Schlumberger Carbon Services

Quantification of Wellbore Leakage Risk Using Non-destructive Borehole Logging Techniques

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Presented by Dwight Peters, North America Business Manager

Carbon Storage R&D Project Review Meeting Developing the Technologies

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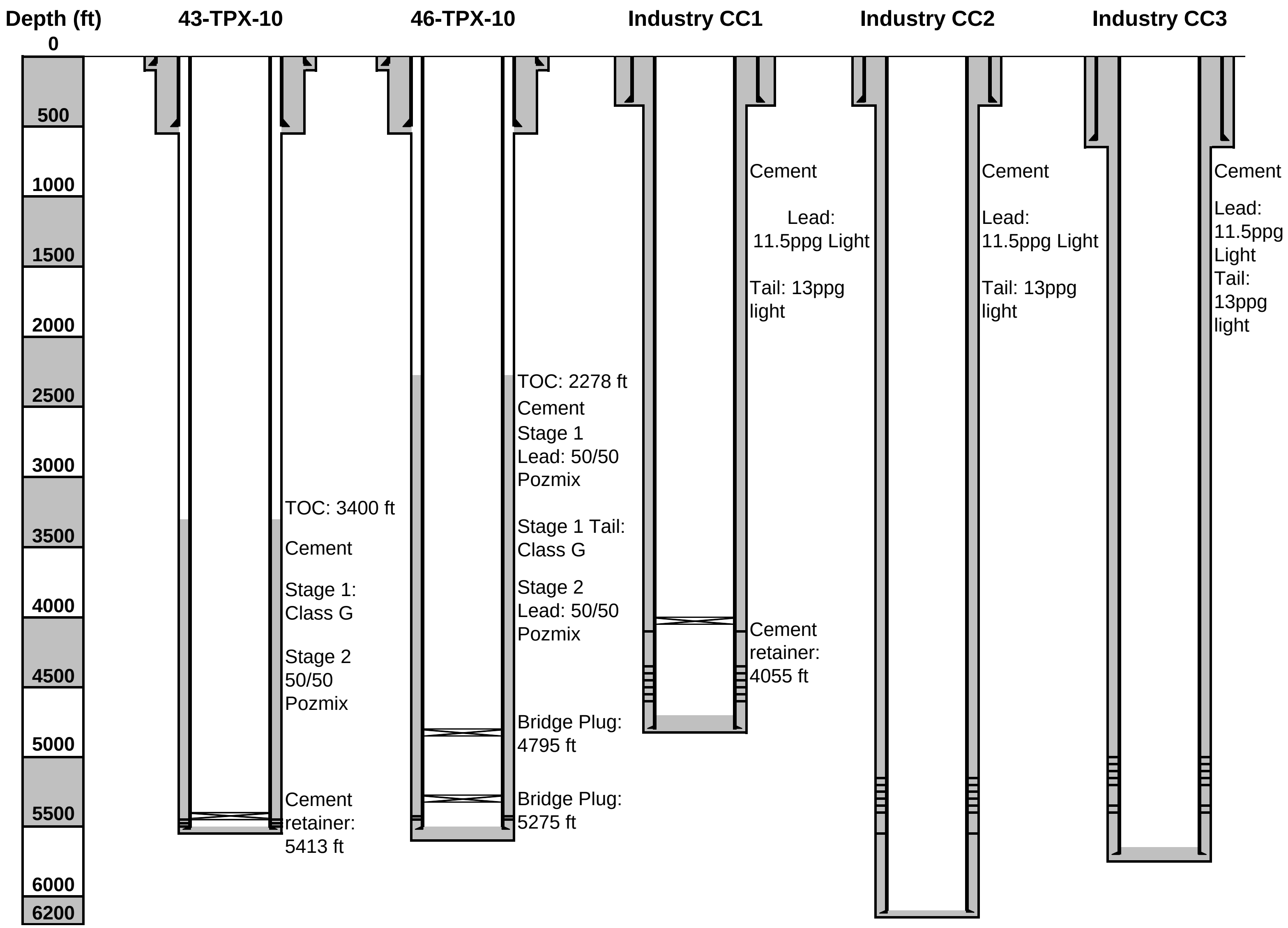
Outline

- Site Information
- Background
- Project Objectives
- Field Work
- Samples, Analysis, and Modeling
- Summary

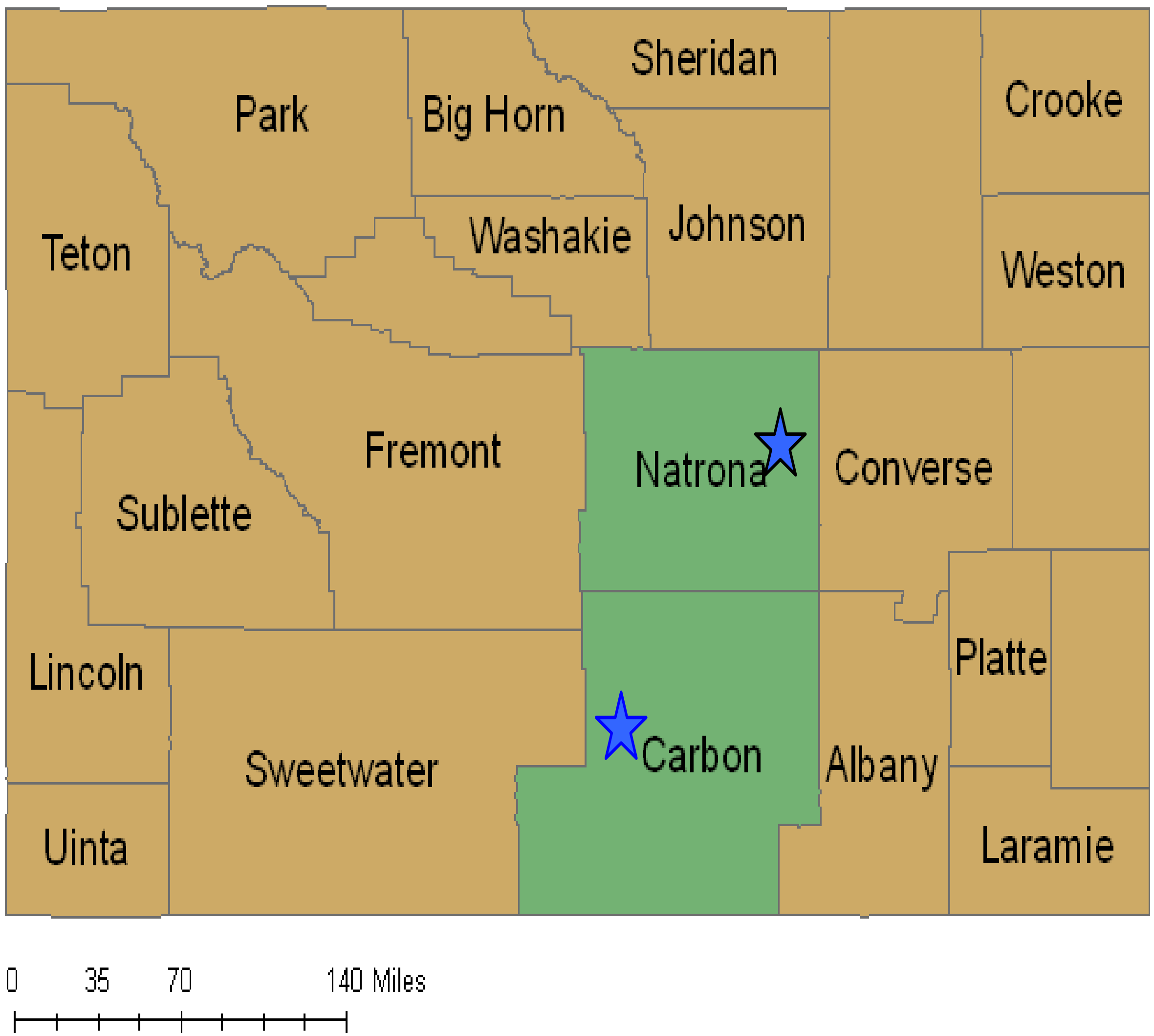
Study Objectives

- Establish average flow parameters (porosity/permeability/mobility) from individual material properties measurements and defects in a well.
- Investigate correlations between field flow-property data and cement logs – used to establish flow-properties of well materials and well features using cement mapping tools.
- Establish a method that uses the flow-property model to analyze the statistical uncertainties associated with individual well leakage to provide basis for risk calculation uncertainty.

