Big Sky Regional Carbon Sequestration Partnership – Kevin Dome Carbon Storage

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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

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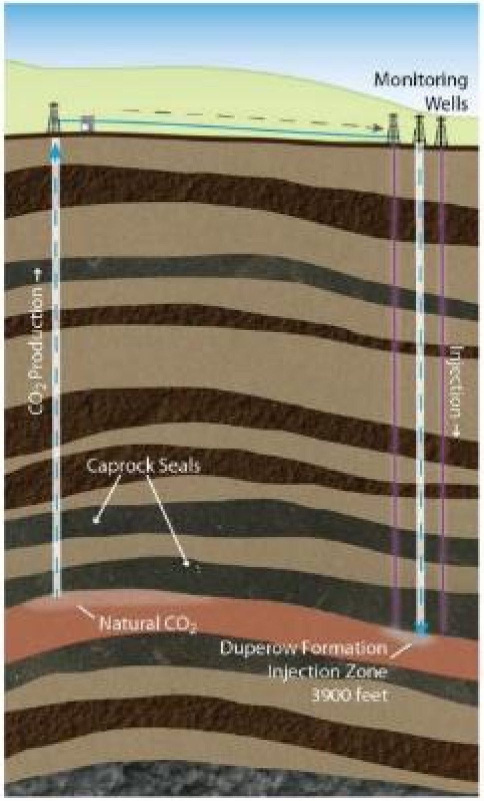
Acknowledgments

- 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

Presentation Outline

- Project Overview
  - Geology of Kevin Dome / Regional Significance
- Site Characterization – Existing Data
- Well Data – Logs and Core
- Serismic
- Modeling
- Results to Date and Accomplishments
- Summary

Site Characteristics – Scientific Opportunities



Natural CO_2 production

- Opportunity to study the natural accumulation and long term effects

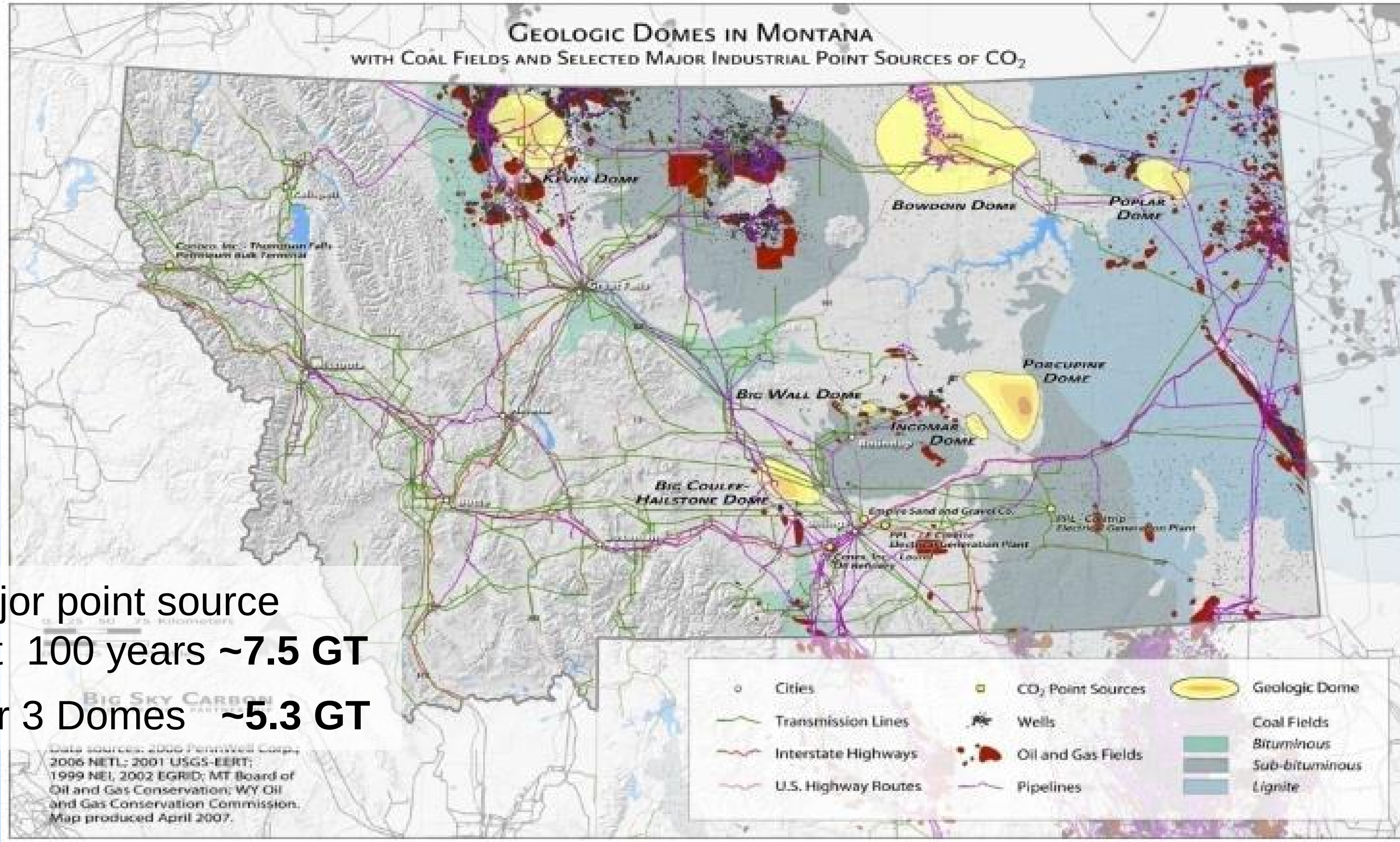
CO_2 in a reactive rock

- 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
- Potential use as carbon warehouse – decouple anthropogenic CO_2 rate from utilization rate

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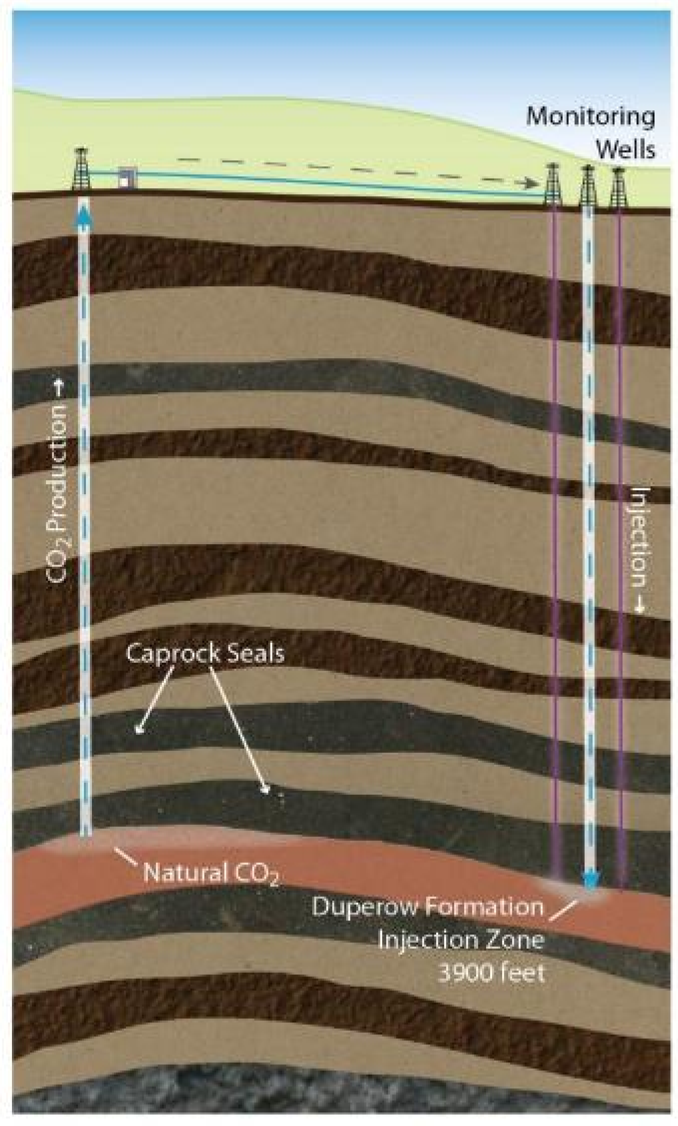
Project Overview

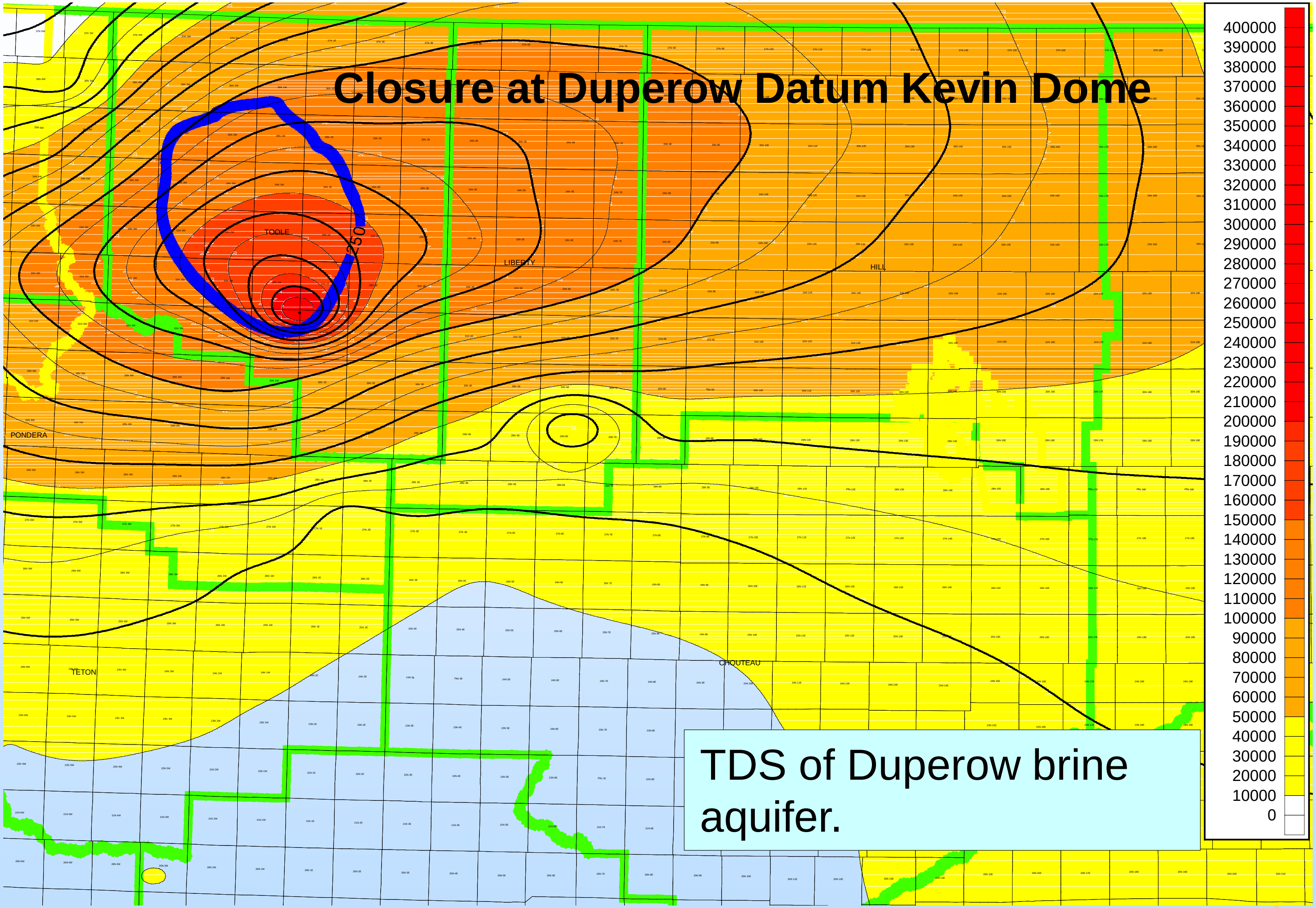
Original Plan

- Permitting & Public Outreach
- Site Characterization
- Infrastructure Development
  - Characterization wells
  - 1 Injection Well
  - Monitoring Wells, Pipelines Compressor
- Injection Operations
  - 4 years
- Monitoring & Modeling
- Site Closure



After extensive efforts by BSCSP, this objective proved to be unachievable for two reasons: (1) although the natural CO_2 was present as expected, BSCSP was unable to produce the CO_2 in large quantities; and (2) the total dissolved solids (TDS) of the brine in the targeted injection formation (Duperow) is less than 10,000 ppm

Regional Water Quality Data



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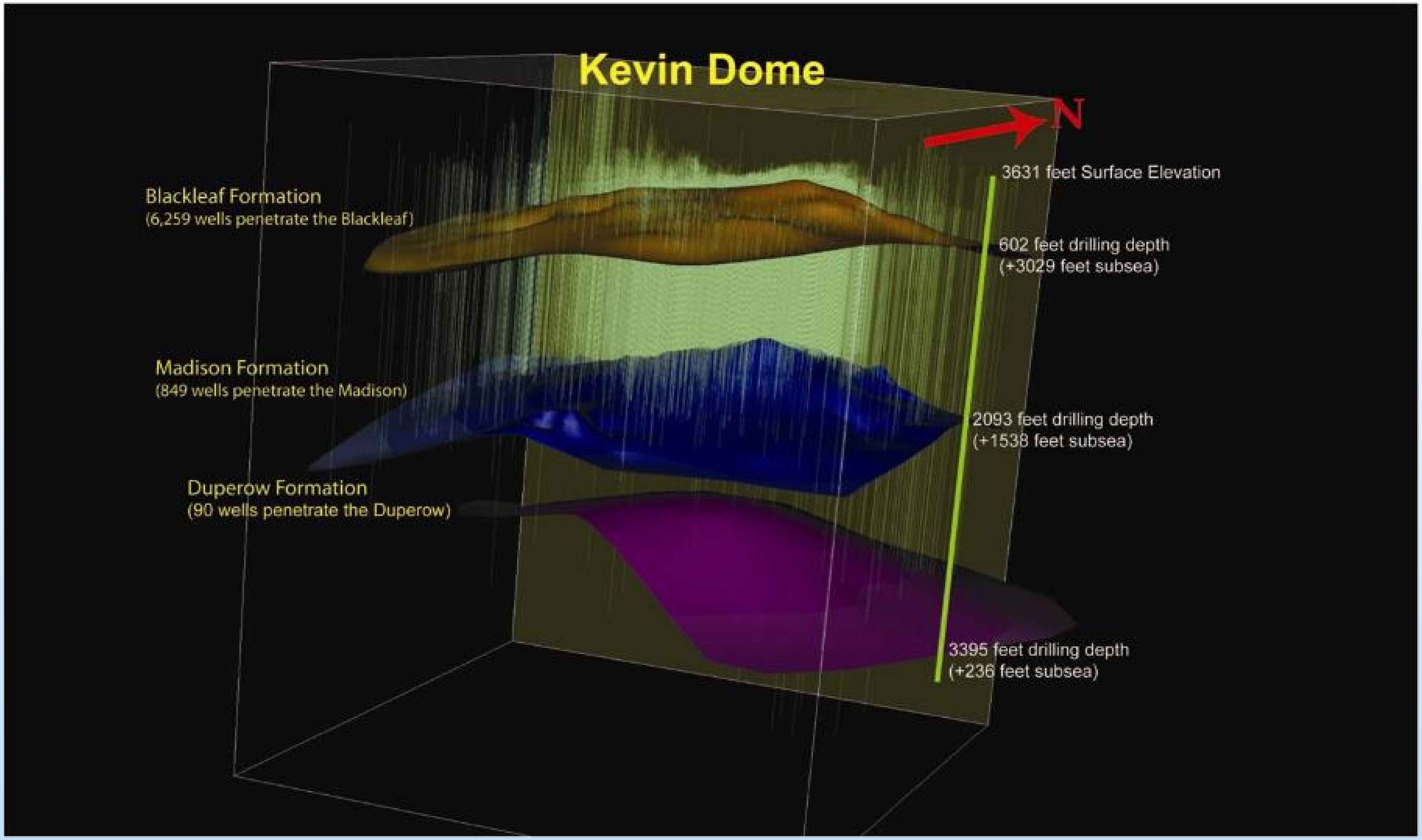
Project Re-Scope

Project Re-scope: Maximize Learnings from Samples and Data

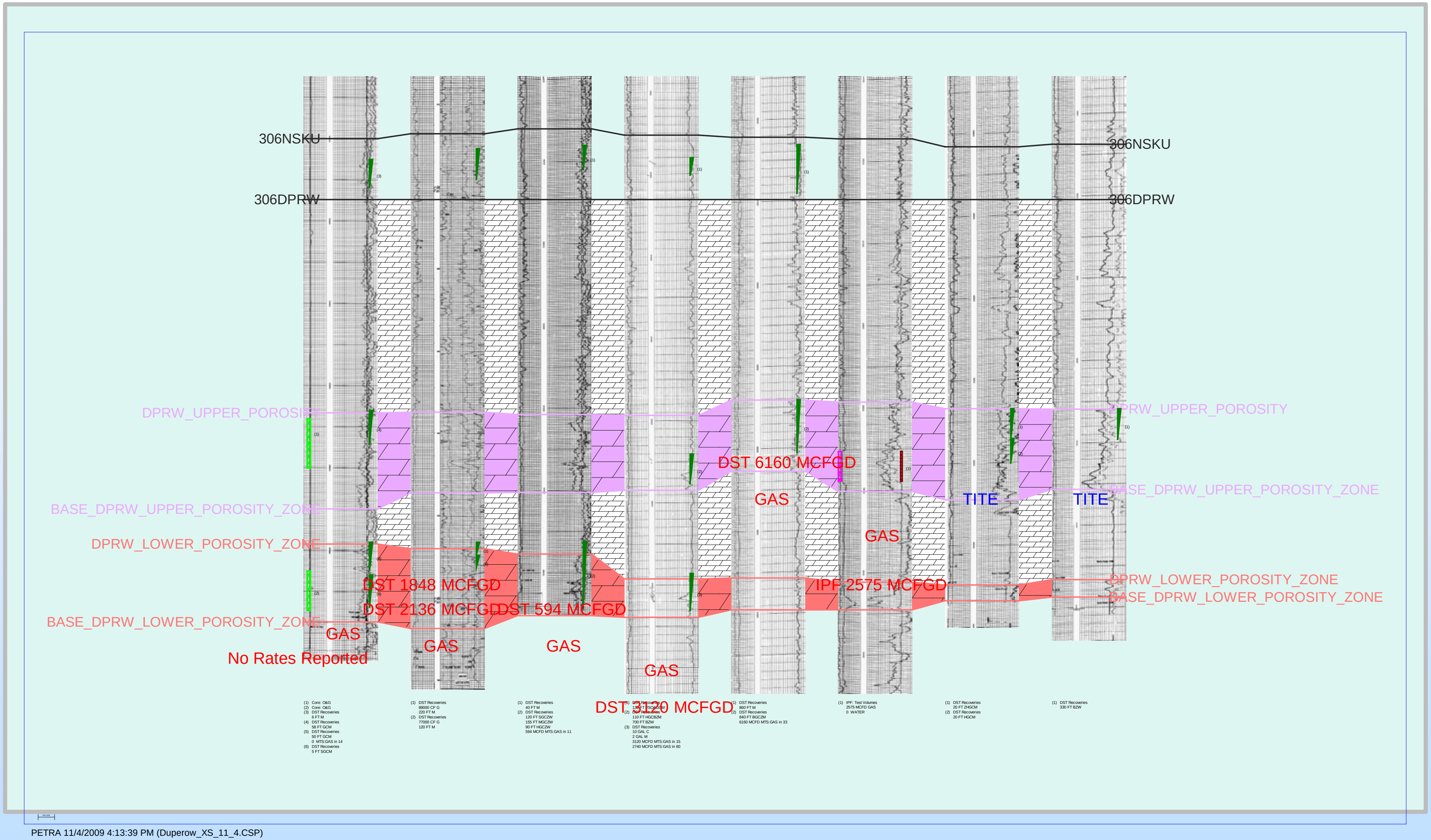
Continued…

- 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.

Kevin Structure Tops & Well Penetrations



NW - SE Cross Section Kevin Dome



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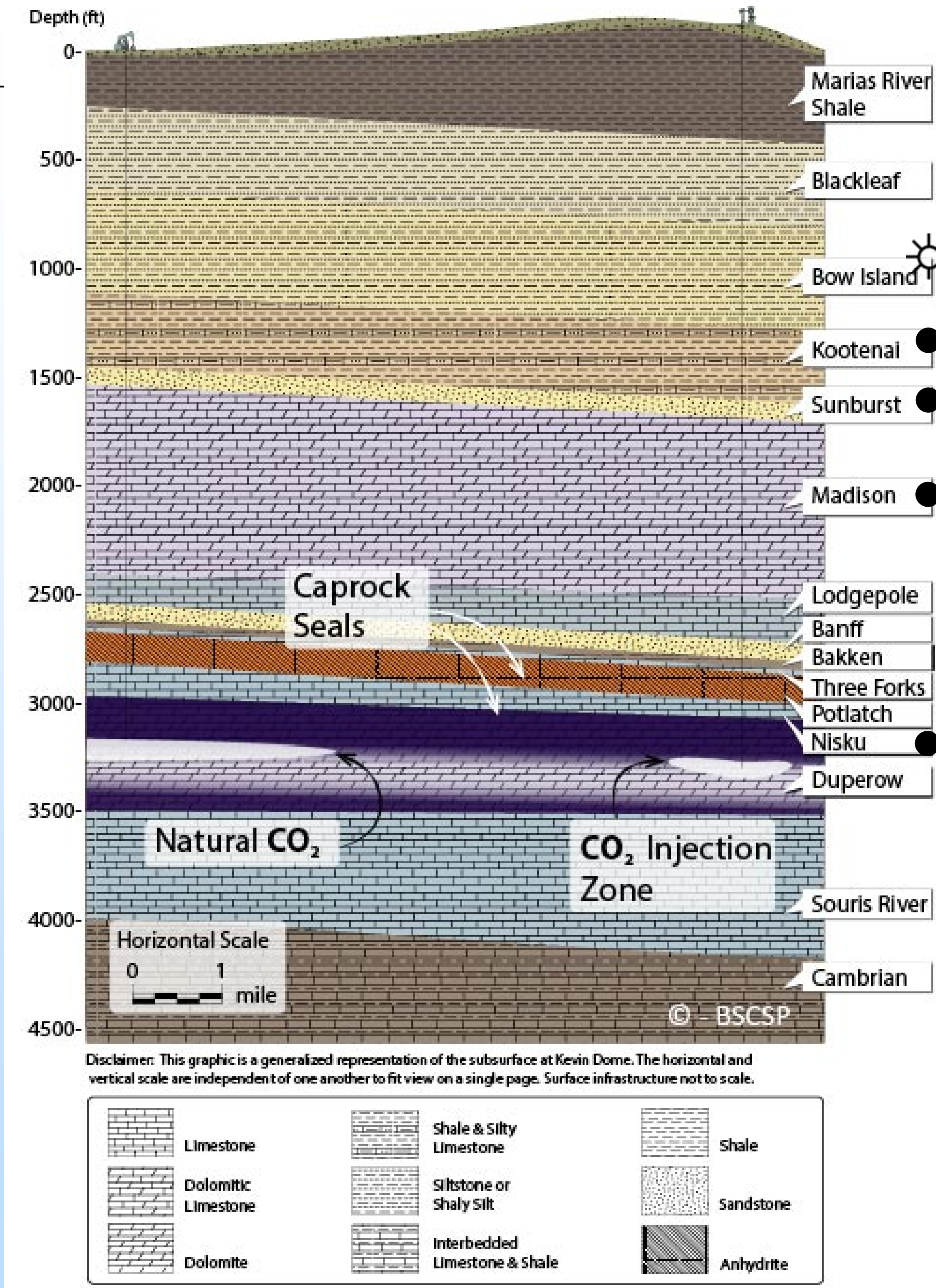
Kevin Dome

CO_2 in middle Duperow

Two “gold standard” seals

- Upper Duperow ~200’ tight carbonates and interbedded anhydites
- Caprock~ 150’ Anhydrite

Multiple tertiary seals



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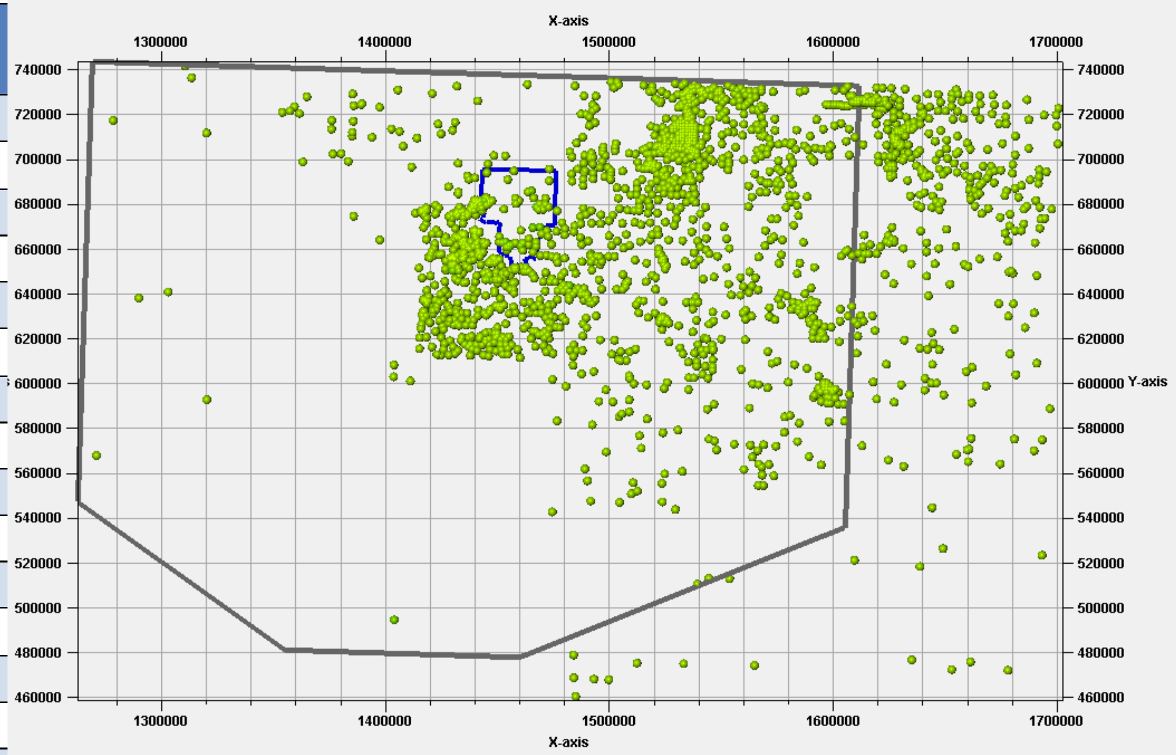
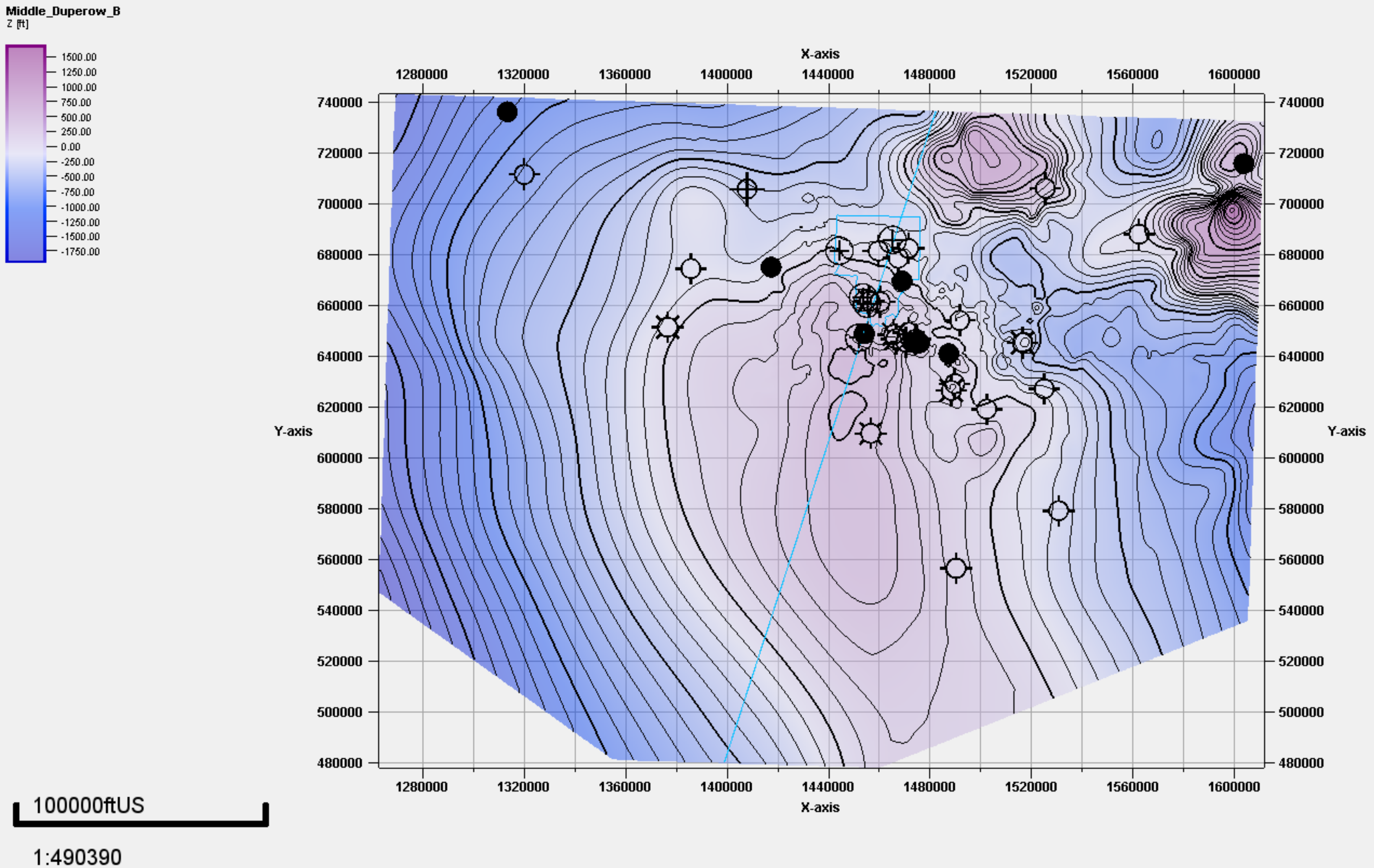
Existing Well Tops Used for Stratigraphy

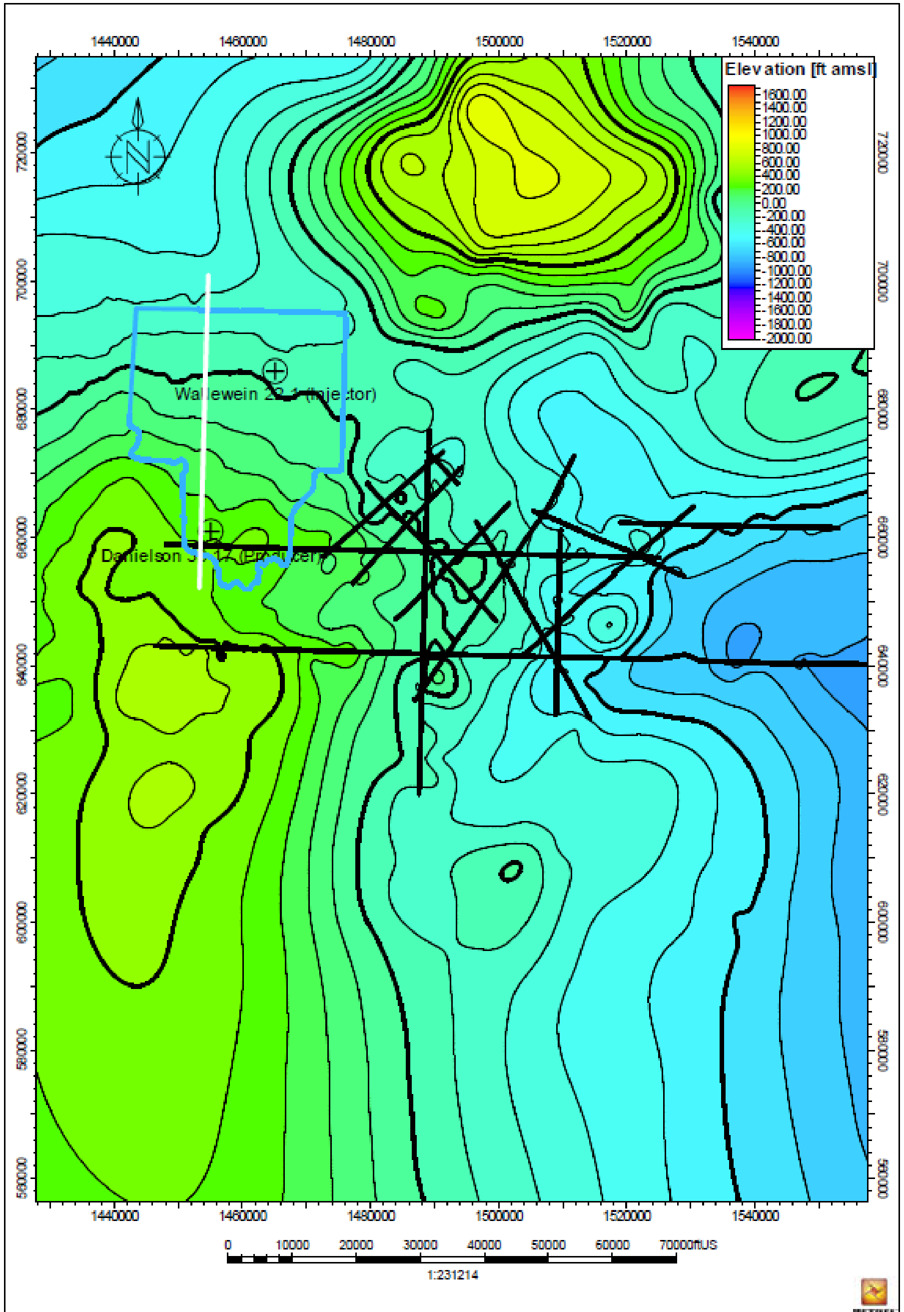
Formation (Zone)	Number of Well Tops
Blackleaf	952
Bow_Island	1,264
Kootenai	1,398
Sunburst	1,526
Morrison_Fm	1,639
Swift	1,612
Rierdon	1,625
Sawtooth	1,330
Madison	647
Banff_Fm_Lodgepole	105
Bakken	108
Three_Forks	110
Potlatch	110
Nisku	110
Upper_Duperow	105
Middle_Duperow	47
Middle_Duperow_B	12
Intermediate_Duperow	39
Lower_Duperow	36
Souris_River	26
Cambrian	14
Precambrian	8



