Maquoketa Shale Caprock Integrity Evaluation

Topical Report

December 8, 2009 through June 30, 2014

Wade Zaluski[1]

[1]Schlumberger Carbon Services
14090 SW Freeway, Suite 240,
Sugar Land, TX 77478

Report Issued: August 18, 2014

Report Number: DOE/FE0002068-9
U.S. DOE Cooperative Agreement Number: DE-FE0002068
An Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basins

Principal Investigator: Dr. Hannes Leetaru
Business Contact: Illinois State Geological Survey
615 E. Peabody Drive
Champaign, IL 61820-7406

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1. Executive Summary

The Knox Project objective is to evaluate the potential of formations within the Cambrian-Ordovician strata above the Mt. Simon Sandstone (St. Peter Sandstone and Potosi Dolomite) as potential targets for carbon dioxide (CO_2) sequestration in the Illinois and Michigan Basins. The suitability of the St. Peter Sandstone and Potosi Dolomite to serve as reservoirs for CO_2 sequestration is discussed in separate reports. In this report the data gathered from the Knox project, the Illinois Basin – Decatur Project (IBDP) and Illinois Industrial Carbon Capture and Sequestration project (IL-ICCS) are used to make some conclusions about the suitability of the Maquoketa shale as a confining layer for CO_2 sequestration. These conclusions are then upscaled to basin-wide inferences based on regional knowledge.

Data and interpretations (stratigraphic, petrophysical, fractures, geochemical, risk, seismic) applicable to the Maquoketa Shale from the above mentioned projects was inventoried and summarized. Based on the analysis of these data and interpretations, the Maquoketa Shale is considered to be an effective caprock for a CO_2 injection project in either the Potosi Dolomite or St. Peter Sandstone because it has a suitable thickness (~200ft. ~61m), advantageous petrophysical properties (low effective porosity and low permeability), favorable geomechanical properties, an absence of observable fractures and is regionally extensive. Because it is unlikely that CO_2 would migrate upward through the Maquoketa Shale, CO_2, impact to above lying fresh water aquifers is unlikely. Furthermore, the observations indicate that CO_2 injected into the St. Peter Sandstone or Potosi Dolomite may never even migrate up into the Maquoketa Shale at a high enough concentrations or pressure to threaten the integrity of the caprock.

Site specific conclusions were reached by unifying the data and conclusions from the IBDP, ICCS and the Knox projects. In the Illinois Basin, as one looks further away from these sites, the formation characteristics are expected to vary. The degree of how well this data can be extrapolated throughout the Basins (regionalized) is difficult to quantify because of the limited amount of data collected on the Maquoketa Shale away from IBDP, IL-ICCS and the Knox projects.

Data gathered from the IBDP/IL-ICCS/Knox projects were used to make conclusions about the suitability of the Maquoketa shale as a confining layer for CO_2 sequestration. This study indicates that the Maquoketa Shale would be a suitable caprock for a CO_2 injection program in either the Potosi Dolomite or St. Peter Sandstone.

2. Knox Project Description

This Knox project is part of a larger project co-funded by the United States Department of Energy (US DOE) under cooperative agreement DE-FE0002068 from December 8, 2009 through September 31, 2014. The objective of the study is to evaluate the potential of formations within the Cambrian-Ordovician strata above the Mt. Simon Sandstone as potential targets for carbon dioxide (CO_2) sequestration in the Illinois and Michigan Basins. The Illinois State Geological Survey (ISGS) requested Schlumberger Carbon Services to evaluate the potential injectivity of the Ordovician age St. Peter Sandstone and the Cambrian age Potosi Dolomite, which is part of the Knox Supergroup. The evaluation of these formations was accomplished using wireline data, core data, pressure data, and seismic data acquired through funding in this project, as well as existing data from two additional, separately funded projects (Figure 1). The first project is the US DOE National Energy Technology Laboratory funded Illinois Basin – Decatur Project (IBDP). The second project, also funded by the US DOE, is the Illinois Industrial Carbon Capture and Storage Project (IL-ICCS). The IL-ICCS project is funded through the American Recovery and Reinvestment Act (ARRA).

Generally, the Knox Project addresses the following questions:

- Could the St. Peter Sandstone and Potosi Dolomite serve as suitable targets for CO_2 sequestration at locations within the Illinois Basin where they lie at depths below the Underground Sources of Drinking Water (USDW)?
- Is the overlying Maquoketa Shale an effective seal to stop the upward migration of CO_2 into overlying formations and USDWs?
- What is the risk of fracturing the seals or the reservoir and allowing CO_2 to move in unanticipated directions?
- How CO_2 will interact with the waters and mineralogy of the seal (Maquoketa Shale) and reservoirs (St. Peter Sandstone and Potosi Dolomite)?

3. Maquoketa Shale Seal Integrity Study Objective

The primary objective of this topical report is to address the following questions related to the CO_2 sealing characteristics of the Maquoketa Shale:

1. To what extent do site-specific data from the IBDP and IL-ICCS projects support the inference that Maquoketa Shale would be an effective caprock?
    - Is the overlying Maquoketa Shale an effective seal to stop the upward migration of CO_2?
    - What is the risk of fracturing the Maquoketa Shale or the reservoir and allowing CO_2 to move in unanticipated directions?
    - How will injected CO_2 interact with the brine waters and mineralogy of the seal (Maquoketa Shale)?
2. To what extent does regional information support the inference that Maquoketa Shale would be would be an effective caprock; generally in the Illinois and Michigan Basins, and sub-regionally in different areas?

3. To what extent can the site-specific and regional data be regionalized (extrapolated throughout the basins) so as to provide plausible inferences that are valid beyond the IBDP and IL-ICCS locations?

This caprock integrity evaluation was focused on the Maquoketa Shale because it is deemed to be a much more reliable barrier to upward CO_2 migration than the formations directly overlying the CO_2 injection target zone (Potosi Dolomite and St. Peter formations) (Figure 2). Formations directly overlying the Potosi Dolomite (Shakopee, New Richmond and Oneoto) are considered to be secondary storage formations rather than caprocks because they have porosity, high permeability and significant natural fracture density that would allow for CO_2 movement. For similar reasons, the Supergroups (Plattesville and Galena) above the St. Peter Sandstone may not always be considered a caprock. The Maquoketa Shale is considered to be an effective caprock for a CO_2 injection project in either the Potosi Dolomite or St. Peter Sandstone because it has a sufficient thickness (~200ft.; ~61m), advantageous petrophysical properties, favorable geomechanical properties, and an absence of observable fractures and is regionally extensive.

These objectives were accomplished by means of a workflow comprising the following main tasks:

1. An inventory of available data from the IBDP, IL-ICCS and Knox projects for the Maquoketa Shale was compiled.
2. An inventory of available interpretations and conclusions that was derived from data that were collected from IBDP, IL-ICCS and Knox projects has been summarized for the Maquoketa Shale.
3. An inventory of available regional interpretations has been summarized.
4. Available data, interpretations and conclusions have been integrated and a unified evaluation of the CO_2 sealing characteristics of the Maquoketa Shale has been completed.
5. The risks and uncertainties that are associated with this evaluation have been summarized.

4. Regional Geology of the Maquoketa Shale

Within the Illinois Basin (Figure 1) a stratigraphic column presented in Figure 2 shows the position of the Knox Supergroup and Maquoketa Shale. The formation depths and naming nomenclature are taken directly from the local IBDP and IL-ICCS study area. In addition to geological variation, throughout the Illinois Basin and into the Michigan Basin, the formations often go by different names. For example, the Maquoketa Shale is known as the Utica Shale in the Michigan Basin.

Within the Illinois Basin, Michigan Basin, and some adjacent regions, the Knox is everywhere overlain by the St. Peter Sandstone. The Maquoketa Shale (or its Michigan-Basin equivalent Utica Shale) also has regional extent, and is thought to be a reliable caprock for CO_2 injected into underlying formations of the Knox Supergroup.

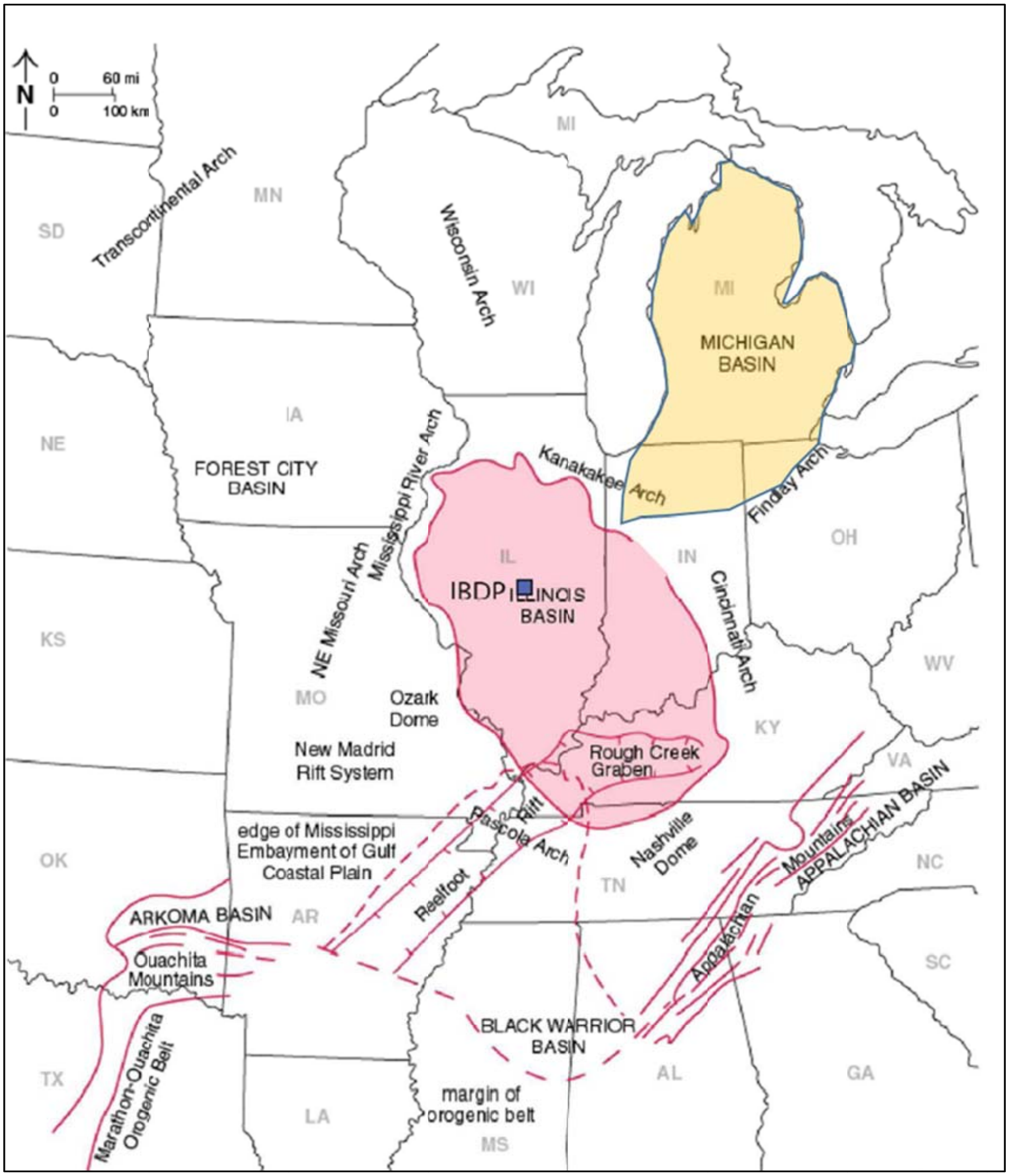


Figure 1: Regional map showing the location of Illinois and Michigan Basins, IBDP and important regional tectonic features (1)

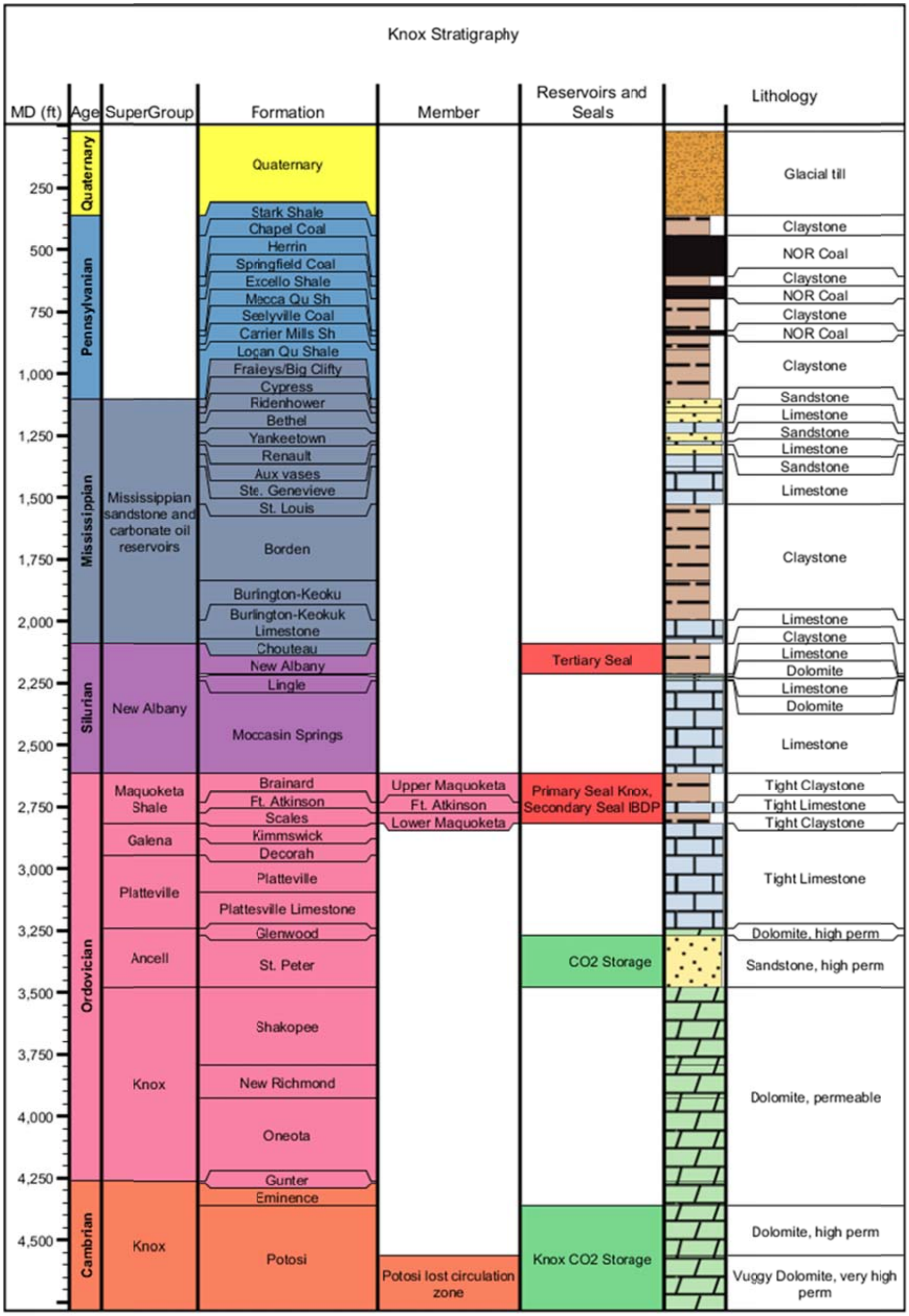


Figure 2: Illinois Basin Knox Supergroup and overlying stratigraphic, formation depths (Nomenclature is taken from the IBDP project).

5. IBDP and IL-ICCS Well Summary

During the development of the IBDP and IL-ICCS projects, five wells have been drilled as of July 2014 with a 6th well planned. Table 1 provides a brief summary of the wells, the associated project and the well description. Figure 3 is a well location map displaying where these wells are located in relation to one another.

Well (Short Name)	**Well (Long Name)**	**Project**	**Well Description**
CCS1	Carbon Capture and Storage Well #1 (CCS1)	IBDP	CO_2 injection well currently in operation.
CCS2	Carbon Capture and Storage Well #2	IL-ICCS	Proposed CO_2 injection well not yet drilled.
GM1	Geophysical Monitoring Well #1 (GM1)	IBDP	GM1 was drilled and instrumented with a permanent geophone array to facilitate the acquisition of time-lapse 3D VSP surveys over the life of the project.
GM2	Geophysical Monitoring Well #2 (GM2)	IL-ICCS	GM2 was drilled and will be instrumented with a retrievable geophone array.
VW1	Verification Well #1 (VW1)	IBDP	VW1 and VW2 were designed to monitor the storage formation and formations immediately above the primary caprock using continuous pressure monitoring and intermittent fluid sampling.
VW2	Verification Well #2 (VW2)	IL-ICCS	

Table 1: IBDP and IL-ICCS well summary

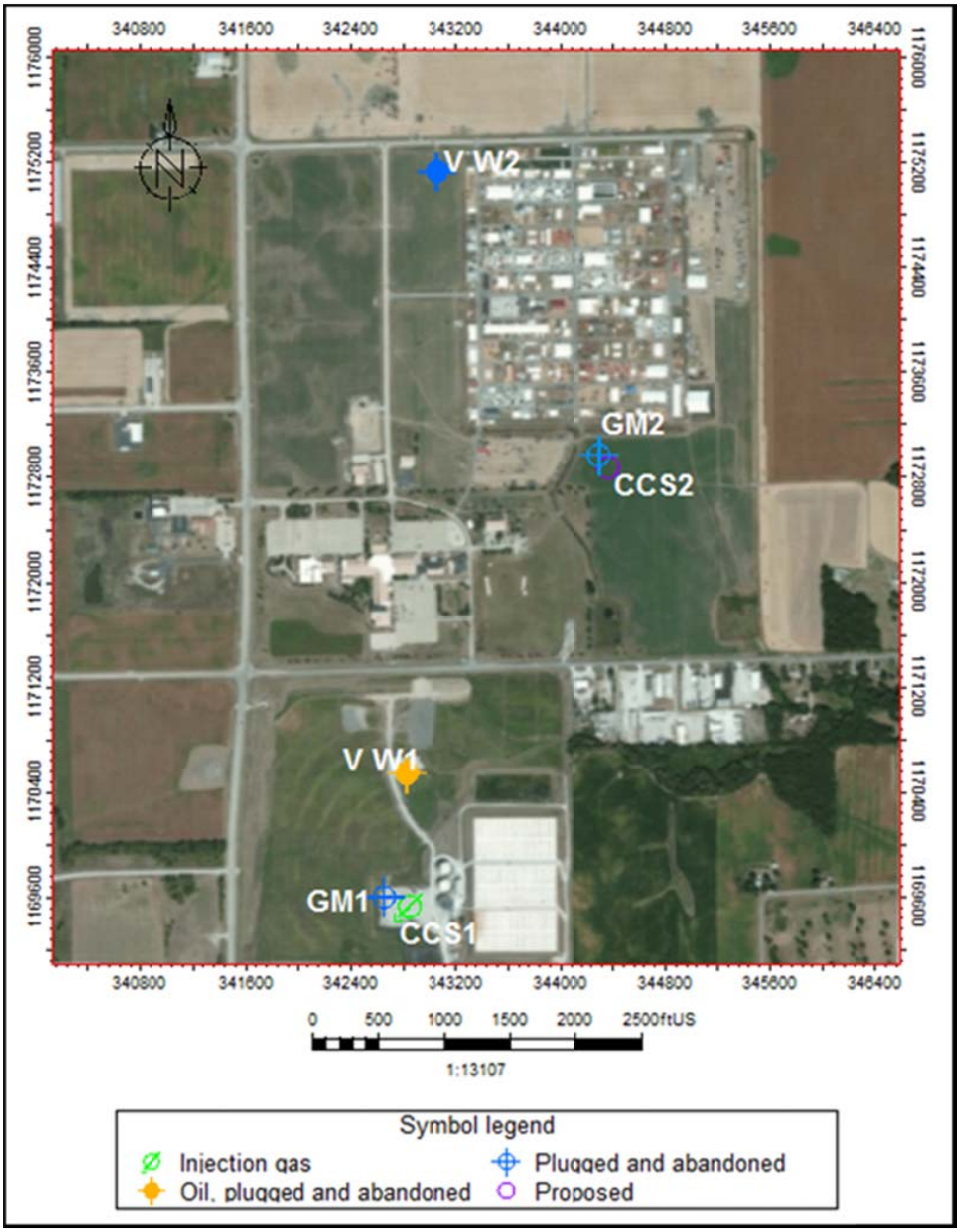


Figure 3: IBDP and IL-ICCS well location map

6. Site Specific (IBDP/IL-ICCS) Available Maquoketa Shale Data and Interpretations

For the IBDP, IL-ICCS, and Knox projects, there have been many different types of data collected with various technology specific interpretations. The challenge with utilizing data from IBDP and IL-ICCS was that these data are taken from a very small area of the Illinois Basin and that most of the data collection and interpretation was focused on the lower lying Mt. Simon Sandstone, which is the CO_2 target injection formation and the Eau Claire Formation, which is the primary seal. An extensive data review of IBDP, IL-ICCS, and Knox was completed to identify what data was available or relevant to an evaluation of the Maquoketa Shale. Table 2 is a brief summary of what primary types of data and previous interpretations were used for the evaluation of the Maquoketa Shale. Data that are not relevant to the Maquoketa Shale are not listed.

Data Type	Data From IBDP	Data From IL-ICCS	Data From Knox
Wireline Program	4 wells (CCS1, VW1, GM1, GM2) Comprehensive Logging program.	1 Well (VW2) Comprehensive Logging program.	-
Geological Modeling	Geological model	Geological model	Geological model (2)
Petrophysical Analysis	ELANPlus* advanced multimineral log analysis (CCS1, VW1, GM1, GM2)	ELANPlus analysis (VW2)	-
Fracture Analysis	FMI* fullbore formation microimager (CCS1, VW1, GM1, GM2)	FMI (VW2)	Fracture Analysis FMI (CCS1, VW1, GM1, GM2
Core Analysis and Geomechanics		-	GM2 Maquoketa Shale whole core (2599-2616ft; 792.3-797.6m) and analysis
Wellbore Integrity Evaluations	Cement Bond Log (CBL) on IBDP wells Review of abandoned wells in the immediate area	CBL on VW2 well	-
Geochemical Investigations	-	-	Report on CO_2-Brine-Rock Interactions (3)
Risk	-	-	Risk evaluation process (4)
3D seismic	3-dimensional (3D) seismic survey	-	Post-stack Seismic Inversion for the Knox Fm (5)

Table 2: Available data and interpretations from the IBDP, IL-ICCS and Knox projects as applicable to the Maquoketa Shale.

(Mnemonics are described in the following sections of this report)

6.1. Wireline Program

The wireline data collected from IBDP and IL-ICCS were used to develop a petrophysical interpretation of the formations within the stratigraphic column (Figure 2). Table 3 and Table 4 summarize the logging suits run on the wells and the specialty logging analysis that was completed.

Well Logging Tool	Abbreviation	Open-hole (OH) / Cased-hole (CH)	CCS1	VW1	VW2	GM1	GM2
4 Arm Caliper	PPC	OH	X	X	X	X	X
Casing Collar Locator - Junk Basket - Gauge	CCL-JB-Gauge	CH	X				
Cement Bond Log	CBL-VDL	CH	X	X	X	X	X
Correlation Log	CCL-GR-P/T	CH	X				
Directional Survey	DIR	OH	X	X			
ECS* elemental capture spectroscopy sonde	ECS	OH	X	X			
HRLA* high-resolution laterolog array tool	HRLA	OH	X	X		X	
Hostile Environment Natural Gamma Ray Sonde	HNGS	OH	X	X			
Isolation Scanner* cement evaluation service	Isolation Scanner	CH	X	X			
MSCT* mechanical sidewall coring tool	MSCT	OH	X	X			
MDT* modular formation dynamics tester	MDT	OH					
Platform Express* integrated wireline logging tool	Platform Express	OH	X	X	X	X	X
Pressure Temperature	P/T-GR-CCL	CH	X	X		X	
PS Platform* production services platform	PS Platform	CH	X	X			
RST* reservoir saturation tool	RST	CH	X	X		X	
Spontaneous Potential	SP	OH		X			
USI* ultrasonic imager	USI	CH		X			

Table 3: Well log inventory as applicable to the Maquoketa Shale

Special Logging Tool and Analysis	Abbreviation	Open-hole (OH) / Cased-hole (CH)	CCS1	VW1	VW2	GM1	GM2
CMR-Plus* combinable magnetic resonance tool	CMR-Plus	OH	X	X			
ELANPlus* advanced multimineral log analysis	ELANPlus	OH	X	X	X	X	X
FMI* fullbore formation microimager	FMI	OH	X	X	X		
Sonic Scanner* acoustic scanning platform	Sonic Scanner	OH	X	X	X		
PoroSpect* carbonate porosity solution (Open Fracture Analysis)	PoroSpect	OH		X	X		

Table 4: Special well log inventory and analysis as applicable to the Maquoketa Shale

6.2 Geological Modeling

All three projects (IBDP, IL-ICCS, and Knox) utilized the Petrel* E&P software platform to develop project specific geologic models; however the Knox model is focused on incorporating relevant data with regards to the scope of the project (2). These data were used to develop geocellular models and reservoir simulations with a focus on the Potosi Dolomite (vuggy dolomite) and therefore do not incorporate formations above the Oneota Formation. Reservoir simulation work was also completed on the St. Peter Sandstone. However, the data and analysis from these overlying formations has been included in the caprock evaluation and has proved valuable in formulating the conclusions that follow in this report.

6.3 Stratigraphic Position and Petrophysical Analysis

All relevant Knox data collected, analyzed, and interpreted have been incorporated into a unified geological model. Figure 3 is a site map which illustrates the location of the IBDP and IL-ICCS wells. Figure 4 shows a legend for VW2 and GM1 log sections (Figure 5 and Figure 6). Table 5 lists additional track mnemonics described later in figures and later sections of this report. In addition to the gamma ray log that is displayed, the results of on ELANPlus are presented. ELANPlus analysis utilizes the variety of available logging curves to calculate effective porosity, permeability and the formation lithology fractions. Figure 5 (Maquoketa Shale) displays the ELANPlus results and brief geological description of the Maquoketa Shale at GM2. This figure displays how the Maquoketa Shale is divided by the Fort Adkinson Limestone into the Upper and Lower Maquoketa Shale. A summary of the geological characteristics for formations relevant to the Knox Project are presented in Figure 6 (New Albany Shale to Base of Potosi Dolomite).

Between the four wells, a close look at the lithology fraction track from the ELANPlus results will show some variability. Some formation lithological variability is expected because these are different wells; however, in this case, the primary reason for this is because the types of logging curves that were available to compute the lithology fractions varied in the each well. The lithology fractions calculated at VW1 is considered to be the most representative of the Maquoketa Shale because there was a more comprehensive logging suite run across this formation which resulted in more accurate lithology fraction calculations. There will also be some variation in the way the effective porosity and permeability is calculated; this is because borehole rugosity which artificially raise the results. The effective porosity and permeability calculated at GM1, GM2 and VW1 are considered to be representative of the Maquoketa Shale because there was less borehole rugosity in these wells.