Project Wells

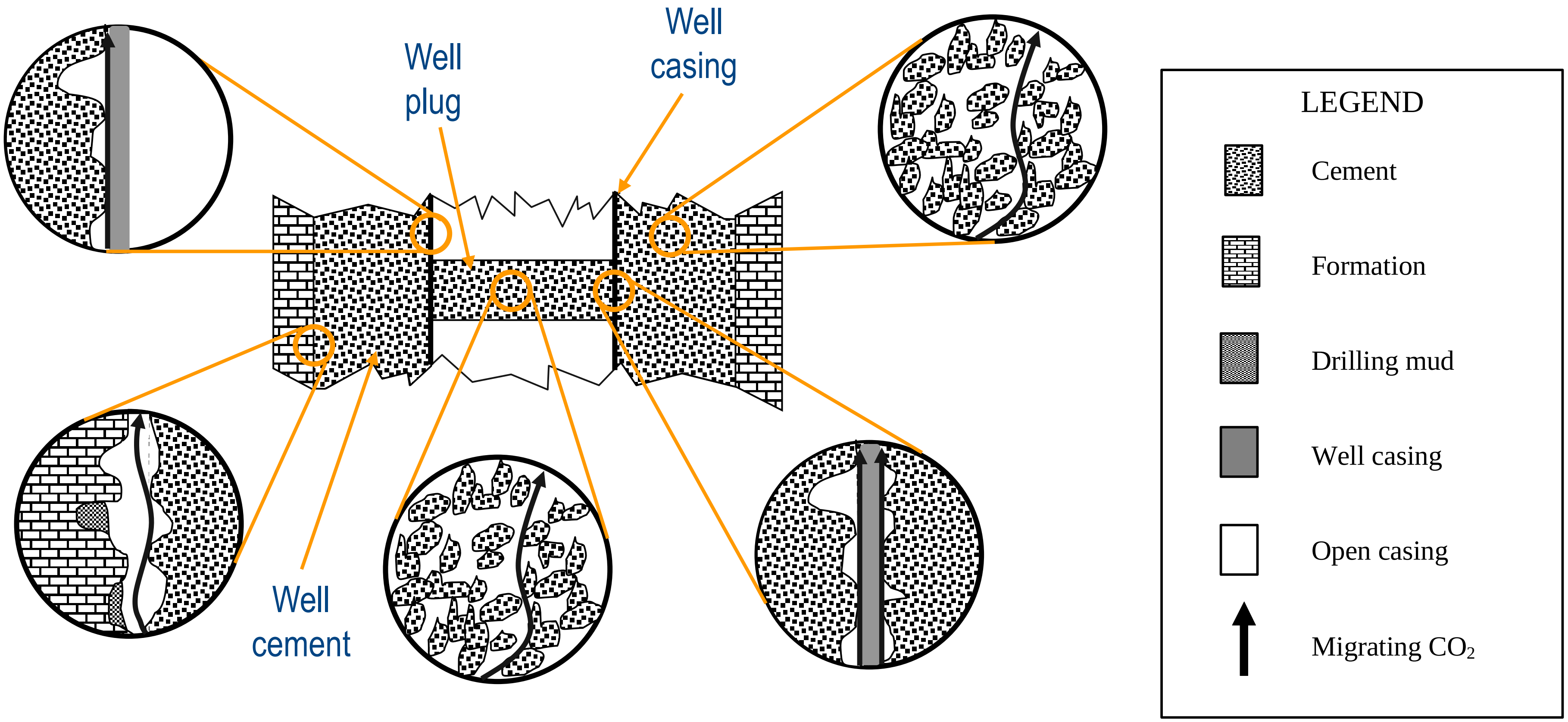


Well Sites



Sheridan
Park
Big Horn
Crooke
Teton
Washakie
Johnson
Weston
Fremont
Natrona
Converse
Sublette
Platte
Lincoln
Carbon
Sweetwater
Albany
Uinta
Laramie
0
35
70
140 Miles

Potential Avenues for Leakage



Background: Typical Well Cement Composition

Unhydrated

Phase	Percent
$3CaO \bullet SiO_2$	50
$2CaO \bullet SiO_2$	30
$3CaO \bullet Al_2O_3$	5
$4CaO \bullet Al_2O_3 \bullet Fe_3O_3$	12

Hydrated

Phase	Abbreviation	Percent
$Ca_3Si_2O_7 \bullet 4H_2O$	C-S-H	50-70
$Ca(OH)_2$	CH	20-25
$3(3CaO \bullet Al_2O_3 \bullet CaSO_4 \bullet 12H_2O)$	AFm	10-15
$4CaO \bullet (Al,Fe_2O_3) \bullet 13H_2O$	AFt	

Data from Nelson, 1990

Background: Cement Degradation Reactions

Ca(OH)2 dissociation

$$Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^-$$

May open up new porosity

CO2 dissociation

$$CO_2 + H_2O \leftrightarrow H_2CO_3^* \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

Cement dissolution

$$Ca(OH)_2(s) + 2H^+ + CO_3^{2-} \rightarrow CaCO_3(s) + 2H_2O$$

$$Ca_3Si_2O_7H \bullet 4H_2O(s) + 2H^+ + CO_3^{2-} \rightarrow CaCO_3(s) + SiO_xOH_x(s)$$

$$Ca(OH)_2(s) + H^+ + HCO_3^- \rightarrow CaCO_3(s) + 2H_2O$$

$$Ca_3Si_2O_7H \bullet 4H_2O(s) + H^+ + HCO_3^- \rightarrow CaCO_3(s) + SiO_xOH_x(s)$$

Precipitation of $CaCO_3$ blocks connected pores and reduces permeability

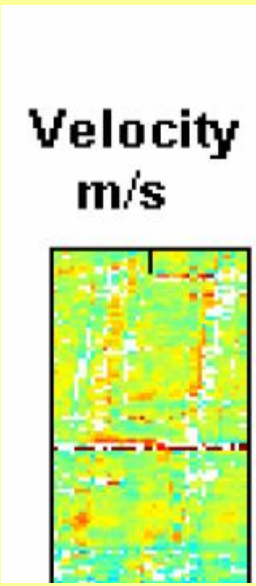
Calcium carbonate dissolution

$$CO_2 + H_2O + CaCO_3(s) \leftrightarrow Ca^{2+} + 2HCO_3^-$$

$$2H^+ + CaCO_3(s) \leftrightarrow CO_2 + Ca^{2+} + H_2O$$

Opens pores blocked by $CaCO_3$ precipitation and additional porosity created by the dissolution of cement reaction products

