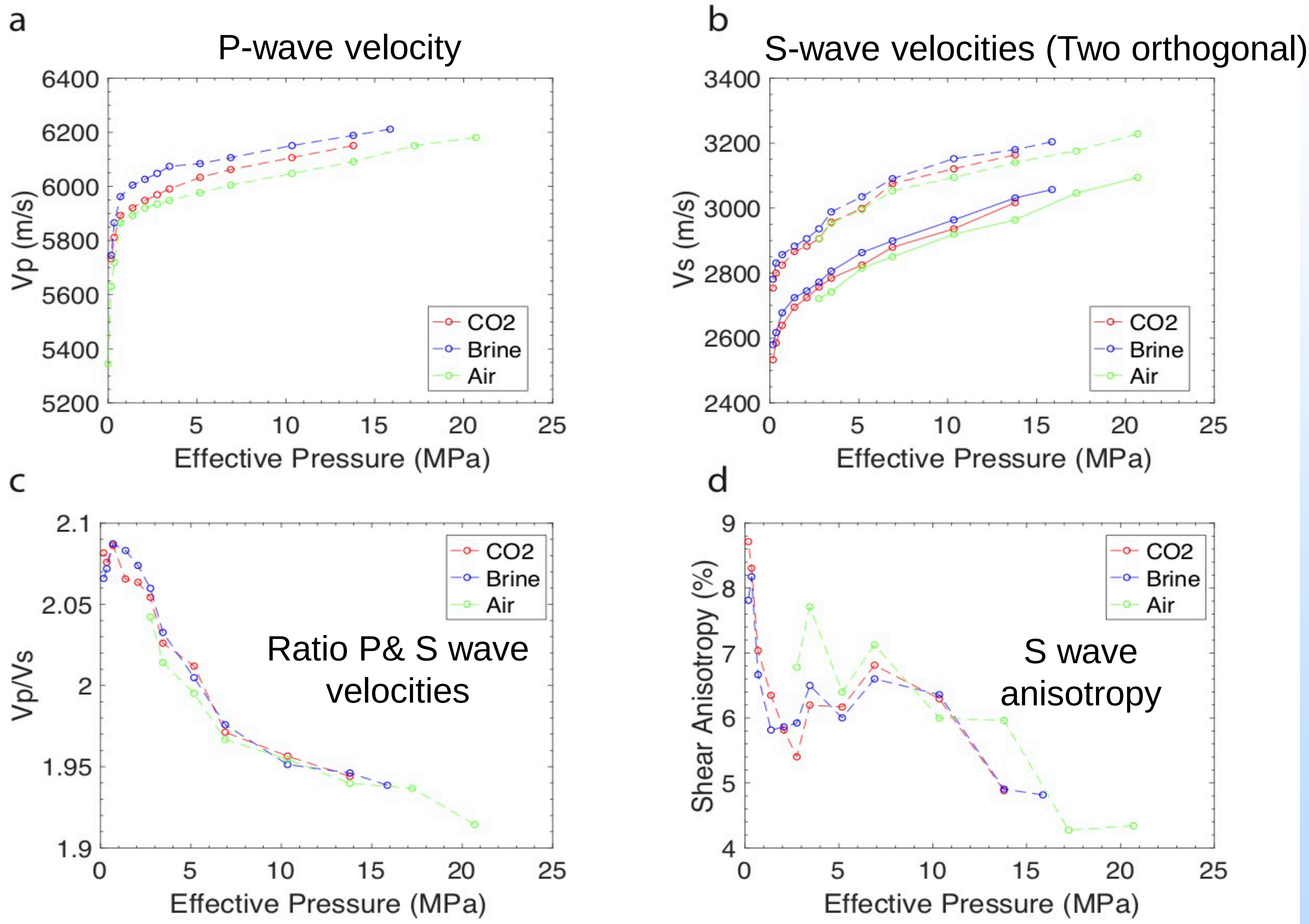
BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Illustration of subcore orientation. A 1.5” diameter by 1” long core was fabricated intersecting a natural fracture to test the seismic properties of a fractured, low porosity reservoir.