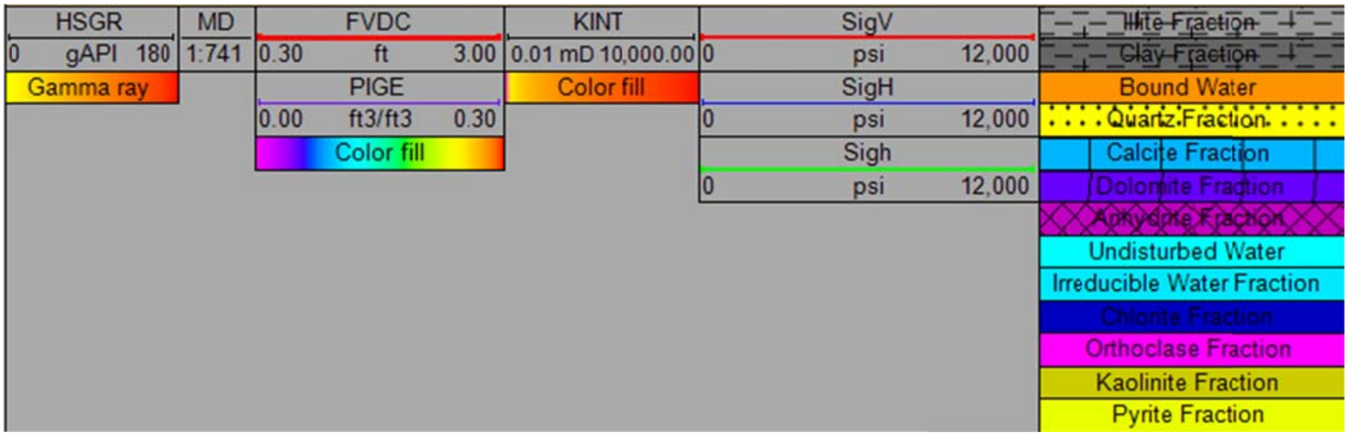


Figure 4: Legend for cross sections

Curve	Curve Description
HSGR	HNGS Standard Gamma-Ray
MD	Measured Depth (feet)
PIGE	Effective porosity which is the porosity available to free fluids, excluding non-connected porosity and space occupied by bound water.
FVDC	Fracture Density per foot from open fracture analysis from FMI.
KINT1	Permeability, originates from CMRPlus and calculated in ELANPlus.
SigH	Maximum horizontal stress (geomechanics)
Sigh	Minimum horizontal stress(geomechanics)
SigV	Vertical stress (geomechanics) Vertical or overburden stress comes from the combined weight of the rock and the pore fluids (water, oil, and gas) overlying the formation of interest
Lithology Fraction	Calculated lithology fraction from ELANPlus analysis

Table 5: Logging track mnemonics

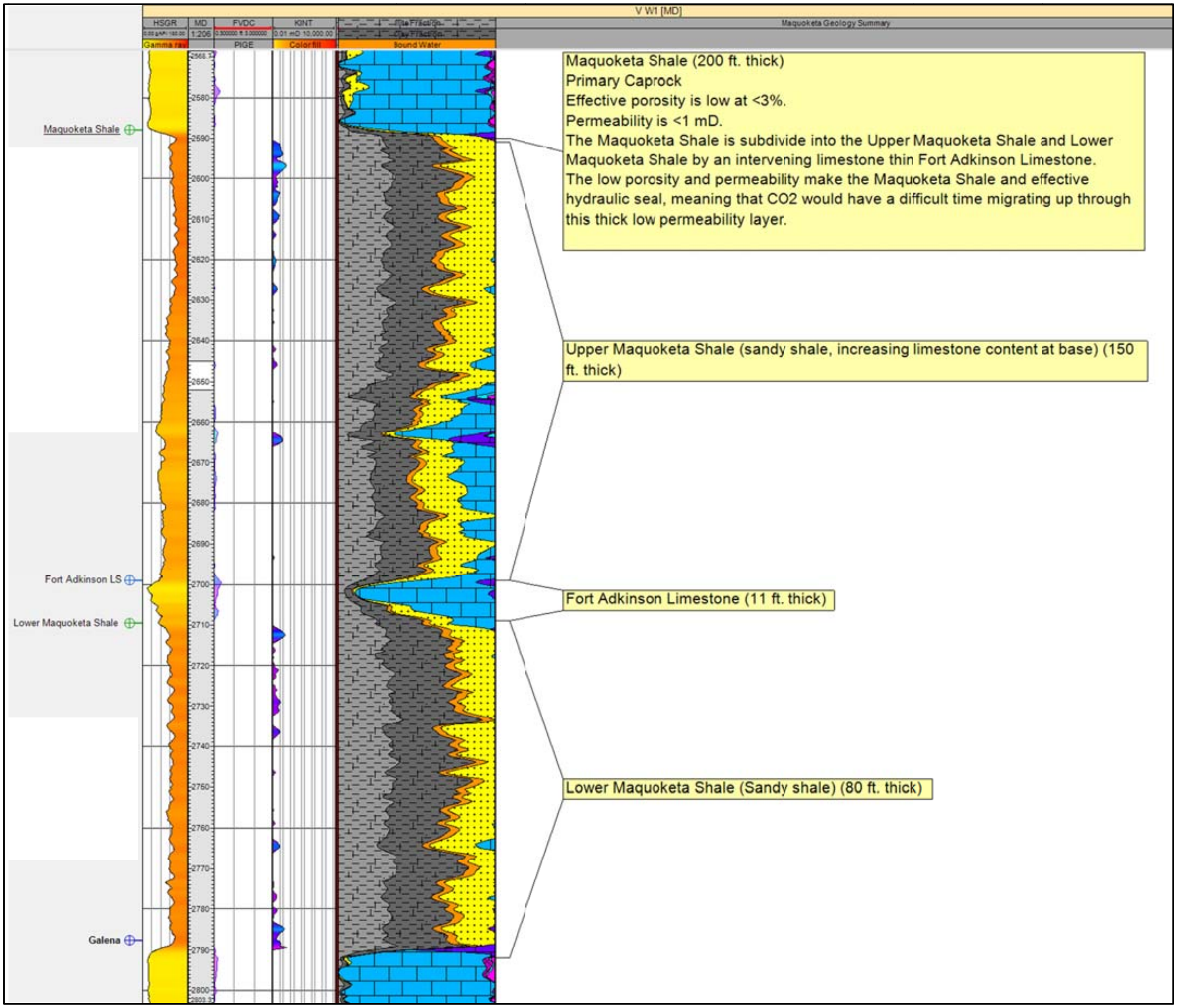


Figure 5: ELANPlus log of VW1 and geological summary (Maquoketa Shale)

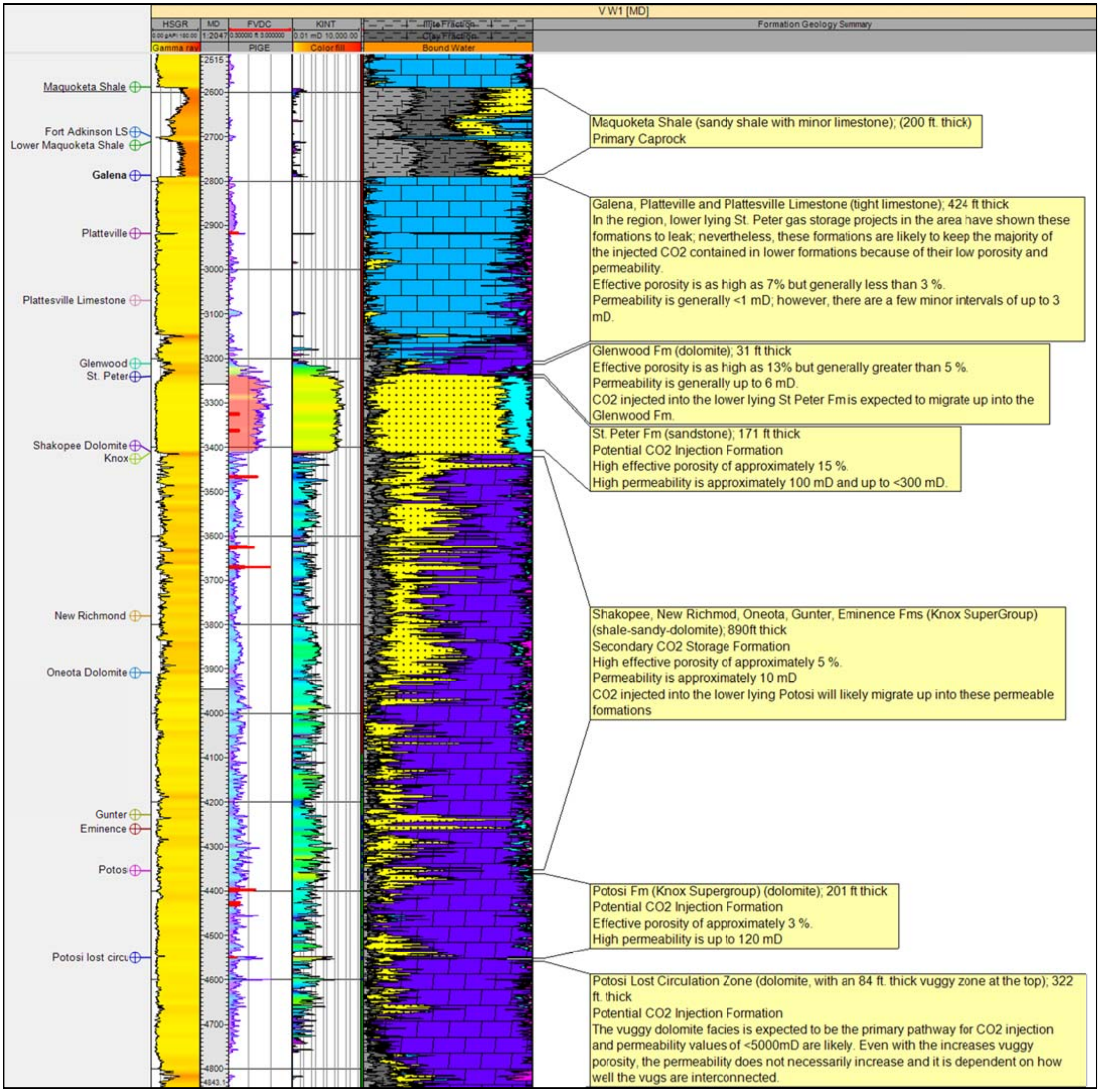


Figure 6: ELANPlus log of VW1 and geological summary (Top of Maquoketa Shale to Base of Potosi Dolomite)

6.4 FMI Fractures Analysis

In order to evaluate the occurrences of natural fractures in the formations, FMI logs were acquired in CCS1, VW1, and VW2. Open fracture analysis of VW1 and VW2 (Figure 7) indicate that there were very limited naturally occurring fractures in the Maquoketa Shale. A significant fracture density (0.73 fractures/foot) was not observed until depths corresponding to the lower lying Galena Supergroup. Naturally occurring fractures below this appear to be isolated to thin sections of the lower lying formations. Because of the low fracture intensity, it is deemed unlikely that fracture connectivity exists to provide a migration pathway for CO_2 through the shale section. Therefore, the hydraulically integrity of the Maquoketa Shale is considered to be high.

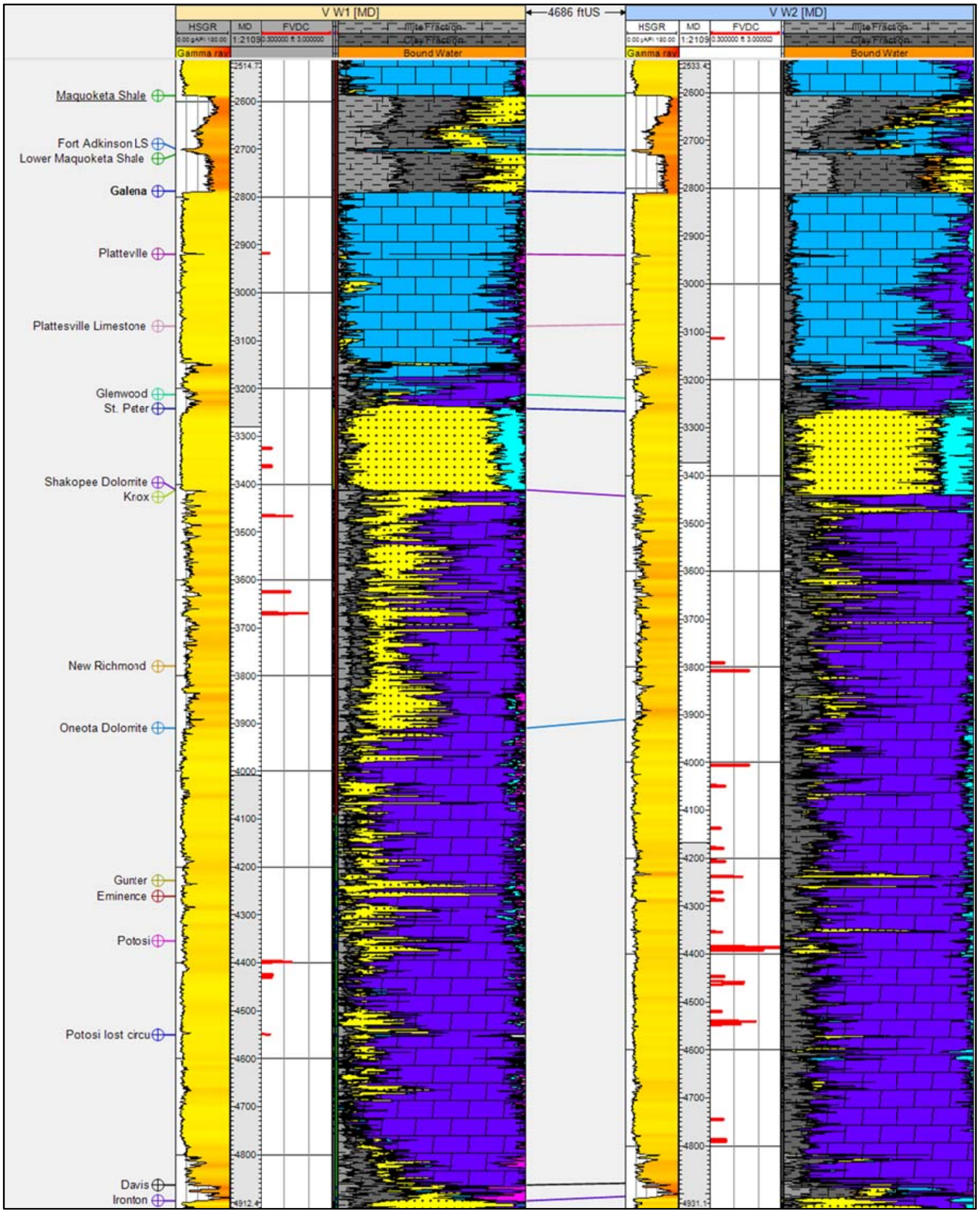


Figure 7: Open fracture analysis of VW1 and VW2

FVDC in red, plots the fracture frequency/foot

6.5 Core Analysis

Two sections of core were cut and collected from the Upper and Lower sections of the Maquoketa Shale. The details of the core collected are presented in Table 6 and Figure 8). These cores also cover the transition zone above and below the Maquoketa Shale. The results from the associated core analysis and from lower lying formations were used in petrophysical analysis and in the development of a one dimensional (1D) Mechanical Earth Model (MEM) as discussed in the below sub section

6.6 Core Test Interpretation and 1D MEM

Well	Formation	Core Length (ft)	Top Measured Depth (MD) (ft)	Bottom (MD) (ft)	Core Length (m)	Top (MD) (m)	Bottom (MD) (m)
GM2	Base Silurian/Upper Maquoketa Shale Transition	13	2,599	2,612	4	792	796
	Upper Maquoketa Shale	24	2,612	2,636	24	796	803
	Lower Maquoketa Shale	17	2,795	2,812	17	852	857
	Lower Maquoketa Shale/Galena Transition	13	2,812	2,825	13	857	861

Table 6: Summary of where core was recovered from the Maquoketa Shale

Figure 8 below illustrates the GM2 well log with 6 sample photographs (2 ft. sections) of the whole core. These images show the dark gray to black laminated shale facies of the Maquoketa Shale and the transition zones above and below. The images of the core section and a lithological description (6) are presented in Appendix 2: Maquoketa Whole Core Images and Geological Description.

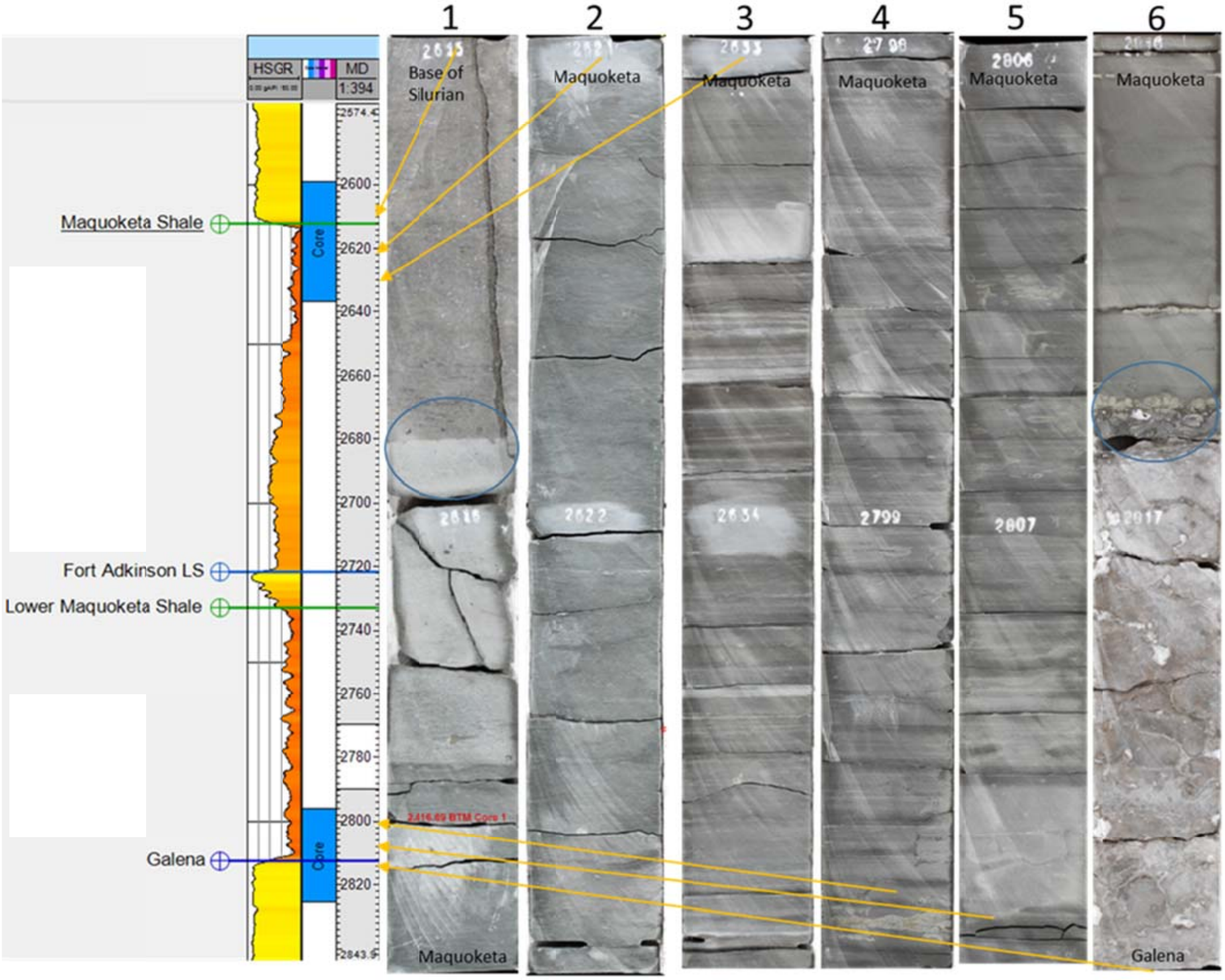


Figure 8: Maquoketa Shale whole core photos from GM2. The blue circles in the image highlight the transition zones

6.6 Core Test Interpretation and 1D MEM

6.6.1 Introduction

Rock mechanical properties tests were performed on core samples collected from the GM2 and VW1 wells. These tests were performed to evaluate the Maquoketa Shale as a seal and the Potosi Dolomite in the Knox group as a potential reservoir for CO_2 sequestration. The physical and mechanical response of a material is dependent on the rate at which it is loaded and the applied stress and strain amplitude. Logging-based measurements are in the kilohertz range; whereas actual physical loading rates acting on a wellbore are generally much slower (pseudo-static). Rock failure (tensile or shear) is a pseudo-static process. This is the rationale for performing laboratory pseudo-static testing on the core samples.

The testing program consisted of:

- Indirect tensile strength tests (Brazilian method) with stress oriented perpendicular, parallel, and oblique to bedding (7)
- Unconfined compressive strength (UCS) (8)
- Multi-stage triaxial compression tests with concurrent ultrasonic velocity measurements on as-received vertical samples (8) (9)

The core test results provided valuable rock mechanical properties that can provide only a qualitative assessment of the caprock integrity (Maquoketa Shale) and reservoir quality (Potosi Dolomite). The results of the qualitative assessment are presented in Appendix 1: Qualitative Implications of the Core Results (10). To provide a one dimensional (1D) static quantitative interpretation of the caprock integrity a 1D Mechanical Earth Model (1D MEM) was constructed using these core data for calibrating the rock properties. This task is of high importance because if CO_2 is injected into a reservoir, the operations management and regulators need to be confident that the integrity of the overlying caprock will not be compromised and that the reservoir quality is suitable for a safe CO_2 injection project. The 1D MEM was completed by Schlumberger Petrotechnical Services (PTS) on June 19, 2014 and a presentation of results is contained in Appendix 3: Geomechanical (11).

6.6.2 Objective

The objective of performing these rock mechanical properties tests on core samples was as follows:

- In order to help answer, assess and make a prediction of:
    - The integrity of the Maquoketa shale as a caprock (i.e. the caprock functions without any breach either due to deformation &/or failure),
    - The wellbore integrity during drilling, logging and completions (i.e. the borehole stays stable),
    - And the integrity of Potosi Dolomite as a reservoir (i.e. the reservoir functions as a good sequestration target).

  The answers to these questions are supported by the results of the core tests which provide the following poro-elastic parameters:

    - Peak compressive and tensile strength,
    - Quasi-static elastic properties (Young's Modulus and Poisson's Ratio),
    - And Mohr-Coulomb failure envelope delineation (Cohesion and Friction Angle).

- The above static and dynamic mechanical rock properties from core tests were then used for correlating well-log derived rock properties and assisting in calibration of the 1D MEM. The aim is to understand and make realistic predictions and inferences of geomechanical behavior of the Maquoketa Shale and Potosi Dolomite based on core test data and the 1D MEM.

6.6.3 1D Quantitative Evaluation of Caprock Integrity Using the 1D MEM and the Core Results

6.6.3.1 1D MEM Objective

The primary objective of constructing a 1D MEM is to determine the earth stress in the Maquoketa Shale in order to be able to quantitatively assess its failure limits as a primary caprock. The construction of the 1D MEM was completed on VW1 using offset well data from VW2, GM2 and CCS1 and involved the following four task summary of the 10 steps outlined in Figure 10.

- Task 1: Data collection, review and quality check (Step 1)
- Task 2: Construction of 1D Mechanical Earth Model (MEM) for an existing VW1 using also data from the offset CCS1, VW2 and GM2. (Step 2-9)
- Task 3: Perform Wellbore Stability (WBS) analysis to assess failure of the rock at the wellbore and to ascertain the formation stress regime and their contrast.   (Step 10 looping with 8 and 9)
- Task 4: Analysis of the result. The 1D MEM report figures are provided in Appendix 3: Geomechanical and a summary of the results are presented below.

6.6.3.2 Task 1: Data collection, review and quality check

PTS was supplied with the necessary data in order to build the 1D MEM. Additionally, drilling reports and operation logs were reviewed for extracting calibration data (MDT, mini frac, drilling events such as losses, tight hole, kicks etc.

6.6.3.3 Task 2: Construction of 1D MEM

A 1D MEM is the building block of any geomechanical study (Figure 9). This 1D MEM was constructed using the geological model of the area. Formation tops, unconformities were identified and a proper mechanical stratigraphy was modeled. The mechanical stratigraphy differentiates whether the facies are grain supported or clay supported or non-clastic. It also provides the deformation mechanism. As listed below, this mechanical stratigraphy was then used along with petrophysical logs to evaluate the elastic properties and strength parameters of the rock followed by determination of the pore pressure and three principal stresses.

1. UCS: The strength of a rock sample when crushed in one direction (uniaxial) without lateral restraint.
2. Young's Modulus (YME or E): is a measure of the stiffness of a rock.
3. Poisson's Ratio (PR): is the ratio of transverse contractional strain to longitudinal extensional strain, i.e. measure of a material compressed in one direction and associated expansion in the other two directions perpendicular or parallel to the direction of stress.
4. Pore Pressure: is the pressure of fluid held within a rock, in gaps between particles.
5. Three Principal Stresses: Minimum horizontal stress, maximum horizontal stress and vertical stress

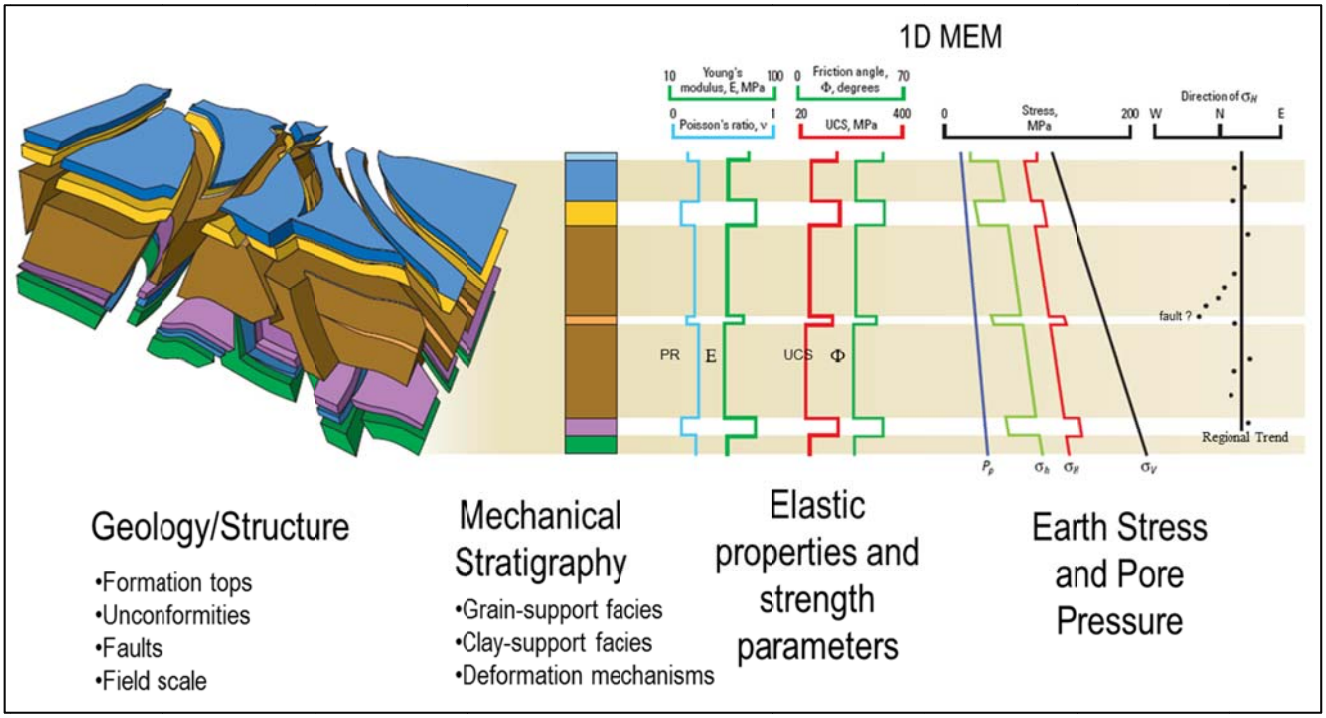


Figure 9: Example of a mechanical earth model (11)

The construction of the 1D MEM is a ten step workflow which is outlined below in Figure 10. The steps listed below reference the specific slides within the 1D MEM report (Appendix 3: Geomechanical).

1. Data collection audit and review
2. Utilizing already the available geologic model and review drilling reports and extraction of calibration data from all sources including drilling events, ELANPlus etc. (Slide 3)
3. This step involves classification of lithological facies into grain supported versus clay supported or non-clastic zones to provide mechanical stratigraphy for building the 1D MEM (Slide 4)
4. Overburden or vertical stress is computed by integrating the bulk density data (Slide 8)
5. Pore pressure is inverted from compressional sonic data and calibrated using available MDT or drilling events (kicks, mud weight etc.) (Slide 9)
6. Rock strength and elastic mechanical properties of the rock at log resolution are computed using standard correlations and calibrated using the core measured rock properties. (Slide 10 and 11)
7. Orientations of horizontal stresses are deduced from FMI image or orientated caliper or sonic scanner data.
8. Minimum horizontal stresses are calculated using horizontal strain equation and calibrated using available mini frac or MDT measured stress measurements results. (Slide 12)
9. Maximum horizontal stresses are also calculated using horizontal strain equation. Maximum horizontal stress are not easy to measure. They are determined by analyzing observed rock failures versus predicted rock failures from modeling in the wellbore stability analysis (Step 10 and Slide 12)
10. This step involves modeling for wellbore stability and analyzing failures such as wellbore breakouts and drilling induced fractures and comparing the models versus what was observed in the wellbore using FMI and caliper logs. In case there is a mismatch (outside of an expected error tolerance) in predicted vs observed then the stresses are reassessed (Steps 8 and 9). (Slide 13 and 14)

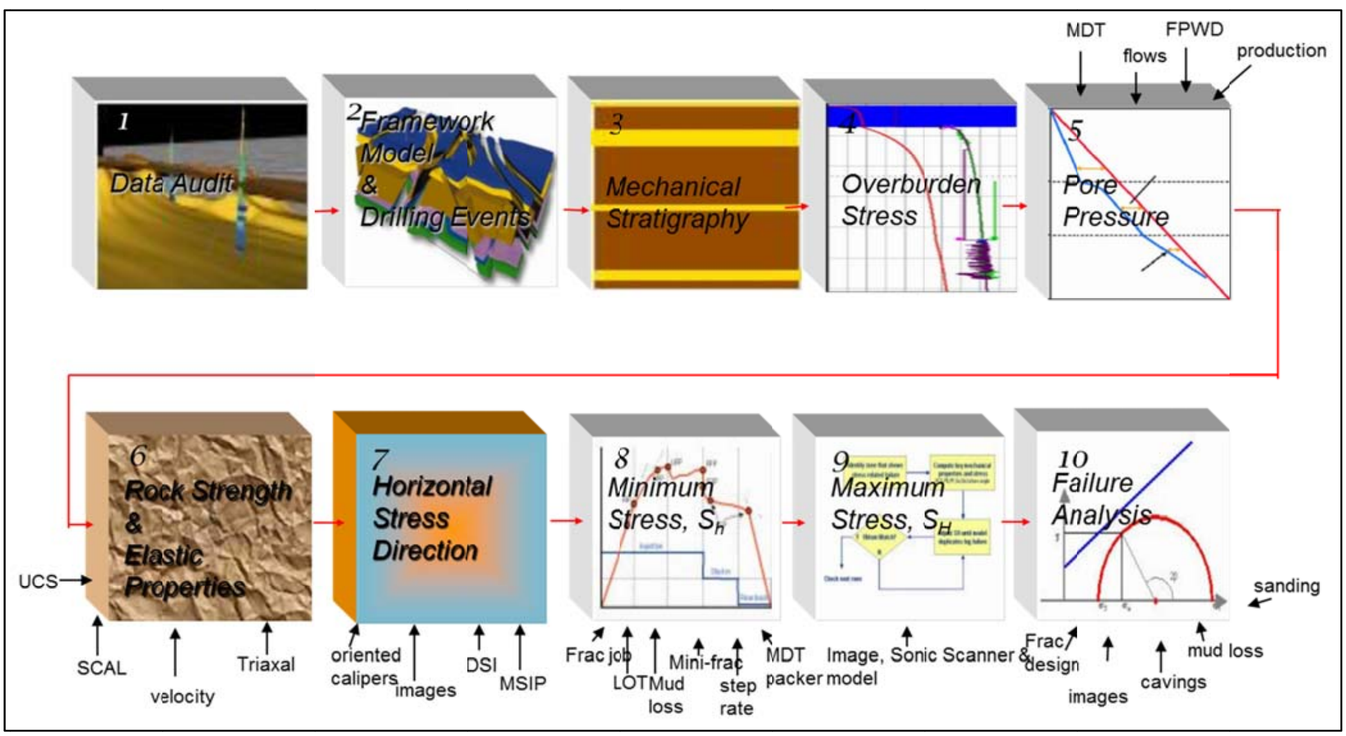


Figure 10: 1D MEM workflow (11)

Arrows with sub text indicate calibration input data the model utilizes. Mnemonics in the above Figure are defined in Appendix 3: Geomechanical Slide 26

6.6.3.4 Task 3: Perform Wellbore Stability Analysis (WBS)

This task is step 10 (Figure 10) in the workflow looping with steps 8 and 9 to constrain the horizontal stresses to failure results (events/data observed in the drilling and wireline data). To evaluate the suitability of a potential caprock, it is important to understand what the minimum and maximum horizontal stresses are. These are important because it is a measure of how and at what induced injection pressure the rock will fail. Figure 11 illustrates the geomechanical risk scenarios with respect to a carbon sequestration project. There are mainly three ways the rock will fail:

1. Tensile fracture: The minimum horizontal stress is exceeded by the advancing plume pressure.
2. Shear fracture: This fracture process is more complex and was not practical to analyze with the limited data available.

Fault reactivation: Induced pressure could reactivate any faults in the area. There were no faults in the Maquoketa Shale within the IBDP/IL-ICCS project areas. The

3. 7.1 Knox Regional 2D Seismic Lines (Figure 16) did identify a regional fault well outside of the IBDP/IL-ICCS project area that penetrates the caprock. Though the majority of the Maquoketa shale studies was not faulted, the identification of this fault outside of the IBDP and IL-ICCS project areas underscores the importance of performing a seismic survey when evaluating a carbon sequestration site.