Create Flow Property Maps from Cement Maps



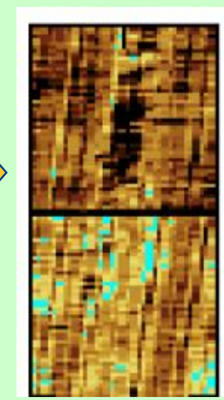
Log and Lab Measurements

Plug into:

$$k = \frac{d^2}{32b}\frac{\Delta V_L}{V_{L0}}$$

$$p = \frac{1}{b}\left(1 - \frac{V_L}{V_{L0}}\right)$$

Permeability / Porosity



Flow Property Map

k=permeability

V_L=longitudinal acoustic velocity

d=capillary tube diameter

E=Young's Modulus

ν =Poisson's Ration

p =Porosity

Note: the subscript 0 denotes 0-porosity cement

$$b = 15\frac{1-\nu_0}{7-5\nu_0}$$

Data Collection

<u>Logging Tools</u>

Isolation Scanner* cement evaluation service

Sonic Scanner* acoustic scanning platform

SCMT* slim cement mapping tool

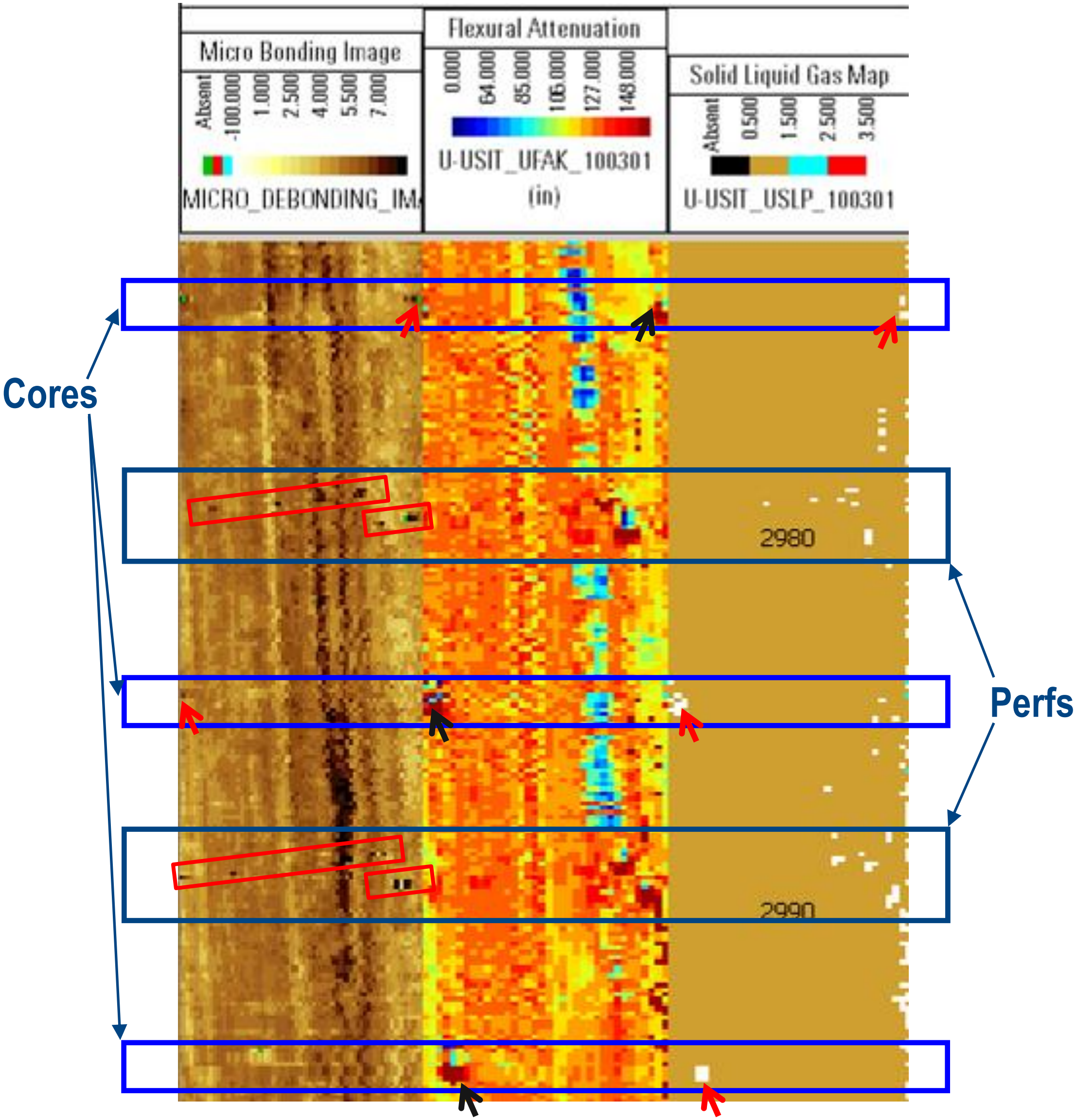
<u>Testing and Sampling Tools</u>

