Core- to Log-Scale Analysis of the Wolfcamp Formation in the Thunder C20-13 #2H Core, Delaware Basin, Reeves County, Texas

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Project Summary

Objective:

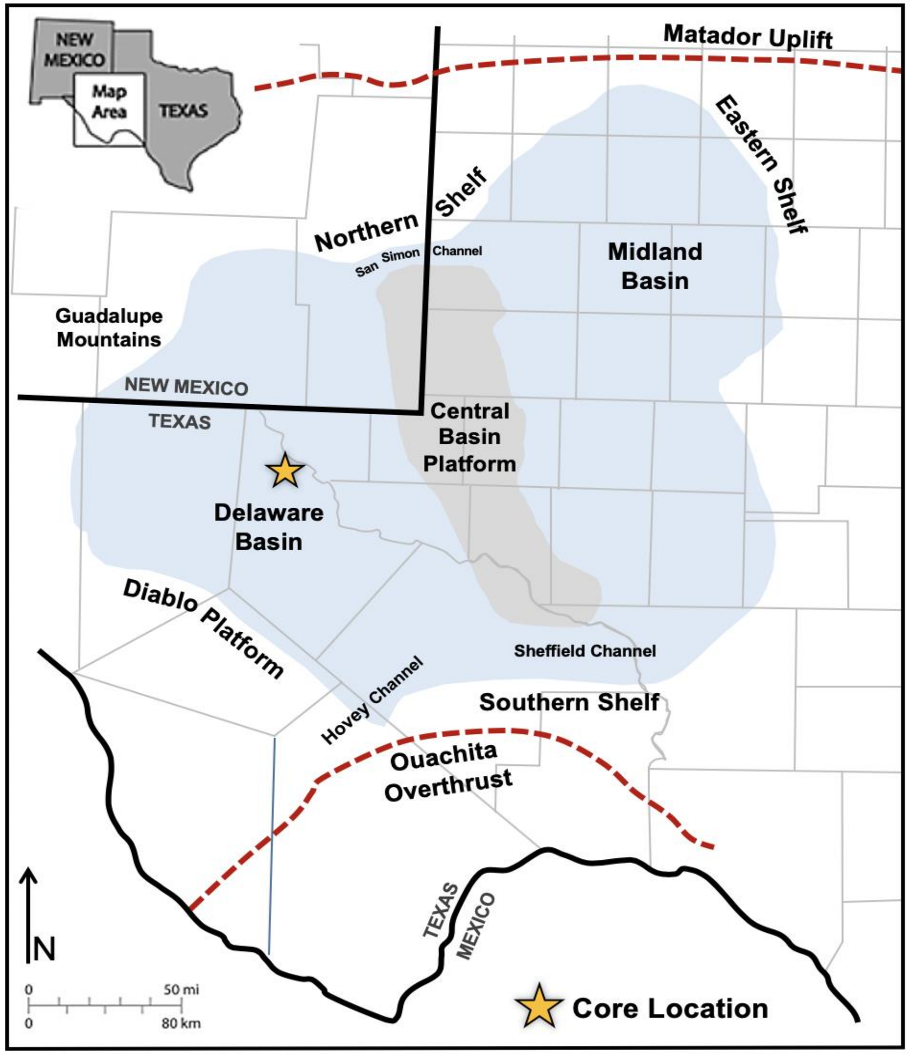
Integrated analysis of core, core associated data and well logs to investigate the vertical variability of lithofacies and reservoir quality in the Wolfcamp A, B, C, and D.