19 Existing Logs Digitized - Petrophysics

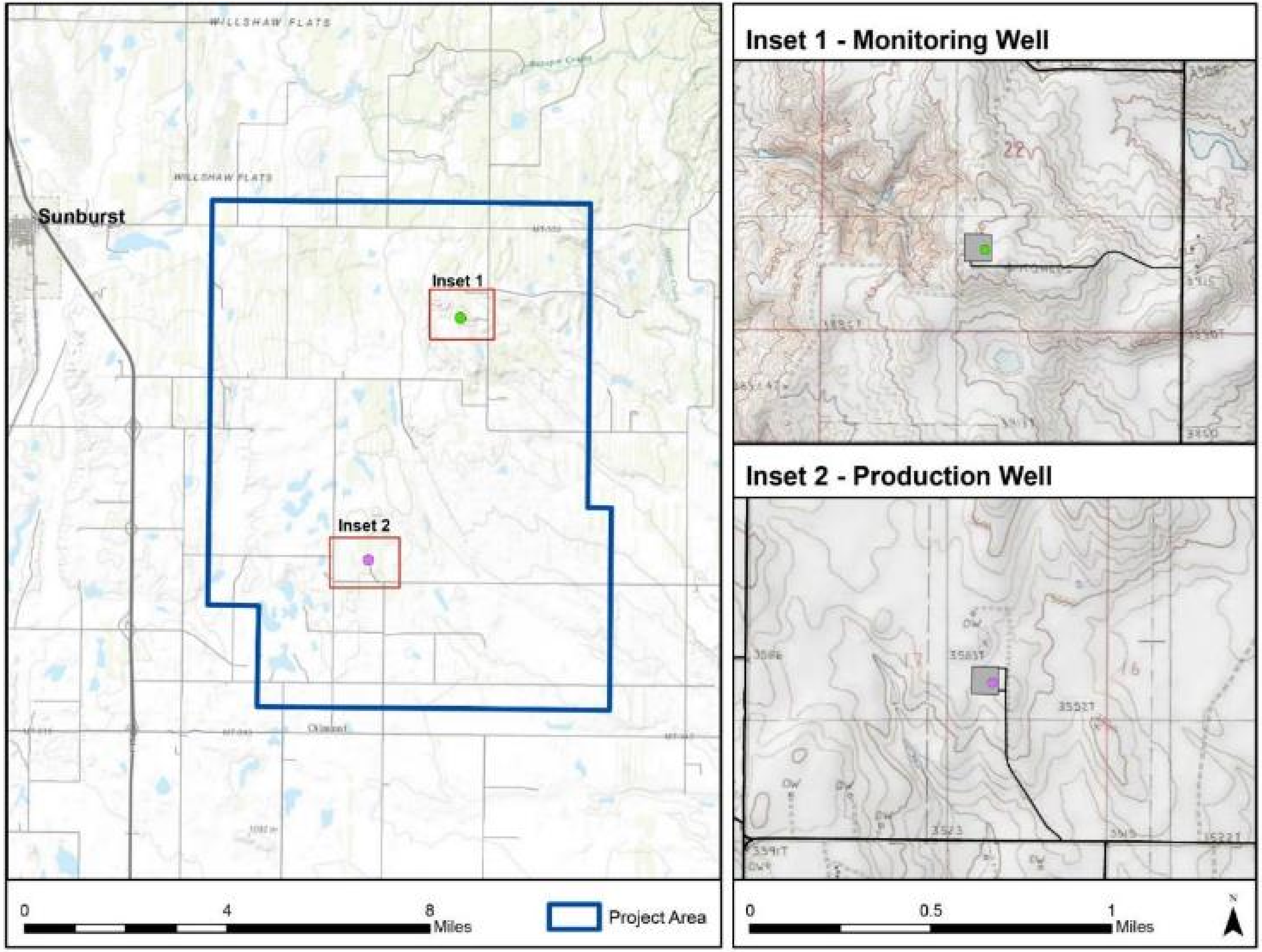


Use Existing Seismic Lines

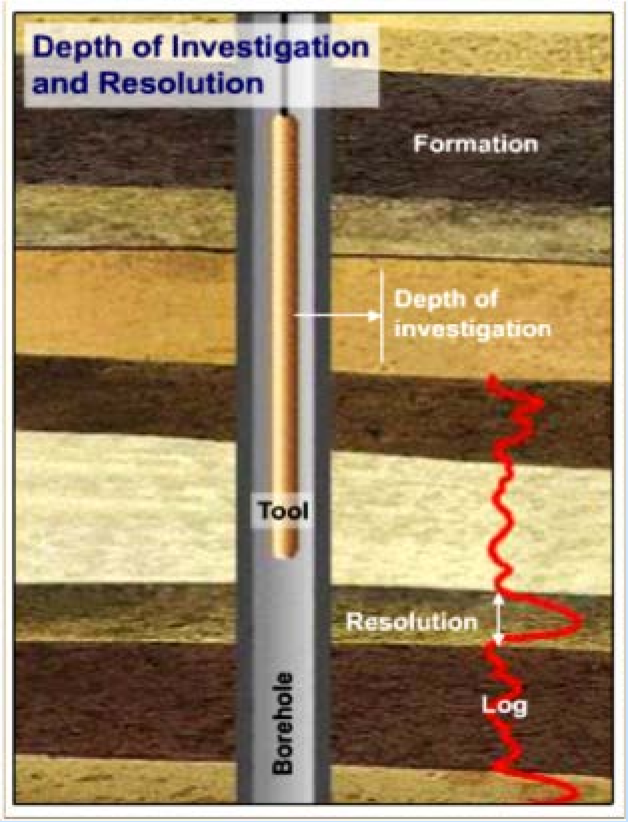


Well Drilling, Log and Core Data

Well Locations

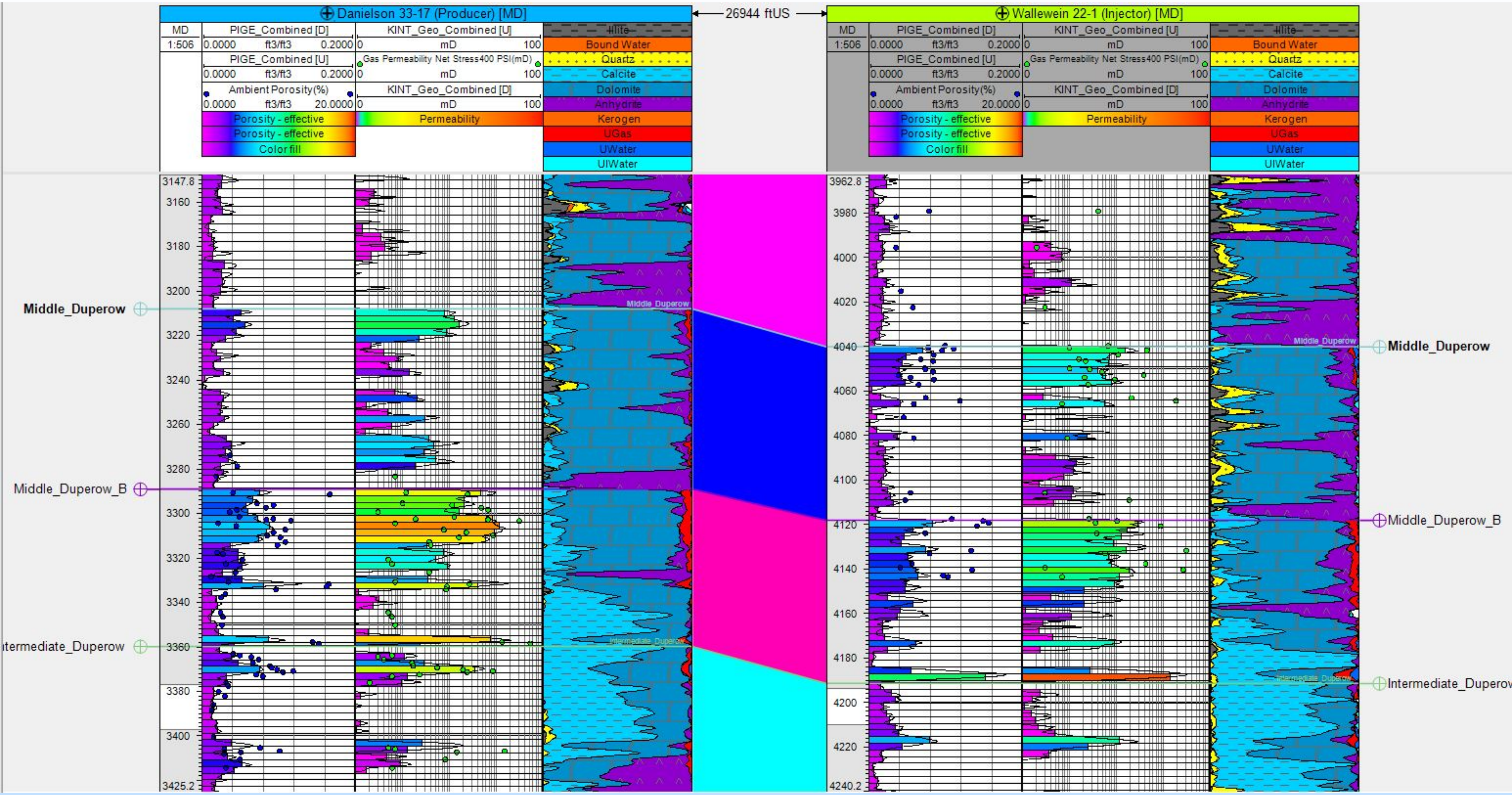


Geophysical Characterization & Monitoring: Well Logging



Logs	Wells	
	1st Prod	Inj
Downhole P & T	Cont.	Cont.
Gamma Ray	Initial	Initial
Resistivity	Initial	Initial
Porosity	Initial	Initial
Density	Initial	Initial
Caliper	Initial	Initial
P&S Sonic	Initial	Initial
Sonic Scanner	Initial	Initial
Isolation Scan	Initial	Initial
FMI	Initial	Initial
NMR	Initial	Initial
Natural Gamma	Initial	Initial
Elemental Spec	Initial	Initial
Cement Eval	Initial	Initial
Pulsed Neutron	Initial	Annual

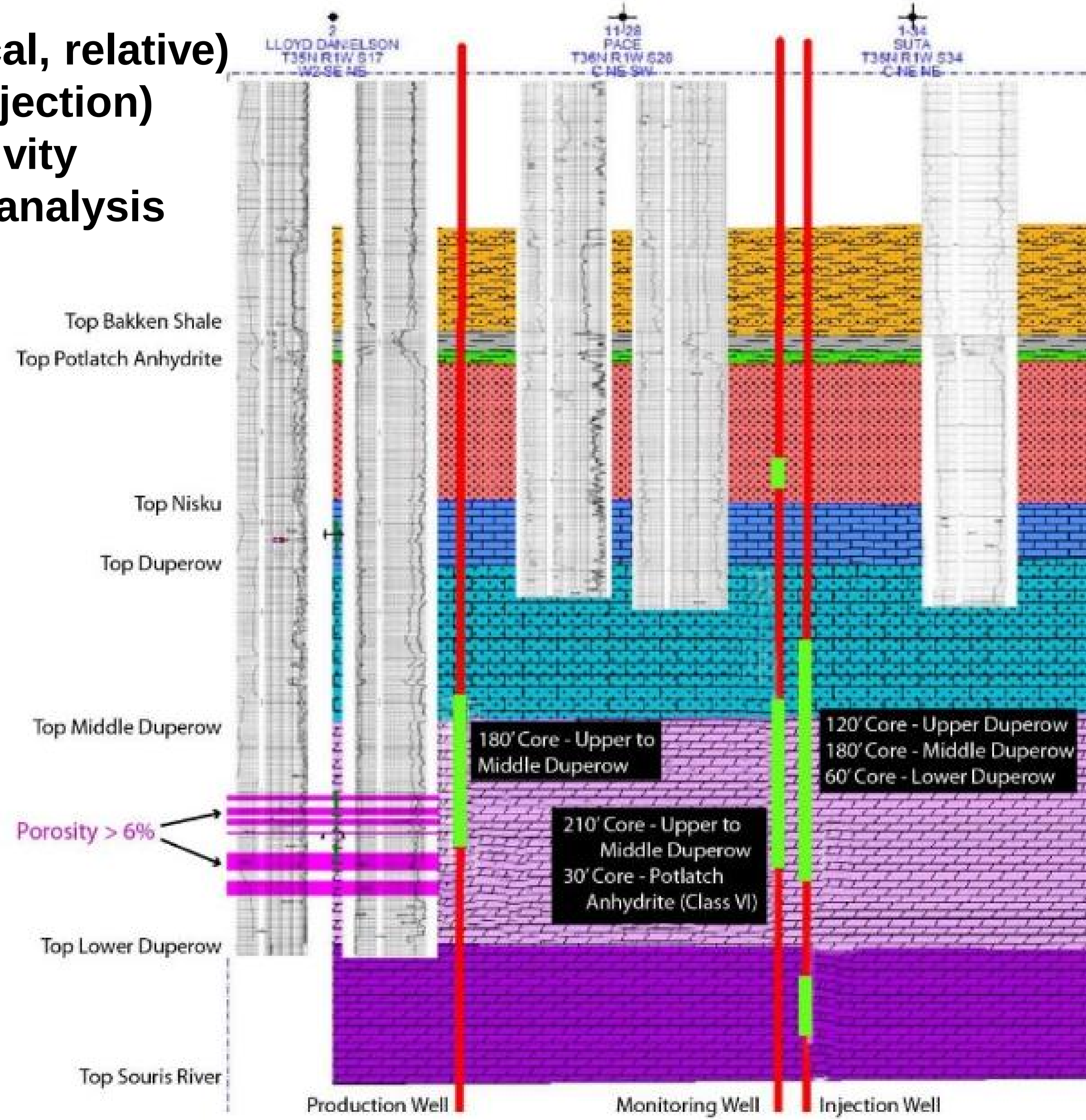
Site Characterization: ELAN Analysis and Well Correlation



Excellent correlation for wells 12.8 km apart

Core Plan – Intervals and Analyses

Porosity
Permeability (horizontal, vertical, relative)
Capillary pressure (mercury injection)
Core flood, geochemical reactivity
Seismic properties, anisotropy analysis
Tight rock analysis)
Petrology/Petrography
Bulk XRD
Powder XRD
NMR calibration
SEM/EDS
Micro-CT imaging
Ductility and rock strength
Bulk composition XRF
BET surface area
Core spectral gamma ray
Whole rock analysis, REE
XrF, ERD
Thin section analysis
Carbon isotopes



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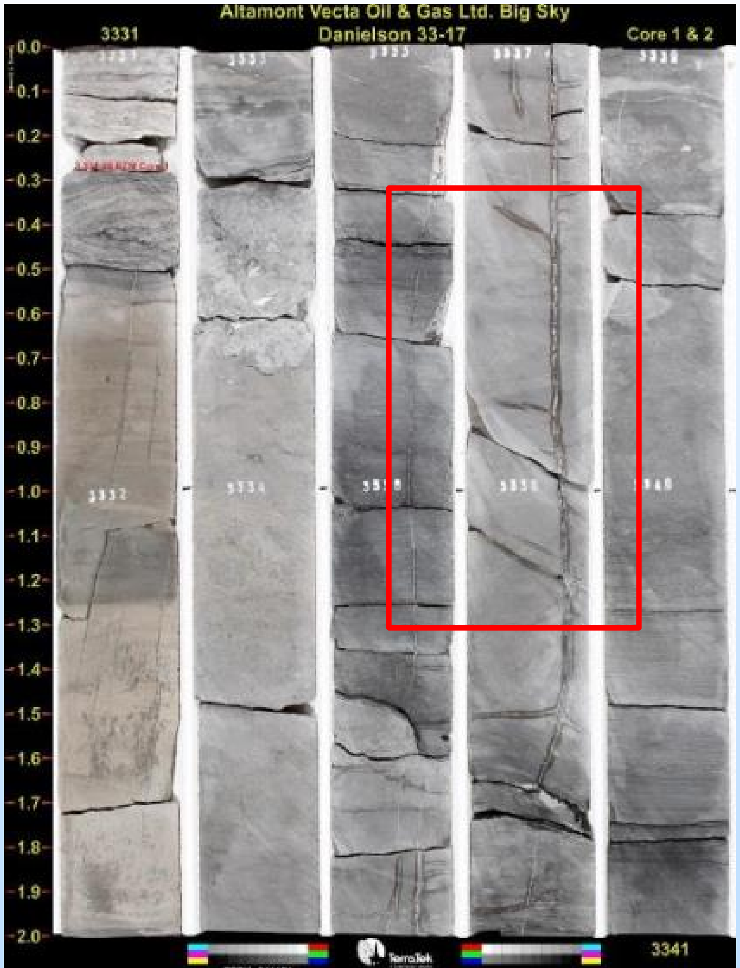
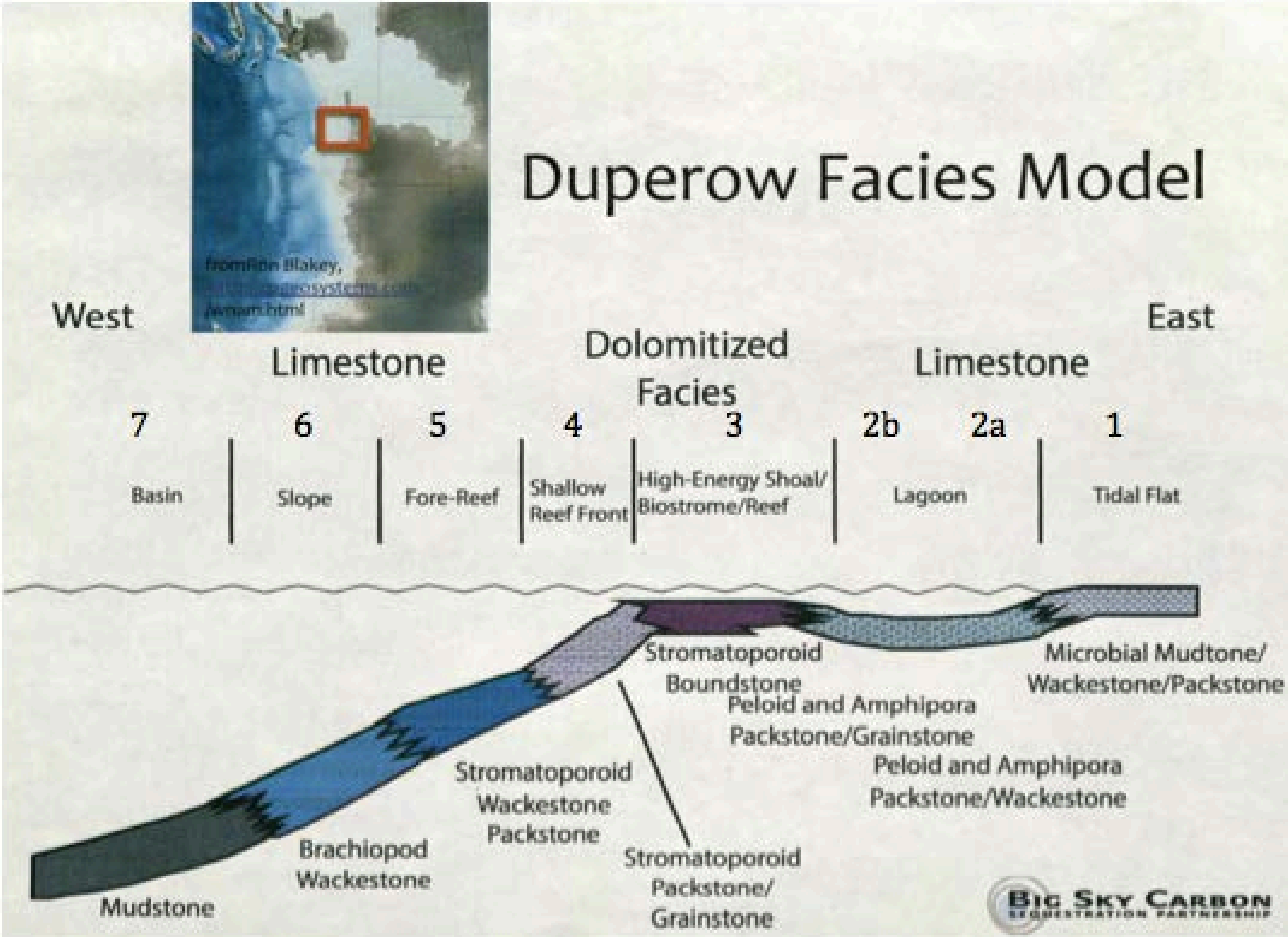
Middle Duperow – Fractures

Site Characterization: Core Fracture Analysis

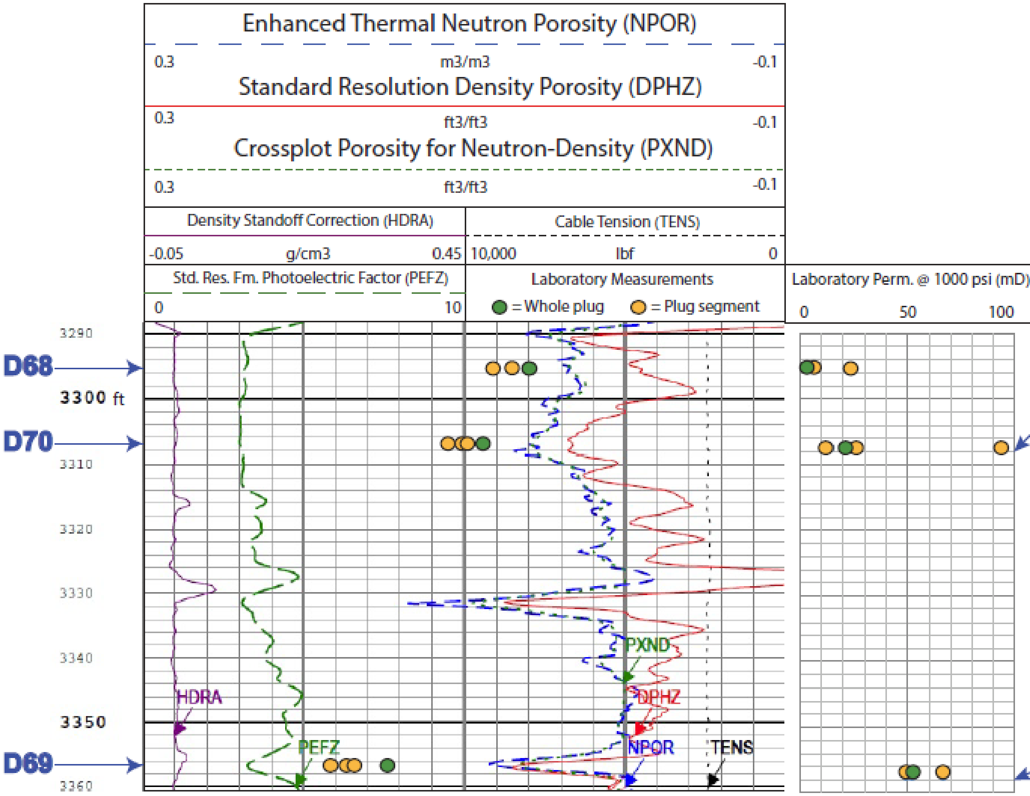


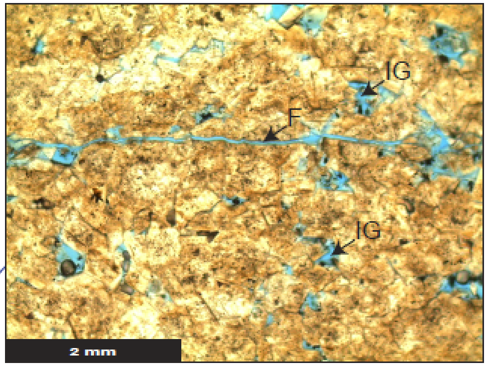
Complicated Depositional Environment in the Duperow



Heterogeneity and Porosity Characteristics of the Middle Duperow

Porosity ***Permeability*** ***Pore Type***





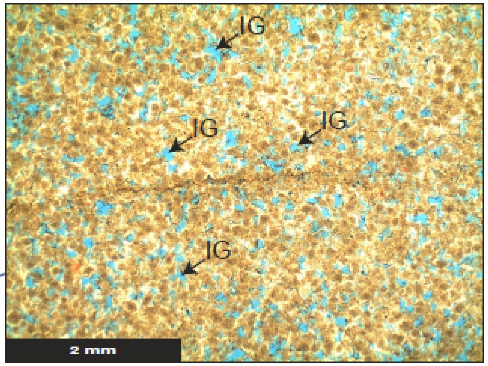
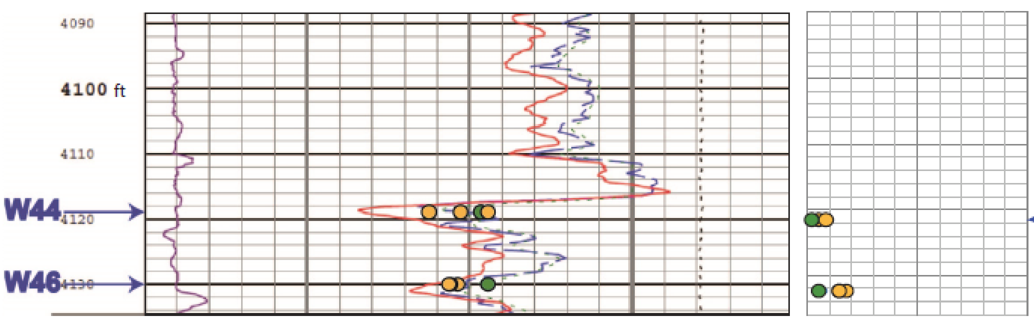
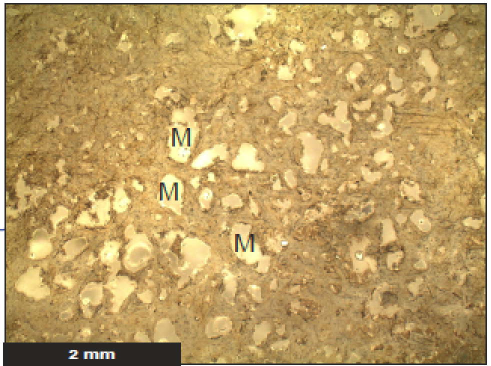


Figure b: Wallawein 22-1

M=moldic, IG= intergranular, F= fracture





Core Analyses

Table 1: Powder XRD whole rock mineralogy for MSU core plugs and analogue outcrop test samples (semi-quantitative weight %)

*No clays appear to be present after following USGS XRD sample preparation protocol in open-file report 01-041
PDF #'s listed for MDI Jade 9.0 Database

Sample ID	Plug ID	Well	Depth (ft.)	Dolomite	PDF	Calcite	PDF	Anhydrite	PDF	Gypsum	PDF	Quartz	PDF
24243_3296_40_A	68	Danielson 33-17	3296.4	93.4	97-008-7088	0	n/a	3.5	98-000-0090	3.1	98-000-0234	0	n/a
24243_3358_25_A	69	Danielson 33-17	3358.25	92.5	97-017-1513	5.6	97-004-0106	0	n/a	0	n/a	1.9	97-006-7124
24243_3308_40_A	70	Danielson 33-17	3308.4	98.1	97-017-1512	0	n/a	0	n/a	0	n/a	1.9	97-006-7124
24242_4120_50_A	44	Wallewein 22-1	4120.5	92.2	97-018-5046	0.7	97-004-0548	0.7	97-001-5876	6.4	97-015-1692	0	n/a
24242_4131_40_A	46	Wallewein 22-1	4131.4	98.6	97-003-1210	0	n/a	0	n/a	0	n/a	1.4	97-064-7410

Table 2: Porosity and permeability for MSU whole core plugs

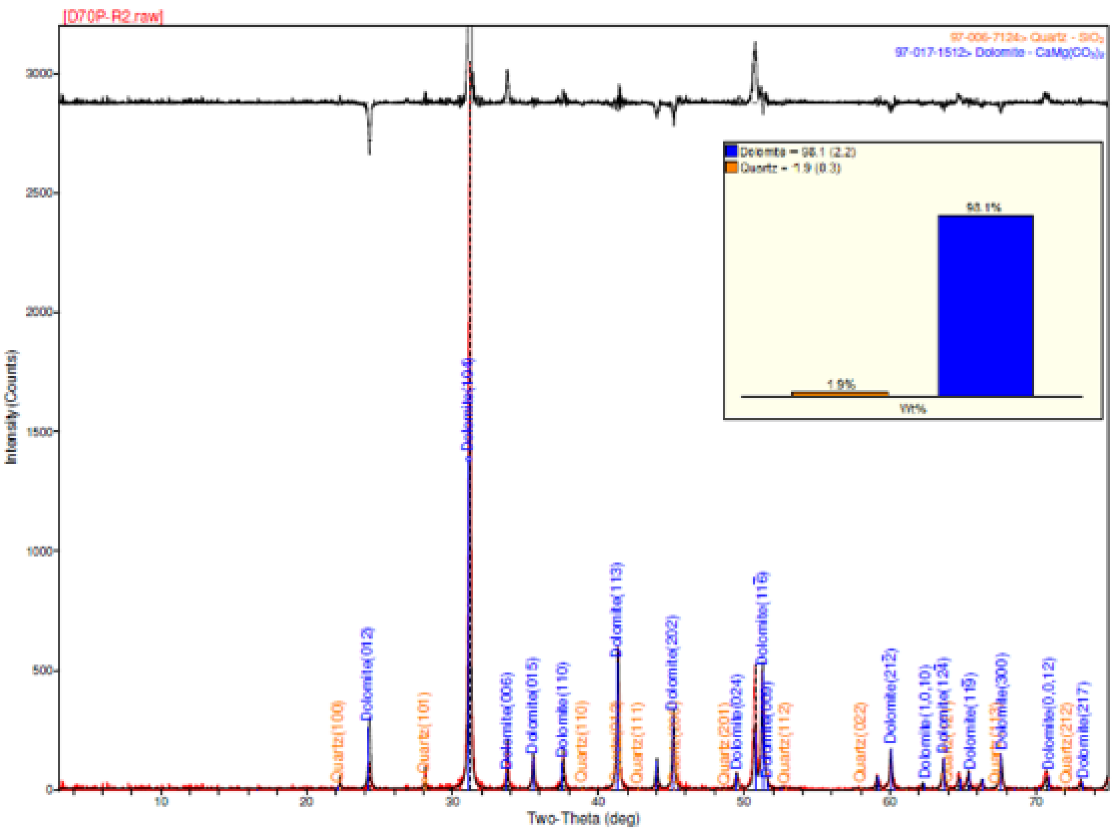
Sample ID	Plug ID	Well	Depth (ft.)	Plug length (cm)	Plug diam. (cm)	Confining pressure (psi)	Porosity (%)	Permeability (mD)	Klinkenberg permeability (mD)
24243_3296_40_A	68	Danielson 33-17	3296.40	5.53	2.51	500	6.36	3.66	3.26
						1100	6.12	2.89	2.55
24243_3358_25_A	69	Danielson 33-17	3358.25	4.74	2.52	500	14.92	56.00	54.10
						1100	14.80	55.00	53.10
24243_3308_40_A	70	Danielson 33-17	3308.40	6.05	2.52	500	8.99	27.20	25.90
						1100	8.81	22.40	21.30
24242_4120_50_A	44	Wallewein 22-1	4120.50	5.36	2.51	500	9.57	3.15	2.78
						1100	9.51	3.12	2.75
24242_4131_40_A	46	Wallewein 22-1	4131.40	4.94	2.52	500	9.27	8.66	7.99
						1100	9.14	8.00	7.36

XRD of Core Plugs (Permeable Zones)

Table 1: Powder XRD whole rock mineralogy for MSU core plugs and analogue outcrop test samples (semi-quantitative weight %)

*No clays appear to be present after following USGS XRD sample preparation protocol in open-file report 01-041
PDF #'s listed for MDI Jade 9.0 Database

Sample ID	Plug ID	Well	Depth (ft.)	Dolomite	PDF	Calcite	PDF	Anhydrite	PDF	Gypsum	PDF	Quartz	PDF
24243_3296_40_A	68	Danielson 33-17	3296.4	93.4	97-008-7088	0	n/a	3.5	98-000-0090	3.1	98-000-0234	0	n/a
24243_3358_25_A	69	Danielson 33-17	3358.25	92.5	97-017-1513	5.6	97-004-0106	0	n/a	0	n/a	1.9	97-006-7124
24243_3308_40_A	70	Danielson 33-17	3308.4	98.1	97-017-1512	0	n/a	0	n/a	0	n/a	1.9	97-006-7124
24242_4120_50_A	44	Wallewein 22-1	4120.5	92.2	97-018-5046	0.7	97-004-0548	0.7	97-001-5876	6.4	97-015-1692	0	n/a
24242_4131_40_A	46	Wallewein 22-1	4131.4	98.6	97-003-1210	0	n/a	0	n/a	0	n/a	1.4	97-064-7410