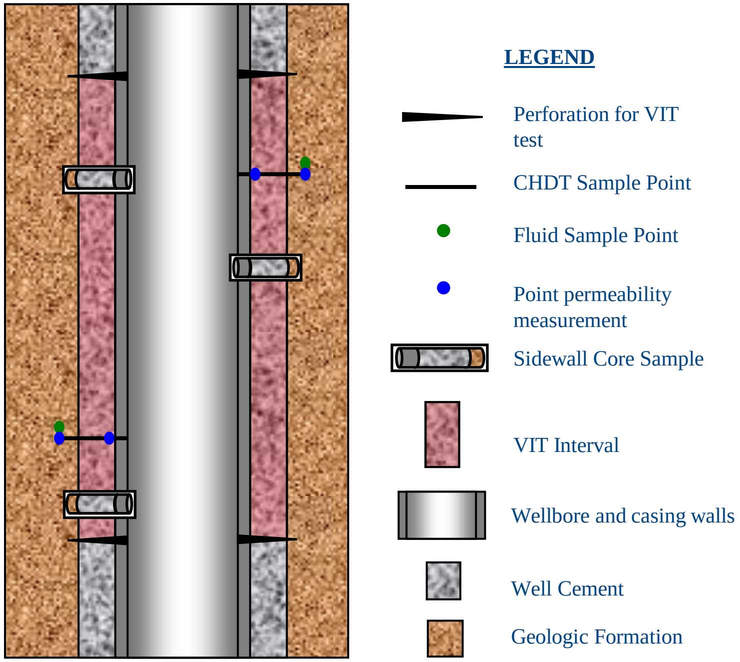
CHDT* cased hole dynamics tester

MDT* modular formation dynamics tester

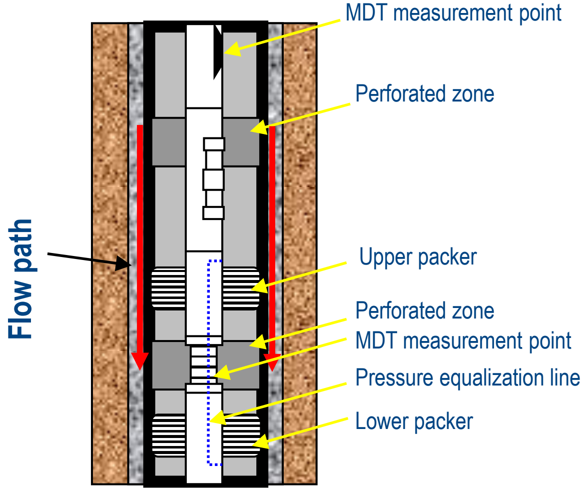
MSCT* mechanical sidewall coring tool

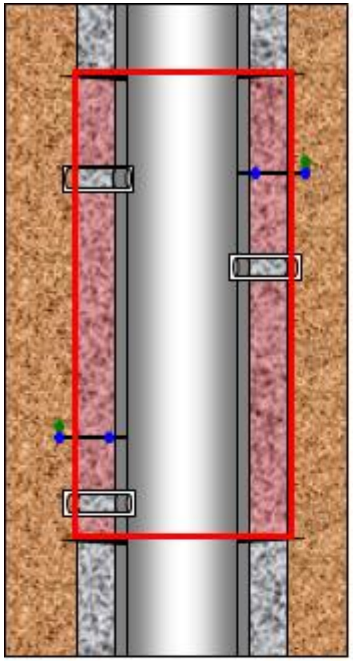
Well Logging and Sampling



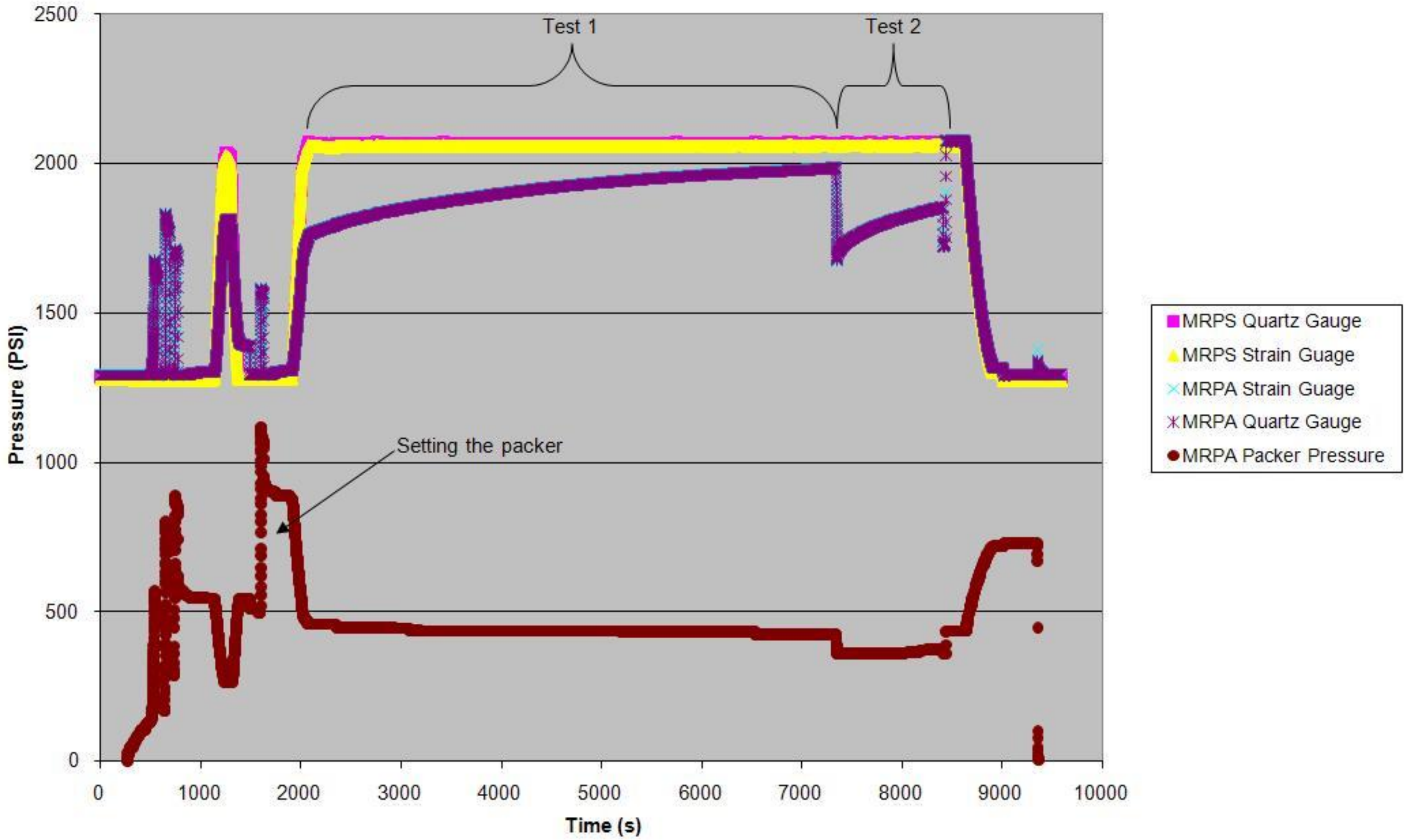


Well Sampling – MDT

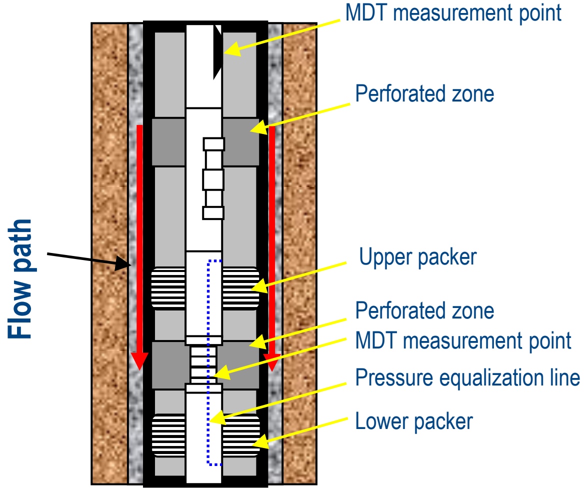


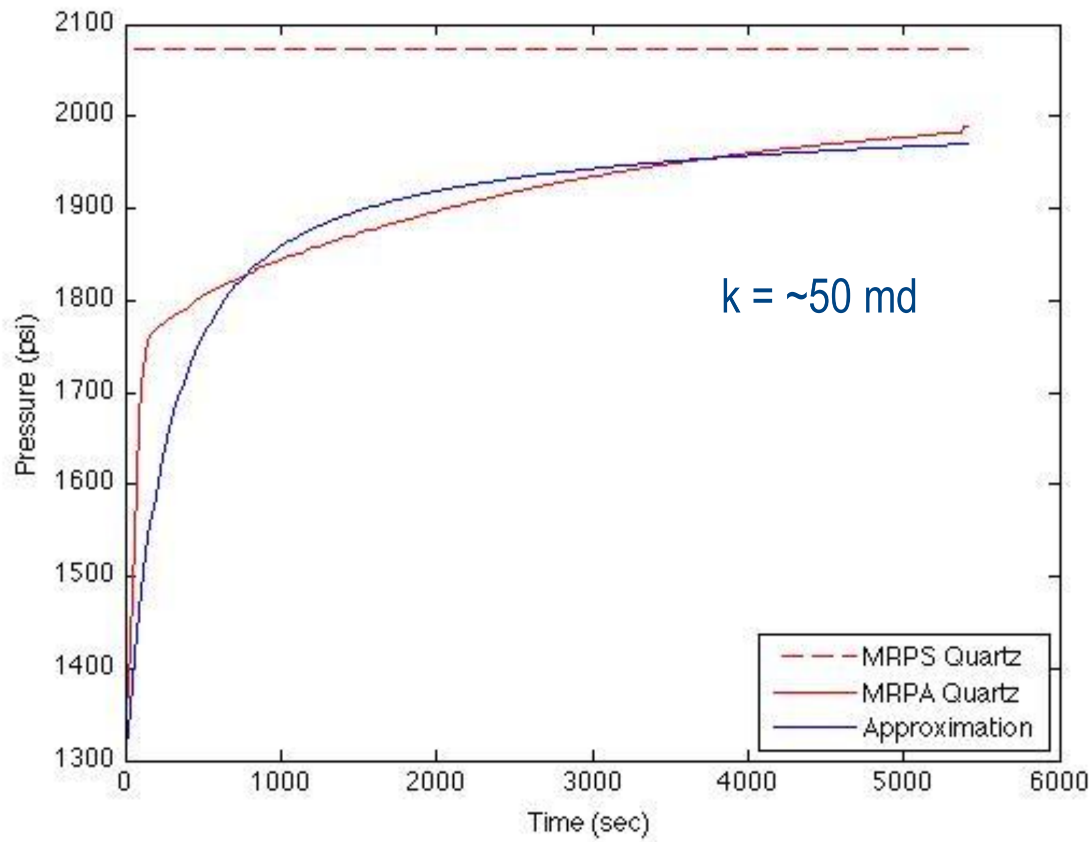


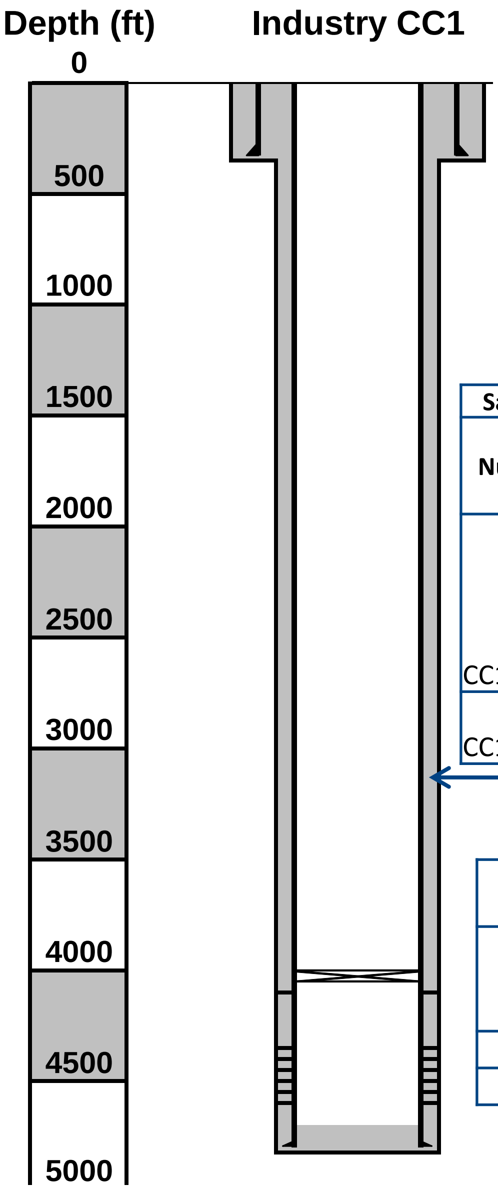
MDT Data


Test 1
Test 2
Setting the packer
Pressure (PSI)
Time (s)
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
MRPS Quartz Gauge
MRPS Strain Guage
MRPA Strain Guage
MRPA Quartz Gauge
MRPA Packer Pressure

MDT Analysis







CC1
3150 feet

Field Photo