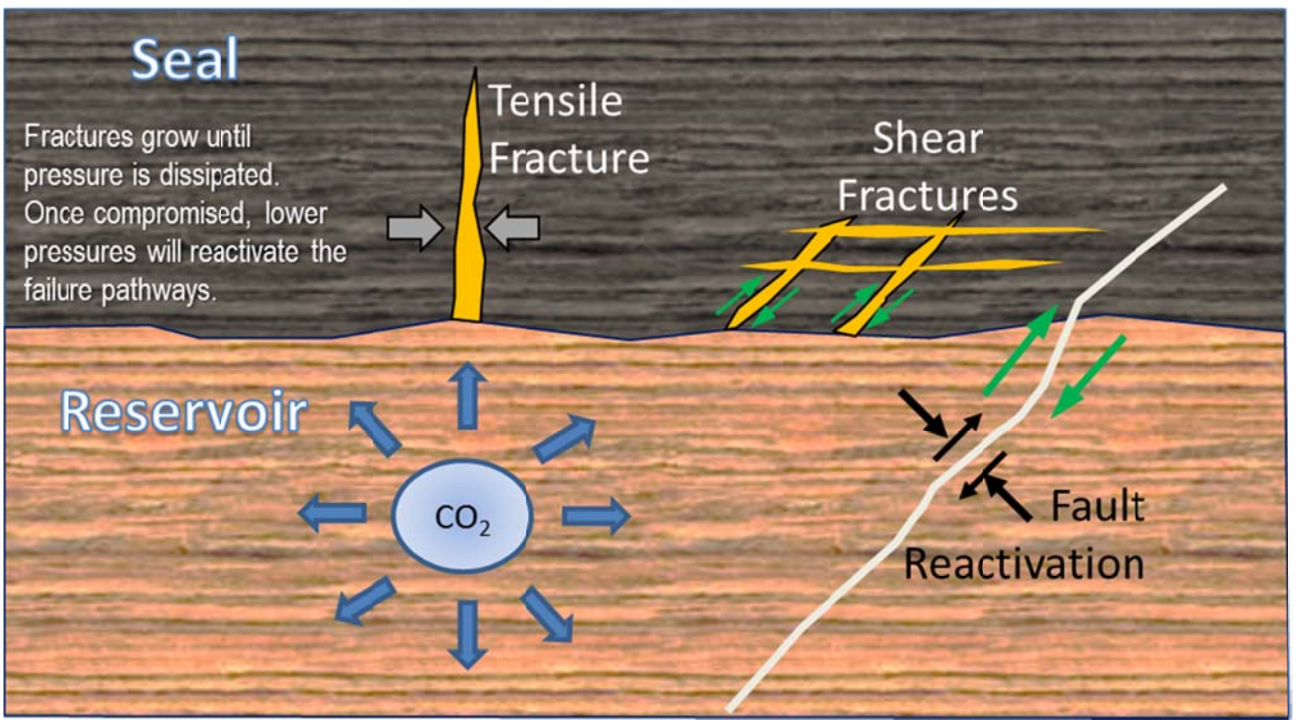


Figure 11: Geomechanical risk scenarios due to CO_2 injection

6.6.3.5 Task 4: Analysis of the results

The 1D MEM results are summarized below:

- Based on the FMI image, the minimum stress direction is 166deg. This is consistent with the known regional stress orientations and the world stress maps (12). (Appendix 3: Geomechanical , Slide 21 and 22)
- The stress regime is predominantly strike slip with large horizontal stress anisotropy. This is also consistent with regional experience and the world stress map (12).

- The minimum horizontal stress of St. Peter Sandstone ranges from 2630 psi to 3325 psi (average 2980 psi) (Sigh, Figure 12).
    - This means that there are zones in St. Peter Sandstone than can experience initiation and propagation of hydraulic fracture if the CO_2 injection pressure exceeds 2630 psi.
- The minimum horizontal Stress in Potosi Dolomite ranges from 1420 psi to 4930 psi (average 4010 psi) (Sigh, Figure 12).
    - This means that there are zones in Potosi Dolomite than can experience initiation and propagation of hydraulic fracture if the CO_2 injection pressure exceeds 1420psi.
- The minimum horizontal stress of the Maquoketa Shale ranges from 2010 psi to 2890 psi (average 2410 psi) (Sigh, Figure 13).
    - This means that if the CO_2 subsurface plume reaches the caprock, its pressure should not exceed 80% of the 2010 psi (i.e. 1610 psi considering 20% safety factor) otherwise the caprock is likely to fail in tension. Another practical implication of CO_2 injection is that the injected zone would have increases in the minimum horizontal stress dynamically while the zone above and below would experience minimum horizontal stress decreases. These dynamic changes can only be understood by 3D reservoir geomechanics simulation and can additionally constrain the limits of failure in the caprock.
    - The mechanical profile of the Maquoketa Shale is subdivided into the Upper and Lower Maquoketa Shale by the intervening Fort Adkinson Limestone. The minimum horizontal stress of the Upper Maquoketa Shale is higher than the Lower Maquoketa Shale. The intervening Fort Adkinson Limestone has an even higher minimum horizontal stress than either the Upper or Lower Maquoketa Shale and it acts as an additional buttress to the integrity of the caprock.

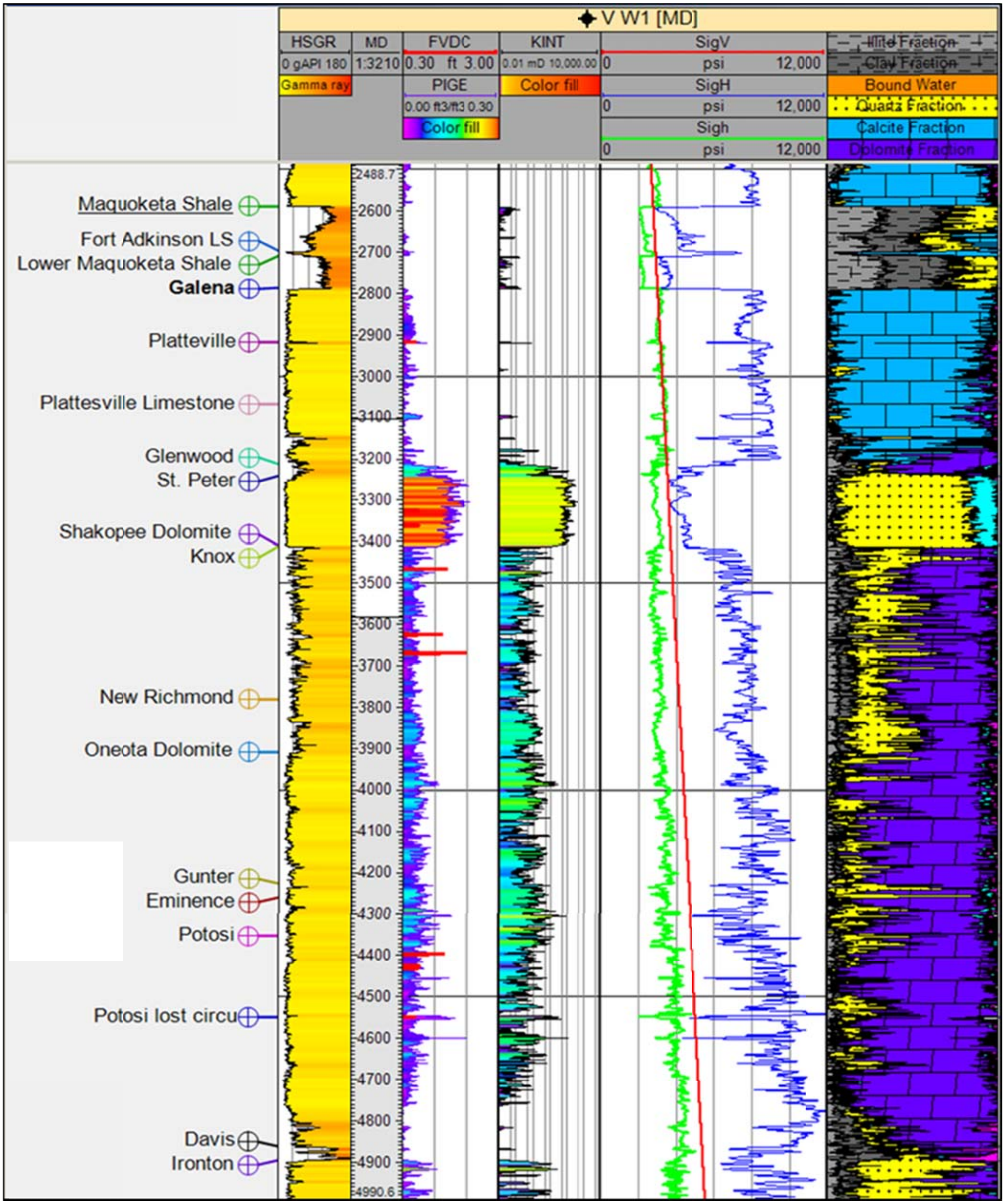


Figure 12: Stress profile at VW1 (Top of Maquoketa Shale to Base of Potosi Dolomite) along with petrophysical properties

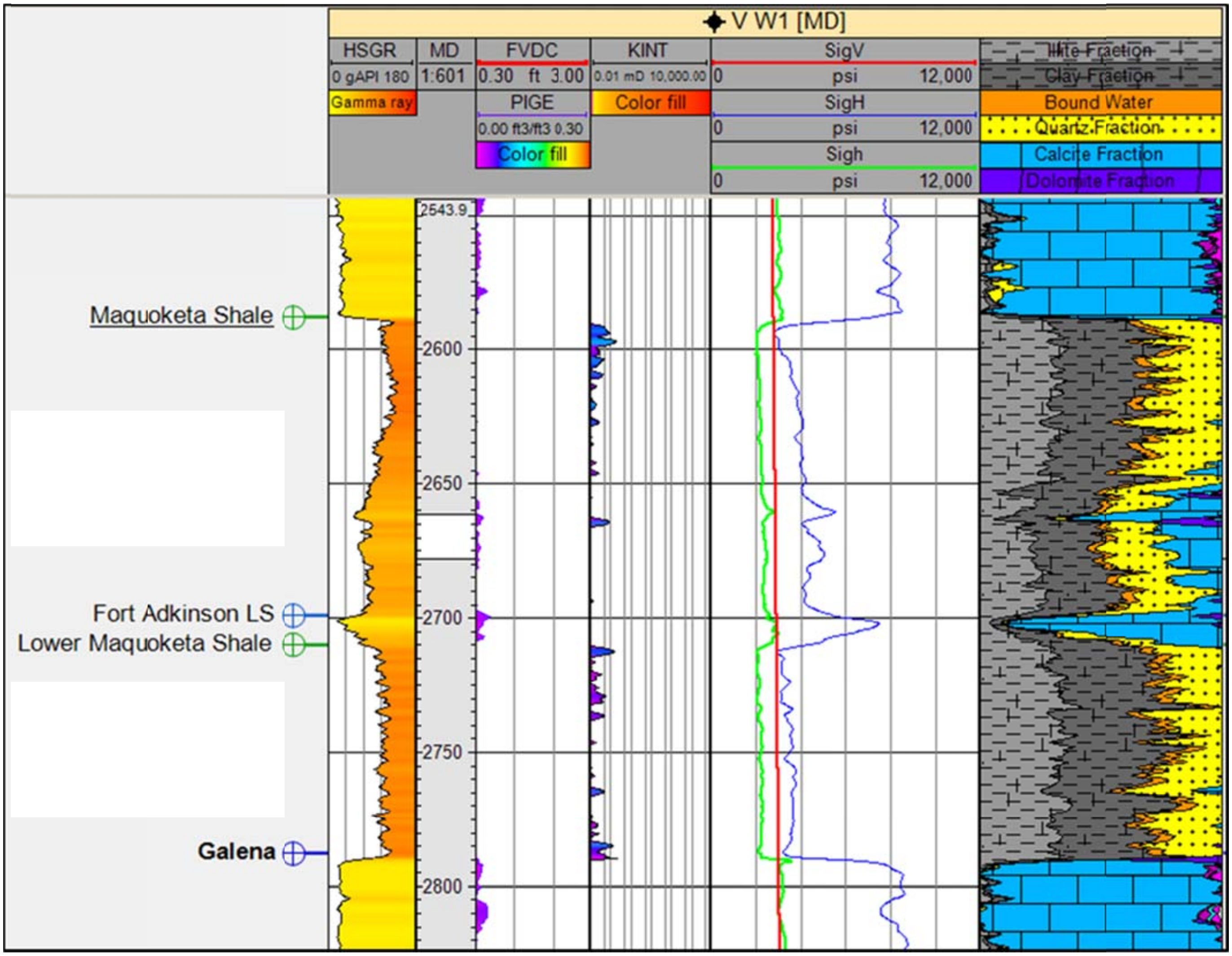


Figure 13: Stress Profile across the Maquoketa Shale at VW1 with petrophysical properties

6.6.3.6 Geomechanics Recommendations

Assessing integrity of the Maquoketa Shale as a caprock is dynamic and 4-dimensional (4D) reservoir geomechanics issue. The 1D MEM results provide a static lower limit above which tensile failure in the caprock can occur breaching its mechanical as well as hydraulic integrity. A 1D MEM is a building block for carrying out such coupled and integrated reservoir, geology and geomechanical simulation study. Therefore, at a prospective CCS Site in the Illinois Basin, to achieve a tangible and realistic prediction on the integrity of the Maquoketa Shale as a caprock at variable CO_2 injection scenarios, the following approach is recommended:

1) Construct 1D MEM for all the offset wells.
2) Construct and integrate the 1D MEM with a 3D geological model and 3D seismic inversion.
3) Construct a discrete fracture network model and integrate with the 3D geological model.

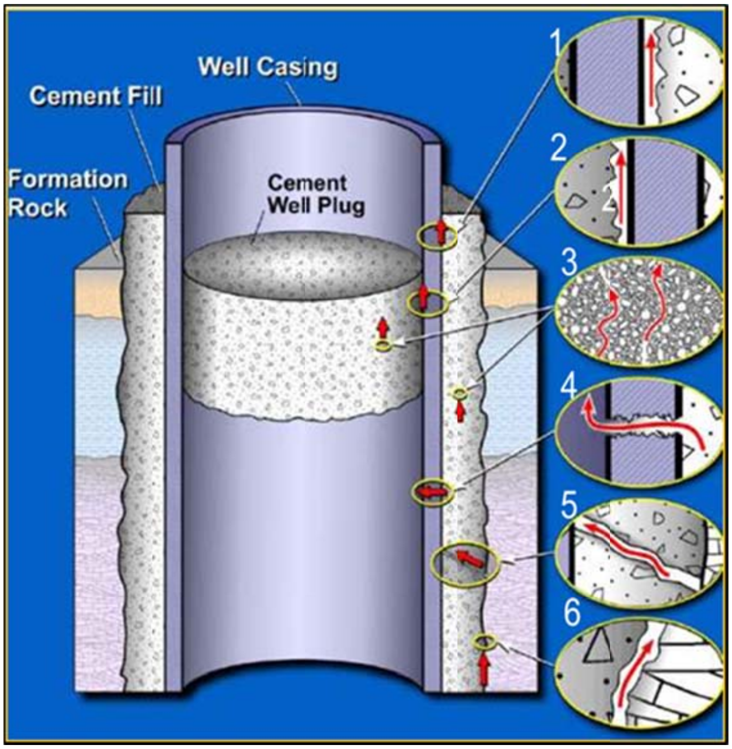
4) Use the seismic data and inversion for distribution of optimal properties of the reservoir, petrophysical and geomechanical into the 3D geological model.
5) Construct reservoir simulation models and a 3D geomechanical model
6) Run a 4D reservoir geomechanics simulation under the planned injection scenarios to dynamically simulate the reservoir with time and assess if the integrity of the caprock would be breached or not.
7) For any planned well or existing well, the following data inputs are essential to help in assessment of the caprock
    - Wireline data with preferably sonic scanner at least across the caprock and target reservoir(s).
    - Stress test or MDT mini-frac in the caprock and reservoir zones.
    - Triaxial geomechanical tests on core collected from the caprock and target reservoir (both unconfined and confined).
8) A fault reactivation study should be complete if there are identified faults in the area.

6.7 Wellbore Integrity Evaluations

Compromised wellbore integrity is a risk that all CCS project operators must evaluate and understand. This section is intended to be a general approach for how to evaluate and how to mitigate this risk with an Illinois Basin specific focus on CO_2 injection projects within the Potosi Dolomite and St. Peter Sandstone which utilize the Maquoketa Shale as a primary caprock. Within the area surrounding an injection well, there is a risk that CO_2 plume or formation brine may migrate up through the Maquoketa Shale into USDWs, not through the formation itself but via compromised wellbores that penetrate the caprock. These wells could be the project's CO_2 injection wells, the CO_2 monitoring wells or legacy oil and gas wells in the immediate area. Because injected CO_2 will naturally rise in the formation via buoyancy, it will take the path of least resistance; if that path is a compromised wellbore, then the wellbore would become a pathway for CO_2 to move into a USDW. Furthermore, there is a risk that the CO_2 injection will cause the formation pressure to increase so as to force formation brine upwards through a compromised wellbore into a USDW.

6.7.1 Examples of compromised well integrity

There are a number of ways well integrity can be comprised and upward migration of CO_2 or brine can occur. Figure 14 is an illustration of potential leakage pathways in an abandoned well. These failures can be the result of poor cement and historical well completion or abandonment methods that are not considered reliable compared to today's standards.



Risks inducing CO_2 leaks

1. Debonding between cement and outside casing
2. Debonding between cement plug and outside inside casing
3. Diffusivity, open porosity in cement
4. Casing corrosion
5. Cracking, mechanical failure of cement
6. Cracking, mechanical failure of cement and geomechanical failure of formation

Figure 14: Examples of compromised well integrity (17)

6.7.2 CCS Well Integrity and Risk Mitigation

A new CCS project will have direct control over the well integrity of the newly drilled and completed CO_2 injection and CO_2 observation wells. For the Knox project a Wellbore Management Plan was prepared (10) that provide a well plan for the drilling of a CO_2 injection well with the long term capability of injecting CO_2. CO_2 resistant completion technology is especially important because these wells will be directly exposed to the highest concentrations of CO_2. There are also several Measurement, Monitoring, Verification, and Accounting (MVA) technologies that can be deployed to monitor for any potential leaks or decreases in wellbore integrity. Examples of special well completion and MVA technologies that should be deployed are listed below; however, selected technologies should be tailored to each project.

- Traditional well cements have a higher potential of being dissolved by CO_2; therefore, CO_2 resistant cement should be used (Figure 14 caption 3).
- Traditional carbon steel casing has a higher potential of being corroded by CO_2. This is of high concern in the section of the well were the primary seal is penetrated. Casing corrosion could form a potential pathway for CO_2 to migrate out of the storage complex; therefore, CO_2 resistant chrome casing and chrome injection packers should be installed (Figure 14 caption 4).
- MMV technologies that should be deployed at a minimum are:
    - CBLs will need to show that the cement is forming a proper seal (Figure 14 caption 1 and 2).
    - Distributed acoustic sensors in the wellbore can detect any rock or cement failure events (Figure 14 caption 5 and 6).
    - Pressure and temperature sensors can potentially detect any fluid movement in the wellbore (Figure 14)

- RST) can be run in the well periodically to measure for CO_2 migrating up beyond the injection zone (Figure 14).

6.7.3 Legacy Well Integrity and Risk Mitigation

In the case of legacy oil and gas wells, like many CCS projects that utilize deep saline storage, the Potosi Dolomite and St. Peter Sandstone are located well below the Mississippian age sandstone and carbonate oil reservoirs (Figure 2). Because of this, oil and gas operators only drilled down to these lower formations for exploration purposes and if hydrocarbon resources were found to be absent, drilling down to these lower formations was rare; however there are some water disposal wells in these formations. Nevertheless, the risk of one of these wells being close to the migration pathway of the CO_2 plume must be mitigated by the considering the following general investigations:

- This risk is already low because there are few legacy wells drilled into these deep saline formations in the Illinois Basin.
- Complete a database well search for wells that penetrate the caprock (Maquoketa Shale) and gather the below information:
    - Distance to the CO_2 injection well
    - Evaluate the well completion and abandonment records
    - Evaluate the cement integrity by examining the CBL logs
- Compare the results of the predictive CO_2 plume extent and formation pressure pulse extent from reservoir simulations with the location of the legacy well. Risk decreases substantially the further the legacy well is from the injected CO_2 plume.
- If a legacy well poses a potential risk, the following steps are available to mitigate this risk.
    - Locate the new CO_2 injection well away from the legacy well.
    - Re-enter the legacy well and quantify its well integrity or abandon the well with modern abandonment technologies.
    - A MMV program should be designed to monitor the plume development over time and there should be a way to detect the plume in the event that it migrates towards the legacy well.
- A geomechanical evaluation will need to be completed to understand how the formation and cement bond could fail around the legacy wells (Figure 14 caption 6). This is unlikely because the CO_2 injection would be at 80% of the rock fracture pressure as found with geomechanical modeling; however, heterogeneity in the mechanical integrity of the rock must be considered. If the rock strength was weaker at the legacy well(s) the formation could fracture and be a conduit for upward CO_2 migration. This becomes much less of a risk the further away the legacy wells are from the CO_2 injection well.
    - A 1D mechanical earth model (MEM) should be completed to evaluate the geomechanical properties at the at risk legacy well. To complete this, a minimum well data set would be a density log and shear and compression sonic velocity logs.
    - A 3D MEM should be completed to understand the heterogeneity in the geomechanical properties of the injection formation and caprock formation.

6.8 Geochemical Investigations of CO_2-Brine-Rock Interactions of the Knox Formation and Maquoketa Shale

As mentioned in Section 3, one of the objectives of this caprock evaluation was to answer the question as to how injected CO_2 will interact with the waters and mineralogy of the Maquoketa Shale. The below section is a word for word summary taken from a report developed by the Illinois State Geological Survey titled Geochemical Investigations Of CO_2-Brine-Rock Interactions Of The Knox Formation And Maquoketa Shale In The Illinois Basin (3) with the permission of the authors.

Considerable interest in deep reservoir injection, storage, and waste disposal has steadily increased throughout the United States with the recent shale gas boom and with the country's efforts to curb the release of man-made greenhouse gas through efforts such as CCS. The Illinois Basin Knox Formation reservoir has little economic interest with respect to oil, gas, or water supply, but may have great potential as a storage reservoir. This study examines laboratory simulated geochemical interactions between reservoir and seal rock, fluid, and CO_2 of the Knox Formation rocks from various locations around the Illinois Basin. This investigation will provide an understanding of the potential interactions of the Knox Formation/Maquoketa Shale seal system and its efficacy as a CO_2 sequestration target.

Portions of the Knox Formation (Potosi Dolomite, Gunter Sandstone, Shakopee Dolomite, New Richmond Sandstone, and Maquoketa Shale) are being assessed for CO_2-sequestation potential as part a regional study of the Illinois and Michigan Basins. The Illinois State Geological Survey (ISGS) is involved in a related project, the IBDP, large-scale carbon capture and storage project in Decatur, Illinois, USA, which allowed access to well core and fluid sampling for our study.

A series of experiments using samples obtained from the IBDP site (rock and brine), other rock samples from within the Illinois Basin (outcrop and core), and laboratory produced synthetic and natural brines, were developed to identify the reaction mechanisms, kinetics, and solid-phase products that are likely to occur in the Knox Dolomite and the Maquoketa Shale when exposed to supercritical CO_2. A total of twelve high-pressure, high-temperature batch reactor experiments were conducted using Potosi Dolomite (SW Missouri outcrop), Gunter and New Richmond Sandstone (Morgan Co, IL), and Maquoketa Shale (IBDP site). In addition to batch experiments five core flood experiments were conducted using Potosi Dolomite (IBDP site), Gunter (Kentucky Blan well, Hancock Co.) and St. Peter (Marion Co., IL) Sandstones. The core flood experiments used either a laboratory produced synthetic brine or DI water.

A variety of analytical techniques were utilized to characterize the physical, geochemical, and mineralogical changes between the pre- and post-reaction products. These included petrography (scanning electron and standard petrographic microcopy), x-ray diffraction and ion chromatography and inductively coupled plasma analysis; results were then used to compare what is expected from numerical geochemical modeling and the laboratory interaction studies.

Analysis of both rock and brine samples strongly indicate dissolution of dolomite (the dominant mineral present throughout the Knox Formation) while in the presence of supercritical CO_2 and brine. High magnification petrographic analysis revealed evidence of dissolution along the edges of dolomite crystals; the pristine dolomite rhombohedra appeared pitted and jagged along crystal faces of post-reaction samples. Additionally, post-reaction brines contained calcium, magnesium, and strontium in concentrations elevated above those of the non-reacted brines, also strongly indicating the dissolution of dolomite. Post-reaction brine analyses indicated the Knox Formation-CO_2-fluid interactions observed in this study did not liberate any EPA-regulated inorganic contaminants that may be present in the solid phase samples.

Speciation calculations based on the post-reaction Potosi brine composition indicate that the system reached equilibrium before the end of the four month experimental duration. As a result, five short term (approximately six hour) core flood experiments were performed. Interpretation of post-reaction brine chemistry and equilibrium modeling of these short term experiments indicate that the systems reached equilibrium within the approximately six hour duration of the experiments. The fast reaction rates observed in the experiments suggest that larger scale models simulating CO_2 sequestration reactive transport for the Knox formation do not need kinetic constraints to create an accurate picture of reservoir processes.

In summary, results suggest that although an initially chemically reactive scenario is presented for the Knox Formation-CO_2-brine system for the sample locations indicated, the effect of this reactivity would likely reach equilibrium shortly after injection of CO_2 into the reservoir ceased. According to IBDP site geophysical logs, the Maquoketa Shale is approximately 200 feet thick in the central Illinois Basin, and a secondary (New Albany Shale) seal is 130 feet thick. Although lab analyses and interpretation of results for the reactivity of Maquoketa Shale are currently completed suggest it is highly unlikely that dissolution of the mineral constituents caused by sequestration activities in the region studied could result in a breach of the Maquoketa and overlying New Albany Shale seals before the reactions ceased.

Results from this study and work that continues at the ISGS will aid in the development of improved methods for similar studies and provide needed data for computational modeling relevant to the Illinois Basin and elsewhere. Data from this study and further modeling efforts will provide information about the ability for deep saline reservoirs and shale seal rocks to safely store injected CO_2 while minimizing the likelihood of contamination.

6.9 Risk Assessment

A risk evaluation process was prepared that describes a process and provides seed information for identifying and evaluating risks pertinent to a hypothetical CCS project (4). This risk evaluation identified generic risks and the technical questions raised were the center of all the investigations that have been completed for the Knox project. These investigations quantified the risks were qualitative before any of this work was completed. Any prospective CCS site located elsewhere in the Basin would require a site specific risk assessment. From this risk evaluation, there were four features events and processes (FEPs) that were applicable to the sealing characteristics of the Maquoketa Shale. FEPs are the broad project-relevant concepts or elements that may combine through various chains of events to create various desirable and undesirable outcomes. The Maquoketa Shale specific FEPs are presented in Table 7 below. These risks are considered to be low.

FEP NAME	Scenario Example
Subsurface conflicts, caprock	Maquoketa becomes a target for shale gas production, and operators object to CCS injection permits that involve Maquoketa.
Primary caprock identification	CO_2 trapping may occur somewhere within the thick dolostone beneath the Maquoketa. Inability to positively identify a single discrete trapping horizon before injection causes expansion of the monitoring footprint, extra cost, and uncertainty in monitoring design.
Caprock separation thickness above reservoir	Position of the ultimate shale caprock (Maquoketa) a large thickness above the injection horizon (Potosi Dolomite) and uncertainty about trapping in the intervening dolomite causes long delay in injection permit.
Hydrocarbons	Multiple scenarios related to previous oil and gas activity, future resource availability and/or sterilization (including possibility of shale gas in Maquoketa), abandoned wells.

Table 7: Features events and processes (FEPs) relevant to the Maquoketa Shale

6.10 Post-stack Seismic Inversion for the Knox Dolomite

Over the IBDP site, there was a 3D seismic survey completed in 2010 and a 3D seismic survey extension completed in 2011 (5). These data sets were merged and a post-stack inversion was completed with a focus on the Knox Supergroup. In addition to providing a method for interpreting formation horizons over the survey area, the 3D seismic results were utilized for a post stack seismic inversion as a means of quantifying porosity over the Knox Supergroup. Post-stack inversion for generating acoustic impedance from seismic stack amplitude is commonly used in lithology analysis and reservoir characterization. It is especially meaningful when transforming the inverted acoustic impedance (AI) volume into porosity using regression equations derived from well logs and cross-plotting analyses. Further geobody extraction and reservoir simulation work can fully benefit from these products. Because these post-stack inversion regression equations were derived from the Knox Supergroup dolomites, they are not applicable to the different overlying lithologies (sandstones and shale); therefore, acoustic impedance was not transformed into porosity over the Maquoketa Shale.

7. Regional Maquoketa Shale Data and Interpretations for the Illinois and Michigan Basins

7.1 Knox Regional 2D Seismic Lines

In a continuing collaboration with the Midwest Geologic Sequestration Consortium (MGSC) on the Evaluation of the Carbon Sequestration Potential of the Cambro-Ordovician Strata of the Illinois and Michigan Basin project, Schlumberger Carbon Services and WesternGeco acquired substantial two-dimensional (2D) seismic data in the Illinois Basin. This work included the design, acquisition and processing of approximately 125 miles of (2D) seismic reflection surveys running west to east in the central Illinois Basin (Figure 15). Schlumberger Carbon Services and WesternGeco oversaw the management of the field operations (including a pre-shoot planning, mobilization, acquisition and de-mobilization of the field personnel and equipment), procurement of the necessary permits to conduct the survey, post-shoot closure, processing of the raw data, and provided expert consultation as needed in the interpretation of the delivered product.