<u>92 – 98% Dolomite</u>

0 – 5.6% Calcite

0 – 2% Quartz

0 – 3.5% Anhydrite

0 – 6.4 % Gypsum

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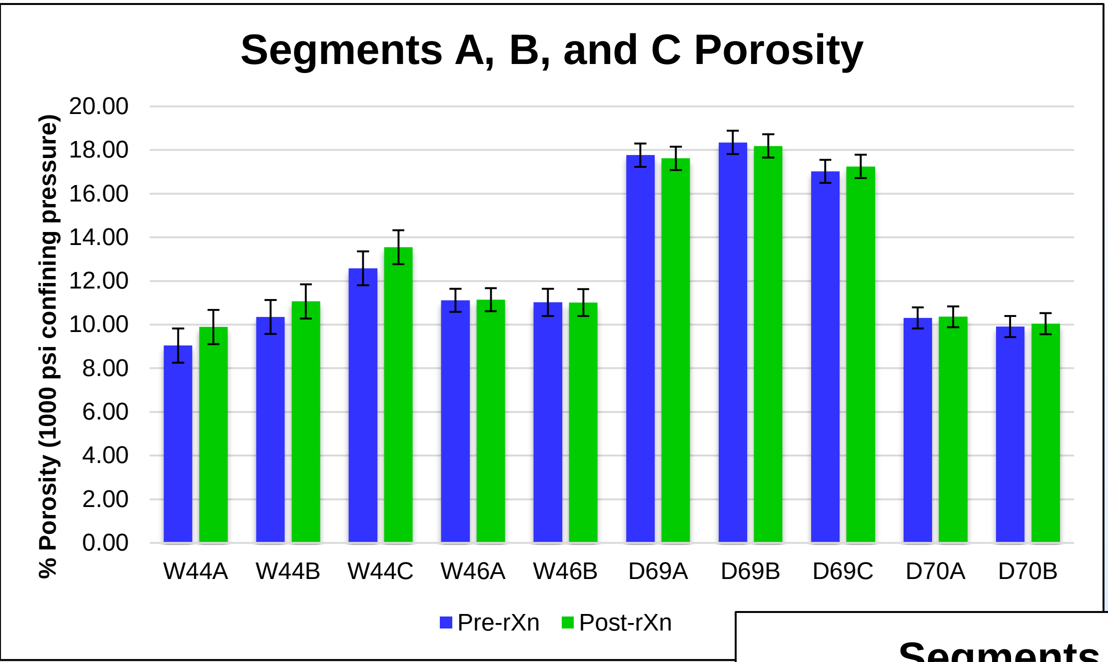
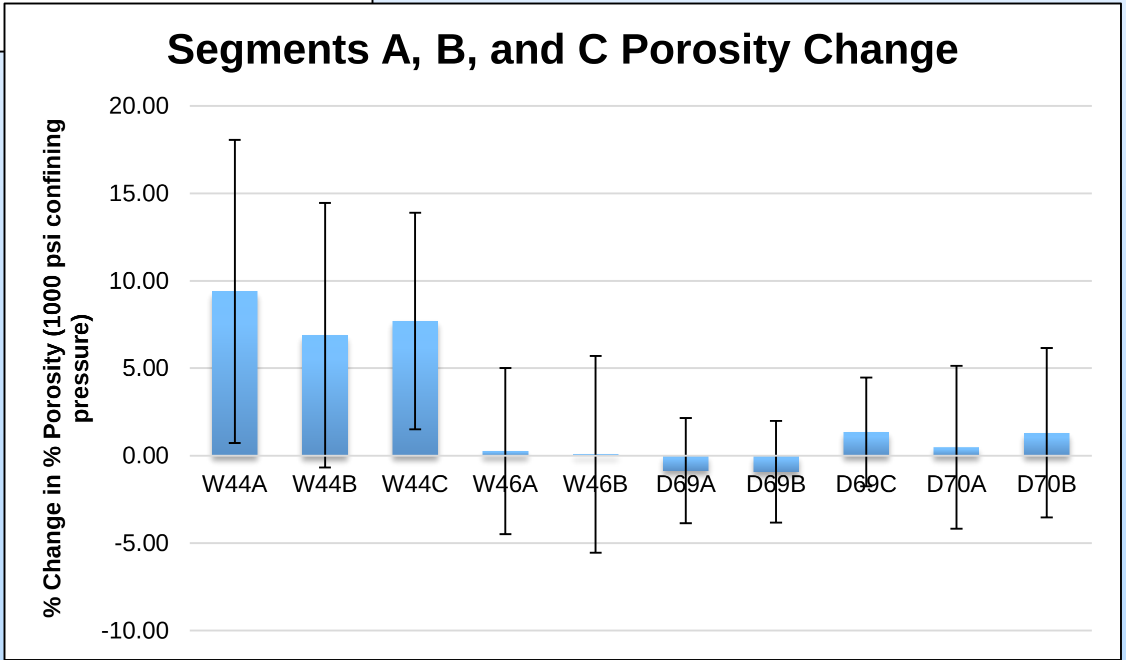
Core Flood Experiments

	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





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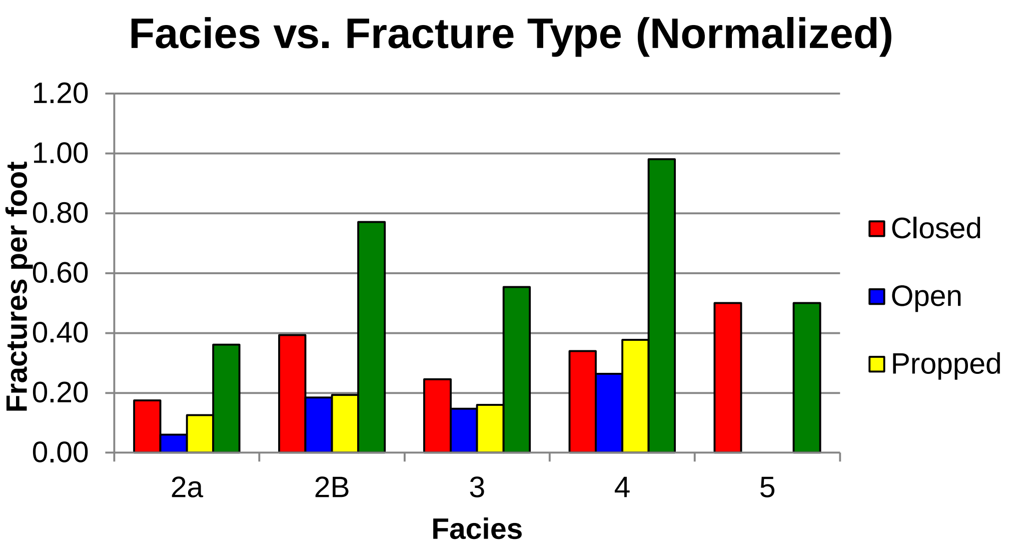
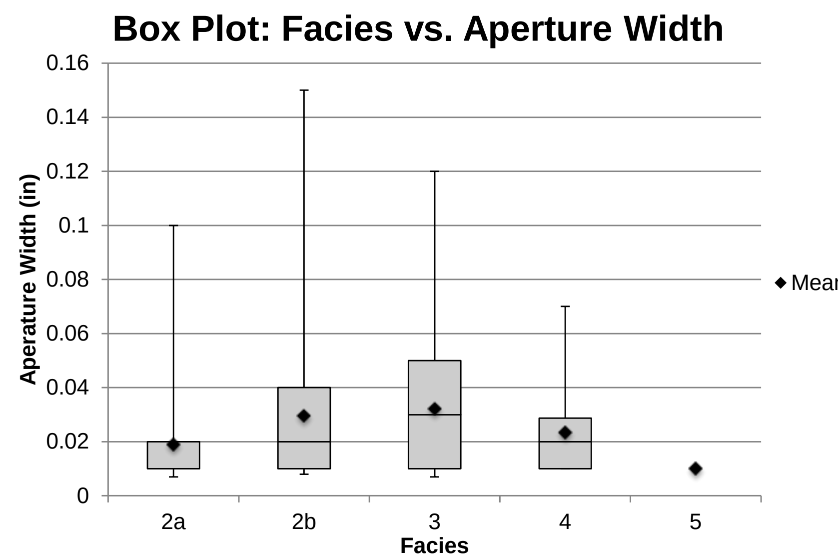
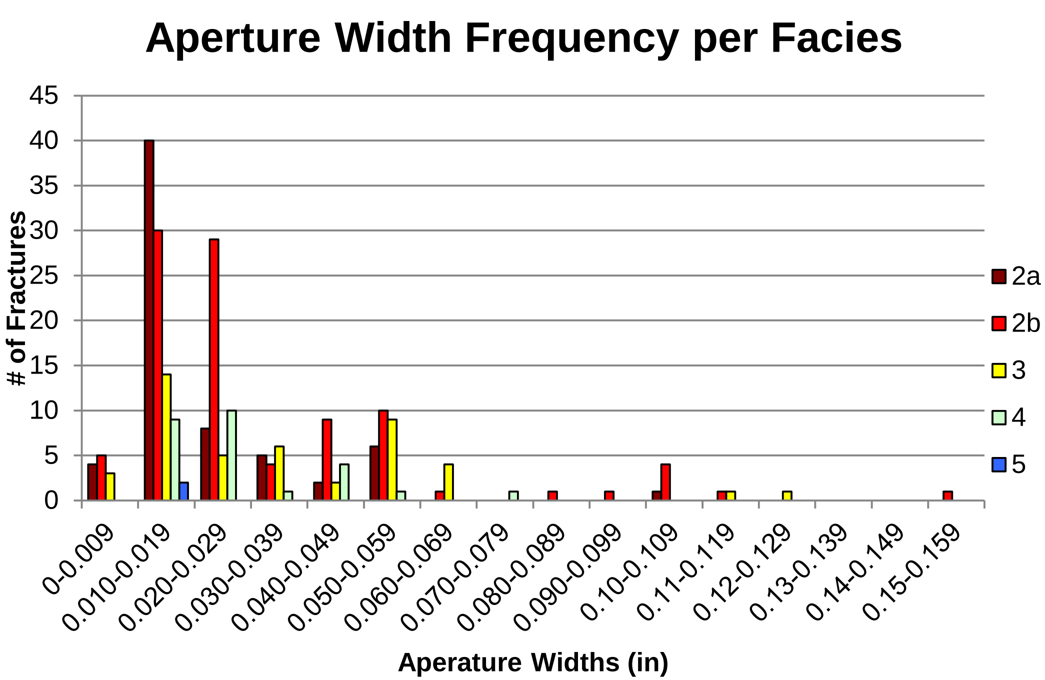
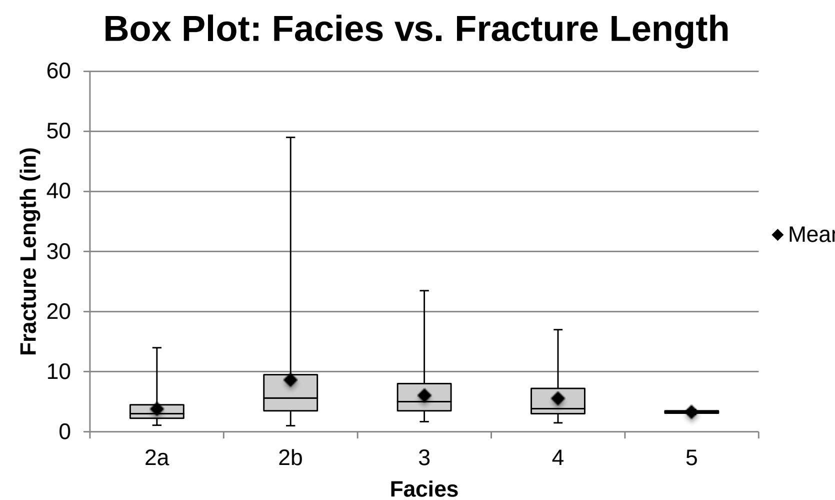
Fracture Analysis of Cored Intervals of the Duperow









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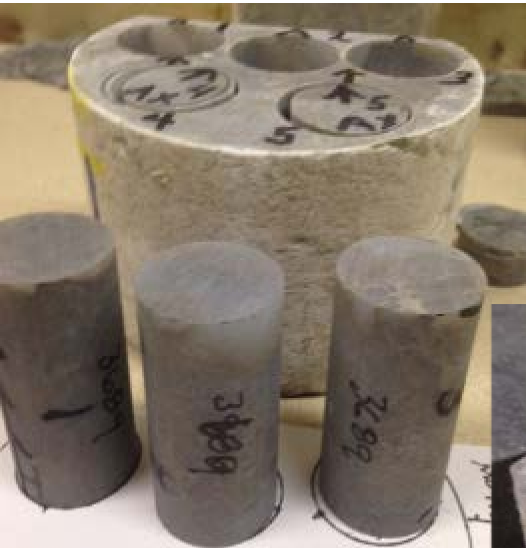
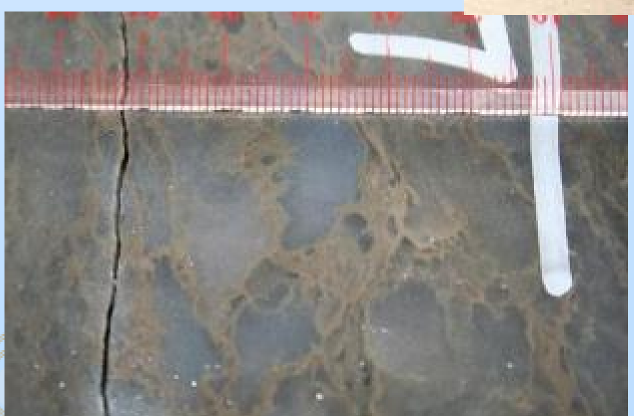
Task R1. Core Studies: Motivation

- 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

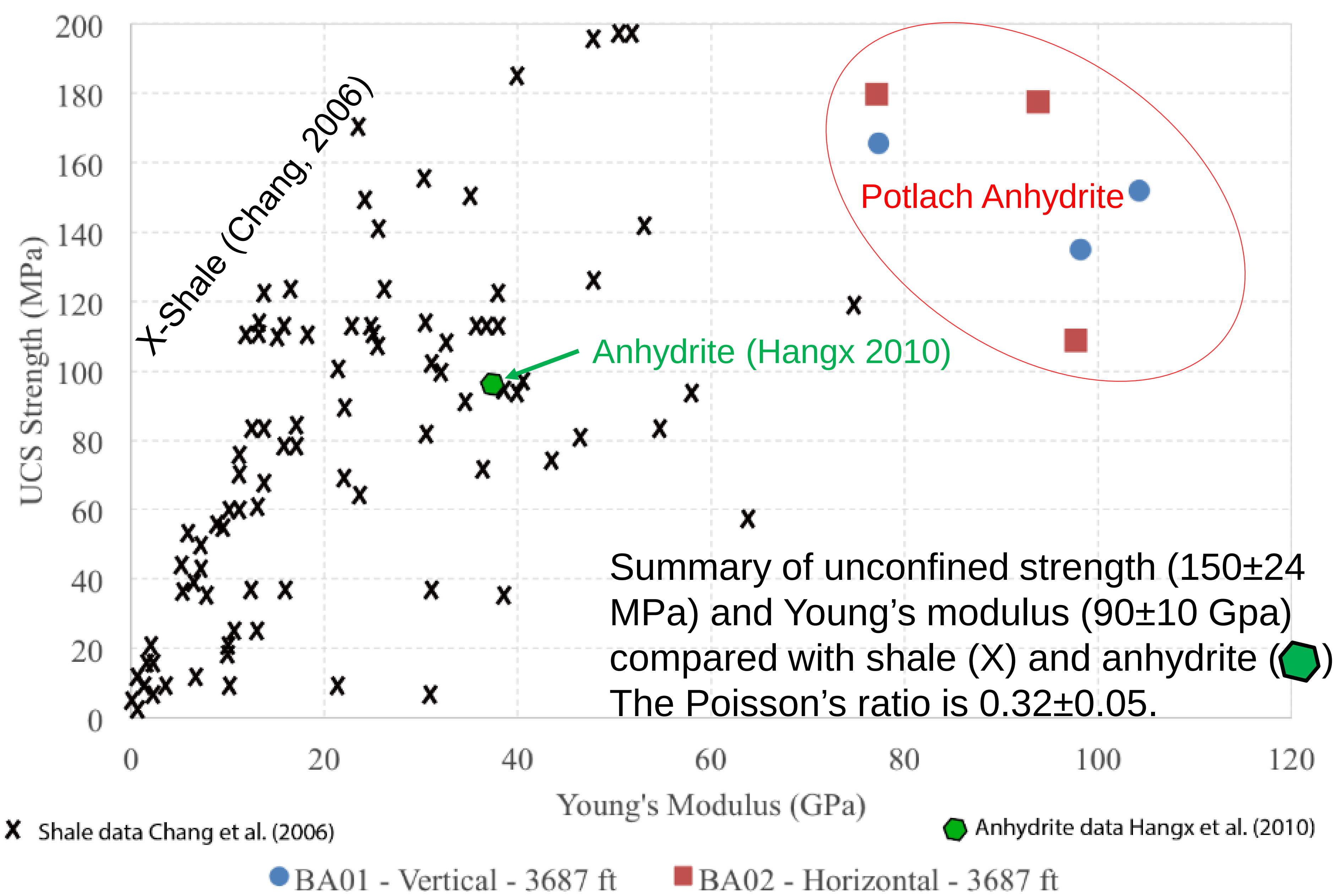
Caprock Geomechanical Tests





- **Potlatch Anhydrite**
- **3687'-depth of the Wallawein well**
- **Sample density 2.5 - 2.83 g/cm^3(close to the theoretical density of anhydrite (2.97 g/cm^3 indicating nearly pure anhydrite with very little porosity.)**
- **Single crystals of anhydrite appear to be as large as 1-3 cm**

Caprock Geomechanical Tests

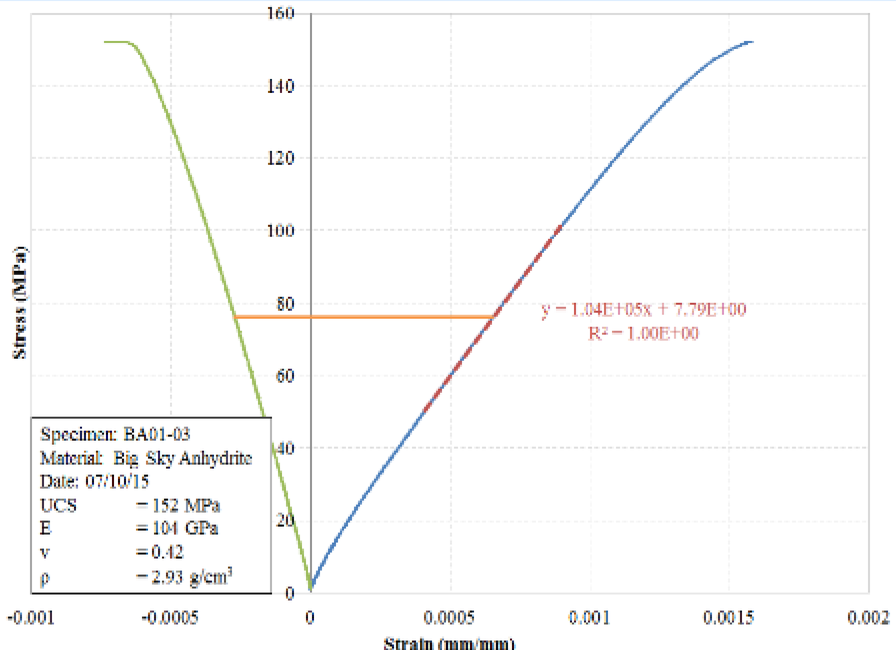


Summary of unconfined strength (150±24 MPa) and Young's modulus (90±10 Gpa) compared with shale (X) and anhydrite (⬢) The Poisson's ratio is 0.32±0.05.

Caprock Geomechanical Tests

	UCS (MPA)			Young's (GPa)			Poisson		
	All	Vert	Horiz	All	Vert	Horiz	All	Vert	Horiz
Mean	153.1	150.8	155.4	91.42	93.29	89.55	0.32	0.35	0.30
StdDev	27.47	15.30	40.46	11.49	14.15	10.94	0.06	0.07	0.04

- **The Potlatch Anhydrite is very strong in both orientations**
- **The average Young's modulus (91 Gpa) reflects a very stiff material**
- **Samples dilated strongly at peak strength before failing indicating significant plasticity even under unconfined conditions**



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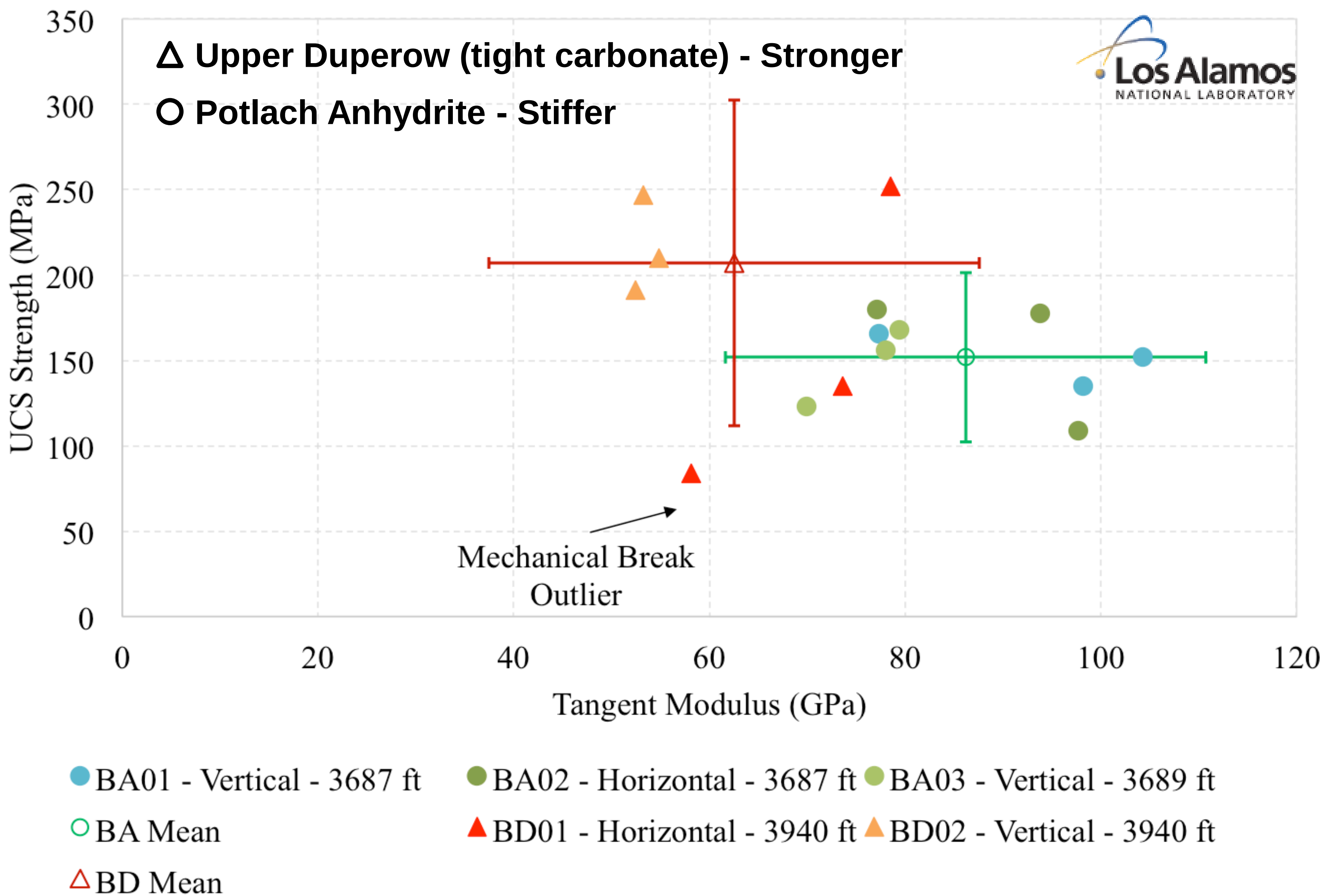
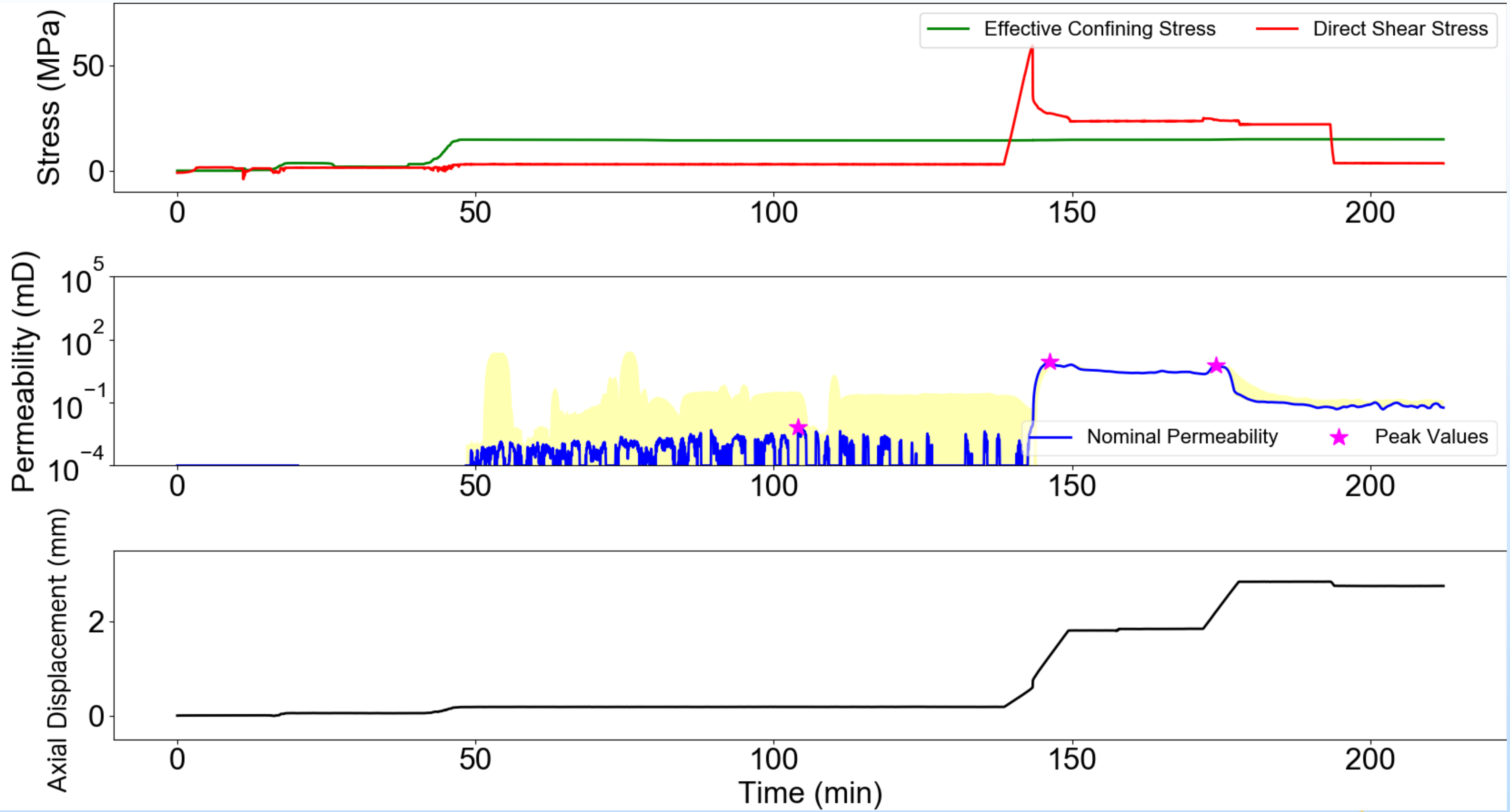
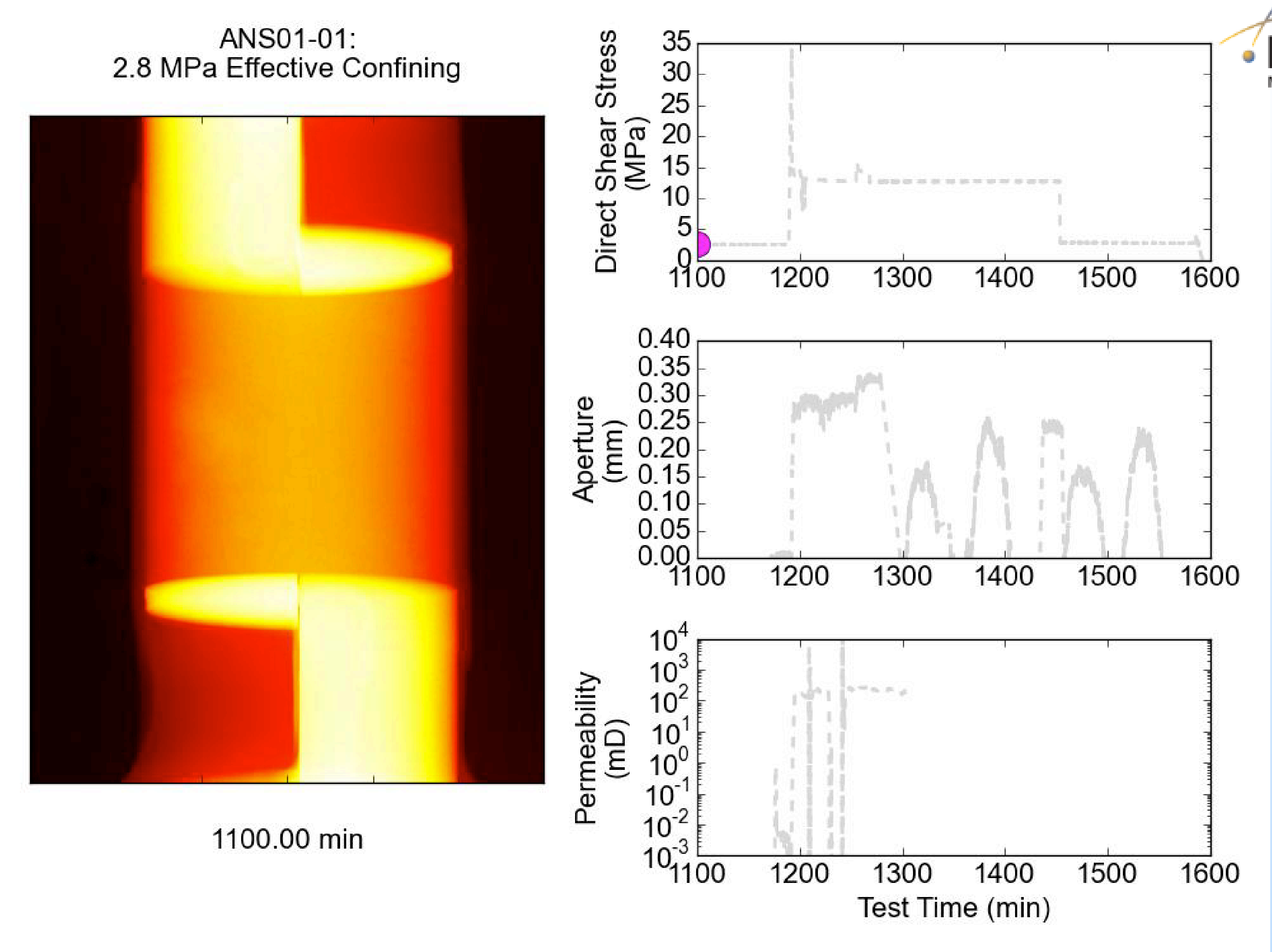
Caprock Geomechanical Analysis