High Pressure Ultrasonic Results



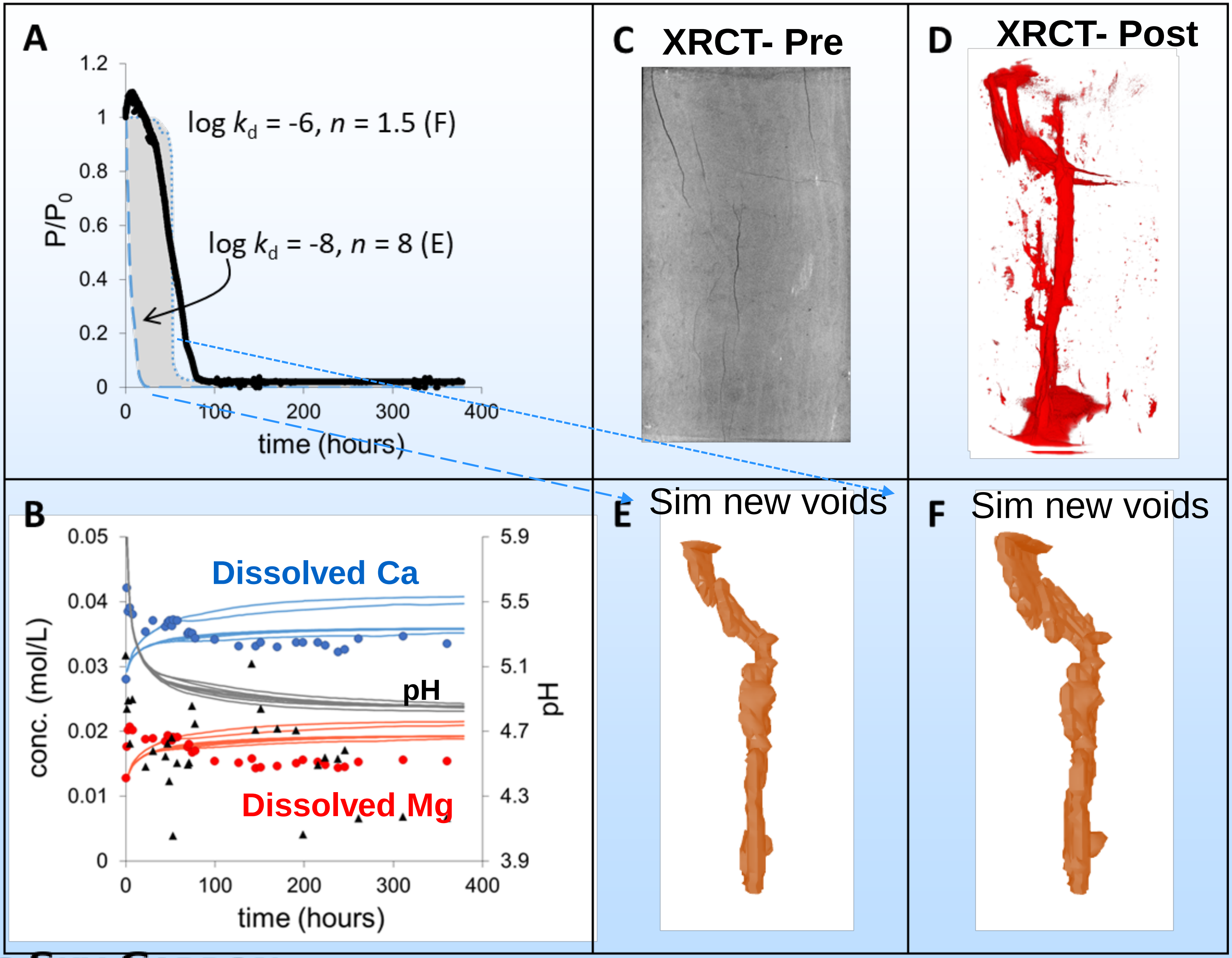
Validation of LLNL Reactive Transport Model