Sample Number	Material	Sample Depth (ft)	Sample Length (in)	Sample Diameter (in)	Ambient Porosity (%)	Dry Bulk Density (g/cc)	Grain Density (g/cc)	Gas Permeabili ty (md)	NOB Stress (psi)	Comments
CC1-3B	Formation	3150	0.726	0.894	9.65	2.339	2.588	N/A	400	poor dimensions, two pieces, uneven
CC1-3A	Cement	3150	0.685	0.873	63.49	0.832	2.278	1.44	400	broke in hassler

3150 ft Lewis Shale(Casing, Cement, Mud, Formation)

Sample Number	Material	As-Tested Density (g/cm^3)	P-Wave Velocity (ft/s)	S-Wave Velocity (ft/s)	Poisson's Ratio	Young's Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Shear Modulus (10^6 psi)

Well Sampling – MSCT

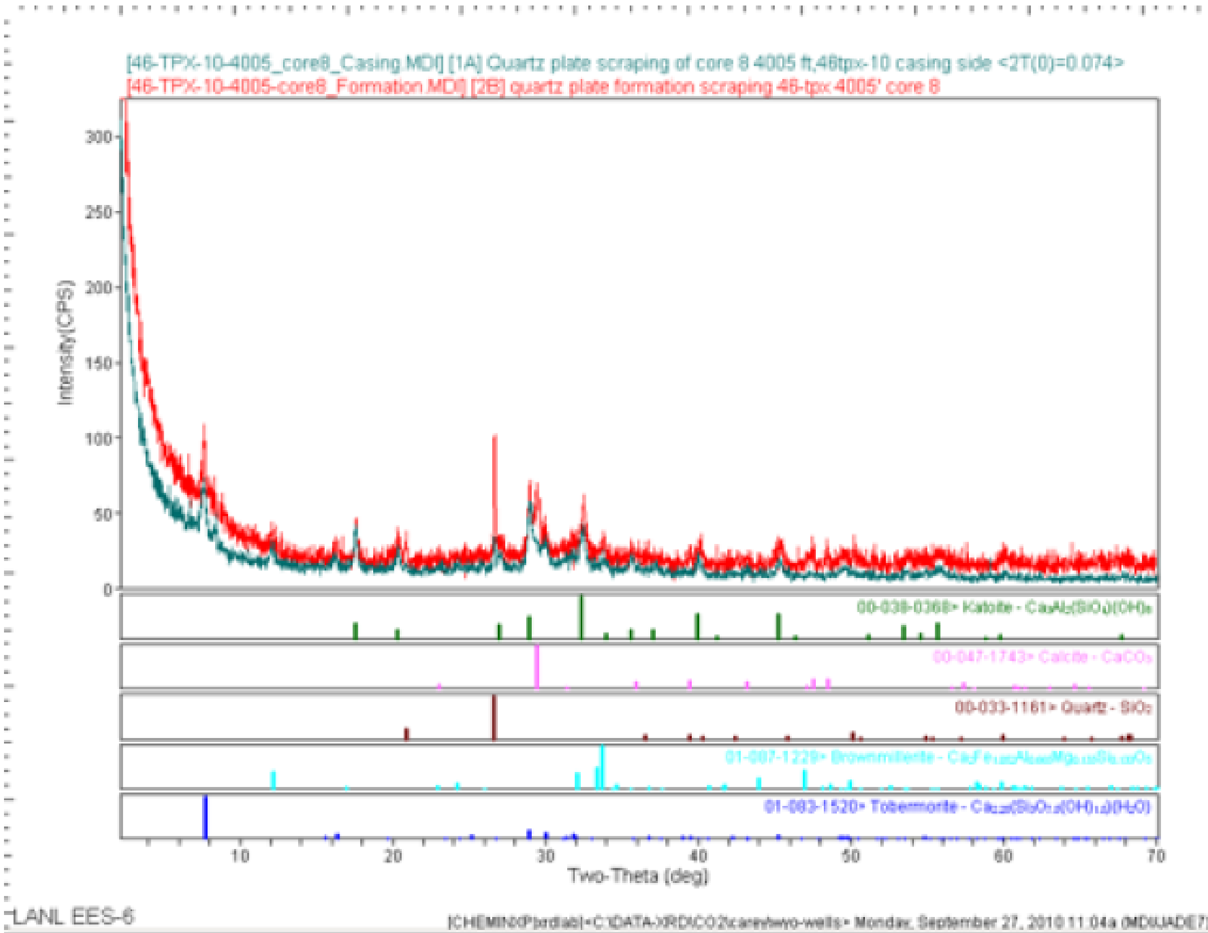
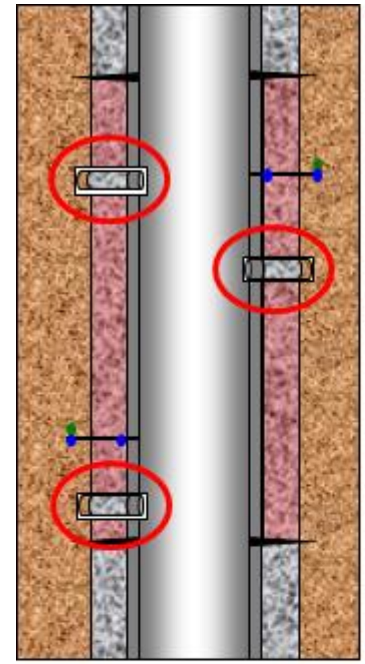
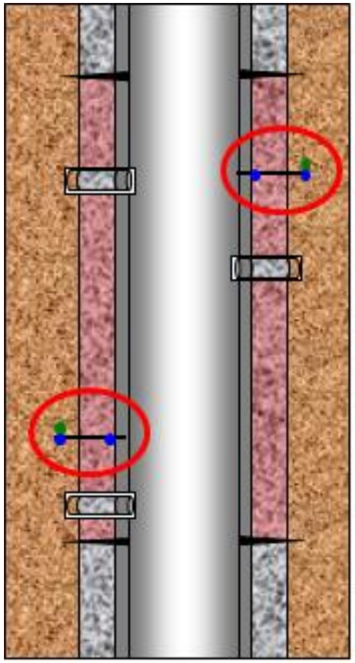