Potlatch: 15 MPa Effective Stress Experiment



X-ray radiography of 3.5 MPa experiment



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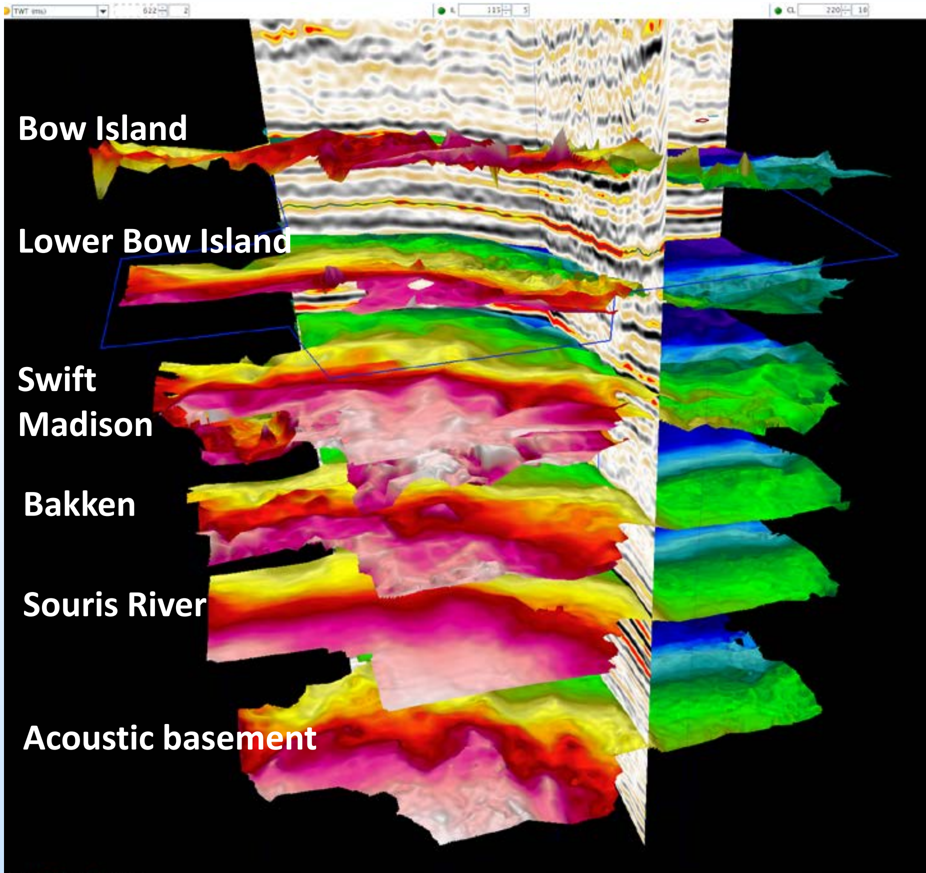
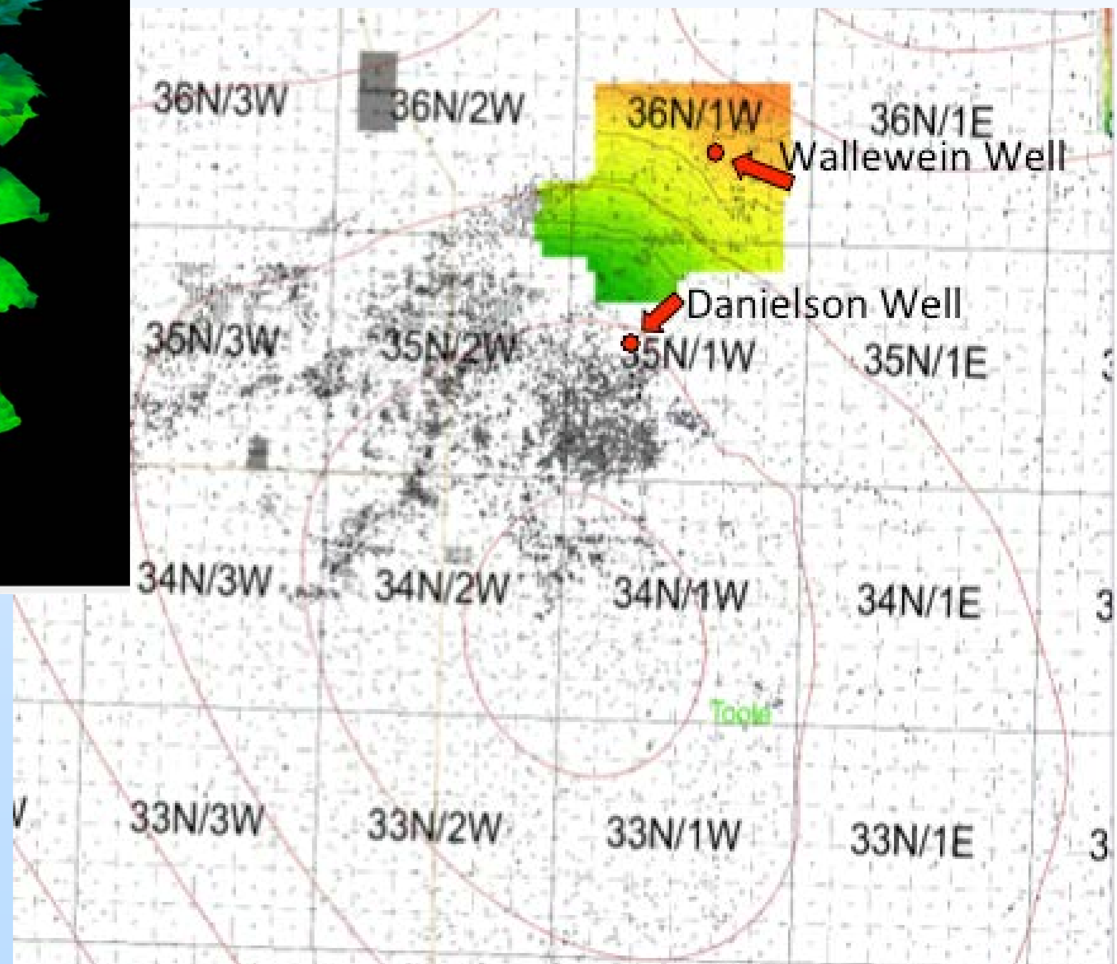
Seismic Structural Data



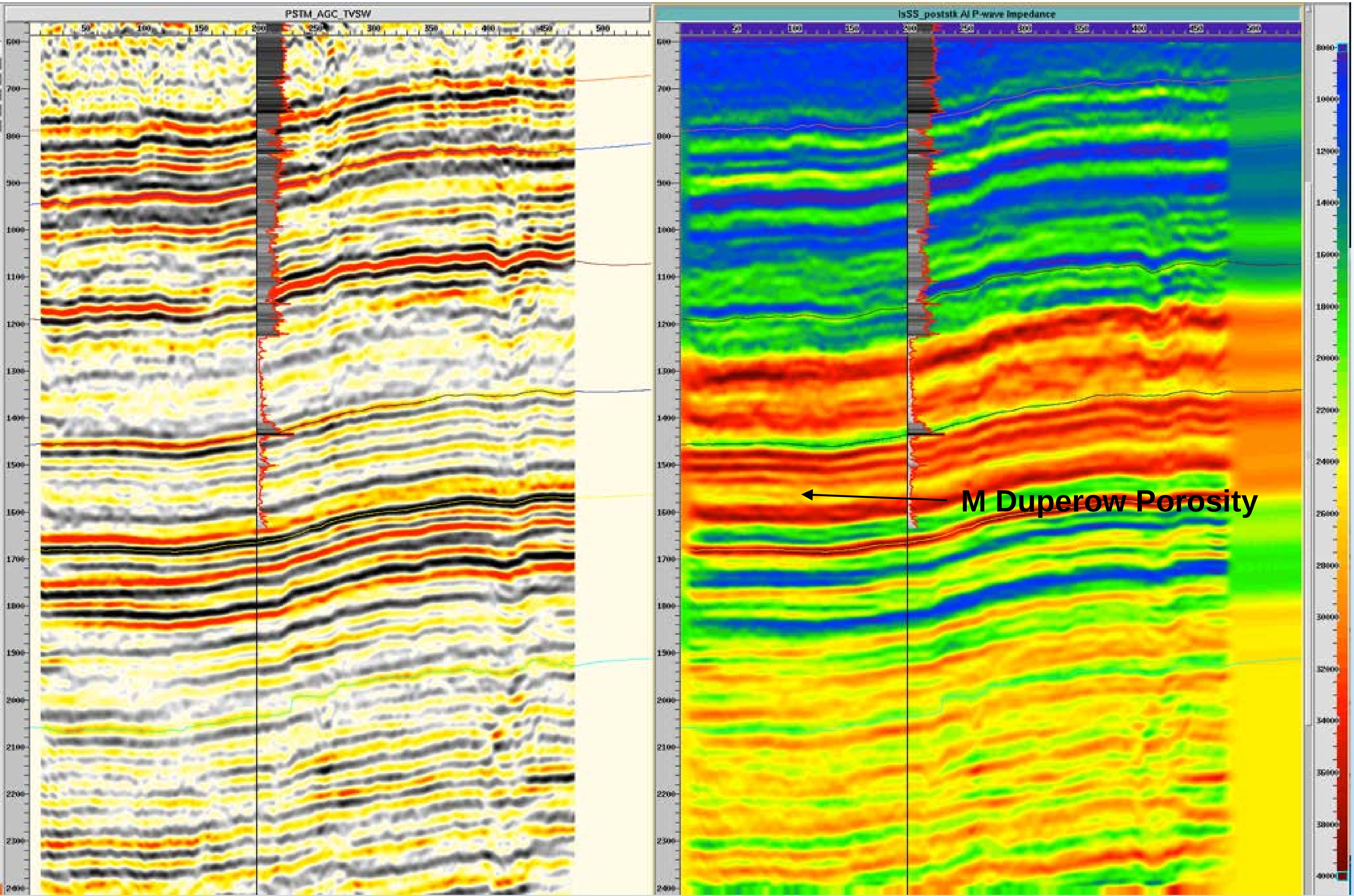
Structure Top Duperow from Well Control and Structure Top Bakken Shale from Seismic



Structural surfaces from Shear Wave (SH) Seismic BSCSP Kevin Dome

BSCSP Seismic Monitoring Program

Poststack P and SH inversion IsSS with Wallewein GR

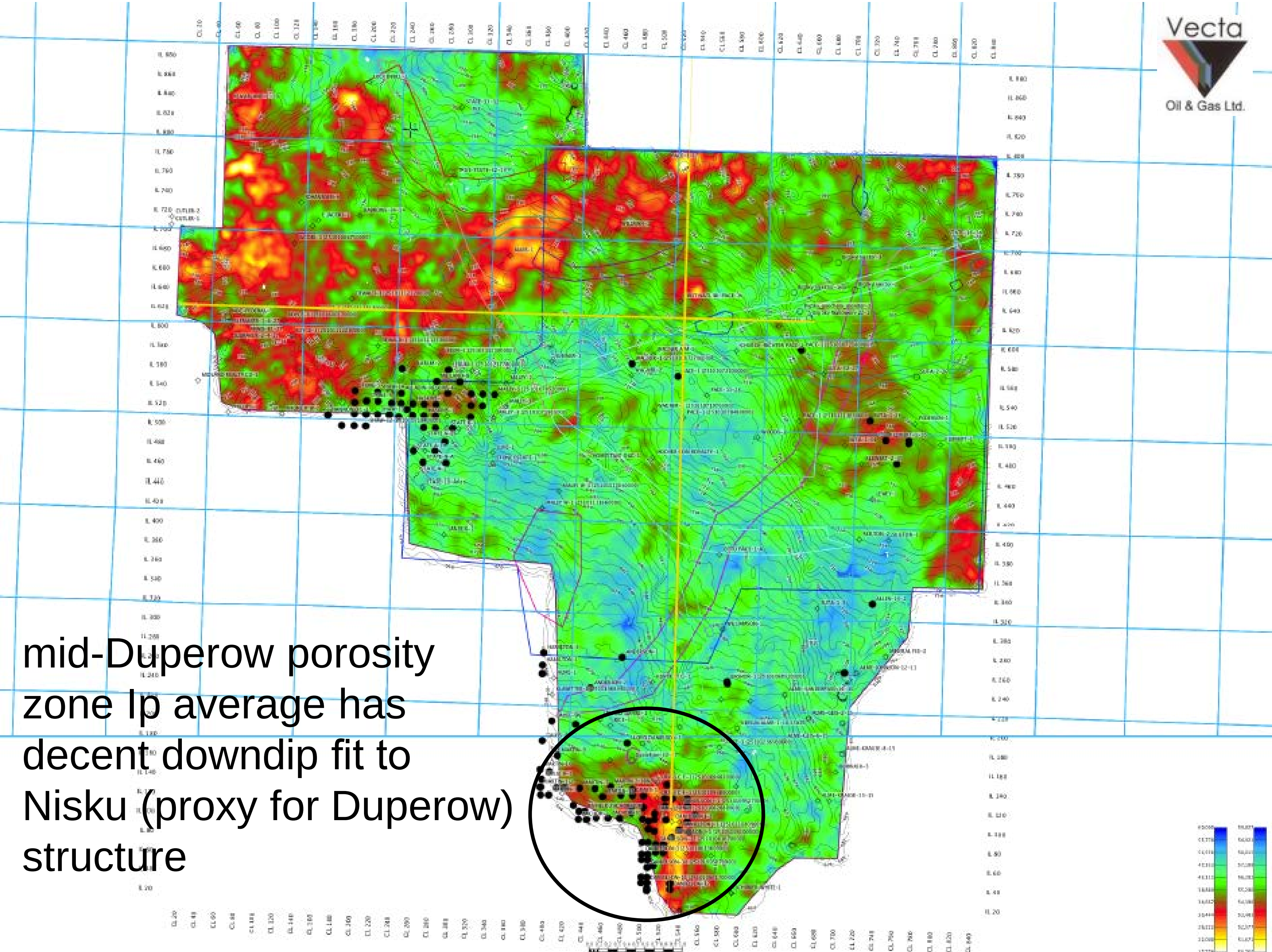


BSCSP Seismic Monitoring Program

9C dataset has good to excellent P and SH signal useful for characterizing Middle Duperow porosity zones

- Well to seismic matches, particularly in paleozoic, are excellent on P and SH datasets
- Subtle NE-SW structural fabric points back at crest of Kevin dome throughout paleozoic section
- Joint inversion performance was good, as expected, and middle Duperow porosity zone is readily visible on both impedances
- Meaningful impedance variations are visible on joint inversion output at middle Duperow level

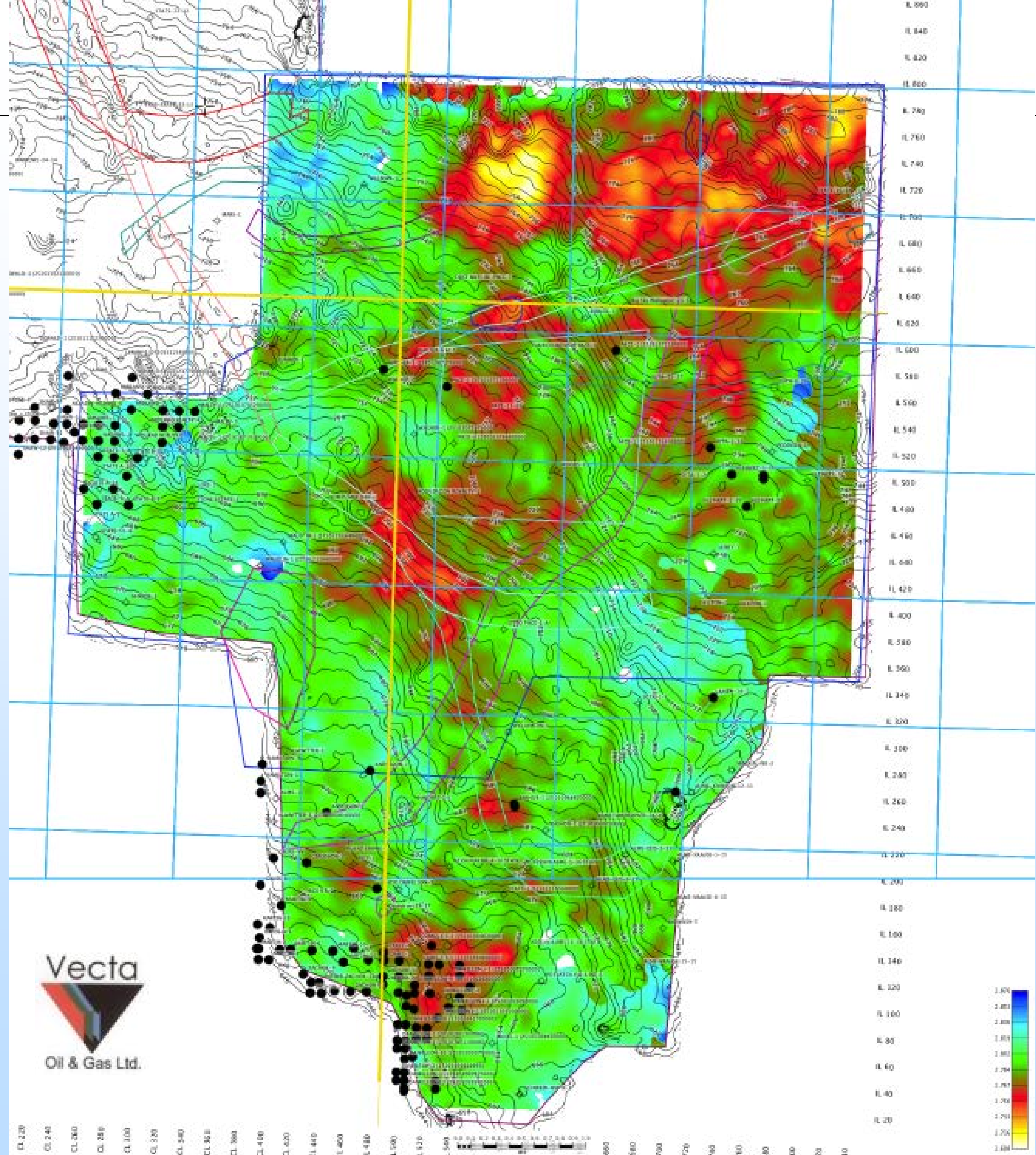
Vecta
Oil & Gas Ltd.



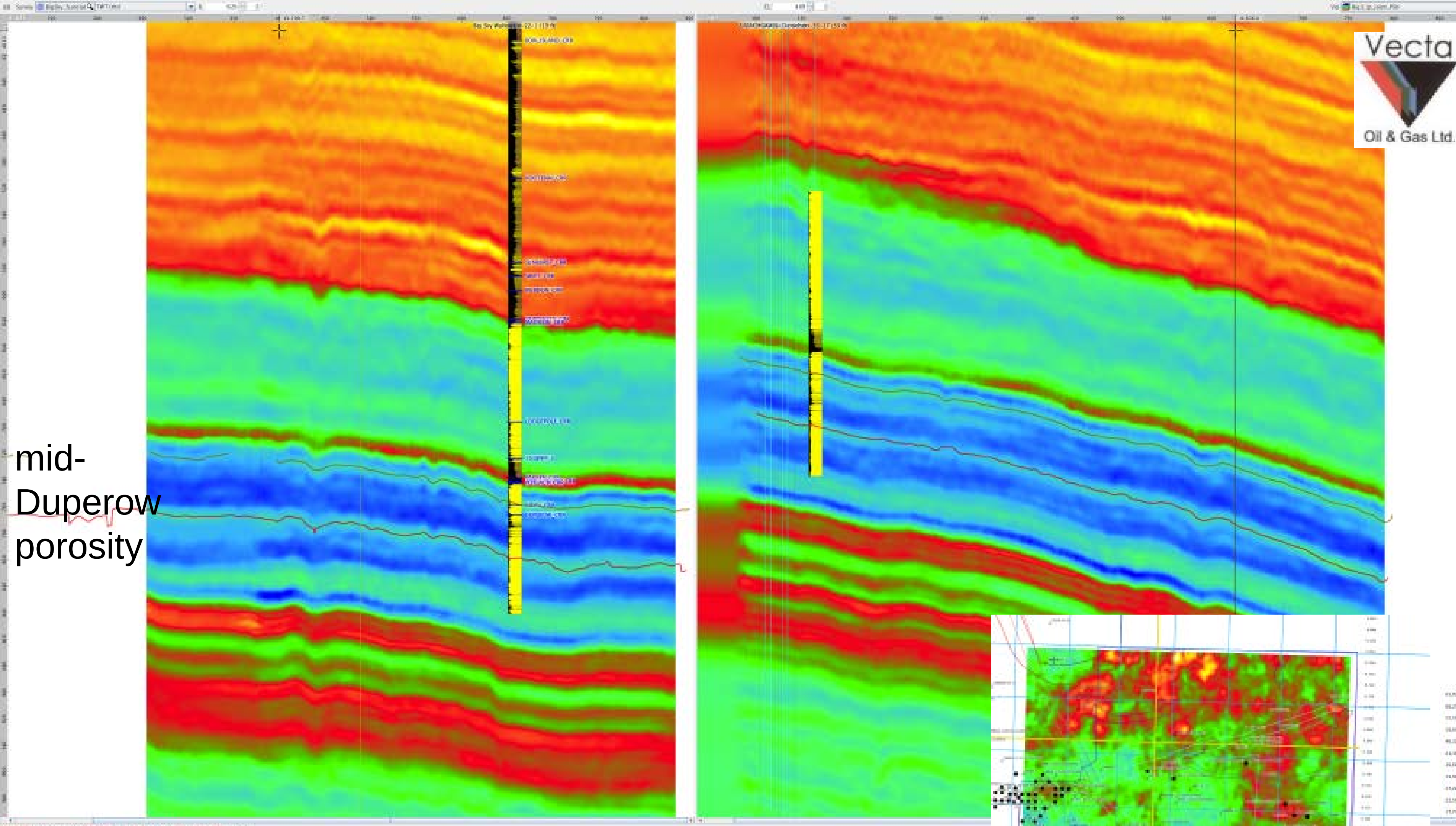
mid-Duperow porosity zone Ip average has decent downdip fit to Nisku (proxy for Duperow) structure

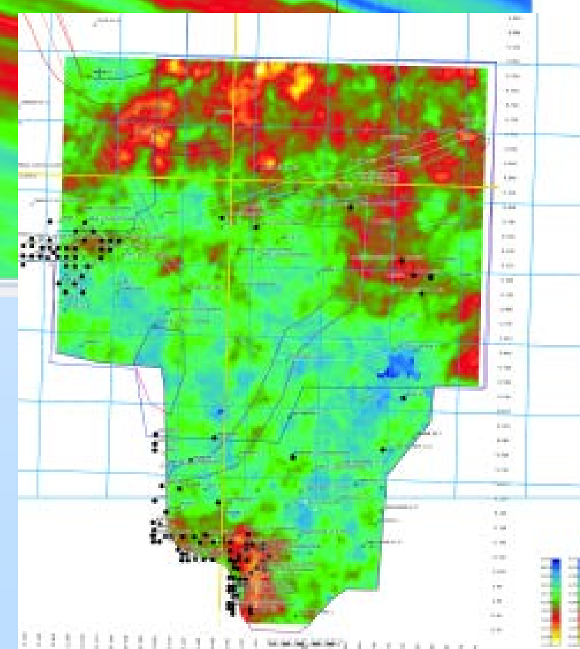
Mid-Duperow ρ from P/SH/SV inversion also shows some downdip fit.

SV offset >20 deg. To emphasize density



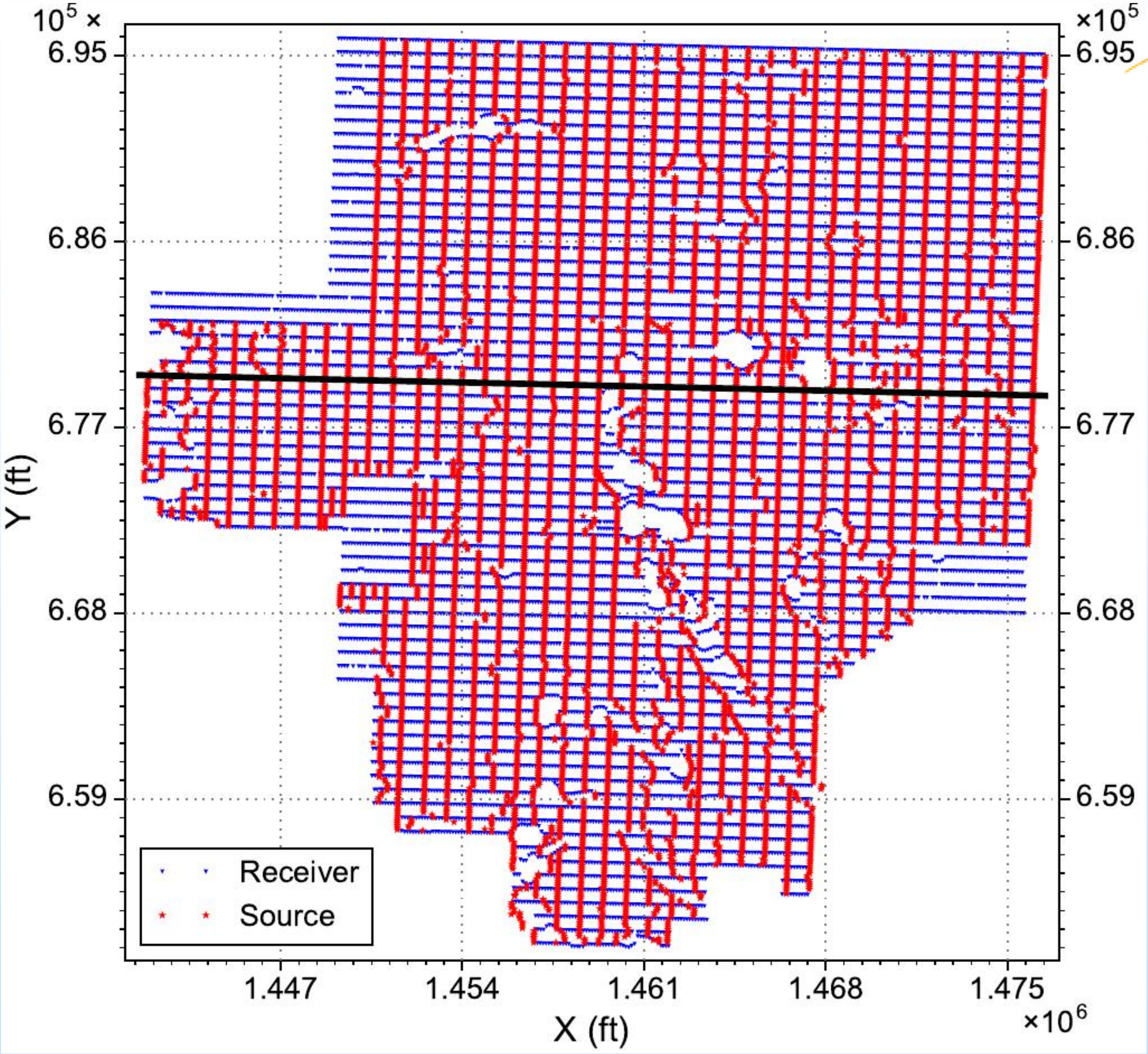
BIG SKY CARBON
SEQUESTRATION PARTNERSHIP





Inline (left) and crossline (right) through Wallewein and Danielson wells; seismic is Ip from Vecta joint P/SH inversion; line locations shown on index map on left

Task R2. Full-Waveform Inversion and Reverse-Time Migration of a 2D Line Kevin Dome Seismic Data



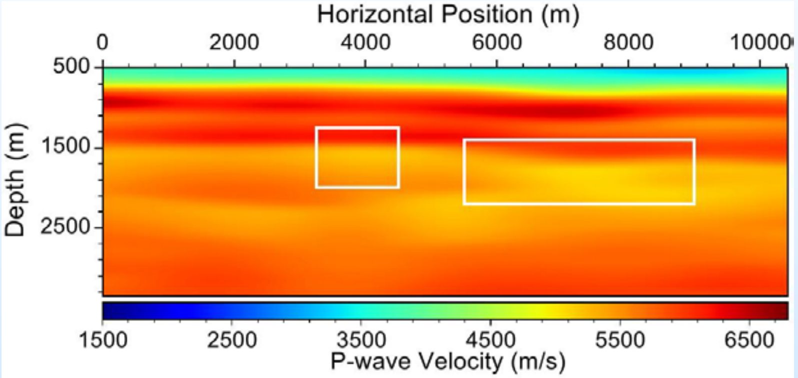
Sources in red and receivers in blue of the Kevin Dome seismic survey. Initial data analyses are on a 2D line in black

Los Alamos NATIONAL LABORATORY

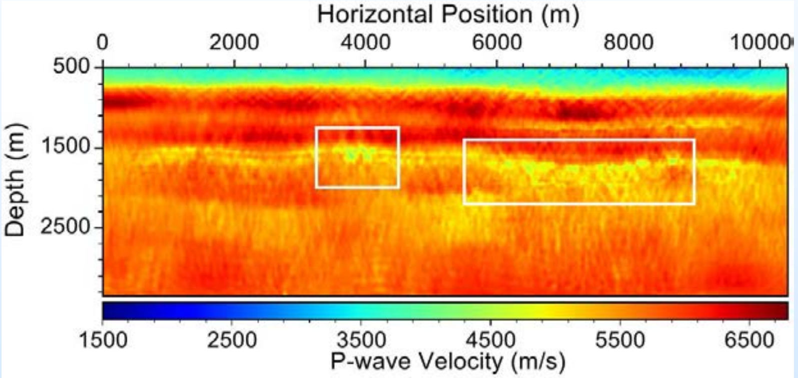
BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Full-Waveform Inversion of a 2D Line Kevin Dome Seismic Data: Revealing some low-velocity zones



Initial low-resolution P-wave velocity model

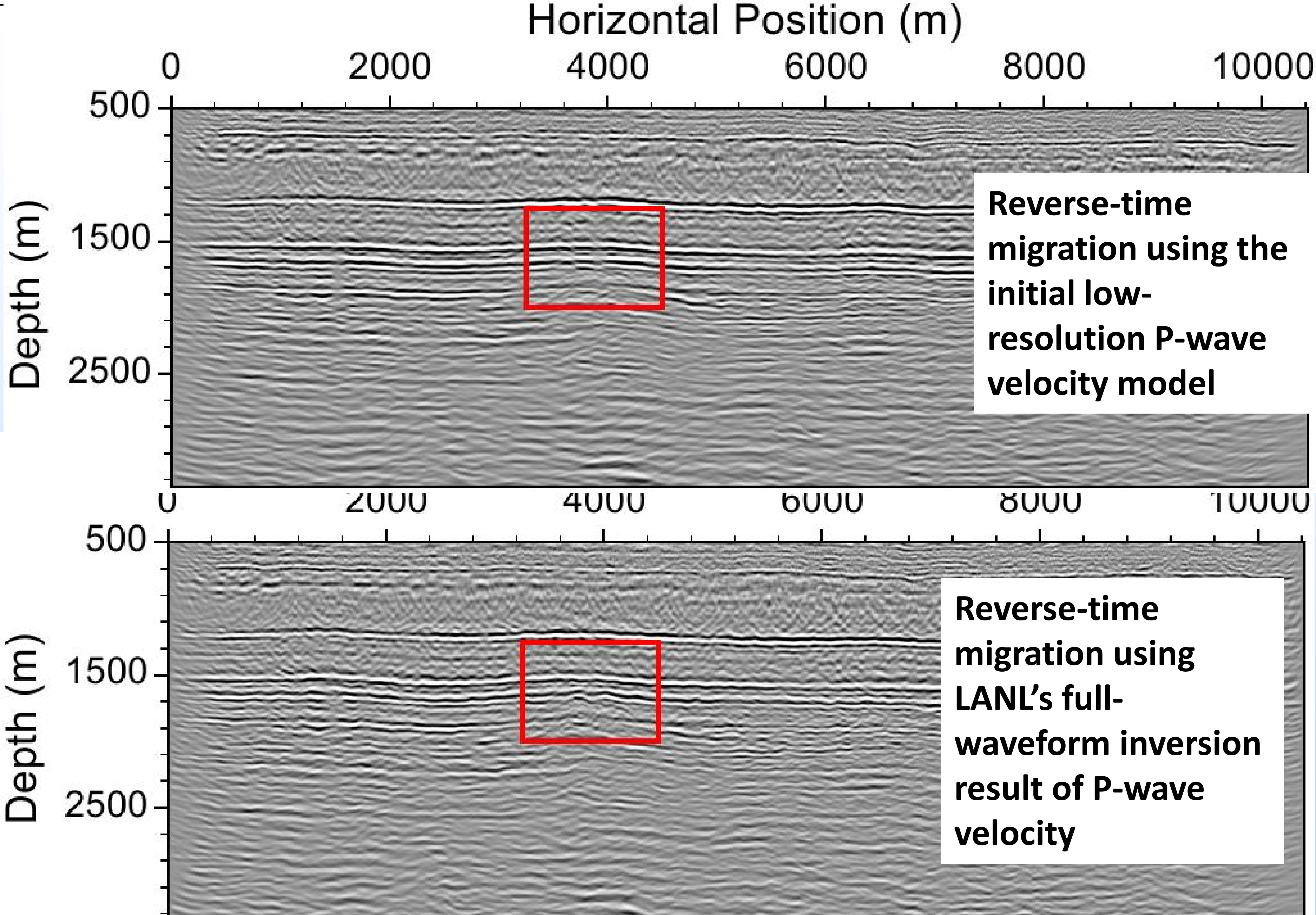


LANL's full-waveform inversion result of P-wave velocity containing some low-velocity zones

