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
Carbon Storage R&D Project Review Meeting
Mastering the Subsurfacethrough technology Innovation and Collaboration

August 16-18, 2016

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

Presentation Outline

- Program Goals / Scope of Work / Goals & Objectives
- Project Overview
  - Geology of Kevin Dome / Regional Significance
  - Site Characteristics – Scientific Opportunities
- Site Characterization
- Modeling
- Monitoring
- Results to Date and Accomplishments
- Summary

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 actual storage compared to predicted. 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, VSP, in zone and above zone geochemical sampling, repeat pulsed neutron logging, tracers, distributed T and P sensors and assurance monitoring techniques to verify location that the CO_2 remains in the storage complex.

Benefit to the Program

- **Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.**
  - Pulsed neutron logging and heat pulses to the reservoir combined with distributed temperature sensing should provide saturation information which can be studied as a function of injection rate. We will also measure rock physics properties as a function of CO_2 saturation to try to improve understanding of seismic response to S_{CO2}.

- **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.

Big Sky Carbon Sequestration Partnership

Montana State University

Project Overview: Goals and Objectives

Primary objective - Demonstrate that the target formation and other analogous formations are a viable and safe target for sequestration of a large fraction of the region's CO_2 emissions.

Success Criteria – Project safely injects CO_2 into the storage formation and models and monitoring indicate permanence of storage in the reservoir.

Other objectives include improving the understanding of injectivity, capacity, and storativity in a regionally significant formation.

Success Criteria – Site characterization, laboratory core studies, well tests, models coupled with operational data deepen understanding of use of site characterization data for predicting geologic system performance. Comparison of natural analog data with laboratory studies and geochemical sampling in the injection region improve understanding of injected CO_2 behavior in reactive rock.

Project Overview: Goals and Objectives

Operational objectives - Safely procure, transport, inject and monitor up to one million tons of CO_2 into the target formation; understand the behavior of the injected CO_2 within the formation; verify and improve predictive models of CO_2 behavior; test and validate monitoring, verification and accounting (MVA) methodology.

Success Criteria – Safe and successful injection; good history matching of multi-phase flow and reactive transport models; monitoring techniques detect CO_2 when present and provide information of plume development.

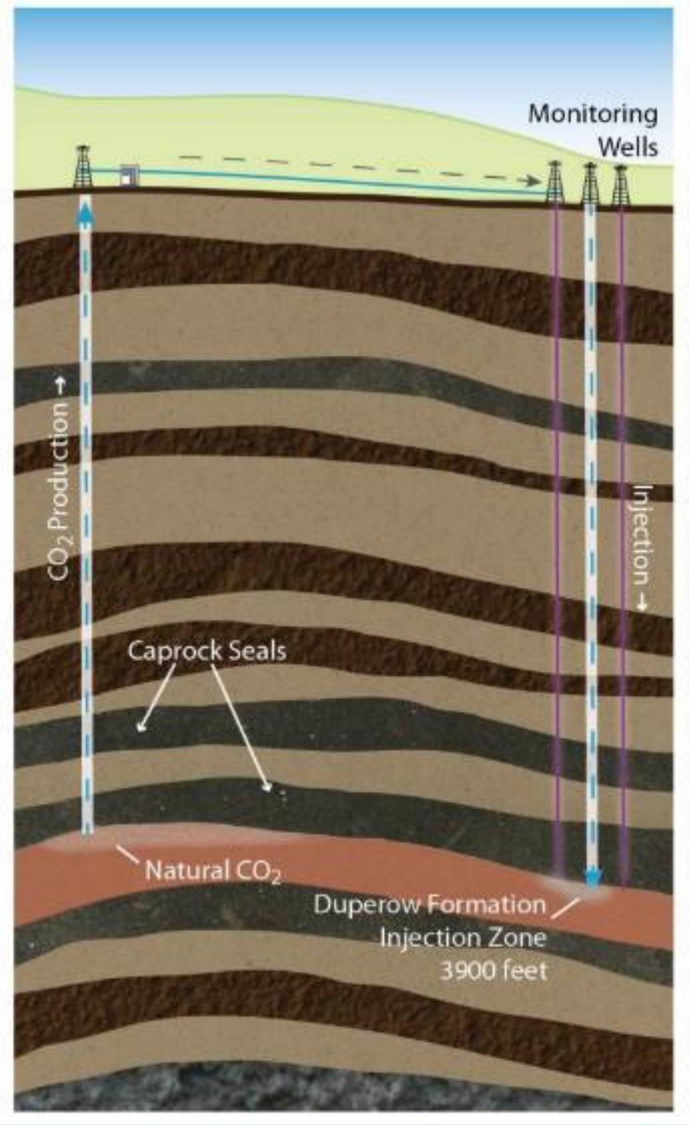
Post-injection phase objective - Assess any resultant changes from the CO_2 injection and to continue to monitor the CO_2 plume.

Success Criteria – Continued detection of plume evolution and models showing predictive capability.

Regional characterization objectives - Understand the costs of carbon sequestration; determine the best management practices to sequester carbon in the soil of agricultural systems; and refine regional assessments of CO_2 sources and capacity estimates.

Project Overview

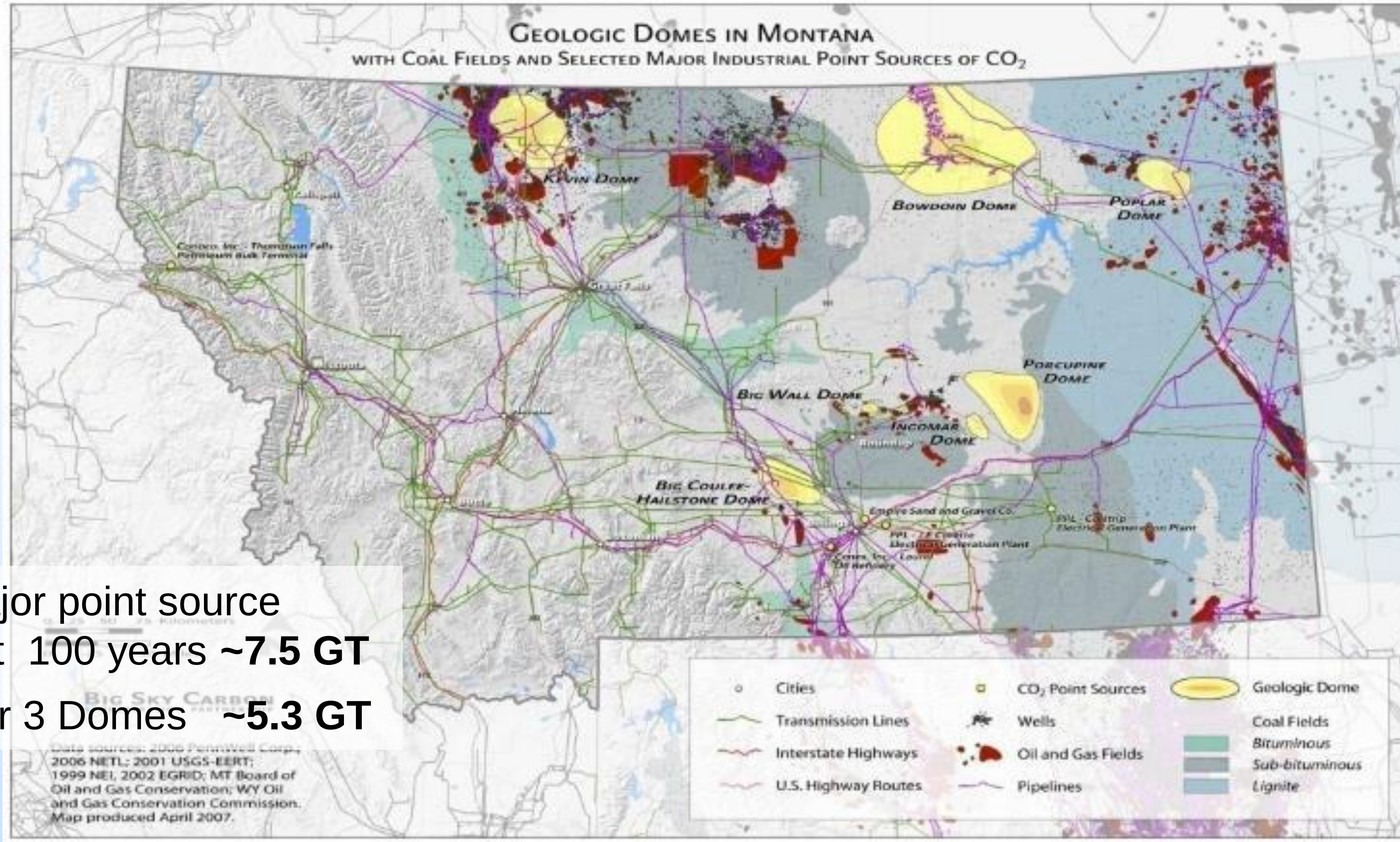
- Permitting & Public Outreach
- Site Characterization
- Infrastructure Development
  - Characterization wells
  - 1 Injection Well
  - Monitoring Wells, Pipelines Compressor
- Injection Operations
  - 4 years
- Monitoring & Modeling
- Site Closure



BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Domes Are Attractive Early Storage Target



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

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

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

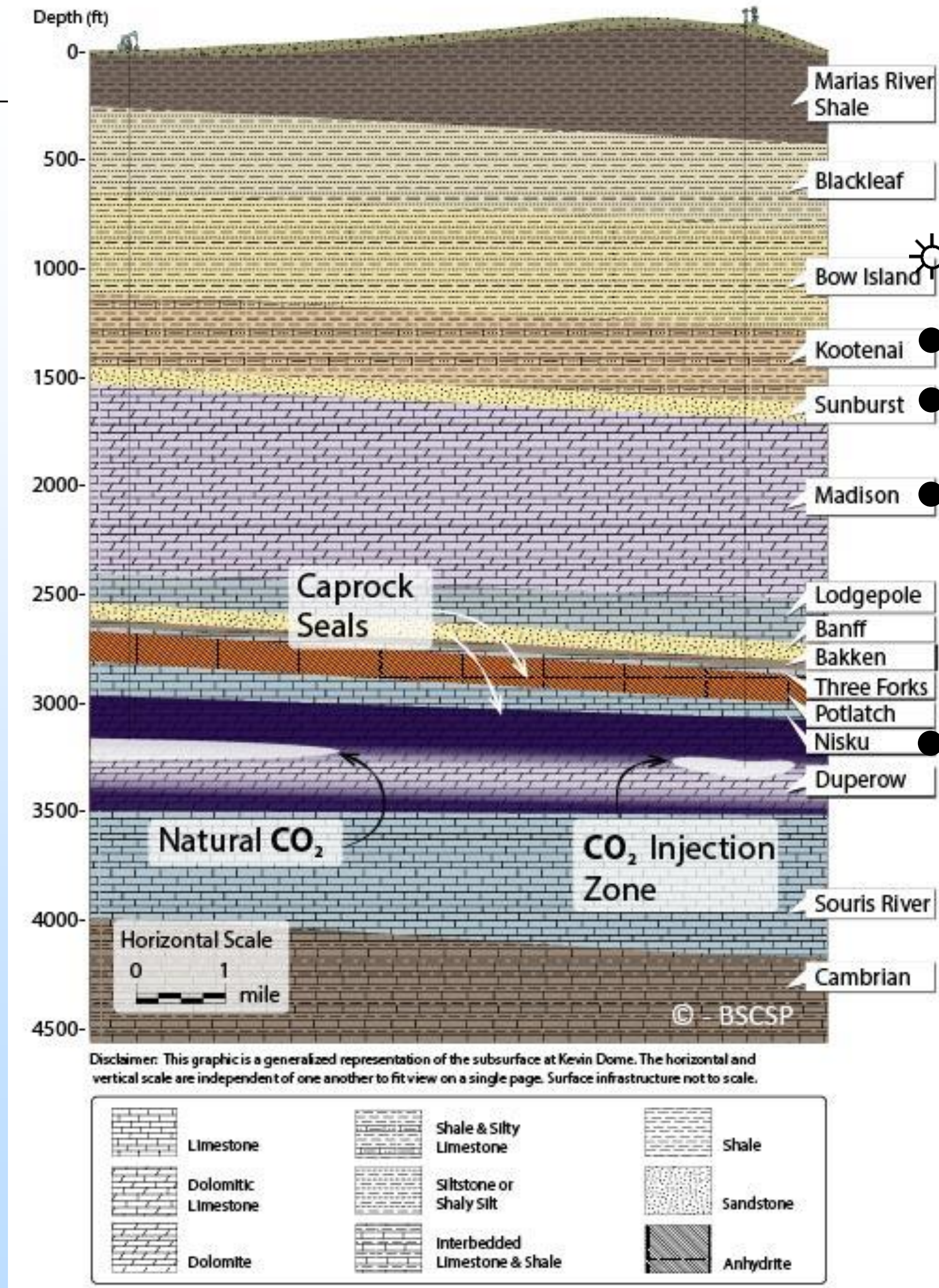
Kevin Dome

CO_2 in middle Duperow

Two “gold standard” seals

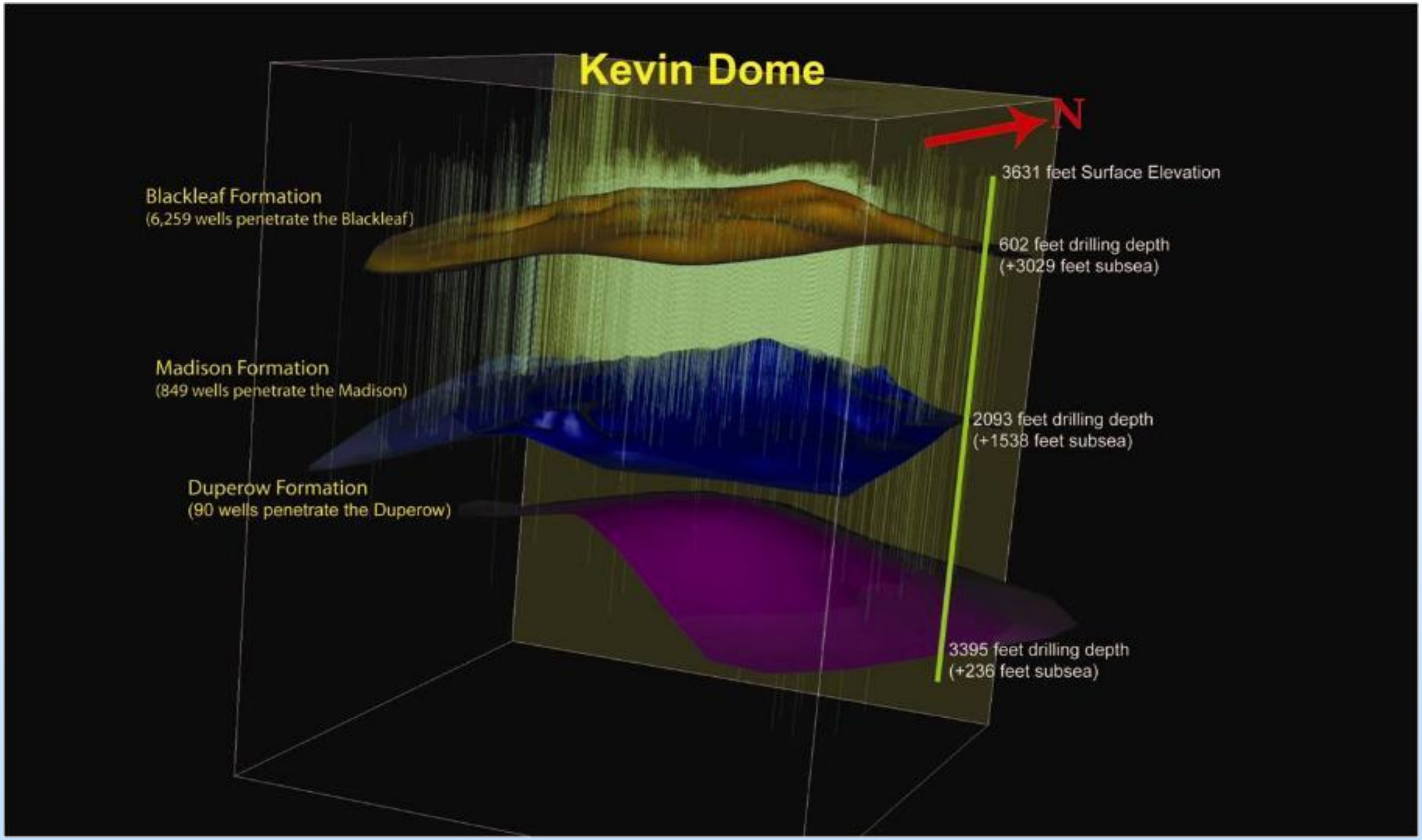
- Upper Duperow ~200’ tight carbonates and interbedded anhydites
- Caprock~ 150’ Anhydrite