International Journal of Greenhouse Gas Control
Volume 90, November 2019, 102797

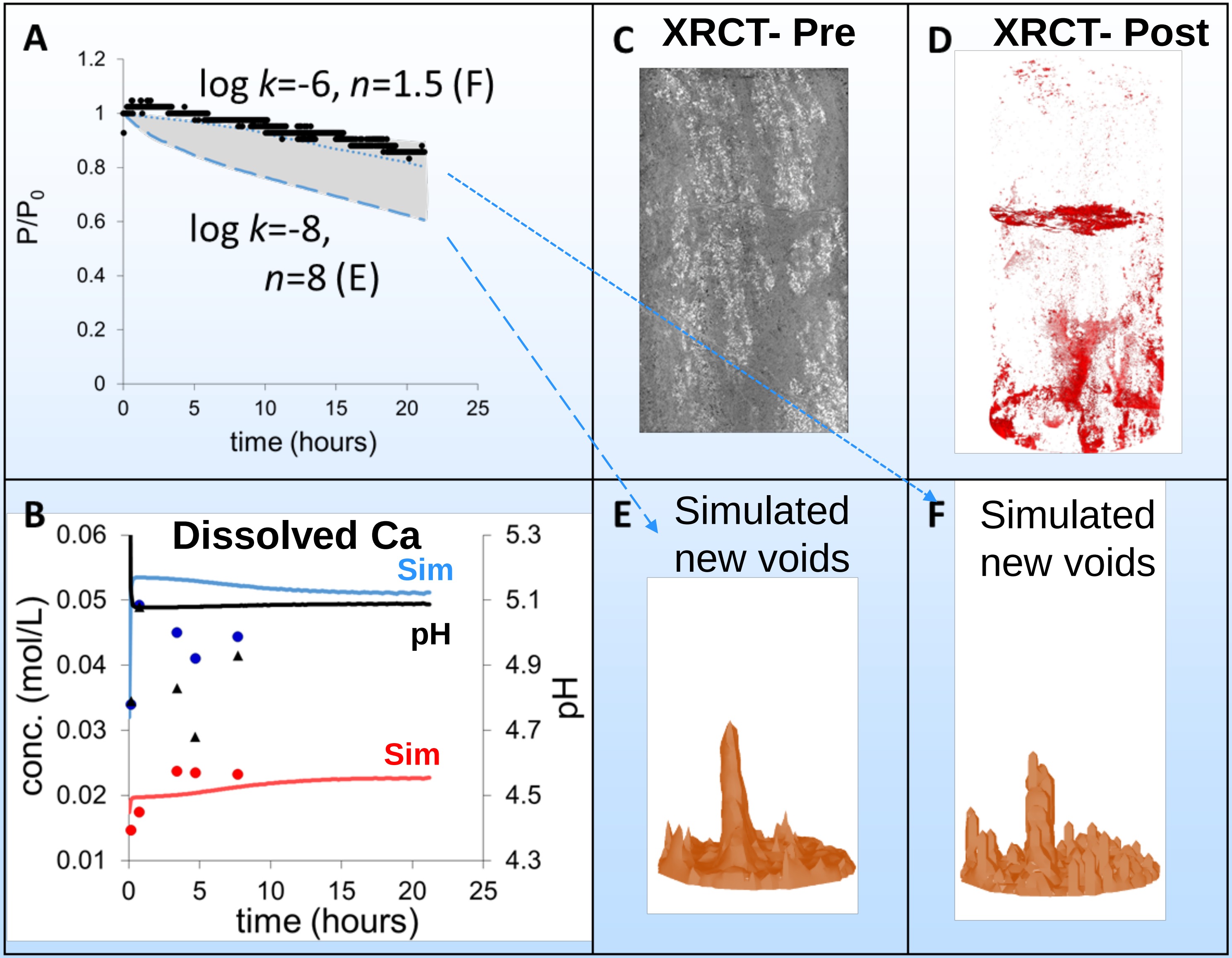
Validation of a reactive transport model for predicting changes in porosity and permeability in carbonate core samples

Megan M. Smith[*,1], Yue Hao[1], Lee H. Spangler[2], Kristin Lammers[1,†], Susan A. Carroll[1]

Moderate Permeability Sample



Higher Permeability Sample



Accomplishments to Date

- 430 ft of carbonate core from regions both with and without CO_2 representing 7 different depositional environments
- Core flood / flow experiments investigating reactivity
- Provided samples, data to verify LLNL reactive transport model
- Laboratory investigation of dual permeability (fracture-matrix) response to CO_2 flood (capillary entry pressure, saturation, etc.)
- Model development for dual permeability systems
- Acquisition of core on two caprock materials, tight carbonate and anhydrite (30')
- Unique mechanical testing of permeability – stress relationship in caprock material
- Development of a geostatic model using Neural Nets to match well logs to facies and using p and s wave seismic to inform reservoir heterogeneity

Accomplishments to Date

- Investigation of multi-fluid / Joule-Thompson cooling effects on wellbore flow. Model improvement.
- Application of NRAP tools to risk assessment at multiple stages of the project
- Largest 3D – 9C seismic shoot 32 sq. mi.
- Improved multi-component seismic processing
- First quadri-joint inversion
- Demonstrated high resolution velocity model from full wave inversion
- Lab measurements of pressure and fluid fill effects on seismic response in fractured carbonates
- Development of a core-viewer application for viewing core, plugs, and rock data
- Development of a Drupal application for a rock database for EDX

Wellbore Sealing Projects (Not BSCSP)

WELLBORE INTEGRITY AND MITIGATION 1
Rooms 301, 302

Thursday

10:20 AM Methods to Enhance Wellbore Cement Integrity with Microbially Induced Calcite Precipitation • Adrienne Phillips, Montana State University

11:20 AM Wellbore Leakage Mitigation Using Advanced Mineral Precipitation Strategies (FE0026513) • Adrienne Phillips, Montana State University