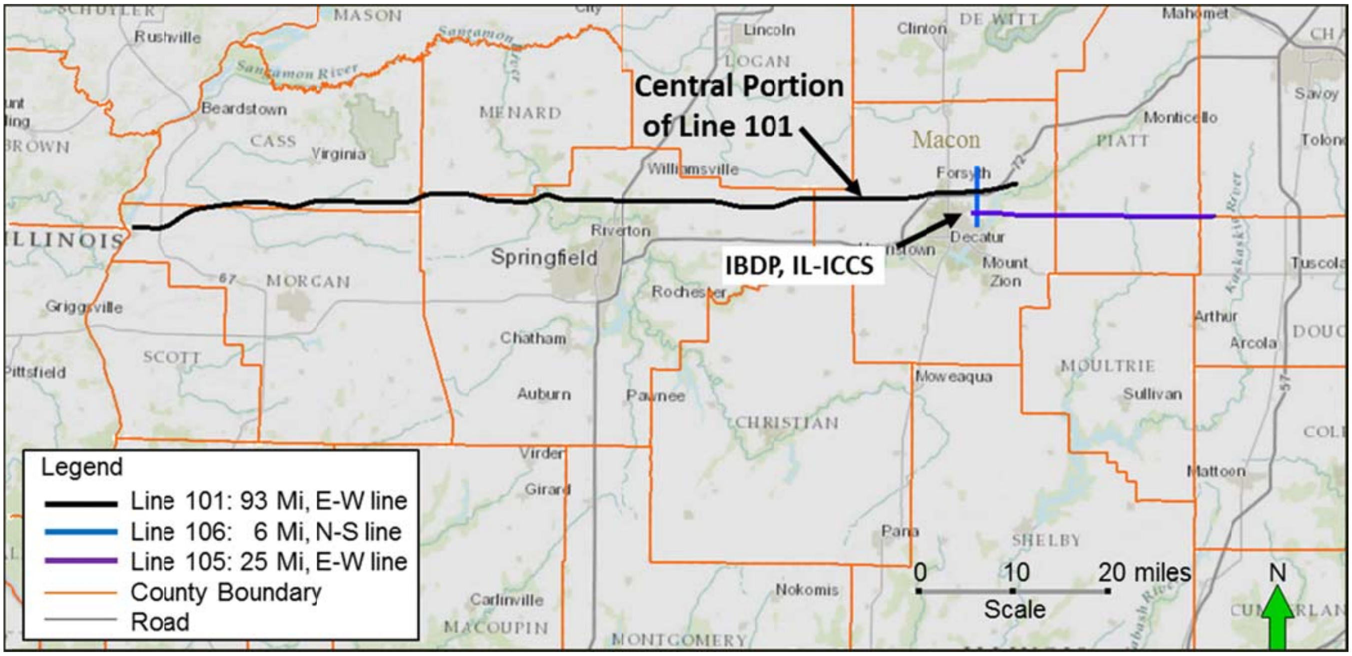


Figure 15: Location of 2D seismic line layouts across central Illinois (13)

Three 2D seismic lines were acquired across central Illinois during November and December 2010 and January 2011. Traversing the Illinois Basin, this 2D seismic survey was designed to image the stratigraphy of the Cambro-Ordovician sections and also to discern the basement topography.

Prior to this survey, there were no regionally extensive 2D seismic data spanning this section of the Illinois Basin. Between the NW side of Morgan County and northwestern border of Douglas County, these seismic lines ran through very rural portions of the state. Starting in Morgan County, Line 101 was the longest at 93 miles in length and ended NE of Decatur, Illinois. Line 501 ran W-E from the IBDP site to northwestern Douglas County and was 25 miles in length. Line 601 was the shortest and ran N-S past the IBDP site and connected lines 101 and 501. All three lines are correlated to well logs at the IBDP site.

Originally processed in 2011, the 2D seismic profiles exhibited a degradation of signal quality below ~400 millisecond (ms) which made interpretation of the Mt. Simon and Knox sections difficult. The data quality also gradually decreased moving westward across the state. To meet evolving project objectives, in 2012 the seismic data was re-processed using different techniques to enhance the signal quality thereby rendering a more coherent seismic profile for interpreters. It is believed that the seismic degradation could be caused by shallow natural gas deposits and Quaternary sediments (which include abandoned river and stream channels, former ponds, and swamps with peat deposits) that may have complicated or changed the seismic wavelet.

Where previously limited by seismic coverage, the seismic profiles have provided valuable subsurface information across central Illinois. Some of the interpretations based on this survey included, but are not limited to:

- Stratigraphy generally gently dips to the east from Morgan to Douglas County.
- The Knox Supergroup roughly maintains its thickness.
- The data suggests that there are resolvable faults penetrating the Knox interval. Figure 16 shows an example of a possible fault that penetrates through the entire Knox interval, the Maquoketa (the primary seal for the Knox) and New Albany formations along Line 101 (Figure 15). This particular fault is significant since it had not been previously

observed. Faults that penetrate seals form potential leakage pathways. CO_2 sequestration projects involving the Knox Group should not be located near these structural features that penetrate either the CO_2 injection reservoir or Maquoketa Shale.

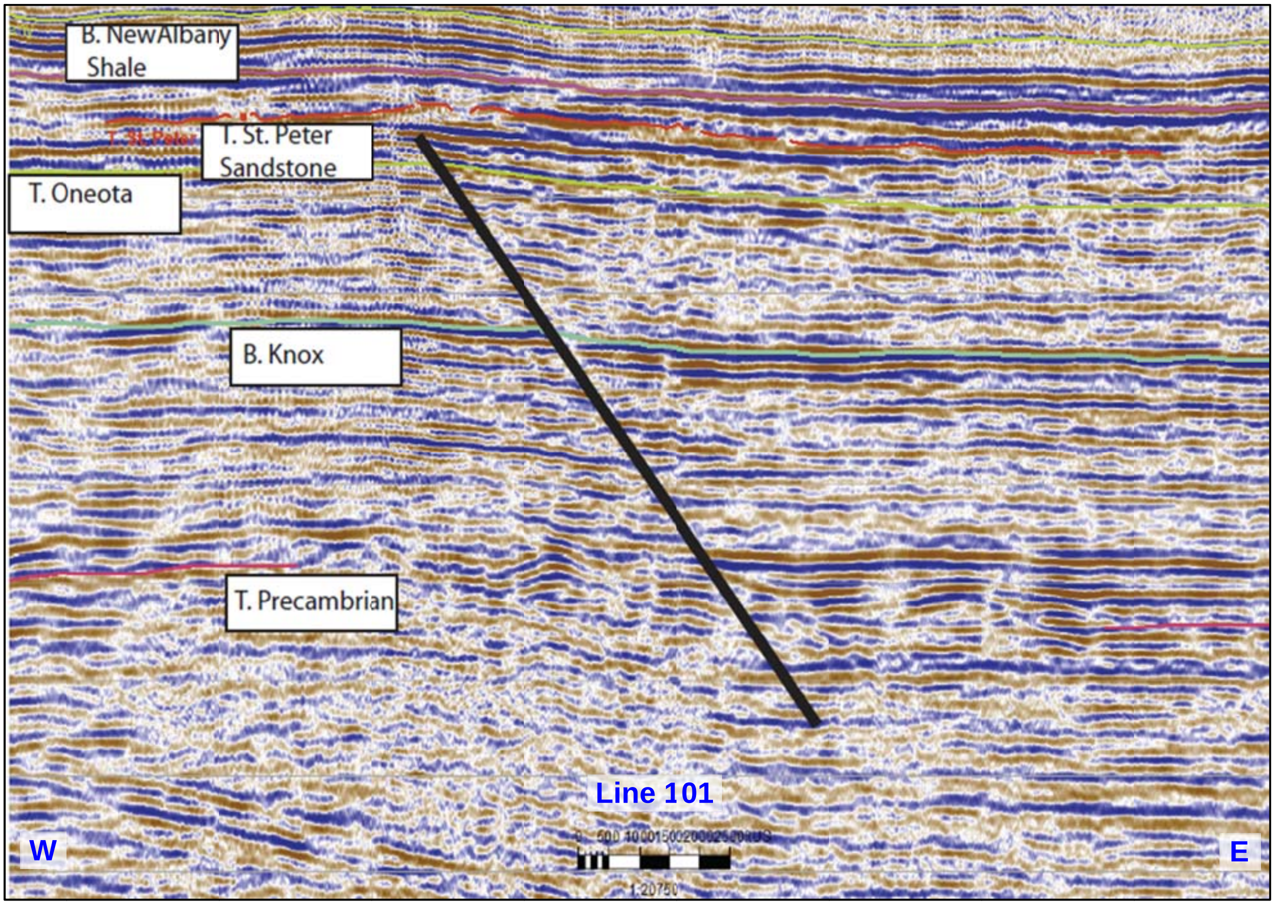


Figure 16: Central portion of 2D seismic Line 101 (13)a. The black line is interpreted to be a fault that penetrates the entire Knox interval, the Maquoketa Shale, and probably the New Albany Formation. Location highlighted in Figure 15.

7.2 Depth and Isopach Map of the Maquoketa Shale in the Illinois Basin

As displayed in Figure 17, the thickness of the Maquoketa Shale is relatively uniform at approximately 230 feet (70 m) in central Illinois. The formation thickens to the east (~100 m; 328 ft.) and thins to the southwest (40 m; 131 ft.) (14).

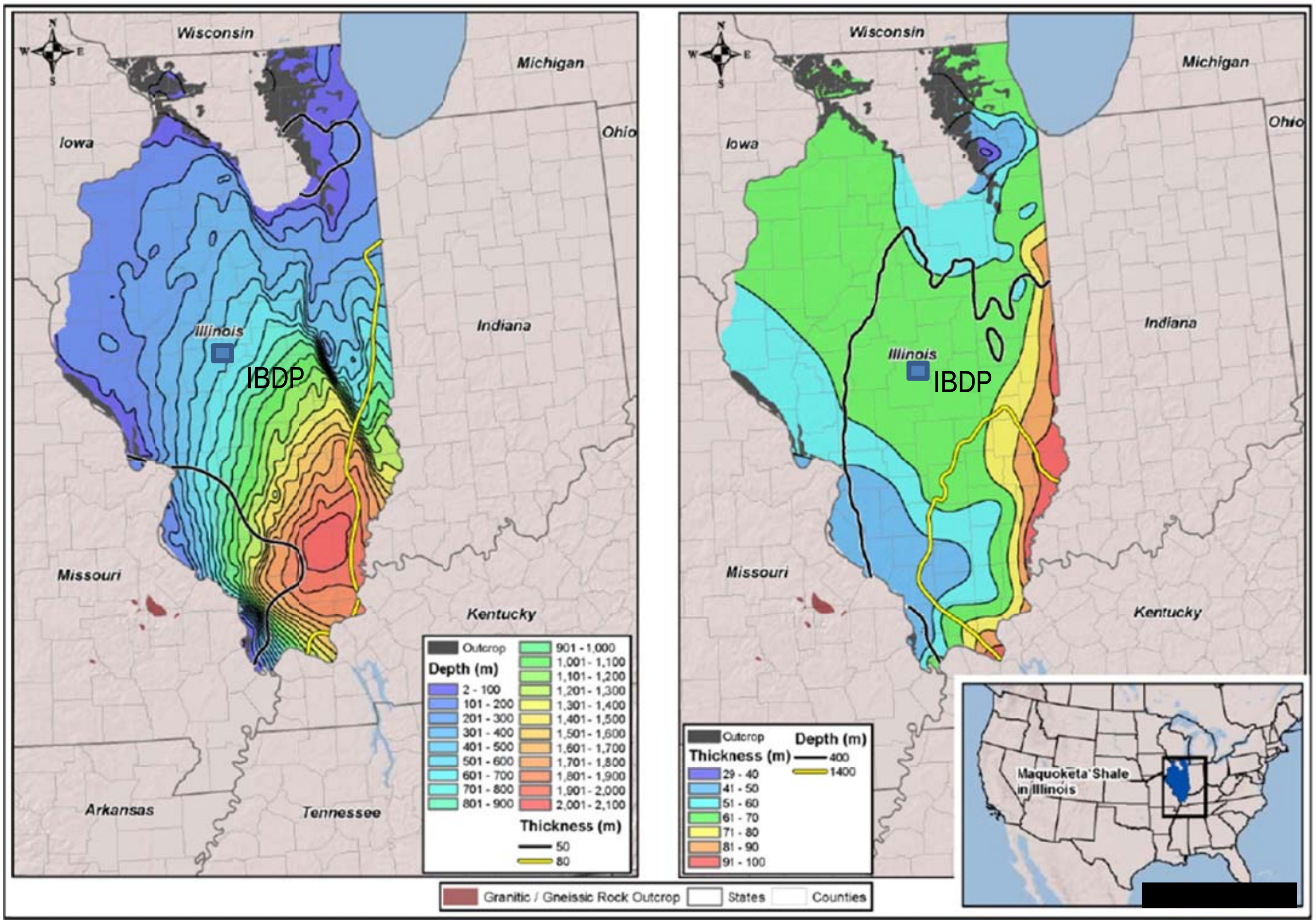


Figure 17: Depth and Isopach map of the Maquoketa Shale in the Illinois Basin cropped to the state of Illinois (14)

7.3 Structure and Isopach Map of the Utica Shale (Maquoketa Shale) in the Michigan Basin

As displayed in Figure 18 and Figure 19, the thickness of the Utica Shale (Maquoketa Shale) in Michigan is greater than 150 ft. (45.7 m) and as thick as 600 ft. (182 m) in the southeast (15).

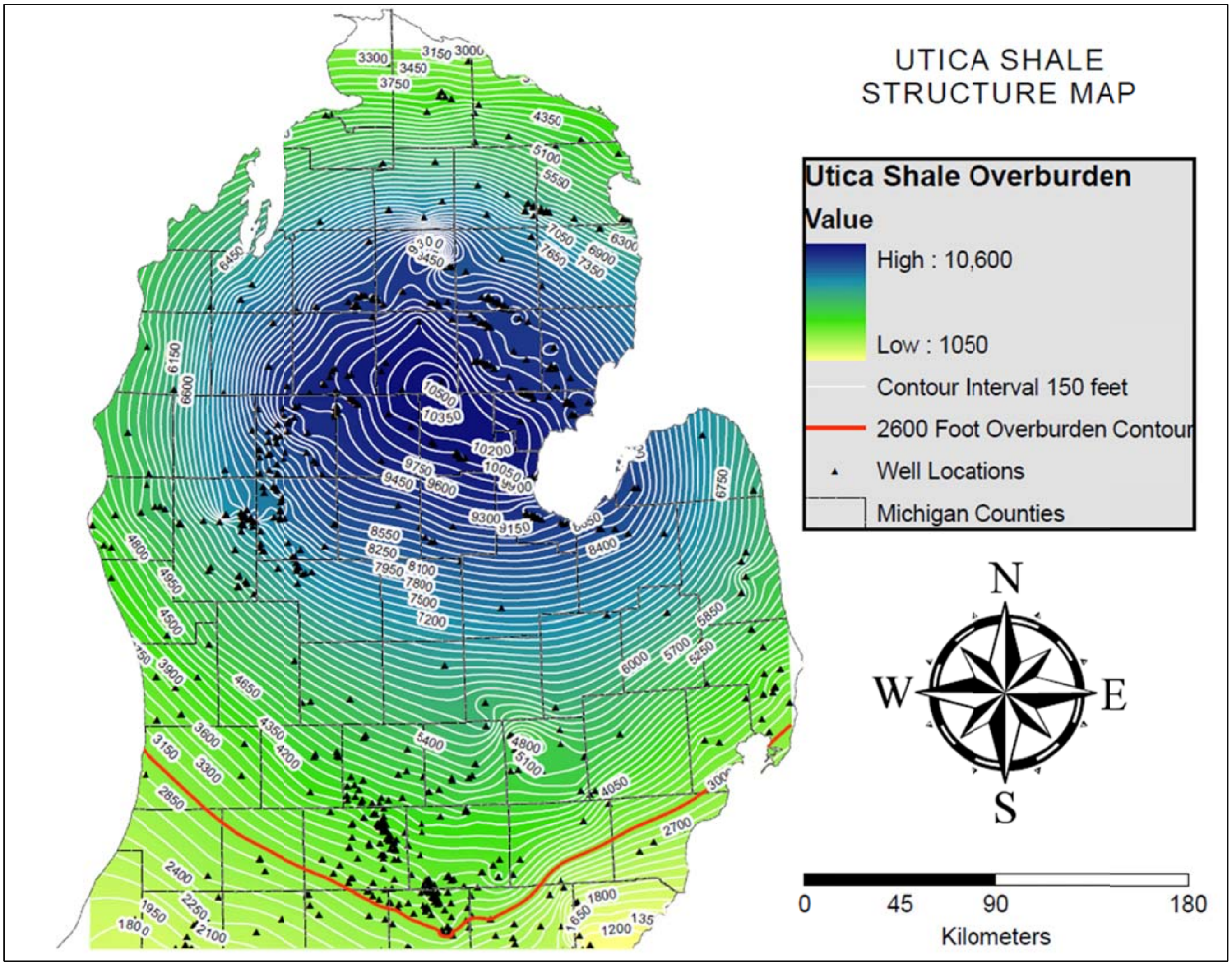


Figure 18: Structure Map of the Utica Shale in Michigan (15)

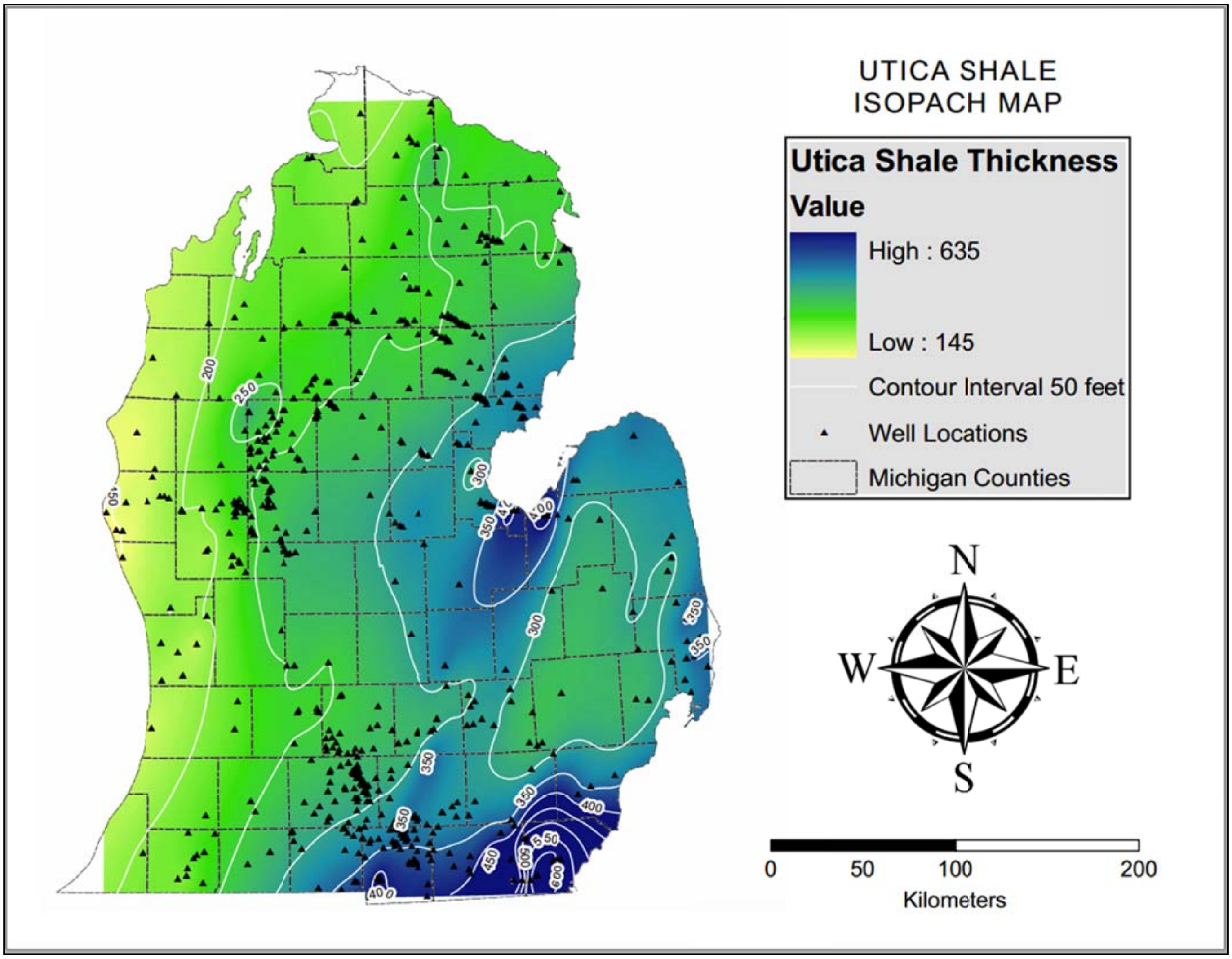


Figure 19: Isopach Map of the Utica Shale in Michigan (15)

8. Conclusions (Maquoketa Shale Caprock Characteristics)

Figure 20 and Table 8 summarize the observations which indicate that the Maquoketa Shale would be an effective caprock for a CO_2 injection project in the areas studied. The conclusions presented in this report, satisfy the scope of work that was established for the Knox project. Additional work could be completed to strengthen conclusions; however, this additional work would have been out of scope for the Knox project.

The Maquoketa Shale is considered to be an effective caprock for a CO_2 injection scheme in either the Potosi Dolomite or St. Peter Sandstone because it has a sufficient thickness (~200ft; ~61m), advantageous petrophysical properties, favorable geomechanical properties, an absence of observable fractures and is regionally extensive as supported by the data analyzed in this report. As a result, it is unlikely that CO_2 would migrate upward through the Maquoketa Shale and therefore that CO_2 impact to USDWs above is unlikely. Furthermore, the observations indicate that CO_2 injected into the St. Peter Sandstone or Potosi Dolomite may never even migrate up into the Maquoketa Shale at a high enough concentrations or pressure to threaten the integrity of the caprock.

The site specific conclusions were reached by unifying the data and conclusions from the IBDP, IL-ICCS, and the Knox projects. In the Illinois Basin, as one looks further away from these sites, the regionalized (extrapolated throughout the Basins) data and conclusions are expected to vary. The degree of variability is difficult to quantify because of the limited amount of data collected on the Maquoketa Shale away from IBDP, IL-ICCS, and the Knox projects. Any potential CCS project located elsewhere in the Illinois Basin could use these conclusions as a reference point; however, to verify the sealing capabilities of the Maquoketa Shale at another location, many of the methodologies described above would need to be completed as discussed below in the Recommendations.

All the objectives outlined in this projects scope of work were achieved. Data gathered from the IBDP/IL-ICCS/Knox projects were used to make conclusions about the suitability of the Maquoketa shale as a confining layer for CO_2 sequestration. This study indicates that the Maquoketa Shale would be a suitable caprock for a CO_2 injection program in either the Potosi Dolomite or St. Peter Sandstone.

Conclusions Type	Supporting Data Type	Observations relevant to the Maquoketa Shale Which Indicate Suitable Caprock Effectiveness
IBDP/IL-ICCS Site Specific Conclusions	Stratigraphic Position and Petrophysical Analysis	The stratigraphic position, the low permeability and low porosity of the Maquoketa Shale indicate that it would be an effective caprock. A thickness of ~200 ft. (61m)., a low effective porosity (<3%) and low permeability (<0.1mD) indicate that the Maquoketa Shale will be a reliable hydraulic barrier for the upward movement of CO_2. Before CO_2 injected into the St. Peter Sandstone could reach the Maquoketa Shale, it would have to migrate up through the Galena Group, Platteville Fm. and Platteville Limestone Fm., which act as thick (424 ft.; 130 m), low porosity (<3%), low permeability (<0.1mD) barrier to upward CO_2 migration. CO_2 injected into the Potosi Dolomite would most likely never reach the Maquoketa Shale (1570 ft.; 778m upwards). Injected CO_2 would have to migrate upwards into the thick (950 ft.; 290m) overlying Oneota Fm. and Shakopee Fm. These formations have higher effective porosity (~5%) and permeability (<8mD) and would likely act as secondary storage formations with some intraformational barriers. If the CO_2 migrates through these formations it would disperse into the very permeable St. Peter Sandstone.
	Fracture Analysis	The absence of observable fractures in the Maquoketa Shale and the low level of fracturing observed in lower lying formations suggest that connected migration pathways

		are highly unlikely.
	Core Analysis and Geomechanics	The 1D MEM results show that the minimum (2010 psi) and maximum horizontal stresses in the Maquoketa Shale make it a mechanically suitable caprock. The intervening layers above the St. Peter Sandstone show high mechanical integrity and will also act as a seal.
	Geochemical Investigations	Based on geochemical analysis, it is deemed highly unlikely that dissolution of the mineral constituents caused by sequestration activities in the region studied could result in a breach of the Maquoketa and overlying New Albany Shale seals before the reactions ceased.
	Risk	For the identified FEPs, the risks were low concerning the Maquoketa Shale.
	3D Seismic	The 3D seismic at IBDP showed that the thickness of the shale displays minor variability.
Regional Conclusions	2D Seismic	The regional 2D seismic showed minor variability in the thickness of the Maquoketa Shale. One fault was identified that penetrates the Maquoketa. To safely mitigate this, CO_2 sequestration projects involving the Knox Group should not be located near these structural features.
	Thickness (Isopach Maps)	Isopach maps of the Maquoketa Shale in the Illinois Basin and the Utica Shale in the Michigan Basin display suitable caprock thickness throughout Illinois and Michigan.

Table 8: Observations relevant to the Maquoketa shale which indicate suitable caprock effectiveness

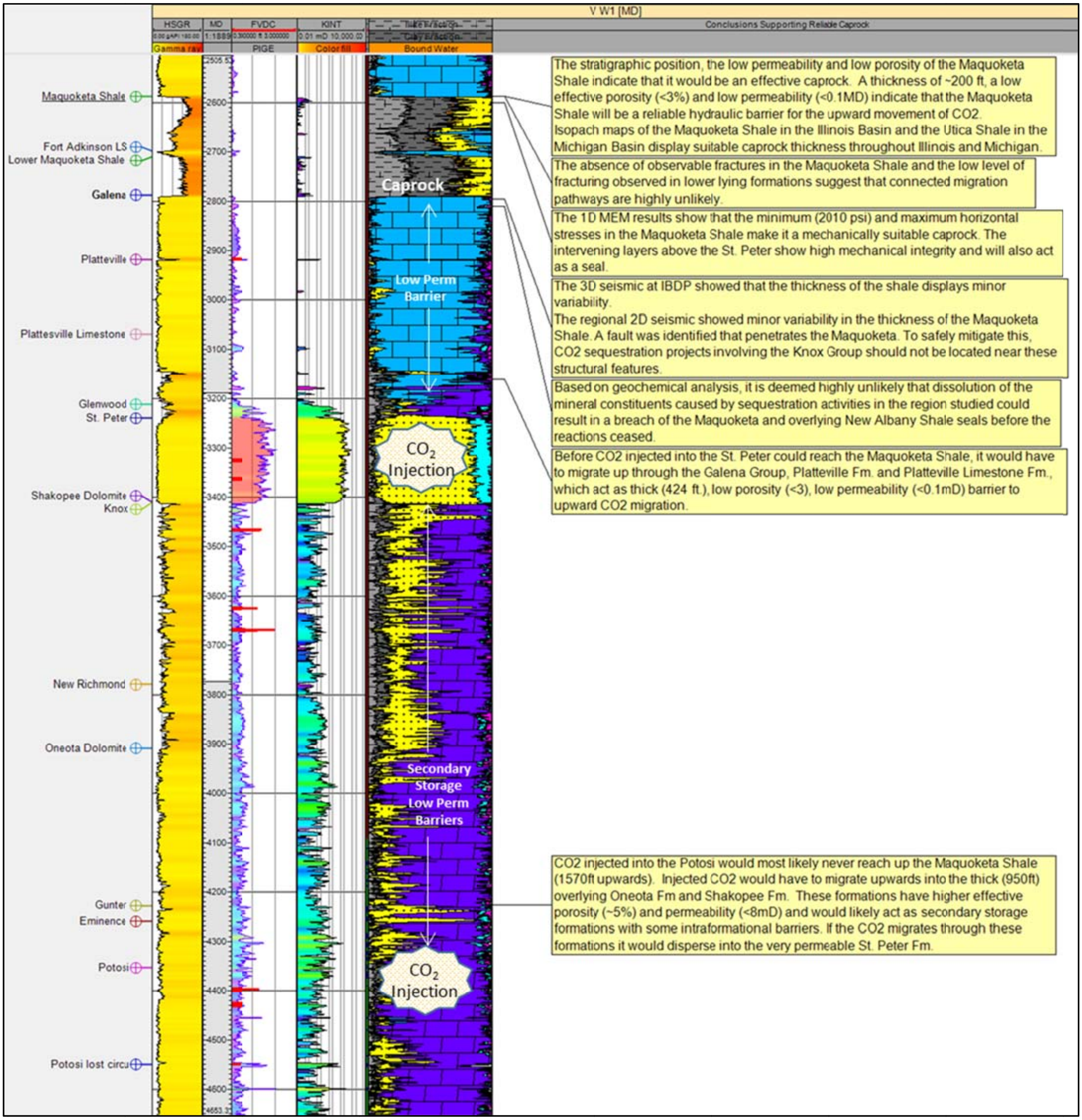


Figure 20: Site specific (IBDP/IL-ICCS) observations relevant to the Maquoketa Shale which indicate suitable caprock effectiveness

9. Recommendations for Future Projects

The data and conclusions presented in this report are limited to only a very small area in the Illinois Basin. As discussed above in the Conclusions Section, the sealing capabilities of the Maquoketa Shale are favorable for a CCS injection project in the St. Peter Sandstone and Potosi Dolomite at the IBDP, IL-ICCS, and Knox location. Assumptions and extrapolation of these results away from this area further into the Illinois Basin or into the Michigan Basin must be completed with caution. The conclusions presented here can be a good reference point to future investigations at other locations. Future investigations would need to use similar and some additional methodologies to prove the sealing capabilities of the Maquoketa Shale at the specific study site. The below items are recommendations to a future CCS project at another location evaluating the sealing capabilities of the Maquoketa Shale.

- Complete similar caprock characterization work on the Maquoketa Shale as outlined in this report.
- In order to understand the potential risk of caprock failure, conduct reservoir simulations of CO_2 injection into the Potosi Dolomite and St. Peter Sandstone and model the effect up to and including the Maquoketa Shale.
- Further any 1D MEM work and complete a 3D MEM with the incorporation of any available seismic inversion results.
- In the case of an operational CCS project pressure and temperature sensors should be deployed to measure for any changes in reservoir conditions that may indicate upward CO_2 migration. Distributed acoustic sensors should be deployed to listen for and induced seismic events that may indicate rock failure of the caprock.

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11. Appendix 1: Qualitative Implications of the Core Results

11.1 Maquoketa Shale

Representative samples were selected for testing in both the Upper and Lower portions of the Maquoketa Shale on core collected from the GM2 well (Figure 5). Only two samples were tested and, while these samples are assumed to be representative, they cannot themselves entirely capture the vertical heterogeneity and complex anisotropic properties intrinsically present in shale. They can, on the other hand, lend some insight into the expected behavior of the shale. The tensile strength (TSTR) of the Lower Maquoketa sample tested at 2,800.4 ft. (853 m) is less than that of the Upper Maquoketa sample tested at 2,635.55 ft. (803 m) (Table 9). Therefore, the conclusion is that the Lower Maquoketa sample is weaker than the Upper Maquoketa sample tested. Furthermore, the magnitude of the tensile strength in the Maquoketa Shale is lower than those of the Potosi Dolomite samples; however, in terms of gradient (psi/ft.) they are similar 0.3 to 0.5 psi/ft. This tensile strength gradient typically implies fairly competent and strong rock consistent with respect to its depth of burial. This further suggests that geomechanically; there are no strength related abnormalities in the Maquoketa Shale which would undermine its ability to act as a competent caprock.