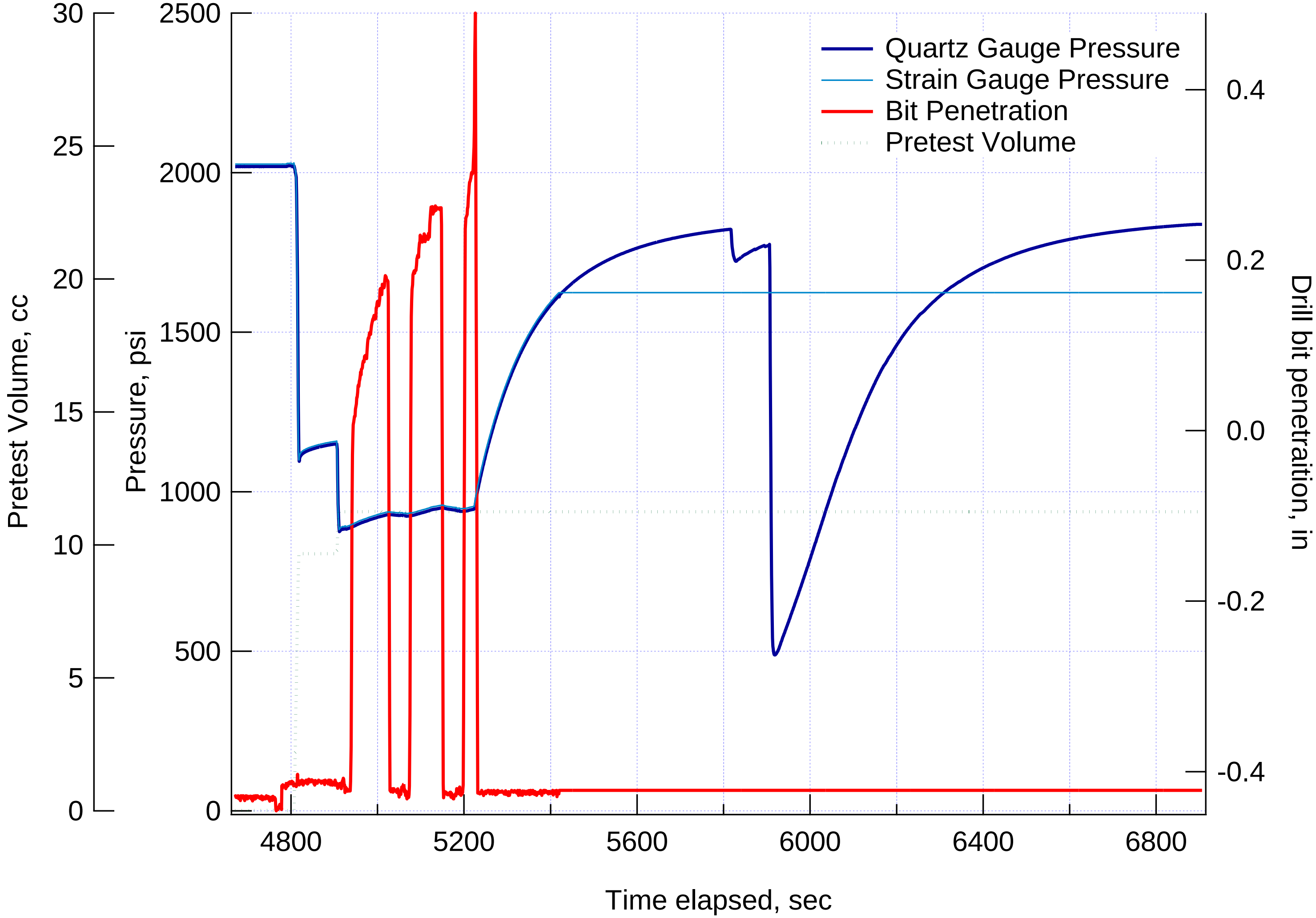
Figure 7: tpx-46-10-4005-xrd: Quartz is more abundant in formation side; an unassigned peak at 8.3, possibly corresponds to jennite; the formation side has calcite whereas the casing has very little; katoite is the dominant phase.



Well Sampling – CHDT

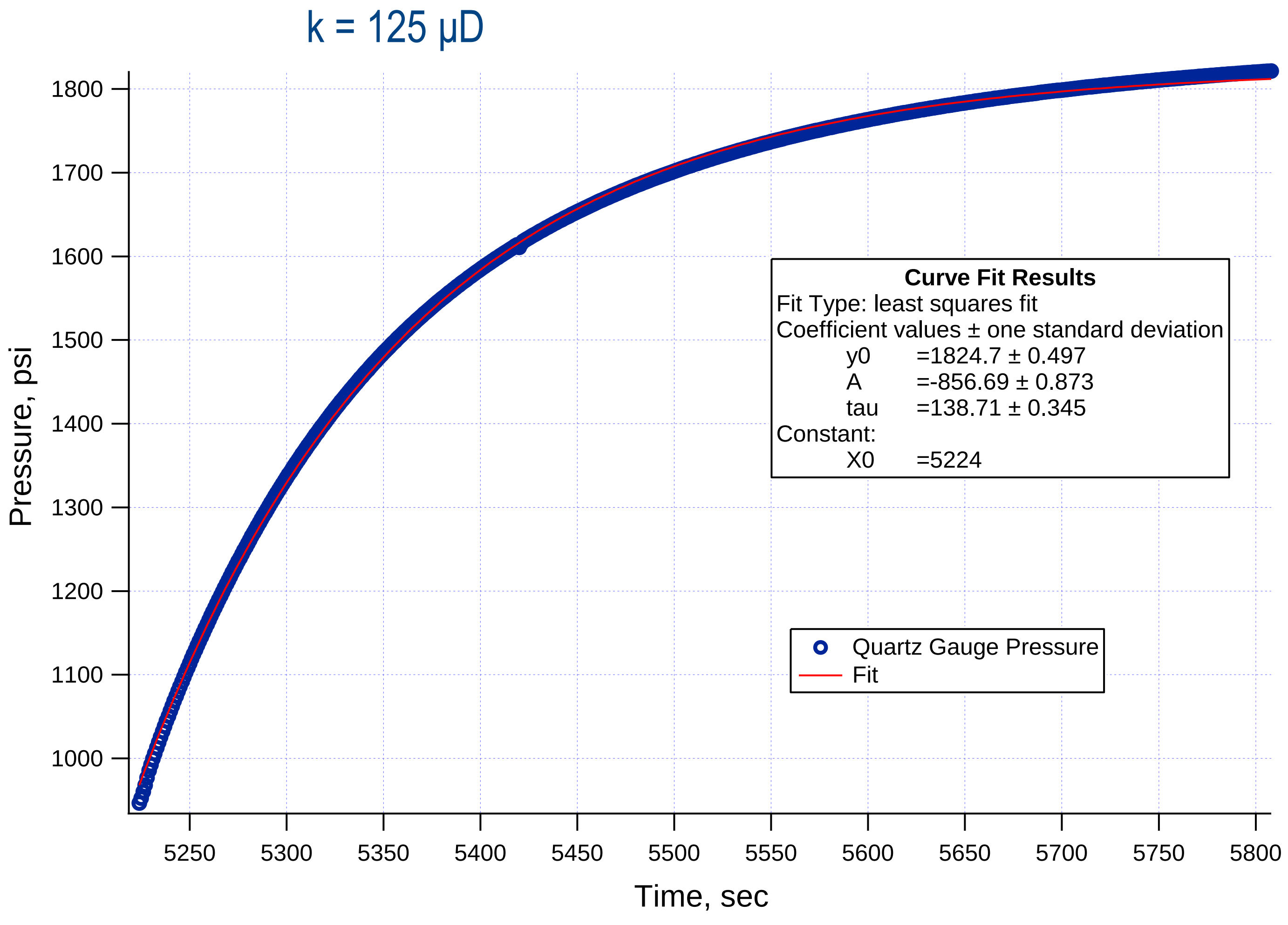


CHDT Data



Quartz Gauge Pressure
Strain Gauge Pressure
Bit Penetration
Pretest Volume
Pretest Volume, cc
30
25
20
15
10
5
0
Pressure, psi
2500
2000
1500
1000
500
0
Drill bit penetraition, in
0.4
0.2
0.0
-0.2
-0.4
4800
5200
5600
6000
6400
6800
Time elapsed, sec