Multiple tertiary seals

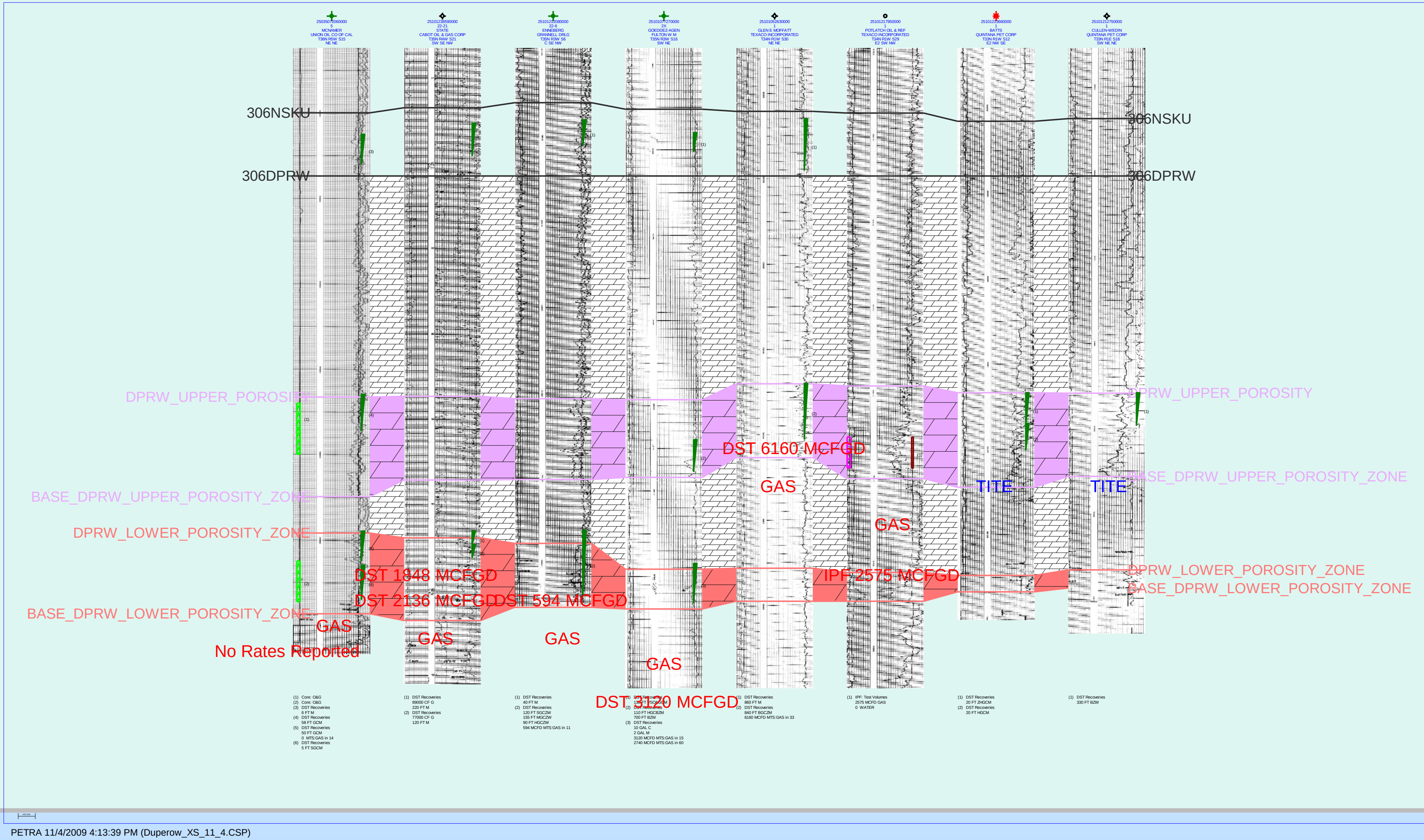


BIG SKY CARBON SEQUESTRATION PARTNERSHIP

Kevin Structure Tops & Well Penetrations



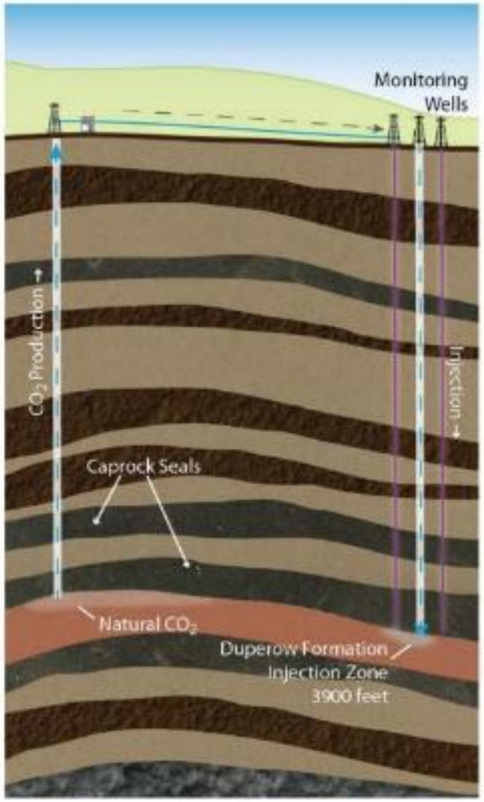
NW - SE Cross Section Kevin Dome



Big Sky Carbon Sequestration Partnership

Montana State University

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

Site Characterization Approach / Accomplishments

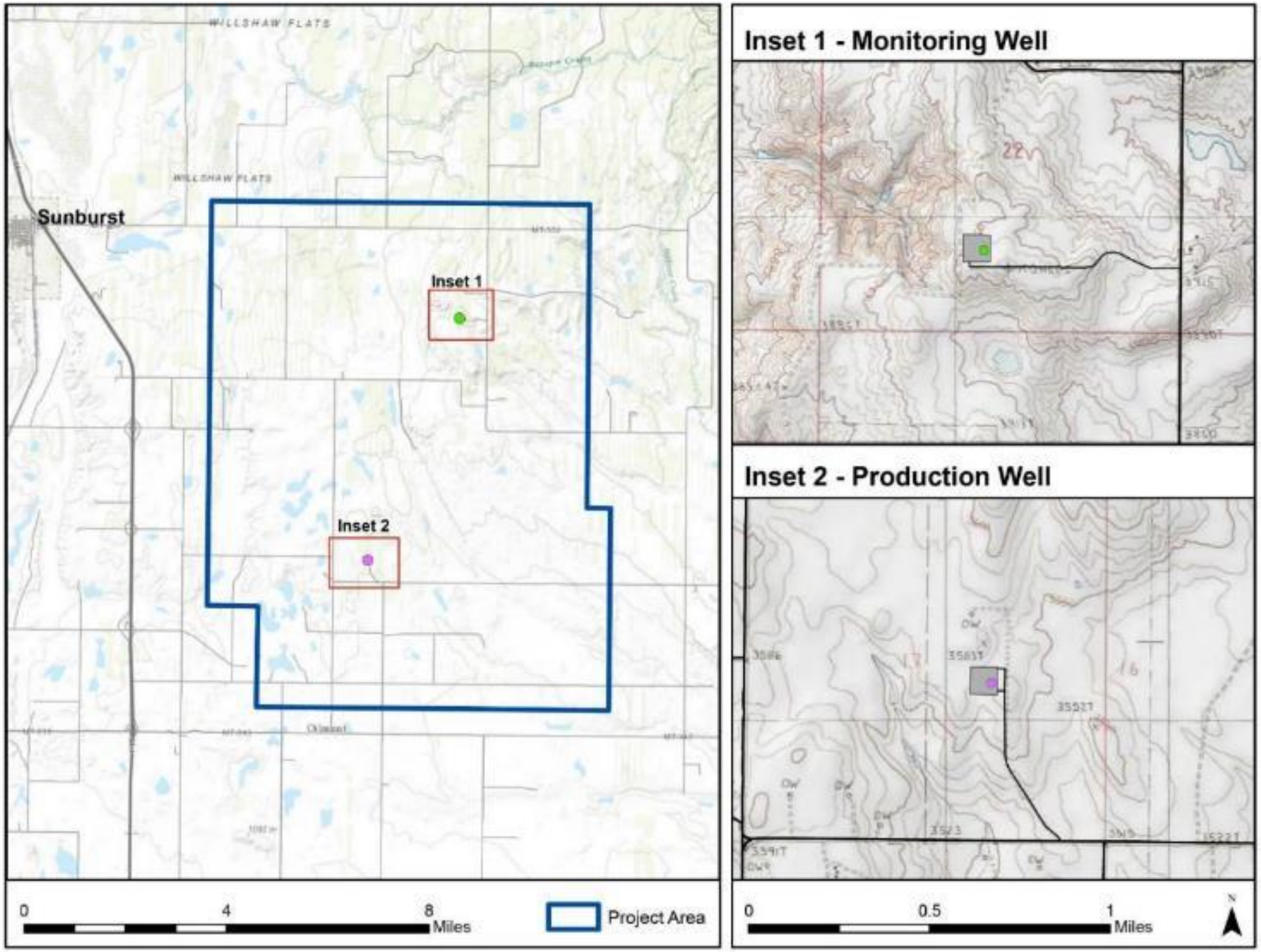
Approach

- Assimilate surface data
  - Topography, water features, viewsheds, infrastructure, cultural resources, biological resources, etc.
- Create GIS products for surface features
- Perform baseline monitoring
- Assimilate subsurface data
  - Wells, tops, logs, 2D seismic, produced water, drilling records
- Create database
- Create static model
- Shoot 3D, 9C seismic
- Drill, log and core 2 wells
  - Perform well tests and core analysis

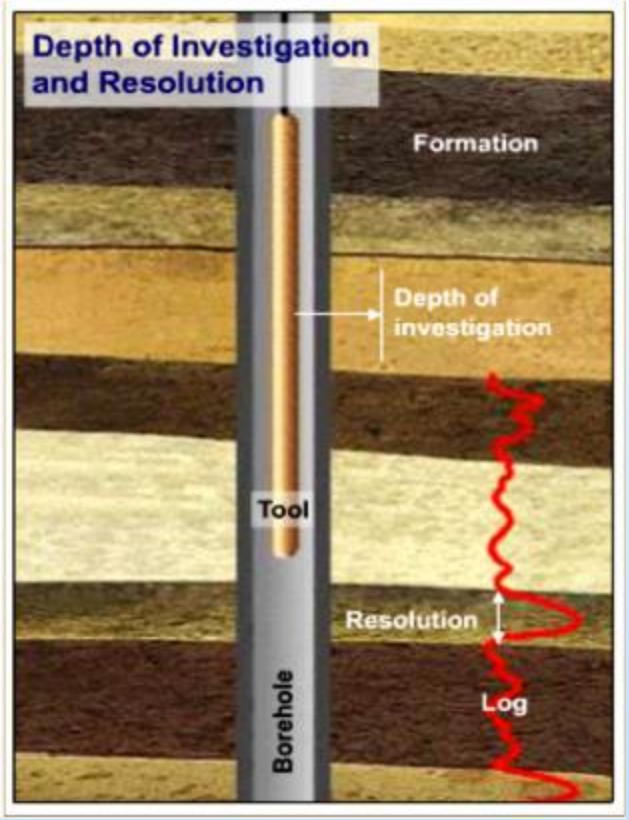
Key Accomplishments

- Kevin Atlas created with surface and subsurface data incorporated
- ~ 36 sq. mi. 3D, 9C seismic shot, processed and being interpreted
- 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
- Cores and logs acquired / analyzed
- Well tests performed
- Second flow modeling performed

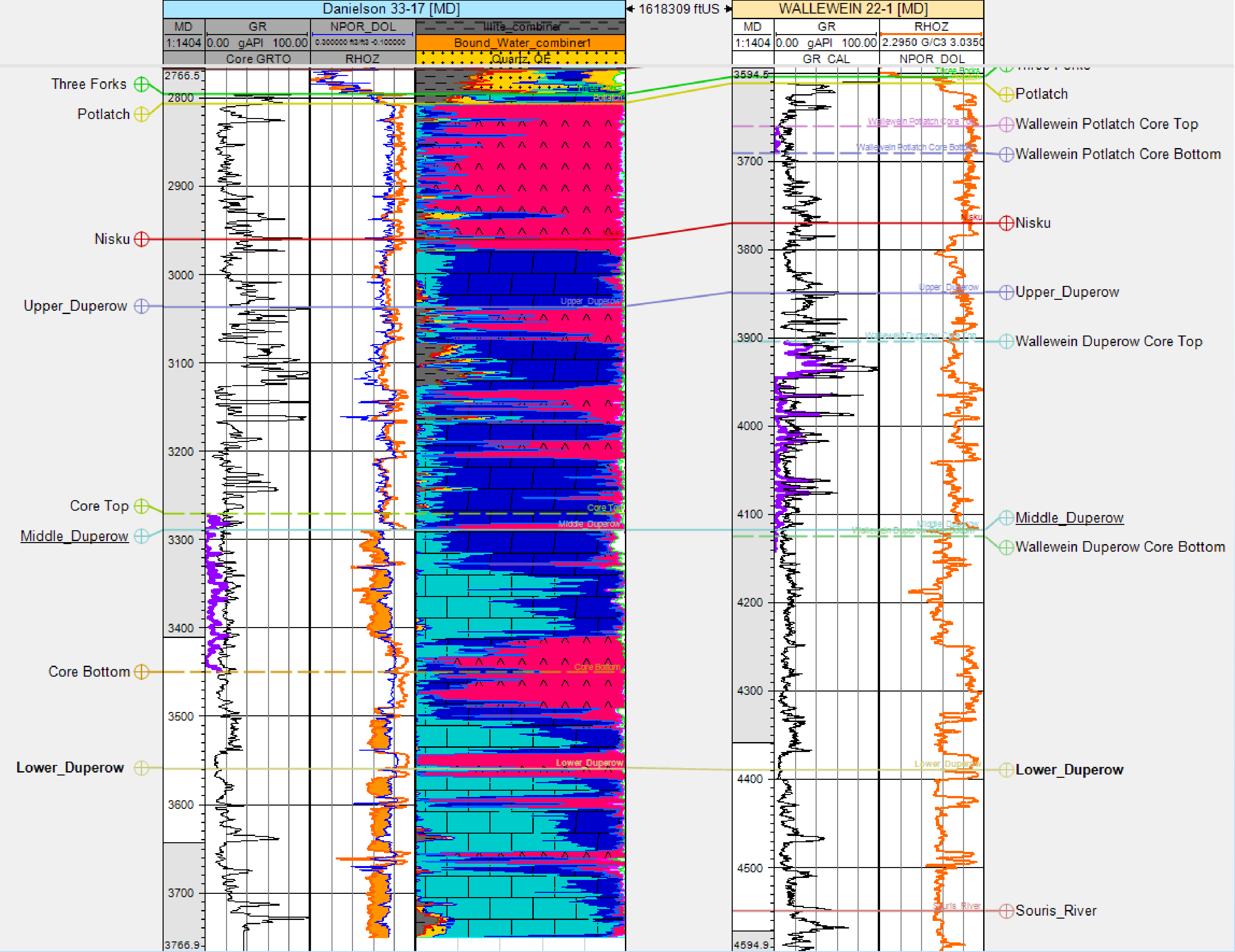
Well Locations



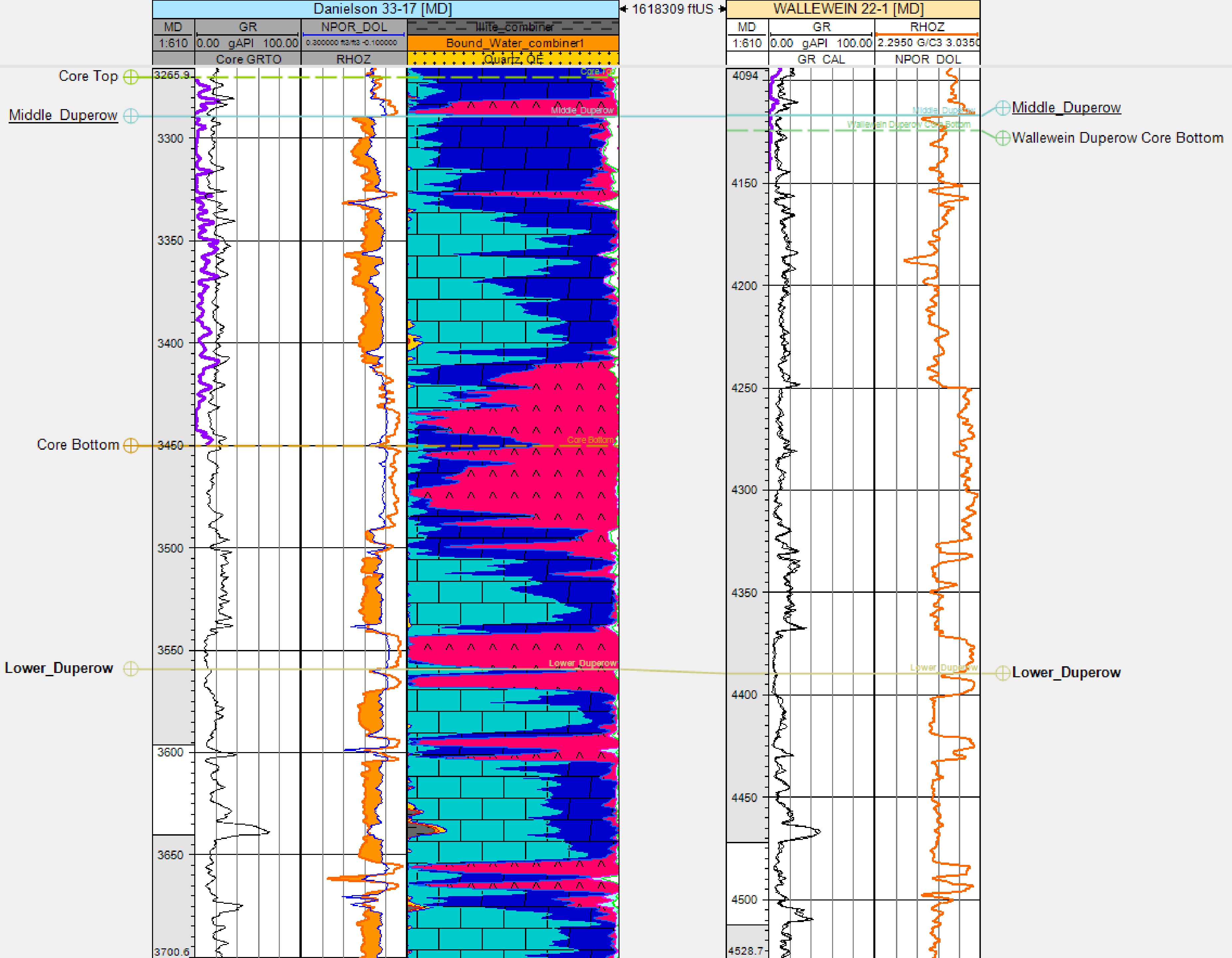
Geophysical Characterization & Monitoring: Well Logging



Logs	Wells			
	1st Prod	Inj	Mon	All
Downhole P & T	Cont.	Cont.	Cont.	Cont.
Gamma Ray	Initial	Initial	Initial	Initial
Resistivity	Initial	Initial	Initial	Initial
Porosity	Initial	Initial	Initial	Initial
Density	Initial	Initial	Initial	Initial
Caliper	Initial	Initial	Initial	Initial
P&S Sonic	Initial	Initial	Initial	Initial
Sonic Scanner	Initial	Initial	Initial	
Isolation Scan	Initial	Initial	Initial	
FMI	Initial	Initial	Initial	
NMR	Initial	Initial	Initial	
Natural Gamma	Initial	Initial	Initial	
Elemental Spec	Initial	Initial	Initial	
Cement Eval	Initial	Initial	Initial	Initial
Pulsed Neutron	Initial	Annual	Annual/ 2 Annual	Initial



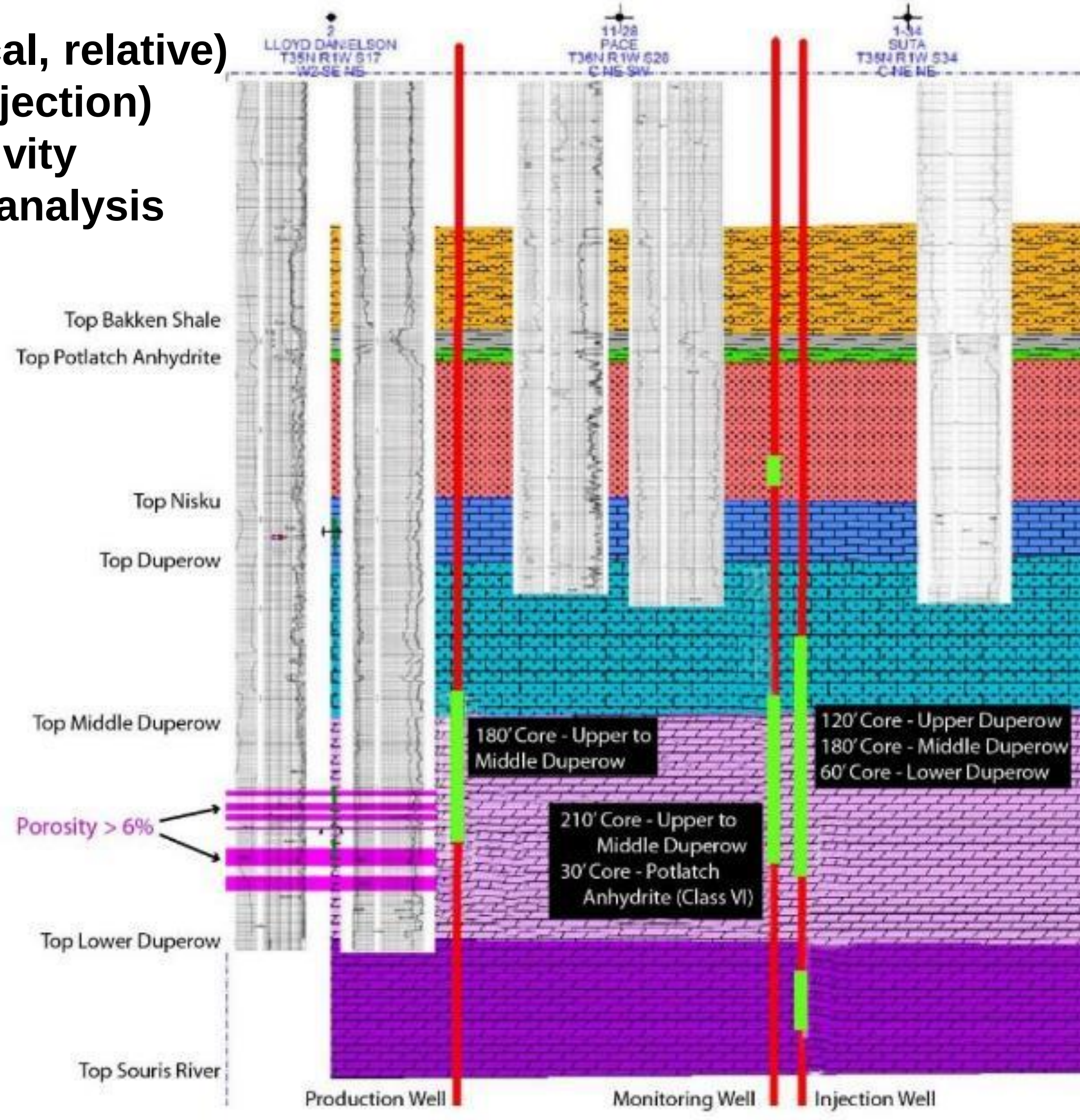
Danielson 33-17 [MD]
1618309 ftUS
WALLEWEIN 22-1 [MD]
MD
GR
NPOR_DOL
Lithe_combiner
Bound_Water_combiner1
Quartz_QE
1:1404
0.00 gAPI 100.00
Core GRTO
RHOZ
GR CAL
2.2950 G/C3 3.0350
Three Forks
Potlatch
Wallewein Potlatch Core Top
Wallewein Potlatch Core Bottom
Nisku
Upper_Duperow
Wallewein Duperow Core Top
Core Top
Middle_Duperow
Wallewein Duperow Core Bottom
Core Bottom
Lower_Duperow
Souris_River
2766.5
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3766.9
3594.5
3700
3800
3900
4000
4100
4200
4300
4400
4500
4594.9