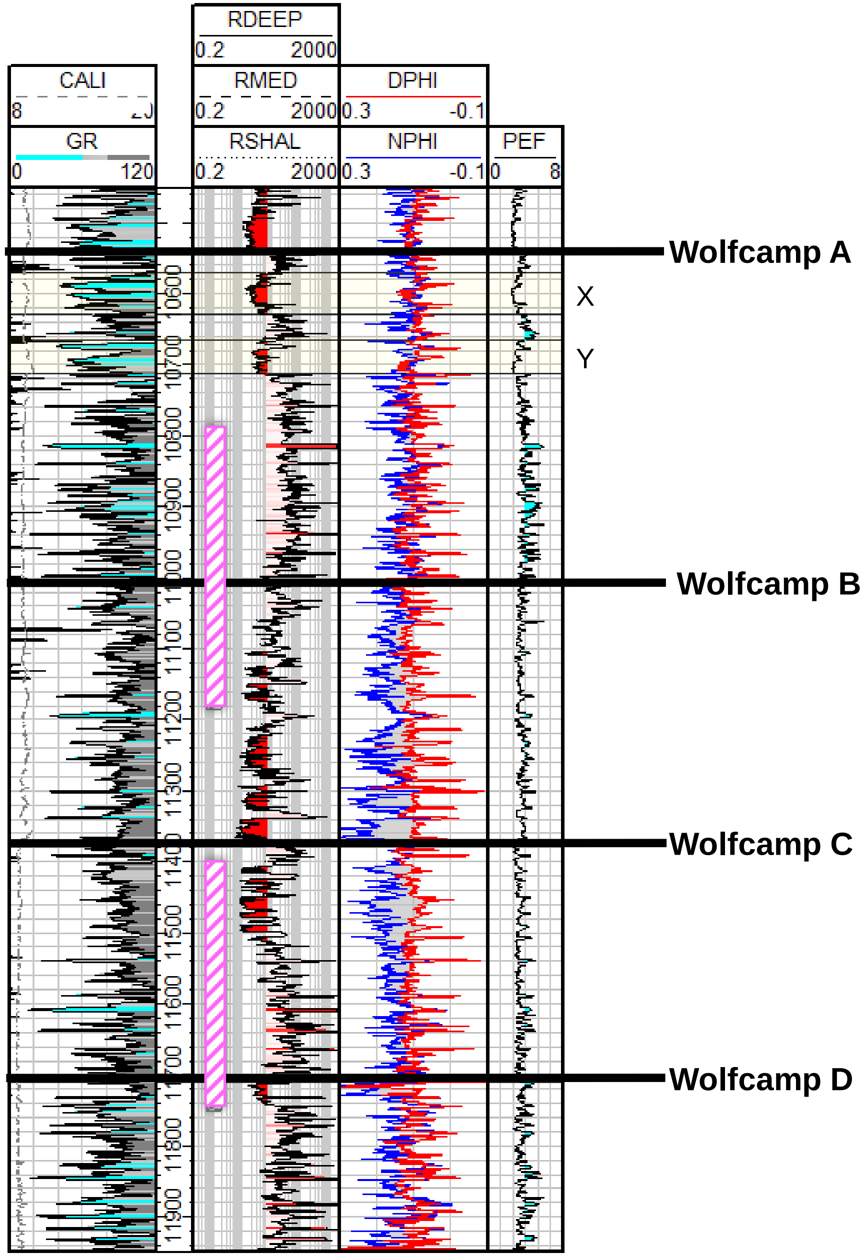
Research Outline

- Location and Dataset
- Core Analysis (Lithofacies and Facies Distribution)
- Elemental Analysis (Mineral Model, Chemofacies and Indicators)
- Source Rock Analysis
- Reservoir Characterization
- Conclusions

Core Location and Dataset

Cimarex Thunder C20-13 #2H





Core Analysis

Core Totaling 738.4 ft

- Wolfcamp A (215.5')
- Wolfcamp B (175.9')
- Wolfcamp C (310.3')
- Wolfcamp D (36.7')

Thin Section Photos

- 268 photomicrographs

X-ray Diffraction (XRD)

- 67 samples

Elemental Analysis

X-ray Fluorescence (XRF)

- 799 (WCMP A and B)

Reservoir Characterization

Source Rock Analysis

- 67 samples

Rock Hardness (UCS)