Formation	Core Depth (ft.)	Orientation	Bulk Density (g/cc)	Tensile Strength	Tensile Strength Gradient (psi/ft.)
Upper Maquoketa Shale	2,635.55	Perpendicular	2.591	1,395	0.53
		Parallel	2.590	795	0.30
		45	2.554	1,007	0.38
Lower Maquoketa Shale	2,800.40	Perpendicular	2.564	1,232	0.44
		Parallel	2.561	438	0.16
		45	2.566	763	0.27
Knox-Eminence Dolomite	4,219.7	Perpendicular	2.781	2,108	0.50
		Parallel	2.792	1,298	0.31
		45	2.791	2,210	0.52
Knox-Potosi Dolomite	4,540.1	Perpendicular	2.745	1,748	0.39
		Parallel	2.706	1,902	0.42
		45	2.682	1,454	0.32
Knox-Potosi Dolomite	4,551.1	Perpendicular	2.810	2,577	0.57
		Parallel	2.822	2,437	0.54
		45	2.806	2,062	0.45

Table 9: Appendix 1: Qualitative Implications of the Core Results summary of indirect tensile strength tests (Brazilian method)

The magnitude of UCS observed in Maquoketa also signifies a generally high strength class of rock, which is a favorable quality of a good caprock (Table 10). The tests results of UCS in the vertical direction were over 104 psi for both upper (2,635 ft.) and Lower (2,800 ft.) Maquoketa Shale cored interval. The UCS in the horizontal direction for the Lower Maquoketa is 36% less than that of the Upper Maquoketa sample tested. This provides further indication that the Lower Maquoketa is weaker than the Upper Maquoketa sample tested.

Overall the Poisson's ratio (PR) in the samples tested in the Maquoketa Shale are lower than the samples tested in the Potosi Dolomite and are generally low for a typical shale (see Table 10). The implication of this is that the horizontal stresses could be lower which may not be good for a caprock, as it would be easier to deform and fail the rock. The vertical PR is lower than the horizontal and the PR for Lower Maquoketa sample (2,800.4 ft.) is lower than the Upper Maquoketa sample (2,635.55 ft.). This indicates that it would be easier to deform vertically than horizontally, and that the Lower Maquoketa interval is more prone to deformation than the Upper Maquoketa interval.

Well	Formation	Core Depth (ft.)	Orientation	Net Confining Pressure (psi)	Bulk Density (g/cc)	Triaxial Peak Strength (psi)	UCS Peak Strength (psi) *Net Confining Pressure =0	Young's Modulus (psi)	Poisson's Ratio	Cohesion (psi)	Friction Angle (degrees)
GM2	Upper Maquoketa Shale	2,635.5 +/- 0.5	Vertical	1647	2.566	17,338	10,929	2.63 E+06	0.18	2696	37
			45	1647	2.554	11,739	5,766	2.89 E+06	0.22	1834	31
			Horizontal	1647	2.569	19,214	11,747	5.3 E+06	0.23	1409	49
GM2	Lower Maquoketa Shale	2,801.5 +/- 1.5	Vertical	1750	2.594	17,785	13,201	2.66 E+06	0.17	1205	47
			45	1750	2.578	13,132	3,935	3.12 E+06	0.23	560	44
			Horizontal	1750	2.577	18,345	7,569	4.89 E+06	0.20	2311	40
VW1	Knox-Eminence Dolomite	4,218.75	Vertical	2595	2.614	39,105	21,040	8.68 E+06	0.32	3900	48.7
VW1	Knox-Potosi Dolomite	4,540.1	Vertical	3100	2.825	>75,970	14,660	14.66 E+06	0.31	2140	64.6
VW1	Knox-Potosi Dolomite	4,551.6	Vertical	3133	2.779	56,868	17,640	13.31 E+06	0.33	2370	58.2

Table 10: Appendix 1: Qualitative Implications of the Core Results summary of Mohr-Coulomb failure envelope parameters

Mohr-Coulomb failure analysis shows that overall the cohesion and friction angles are high which is good for a caprock (Table 10); however, there are clear differences between the vertical and horizontal directions and between the Upper and Lower Maquoketa intervals. The vertical direction cohesion is higher for the Upper Maquoketa sample while in the Lower Maquoketa sample the horizontal cohesion is higher. Nevertheless, the Lower Maquoketa is more prone to failure in vertical and oblique direction when compared to the Upper Maquoketa.

As expected of an anisotropic rock like shale, the Young's modulus (Table 10) which is a measure of stiffness is almost twice as large in horizontal direction compared to the vertical. Overall a higher magnitude of the Young's modulus would imply stiffer caprock which would have higher integrity against breach.

Additionally, apart from the mechanical testing another advanced core analysis called Tight Rock Analysis (TRA) (16) was performed for the Maquoketa interval. The results of these tests are presented at the end of Table 11 and plotted in Figure 21. These results demonstrate that Maquoketa shale is a low porosity and low permeability rock which is favorable quality for hydraulic sealing capacity of a caprock.

Well	Sample Depth (ft.)	Porosity (%)	Dry Bulk Density (g/cc)	Grain Density (g/cc)	Gas Permeability (md)	Formation	Lithology
VW1	4,477.00	1.13	2.785	2.817	42.69	Potosi	LS, pale yel gy, vug, lam, vug, xls
VW1	4,481.00	27.25	1.653	2.272	0.03	Potosi	SLST-MS, m gy, mica, carb, sl calc
VW1	4,487.00	0.81	2.813	2.836	4063.6	Potosi	LS, dsky yel bn, vug, xls
VW1	4,564.00	1.73	2.797	2.846	0	Potosi	LS, pale yel bn, arg, sl vug, xls,
VW1	4,587.00	3.32	2.728	2.822	<.01	Potosi	LS, dsky yel bn, arg
VW1	4,642.00	8.7	2.583	2.829	0.33	Potosi	LS, lt ol gy, arg, vug, xls
VW1	4,661.00	10.02	2.478	2.753	64.11	Potosi	LS, lt ol gy, arg, vug, xls, mot
VW1	4,666.00	2.56	2.73	2.801	0.01	Potosi	LS, gy yel gn, arg, lam, tr glau lam
VW1	4,671.00	4.46	2.703	2.829	<.01	Potosi	LS, ol gy, arg, cff
VW1	4,803.00	1.39	2.8	2.839	<.01	Potosi	LS, ol gy, mot, lam, sl vug
GM2	2,635.73	7.55	2.575	2.682	0.0001	U. Maquoketa	Sh
GM2	2,800.52	7.28	2.598	2.659	0.0002	L. Maquoketa	Sh

Table 11: Appendix 1: Qualitative Implications of the Core Results summary of petrophysical reservoir properties - routine core analysis

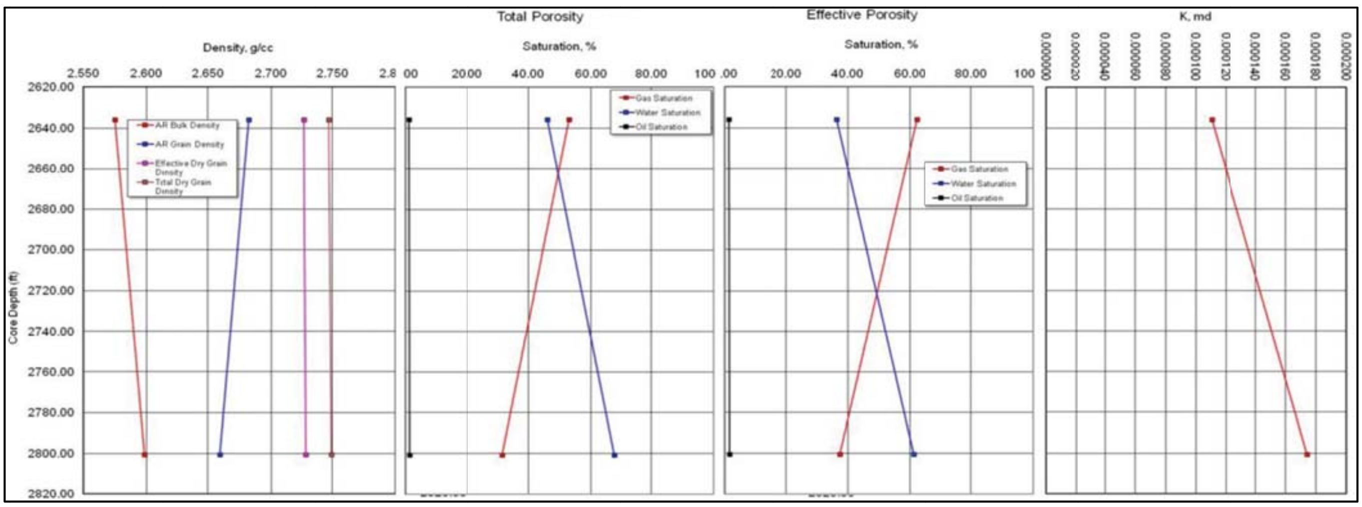


Figure 21: Appendix 1: Qualitative Implications of the Core Results tight rock analysis results plots of density, porosity and permeability in the Maquoketa Shale

In summary, even though the Lower Maquoketa appears to be a generally weaker rock than the Upper Maquoketa. Overall, the core results show high values of Young's Modulus, UCS and Friction Angle in the Maquoketa, all of which are indicative of tough rock to breach with fairly high strength. With regards to wellbore integrity, core results indicate a high chance of having a stable borehole based on the high strength and stiff quality of Maquoketa shale. However, wellbore stability or integrity is heavily dependent on stress regime, stress magnitude, pore pressure, mud weight, borehole trajectory and drilling practice, all of which must be considered in a CO_2 sequestration project and well drilling.

11.2 Potosi Dolomite

Representative samples were selected for testing in the Potosi Dolomite on core collected from the VW1 well. Additionally, a sample was selected for testing in the Eminence dolomite (the formation overlying the Potosi.Dolomite). Similar to the Maquoketa, while these samples are assumed to be representative they cannot themselves entirely capture the vugular and fracture heterogeneity present in these dolomite formations. They can on the other hand lend some insight into the expected behavior of the dolomite reservoir. Reservoir quality for CO_2 sequestration in a dolomite is heavily dependent on porosities, permeability, presence of natural fractures, vugs, pore pressure, and the ability to maintain mechanical integrity during injection. These properties were tested on the core samples taken. Rotary Sidewall cores were taken throughout the Knox and the Maquoketa in the VW1 well. Table 11 lists the petrophysical reservoir properties from routine core analysis performed on the Potosi rotary sidewall core samples as well as the Maquoketa samples to investigate reservoir and caprock quality respectively. The data show the Potosi reservoir to have fair sequestration potential with some intervals of quite high permeability and porosity (normally associated with vugs) compared to others of lower permeability and porosity as is to be expected in a vuggy dolomitic rock.

The tensile strength of the core tested from 4,219.7 ft. (1286 m) (in the Eminence Formation) is lowest parallel to bedding in contrast to other orientations and other core depths (Table 9). This means that (for this formation) it would be easiest to fail the rock in tensile mode vertically in this interval compared to the deeper interval. The tensile strength of the core at 4,551.1 ft. (1387 m) in the Potosi Dolomite which is within the zone of lost circulation zone observed during drilling) is largest when compared to the two other Knox samples tested (shallower in the Potosi Dolomite 4,540.1 ft. (1384 m) and the Eminence dolomite 4,219.7 ft.(1286 m)). This is a good indication that the target reservoir rock, which would be storing the CO_2, is a strong reservoir.

Unconfined compressive strength of the shallower Knox core (4,218.75 ft.; 1286 m) in the Eminence dolomite is higher than that of the deeper samples (in the Potosi Doloite) which would indicate the Eminence could withstand a higher shear stress than the Potosi before failing (see Table 10). This is a desirable characteristic of a formation overlying the reservoir. The Mohr-Coulomb failure test shows that the sample tested at 4,218.75 ft. (1286 m)in the Eminence dolomite has the highest cohesion, which gives further confidence in the overlaying formation mechanical integrity in regards to shear stresses.

The Young's modulus which is a measure of stiffness of the rock is smaller for the shallower Knox sample at 4,218.75 ft. (1286 m) in the Eminence compared to deeper Potosi samples at 4,540.1(1384 m) and 4,551.1 ft. (1387 m) In general the higher the Young's modulus and Poisson's ratio the stronger and tougher the rock is and therefore more resistive to failure. For example, a crystalline igneous rock like granite is much tougher than a sedimentary rock such as unconsolidated sandstone. The relatively high values for the samples tested indicate a stable rock and reservoir. These would be favorable characteristics for borehole stability during drilling and CO_2 injection. Although as mentioned earlier, wellbore stability is also heavily dependent on stress regime, stress magnitude, pore pressure, mud weight, borehole trajectory and drilling practice.

12. Appendix 2: Maquoketa Whole Core Images and Geological Description

GM2 Geological Description

API #: 12-115-23594-00 County: Macon Status: CONF

Company: Pioneer Oil Co., Inc.

Well Name: Geophysical Monitoring 2 # Total Depth: 3,550'

S-T-R: 32 - 17N - 3E Location: NW NW SE

Elevation: '

Described By: Martin Palkovic on 09/23/2013

ISGS Geologist Described the Core. Initials and name indicate who entered the data.

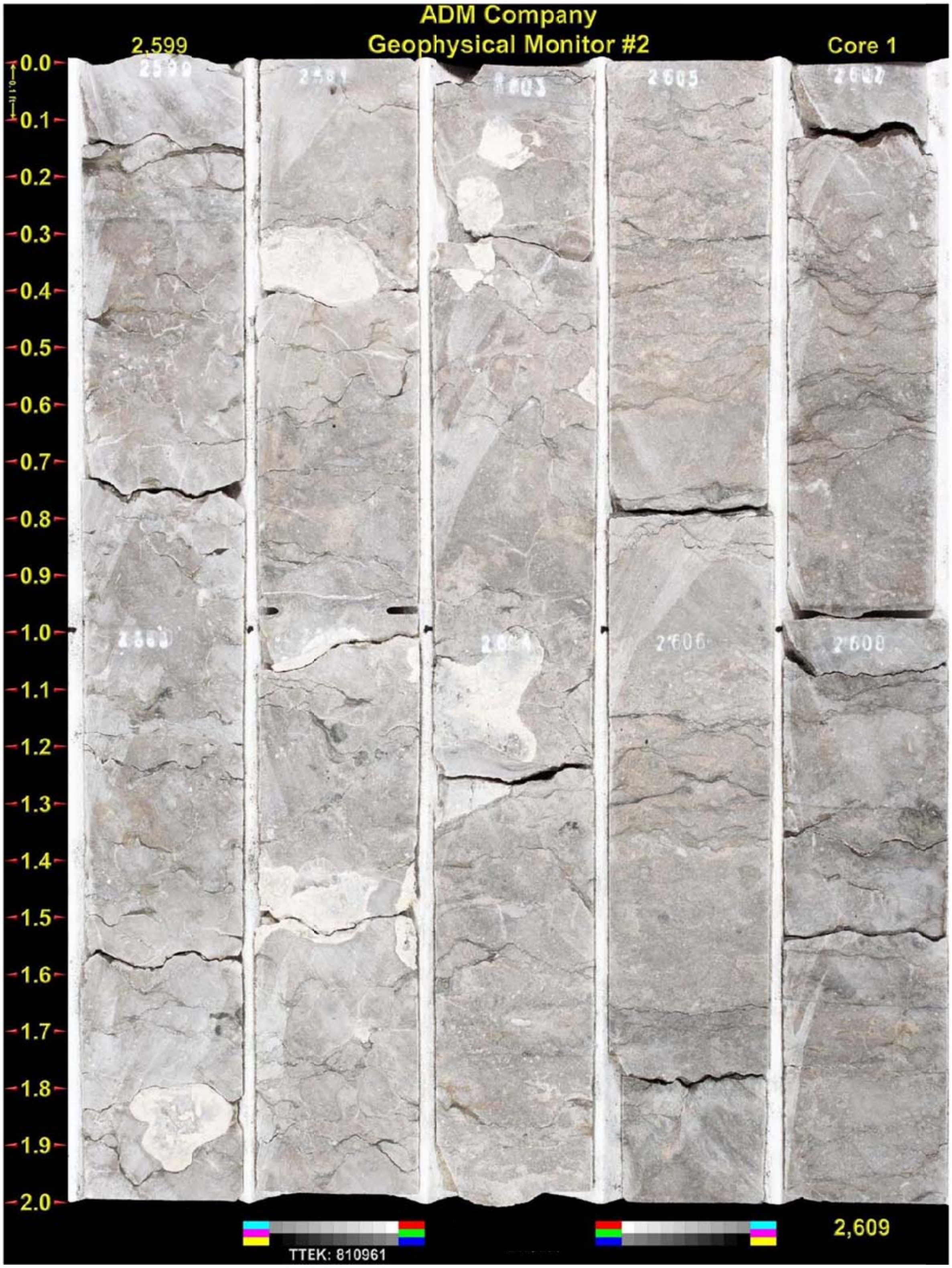
Description	Thickness	Top	Bottom
Unit 1-1: Gray-light pink limestone. Highly stylolizied with trace suturing along stylolite Isolated mm-scale chert pieces. Pyrite along some stylolites. Wackestone.	1.8	2599	2600.8
Unit 1-2: Similar to above unit with chert nodules up to 5 cm spaced out every .75'. Large brachipod at chert nodule at 2602. Possible peloids or other circular fossils at chert nodule.	3.5	2600.8	2604.3
Unit 1-3: Similar as above with no chert beds. Isolated mm-scale chert debris. Possible tempestites of small fossil debris.	1.3	2604.3	2605.6
Unit 1-4: Similar to above unit with one possible .1' thick tempestite bed at 2606. Pyrite replacing coral head near top.	4.5	2606.7	2611.2
Unit 1-5: Similar to above unit. Minimal fossil debris throughout. Large cm-scale isolated coral fossils throughout. Slight darker gray color than above.	4.5	2606.7	2611.2
Unit 1-6: Similar to Unit 4 and 5. Isolated coral fossils up to 2 cm. Calcite filled horizontal fracture or vug just above 2612.	2.1	2611.2	2613.3
Unit 1-7: Dark gray to pink dolomite. Darkens with depth, changing to a very dark gray. Minimal fossil debris throughout. Possible Iron staining along trace fossils near top. Bedding appears more wavy near base mostly massive.	2.5	2613.3	2615.8
Unit 1-8: Gray-blue-green shale. Sharp unconformable contact with above unit. Micro-network of planolites burrow. mm-scale pyrite concretion near base. Vertical fractures likely induced from drilling.	.7	2615.8	2616.5
Unit 1-9: Gray-blue-green shale. Similar to above with less bioturbation. Isolated maroon ferruginous-like mm-scale clay features interlaminated within shale. Bedding not apparent, to massive.	1.5	2616.5	2618
Unit 1-10: Preserved Sample PS-1	1	2618	2619
Unit 1-11: Similar to above unit, with increasing maroon clay features. Pyrite nodule and pyrite along thin laminae bedding not apparent, to massive.	3.1	2619	2622.1
Unit 1-12: Similar to above unit with increasing maroon mottling. Abundant bioturbation infilled with blue-green mud.	1.9	2622.1	2624
Unit 1-13: PS-2	1	2624	2625
Unit 1-14: Similar to above unit. Tempestite like beds with small debris or concretions. One in center of interval and one at base. Basal one appears more as	1	2625	2626
Unit 1-15: Similar to above unit with more wavy looking bedding and more bioturbation. Conostichus-like burrow at 2627.1'. Skolithos burrow at 2629.6' with very good laminar accommodation space sorting. Gamma (k) kick at 2630. Smaller burrows throughout. Bedding appears wavy laminated.	6.4	2626	2632.4

Geological Description

API #: 12-115-23594-00

Description	Thickness	Top	Bottom
Unit 1-16: Gray-blue-green to maroon shale, planar laminated. Maroon laminations are abundant. Pyrite concentrated in more blue green beds. Trace bioturbation.	6.4	2626	2632.4
Unit 1-17: Similar to above, but wavy laminated.	1	2635.9	2636.9
Unit 1-18: Dark gray to black shale. Planar laminated. Dark gray-tan laminae are likely the result of silt content.	2	2790	2792
Unit 1-19: Preserved Sample	1	2792	2793
Unit 1-20: Similar to above with thicker dark gray beds resulting from higher silt content. Planar laminated.	3	2793	2796
Unit 1-21: Preserved Sample	1	2796	2797
Unit 1-22: Similar to above	3	2797	2800
Unit 1-23: Removed Sample	1	2800	2801
Unit 1-24: Similar to above. Trace ripple lamination, mostly planar laminated.	4	2801	2805
Unit 1-25: Preserved Sample	1	2805	2806
Unit 1-26: Similar to above with thicker siltier gray beds. Trace pyrite nodules	4	2806	2810
Unit 1-27 Preserved Sample	1	2810	2811
Unit 1-28: Similar to above, but large dark gray bed. Trace pyrite nodules.	.7	2811	2811.7
Unit 1-29: Black to dark gray shale. Ripple to planar laminated. Large pyrite nodule at 2813.7'.	3.3	2811.7	2815
Unit 1-30: Dark gray to dark tan shale. Top and bottom of interval is marked by 1 cm thick pyrite beds. Bedding is planar to massive.	1.8	2815	2816.8
Unit 1-31: Gray-tan-pink limestone. Heavily bioturbated with mottled look. Vugs up to 2.5 cm completely filled with calcite spar. Calcite fills thin hairline fractures. Dominantly a wackestone. Occasional tempestite 2-3 cm thick with mm-scale fossil debris. Abundant stylolites with suturing up to 3 cm.	2	2816.8	2818.8
Unit 1-32: Similar to above but with some dolomitization (dark tan) along vugs, fractures, burrows and fossils. Dark. blue-black mottling near base.	2.7	2818.8	2821.5
Unit 1-33: Similar to above unit, with less mottling and mm-scale stylolite at 2822.2'.			
Unit 1-34: Gray-tan-pink limestone, wackestone. Occasional tempestites. Occasional mm-scale fossils throughout. Abundant stylolites.			

Page 2 of 2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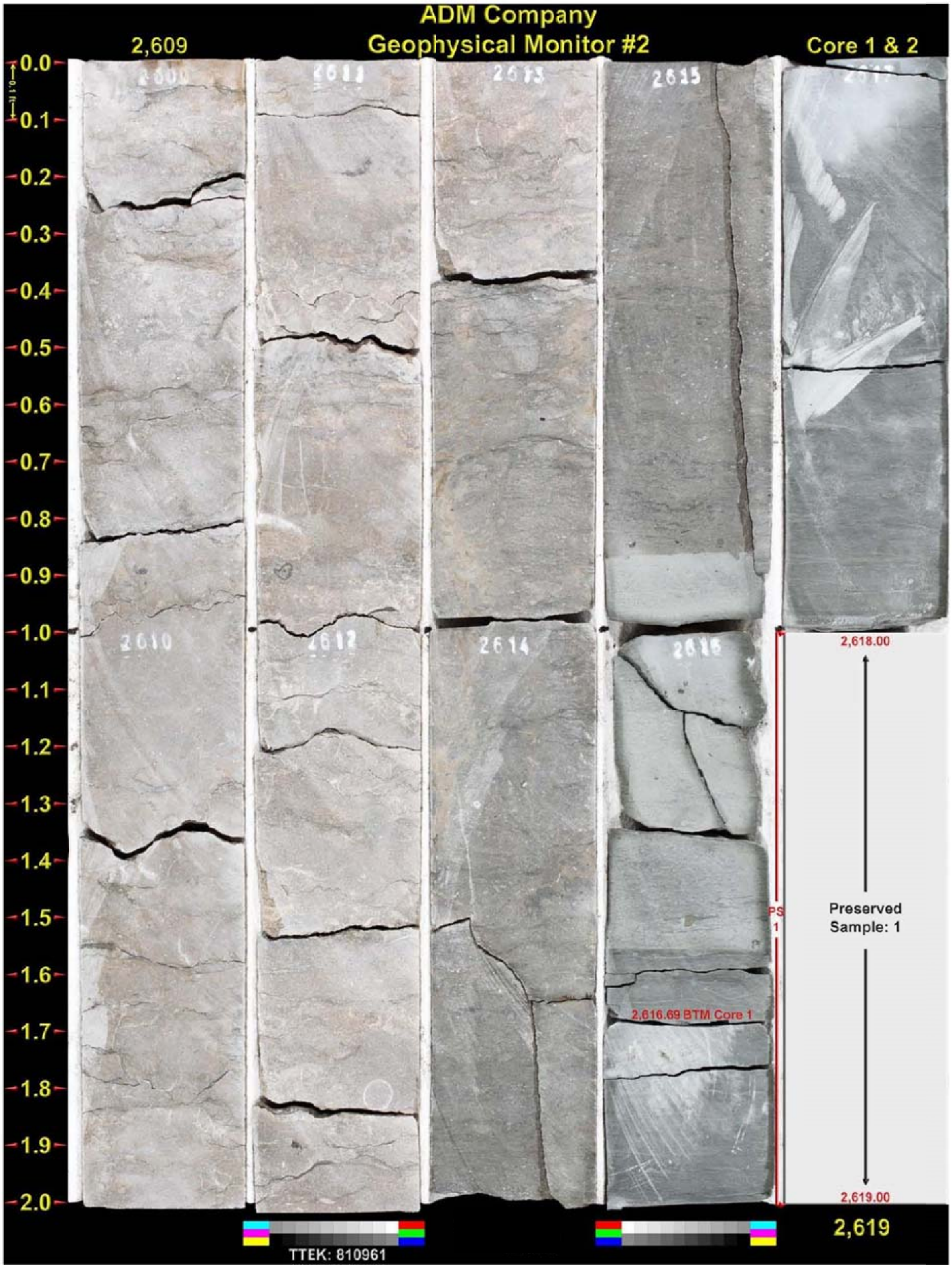
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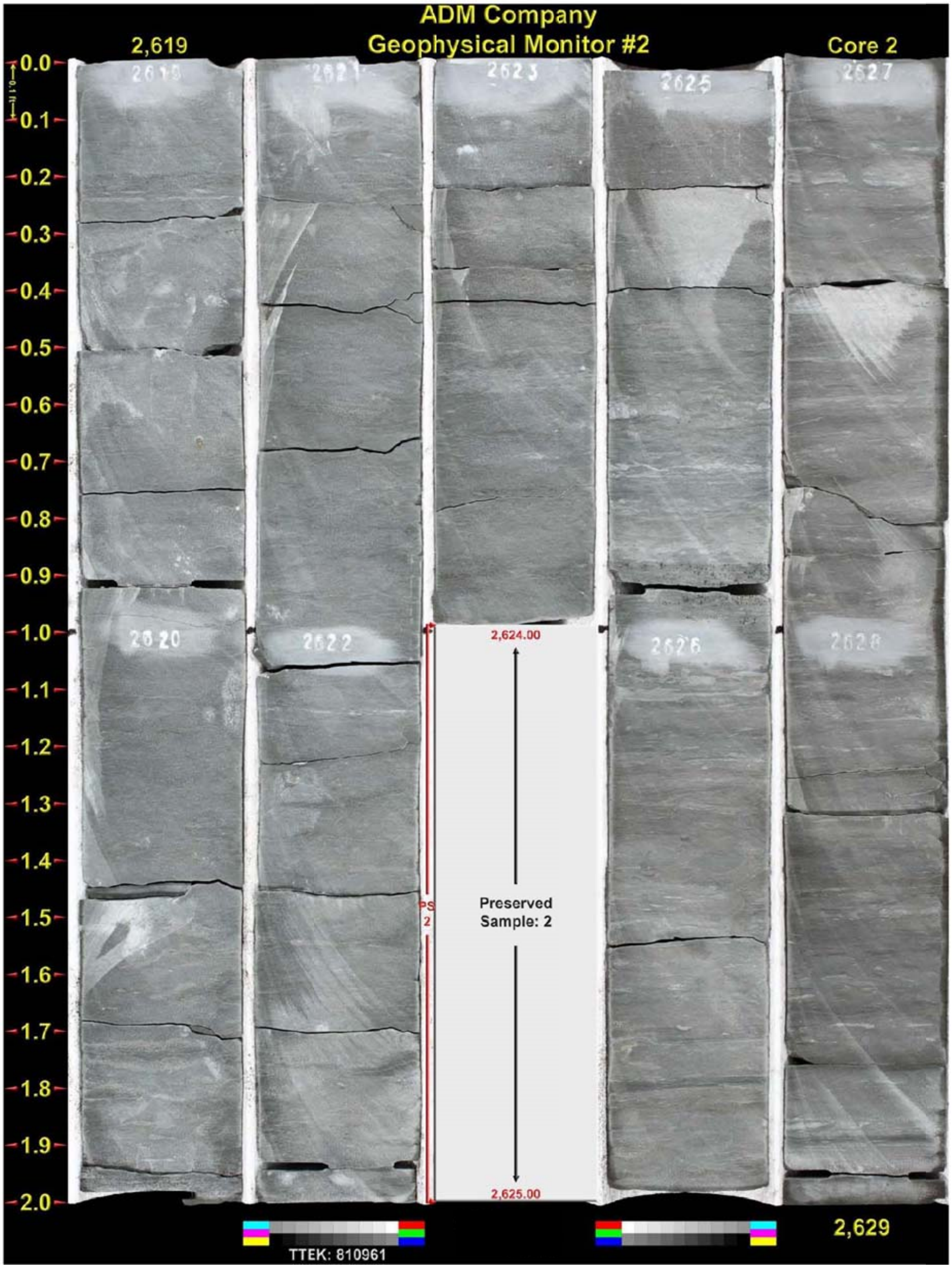