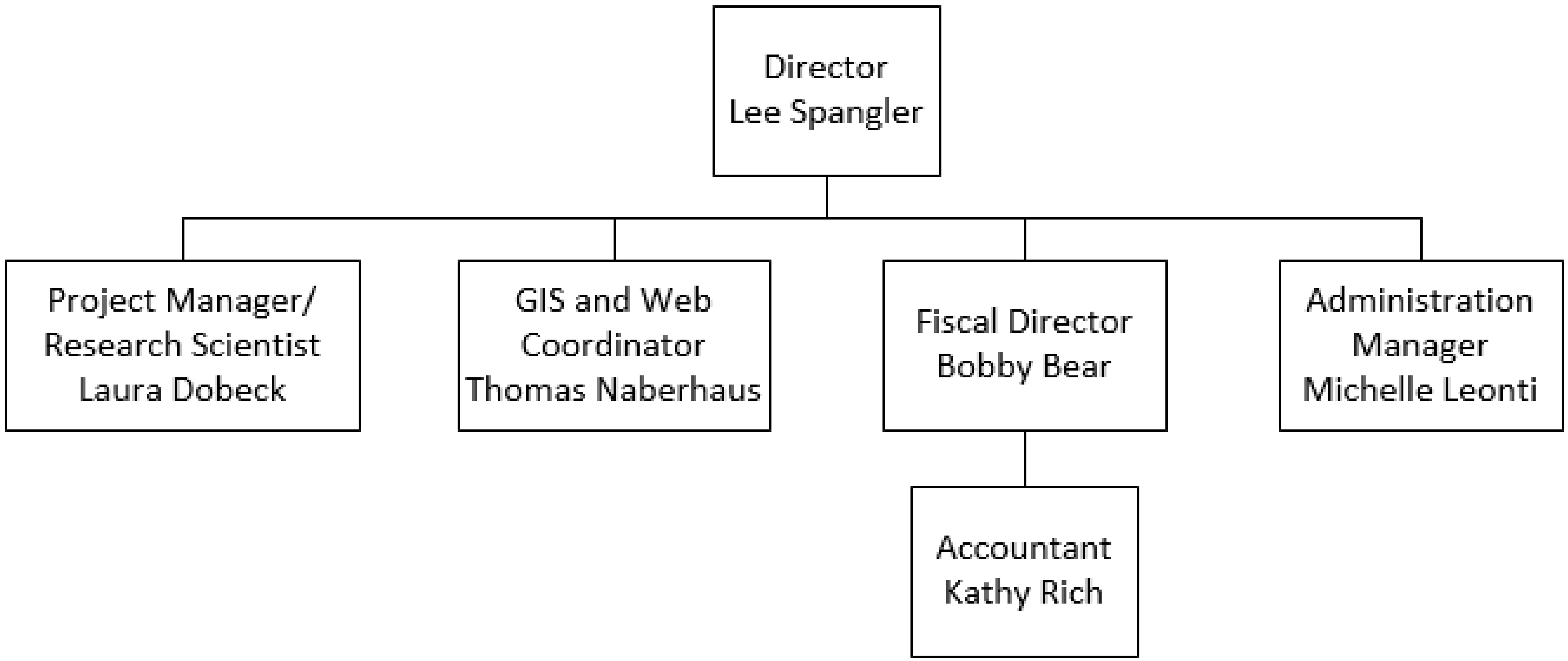
Wednesday

Poster Developing Biomineralization Technology for Ensuring Wellbore Integrity • Adrienne Phillips and Lee Spangler, Montana State University