- 1,277 analyzed

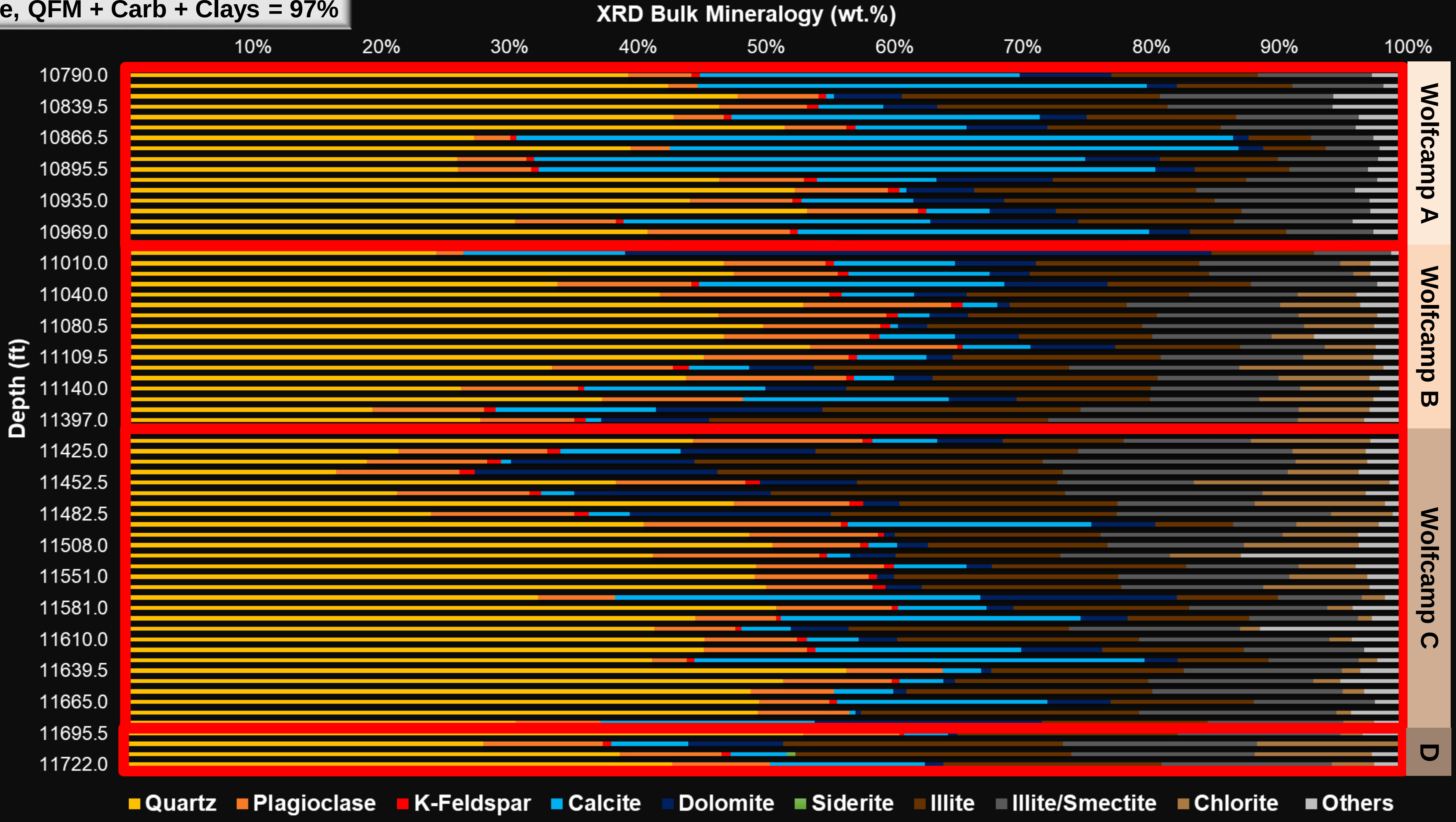
Routine Core Analysis

- 67 samples

Normal Well Log Suite

Compositional Analysis