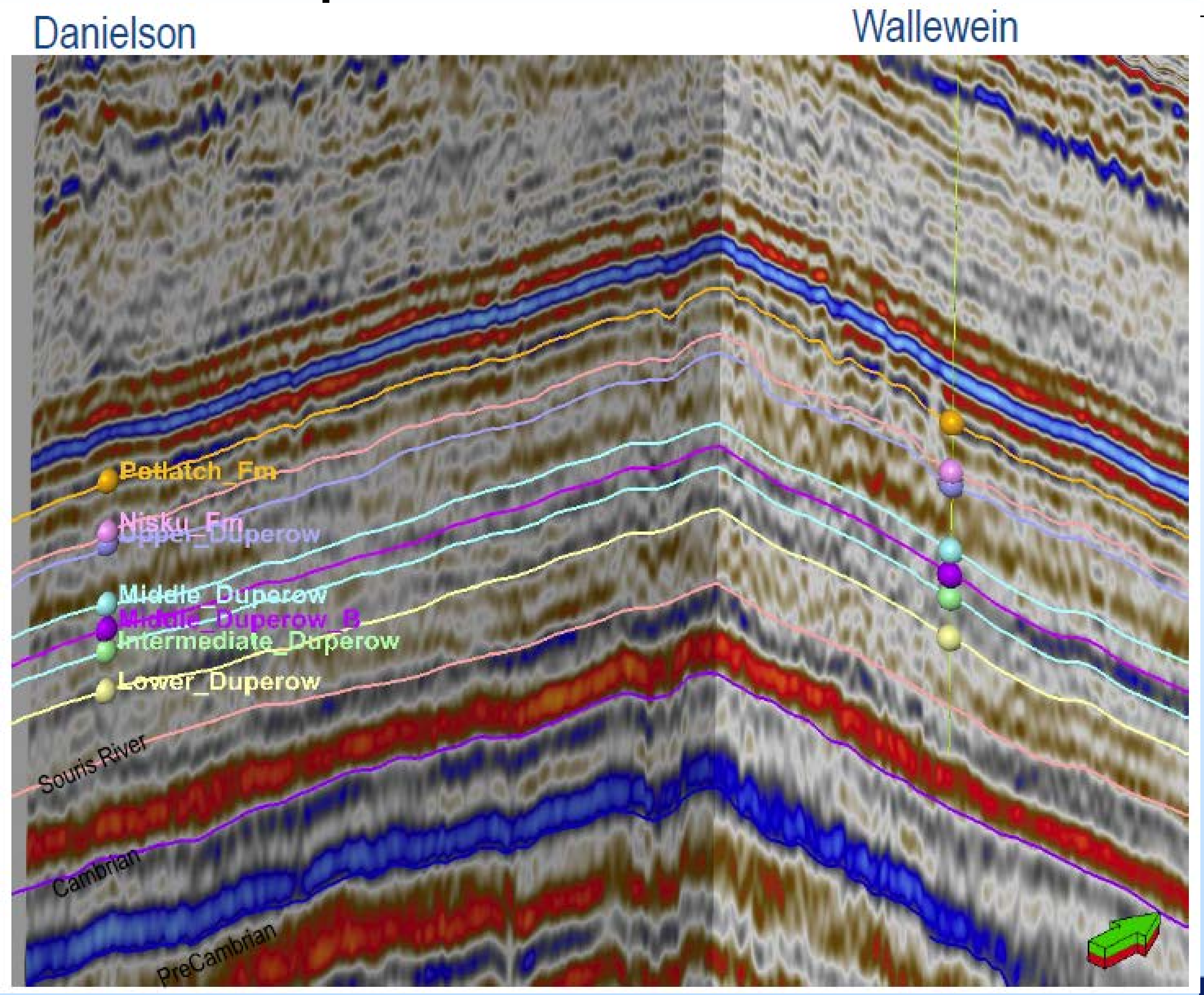
Big Sky Carbon Sequestration Partnership

Montana State University

Reverse-Time Migration of a 2D Line Kevin Dome Seismic Data



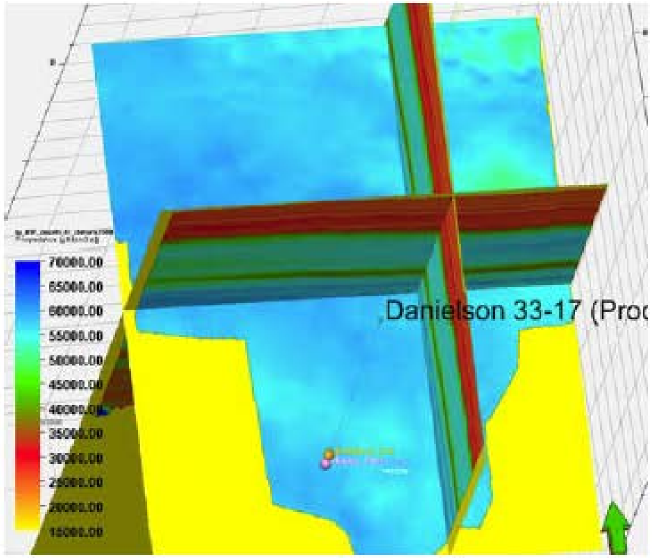
3D Depth Converted Seismic



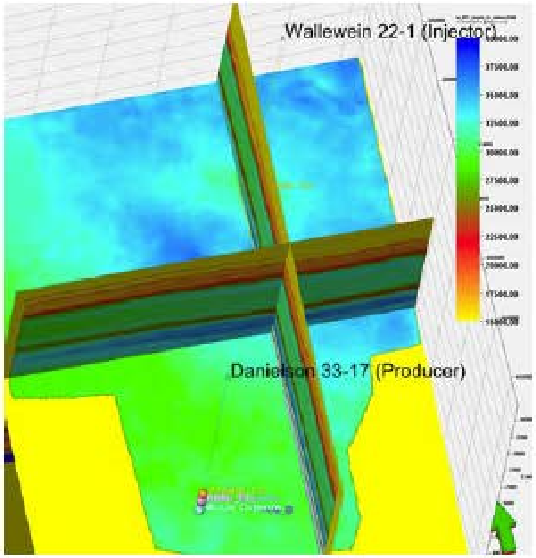
3D Depth Converted Seismic with IP, IS, Density

Schlumberger Carbon Services

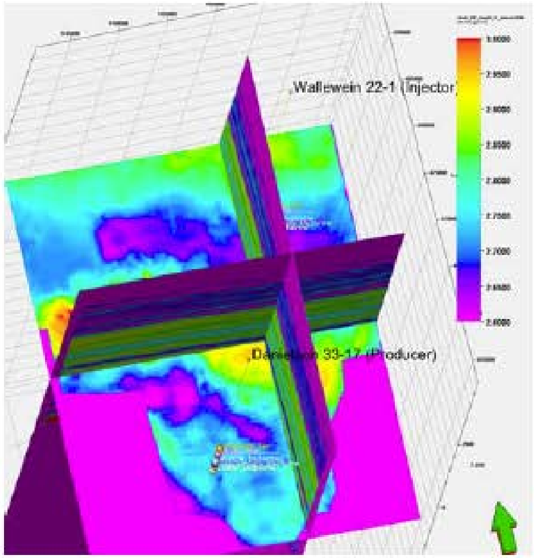
P-Impedance



S-Impedance



Density



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MONTANA STATE UNIVERSITY

THE LEADING EDGE OCTOBER 1998, p 1396

Dynamic reservoir characterization of Vacuum Field

DANIEL J. TALLEY, Chevron North American Exploration and Production, New Orlea
THOMAS L. DAVIS and ROBERT D. BENSON, Colorado School of Mines
STEVEN L. ROCHE, Input/Output, Sugar Land, Texas

Time-lapse multicomponent seismic surveying enables dynamic reservoir characterization and the production of a dynamic reservoir model. This, in turn, assists in producing structured economic and technical decisions that will extend reservoir life and improve recovery while reducing risk and environmental impact.

This article briefly describes the

S-waves enable the discrimination of rock and fluid properties, their characteristics, and their changes over time.

When combined into time-lapse multicomponent (4-D, 3-C) seismology, the resulting method is a tool for volume resolution: i.e., it provides the ability to sense changes in the bulk rock/fluid properties of the

gives us a
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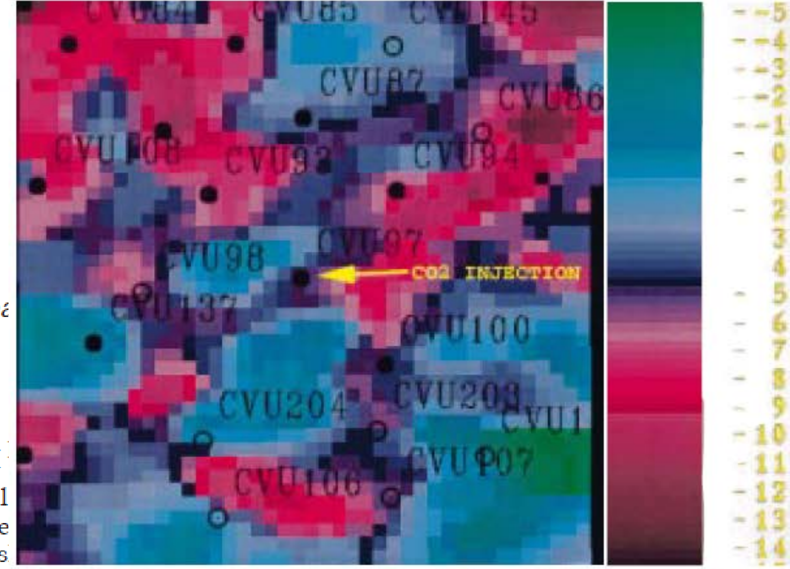


Figure 5. Velocity anisotropy map from the base 3-D, 3-C survey. The area south of the CO_2 injection shows values of near zero percent anisotropy, indicating vertical open fractures both parallel and perpendicular to the maximum horizontal stress field.

"The shear-waves responded to a change in pore aspect ratio or preferential opening of microfractures resulting from the injection of CO_2. The faster shear-wave (S1) velocity was attenuated less with the resulting change in low-aspect ratio crack porosity."

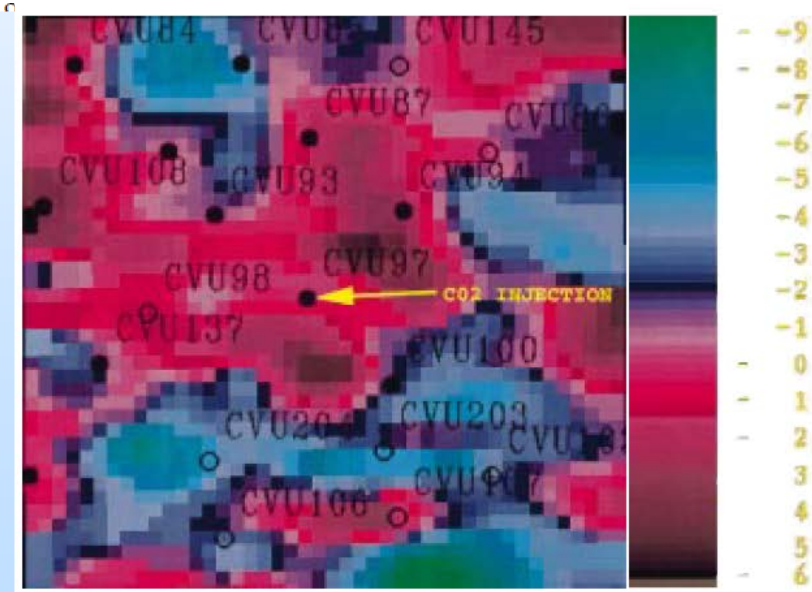


Figure 6. Velocity anisotropy map from the repeat 3-D, 3-C survey. The zone of zero percent anisotropy from the base survey is now showing 6% positive anisotropy, indicating a higher density of vertical open fractures parallel to the maximum horizontal stress direction or stiffening of the frame due to viscosity and/or saturation change of the fluid and a reduction in bulk density.

Modeling

Static Geologic Model

- Three domain sizes (Regional, Dome, Production / Injection)

Multiphase Flow Modeling For CO_2 Injection

- Sensitivity Analysis
  - Three rock parameters (different k, Φ)
  - Two injection rates (constant, stepped)
- Multiple Interacting Continua modeling to account for both fracture and matrix permeability

Multiphase Flow – Production

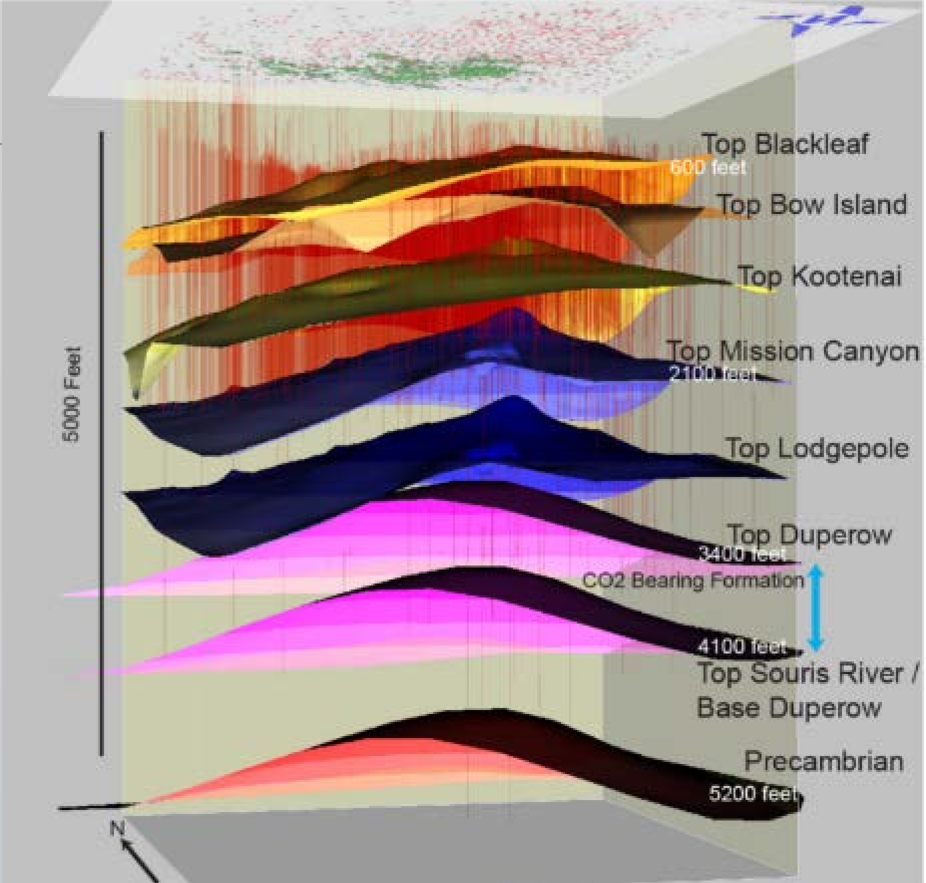
- Sensitivity Analysis
  - Three Gas-water contact heights
  - Pressure effects at multiple distances as a function of production rate / duration

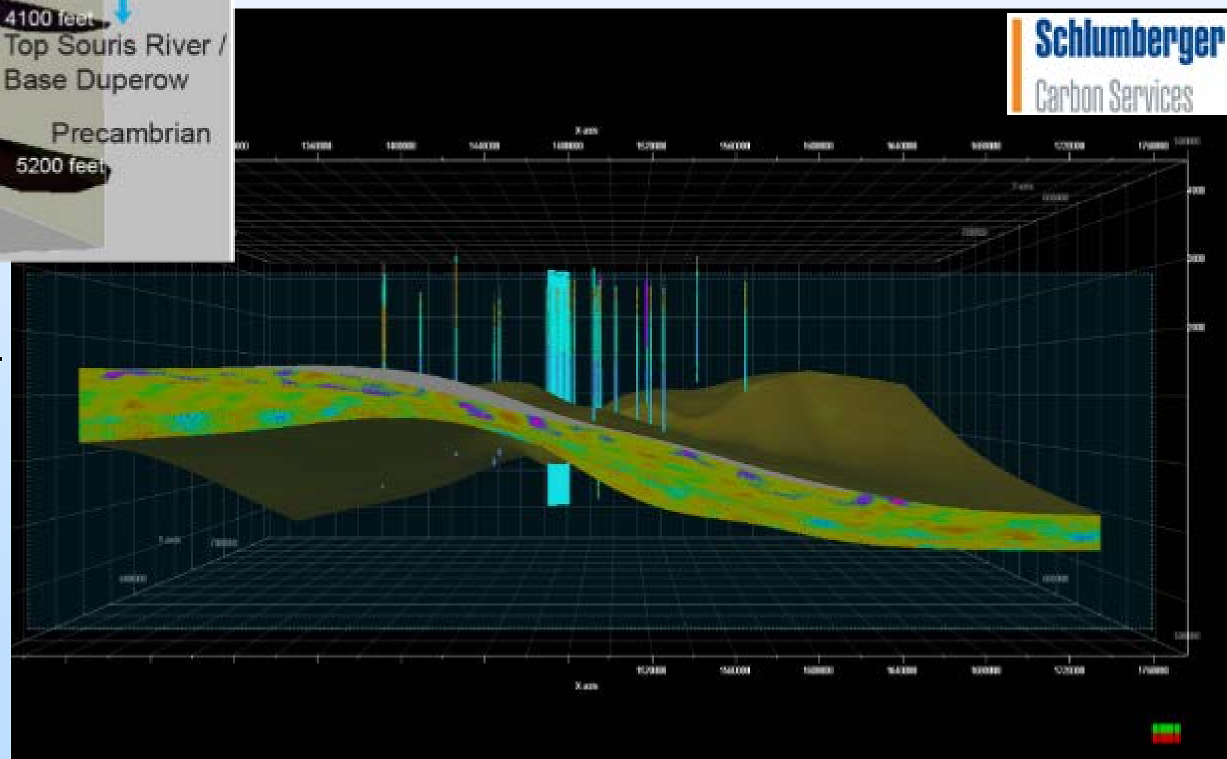
Geochemical & Reactive Transport Modeling

Risk Modeling

Static Model

Petra – Works with IHS well log database. Use ~1000 wells to pick formation tops. Good for structural information. Export info to Petrel.





Petrel – Incorporate logs, petro-physical properties (18 wells in injection zone), existing 2D seismic and BSCSP acquired 3D seismic. Export cellular model info for flow modeling.

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

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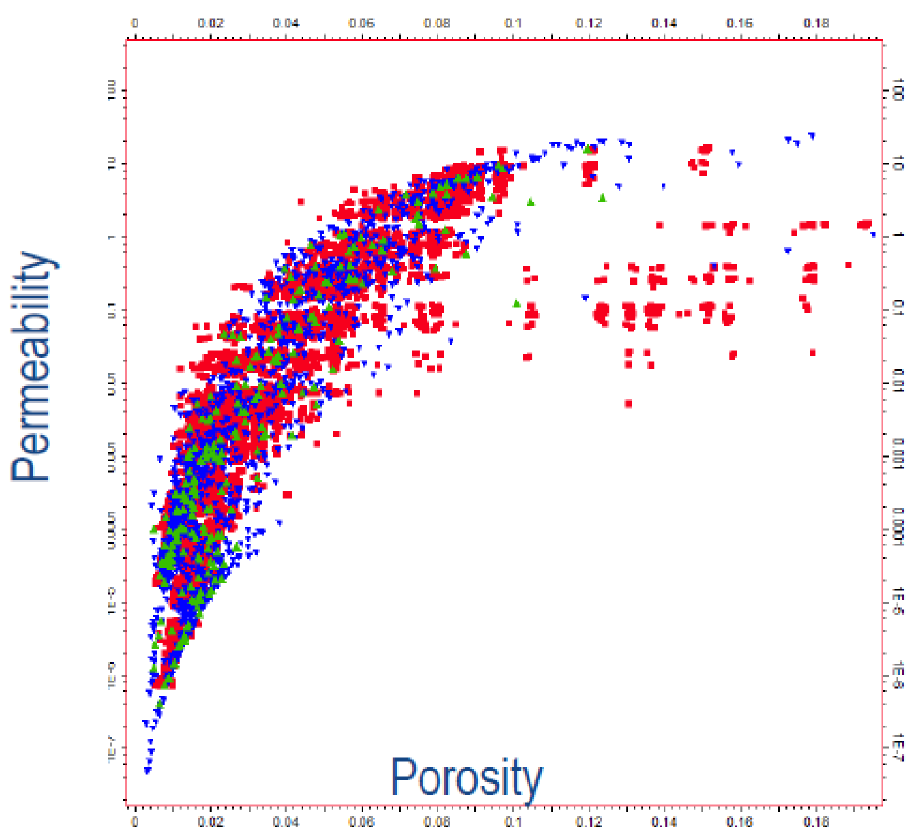
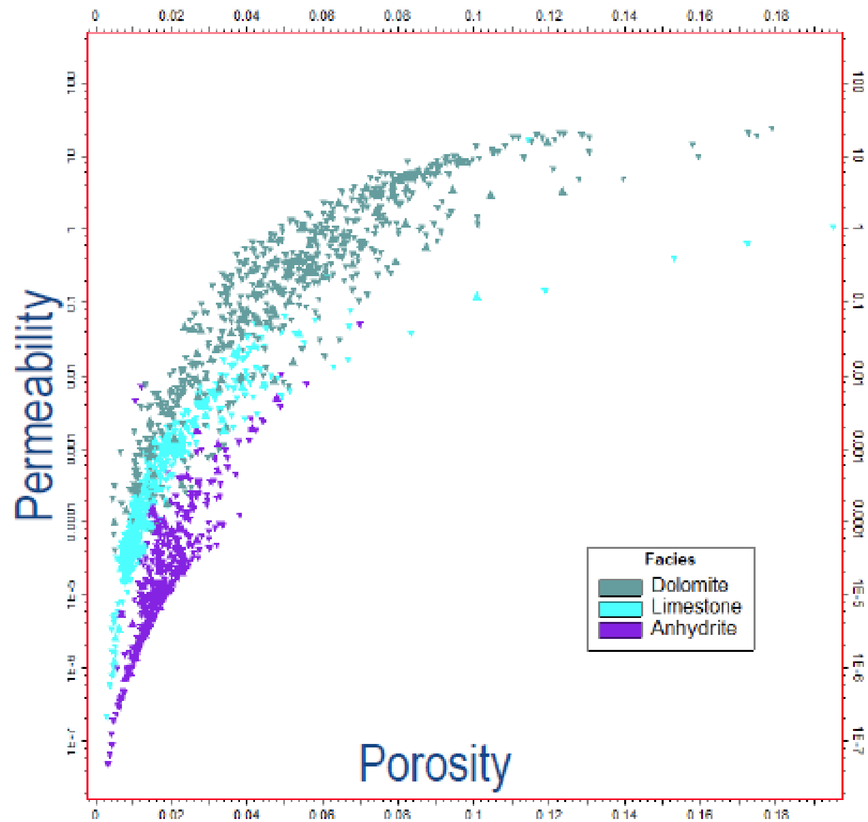
Porosity & Permeability Modeling Within Rock Types

Schlumberger Carbon Services

(Mid Duperow B and Intermediate Duperow)





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

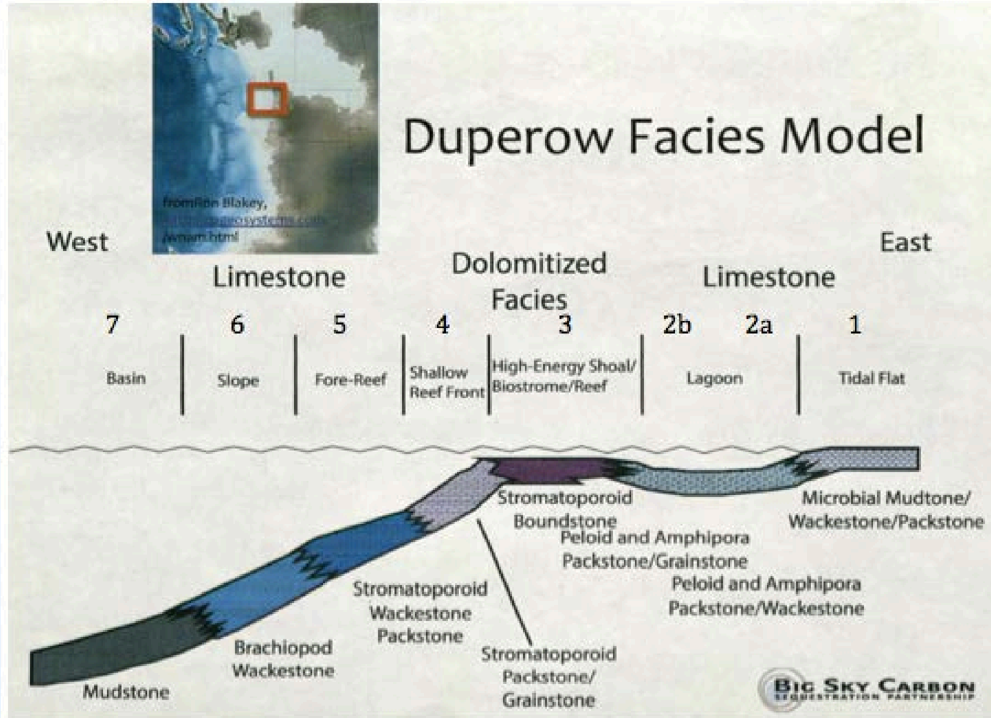
Note the separate porosity/permeability relationships for the 3 rock types

Refine Model Based on Geologic Interpretation

Schlumberger Carbon Services

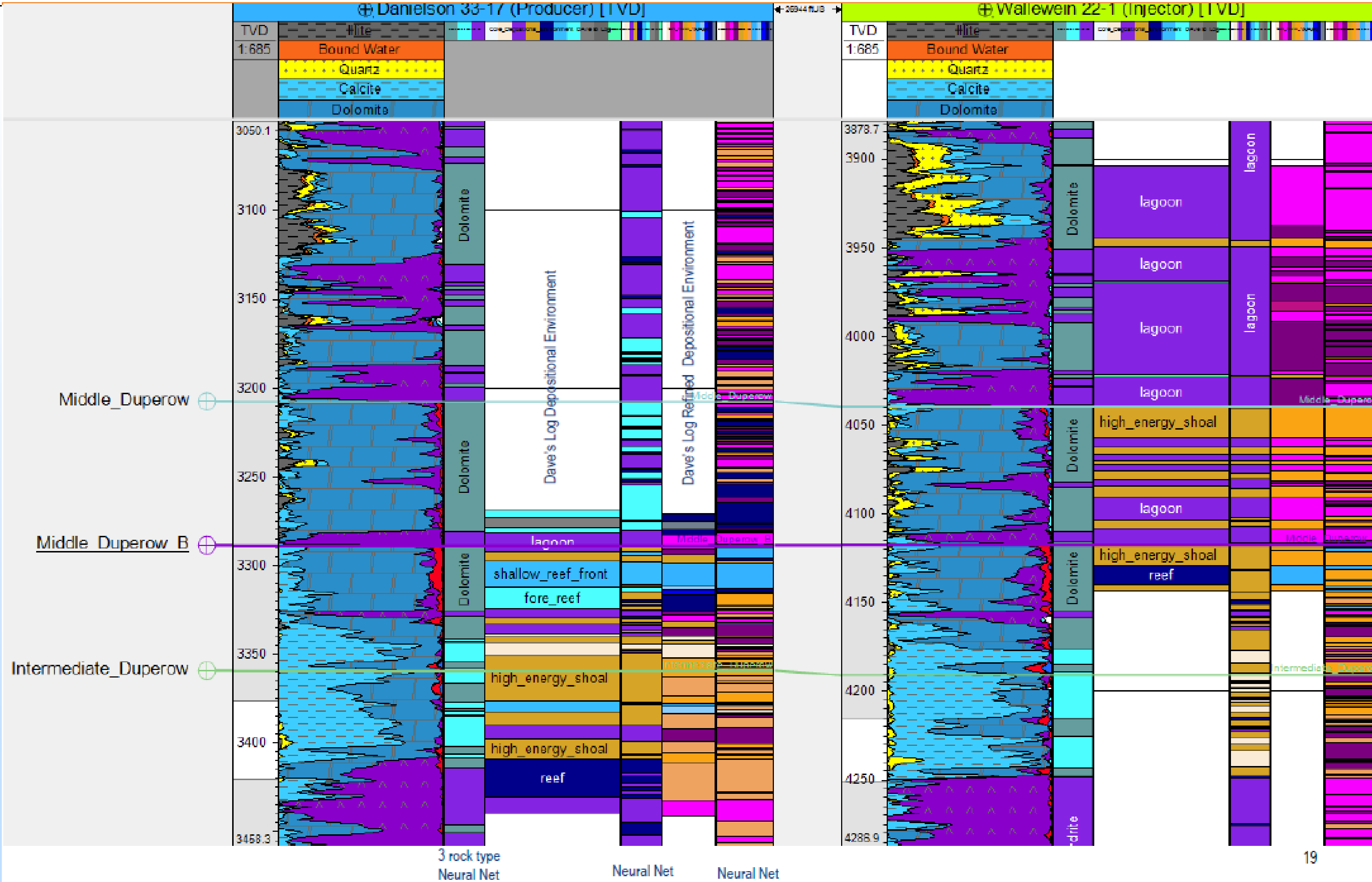
Depositional Environment

tidal_flat		
lagoon		
high_energy_shoal		
reef		
shallow_reef_front		
fore_reef		
slope		
Basin		
back_reef		



Neural Net Depositional Env. Predictions

Schlumberger
Carbon Services



Good Neural Net Match Along Core Interval

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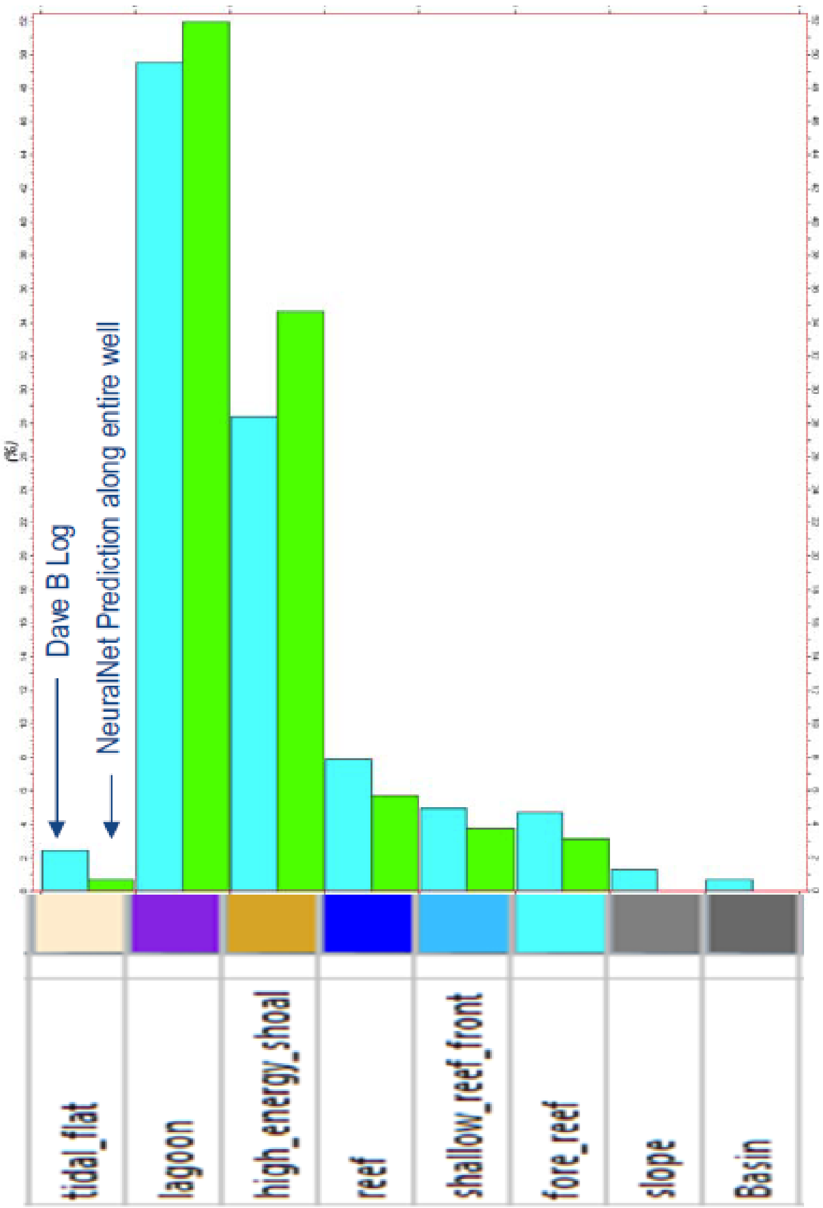
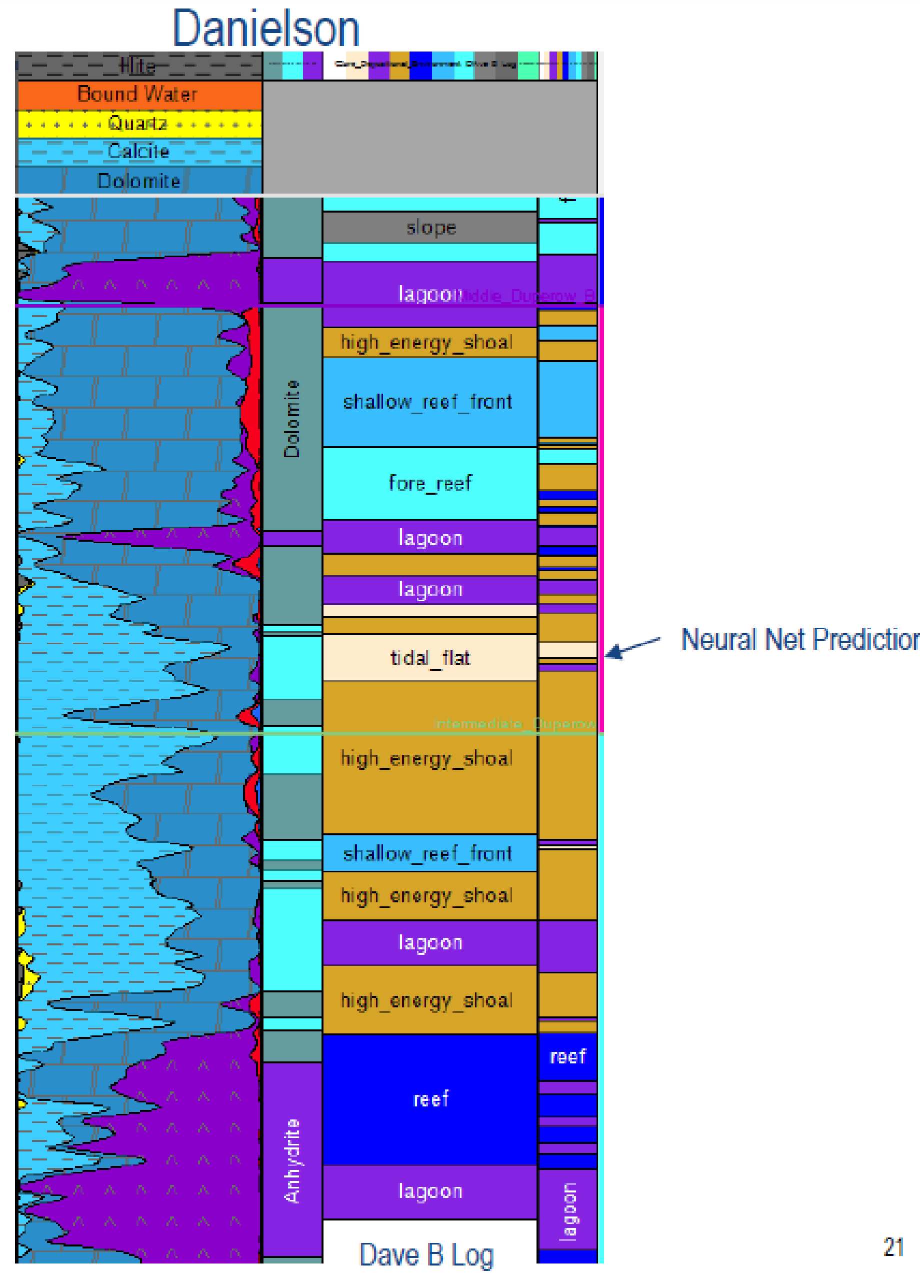
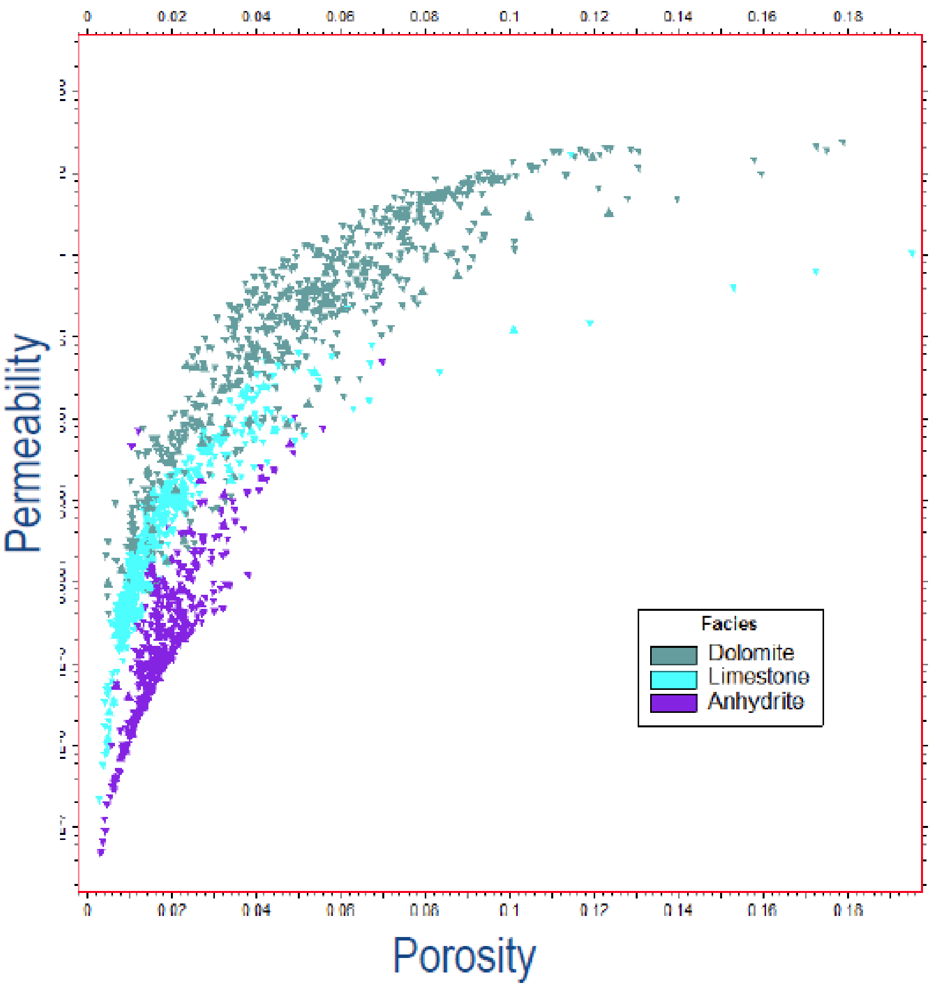
Carbon Services