CHDT Analysis

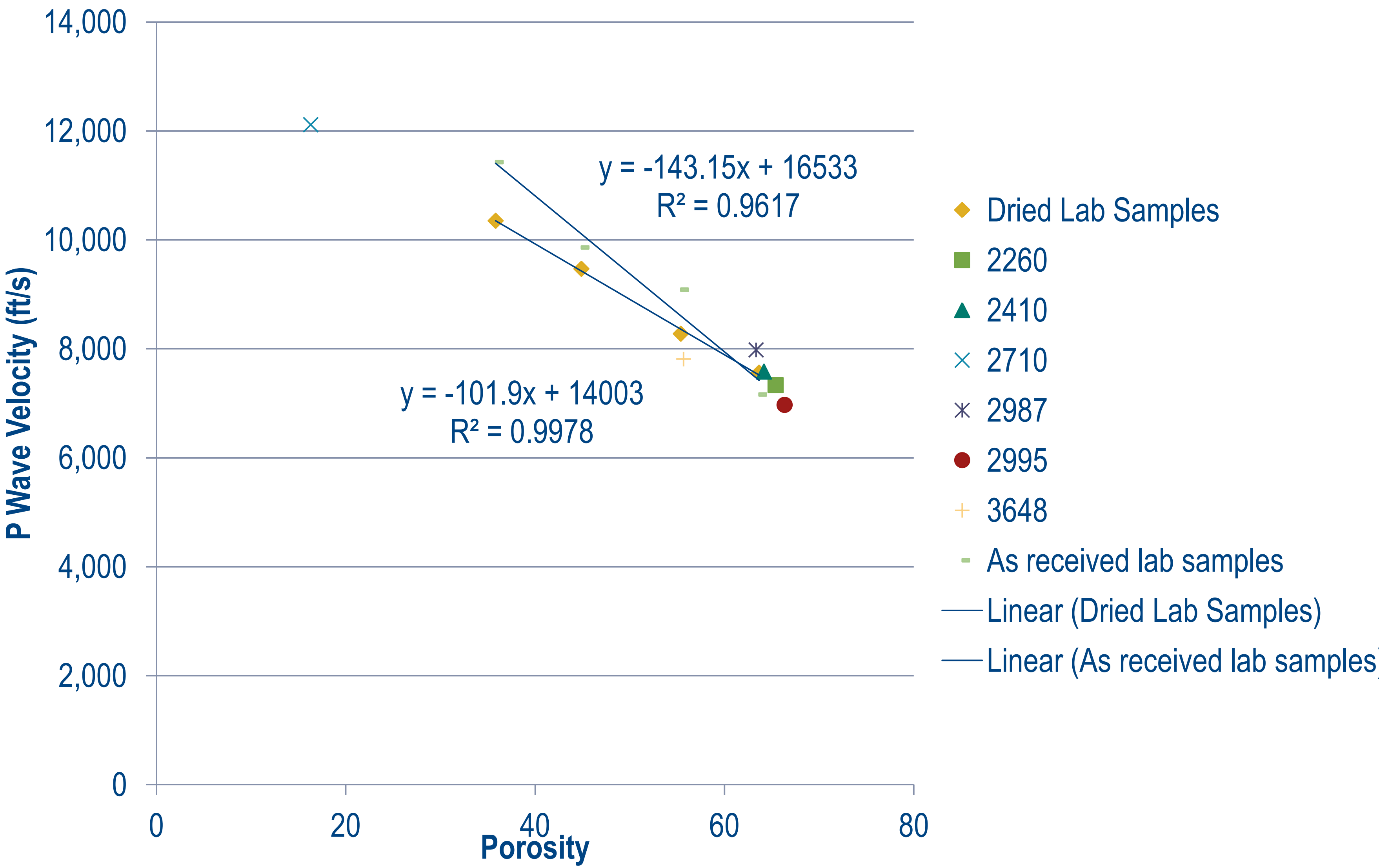


Lab Cements

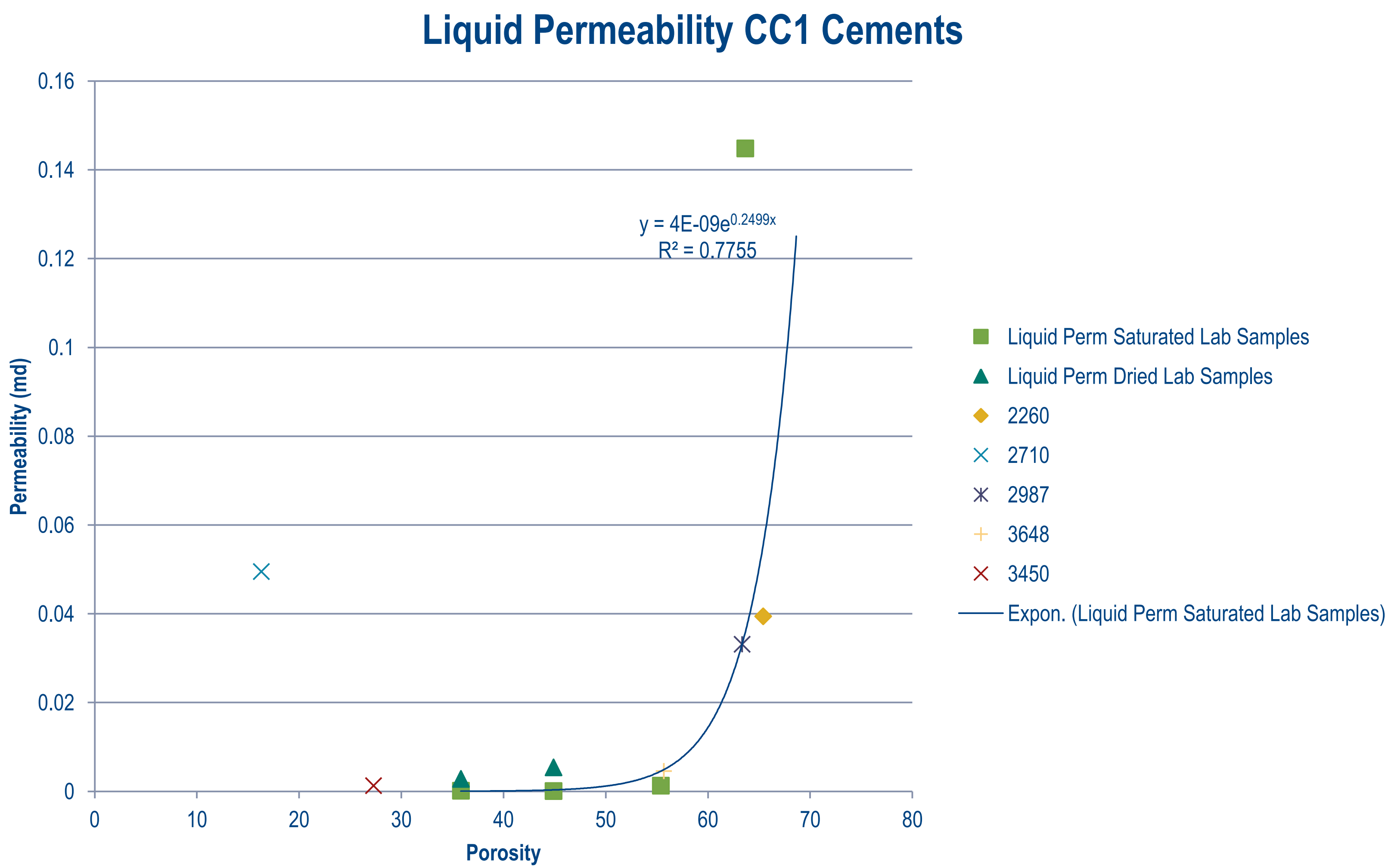
TerraTek* rock mechanics and core analysis services