Danielson 33-17 [MD]
1618309 ftUS
WALLEWEIN 22-1 [MD]
MD
1:610
GR
0.00 gAPI 100.00
Core GRTO
NPOR_DOL
RHOZ
Lith_combiner
Bound_Water_combiner1
Quartz_QE
RHOZ
2.2950 G/C3 3.0350
GR CAL
NPOR_DOL
Core Top
Middle_Duperow
Core Bottom
Lower_Duperow
Wallewein Duperow Core Bottom
3265.9
3300
3350
3400
3450
3500
3550
3600
3650
3700.6
4094
4150
4200
4250
4300
4350
4400
4450
4500
4528.7

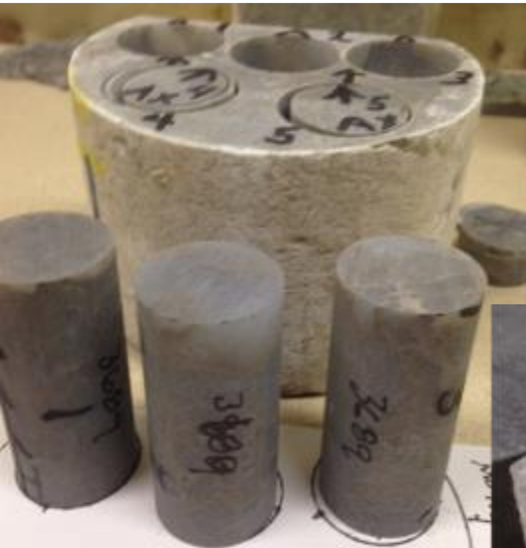
Core Plan – Intervals and Analyses

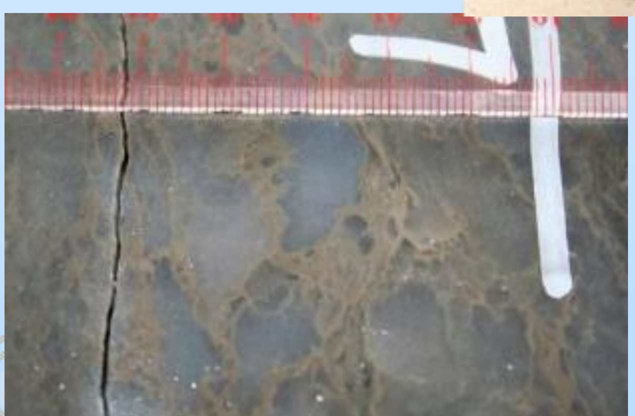
Porosity
Permeability (horizontal, vertical, relative)
Capillary pressure (mercury injection)
Core flood, geochemical reactivity
Seismic properties, anisotropy analysis
Tight rock analysis)
Petrology/Petrography
Bulk XRD
Powder XRD
NMR calibration
SEM/EDS
Micro-CT imaging
Ductility and rock strength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



BIG SKY CARBON
SEQUESTRATION PARTNERSHIP

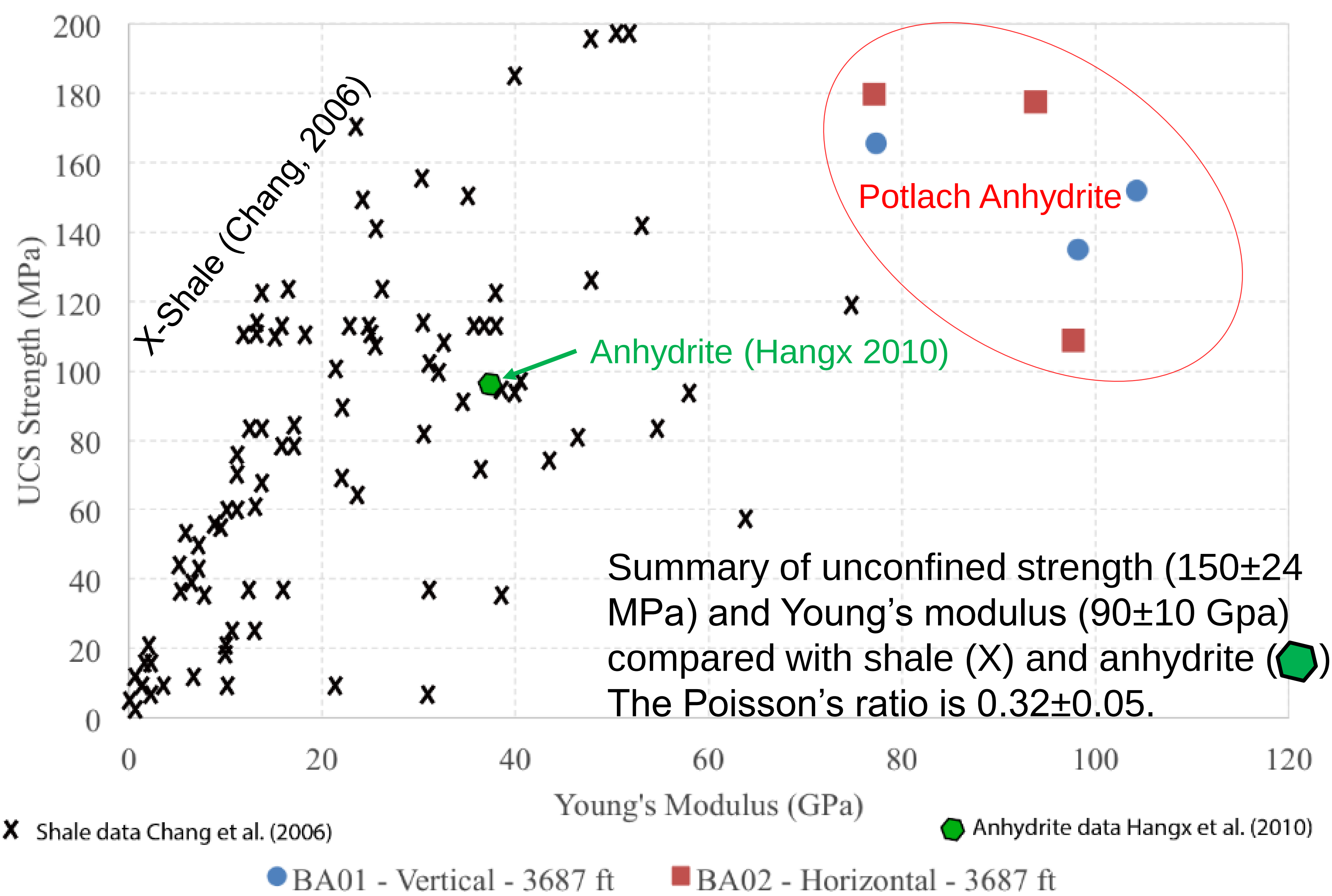
Caprock Geomechanical Tests





- **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

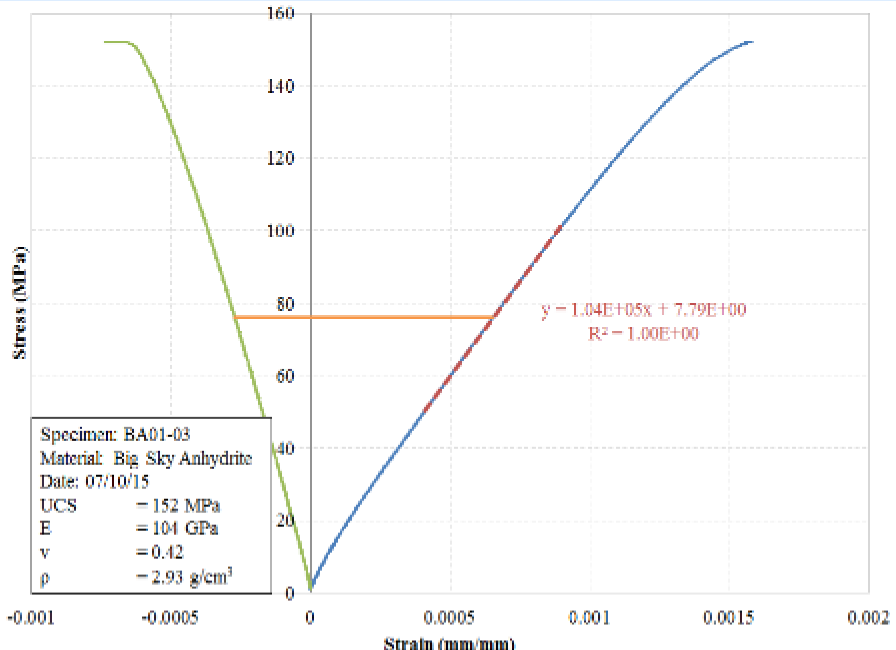


Summary of unconfined strength (150±24 MPa) and Young's modulus (90±10 Gpa) compared with shale (X) and anhydrite ( ) The Poisson's ratio is 0.32±0.05.

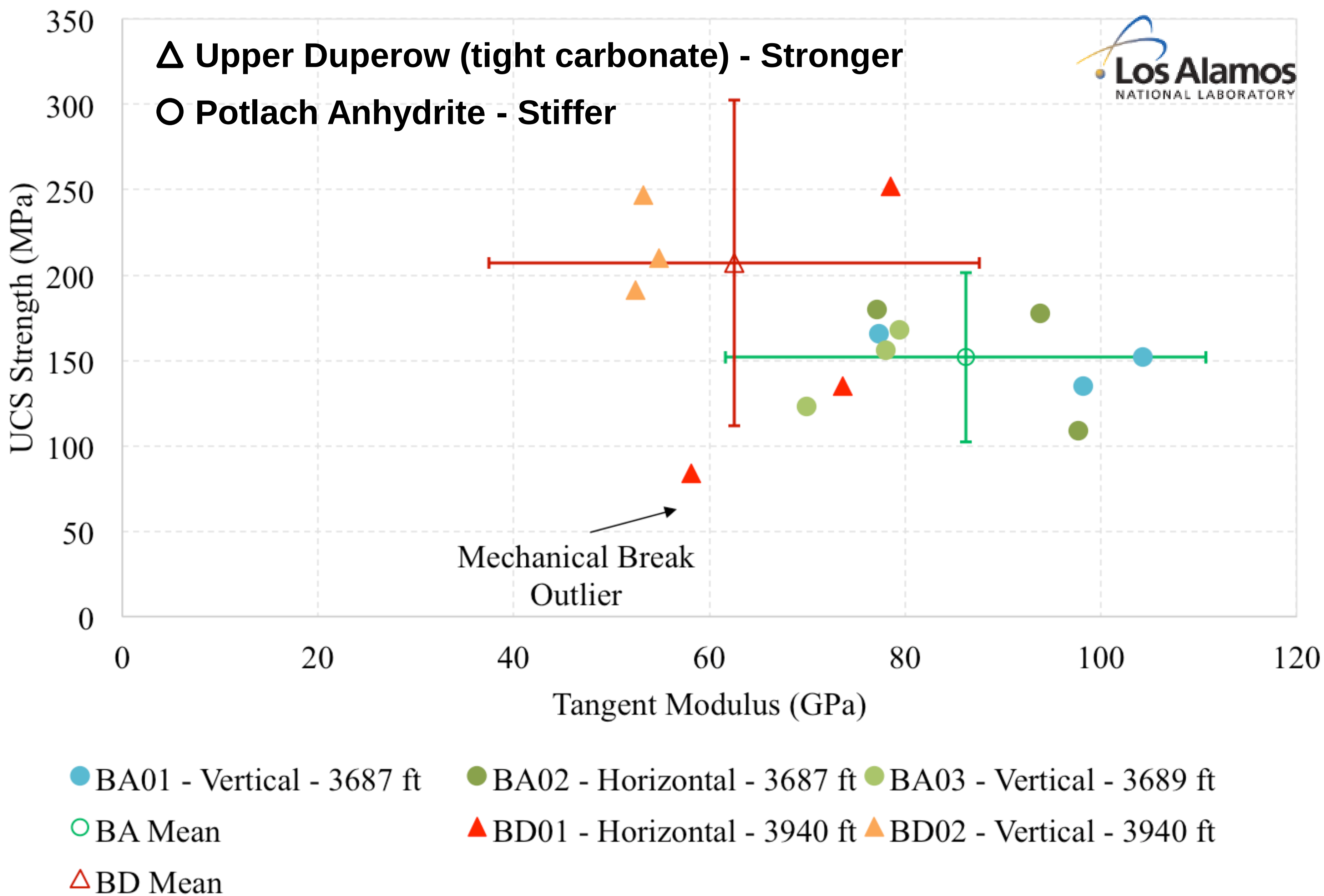
Caprock Geomechanical Tests

	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

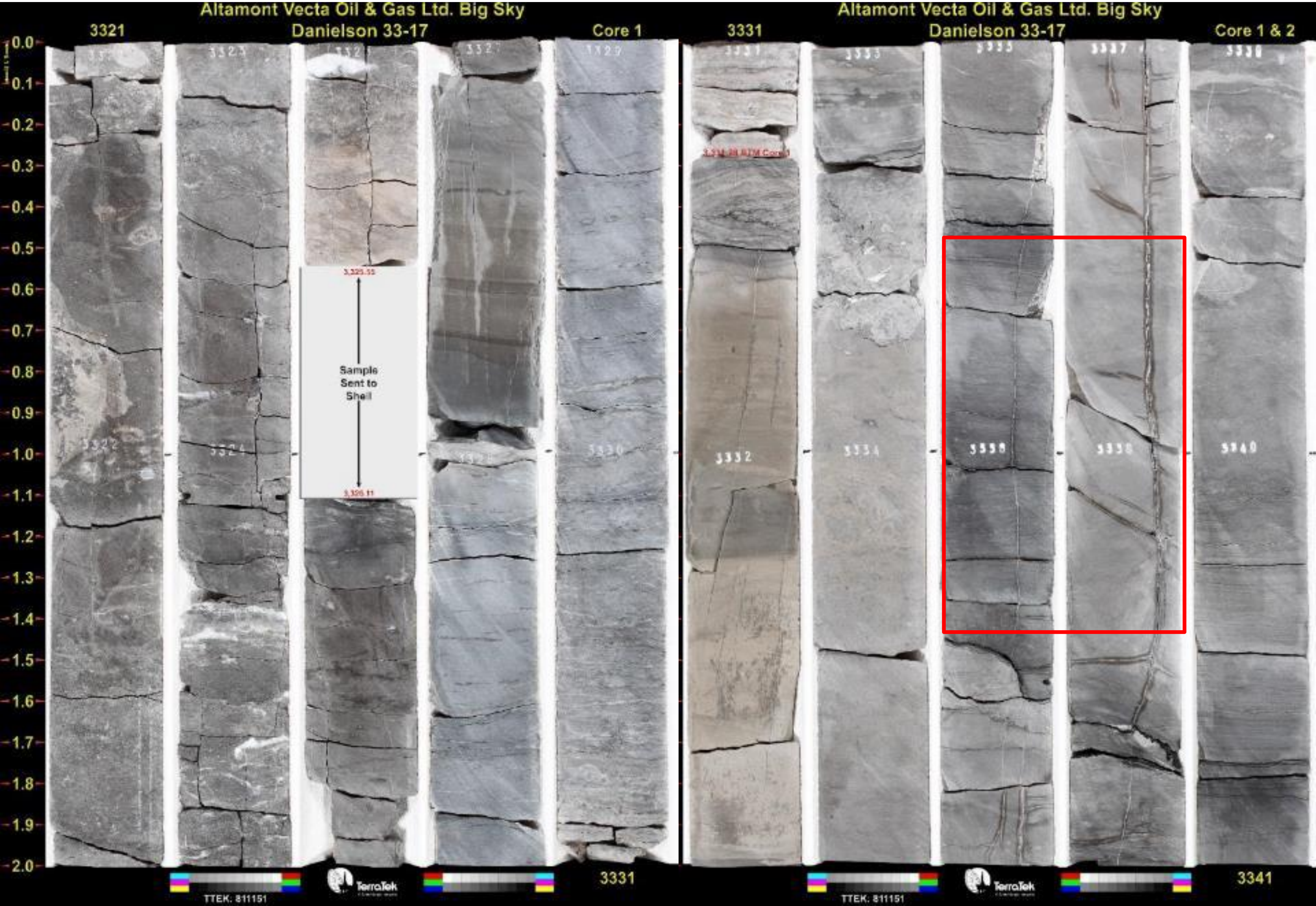
- **The Potlatch Anhydrite is very strong in both orientations**
- **The average Young's modulus (91 Gpa) reflects a very stiff material**
- **Samples dilated strongly at peak strength before failing indicating significant plasticity even under unconfined conditions**