BSCSP


BSCSP

Organization Chart

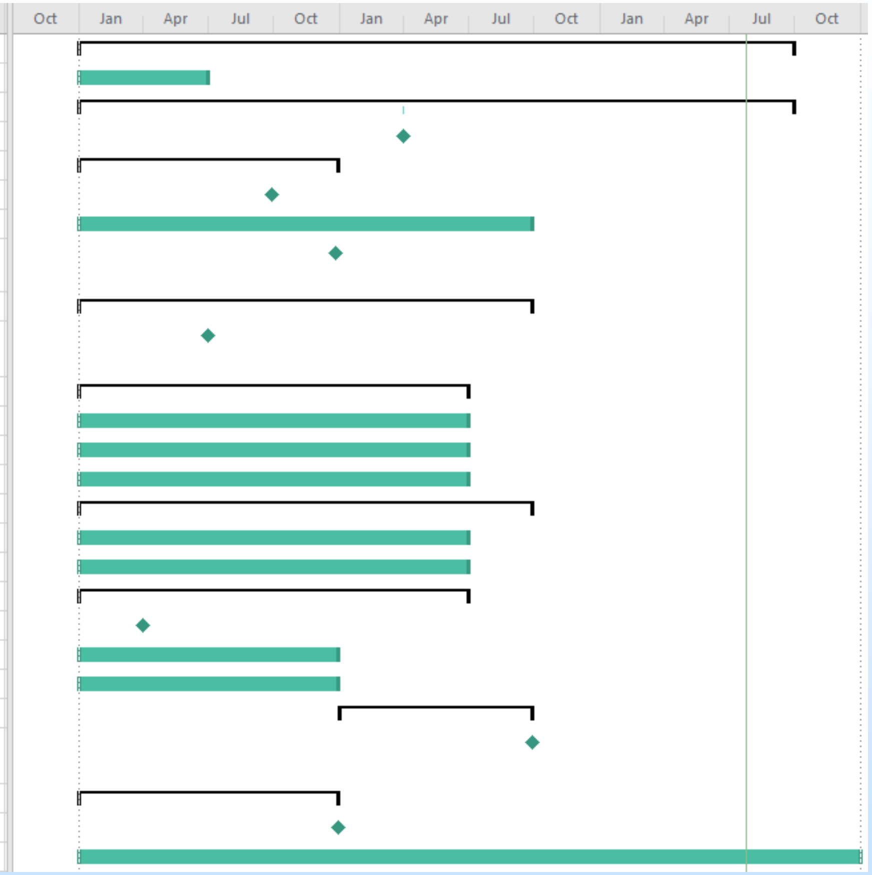


Organization Chart

- **Director** – Lee Spangler
  - **Fiscal Director** – Bobby Bear
    - **Accountant** – Kathy Rich
  - **Administration Manager** – Michelle Leonti
  - **Project Manager/ Research Scientist** – Laura Dobeck
    - **Task R1: Core Research**
      - Laura Dobeck, MSU Lead
      - Bill Carey, LANL
      - Colin Shaw, MSU
      - Dave Bowen, MSU
      - Jonathan Ajo-Franklin, LBNL
    - **Task R2: Seismic Data Interpretation**
      - Lee Spangler, MSU Lead
      - Bryan DeVault, Vecta
      - Lianjie, LANL
      - Dave Bowen, MSU
    - **Task R3: Site Characterization & Modeling**
      - Laura Dobeck, MSU Lead
      - Dave Bowen, MSU
      - Wade Zaluski, SCS
      - Bob Will, SCS
      - Curt Oldenburg, LBNL
      - Quanlin Zhou, LBNL
      - Bill Carey, LANL,
      - Phil Stauffer, LANL
    - **Task R4: Surface Monitoring Data**
      - Laura Dobeck, MSU Lead
    - **Task R5: Regulatory, Risk & Management Analyses**
      - Lee Spangler, MSU Lead
    - **Task R6: GIS Analysis**
      - Laura Dobeck, MSU Lead
    - **Task R7: Site Closure**
      - Laura Dobeck, MSU Lead
      - Jim Kirksey, SCS
    - **Task R8: Outreach and Education**
      - Lee Spangler, MSU Lead
    - **Task R9: Data Management**
      - Thomas Naberhaus, MSU Lead
    - **Task R10: Project Management**
      - Laura Dobeck, MSU Lead