Well	Unique number	Sample Number	Pressure (psi)	Temperature (f)	W/C	Density (PPG)	Cement	Length (mm)	Diameter (mm)
Industry Well 1	9	IW1-14.9PPG-3	475	89	0.5	14.9	35/65	95.5	26
Industry Well 1	10	IW1-14.9PPG-2	475	89	0.5	14.9	35/65	92.5	26
Industry Well 1	11	IW1-13.65PPG-1	475	89	0.7	13.65	35/65	93.5	26
Industry Well 1	12	IW1-13.65PPG-2	475	89	0.7	13.65	35/65	98.5	26
Industry Well 1	13	IW1-12.8PPG-2	475	89	0.9	12.8	35/65	98	26
Industry Well 1	14	IW1-12.8PPG-3	475	89	0.9	12.8	35/65	92	26
Industry Well 1	15	IW1-12.18PPG-4	475	89	1.1	12.18	35/65	89	26
Industry Well 1	16	IW1-12.18PPG-2	475	89	1.1	12.18	35/65	91	26

CC1 P-Wave Velocity vs Porosity



CC1 Liquid Permeability



CC1 Zero-porosity Cement Values

Property	Zero-porosity value (As Received)	Zero-porosity value (Dried)	Units
Poisson's ratio	0.3137	0.2864	
Bulk Density	-	2.2259	g/cc
As tested bulk density	2.3732	2.2207	g/cc
Peak Compressive strength	16990	26686	psi
Young's modulus	3,094,283	2,944,838	psi
P wave velocity	16533	14003	ft/s
S wave velocity	10023	8441.8	ft/s
Ultrasonic Poissons Ratio	0.1568	0.2225	
Ultrasonic Young's Modulus	4902600	3407600	psi
Ultrasonic Bulk Modulus	3369600	2016100	psi
Ultrasonic Shear Modulus	1931100	1399100	psi

CC1 VL Estimates

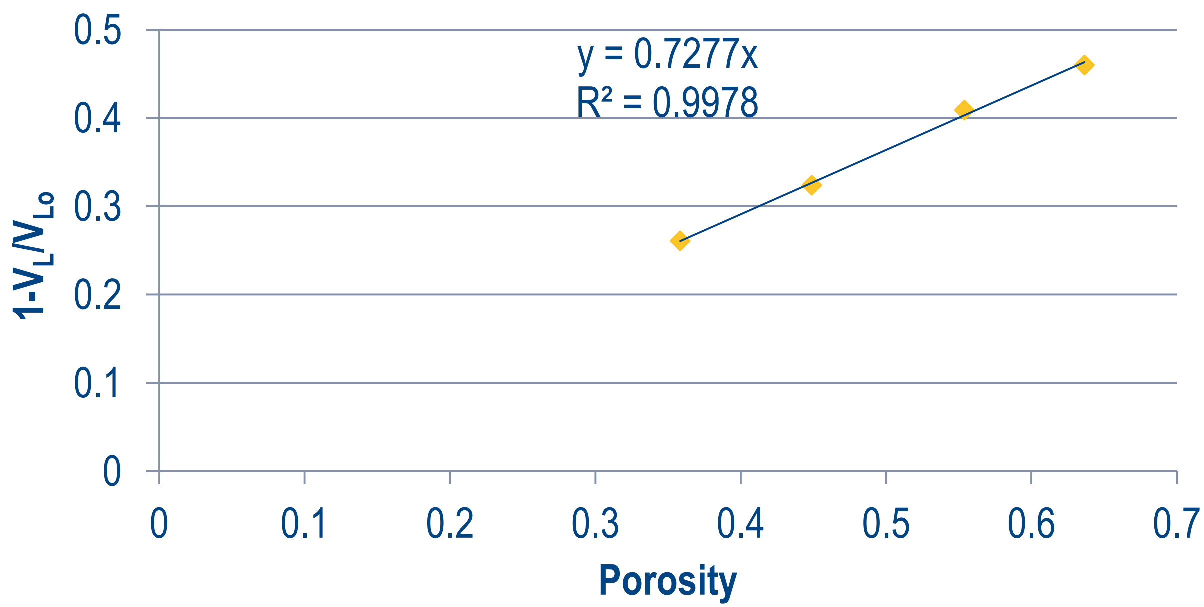
$$V_L = V_{LO}(1 - bp)$$

$$pb = \left(1 - \frac{V_L}{V_{L0}}\right)$$

V_{Lo}	14003	**b** = 0.7277

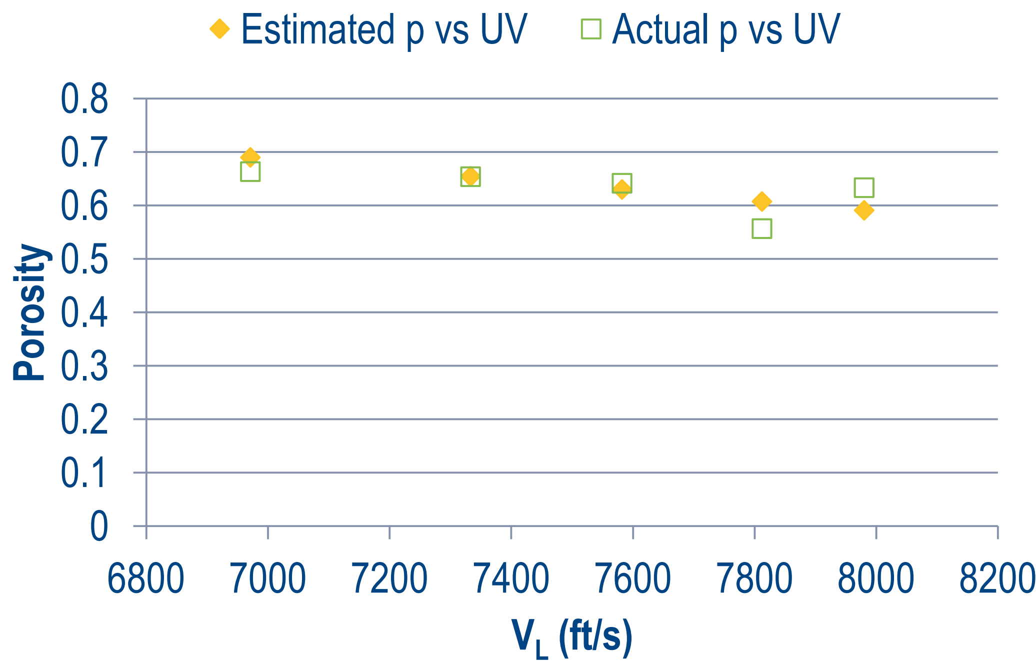
p	Actual V_L (ft/s)	Estimated V_L (ft/s)
0.3583	10,350	10351
0.4489	9468	9428
0.5539	8277	8358
0.6365	7562	7517

$1\text{-}V_L/V_{Lo}$ versus porosity to calculate the constant b for dried CC1 cements



CC1 Field Porosity Data and Estimates

$$p = \frac{1}{b}\left(1 - \frac{V_L}{V_{L0}}\right)$$



Dried samples

Material	Sample Depth (ft)	Ambient Porosity	V_L (P-Wave Velocity) (ft/s)	Estimated Porosity
Cement	2260	0.654	7333	0.654
Cement	2410	0.6417	7582	0.630
Cement	2987	0.6334	7980	0.591
Cement	2995	0.6635	6971	0.690
Cement	3648	0.5568	7812	0.607

Constants	
V_{Lo}	14003
b	0.7277

Results

- Cement isolation logs in the shale zones studied indicate competent cements and do not indicate the existence of microannuli
- The microdarcy magnitude of the permeability measurements of the well cement samples collected in the field as compared to the samples created in the lab indicates that the cements in the wells in the zones sampled has not degraded.
- In-situ permeability estimates using the CHDT match the magnitude of the field cement samples and provide further evidence that the cements in the well have not degraded

Results (continued)

- The difference in magnitude between the cement permeability (microdarcy) and the VIT permeability (millidarcy) implies that the annuli in the well and not the cement represent the most important potential leakage pathway
- Ultrasonic velocity can be used to estimate in-situ porosity.
  - However a knowledge of the cement-specific properties b and V_{Lo} are needed
- The next step is modeling permeability using V_L, V_{Lo}, and b

Questions

Please direct difficult questions to:

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