Caprock Geomechanical Analysis

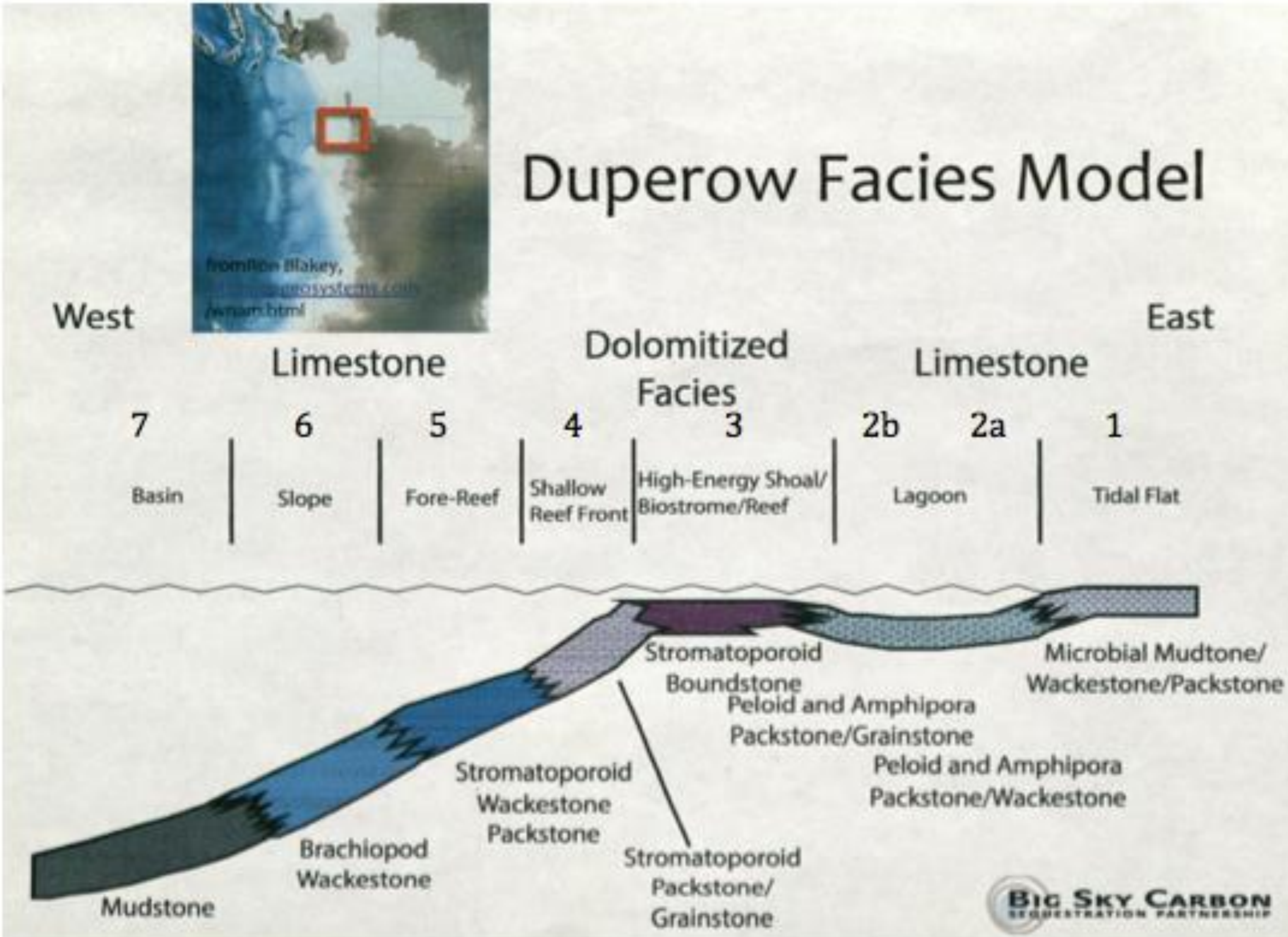


Middle Duperow – Fractures

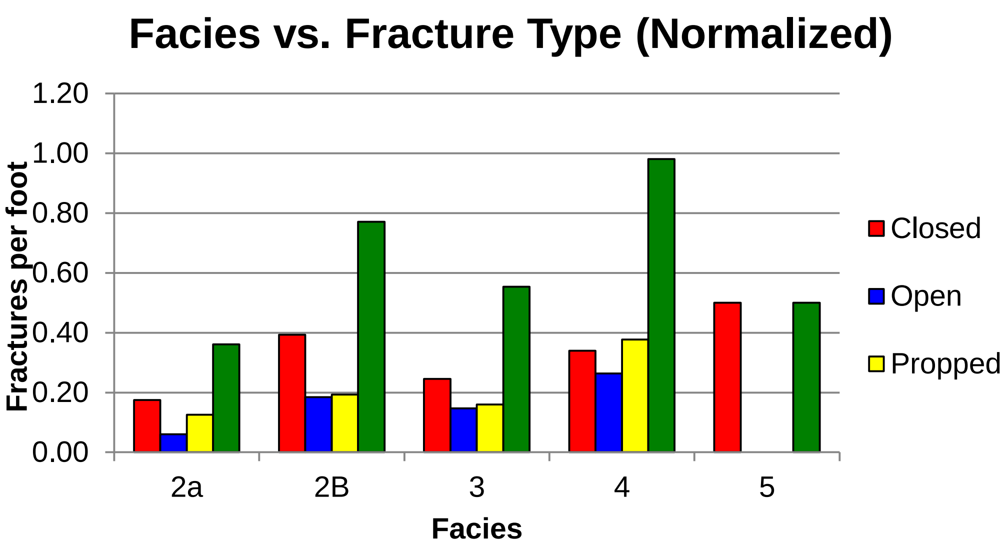


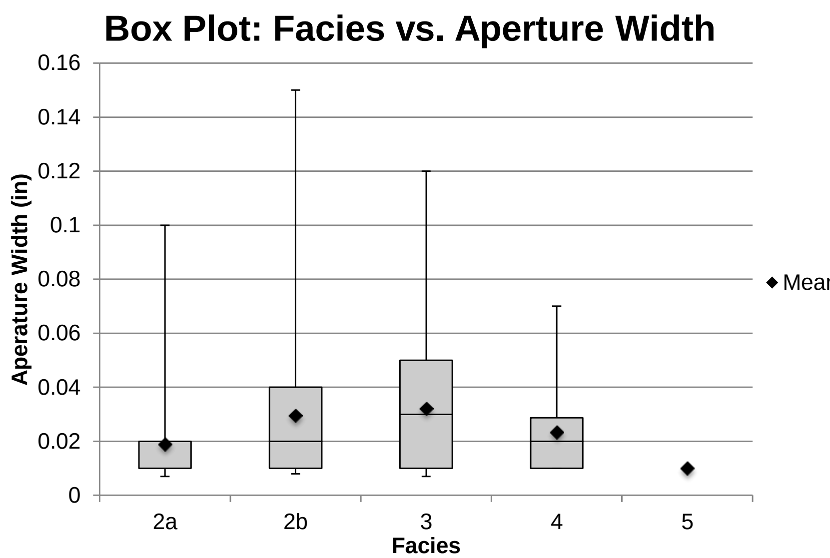
Middle Duperow – Fractures Propped by Precipitates

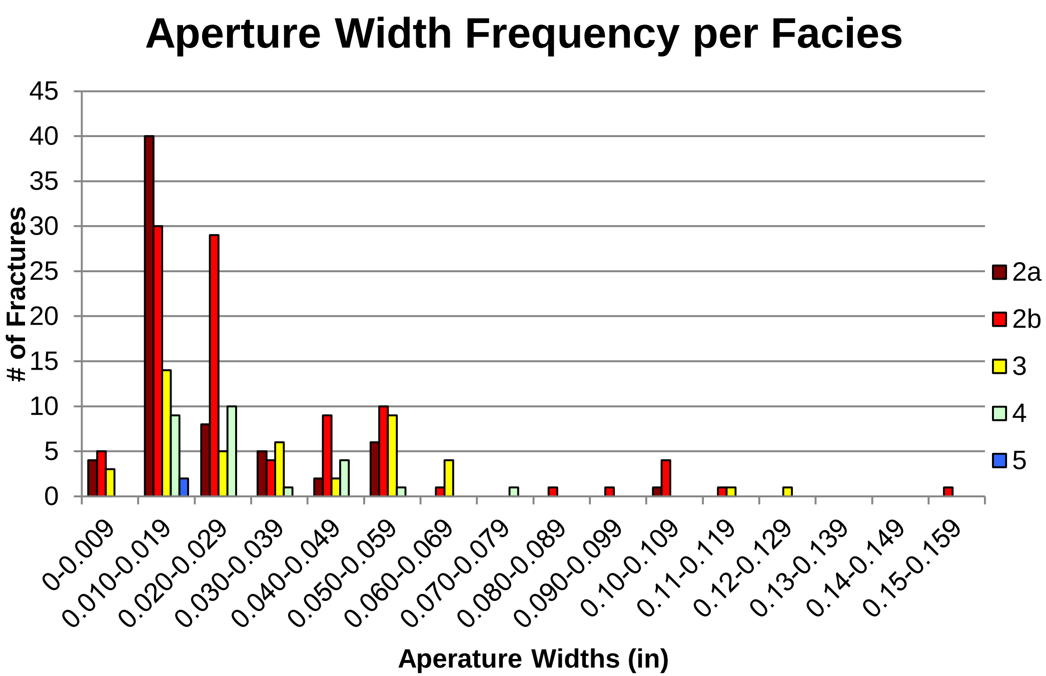
Fracture Analysis of Cored Intervals of the Duperow

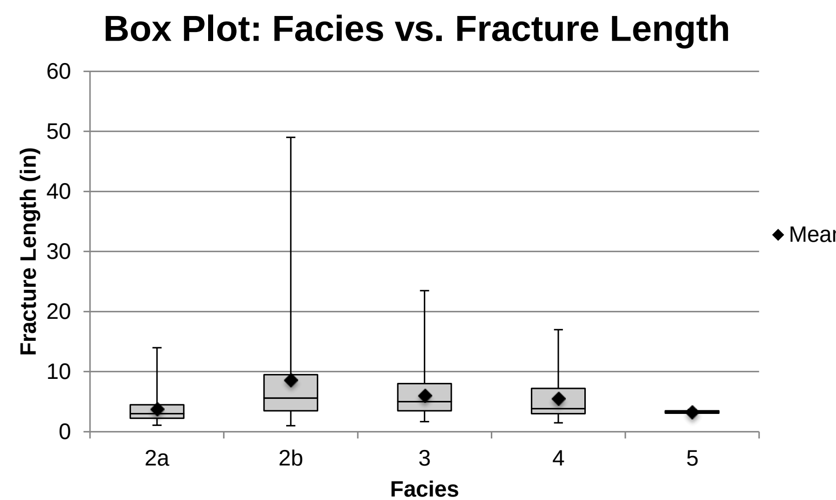


Fracture Analysis of Cored Intervals of the Duperow









MONTANA STATE UNIVERSITY

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

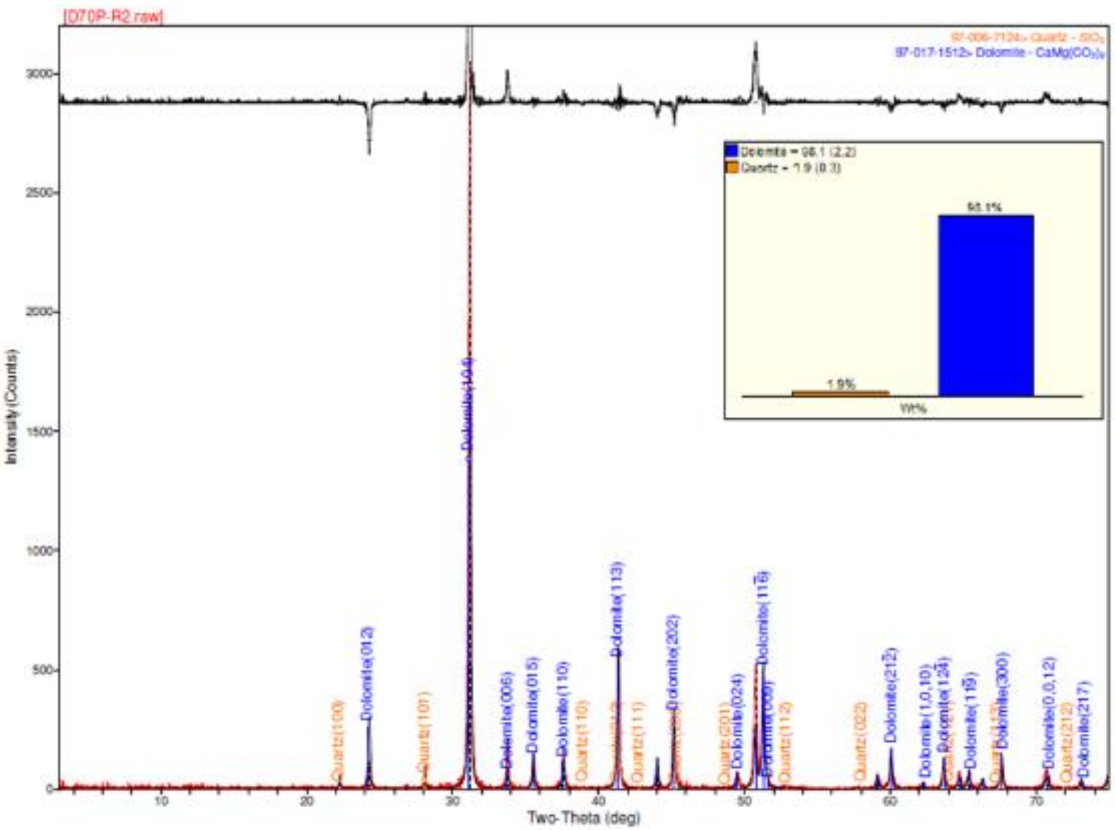
Sample ID	Plug ID	Well	Depth (ft.)	Plug length (cm)	Plug diam. (cm)	Confining pressure (psi)	Porosity (%)	Permeability (mD)	Klinkenberg permeability (mD)
24243_3296_40_A	68	Danielson 33-17	3296.40	5.53	2.51	500	6.36	3.66	3.26
						1100	6.12	2.89	2.55
24243_3358_25_A	69	Danielson 33-17	3358.25	4.74	2.52	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

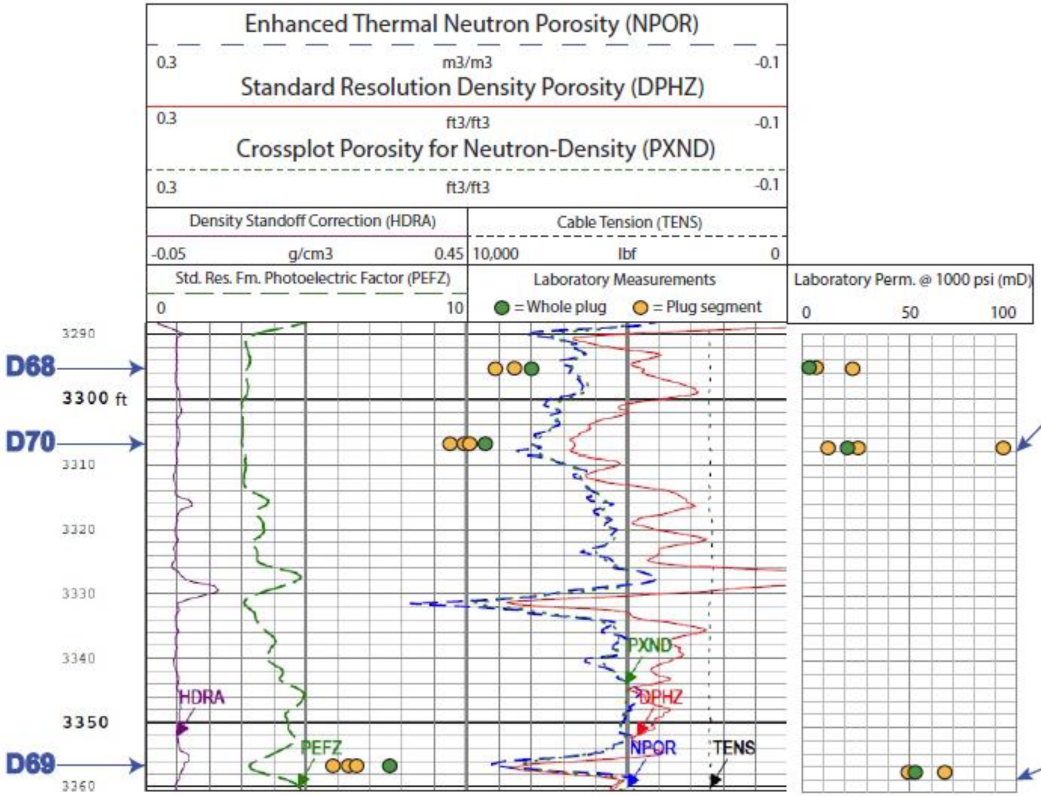
0 – 3.5% Anhydrite

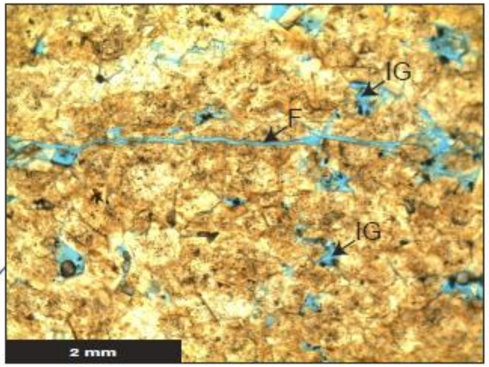
0 – 6.4 % Gypsum

MONTANA STATE UNIVERSITY

Heterogeneity and Porosity Characteristics of the Middle Duperow

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





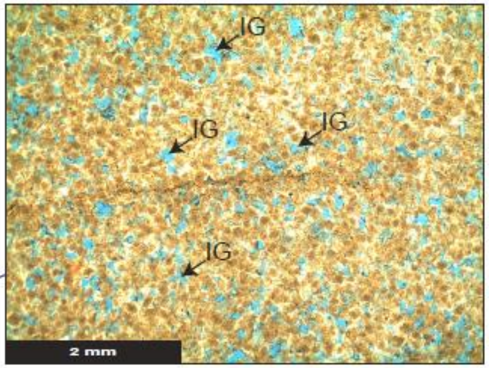
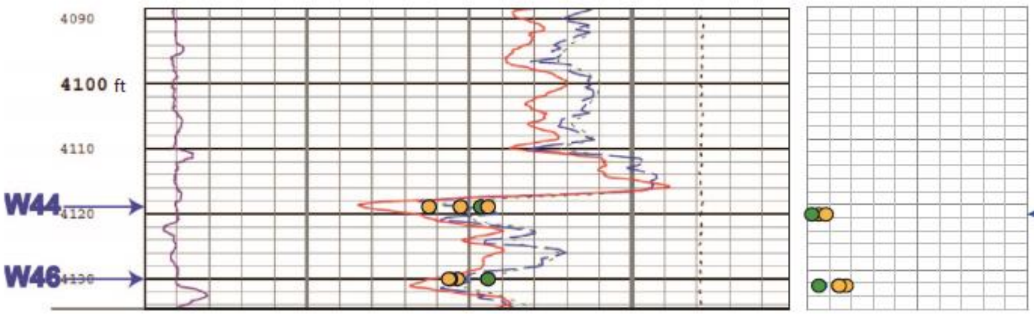
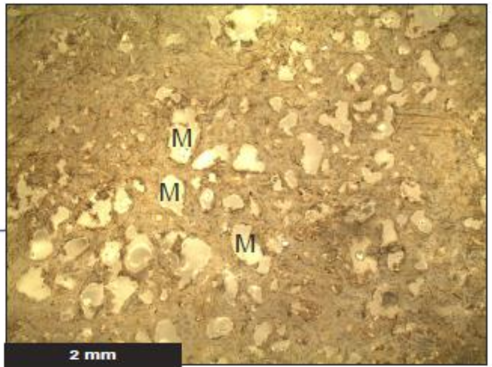