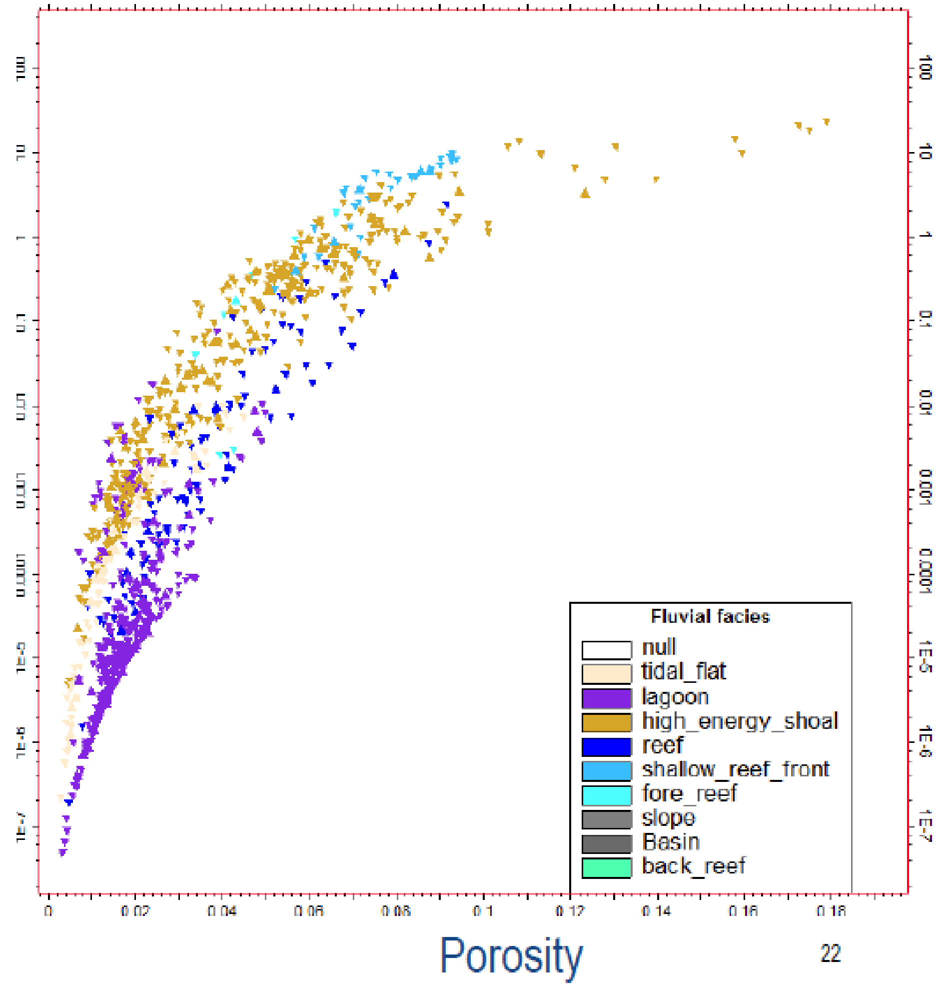




Pore – Perm Cross Plot for Depositional Env

Schlumberger Carbon Services

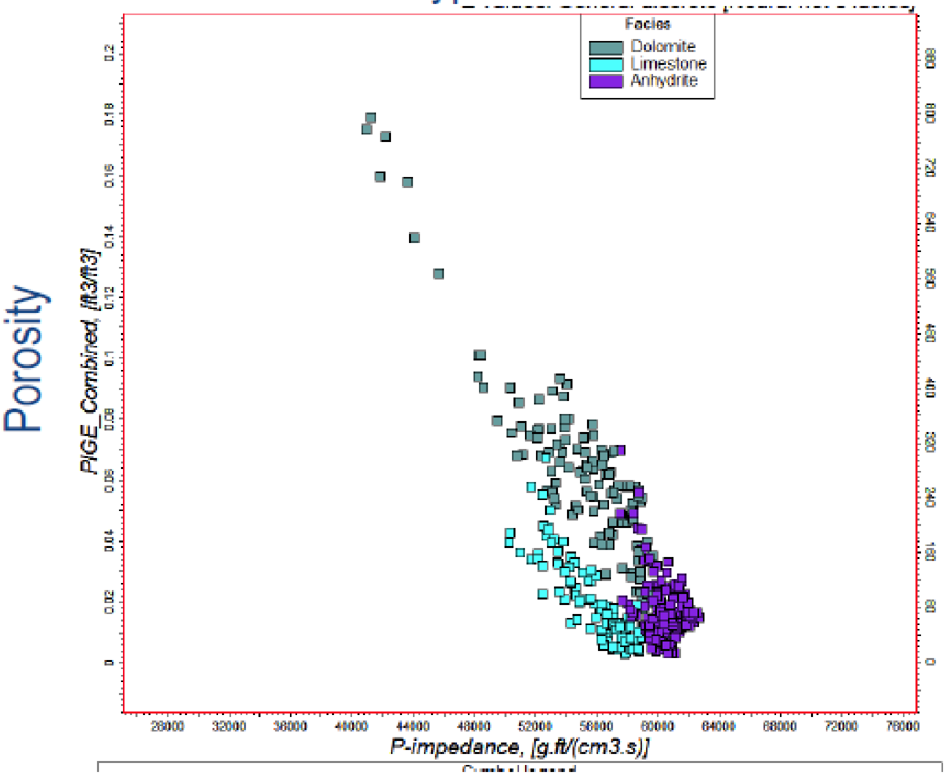




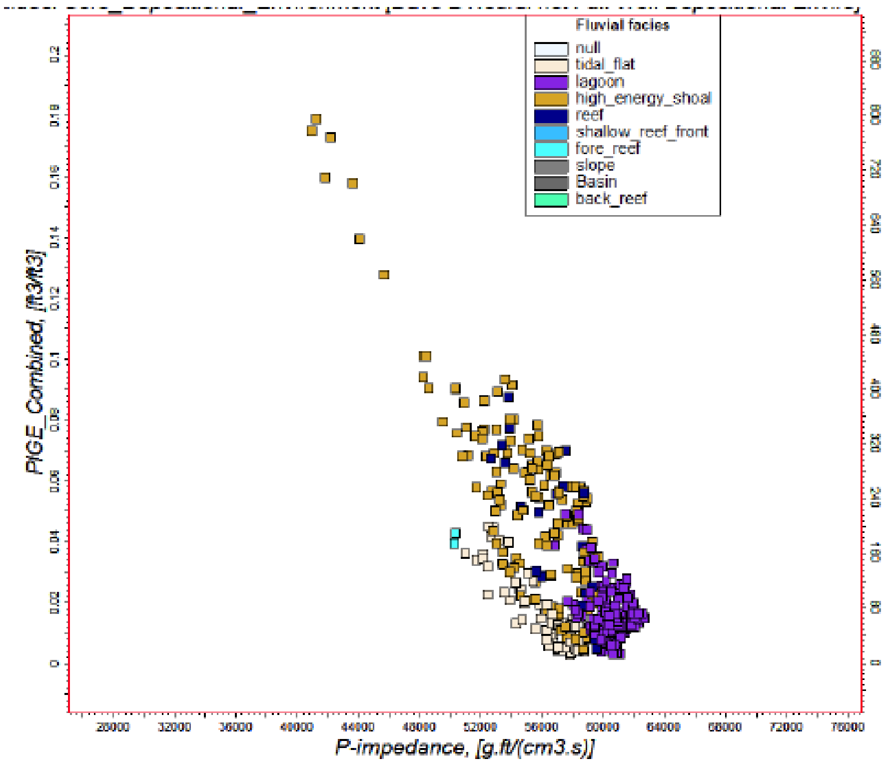
Porosity vs. P-Impedance

Schlumberger Carbon Services

3 Rock Type

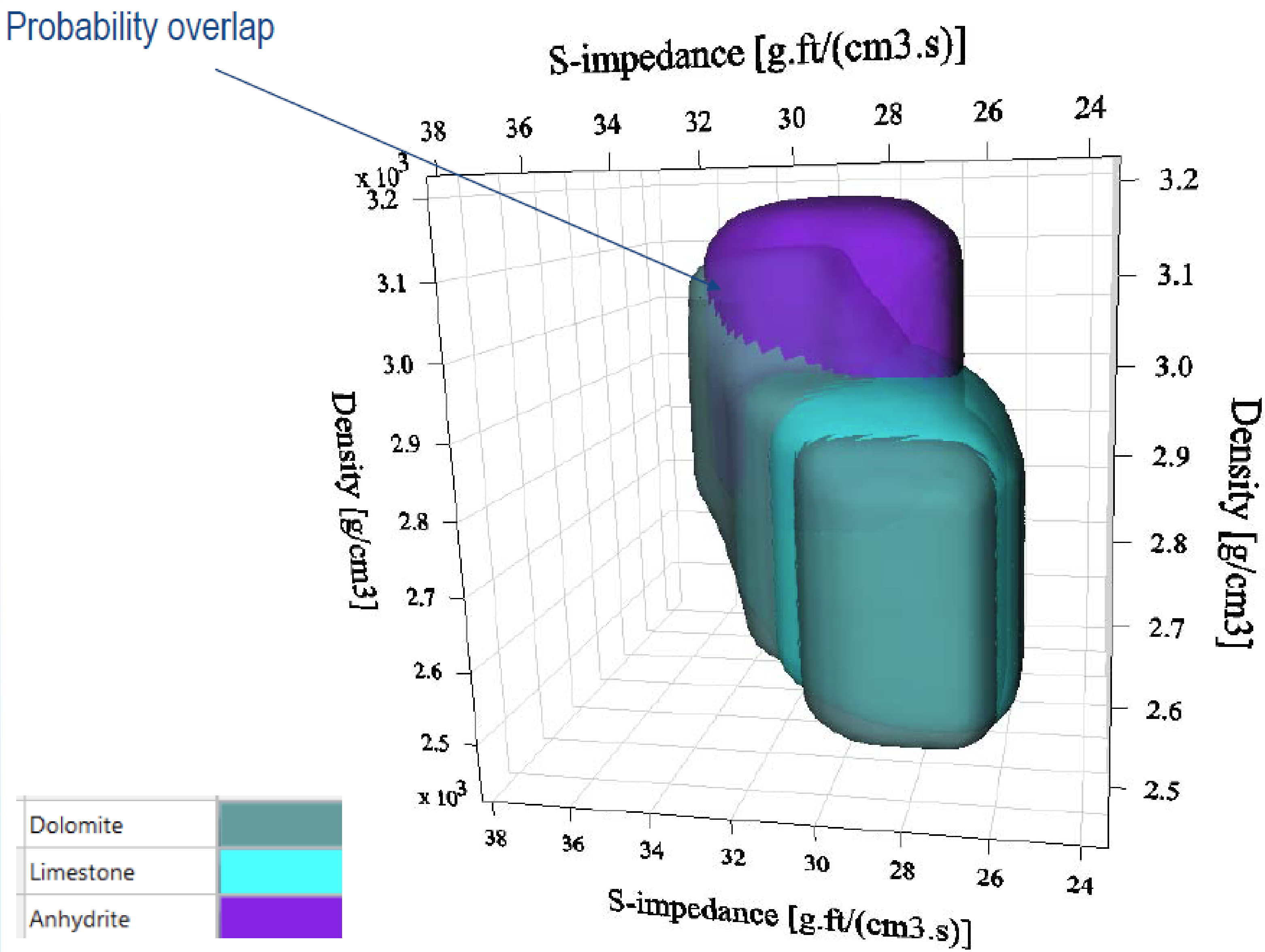


Dave Bowen's Depositional Environment



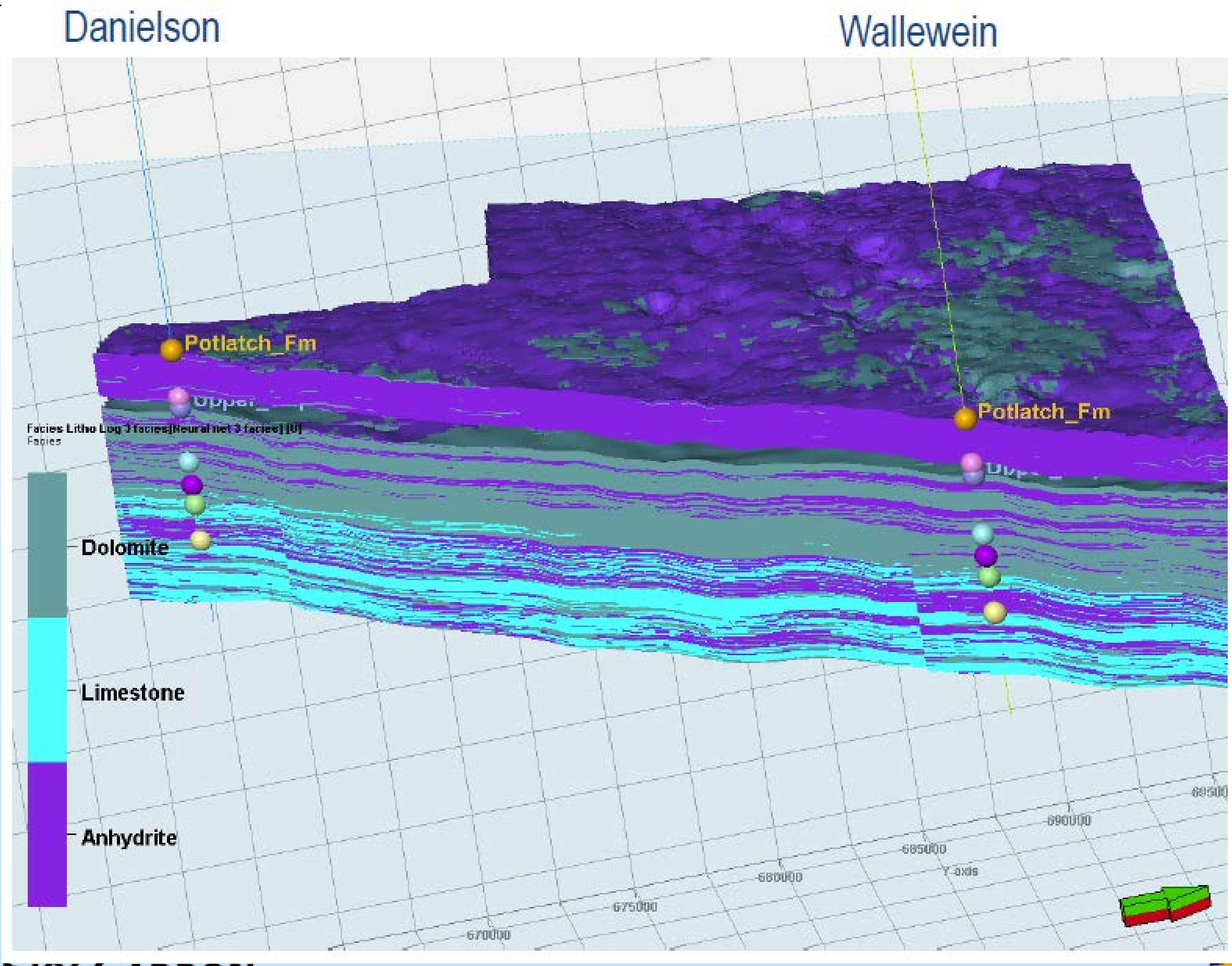
Use Multi-Component Seismic to Model Heterogeneity

Schlumberger Carbon Services



Predicted Rock Types

Schlumberger Carbon Services

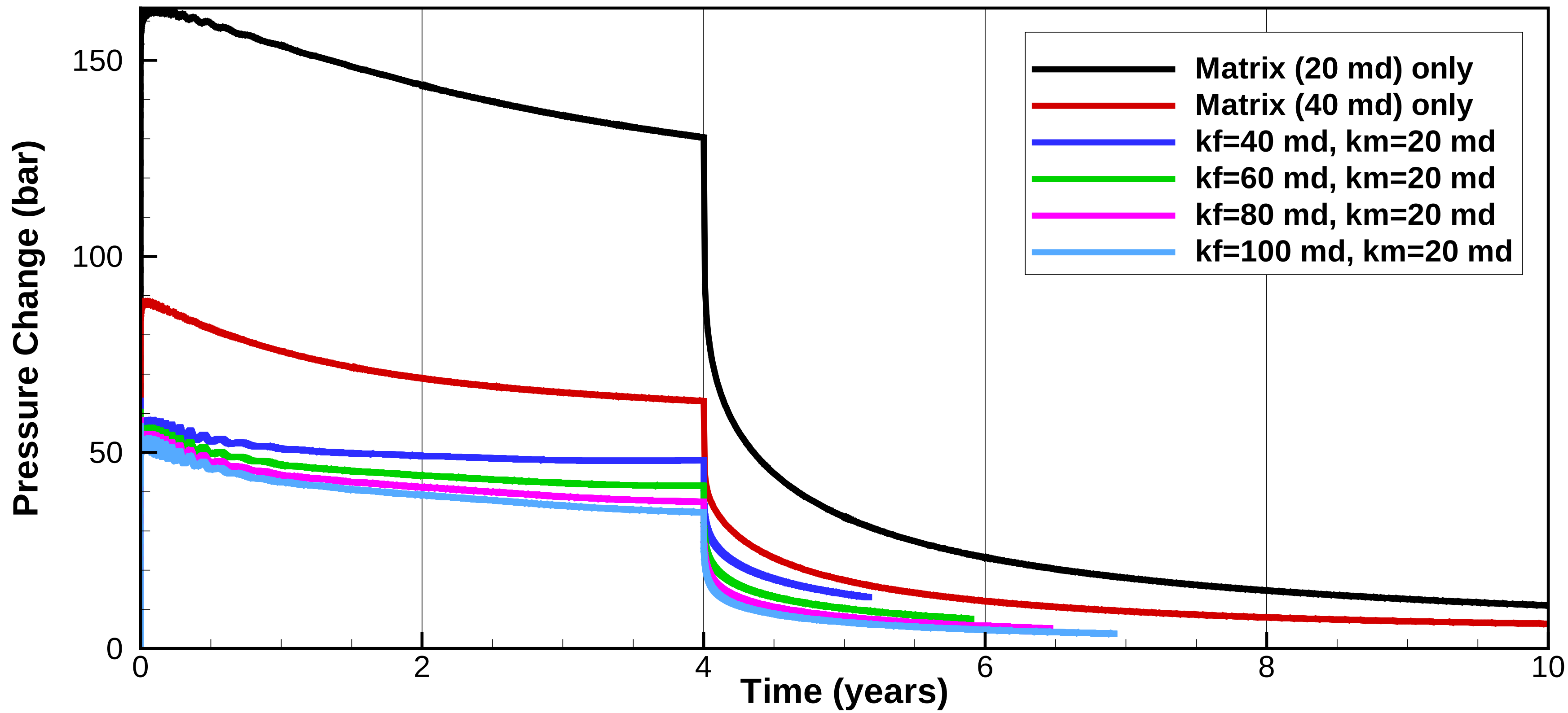


Flow Modeling - Multiple Interacting Continua (MINC)

The cores extracted from both wells and the step-rate injection tests at the monitoring well showed that the target production/injection formation, the Middle Duperow, is highly fractured in its high-porosity zone.

- 2D radial MINC TOUGH2 model, with one fracture continuum and four matrix continua, with volumetric fraction of 0.01, 0.05, 0.20, 0.34, and 0.40, and porosity of 1.0, 0.15, 0.10, 0.10, and 0.08, respectively;
- In this model, global fracture-fracture connections, global matrix-matrix connections, and local fracture-matrix connections are considered;
- Four fracture permeability (Kf) parameters are considered;
- Fracture spacing of the high-porosity layer of the Middle Duperow is based on core fracture mapping and FMI logging, and fracture aperture or fracture permeability is based on the step-rate injection test analysis and sensitivity analysis;
- The matrix permeability (Km) is based on the effective permeability derived from the step-rate injection tests, while matrix porosity is based on core measurements;

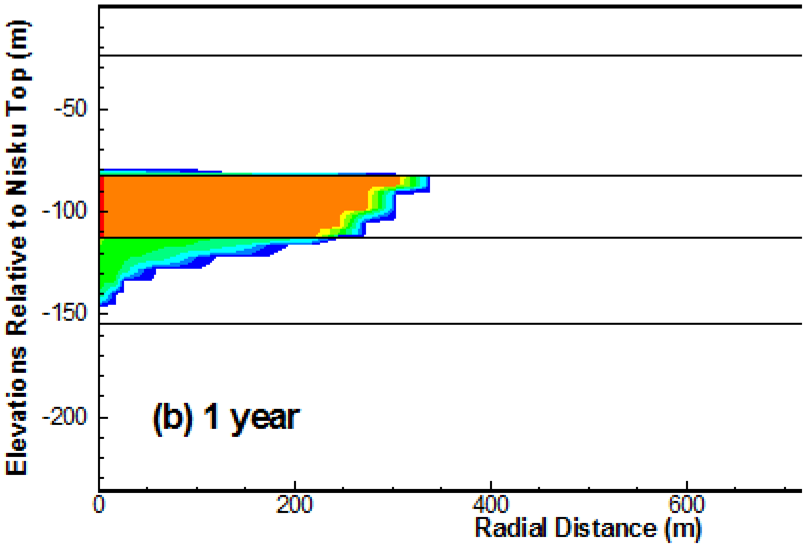
MINC Simulated Pressure Buildup (ΔP)

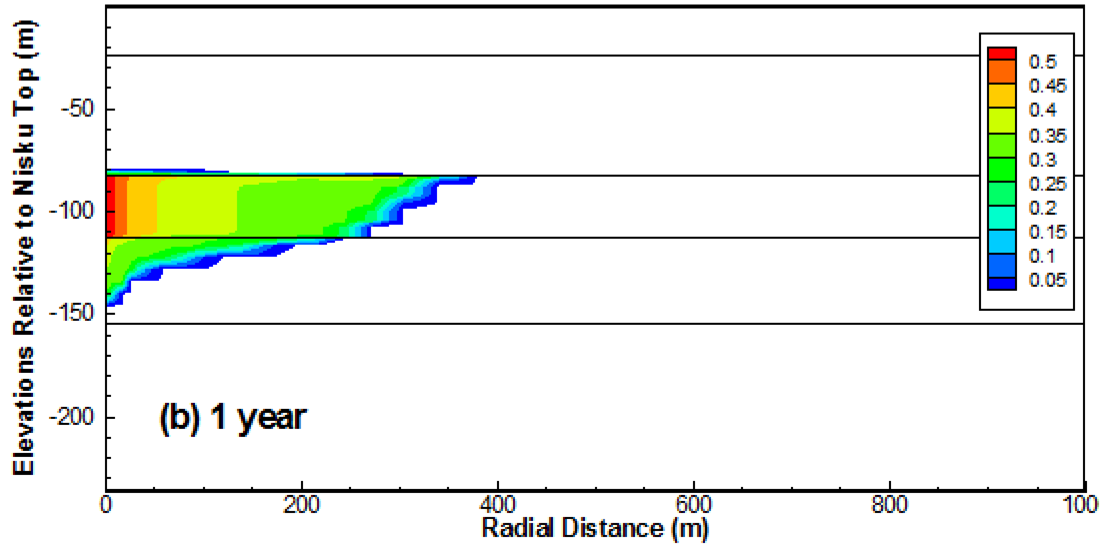


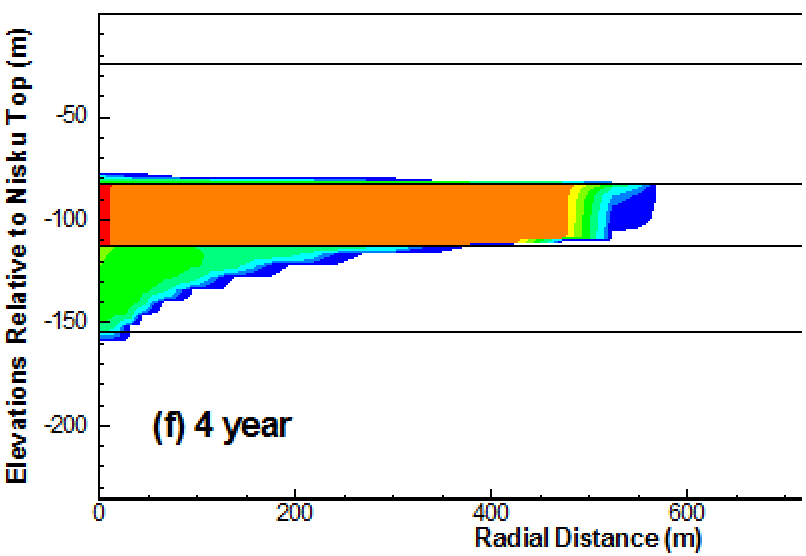
Simulated bottomhole injection ΔP, as a function of time in 6 cases

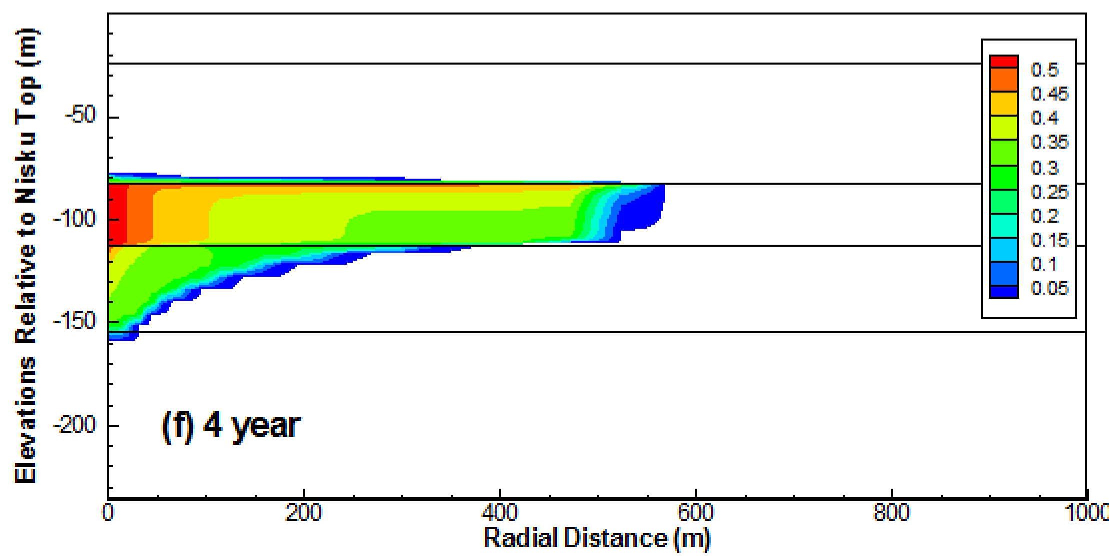
MINC Simulated CO_2 Plumes

Fracture | **Matrix**









MINC Simulation results

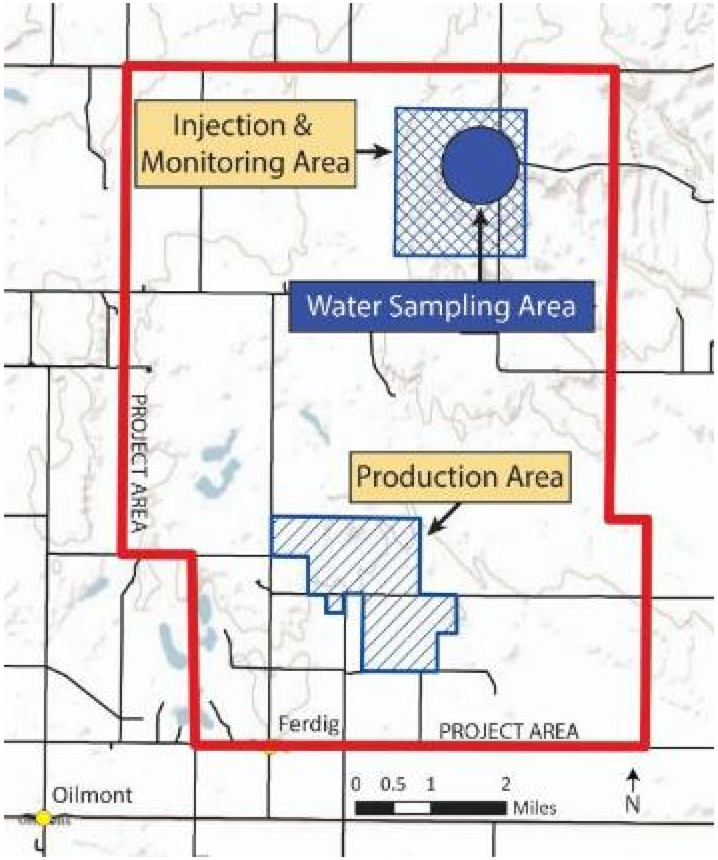
Site-specific data show the Middle Duperow injection target is highly fractured. We developed a MINC model for a 2D radial TOUGH2 model, with one fracture continuum and four matrix continua.

- The site-specific data used in the model includes matrix porosity from core measurements, matrix permeability from the step-rate injection test, fracture spacing from core images, and fracture permeability through different sensitivity cases;
- The injection rate is constant at 250,000 Mt CO_2 /yr over four years;
- The simulated bottomhole injection pressure indicates that the fractured Middle Duperow has sufficient injectivity because fractures significantly lower injection pressure in comparison to matrix only cases;
- The majority of injected CO_2 is stored in the rock matrix because of the strong fracture-matrix interactions of CO_2 flow;
- The benefits of enhanced injectivity and sufficient storage efficiency in fractured rock can be attributed to the high mobility of CO_2 flow in fractures, with high CO_2 saturation and thus relative permeability, and to the strong fracture-matrix interaction of CO_2 flow.

Key Points

- Seismic indicates that structure conforms to the original mapping and no major faults are present in the injection area.
- Modern log suites from the production area and injection area demonstrate rock units in the reservoir intervals are very continuous and correlate extremely well over 7 miles.
- Core and log data indicate very good reservoir properties consistent over large regions.
- Natural fracturing is present but is bedding constrained and confined to the reservoir interval.
- Core from the Potlatch Anhydrite and the Upper Duperow caprock demonstrate the mechanical integrity of both intervals.