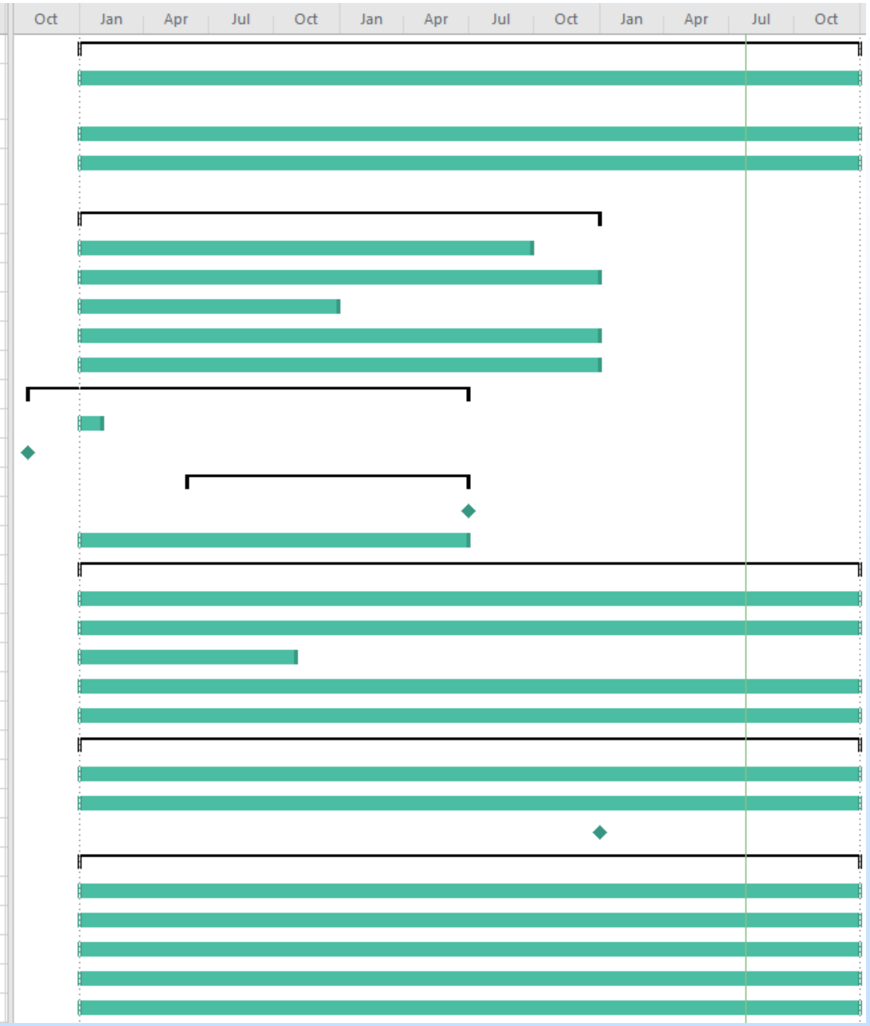
Gantt Chart

Task Name	Start	Finish
Task R1. Core Research	**Mon 1/2/17**	**Mon 9/30/19**
R1.1 Characterization of Duperow fractures	Mon 1/2/17	Fri 6/30/17
R1.2 Laboratory Core Flood Studies	**Mon 1/2/17**	**Mon 9/30/19**
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)	Fri 6/30/17	Fri 6/30/17
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**	**Tue 12/31/19**



Gantt Chart

Task Name	Start	Finish
Task R5. Regulatory, Risk, and Management Analyses	**Mon 1/2/17**	**Tue 12/31/19**
R5.1 Documenting Lessons Learned from BSCSP's Permitting and Regulatory Program	Mon 1/2/17	Tue 12/31/19
R5.2 Documenting Lessons Learned from BSCSP's Risk Management Program	Mon 1/2/17	Tue 12/31/19
R5.3 Documenting Lessons Learned from BSCSP's Management Strategies for Large-Scale Field Activities	Mon 1/2/17	Tue 12/31/19
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
M: Final documentation of the Wallewein well site closure	Thu 10/20/16	Thu 10/20/16
R7.2 Danielson Well	**Thu 6/1/17**	**Fri 6/29/18**
M: Site closure or transer 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
Task R8. Outreach and Education	**Sun 1/1/17**	**Tue 12/31/19**
R8.1 Maintain Website	Mon 1/2/17	Tue 12/31/19
R8.2 Outreach Materials	Mon 1/2/17	Tue 12/31/19
R8.3 Annual Meetings	Sun 1/1/17	Tue 10/31/17
R8.4 National Outreach Working Group	Mon 1/2/17	Tue 12/31/19
R8.5 Collaborative Opportunities and Information Exchange	Mon 1/2/17	Tue 12/31/19
Task R9. Data Management	**Mon 1/2/17**	**Tue 12/31/19**
R9.1 Data Management Electronic Resources	Mon 1/2/17	Tue 12/31/19
R9.2 Management of Geologic Samples	Mon 1/2/17	Tue 12/31/19
M: Complete data preparation for archival	Mon 12/31/18	Mon 12/31/18
Task R10. Project Management	**Mon 1/2/17**	**Tue 12/31/19**
R10.1 Reporting and publications	Mon 1/2/17	Tue 12/31/19
R10.2 Risk Activities	Mon 1/2/17	Tue 12/31/19
R10.3 Energy development opportunities	Mon 1/2/17	Tue 12/31/19
R10.4 Final Project Report and Technical Briefing	Mon 1/2/17	Tue 12/31/19
R10.5 Project and Budget Management	Mon 1/2/17	Tue 12/31/19



Bibliography

Chang, C., Kneafsey, T.J., Zhou, Q., Core-scale flow experiments on three-dimensional fracture-matrix interaction with application to CO2 geological sequestration. 2019 (to be submitted).

Oldenburg, C.M., Pan L., Zhou, Q., Fairweather, S. and Spangler L.H., On Producing CO2 from Subsurface Reservoirs: Simulations of Decompression Cooling and Phase Change, Greenhouse Gases: Science and Technology, 2019 submitted.

Mangini, S., Shaw, C.A., Skidmore, M., in preparation. Evaluation of the Jefferson Formation outcrop in Sun River Canyon, Montana as an analog for Devonian carbonates in the subsurface of the Kevin Dome. Rocky Mountain Geology 2019 (to be submitted).

Shaw, C.A., Omosebi, O., Experimental study of the effects of supercritical carbon dioxide injection on the three-dimensional pore structure of carbonate and evaporite rocks. 2019 (in preparation).

Bibliography

Omosebi, O., Shaw, C., *Thrane, L., Codd, S.L., in preparation. Experimental study of the reactivity of carbonate and evaporite rocks under geological carbon storage conditions. Environmental Science and Technology 2019 (to be submitted).

Mangini, S., Skidmore, M., Shaw, C.A., in preparation. Investigation of the reactions of CO2 with iron oxides and sulfides under simulated geologic carbon sequestration conditions. G3 – Geochemistry, Geophysics, Geosystems 2019 (to be submitted).

Mangini, S., Shaw, C.A., Skidmore, M., in preparation. Evaluation of the Jefferson Formation outcrop in Sun River Canyon, Montana as an analog for Devonian carbonates in the subsurface of the Kevin Dome. Rocky Mountain Geology 2019 (to be submitted).