Figure b: Wallawein 22-1

M=moldic, IG= intergranular, F= fracture

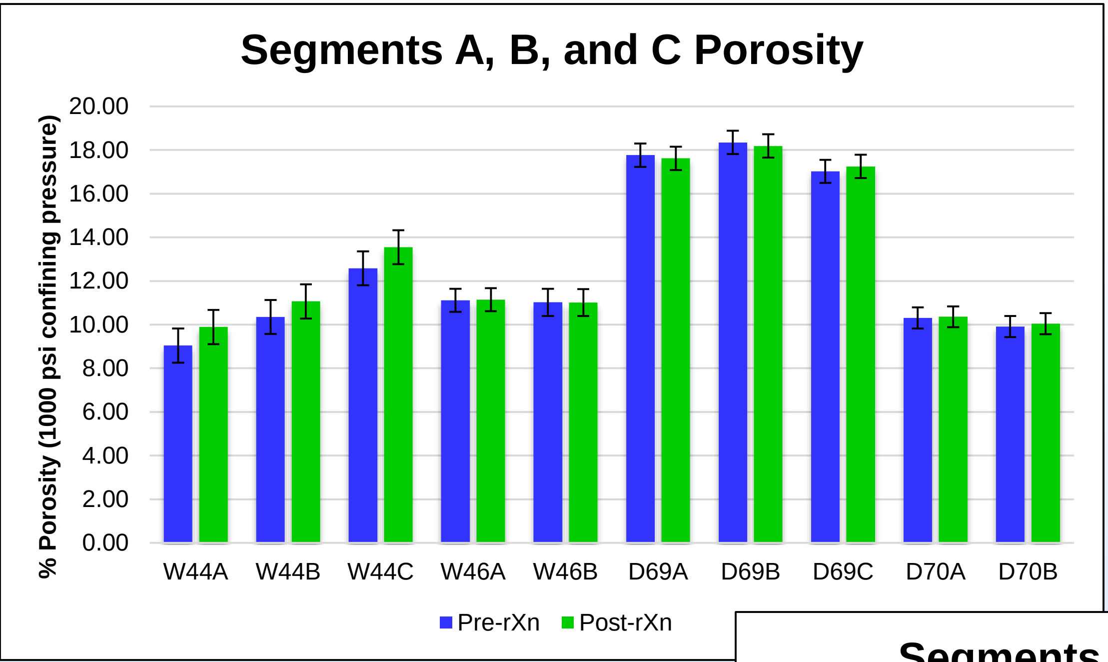


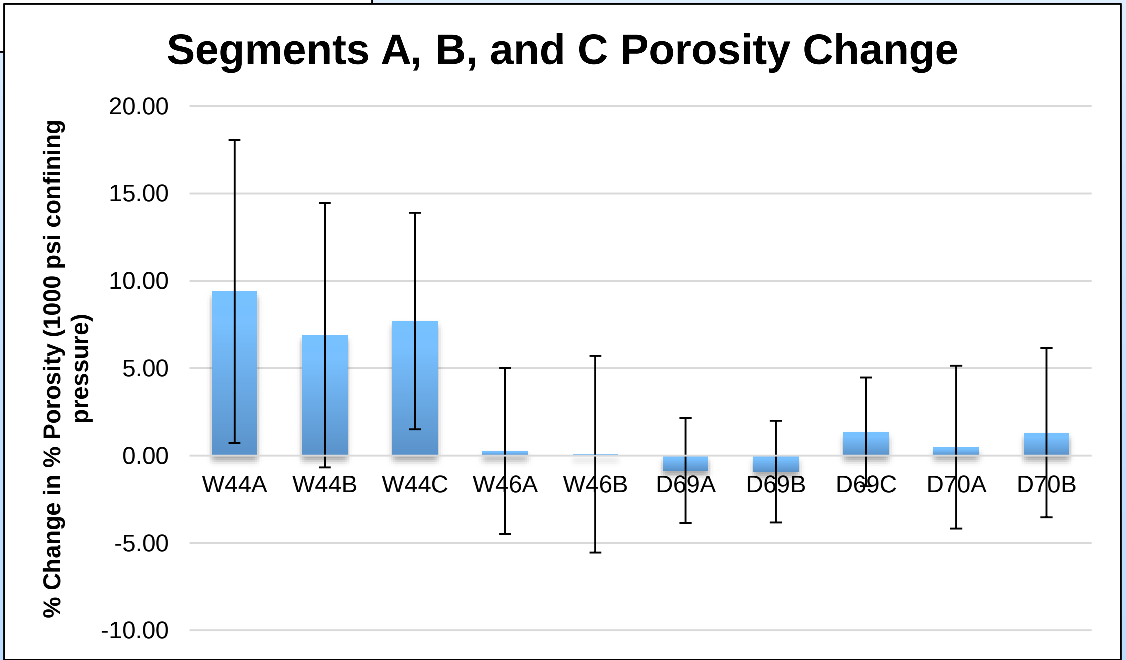


Core Flood Experiments

	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

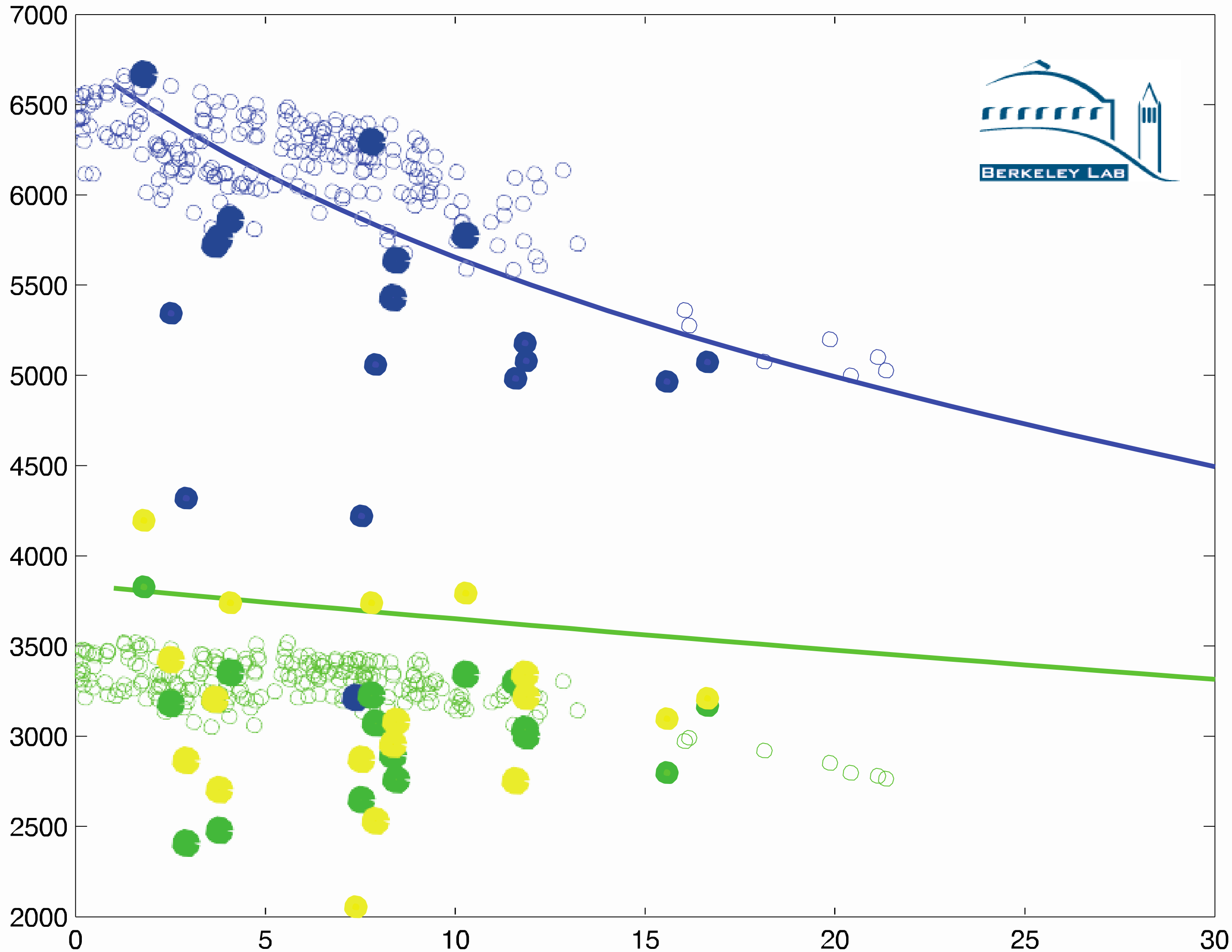




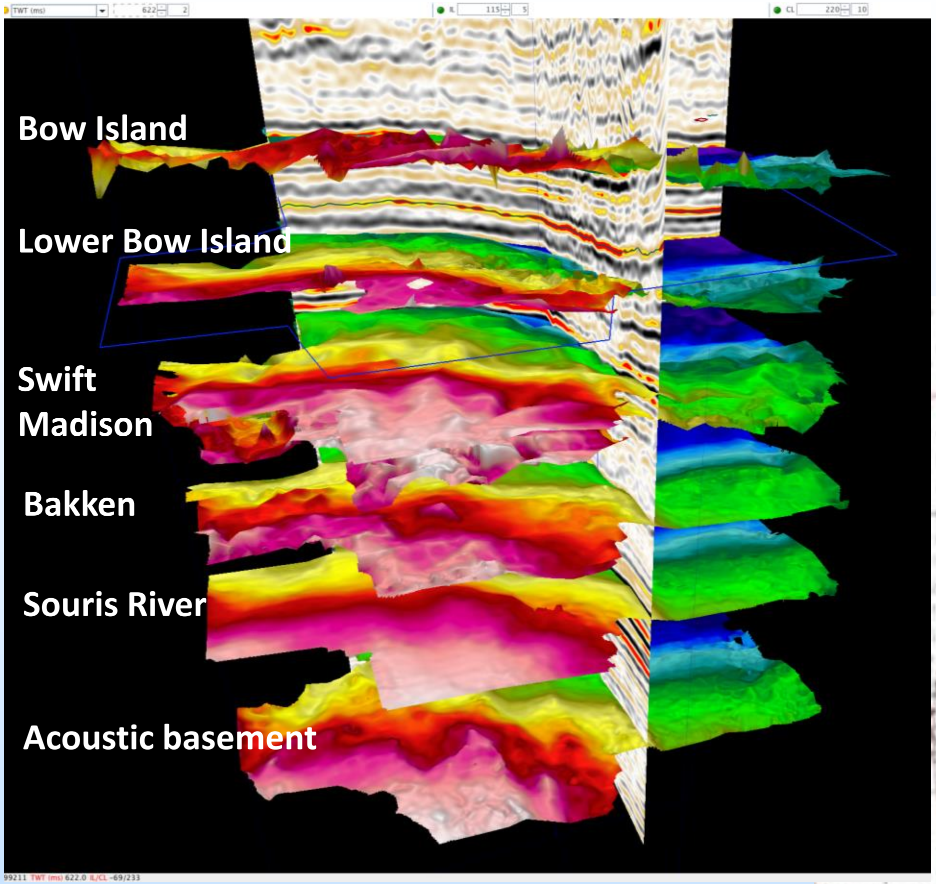
BIG SKY CARBON
SEQUESTRATION PARTNERSHIP

Porosity Dependence of Ambient Vp & Vs for the Duperow Formation:

Ambient pressure Vp (solid blue) as well as Vs (solid yellow/green) compared to sonic log/neutron porosity crossplot (open symbols) and a carbonate effective medium theory based on a modified Kuster-Toksoz relation