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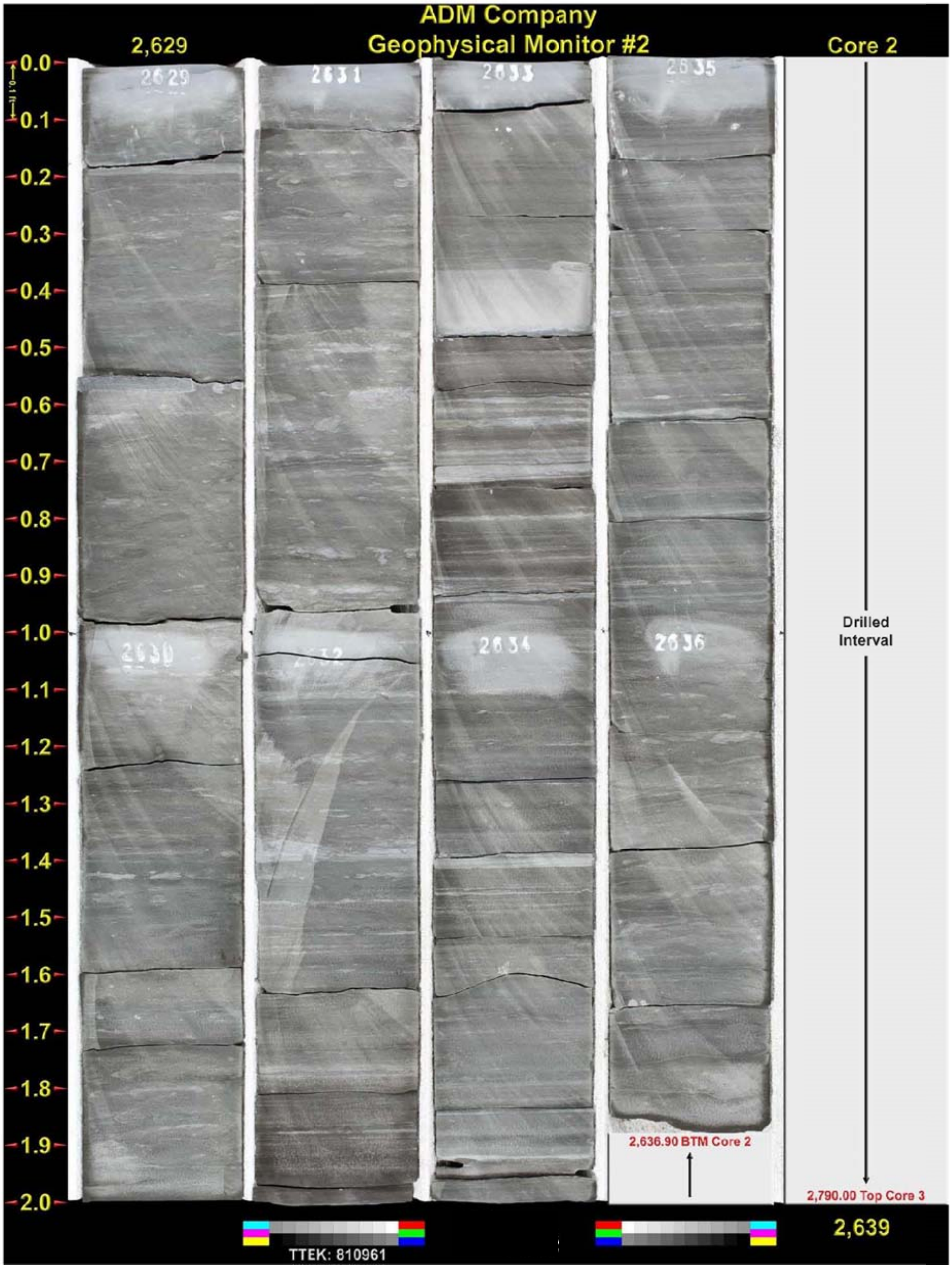
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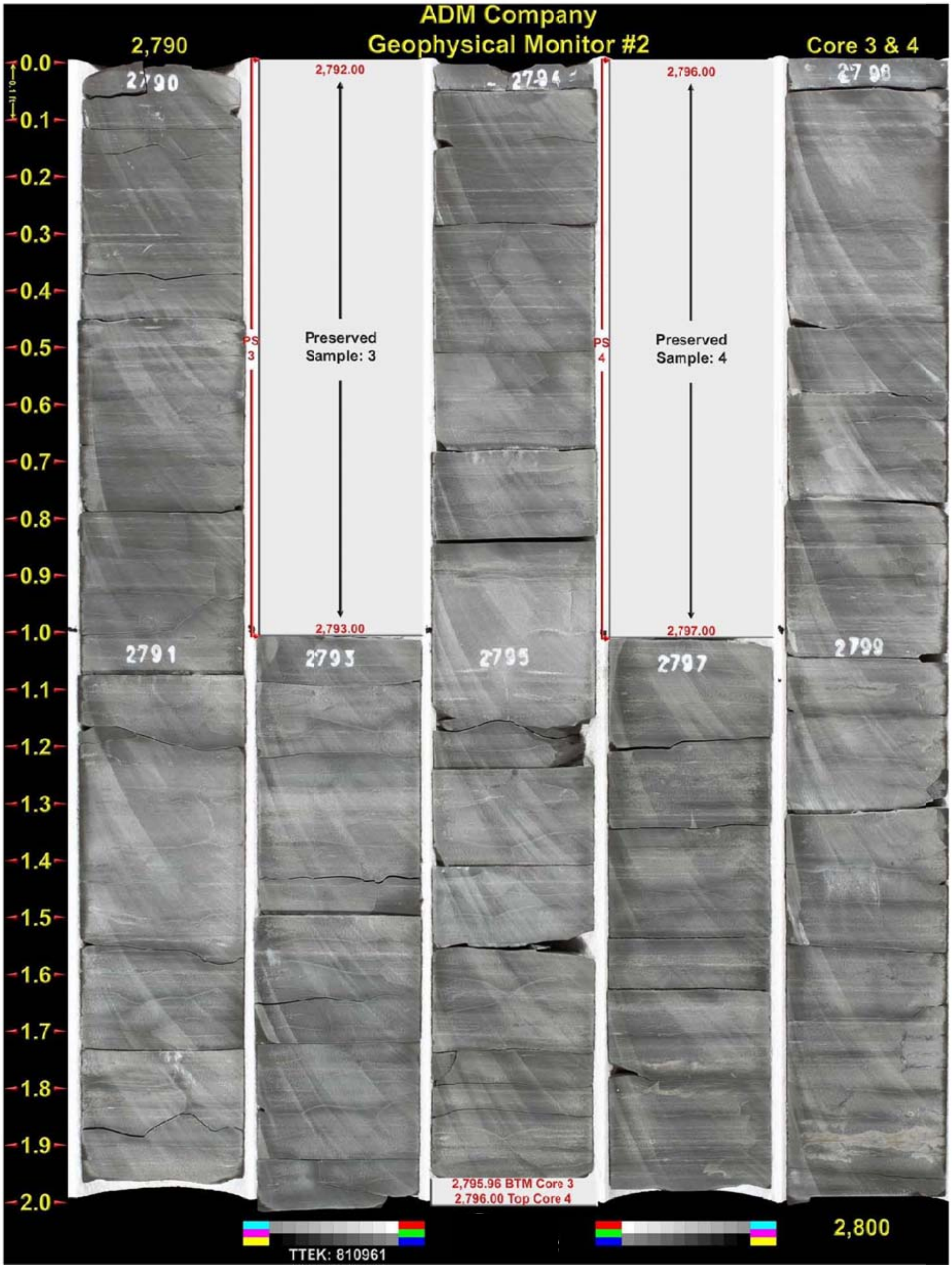
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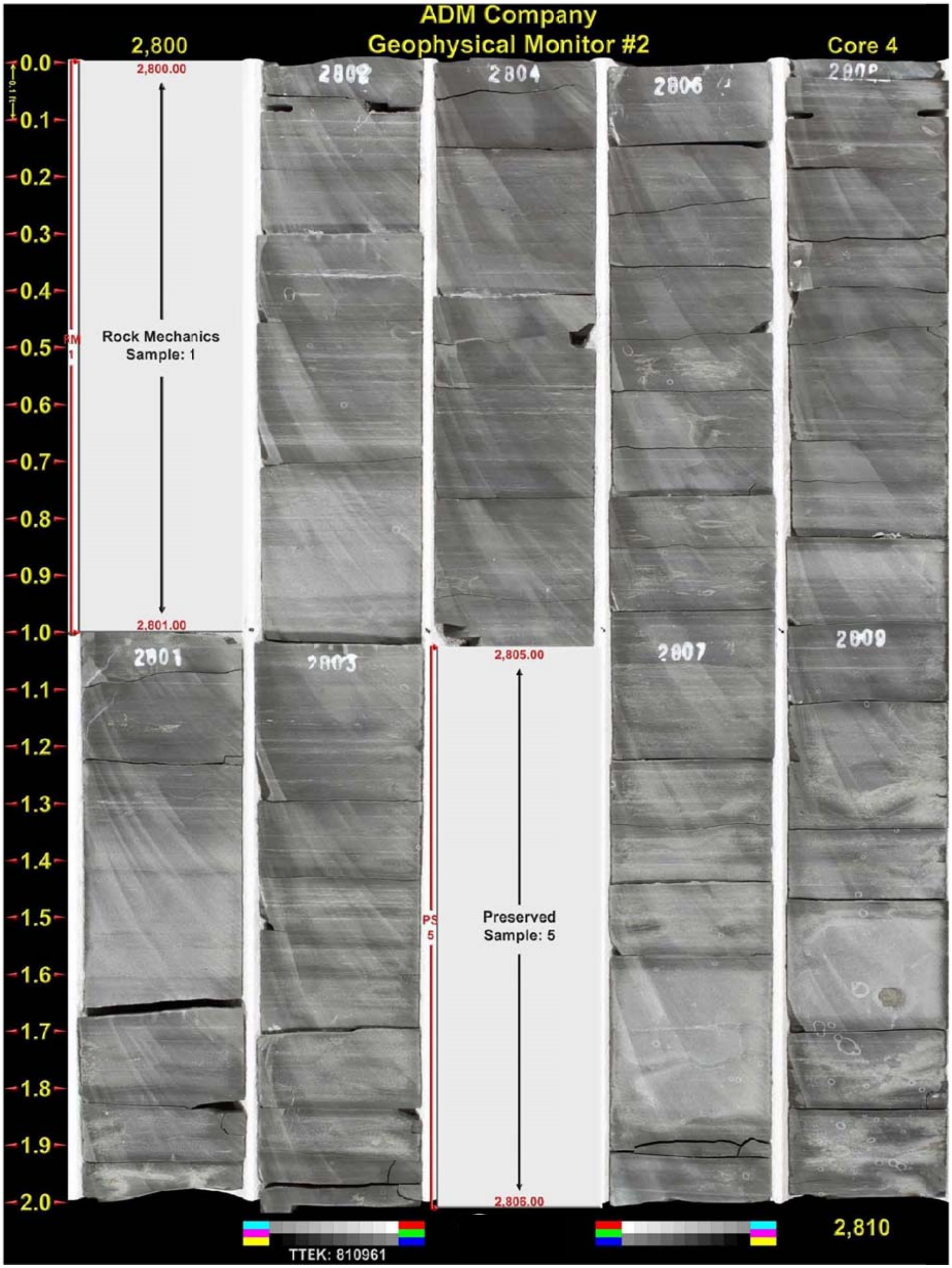

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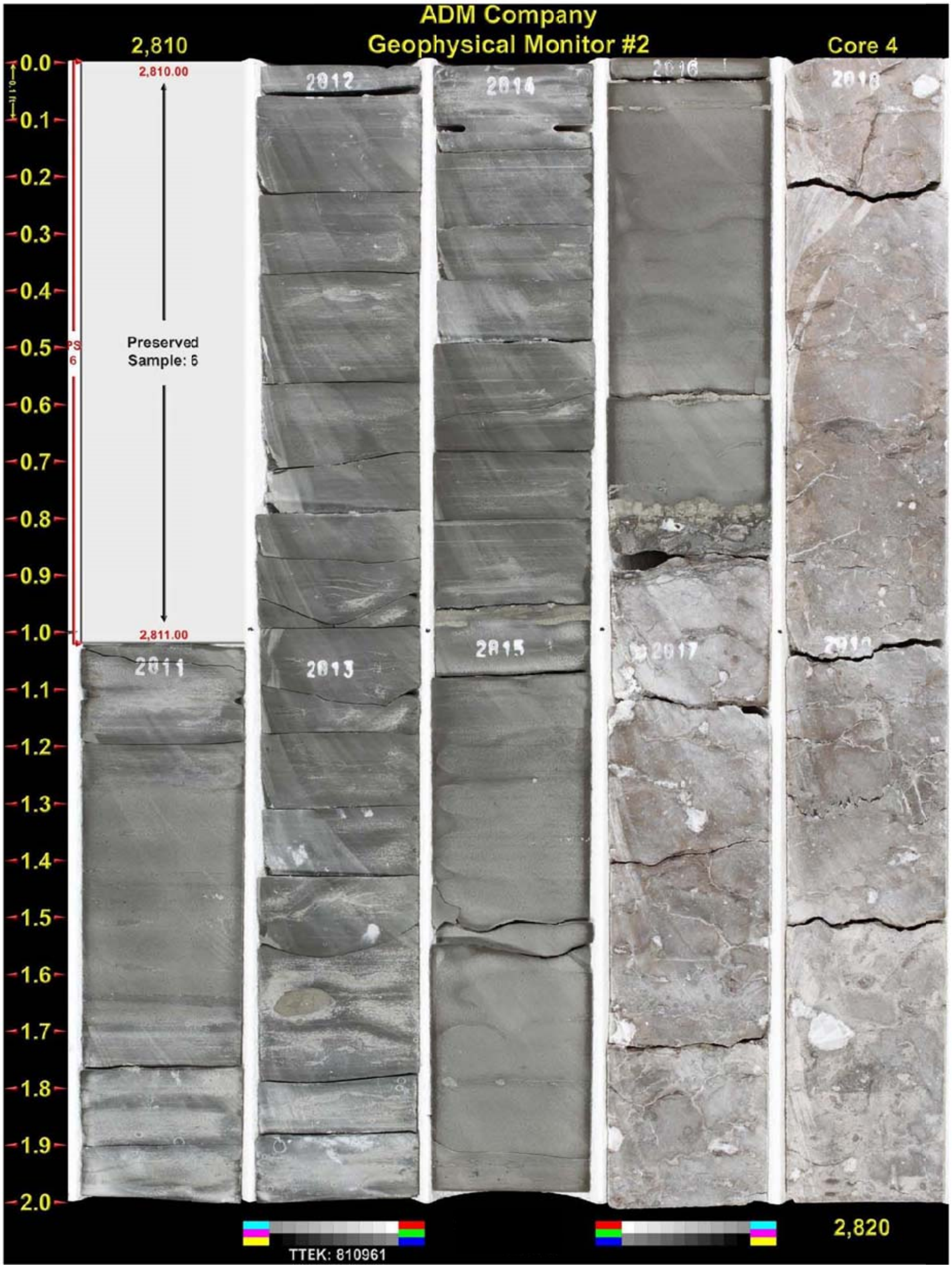
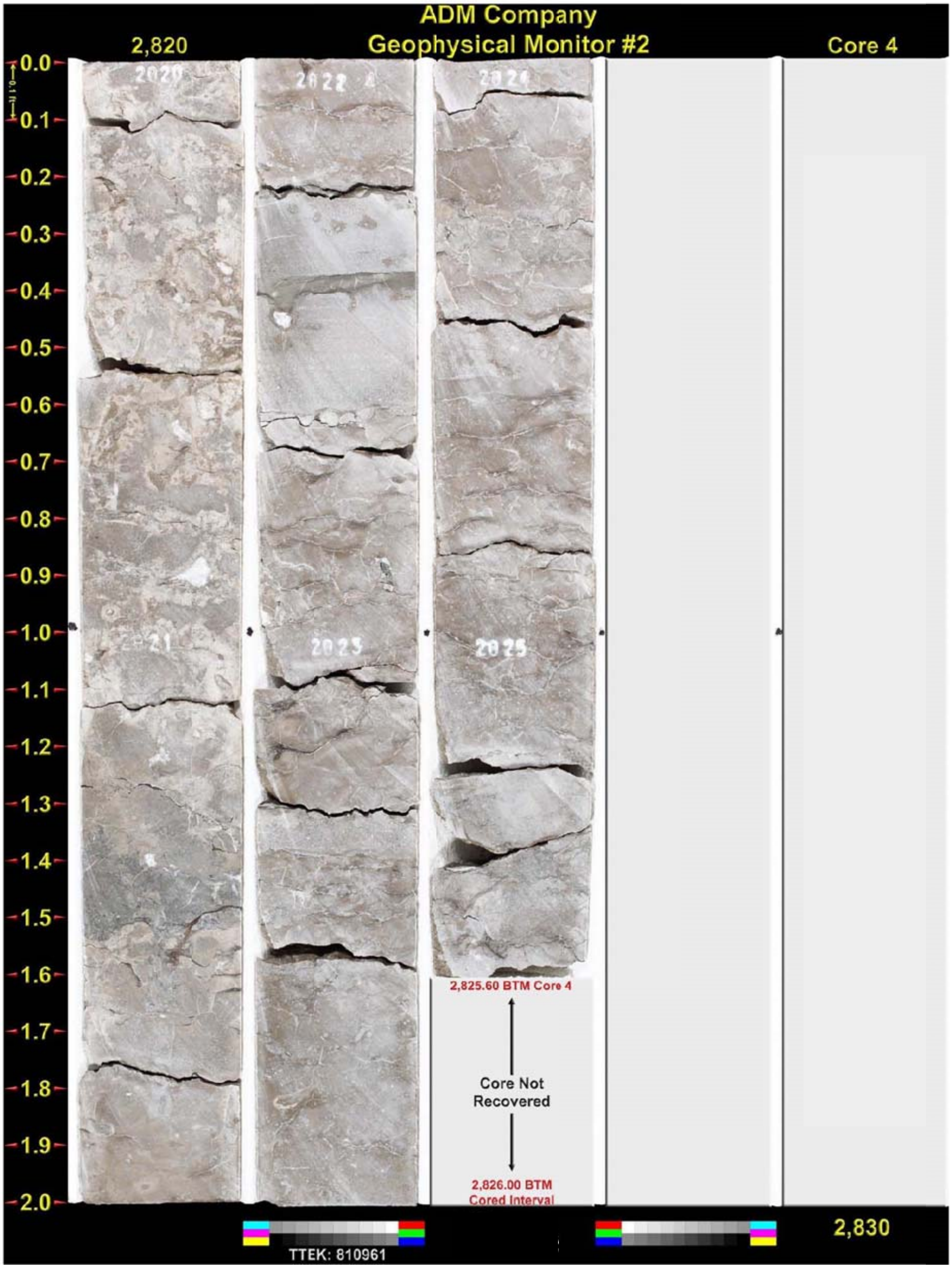
Rock Mechanics
Sample: 1
2,801.00
RM
1
2,805.00
Preserved
Sample: 5
2,806.00
PS
5
2,810
TTEK: 810961



ADM Company
Geophysical Monitor #2
2,810
Core 4
2,810.00
Preserved Sample: 6
2,811.00
PS 6
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2,820
TTEK: 810961


ADM Company
Geophysical Monitor #2
2,820
Core 4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2,825.60 BTM Core 4
Core Not Recovered
2,826.00 BTM Cored Interval
2,830
TTEK: 810961

13. Appendix 3: Geomechanical

1D Geomechanical Modeling for the Knox Project Verification Well 1

Sajjad Ansari
PTS Canada

June 16, 2014

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Project Objectives

- Construct a 1D Mechanical Earth Model to determine the earth stress in the Maquoketa Shale in order to be quantitatively assess its failure limits as a primary Caprock.

Tasks:

- Data collection, review and quality check.
- Construction of 1D Mechanical Earth Model (MEM) for Verification Well #1 (VW1) using data also from offset wells: CCS1, VW2 and GM2.
- Perform Wellbore Stability (WBS) analysis.
- Analysis of the results.

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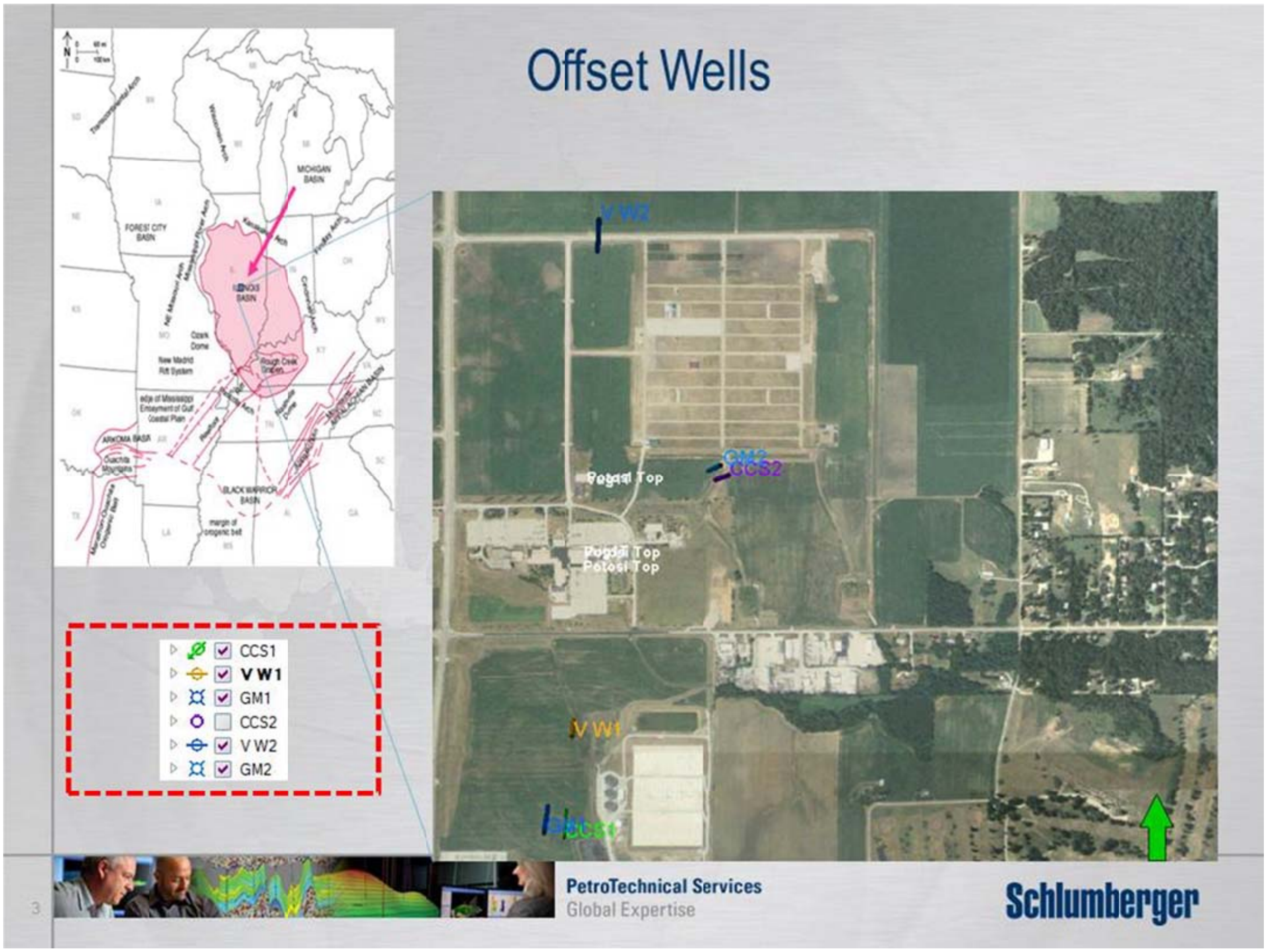
Offset Wells
MICHIGAN BASIN
FOREST CITY BASIN
ILLINOIS BASIN
Ozark Dome
New Madrid Rift System
Rough Creek Graben
BLACK WARRIOR BASIN
ARKOMA BASIN
Ouachita Mountains
CCS1
V W1
GM1
CCS2
V W2
GM2
V W2
GM2
CCS2
V W1
CCS1
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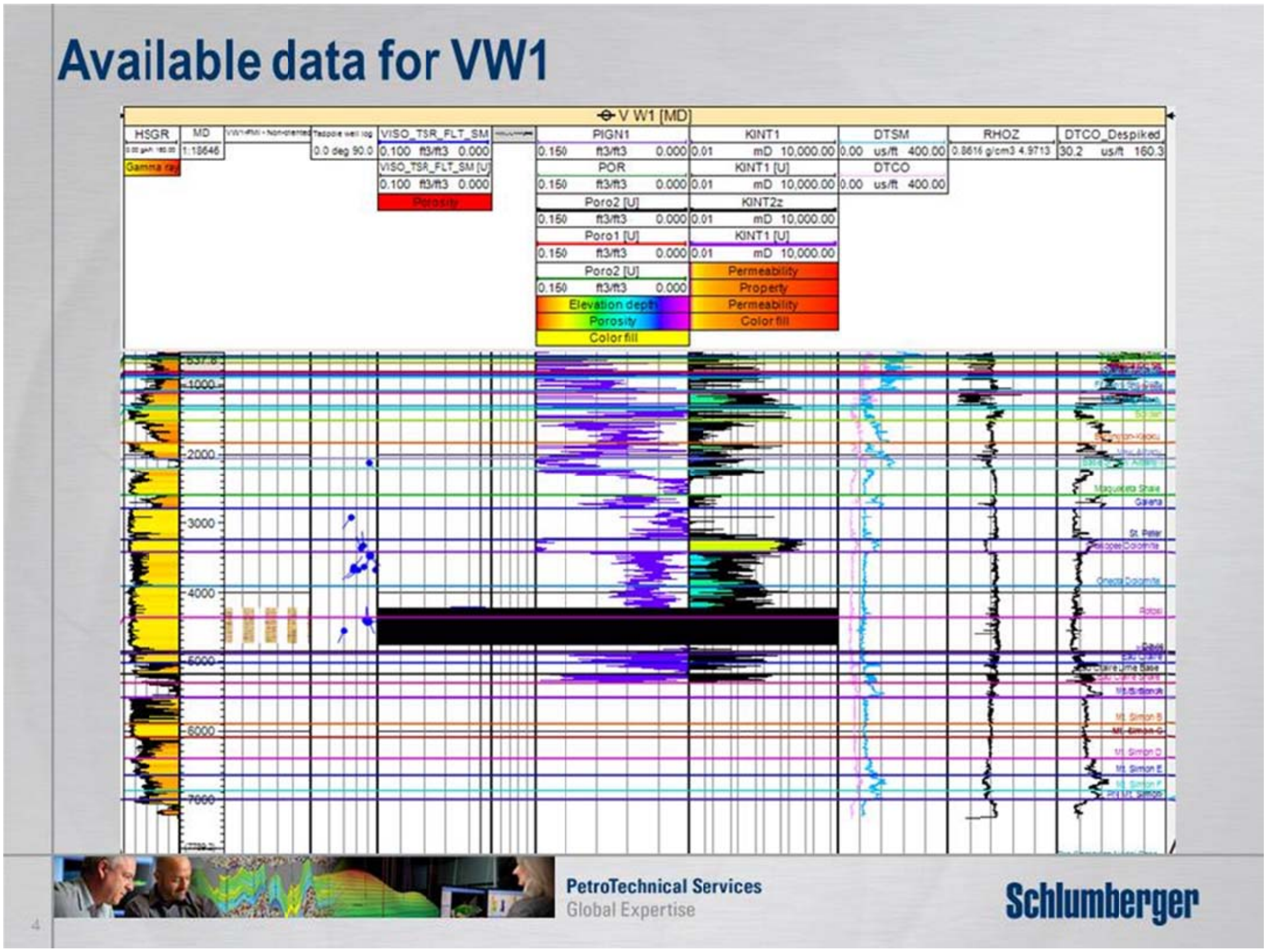