On average, QFM + Carb + Clays = 97%



Lithofacies Ternary Diagram

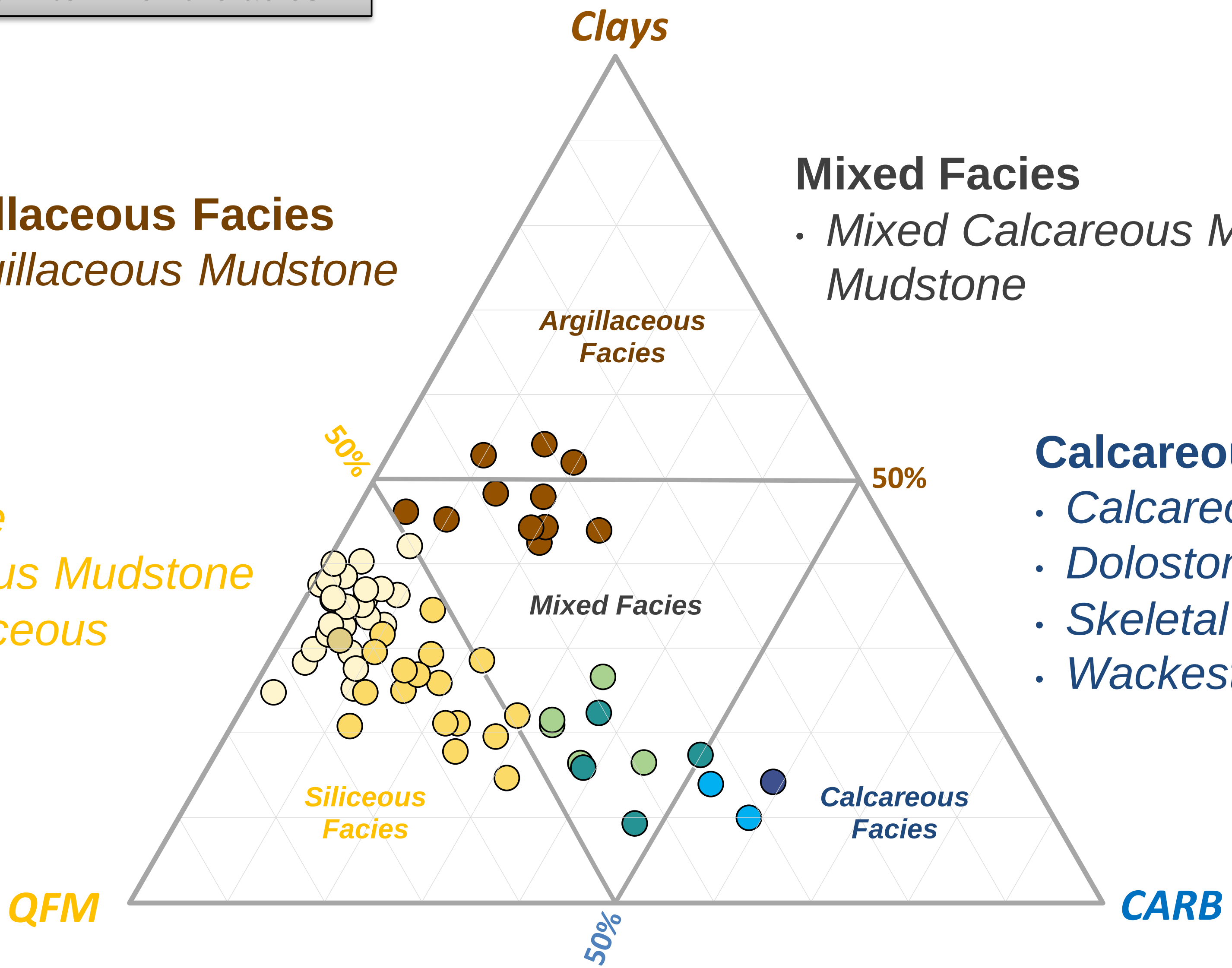
Four facies group subdivided into nine lithofacies