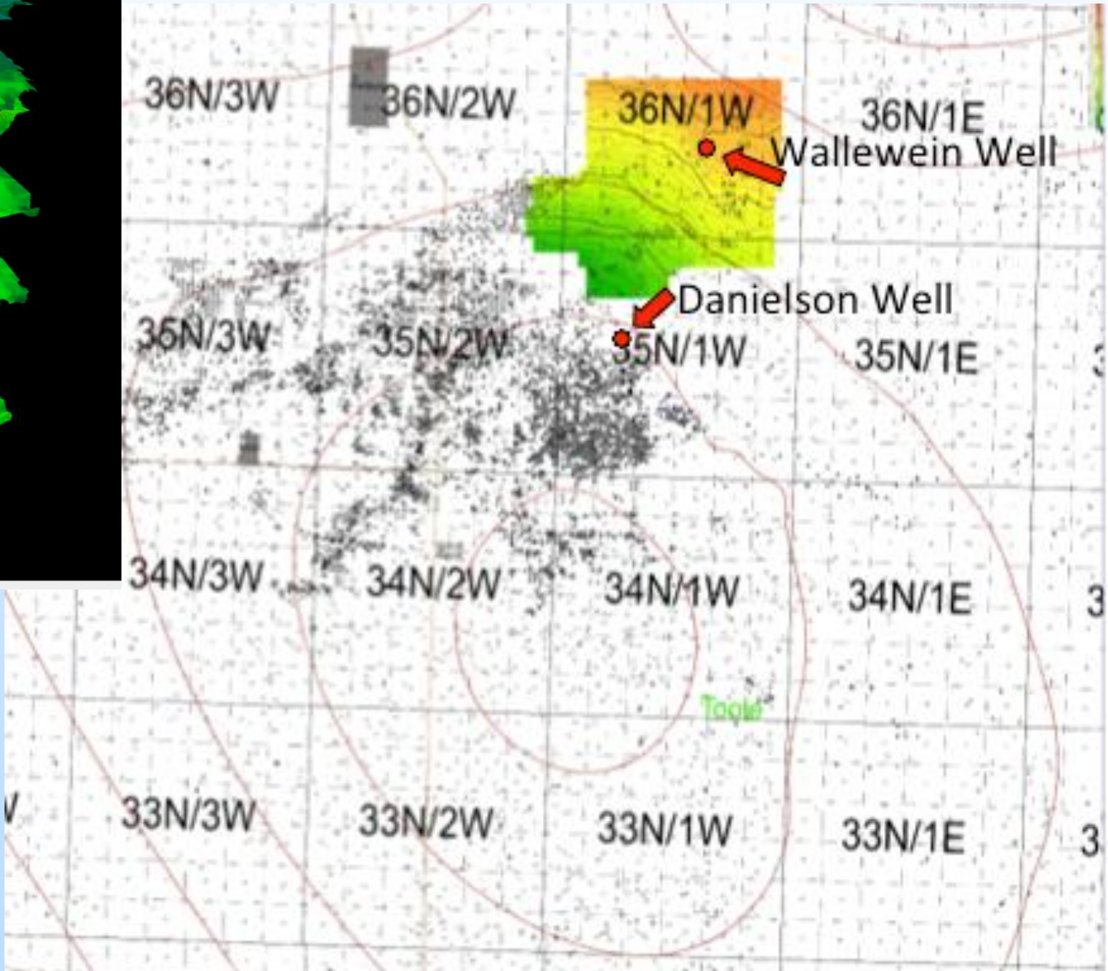
Seismic Structural Data



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

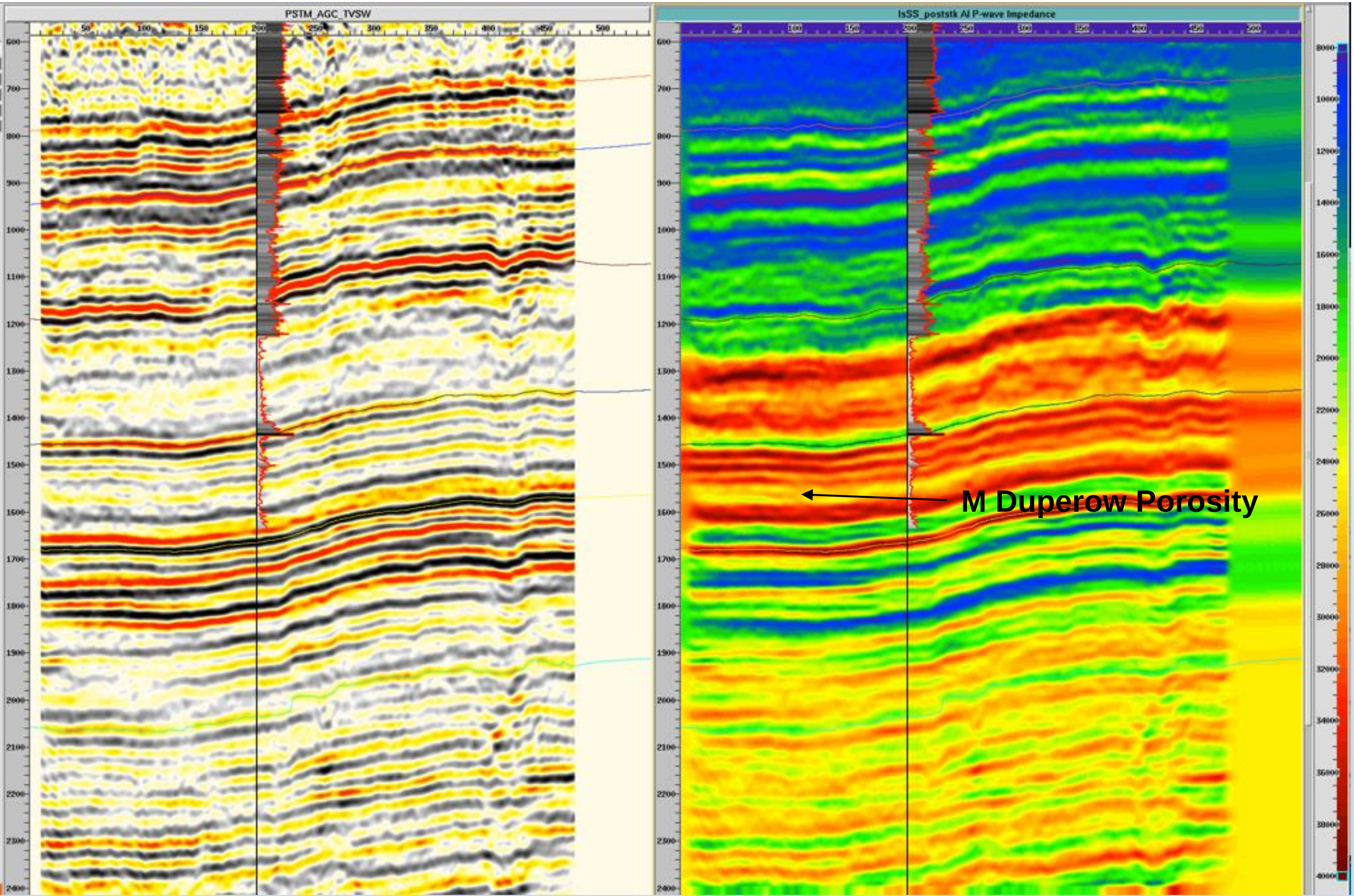
BIG SKY CARBON SEQUESTRATION PARTNERSHIP

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



BSCSP Seismic Monitoring Program

Poststack P and SH inversion IsSS with Wallewein GR

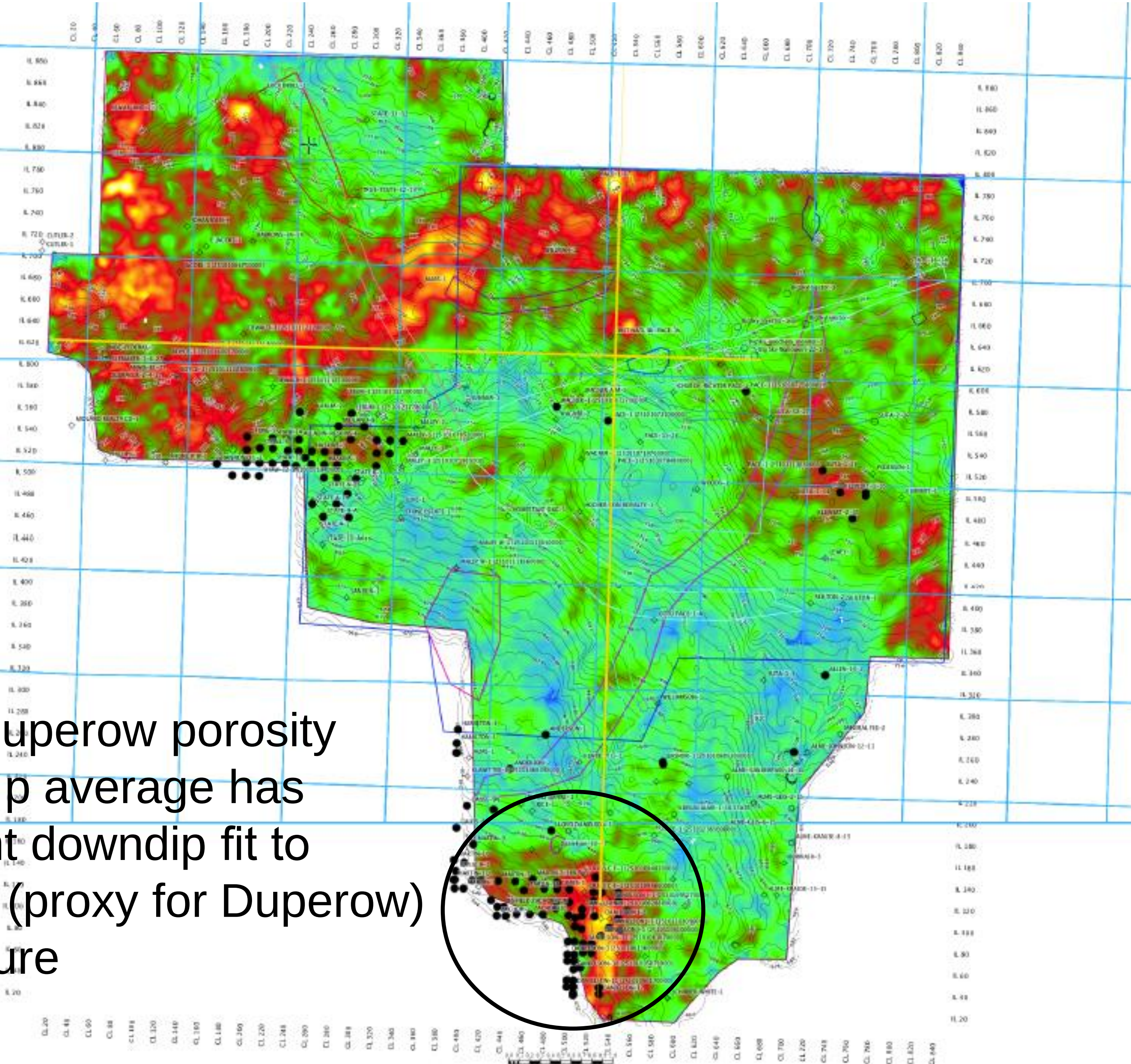


BSCSP Seismic Monitoring Program

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

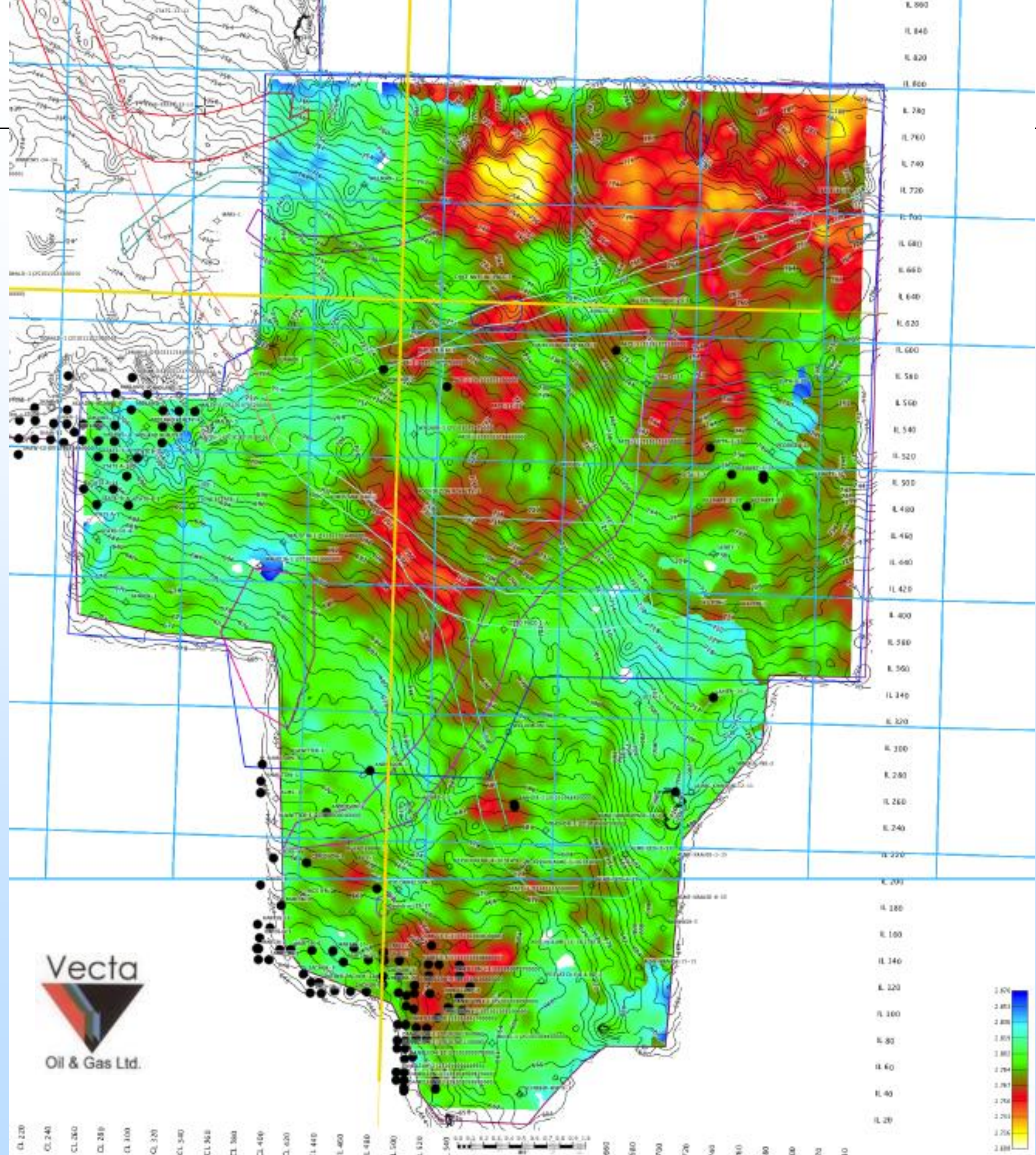
Vecta Oil & Gas Ltd.



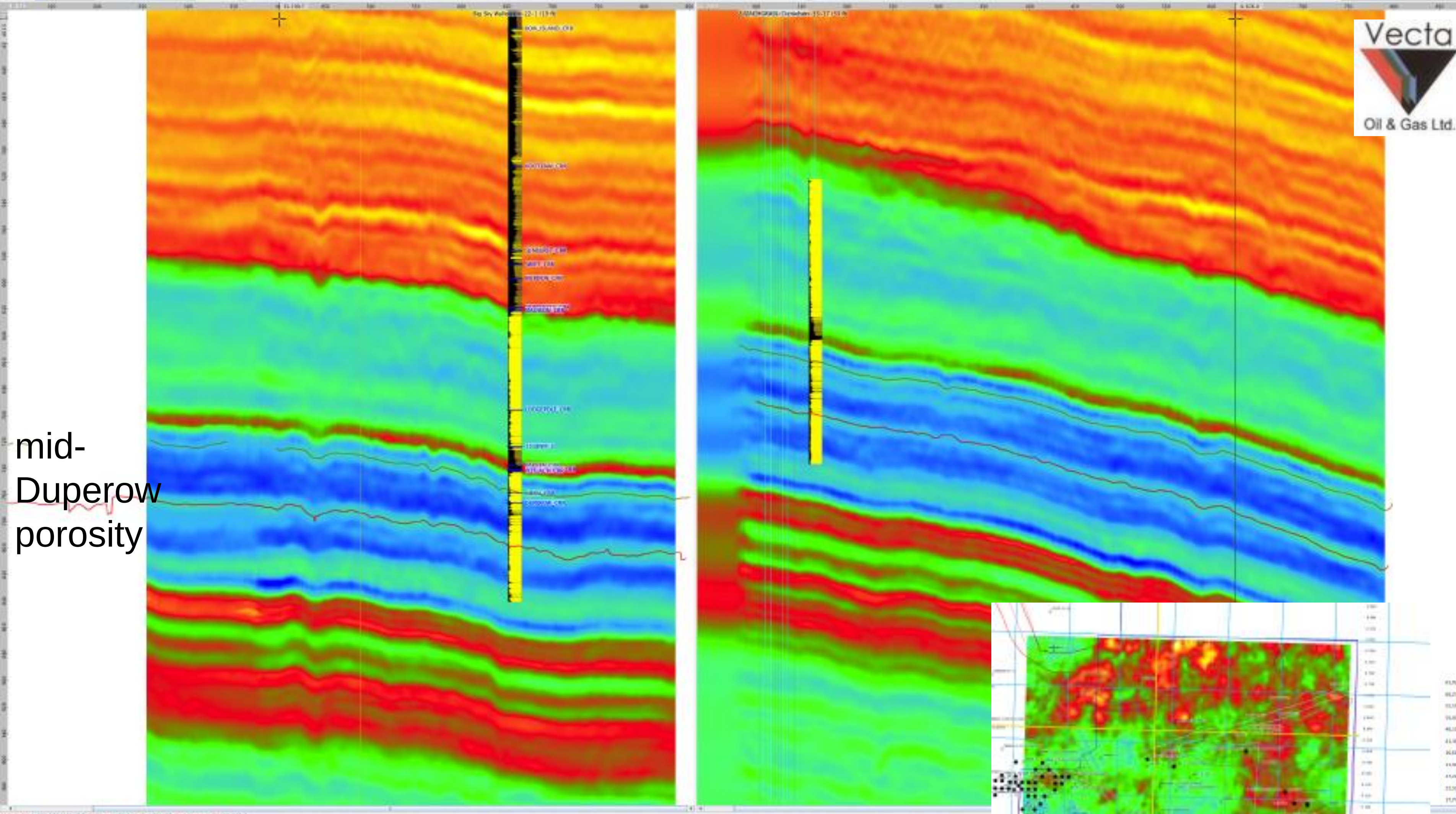
mid-Duperow porosity zone Ip average has decent downdip fit to Nisku (proxy for Duperow) structure

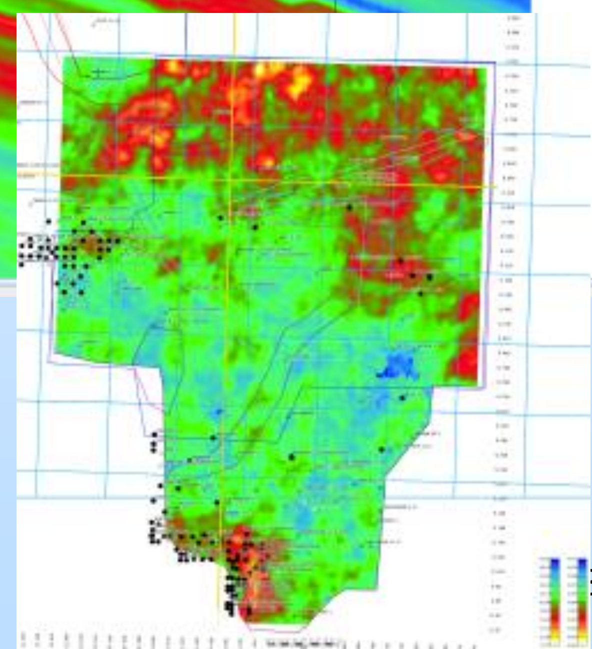
Mid-Duperow ρ from P/SH/SV inversion also shows some downdip fit.

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

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
meability
directional
allel to the
tion. The s
affected by
and is a p
ability, whe
wave is aff
the pores c

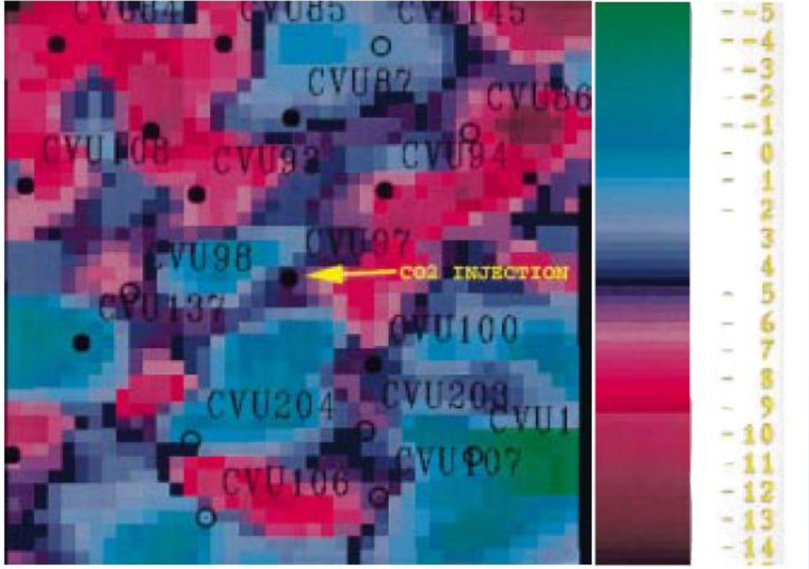


Figure 5. Velocity anisotropy map from the base 3-D, 3-C survey. The area south of the CO_2 injection shows values of near zero percent anisotropy, indicating vertical open fractures both parallel and perpendicular to the maximum horizontal stress field.

"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."

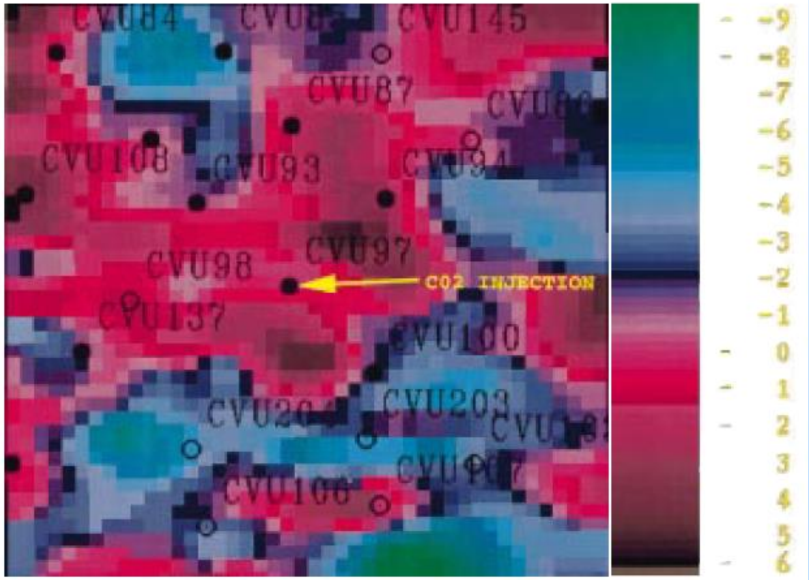


Figure 6. Velocity anisotropy map from the repeat 3-D, 3-C survey. The zone of zero percent anisotropy from the base survey is now showing 6% positive anisotropy, indicating a higher density of vertical open fractures parallel to the maximum horizontal stress direction or stiffening of the frame due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

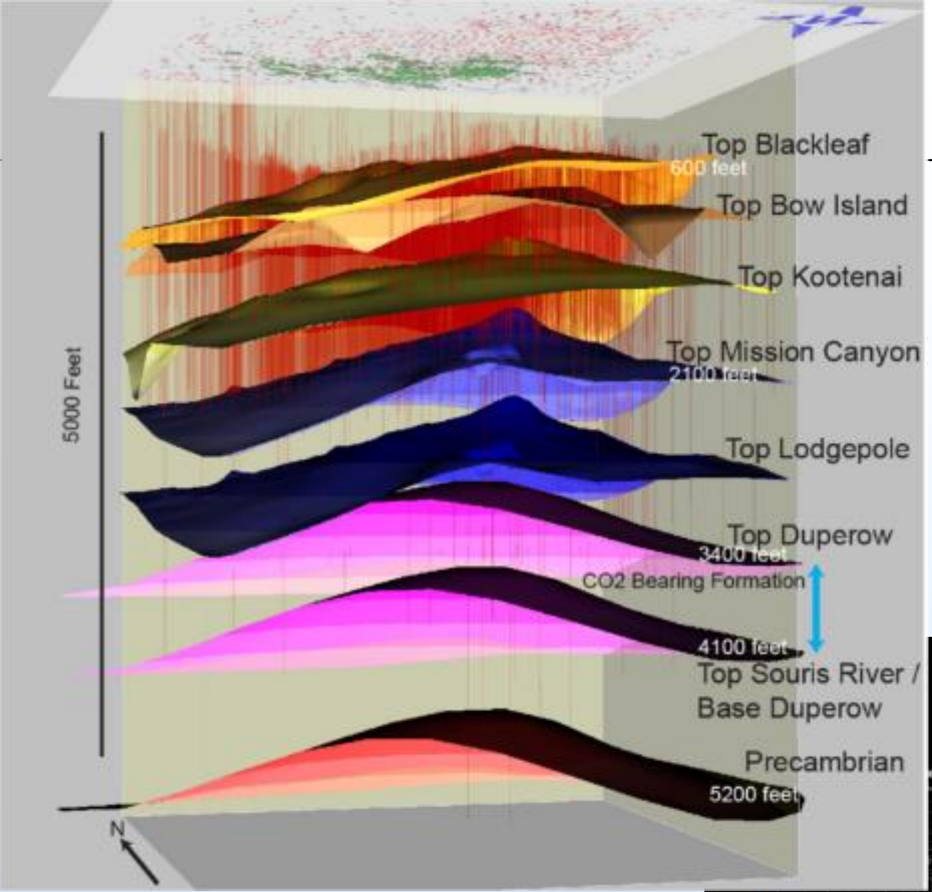
Multiphase Flow – Production

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

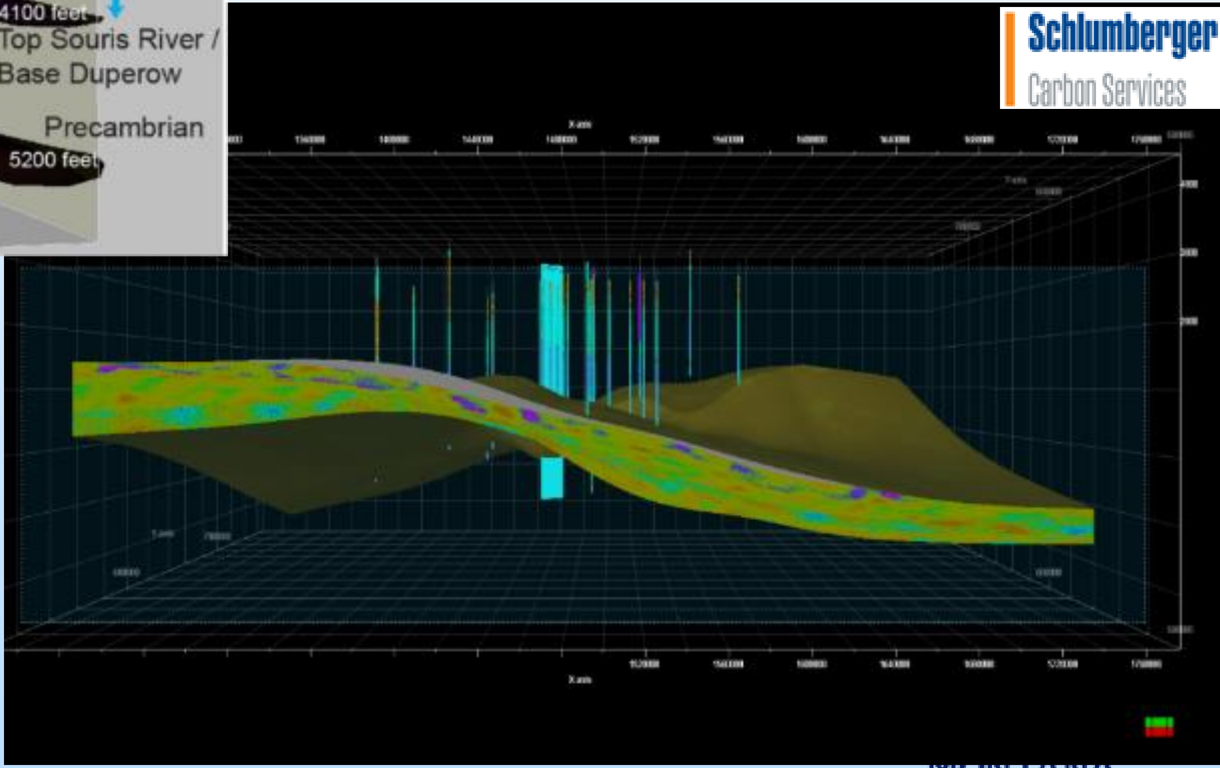
Geochemical & Reactive Transport Modeling

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.