Shaw, C.A., Omosebi, O., Experimental study of the effects of supercritical carbon dioxide injection on the three-dimensional pore structure of carbonate and evaporite rocks. 2019 (in preparation).

Bibliography

Gao, K. and Huang, L., Full-waveform inversion with a total generalized p-variation regularization scheme for sparse seismic data, submitted to Geophysical Journal International. 2018 under review.

Gao, K. and Huang, L., An efficient vector elastic reverse-time migration in the hybrid time and frequency domain for anisotropic media, submitted to Geophysics. 2018 under review.

Zhou, Q., C.M. Oldenburg, and J.T. Birkholzer. Modeling CO2 storage in fractured reservoirs: 1. Buoyancy-driven invasion of supercritical CO2 with matrix capillary continuity, Water Resources Research 2018 (to be submitted).

Oldenburg, C.M., L. Pan, Q. Zhou, L. Dobeck, and L. Spangler. On producing CO2 from subsurface reservoirs: Simulations of decompression cooling and phase change, Greenhouse Gases: Science and Technology 2018 (submitted).

Bibliography

Carey, J. W., Frash, L. P., and Ickes, T. (2018). Experimental investigation of shear fracture development and fluid flow in dolomite. In 52nd US Rock Mechanics / Geomechanics Symposium, Seattle, Washington, USA, June 17-20, 2018, page 6.

Frash, L. P., Carey, J. W., and Ickes, T. (2018). Fracturing, fluid flowing, and x-ray imaging through anhydrite at stressed conditions. In 52nd US Rock Mechanics / Geomechanics Symposium, Seattle, Washington, USA, June 17-20, 2018, page 7.

Omosebi, O., Shaw, C., *Thrane, L., Spangler, L., Characterization of different depositional facies of rocks from the Kevin Dome for carbon sequestration. Social Science Research Network, Greenhouse Gas Control Technologies 14, Special Issue, 2018 (in press).

Bibliography

DeVault, B., Bowen, D.W., Clochard, V., Delepine, N. and Wangkawong, K., Quadri-Joint inversion: Method and application to the Big Sky 9C 3D dataset in Northern Montana. Journal Interpretation, 2018. In Press.

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. 81, 44-65.

Bibliography

McCann, C., Repasky, K.S., Morin, M., Lawrence, R.L. and Powell, S.L., Using Landsat surface reflectance (LaSRC) data as a reference target for multi-swath hyperspectral data collected over mixed agricultural rangeland areas. IEEE Transactions in Remote Sensing, 2017. 55(9): p. 5002-5014 10.1109/TGRS.2017.2699618.

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.

Bibliography

Saltiel, S., Selvadurai, P.A., Bonner, B.P., Glaser, S.D. and Ajo-Franklin, J.B., Experimental development of low-frequency shear modulus and attenuation measurements in mated rock fractures: shear mechanics due to asperity contact area changes with normal stress. Geophysics, 2017. 82(2): p. M19-M36 DOI: 10.1190/GEO2016-0199.1

Spangler, L.H., Repasky, K.S., Morin, M., Lawrence, R.L. and Powell, S.L., A novel histogram based unsupervised classification technique to determine natural classes from biophysically relevant fit parameters to hyperspectral data. IEEE Transactions in Remote Sensing, 2017. 10(9): p. 4138-1148 10.1109/JSTARS.2017.2701360.

Zhoua, Q., Oldenburg, C.M., Rutqvist, J. and Birkholer, J.T., Revisiting the fundamental analytical solutions of heat and mass transfer: The kernel of multirate and multidimensional diffusion. Water Resources Research, 2017. 53(11): p. 9960-9979 DOI: 10.1002/2017WR021040.

Bibliography

Oldenburg, C.M., Cihan, A., Zhoua, Q., Fairweather, S. and Spangler, L., Geologic carbon sequestration injection wells in overpressured storage reservoirs: estimating area of review. Greenhouse Gas Science and Technology, 2016. 2016(00): p. 1-12 DOI: 10.1002/ghg.1607.

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.

Zdhanov, M., Endo, M., Black, N., Spangler, L., Fairweather, S., Hibbs, A., Eiskamp, G.A. and Will, R., Electromagnetic monitoring of CO2 sequestration in deep reservoirs. First Break - Special Topic: Unconventionals & Carbon Capture and Storage, 2016. 31: p. 71-78.

Bibliography

Zhoua, Q., Oldenburg, C.M., Spangler, L. and Birkholer, J.T., Approximate solutions for diffusive fracture-matrix transfer: Application to storage of dissolved CO2 in fractured rocks. Water Resources Research, 2016. 53(2): p. 1746–1762 DOI: 10.1002/2016WR019868.