Available data for VW1
V W1 [MD]
HSGR
MD
1:18646
Gamma ray
VISO_TSR_FLT_SM
0.100 ft3/ft3 0.000
VISO_TSR_FLT_SM [U]
0.100 ft3/ft3 0.000
Porosity
PIGN1
0.150 ft3/ft3 0.000
POR
0.150 ft3/ft3 0.000
Poro2 [U]
0.150 ft3/ft3 0.000
Poro1 [U]
0.150 ft3/ft3 0.000
Poro2 [U]
0.150 ft3/ft3 0.000
Elevation depth
Porosity
Color fill
KINT1
0.01 mD 10,000.00
KINT1 [U]
0.01 mD 10,000.00
KINT2z
0.01 mD 10,000.00
KINT1 [U]
0.01 mD 10,000.00
Permeability
Property
Permeability
Color fill
DTSM
0.00 us/ft 400.00
DTCO
0.00 us/ft 400.00
RHOZ
DTCO_Despiked
30.2 us/ft 160.3
1000
2000
3000
4000
5000
6000
7000
Maquoketa Shale
Galena
St. Peter
Oneota Dolomite
Potosi
Mt. Simon B
Mt. Simon C
Mt. Simon D
Mt. Simon E
Mt. Simon F
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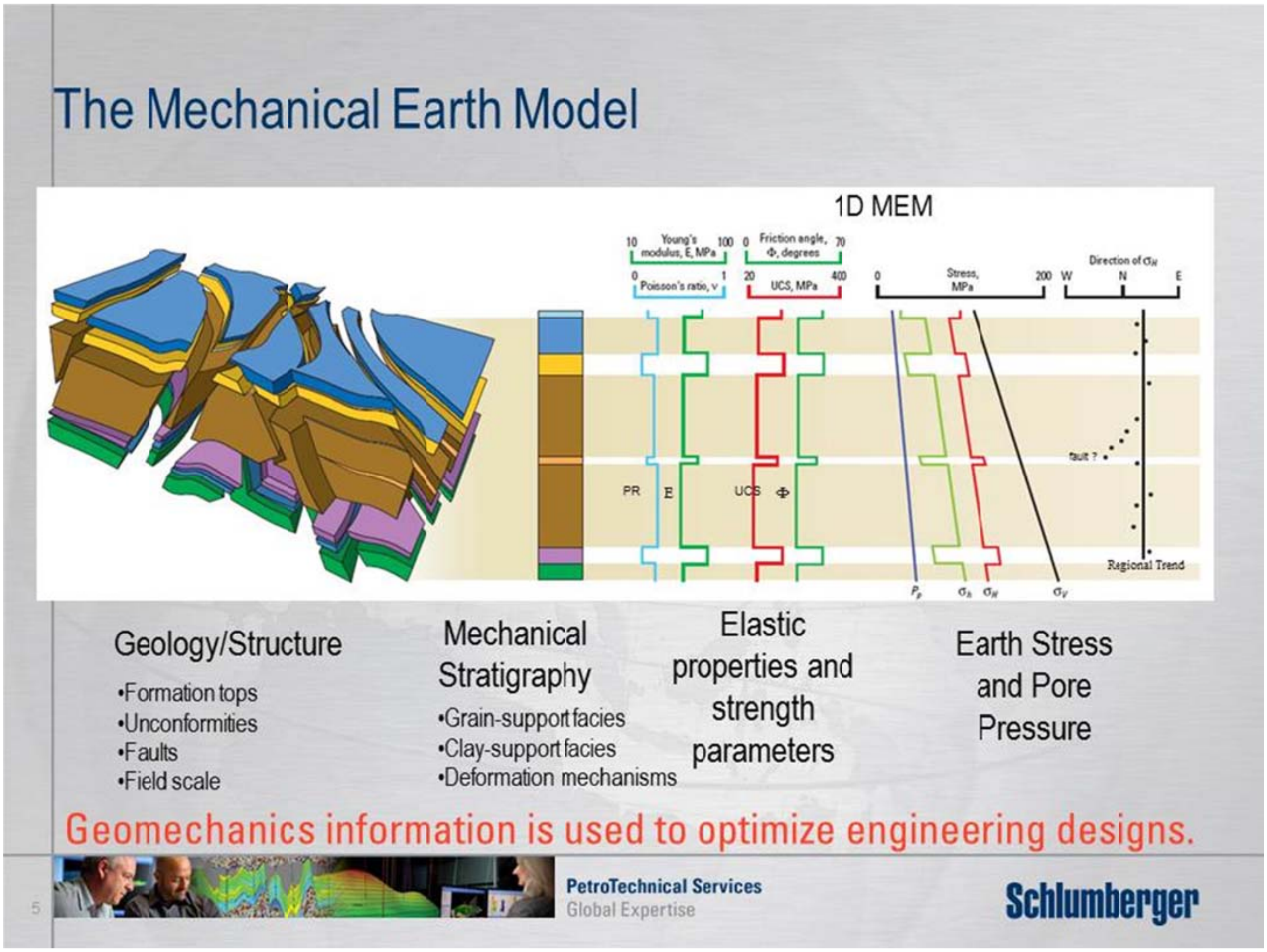
The Mechanical Earth Model
1D MEM
Young's modulus, E, MPa
Friction angle, Φ, degrees
Poisson's ratio, ν
UCS, MPa
Stress, MPa
Direction of σH
PR
E
UCS
Φ
fault ?
Regional Trend
Geology/Structure
•Formation tops
•Unconformities
•Faults
•Field scale
Mechanical Stratigraphy
•Grain-support facies
•Clay-support facies
•Deformation mechanisms
Elastic properties and strength parameters
Earth Stress and Pore Pressure
Geomechanics information is used to optimize engineering designs.
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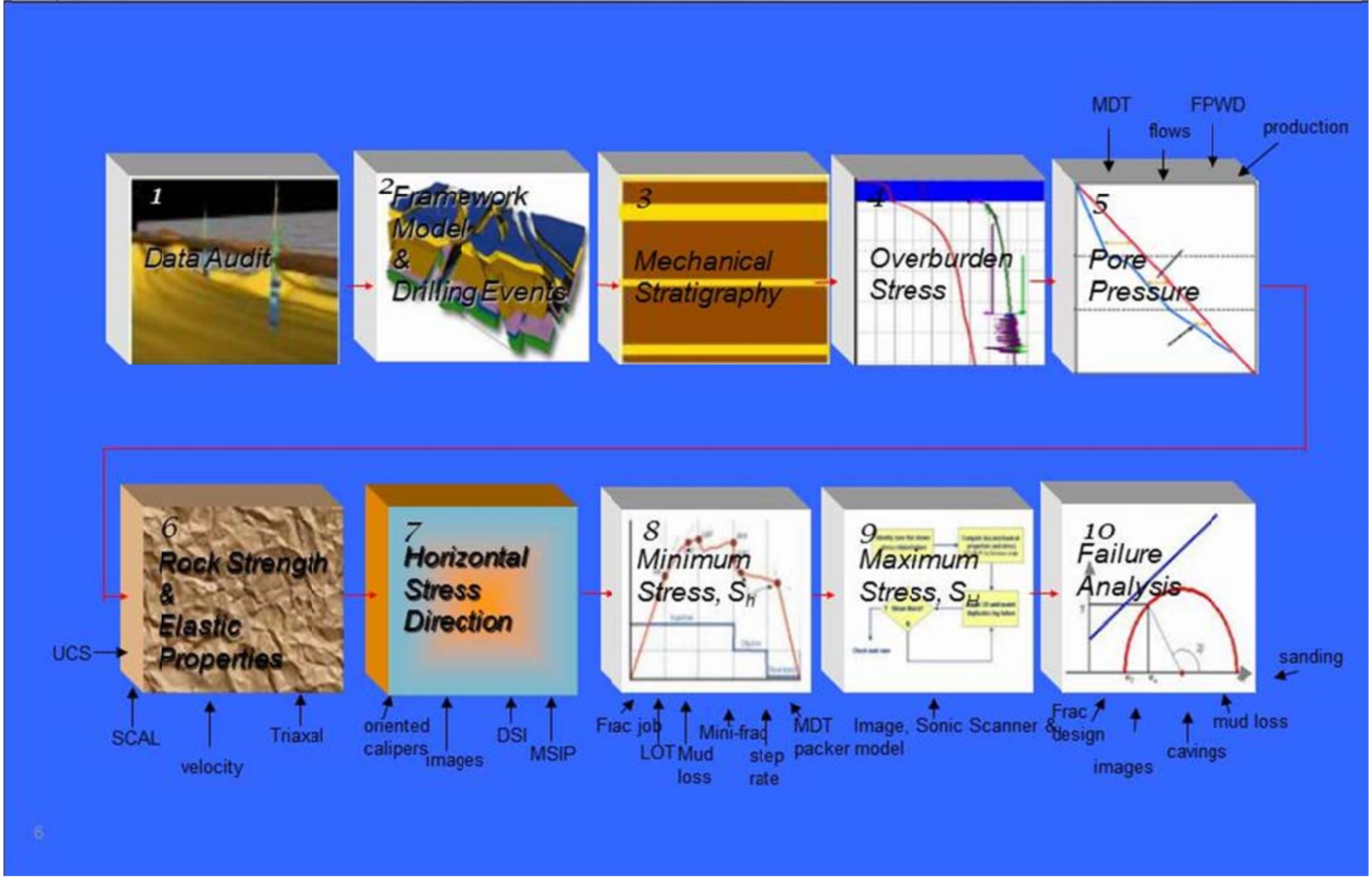
1D MEM and WBS Workflow (10 Steps)



1D Mechanical Earth Model and Wellbore Stability Analysis of Well:

VERIFICATION WELL #1 (VW1)

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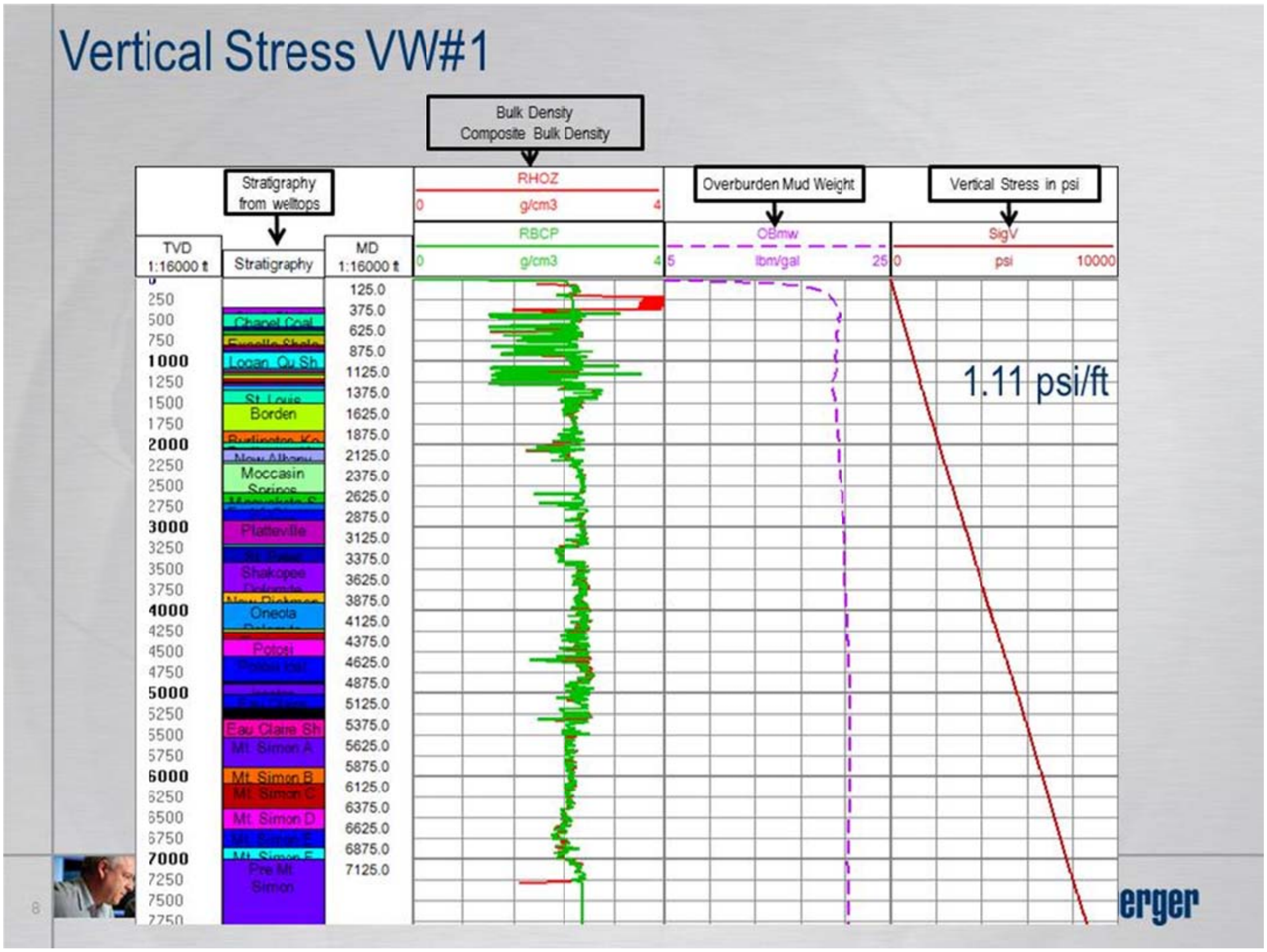
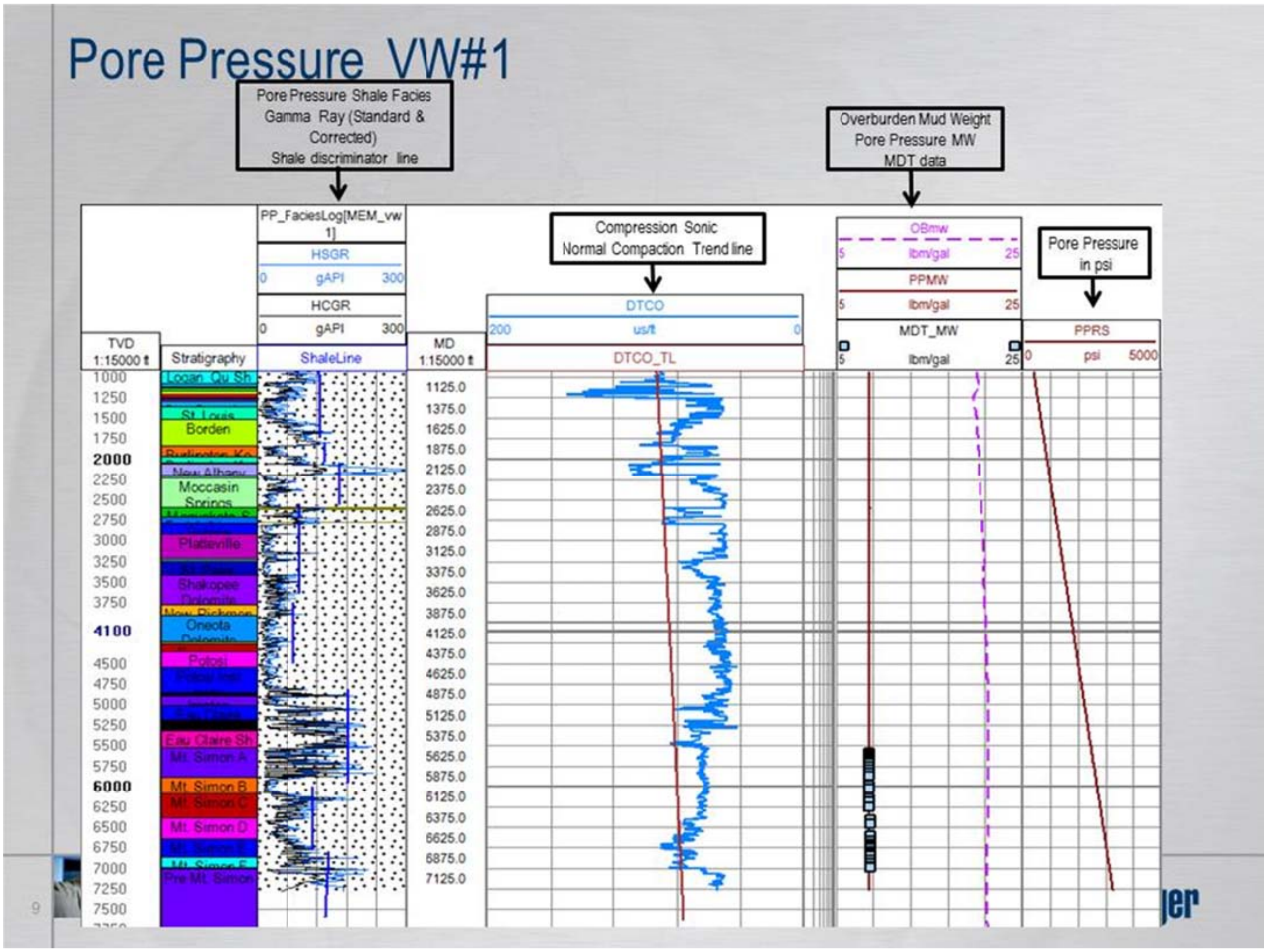
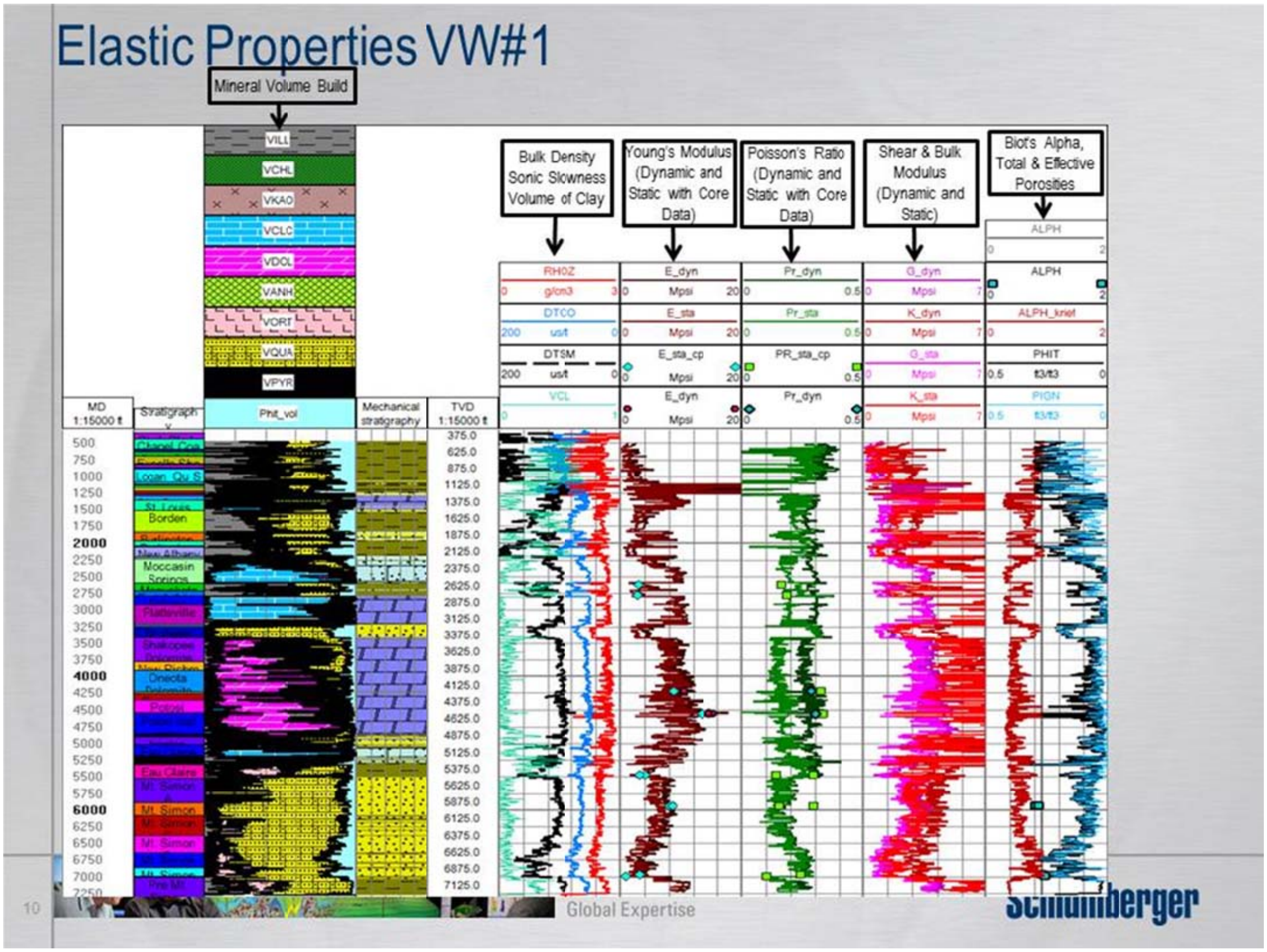


Vertical Stress VW#1
Bulk Density
Composite Bulk Density
Stratigraphy from welltops
Overburden Mud Weight
Vertical Stress in psi
TVD 1:16000 ft
Stratigraphy
MD 1:16000 ft
RHOZ
g/cm3
RBCP
g/cm3
OBmw
lbm/gal
SigV
psi
1.11 psi/ft
Chapel Coal
Logan Qu Sh
St Louis
Borden
Moccasin
Platteville
Shakopee
Oneota
Potosi
Eau Claire Sh
Mt. Simon A
Mt. Simon B
Mt. Simon C
Mt. Simon D
Pre Mt. Simon


Pore Pressure VW#1
Pore Pressure Shale Facies Gamma Ray (Standard & Corrected) Shale discriminator line
Overburden Mud Weight Pore Pressure MW MDT data
Compression Sonic Normal Compaction Trend line
Pore Pressure in psi
PP_FaciesLog[MEM_vw 1]
HSGR
HCGR
ShaleLine
DTCO
DTCO_TL
OBmw
PPMW
MDT_MW
PPRS
TVD 1:15000 ft
Stratigraphy
MD 1:15000 ft
Borden
Moccasin Springs
Platteville
Shakopee Dolomite
Oneota Dolomite
Potosi
Eau Claire Sh
Mt. Simon A
Mt. Simon B
Mt. Simon C
Mt. Simon D
Pre Mt. Simon



Elastic Properties VW#1
Mineral Volume Build
VILL
VCHL
VKAO
VCLC
VDOL
VANH
VORT
VQUA
VPYR
Phit_vol
MD 1:15000 ft
Stratigraphy
Mechanical stratigraphy
TVD 1:15000 ft
Bulk Density Sonic Slowness Volume of Clay
Young's Modulus (Dynamic and Static with Core Data)
Poisson's Ratio (Dynamic and Static with Core Data)
Shear & Bulk Modulus (Dynamic and Static)
Biot's Alpha, Total & Effective Porosities
RHOZ
DTCO
DTSM
VCL
E_dyn
E_sta
E_sta_cp
Pr_dyn
Pr_sta
PR_sta_cp
G_dyn
K_dyn
G_sta
K_sta
ALPH
ALPH_kriet
PHIT
PIGN
Borden
Moccasin Springs
Platteville
Shakopee
Oneota
Eau Claire
Mt. Simon
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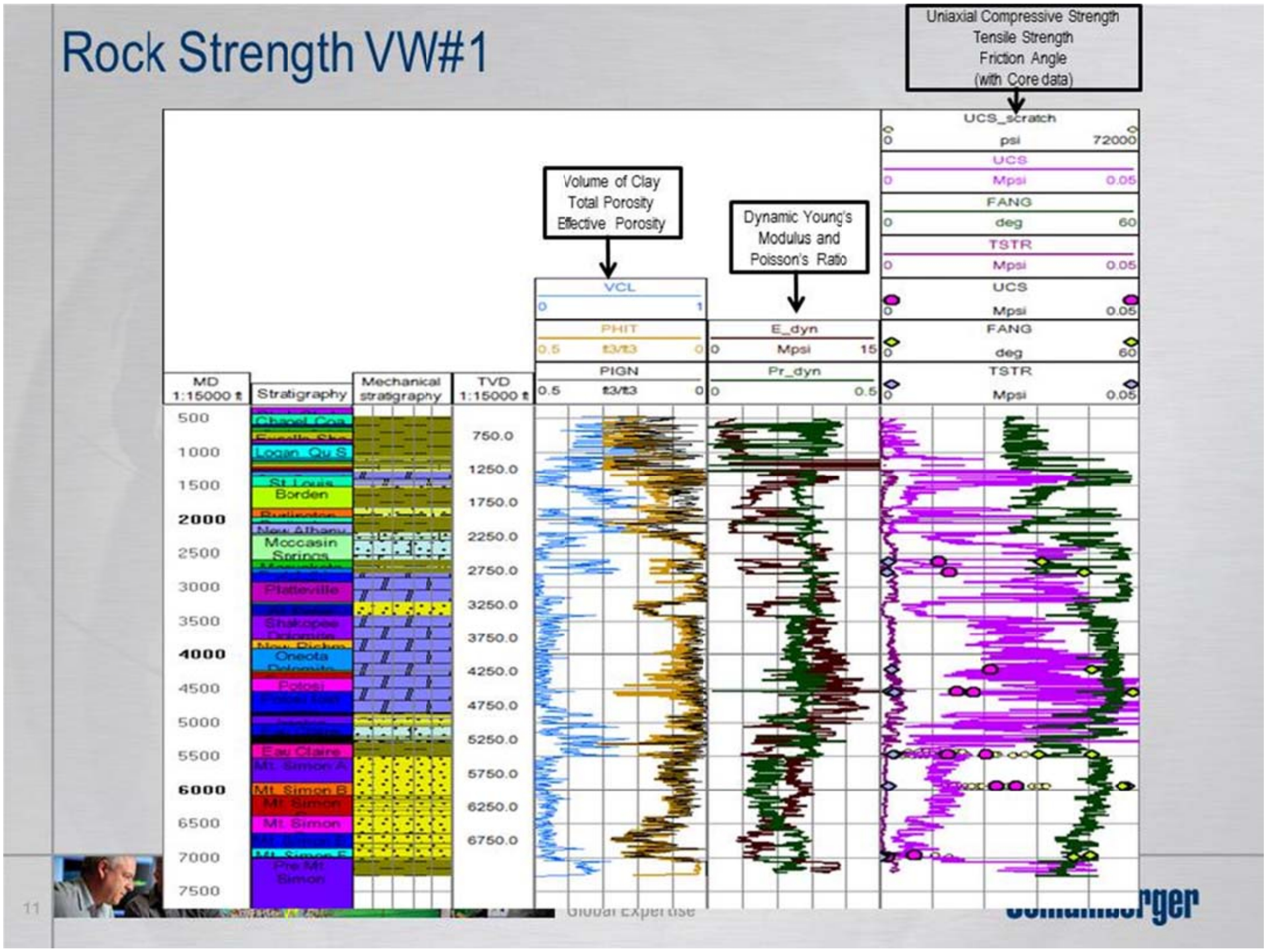
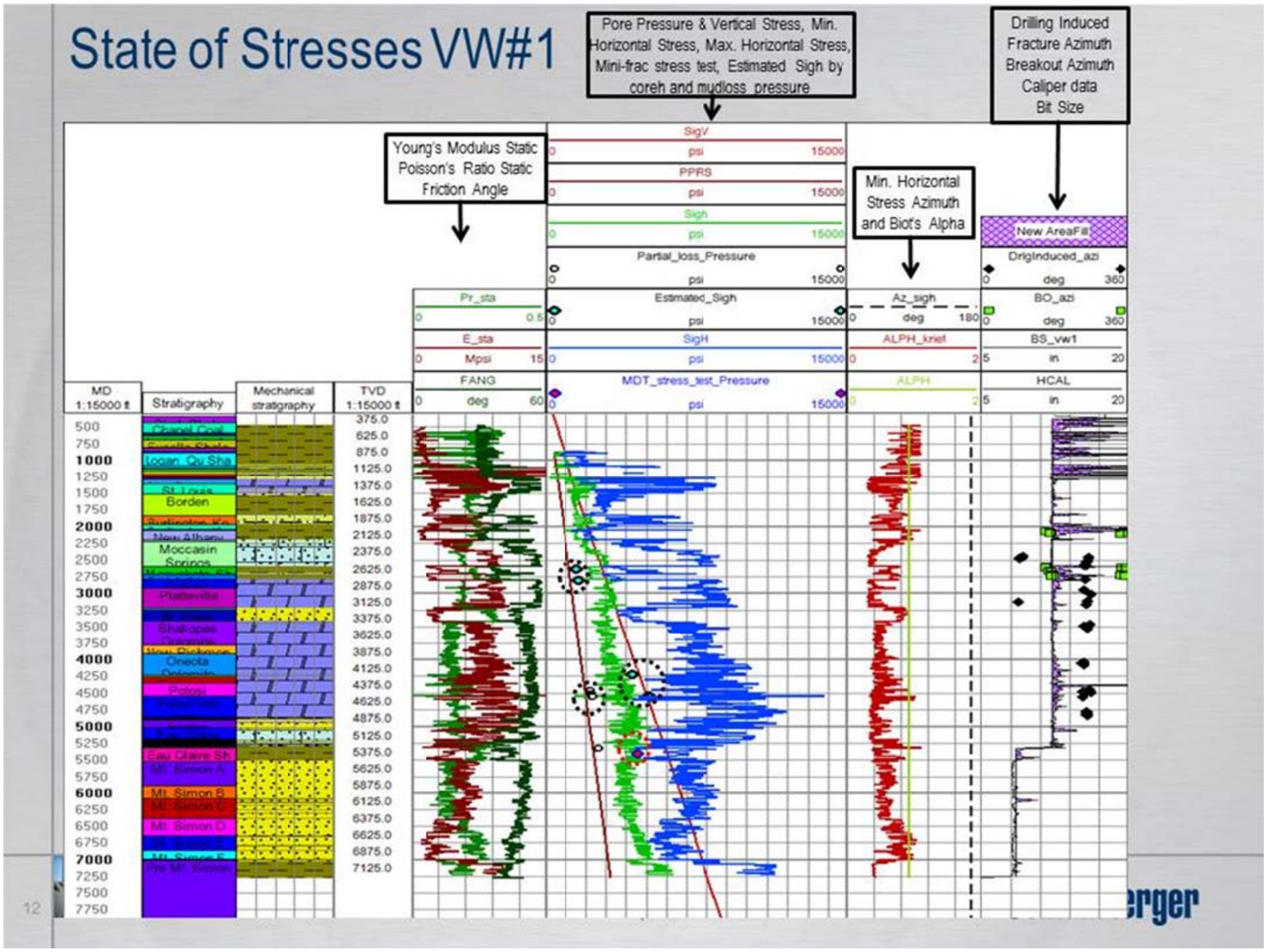
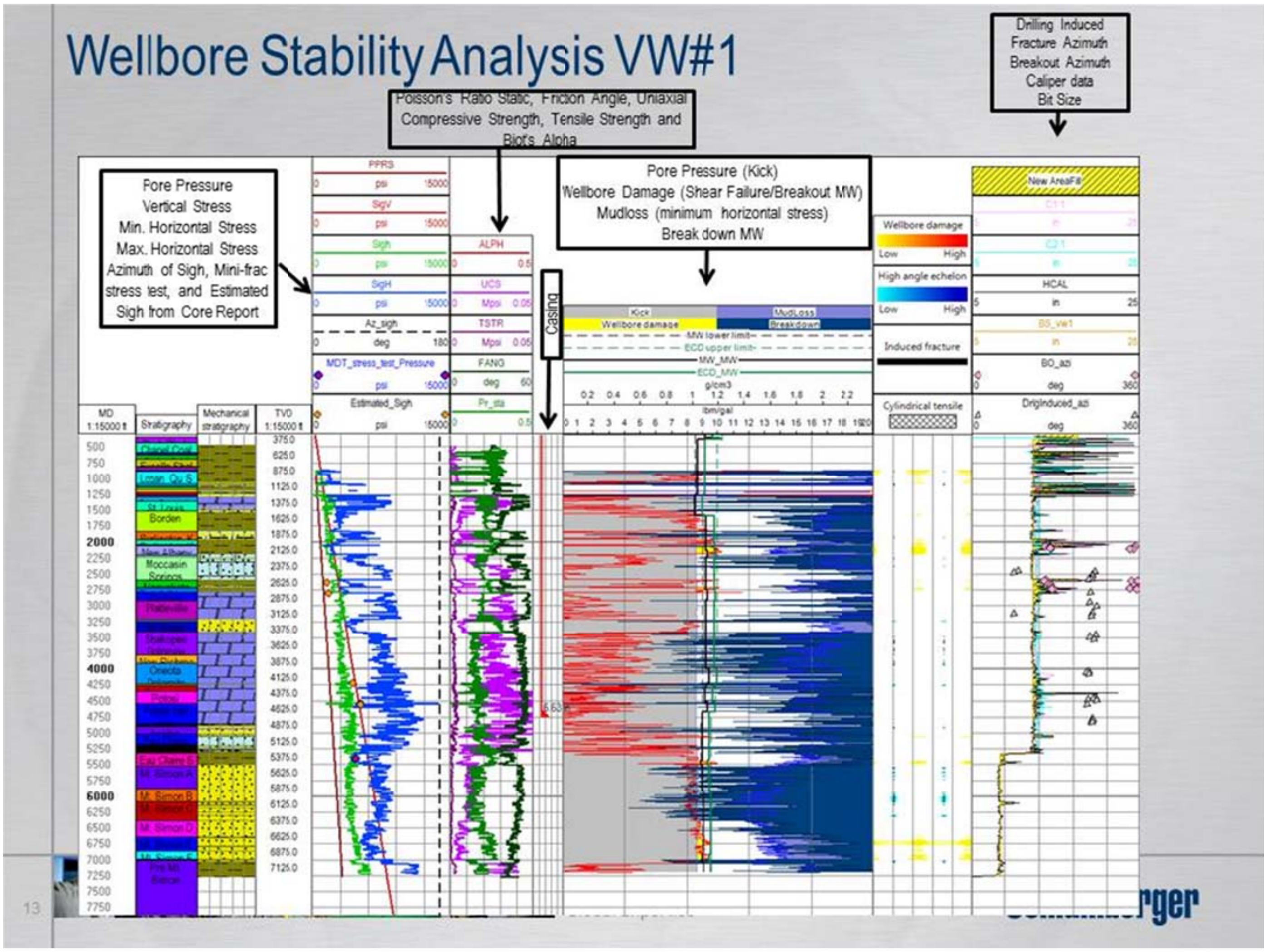
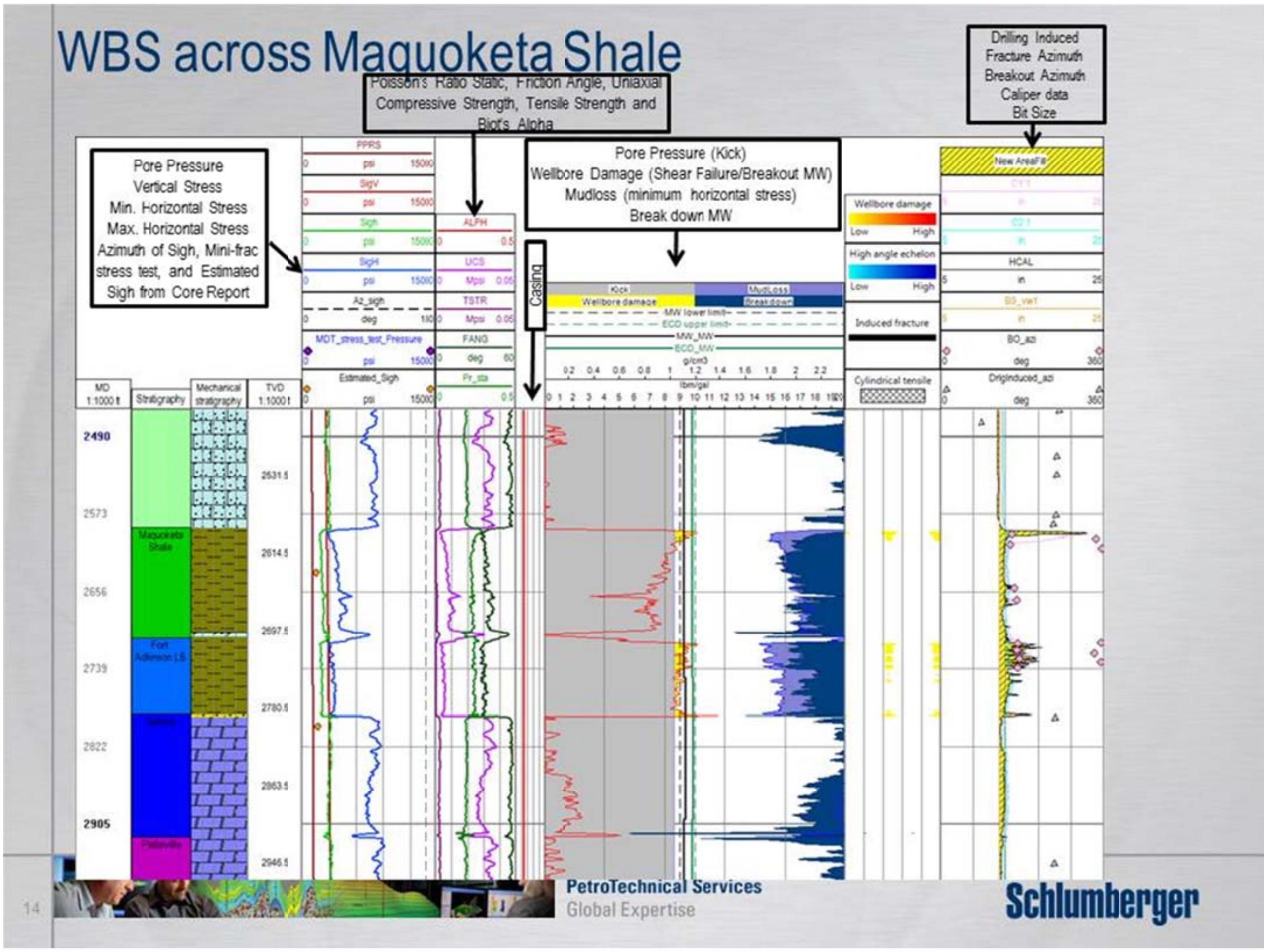