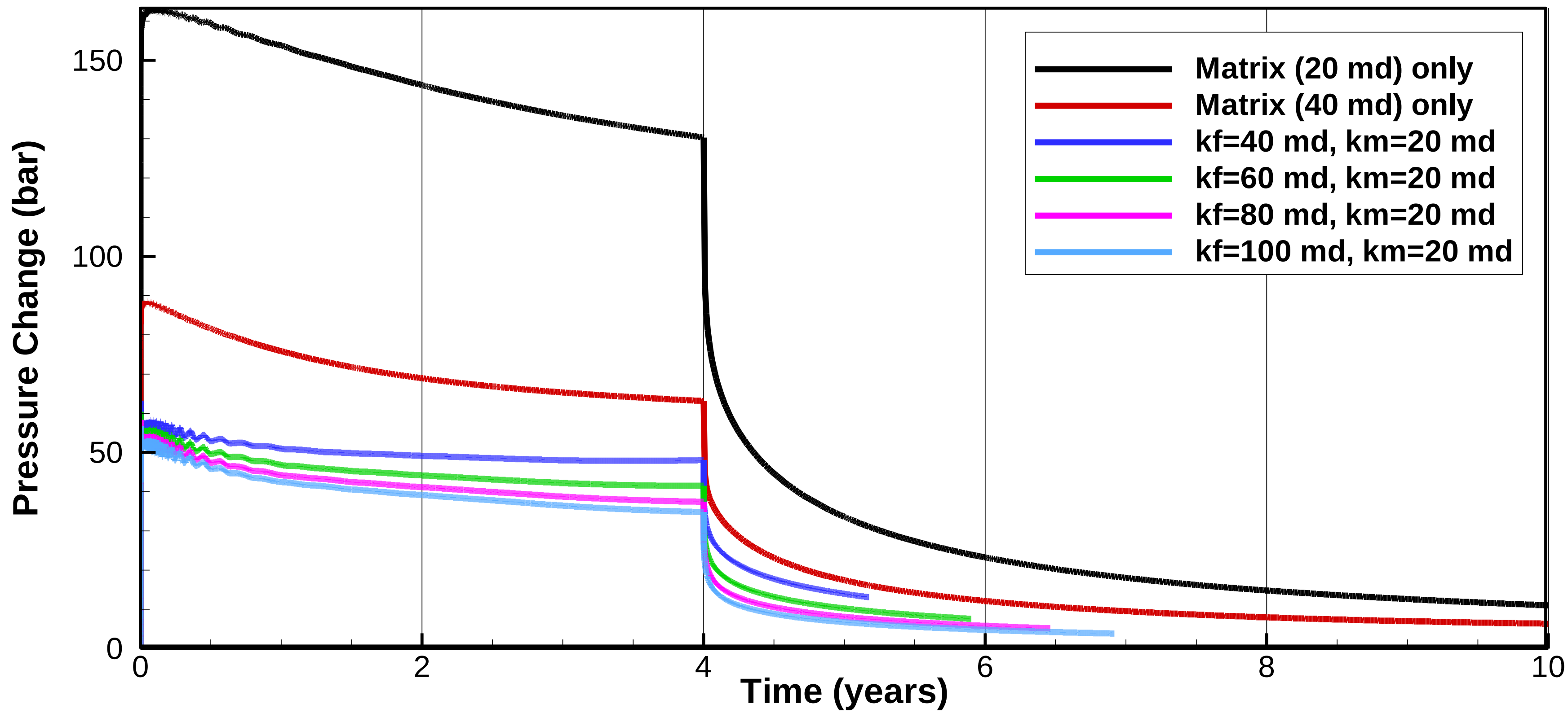
Petrel – Incorporate logs, petro-physical properties (18 wells in injection zone), existing 2D seismic and BSCSP acquired 3D seismic. Export cellular model info for flow modeling.

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)

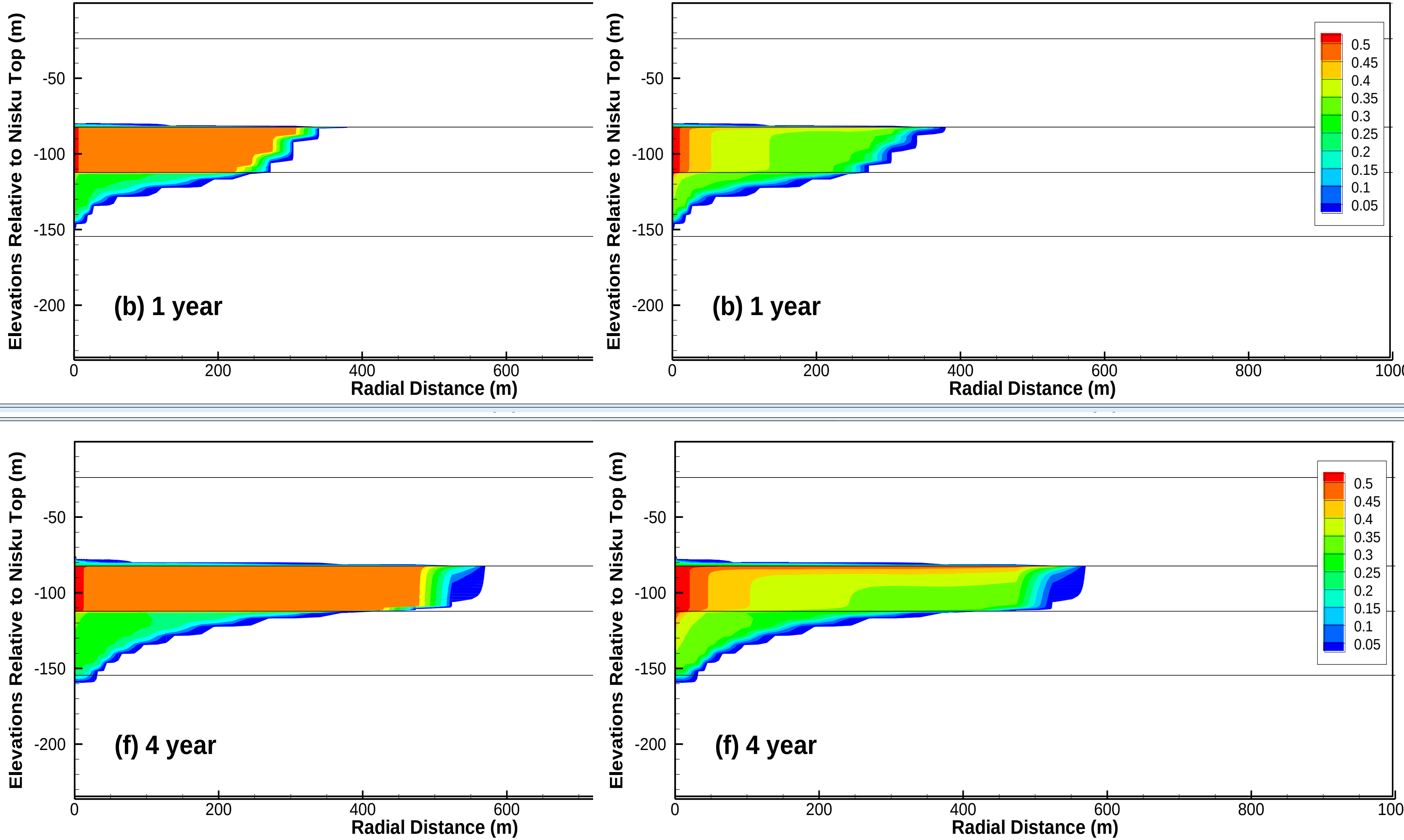


Simulated bottomhole injection ΔP, as a function of time in 6 cases

MINC Simulated CO_2 Plumes

BERKELEY LAB

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.

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**

Synergy Opportunities

- We want to maximize benefit of work done to date
- We are willing to share data and samples for studies different than what our partners already have planned
- Contact us if you are interested in collaborating
- Stacey Fairweather 406-994-5742
- There may be a brief vetting process

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)

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

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

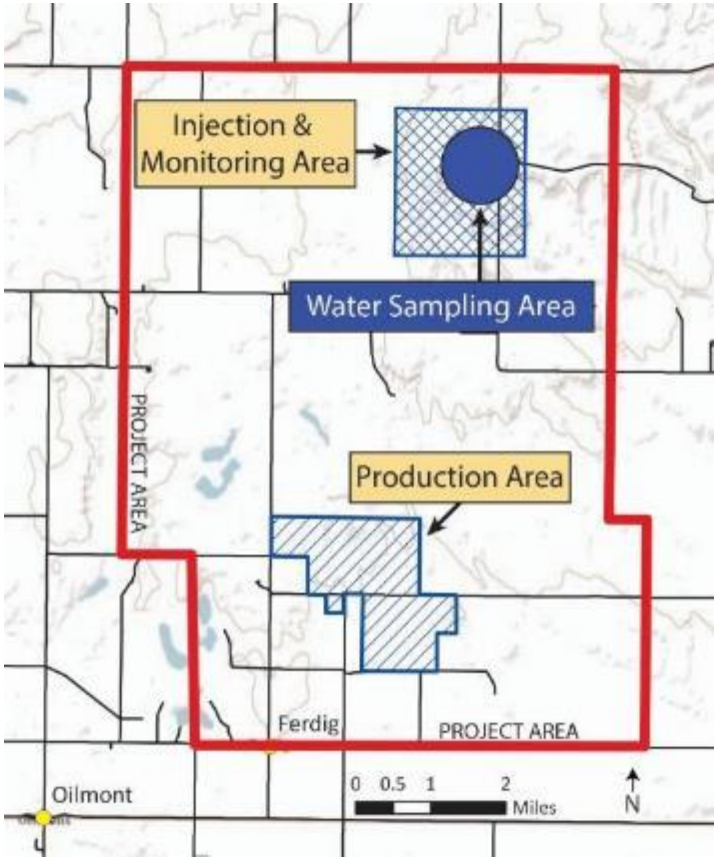
Risk Management

- 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

Assurance Monitoring - Establishing a Baseline Before CO2 Injection

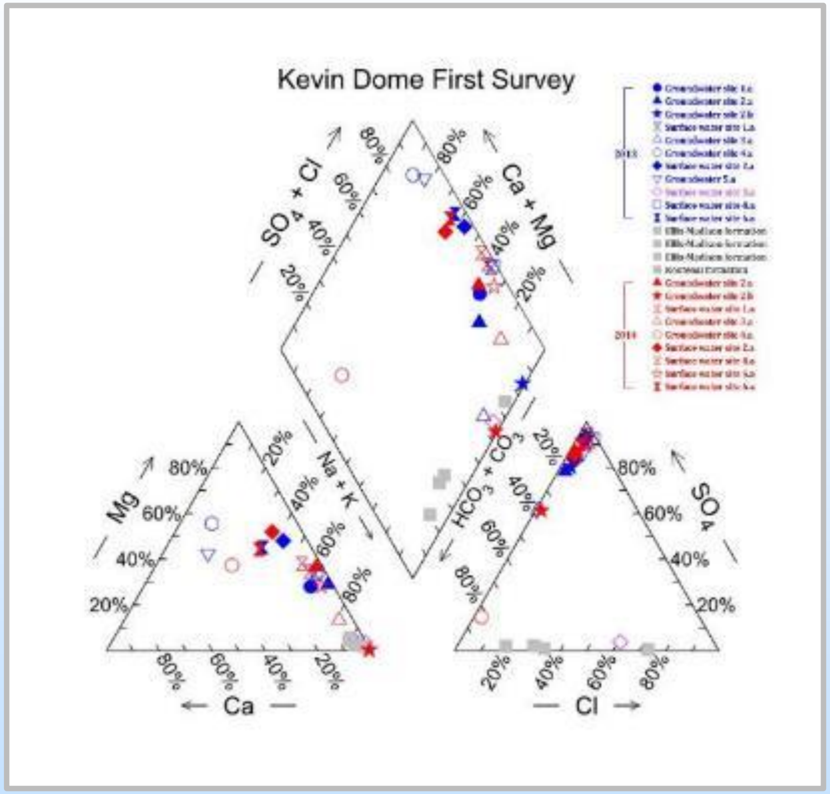


- Water chemistry
- Water quality
- CO_2 soil flux
- Imaging of vegetation
- Atmospheric CO_2

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

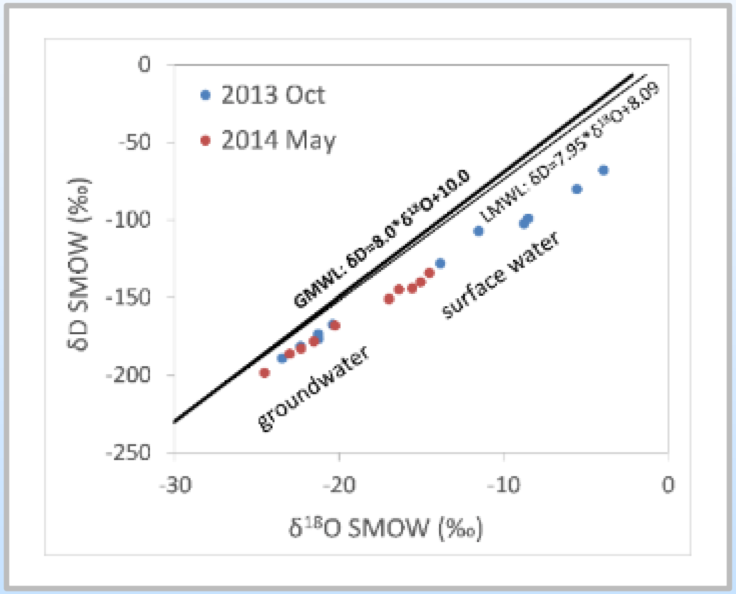
- Most common ions are sodium (Na), sulfate (SO_4), and chloride (Cl)
- Chemically consistent with geology of the area
- Significant seasonal variability

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)

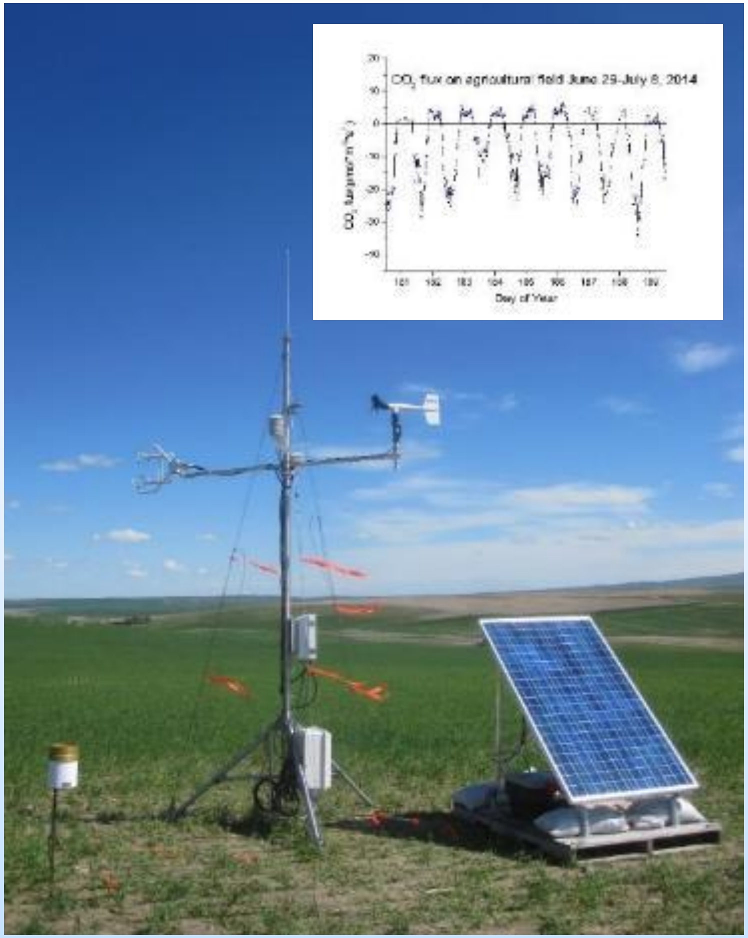
H and O Isotopic Data



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

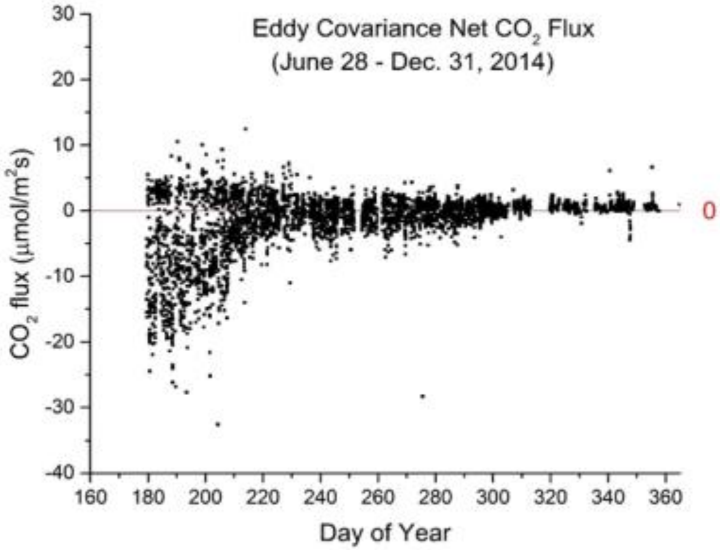
- Installed June 2014
- Data so far consistent with field in agricultural use