Poggio, M., Brown, D.J. and Bricklemyer, R.S., Laboratory-based evaluation of optical performance for a new soil penetrometer visible and near-infrared (VisNIR) foreoptic. Computers and Electronics in Agriculture, 2015. 2015(115): p. 12-20 DOI: 10.1016/j.compag.2015.05.002.

Bellante, G.J., Powell, S.L., Lawrence, R. and Repasky, K.S., Hyperspectral Detection of a Subsurface CO2 Leak in the Presence of Water Stressed Vegetation. PLOS ONE, 2014. 9(10) DOI: 10.1371/journal.pone.0108299.

Bibliography

Dai, Z., Stauffer, P.H., Carey, J.W., Middleton, R.S., Lu, Z., Jacobs, J.F., Hnottavange-Telleen, K. and Spangler, L.H., Pre-site Characterization Risk Analysis for Commercial-Scale Carbon Sequestration. Environmental Science & Technology, 2014. 2014(48): p. 3908-3915 DOI: dx.doi.org/10.1021/es405468p.

Long, J.A., Lawrence, R.L., Marshall, L. and Miller, P.R., Changes in field-level cropping sequences: Indicators of shifting agricultural practices. Agriculture, Ecosystems and Environment, 2014. 189(2014): p. 11-20 DOI: 10.1016/j.agee.2014.03.015.

Tan, S. and Huang, L., Reducing the computer memory requirement for 3D reverse-time migration with a boundary-wavefield extrapolation method. Geophysics, 2014. 79(5): p. 185-194 DOI: 10.1190/GEO2014-0075.1.

Bibliography

Bricklemyer, R.S., Brown, D.J., Turk, P.J. and Clegg, S.M., Improved Intact Soil-Core Carbon Determination Applying Regression Shrinkage and Variable Selection Techniques to Complete Spectrum Laser-Induced Breakdown Spectroscopy (LIBS). Applied Spectroscopy, 2013. 67(10): p. 1185-1199 DOI: 10.1366/12-06983.

Lewicki, J.L., Hilley, G.E., Dobeck, L.M., McLing, T., Kennedy, B.M., Bill, M. and Marino, B.D.V., Geologic CO2 input into groundwater and the atmosphere, Soda Springs, ID, USA. Chemical Geology, 2013. 339(SI): p. 61-70 DOI: doi:10.1016/j.chemgeo.2012.06.013.

Bibliography

Long, J.A., Lawrence, R.L., Greenwood, M.C., Marshall, L. and Miller, P.R., Object-oriented crop classification using multitemporal ETM+ SLC-off imagery and random forest. GIScience & Remote Sensing. GIScience & Remote Sensing, 2013. 50(4): p. 418-436 DOI: 10.1080/15481603.2013.817150.

Vogt, S.J., Shaw, C.A., Brox, T., Maneval, J.E., Skidmore, M.L., Codd, S.L. and Seymour, J.D., Magnetic Resonance Imaging of permeability enhancement in fast-flow-paths during supercritical CO2 injection in sandstone and carbonate rock cores. Journal of Petroleum Science and Engineering, 2013. 122(October 2014): p. 507-514 DOI: 10.1016/j.petrol.2014.08.013.

Bibliography

Borgia, A., Pruess, K., Kneafsey, T.J., Oldenburg, C.M. and Pan, L., Numerical simulation of salt precipitation in the fractures of a CO2-enhanced geothermal system. Geothermics, 2012. 44(October 2012): p. 13-22 DOI: http://dx.doi.org/10.1016/j.geothermics.2012.06.002.

Bricklemyer, R.S., Soil carbon determination using rapid, inexpensive, non-destructive spectroscopy techniques, in Washington State University, Deparptment of Crop and Soil Sciences. Ph.D. 2012. p. 176.

Bricklemyer, R.S., Brown, D.J., Barefield, J.D. and Clegg, S.M., Intact Soil Core Total, Inorganic, and Organic Carbon Measurement Using Laser-Induced Breakdown Spectroscopy. Soil Science Society of America Journal, 2011. 75(3): p. 1006-1018 DOI: 10.2136/sssaj2009.0244.

Bibliography

Leach, A., Mason, C.F. and van 't Veld, K., Co-optimization of enhanced oil recovery and carbon sequestration. Resource and Energy Economics, 2011. 33(4): p. 893-912 DOI: 10.1016/j.reseneeco.2010.11.002.

Watts, J.D., Lawrence, R.L., Miller, P.R. and Montagne, C., An analysis of cropland carbon sequestration estimates for North Central Montana. Climate Change, 2011. 108(1-2): p. 301-331 DOI: 10.1007/s10584-010-0009-1.

Watts, J.D., Powell, S.L., Lawrence, R.L. and Hilker, T., Improved classification of conservation tillage adoption using high temporal and synthetic satellite imagery. Remote Sensing of Environment, 2011. 115(1): p. 66-75 DOI: 10.1016/j.rse.2010.08.005.