Rock Strength VW#1
Uniaxial Compressive Strength
Tensile Strength
Friction Angle
(with Core data)
Volume of Clay
Total Porosity
Effective Porosity
Dynamic Young's
Modulus and
Poisson's Ratio
UCS_scratch
psi
UCS
Mpsi
FANG
deg
TSTR
VCL
PHIT
PIGN
E_dyn
Pr_dyn
MD
1:15000 ft
Stratigraphy
Mechanical
stratigraphy
TVD
1:15000 ft
Borden
Moccasin
Platteville
Oneota
Potosi
Eau Claire
Mt. Simon A
Mt. Simon B
Mt. Simon
Pre Mt Simon


State of Stresses VW#1
Pore Pressure & Vertical Stress, Min. Horizontal Stress, Max. Horizontal Stress, Mini-frac stress test, Estimated Sigh by coreh and mudloss pressure
Drilling Induced Fracture Azimuth Breakout Azimuth Caliper data Bit Size
Young's Modulus Static Poisson's Ratio Static Friction Angle
Min. Horizontal Stress Azimuth and Biot's Alpha
SigV
PPRS
Sigh
Partial_loss_Pressure
Estimated_Sigh
SigH
MDT_stress_test_Pressure
psi
Pr_sta
E_sta
Mpsi
FANG
deg
Az_sigh
ALPH_kriel
ALPH
New AreaFill
DrigInduced_azi
BO_azi
BS_vw1
HCAL
in
MD 1:15000 ft
Stratigraphy
Mechanical stratigraphy
TVD 1:15000 ft
Borden
Moccasin Springs
Platteville
Shakopee
Oneota
Potosi
Eau Claire Sh
Mt. Simon A
Mt. Simon B
Mt. Simon C
Mt. Simon D
Pre Mt. Simon


Wellbore Stability Analysis VW#1
Drilling Induced Fracture Azimuth Breakout Azimuth Caliper data Bit Size
Poisson's Ratio Static, Friction Angle, Uniaxial Compressive Strength, Tensile Strength and Biot's Alpha
Pore Pressure Vertical Stress Min. Horizontal Stress Max. Horizontal Stress Azimuth of Sigh, Mini-frac stress test, and Estimated Sigh from Core Report
Pore Pressure (Kick) Wellbore Damage (Shear Failure/Breakout MW) Mudloss (minimum horizontal stress) Break down MW
Casing
Wellbore damage
Low
High
High angle echelon
Induced fracture
Cylindrical tensile
MD 1:15000 ft
Stratigraphy
Mechanical stratigraphy
TVD 1:15000 ft
Kick
MudLoss
Wellbore damage
Breakdown
HCAL
BO_azi
DrlgInduced_azi
Borden
Moccasin Springs
Oneota
13


WBS across Maquoketa Shale
Poisson's Ratio Static, Friction Angle, Uniaxial Compressive Strength, Tensile Strength and Biot's Alpha
Drilling Induced Fracture Azimuth Breakout Azimuth Caliper data Bit Size
Pore Pressure Vertical Stress Min. Horizontal Stress Max. Horizontal Stress Azimuth of Sigh, Mini-frac stress test, and Estimated Sigh from Core Report
Pore Pressure (Kick) Wellbore Damage (Shear Failure/Breakout MW) Mudloss (minimum horizontal stress) Break down MW
Casing
Wellbore damage
High angle echelon
Induced fracture
Cylindrical tensile
Kick
MudLoss
Wellbore damage
Breakdown
MD 1:1000 ft
Stratigraphy
Mechanical stratigraphy
TVD 1:1000 ft
Maquoketa Shale
Fort Atkinson LS
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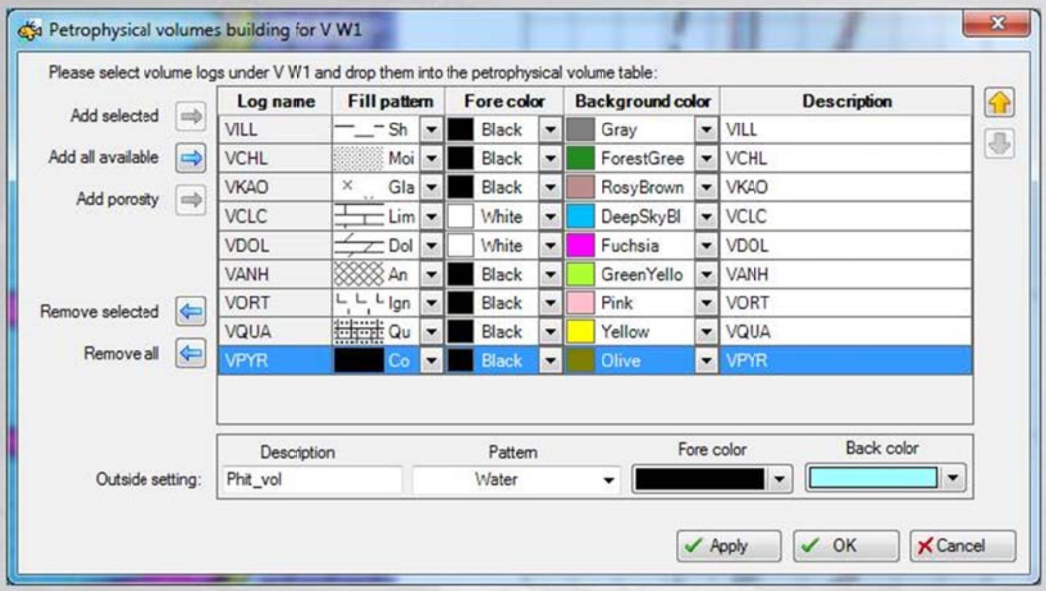
Settings for building Mineral Volume track in Petrel



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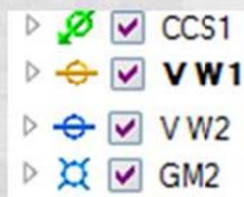
Drilling Reports Review for Drilling related Calibration Events in Offset Wells



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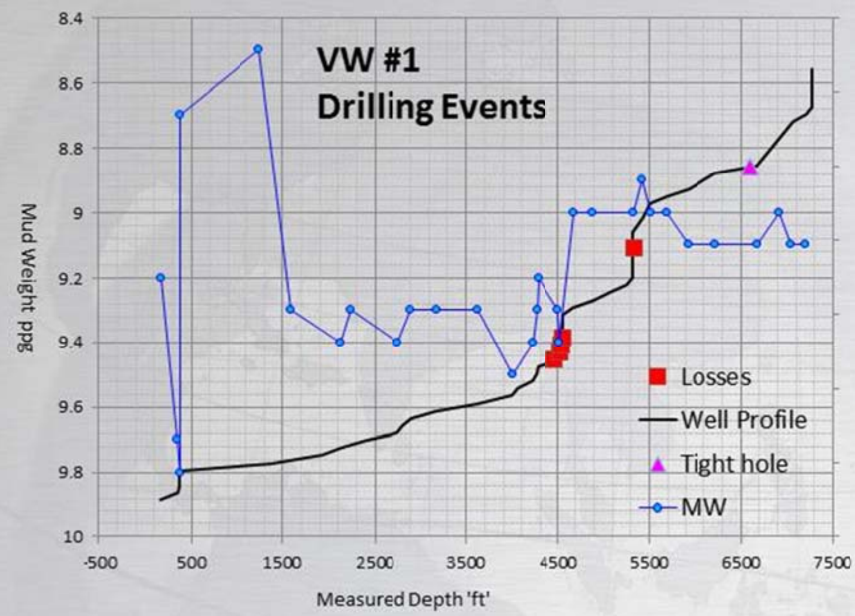
Drilling Events Review VW#1



XPT Data

95 pretests were evaluated resulting in 72 good, 4 fair, 13 low quality formation pressures

8.5+ to 8.8+ ppg

MDT mini-frac

Depth	ppg	psi	psi/ft
5408.4	16.32	4580.915	0.847

FIT = 9.3ppg at 377ft & 9.9ppg at 5320ft

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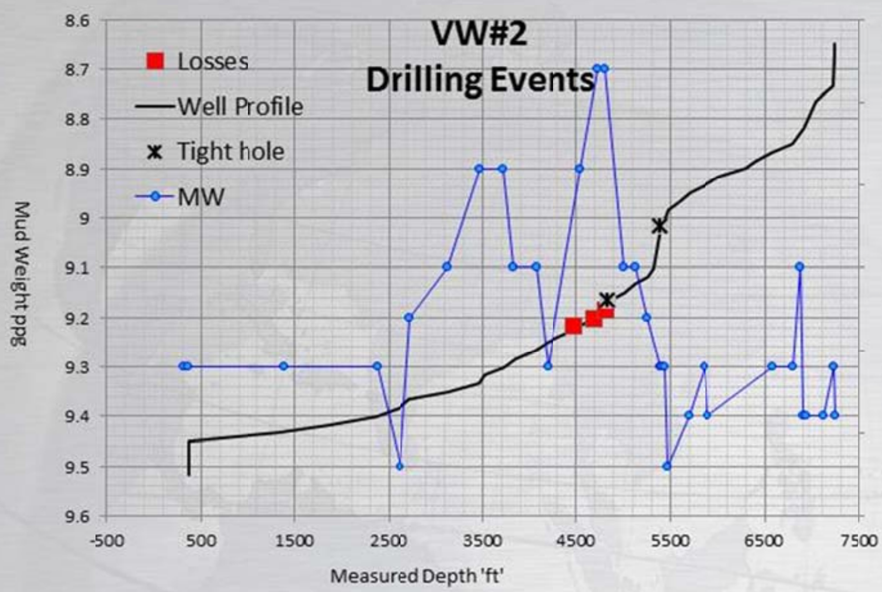
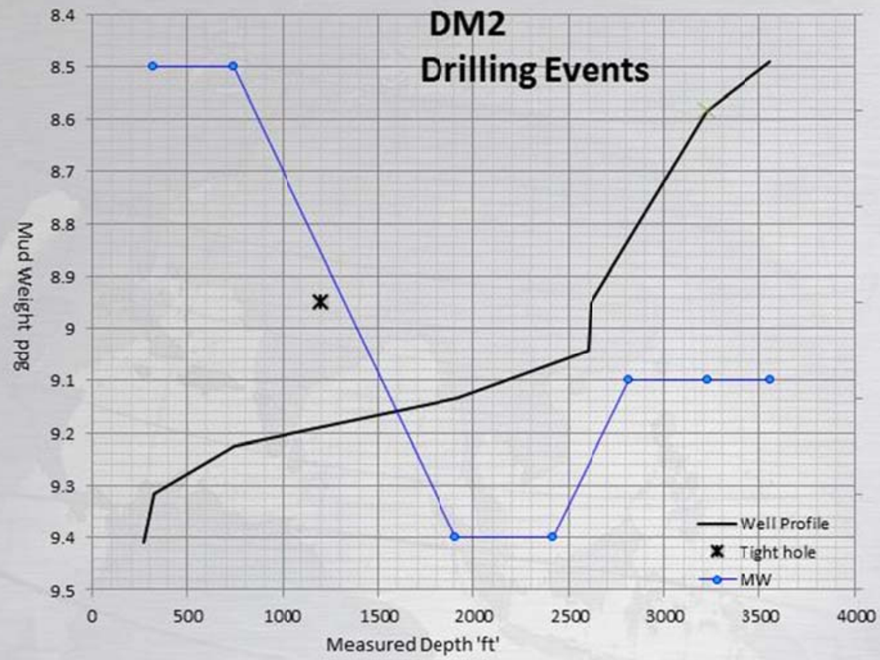
Drilling Events Review VW#2



Drilling Events Review DM#2



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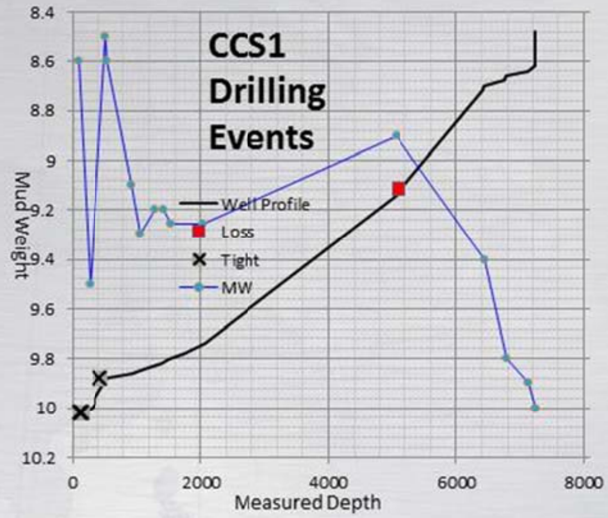
Drilling Events Review CCS#1

INJECTION TEST - FALL OFF				
Formation	Mt. Simon			
Test Interval	5560-7050			
Reservoir Pressure (psi)		3147 psi	0.566 psi/ft	Depth ft
Fracture Gradient (L. Bound)		5077.8	0.934	5435
Fracture Gradient (U. Bound)		5323.6	0.980	5435
Closure Pressure		**4603**	**0.847**	**5435**



Summary: This data indicated that for this isolated section of the Eau Claire formation, the fracture pressure is between 5077.8 PSI and 5323.6 PSI. A closure pressure was established during the fourth cycle and could be as low as 4603 PSIA (0.847 psi/ft). The fracture gradient, taking the lower bound is 5077.8/5435 = .934 PSI/ft to an upper bound of 5323.6/5435 = .9795 PSI/ft.

Overview Mini-Frac 6300 ft (Mt. Simon)

During this test, a fracture could not be initiated due to mechanical limitations of the packer mandrels of 2500 PSIA differential pressure. The only information that can be deduced from this test is that the fracture gradient for this specific interval in the Mt. Simon formation is above .95 PSI/ft.

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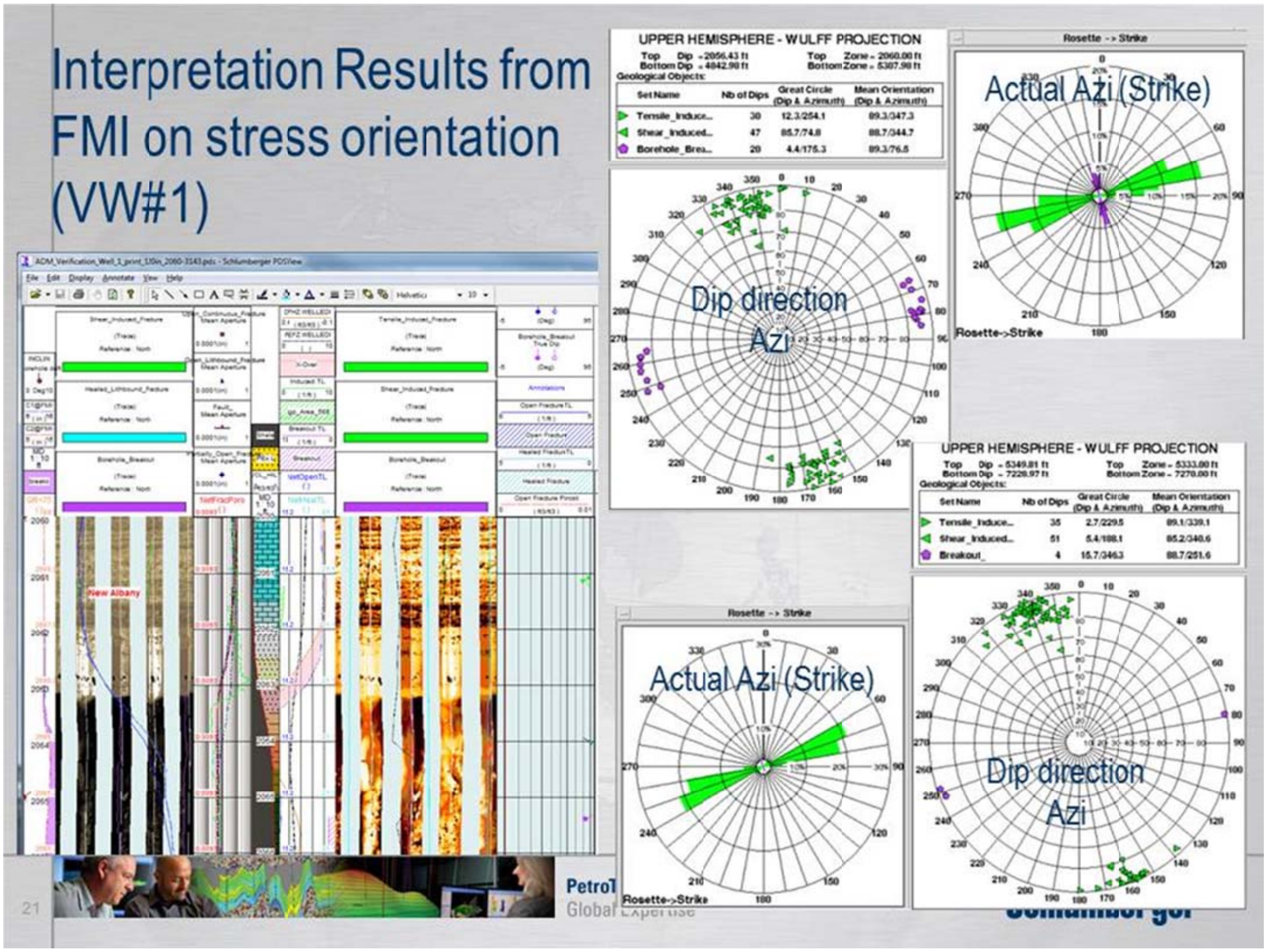
Interpretation Results from FMI on stress orientation (VW#1)
UPPER HEMISPHERE - WULFF PROJECTION
Top Dip = 2056.43 ft Bottom Dip = 4842.98 ft
Top Zone = 2060.00 ft Bottom Zone = 5307.98 ft
Geological Objects:
Set Name | Nb of Dips | Great Circle (Dip & Azimuth) | Mean Orientation (Dip & Azimuth)
Tensile_Induce... 30 12.3/254.1 89.3/347.3
Shear_Induced... 47 85.7/74.8 88.7/344.7
Borehole_Brea... 20 4.4/175.3 89.3/76.5
Dip direction Azi
Rosette -> Strike
Actual Azi (Strike)
Rosette->Strike
UPPER HEMISPHERE - WULFF PROJECTION
Top Dip = 5349.81 ft Bottom Dip = 7228.97 ft
Top Zone = 5333.00 ft Bottom Zone = 7270.00 ft
Geological Objects:
Set Name | Nb of Dips | Great Circle (Dip & Azimuth) | Mean Orientation (Dip & Azimuth)
Tensile_Induce... 35 2.7/229.5 89.1/339.1
Shear_Induced... 51 5.4/108.1 85.2/340.6
Breakout 4 15.7/346.3 88.7/251.6
Rosette -> Strike
Actual Azi (Strike)
Dip direction Azi
Rosette->Strike
New Albany
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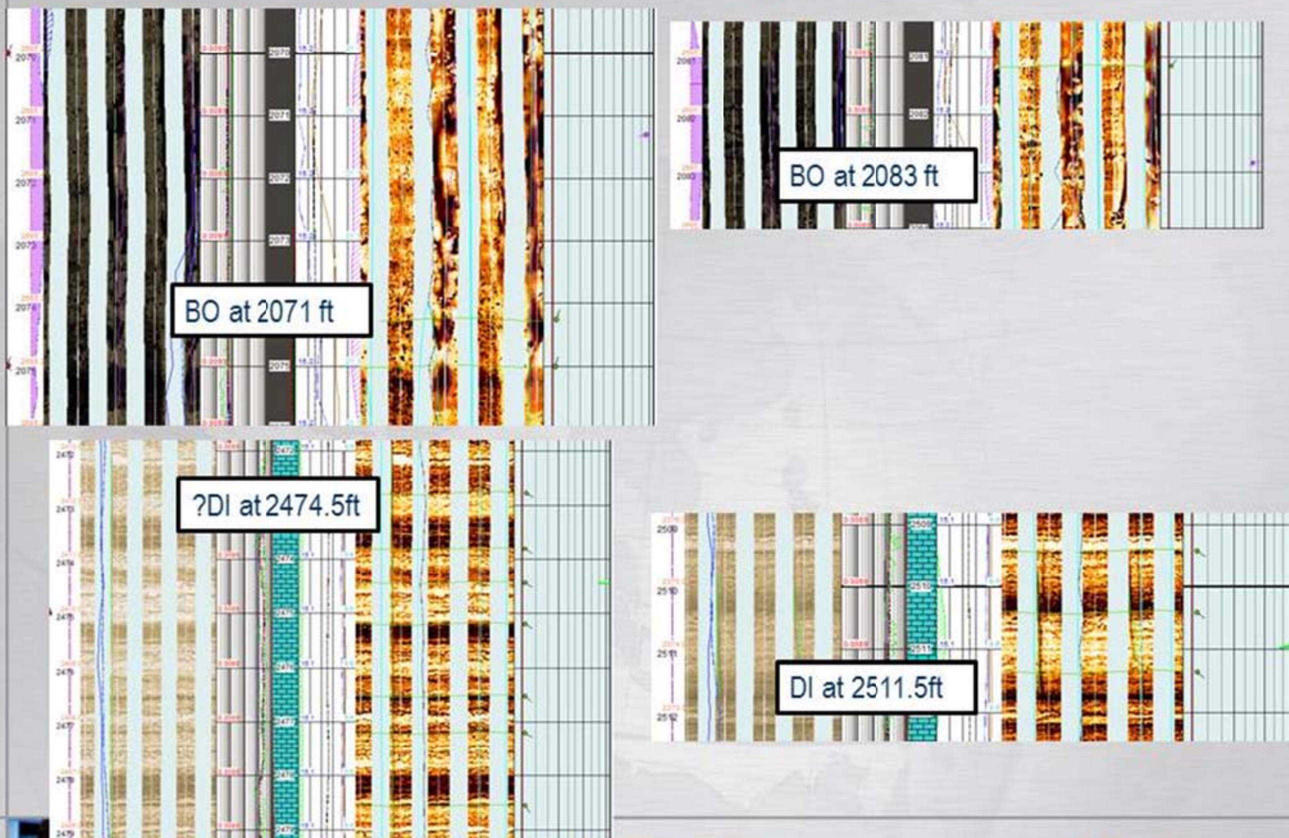
Examples of Break out and Drilling Induced Fractures



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SUMMARY

- Based on the FMI image, the minimum stress direction is (NNW-SSE) 166 deg N.
- Stress regime is predominantly strike slip with large horizontal stress anisotropy
- Minimum Horizontal stress in Maquoketa Shale ranges 2010 psi to 4030 psi (average 2410 psi).
  - Meaning, in the case that a CO2 plume reached the caprock, its pressure should not exceed 80% of the 2010 psi (i.e. 1610 psi considering 20% safety factor)
- Minimum Horizontal Stress in Potosi Limestone ranges 1420 psi to 4930 psi (average 4010 psi).
  - Meaning, there are zones in Potosi that can experience initiation and propagation of hydraulic fracture if the CO2 injection pressure exceeds 1420psi

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Going Forward and Recommendations

Assessing integrity of the Maquoketa Shale as a caprock is dynamic and 4D reservoir geomechanics issue. A 1D MEM results provide a static lower limit above which tensile failure in the caprock can occur breaching its mechanical as well as hydraulic integrity. 1D MEM is building block for carrying out such coupled and integrated reservoir, geology and geomechanical simulation study. Therefore, to achieve a tangible and realistic prediction on the integrity of the Maquoketa Shale as a caprock, a variable CO2 injection scenario approach is needed:

1) Construct 1D MEM for all the offset wells
2) Construct and integrate with 3D Geological Model
3) Construct and Discrete Fracture Network model and integrate with the 3D Geological Model
4) Using Seismic data and inversion for optimal properties distribution of all the reservoir, petrophysical and geomechanical properties into 3D

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Going Forward and Recommendations (contd.)

5) Construct Eclipse simulation model and 3D Geomechanical model

6) Run 4D Reservoir Geomechanics simulation at planned injection scenarios to dynamically simulate with time and analyze whether the integrity of the caprock would be breached or not.

For any planned well or existing well following data acquisition is essential to help in assessment of the caprock:

1) Pex data with preferably Sonic Scanner at least across the caprock and target reservoir/s.
2) Mini-frac stress test or MDT mini-frac at caprock and reservoir zones &/or LOT/XLOT at the casing shoe
3) Triaxial tests on core of caprock and target reservoir (unconfined and confined)

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Glossary of Acronyms

UCS: Uniaxial or Unconfined Compressive Strength
TSTR: Tensile Strength
MEM: Mechanical Earth Model
1D: One dimensional
3D: Three dimensional
4D: Four dimensional
CRI: Caprock Integrity
CO2: Carbon Dioxide
E_dyn: Dynamic Young's Modulus (point data are core measured)
PR_dyn: Dynamic Poisson's Ratio (point data are core measured)
E_sta: Static Young's Modulus (point data are core measured)
PR_sta: Static Poisson's Ratio (point data are core measured)
Rhoz: Bulk density
RBCP: Composite bulk density (actual and missing/corrected data combined)
OBmw: Overburden mud weight
SigV: Vertical stress
Sigh: Minimum horizontal stress
SigH: Maximum horizontal stress
MD: Measured Depth
TVD: True Vertical Depth
PPMW: Pore Pressure in mud weight units
PPRS: Pore Pressure in pressure units
MDT_MW: Modular Dual Tester measure pore pressure in MW units
HSGR/HCGR: Gamma Ray Standard and Corrected
DTCO: Compressional Sonic
DTSM: Shear Sonic
DTCO_TL: Normal compaction trend line for DTCO
E_sta_cp: Core measured Static Young's Modulus with confining pressure
PR_sta_cp: Core measured Static Poisson's Ratio with confining pressure
G_dyn: Dynamic Shear Modulus
K_dyn: Dynamic Bulk Modulus
G_sta: Static Shear Modulus
K_sta: Static Bulk Modulus
ALPH: Biot's Alpha Constant (point data are core measured)
ALPH_krief: Biot's Alpha constant using Krief's correlation
PHIT: Total porosity
PHIG: Effective porosity
ppg: Pounds Per Gallon
UCS_scratch: UCS measure using scratch test on cores
FANG: Friction Angle
Partial_loss_Pressure: Mud losses pressure
Estimated_Sigh: Sigh estimated as reported in the core analysis report
MDT_stress_test_Pressure: Minifrac-Falloff closure stress measurement
BS_vw1: Bit Size (hole sizes) used in VW#1 well
DrlgInduced_azi: Drilling induced azimuth data from FMI interpretation
BO_azi: Breakout azimuth from the FMI interpretation
HCAL: Caliper data
C11 and C12: Additional Caliper data
Az_sigh: Sigh azimuth
VCL: Volume of Clay