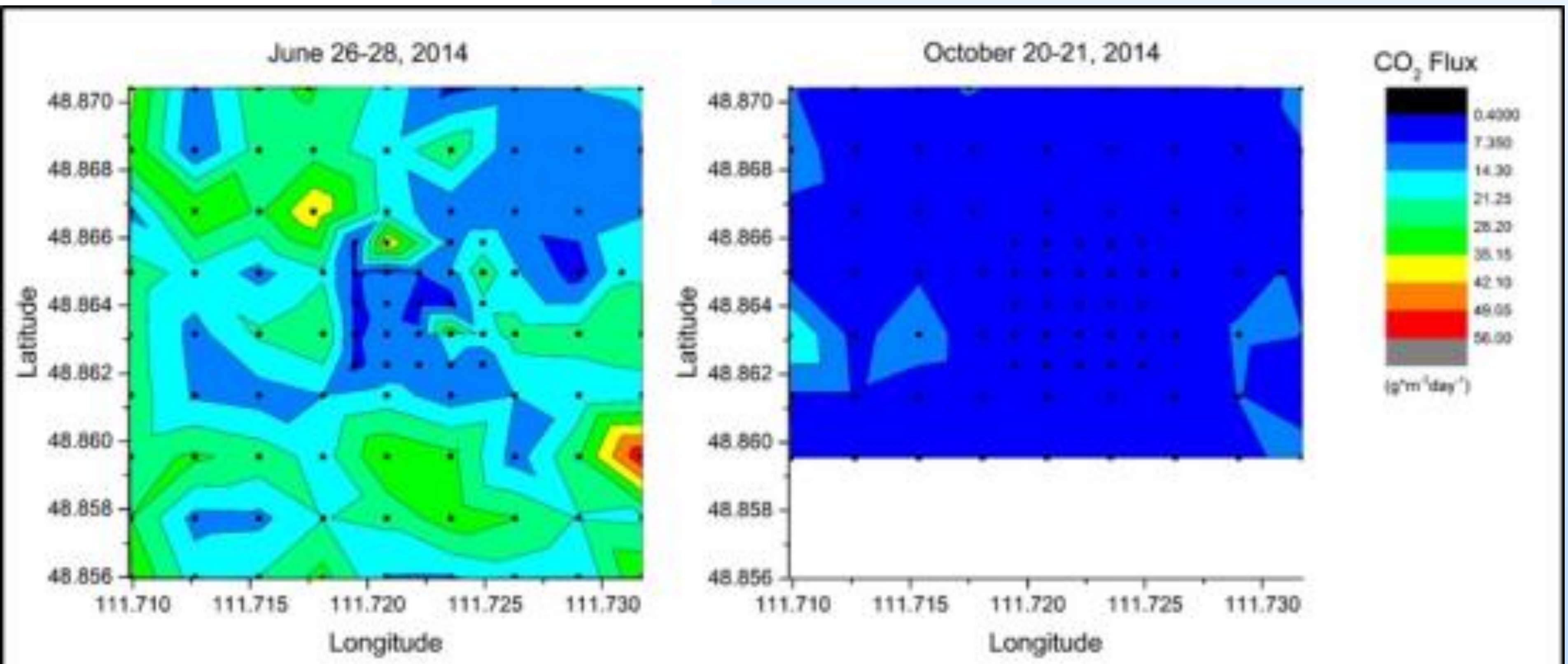
SOIL CO_2 FLUX SURVEY

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

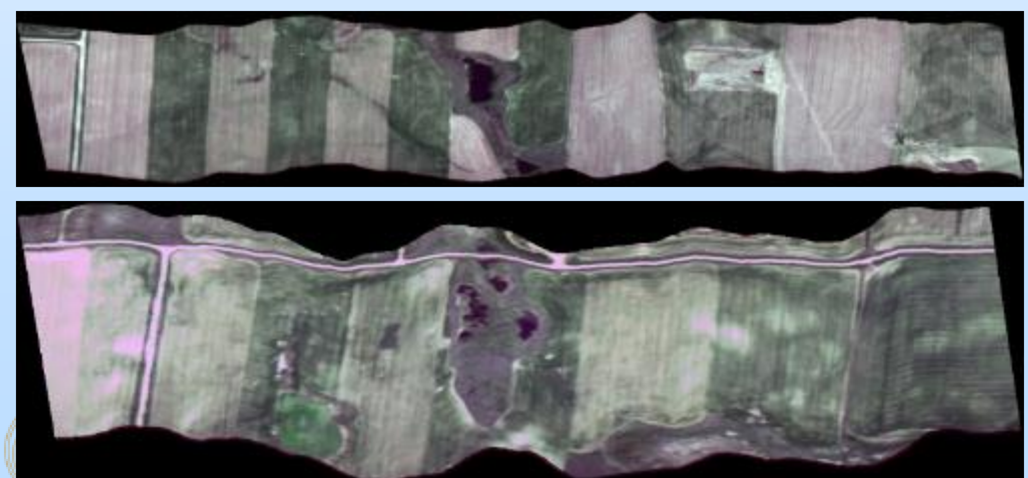




HYPERSPECTRAL IMAGING

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.

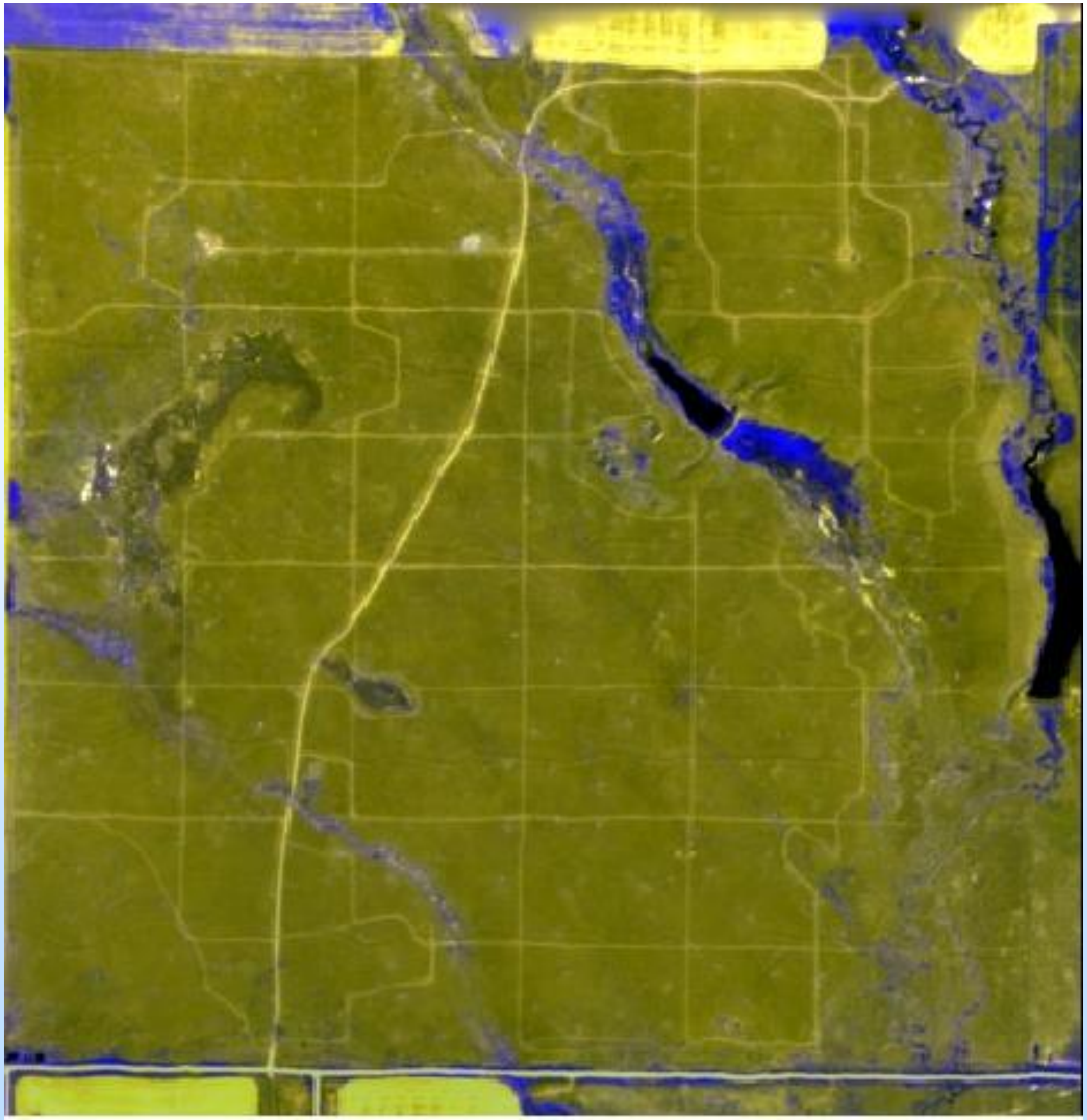


Three color images of two flight paths on June 24, 2014. Initial geo-rectification using the Inertial Measurement Unit was conducted and further improvements to the geo-rectification will utilize ground based GPS data.

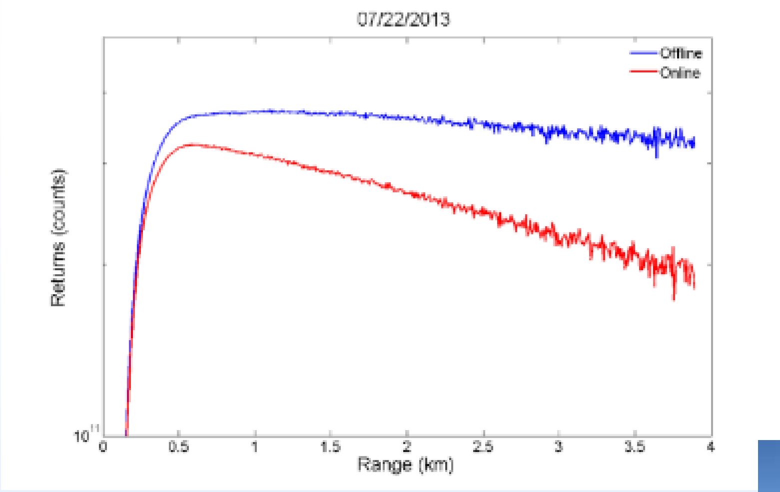
MONTANA STATE UNIVERSITY

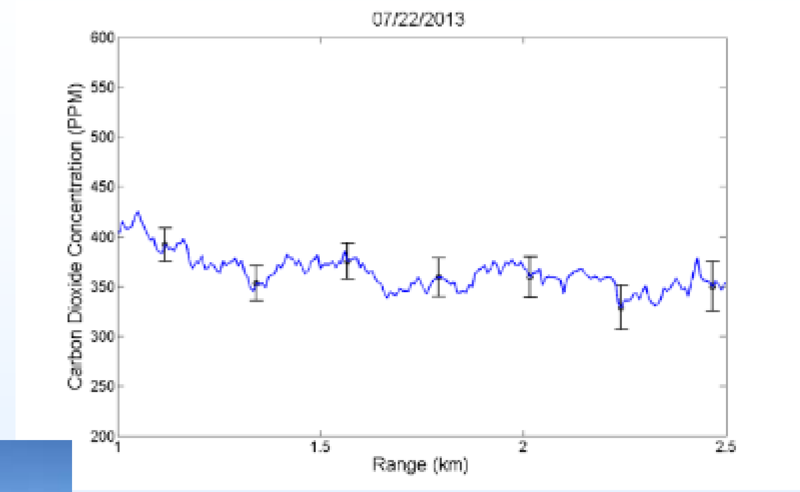
Hyperspectral Imaging

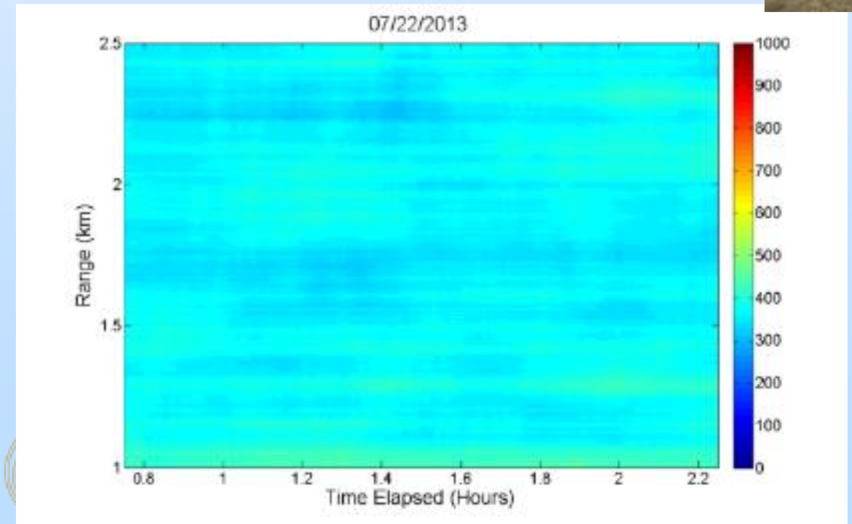
Seismic tracks evident in hyperspectral data when no evidence on the ground was visible

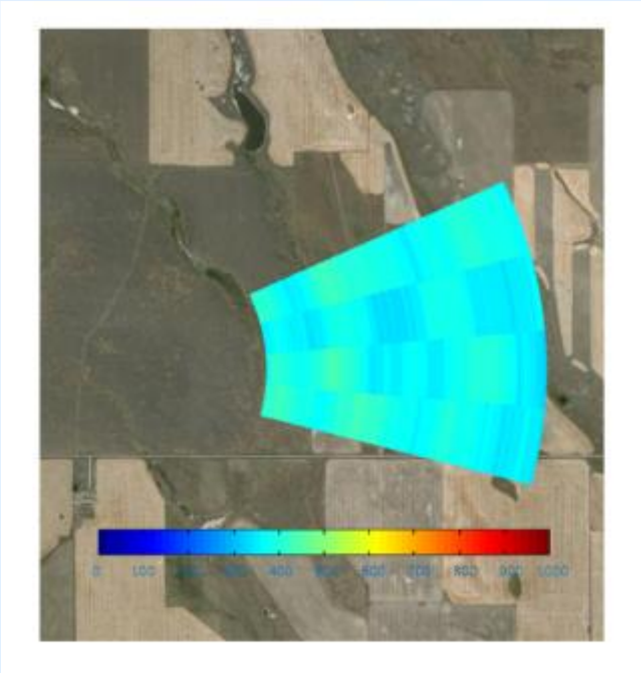


LIDAR (TESTED IN 2013 IN PRODUCTION AREA)









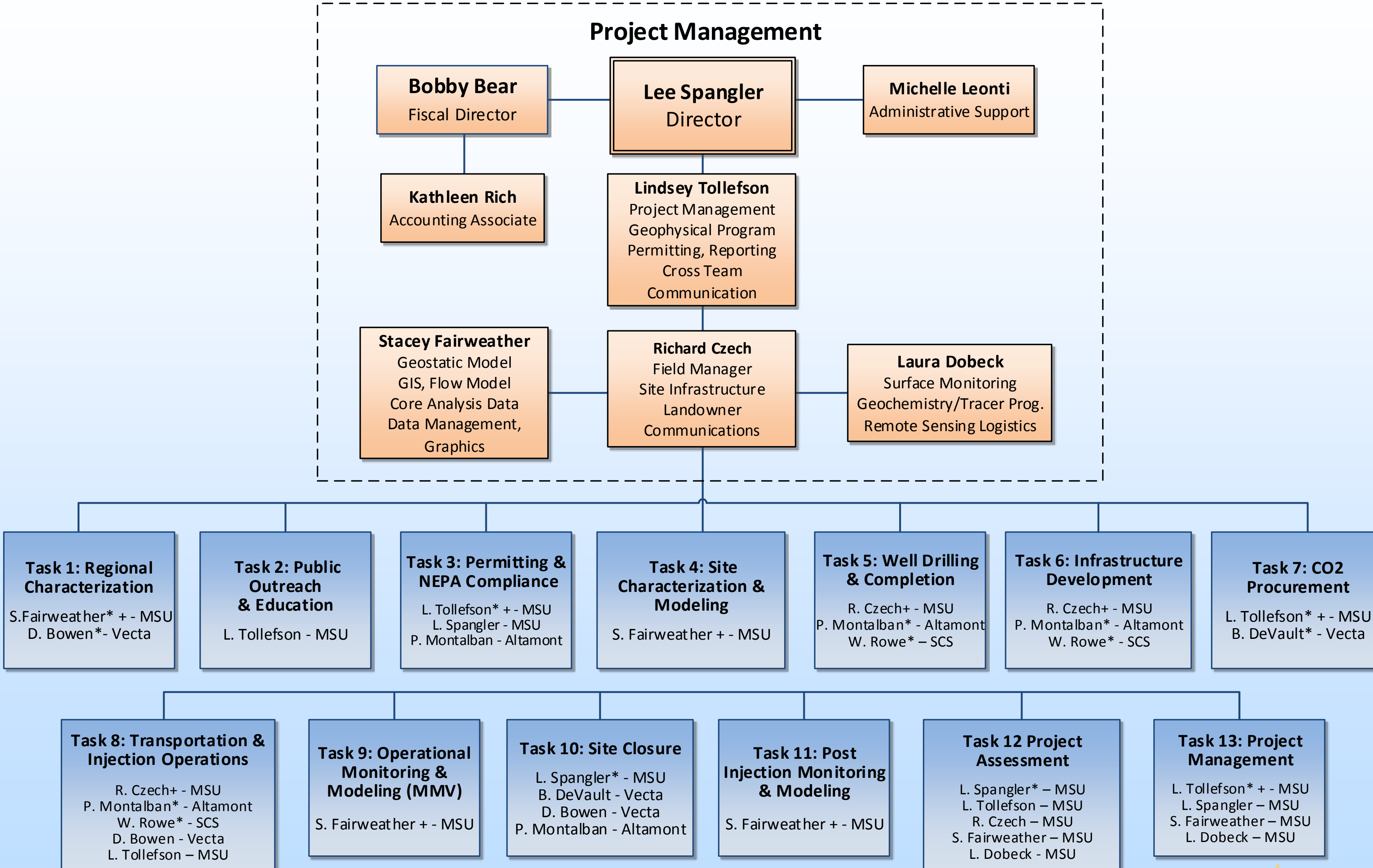
Synergy Opportunities

- 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

Appendix

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

Organization Chart: Management



BIG SKY CARBON SEQUESTRATION PARTNERSHIP

MONTANA STATE UNIVERSITY

Bibliography

1. Oldenburg, C. M., Cihan, A., Zhou, Q., Fairweather, S., & Spangler, L. H. 2014. Delineating Area of Review in a System with Pre-injection Relative Overpressure. Energy Procedia 63: 3715-3722.
2. Tan, S.R., Huang, L.J. 2014. Reducing the computer memory requirement for 3D reverse-time migration with a boundary-wavefield extrapolation method. Geophysics 79(5): S185-S194.
3. Barr, J., Humphries, S., Nehrir, A., Repasky, K., Dobeck, L., Carlsten, J., and Spangler, L. 2014. Laser-Based Carbon Dioxide Monitoring Instrument Testing During a 30-Day Controlled Underground Carbon Release Field Experiment. *International Journal of Greenhouse Gas Control 5*(1): 138-145.
4. Dai, Z., Middleton, R., Viswanathan, H., Fessenden-Rahn, J., Bauman, J., Pawar, R., Lee, S-Y., and McPherson, B. 2014. An integrated framework for optimizing CO_2 sequestration and Enhanced Oil Recovery. Environmental Science & Technology 1(1): 49-54.

Bibliography

5. Dai, Z., Stauffer, P., Carey, W., Middleton, R., Lu, Z., Jacobs, J., Hnottavange-Telleen, K., and Spangler, L. 2014. Pre-Site Characterization Risk Analysis for Commercial-Scale Carbon Sequestration. Environmental Science & Technology 48(7): 3908-3915.

6. Long, J., Lawrence, R., Marshall, L. and Miller, P. 2014. Changes in field-level cropping sequences: Indicators of shifting agricultural practices. *Agriculture, Ecosystems and Environment 189*: 11–20.

7. Zhenxue, D., Stauffer, P., Carey, W., Middleton, R., Lu, Z., Jacobs, J., Hnottavange-Telleen, K., and Spangler, L. Pre-site characterization risk analysis for commercial-scale carbon sequestration. Environmental Science & Technology 48(7): 3908-3915.

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

Bibliography

9. Lewicki, J., Hilley, G., Dobeck, L., McLing, T., Kennedy, B., Bill, M., and Marino, B. 2013. Geologic CO2 Input into Groundwater and the Atmosphere, Soda Springs, Id, USA. Chemical Geology 339: 61-70.
10. Long, J., Lawrence, R., Greenwood, M., Marshall, L., and Miller, P. 2013. Object-Oriented Crop Classification Using Multitemporal ETM+SLC-Off Imagery and Random Forest. GIScience & Remote Sensing 50(4): 418-436.
11. Zhdanov, M., Endo, M., Black, N., Spangler, L., Fairweather, S., Hibbs, A., Eiskamp, G., and Will, R. 2013. Feasibility study of electromagnetic monitoring of CO2 sequestration in deep reservoirs. SEG Technical Program.
12. Zhdanov, M., Endo, M., Black, N., Spangler, L., Fairweather, S., Hibbs, A., Eiskamp, G., and Will, R. 2013. Electromagnetic monitoring of CO2 sequestration in deep reservoirs. First Break 31(2): 85-92.