Assurance Monitoring - Establishing a Baseline Before CO2 Injection



- Water chemistry
- Water quality
- CO_2 soil flux
- Imaging of vegetation
- Atmospheric CO_2

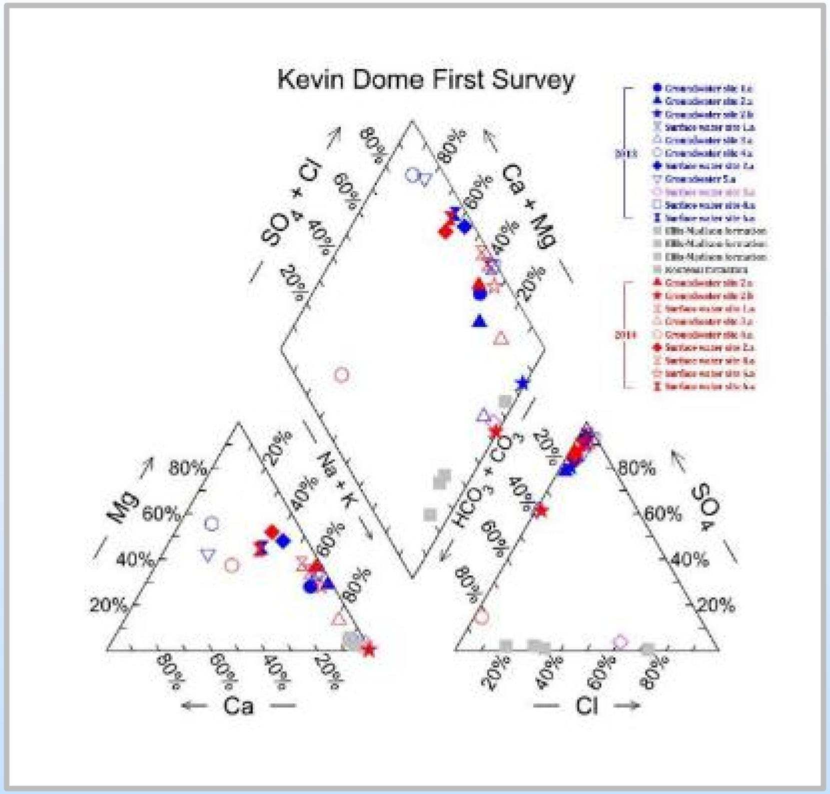
Big Sky Carbon Sequestration Partnership

Montana State University

SAMPLING OF SHALLOW WELLS AND SURFACE WATERS

Samples collected Oct. 2013 and May 2014 from 6 wells and 6 surface waters in a 1.5 mile radius of the proposed injection well site.

General Water Chemistry



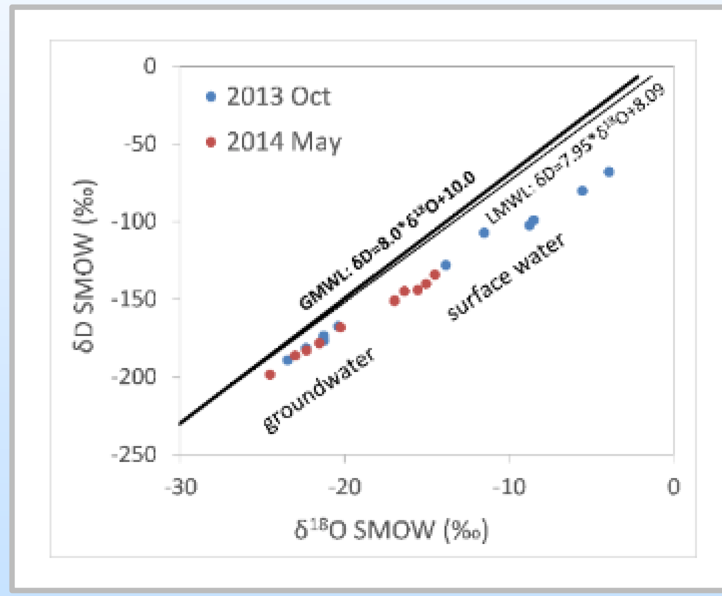
Idaho National Laboratory

- Most common ions are sodium (Na), sulfate (SO_4), and chloride (Cl)
- Chemically consistent with geology of the area
- Significant seasonal variability

Tracers

Establish a baseline for introduced (SF_6, SF_5CF_5, PFC's, ^{14}C) and natural (noble gases, H and O isotopes, ^{13}C) tracers.
RESULTS: Very low levels of SF_6, SF_5CF_3, PFC's measured (mostly below the detection limit)

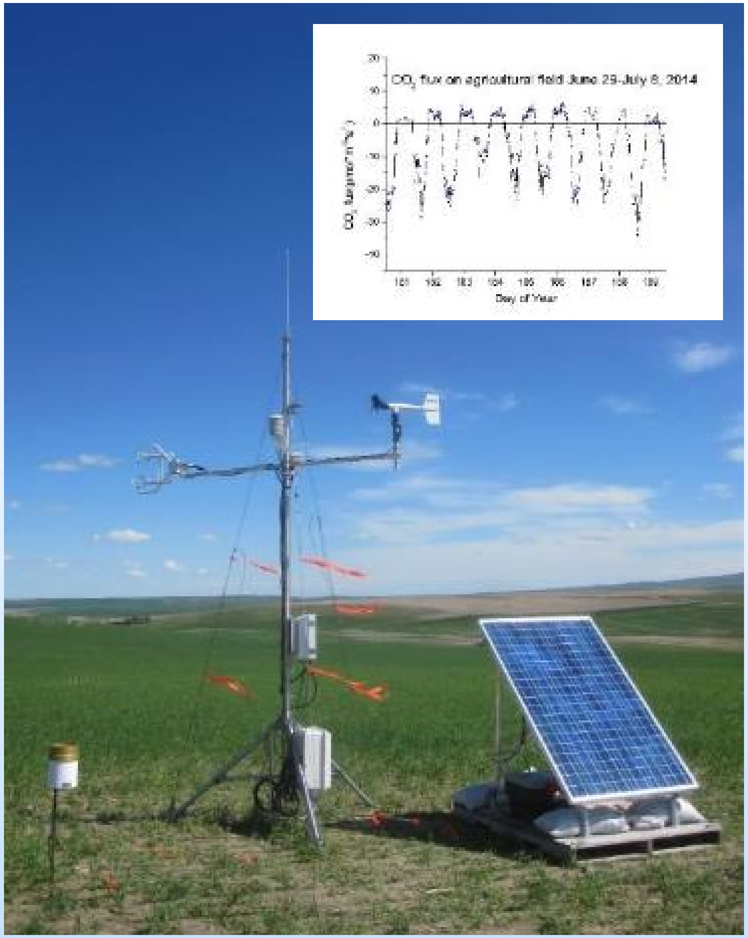
H and O Isotopic Data



Lamont-Doherty Earth Observatory

δ^2H and $\delta^{18}O$ values are slightly below the global meteoric water line (GMWL) and the local meteoric water line (LMWL)

EDDY COVARIANCE



MSU

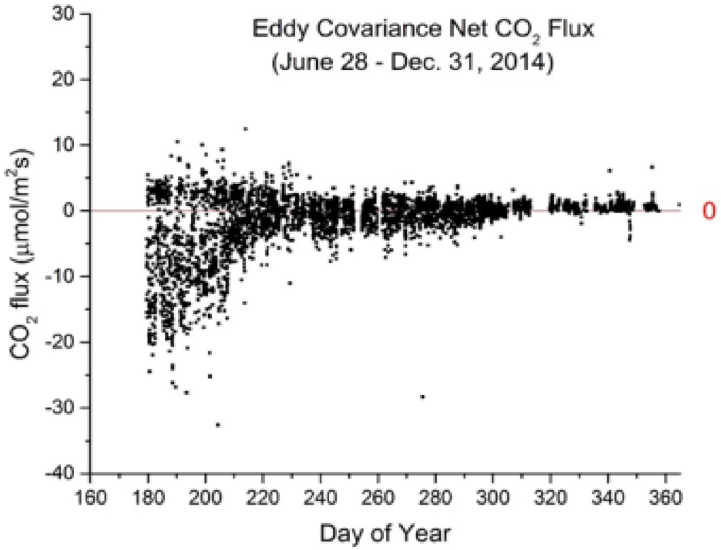
- Installed June 2014
- Data so far consistent with field in agricultural use

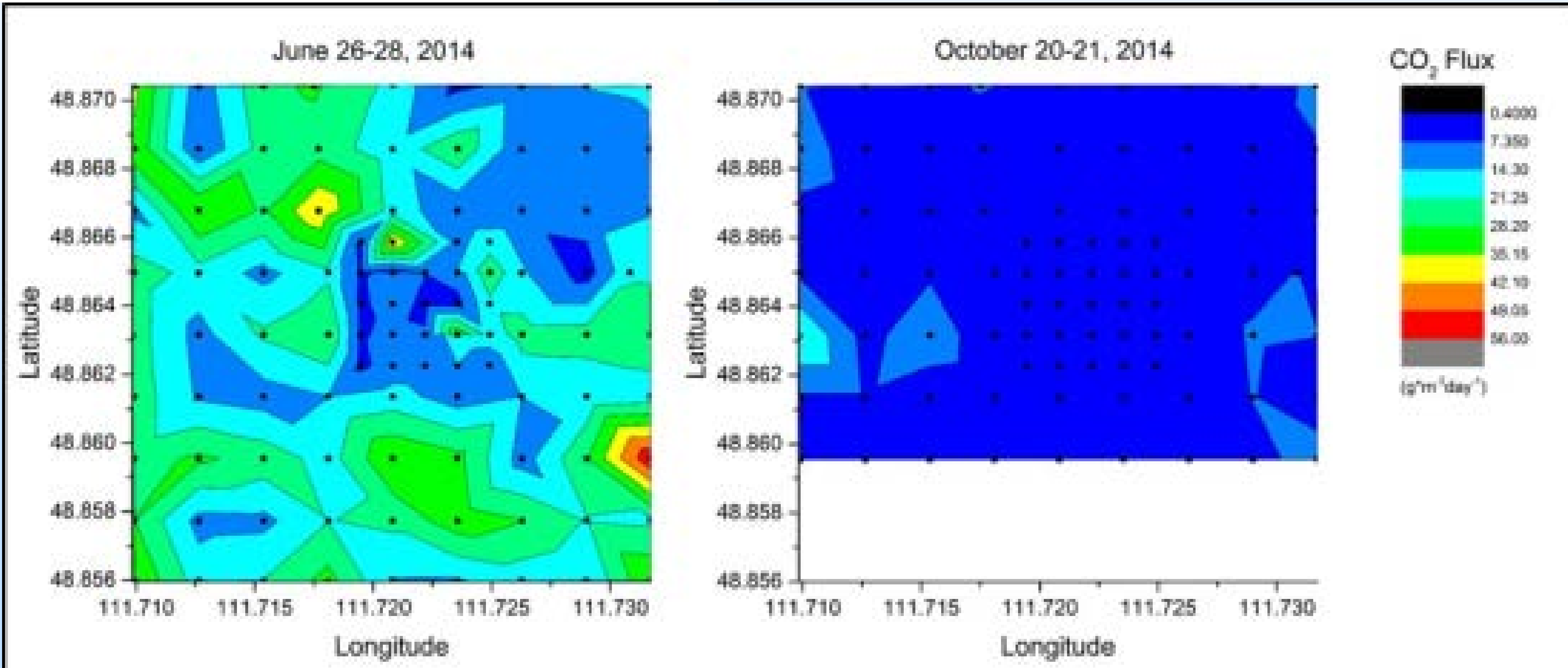
SOIL CO_2 FLUX SURVEY

MSU

- Portable accumulation chamber
- Survey done June 26-28, 2014
- 102-point grid covering 1 square mile centered on proposed injection site
- Values typical of soil under this type of land use

Eddy Covariance & Soil Flux

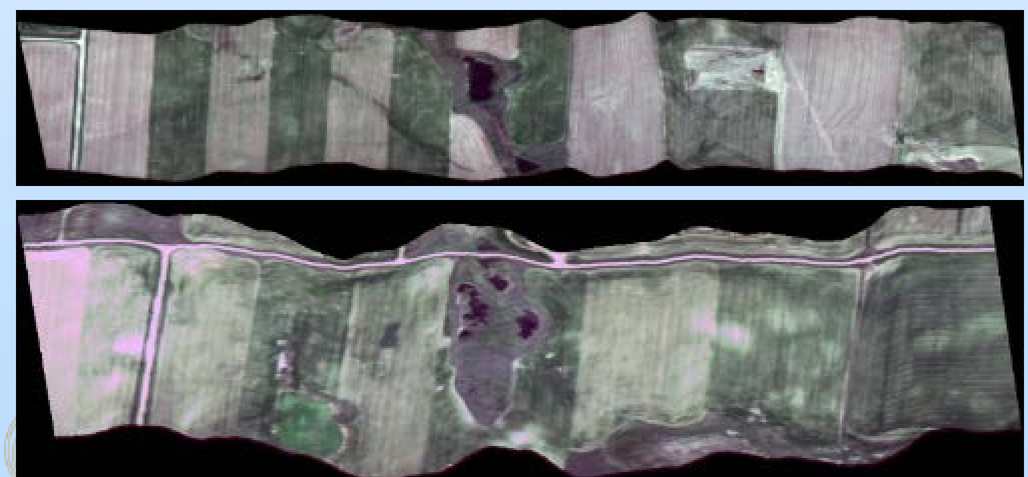




HYPERSPECTRAL IMAGING

The hyperspectral imaging system mounted in a Cessna 172 for flight based monitoring. Spectral reflectance between 400 and 1100 nm for each pixel of a digital image is collected.

The flight plan for monitoring the production well area, pipeline area, and injection well area.

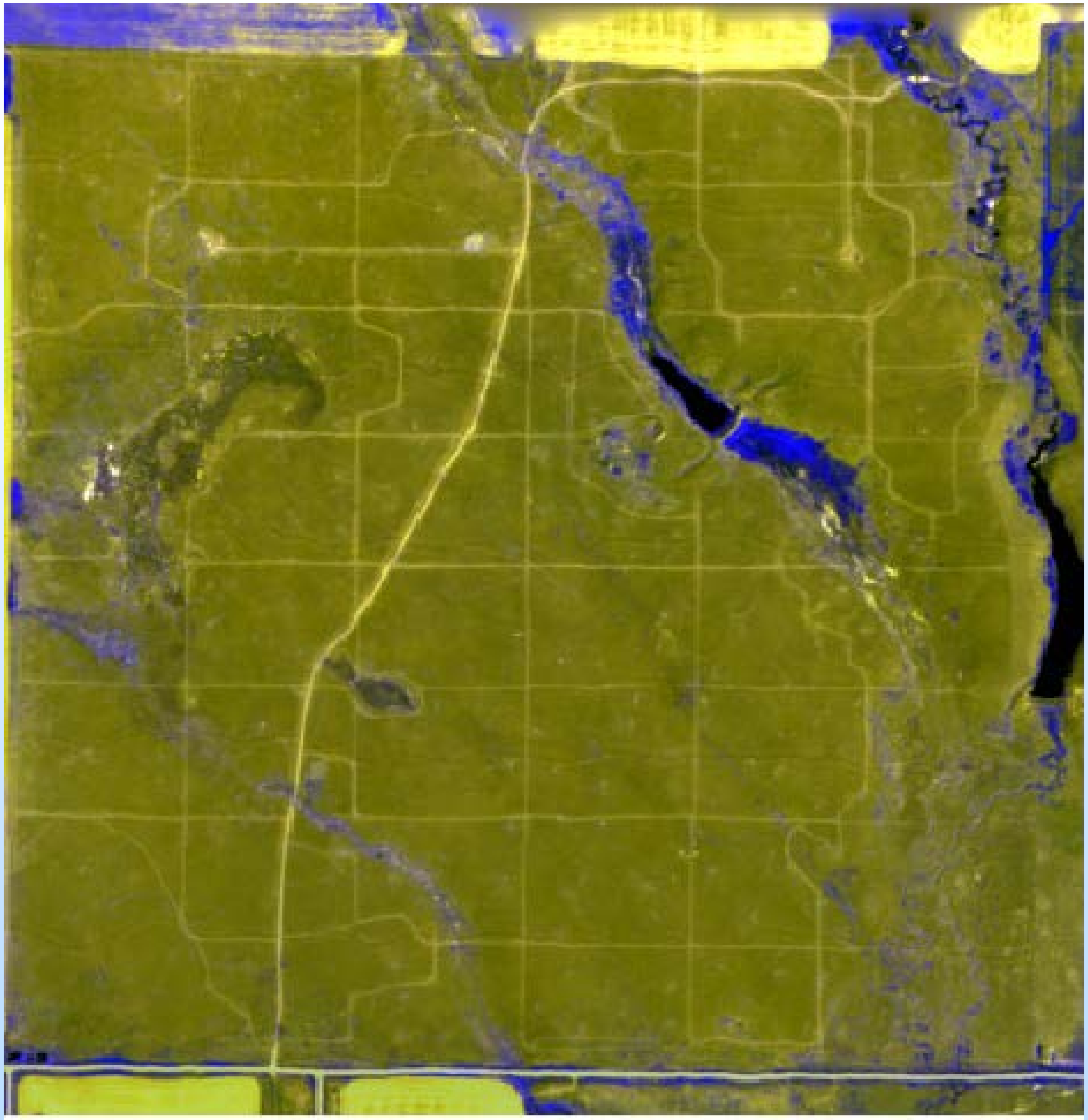


Three color images of two flight paths on June 24, 2014. Initial geo-rectification using the Inertial Measurement Unit was conducted and further improvements to the geo-rectification will utilize ground based GPS data.

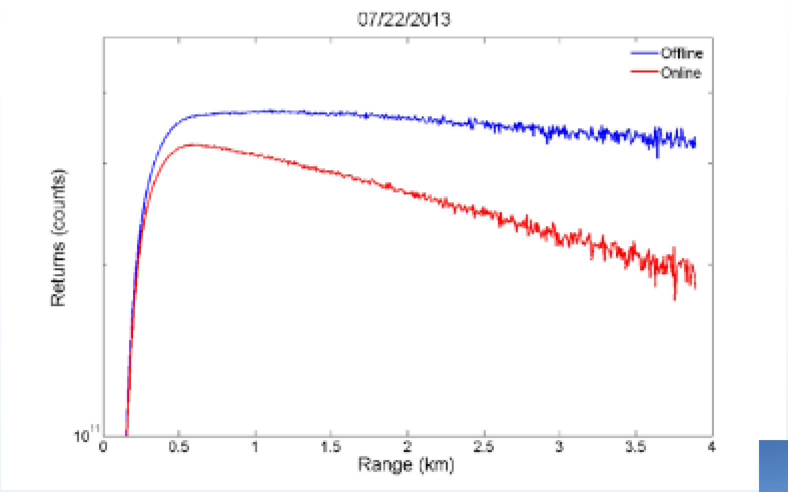
MONTANA STATE UNIVERSITY

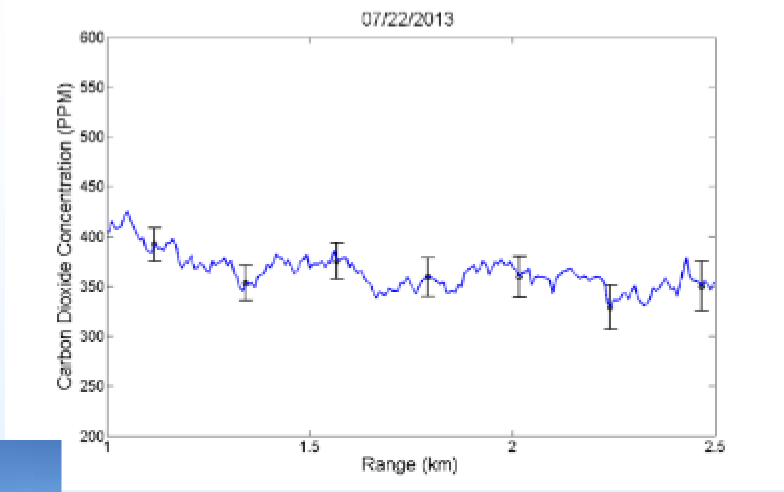
Hyperspectral Imaging

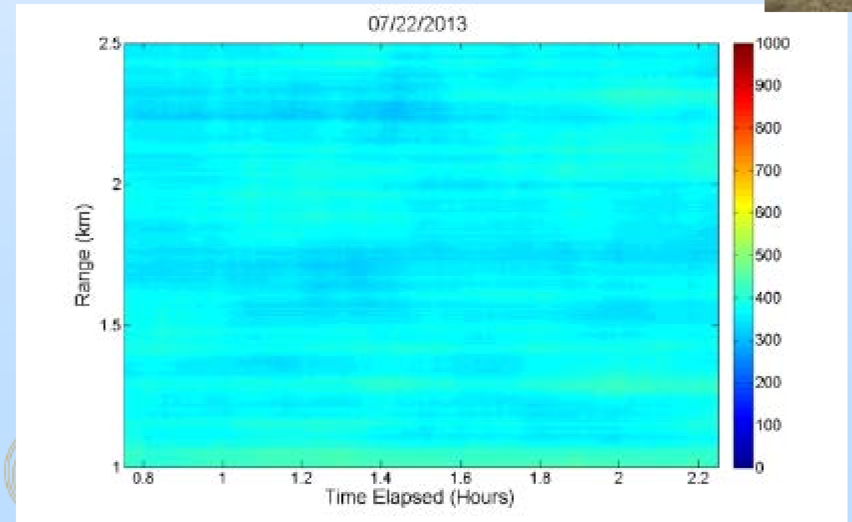
Seismic tracks evident in hyperspectral data when no evidence on the ground was visible

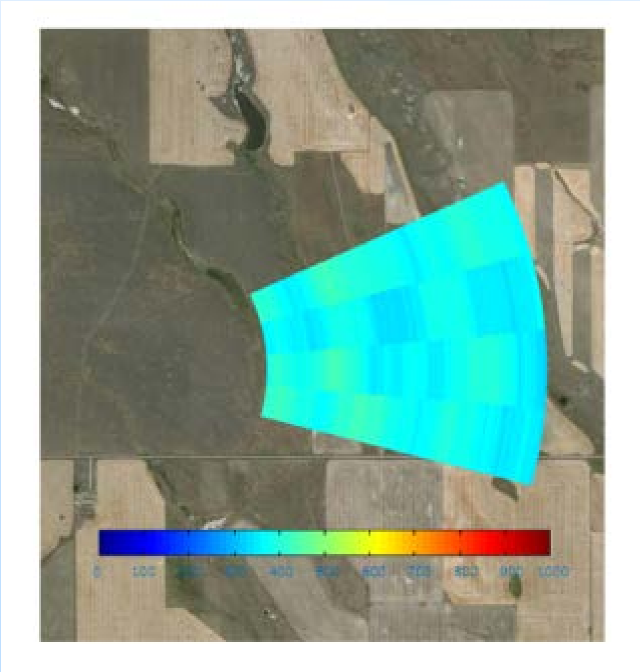


LIDAR (TESTED IN 2013 IN PRODUCTION AREA)









Wallewein (Injection Region) Well Data

Wallewein 22-1 Duperow Samples				
Sample Info				
Well ID	**MSU Sample ID**	**Depth Range**	**Date Collected**	**TDS (ppm)**
Wallewein 22-1	Zone 3, Sample 1	4185-4190	December 22, 2014	**6420**
Wallewein 22-1	Zone 3, Sample 2	4185-4190	December 22, 2014	**6120**
Wallewein 22-1	Zone 3, Sample 4	4185-4190	December 22, 2014	**2815**
Wallewein 22-1	Zone 3, Sample 5	4185-4190	December 22, 2014	**5350**
Wallewein 22-1	Zone 3, Sample 6	4185-4190	December 22, 2014	**7010**
Wallewein 22-1	Zone 5, Sample 1	4040-4057	January 9, 2015	**11000**
Wallewein 22-1	Zone 5, Sample 2	4040-4057	January 9, 2015	**6692**
Wallewein 22-1	Zone 5, Sample 3	4040-4057	January 9, 2015	**9200**
Wallewein 22-1	Zone 5, Sample 4	4040-4057	October 15, 2015	**8510**
Wallewein 22-1	Zone 5, Sample 4a	4040-4057	October 15, 2015	**10200**
Wallewein 22-1	Zone 5, Sample 5	4040-4057	October 22, 2015	**7250**
Wallewein 22-1	Zone 5, Sample 5a	4040-4057	October 22, 2015	**8750**
Wallewein 22-1	Zone 5, Sample 6	4040-4057	October 27, 2015	**7160**
Wallewein 22-1	Zone 5, Sample 6a	4040-4057	October 27, 2015	**8780**
Wallewein 22-1	Zone 5, Sample 7	4040-4057	October 27, 2015	**7190**

Accomplishments to Date

Regional Characterization

- Contributions to Carbon Atlas
- Evaluating EOR opportunities

Outreach

- Multiple community meetings, individual landowner meetings, website, newsletters, etc.
- Significant interest in collaboration

Permitting

- NEPA EA complete
- Landowner permits in place
- Permit database tool

Risk Management

- FEPS & Scenarios complete
- Database created
- Preliminary probabilistic modeling preformed

Site Characterization

- Kevin Atlas created with surface and subsurface data incorporated
- Over 32 sq. mi. 3D, 9C seismic shot
- Static geologic model created
  - Hundreds of wells for tops, 32 logs digitized for geophysical parameters, 2D seismic, 3D, 9C seismic
- Initial flow modeling performed
  - Injection & production regions, sensitivity analysis, reactive transport
- First two wells drilled
  - Core acquired, analyzed
  - Logs acquired
  - Seismic being tied to wells
  - Well tests performed
- Baseline assurance monitoring initiated
  - Three water sampling campaigns
  - Soil flux (chambers, eddy covariance)
  - Hyperspectral Imaging flight
  - LIDAR

Accomplishments to Date

Seismic

- Joint inversions performed, depth converted
- Full waveform inversion initiated

Modeling

- Version 2 static geologic model created
- Version 3 using facies interpretation under way
- Fracture / matrix flow modeling well underway

Core Analysis

- Fracture / matrix core flow experiments initiated
- Caprock studies well underway

US-EPA Class IV Requirements

Project Re-scope: Class VI - § 146.86 Injection well construction

- All well materials must be compatible with fluids with which the materials may be expected to come into contact
- Logging required
- Continuous monitoring of the annulus space between the injection tubing and long string casing.
- Continuous monitoring of injection pressure
- **Surface casing set below lowermost USDW**

US-EPA Class IV Requirements

Project Re-scope: Class VI - 146.93 Post-injection site care

- Default is 50 years
- Alternative PISC can be approved by Director
- PISC Plan requires monitoring methods, locations and frequency and schedule for submitting results to Director
- Alternate PISC time period must demonstrate non-endangerment of USDWs

Main Issues:

- **Duration, especially for pilot / demo projects**
- **Doesn't allow for injectivity tests**
- **May discourage investigating secondary sites**

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 VI, but allowed under Class II

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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).

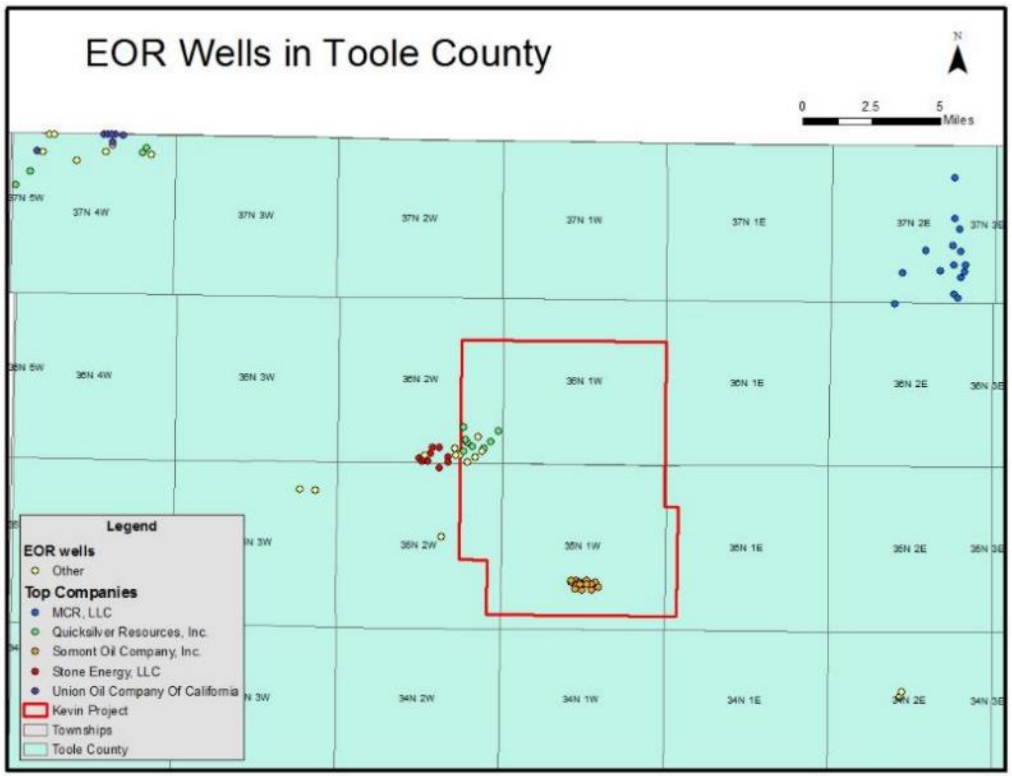
The Madison is oil producing and so is NOT a USDW under Class II because of exemptions

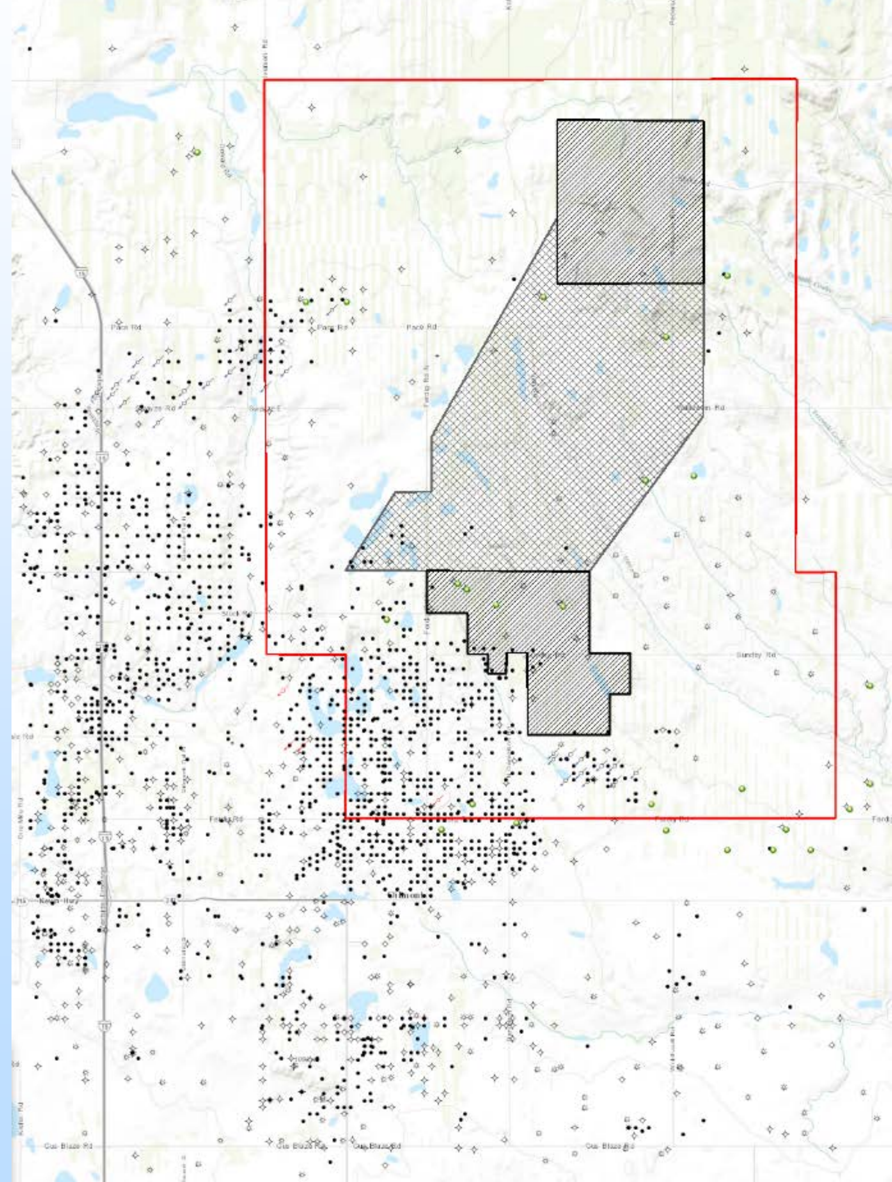
Yet to store in the Duperow beneath the Madison, the CO_2 storage project would have to treat the Madison as a USDW. This would mean:

- 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

US-EPA Class IV Requirements

CO_2 EOR in Could be Permitted in Class VI USDW

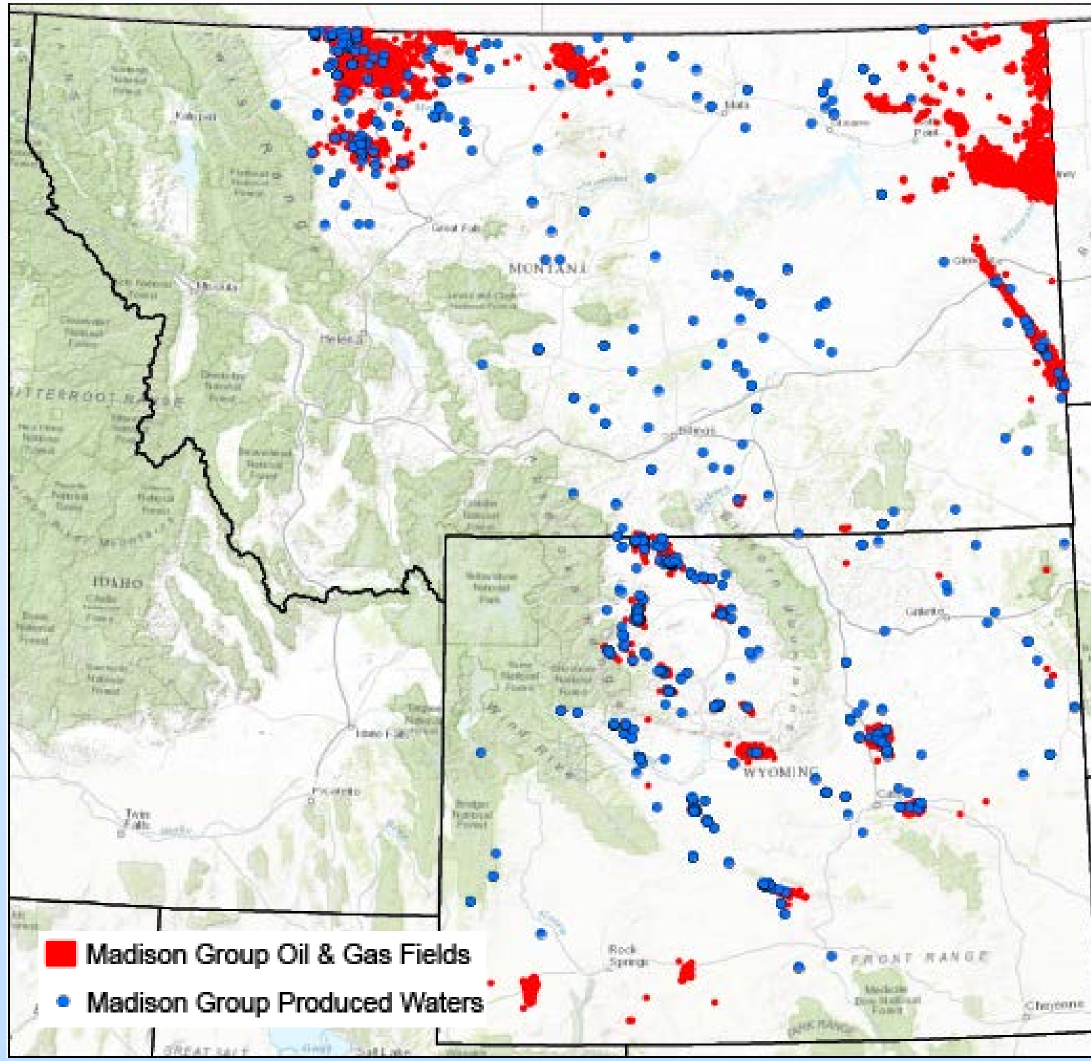




US-EPA Class IV Requirements

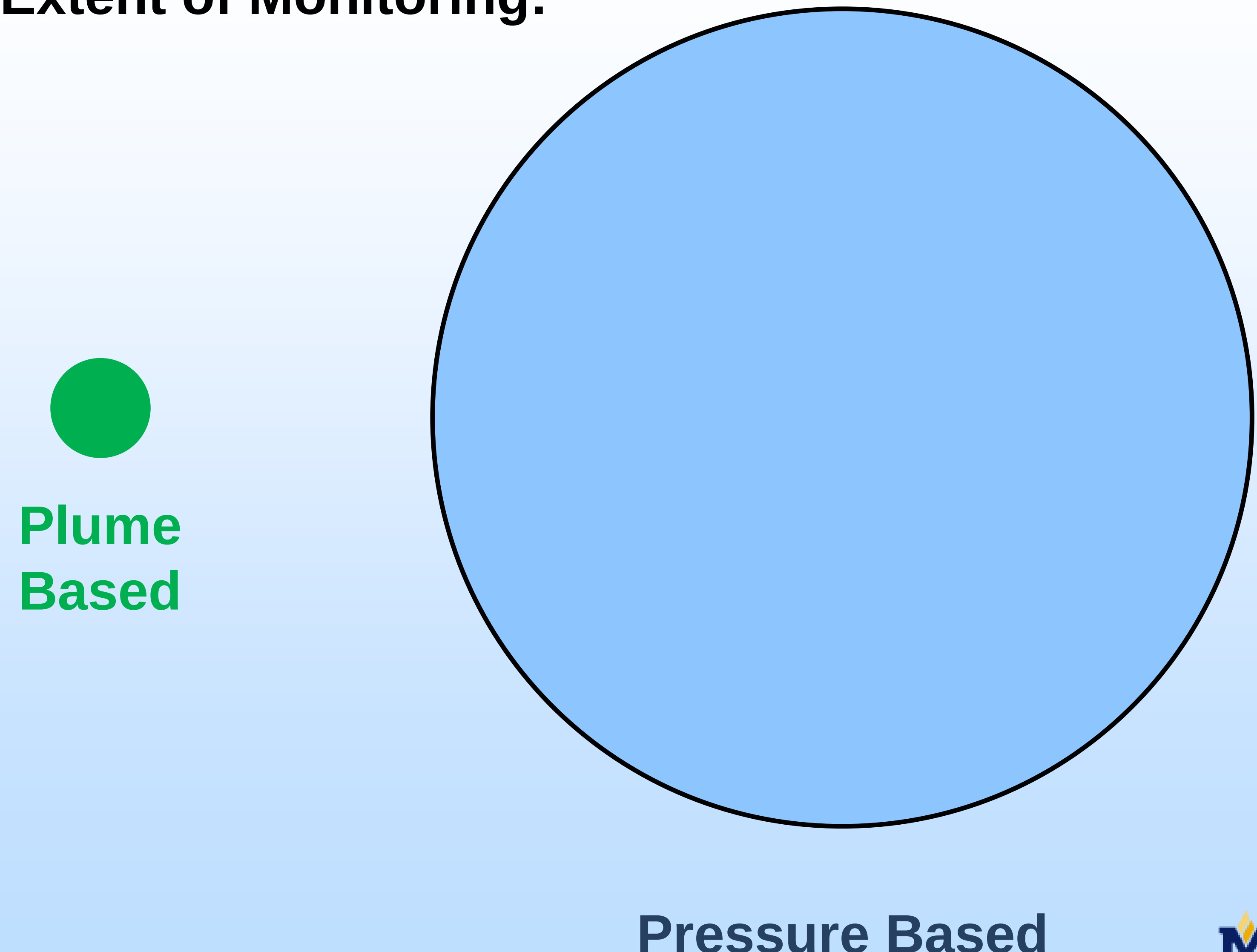
Regional Significance:

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



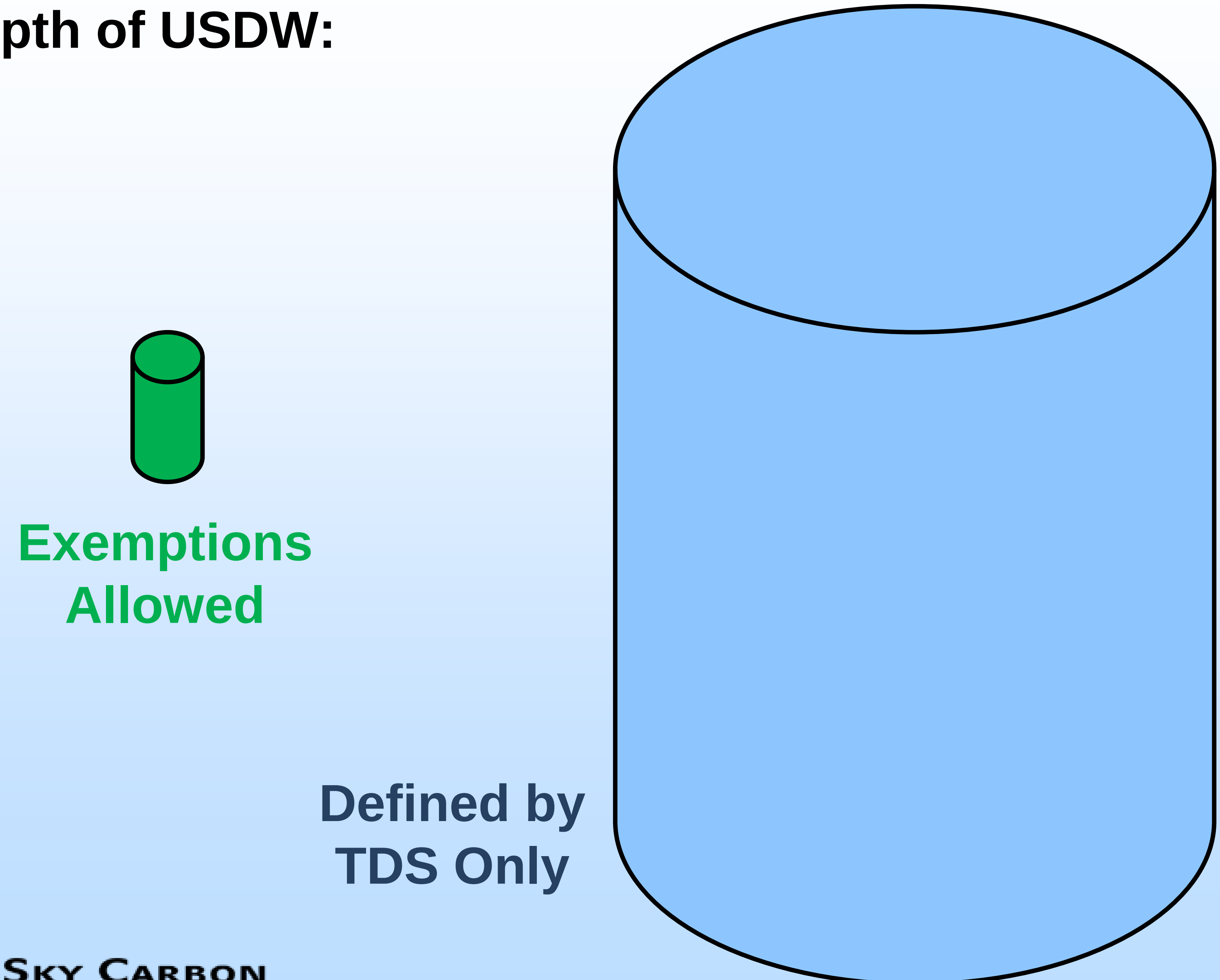
US-EPA Class IV Impact on Research Projects

Areal Extent of Monitoring:



US-EPA Class IV Impact on Research Projects

Depth of USDW:



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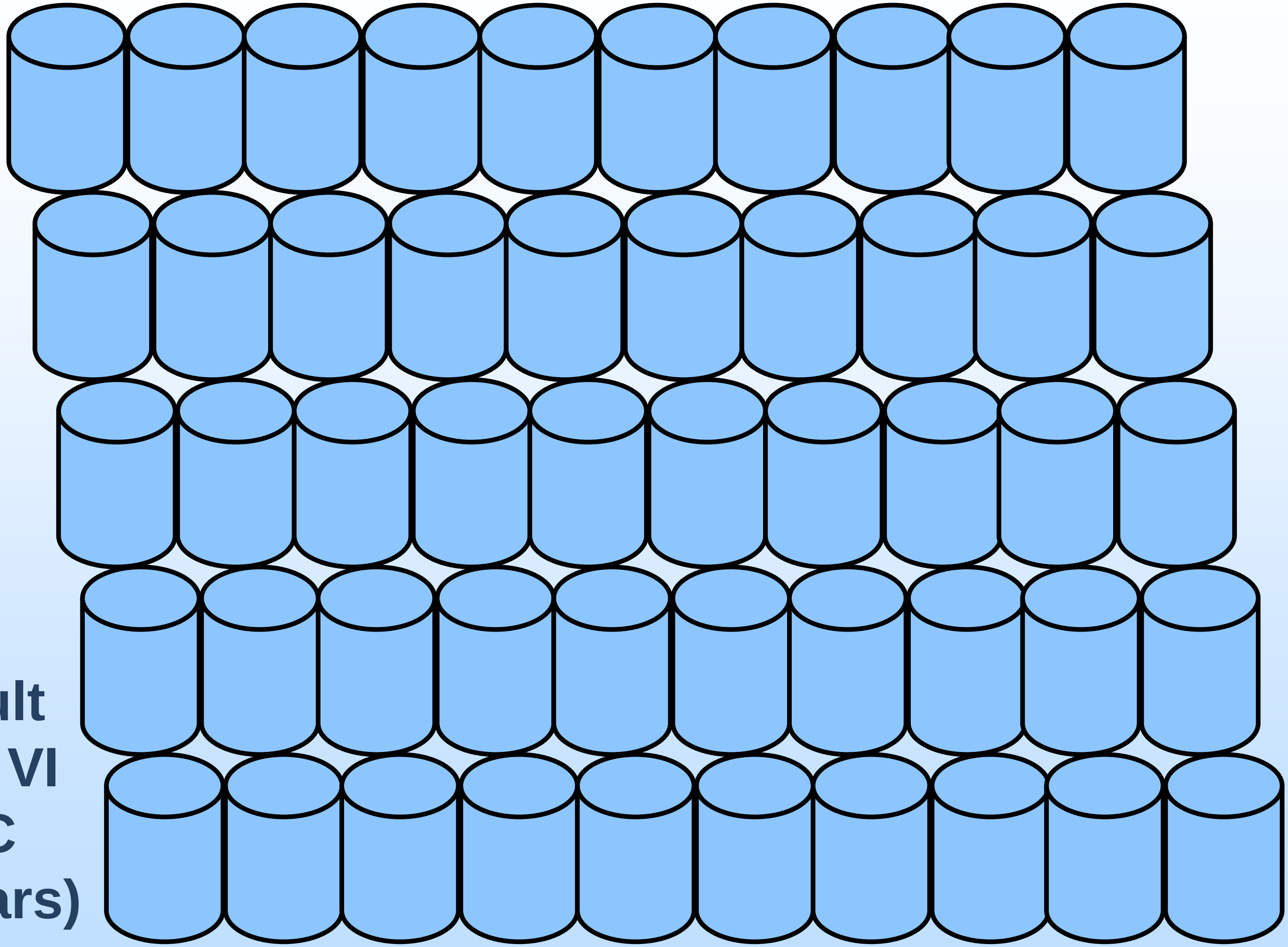
Compliance or Science?

Duration of Monitoring:

Phase III Program (3 years)



Default Class VI PISC (50 Years)

An enormous change in the 4 dimensional post-injection monitoring responsibility

US-EPA Class IV Impact on Research Projects

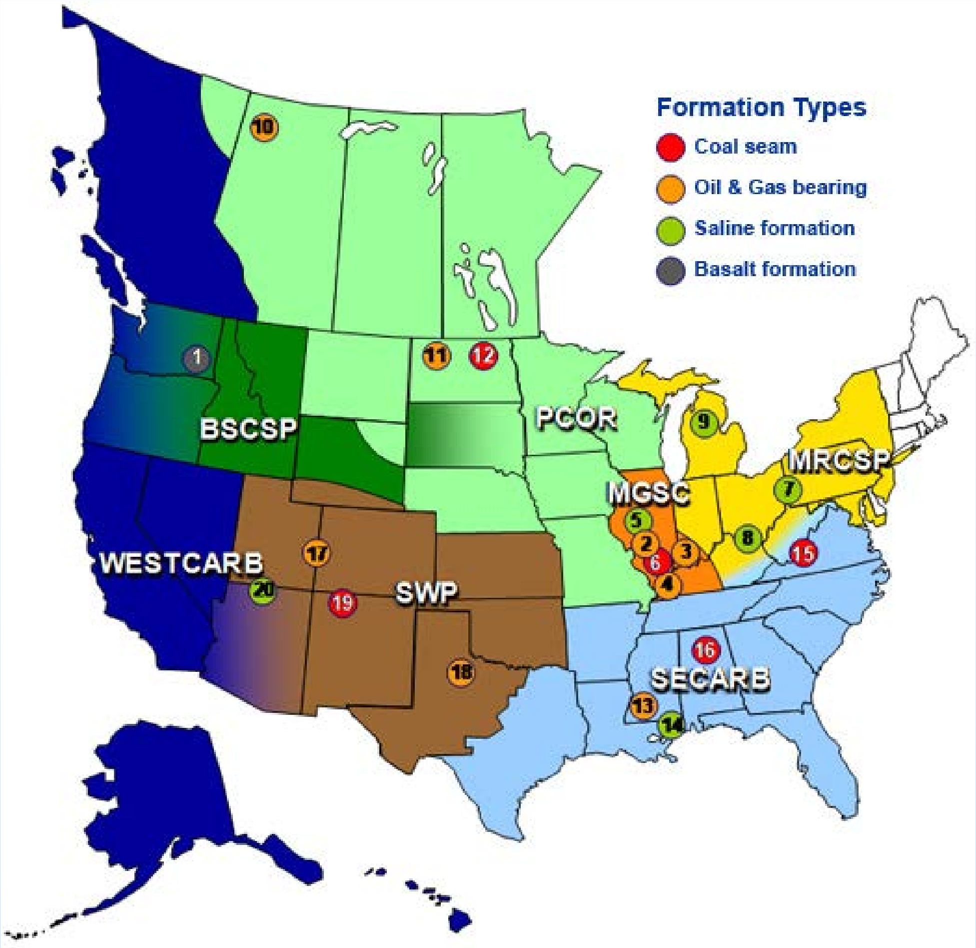
Class VI Scale and Cost:

- EPA documentation indicates concern about risk related to total quantity of injectate (Preamble to Rule, Factsheet, Multiple presentations).
- This makes sense. A 500 MW power –plant could inject ~4MT / yr for 50 years – 200 MT total. And there could be many. This is a different scale than most current UIC activities.
- But current experimental demos are ~250 kT over 4 yrs, 6.25% of the injection rate and 2% total quantity of a commercial project.
- Can we do something to confirm EPAs intuition that risk scales with injectate quantity? Can EPA issue guidance reducing stringency so demos can yield more useful information?

Everything we can do to SAFELY reduce the 4-dimensional extent of compliance monitoring / actions will recoup some of the science

US-EPA Class IV 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

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Synergy Opportunities

- Stiff, thin reservoir zone could be good for studying geomechanical effects
- Danielson well has CO_2 and water present – an opportunity to investigate corrosion issues, wellbore sealing with both fluids present
- GroundMetrics has performed background EM measurements at site

Summary

- Well tests and core indicate dual permeability
- Modeling and well tests indicate fractures contribute strongly to overall permeability
- Modeling suggests very good injectivity
- Tests indicate very good mechanical properties for the caprock
- Joint inversion using shear wave seismic looks promising for imaging the Duperow porosity zone
- TDS in the middle Duperow is too low to get a UIC Class VI permit (even though high levels of H_2S are present)

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

Appendix

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

Benefit to the Program

- **Support industries' ability to predict CO2 storage capacity in geologic formations to within ±30%**
  - The project will correlate logs, core studies, seismic and modeling efforts with multiple iterations through all stages of the project to determine storage capacity in a fractured reservoir. The project also tests storage in a regionally significant formation and in regionally significant structural closures that should refine regional capacity estimates.

- **Develop and validate technologies to ensure 99 percent storage permanence.**
  - The project will use 3D, 9C surface seismic to characterize a fracture reservoir.

Benefit to the Program

- **Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.**
  - We are invstigating the influence of fractures on storagfe efficiency.

- **Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.**
  - BSCSP will use information from this project to contribute to best practices manuals.

Project Overview: Goals and Objectives

Primary objective - maximize the value of the existing Kevin Dome data to DOE's Carbon Storage Program

Success Criteria – Data and analysis from the project fills knowledge gaps in the carbon storage project and assists other carbon storage efforts.

Detailed objectives:

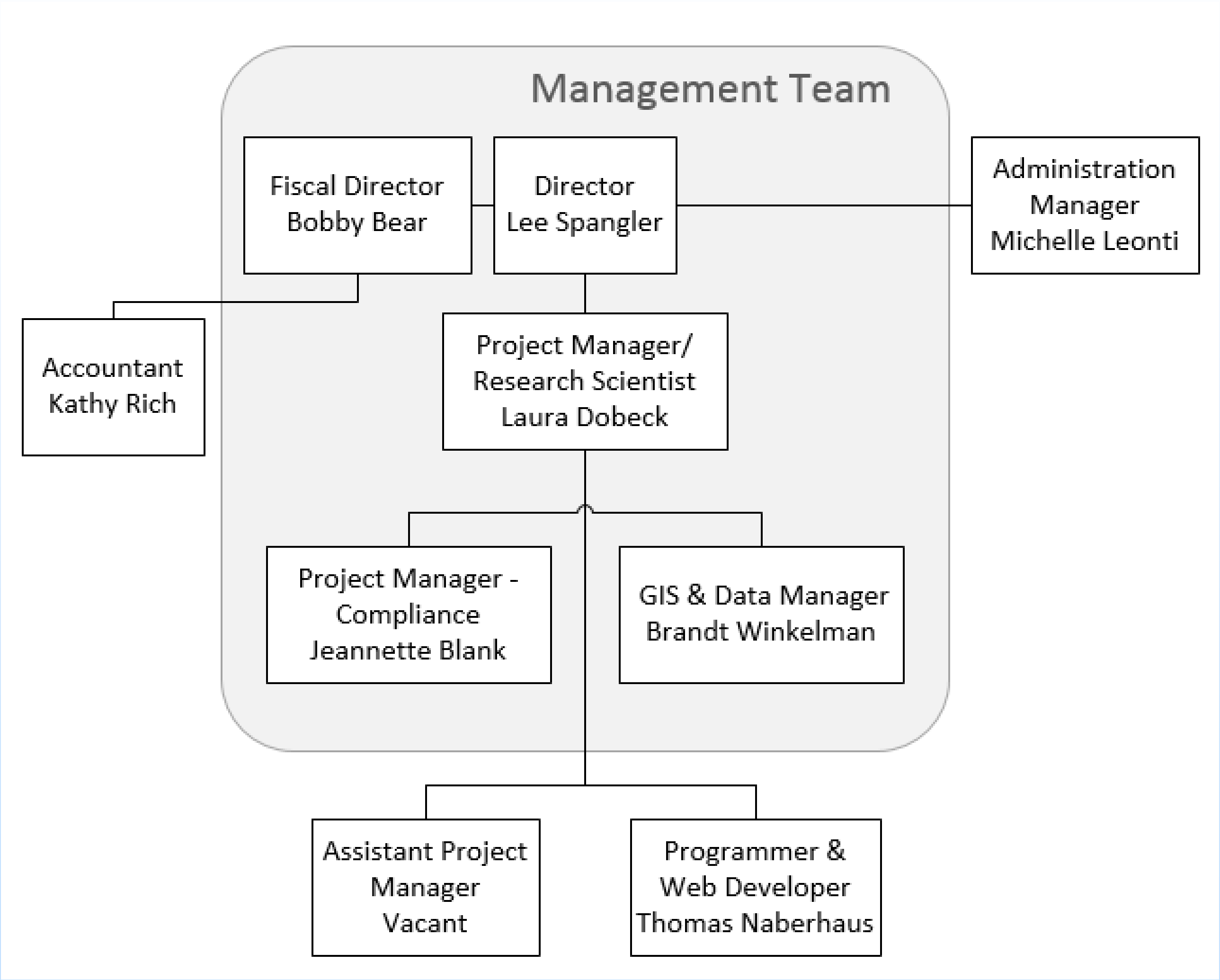
- Complete the core descriptive work and core flood experiments to characterize the pore and fracture geometry of the Duperow formation;
- Measure the fracture-permeability of evaporite and dolomite caprock;
- Perform laboratory measurements of seismic properties as a function of CO_2 saturation;
- Perform 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;

Project Overview: Goals and Objectives

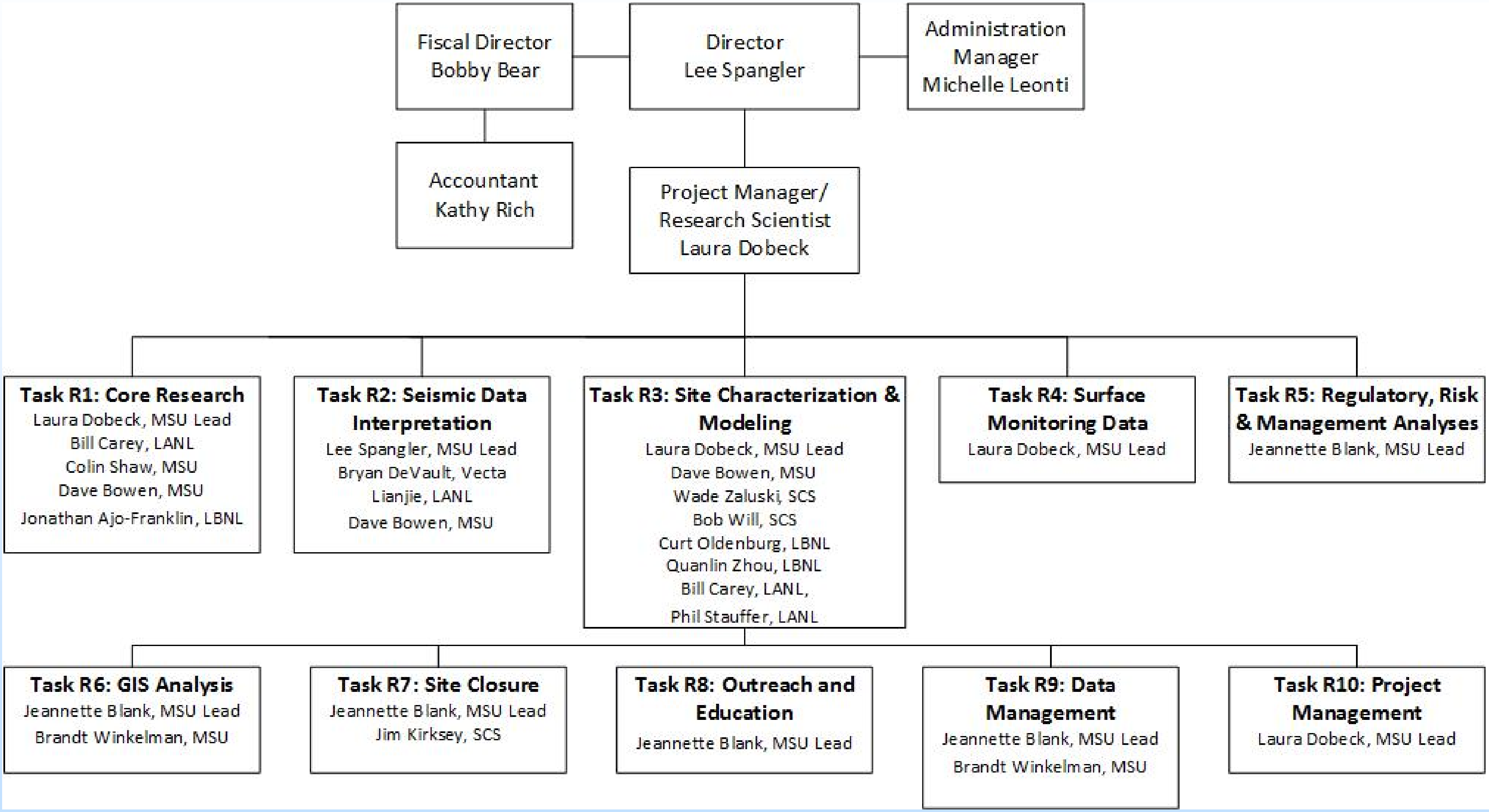
Detailed objectives (continued):

- 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 BSCSP Danielson 33-17 well production data;
- Further develop fracture–matrix permeability interaction models incorporating data previously mentioned;
- Use the dual permeability model to refine large scale storage capacity estimates for fractured carbonate reservoirs;
- Apply an integrated assessment model to Kevin Dome;
- Process and analyze the surface monitoring data;
- Modify assessments of regional and national storage resources with information gained through the Kevin Dome project; and
- 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.

Organization Chart



Organization Chart

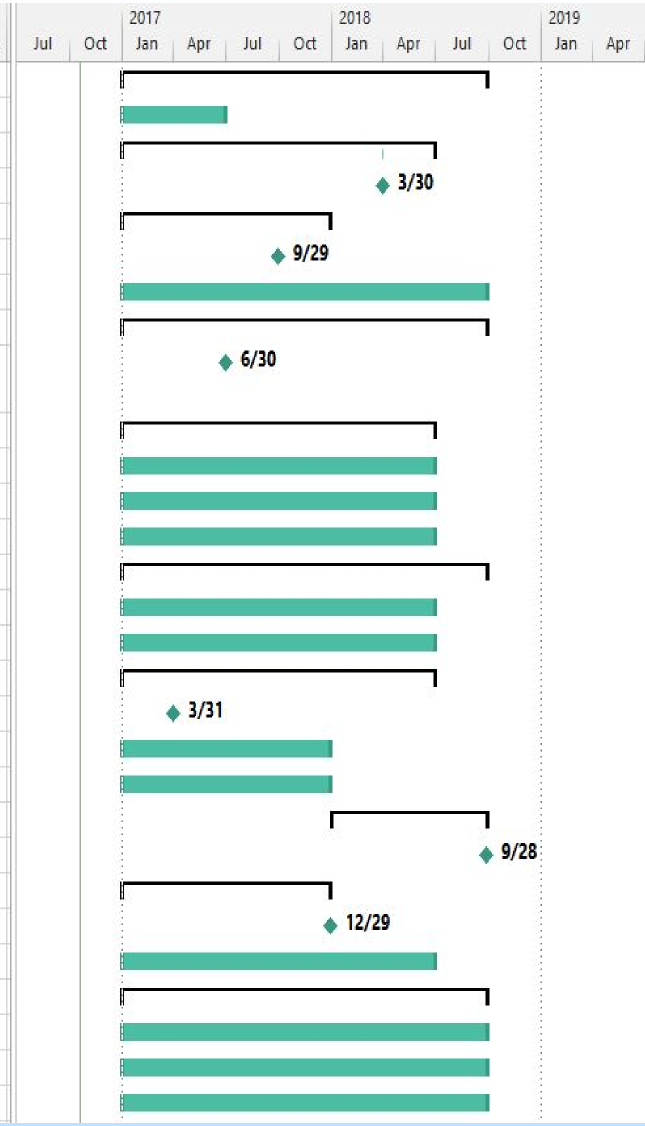


BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

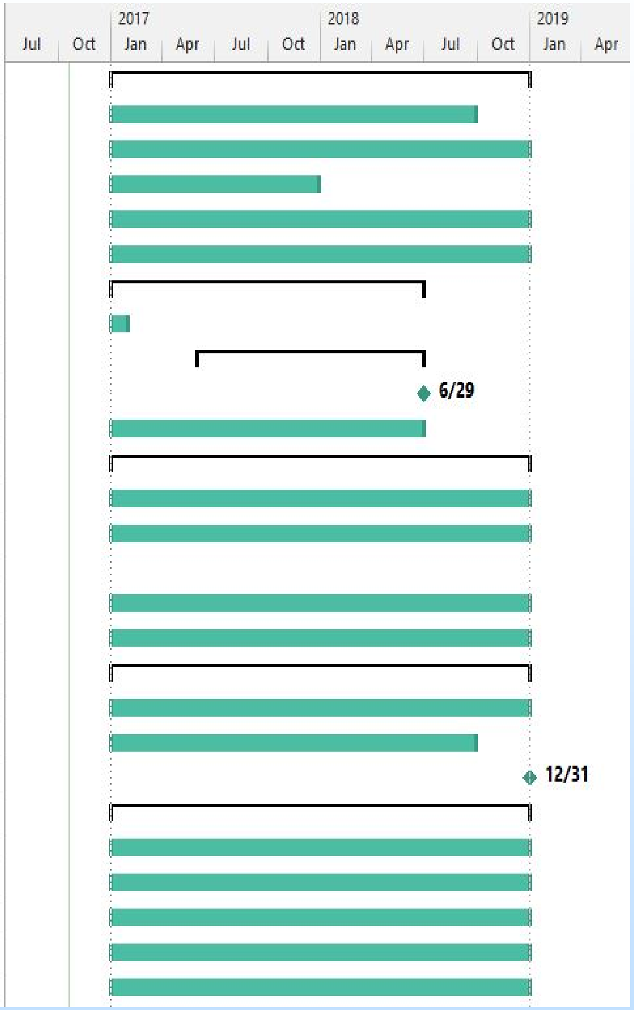
Gantt Chart

Task Name	Start	Finish
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: Complete fracture-permeability measurement of anhydrite caprock	Fri 9/29/17	Fri 9/29/17
R1.4 Core seismic properties	Mon 1/2/17	Fri 9/28/18
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**	**Fri 6/29/18**
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



Gantt Chart

Task Name	Start	Finish
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	**Mon 1/2/17**	**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: Complete closure of the Danielson well site	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	**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
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 12/31/1	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



Bibliography

1. McCann, C., Repasky, K.S., Morin, M., Lawrence, R.L. and Powell, S.L., Using Landsat as a calibration target for radiometric correction of high resolution multi-swath hyperspectral imagery. IEEE Transactions in Remote Sensing, 2017. Accepted.
2. 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 DOI: 10.1002/2017JB014219.
3. 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. Accepted.

Bibliography

4. 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. In revision.
5. 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.
6. 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, 2016. In Review.

Bibliography

7. 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.
8. 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

9. 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.
10. 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.
11. 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

12. 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.
13. 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.
14. 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

15. 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.
16. 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

17. 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.
18. 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

19. 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.
20. 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.
21. 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

22. 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.
23. 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.
24. 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.