Argillaceous Facies
- *Argillaceous Mudstone*

Mixed Facies
- *Mixed Calcareous Mudstone to Silty Mudstone*

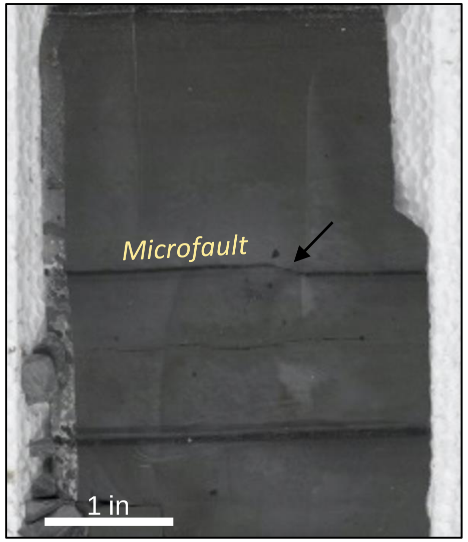
Siliceous Facies
- *Siliceous Mudstone*
- *Bioturbated Siliceous Mudstone*
- *Carbonate-rich Siliceous Mudstone*

Calcareous Facies
- *Calcareous Siltstone*
- *Dolostone*
- *Skeletal Packstone**
- *Wackestone**

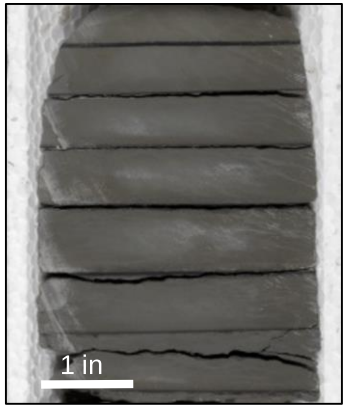


Lithofacies

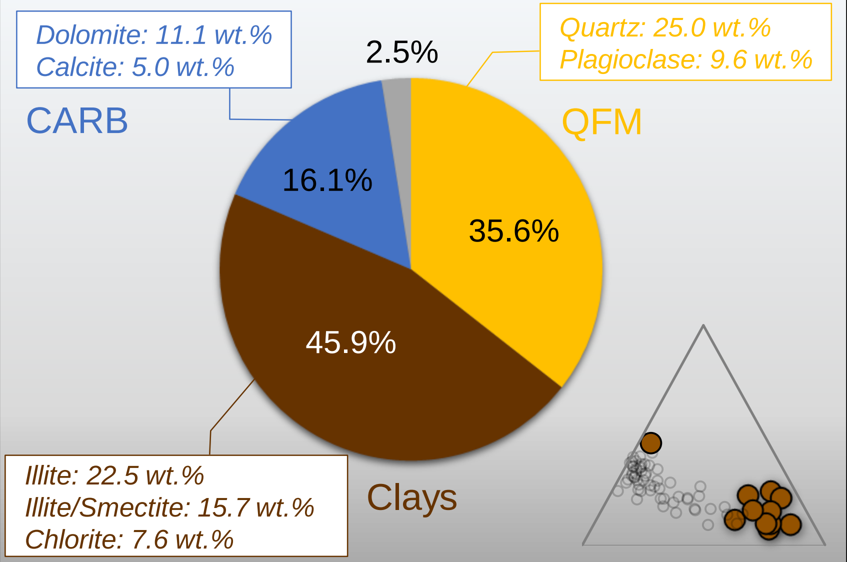
Argillaceous Mudstone



TOC: 0.4 wt.%
Porosity: 9.9 %
Permeability: 1.3 nD

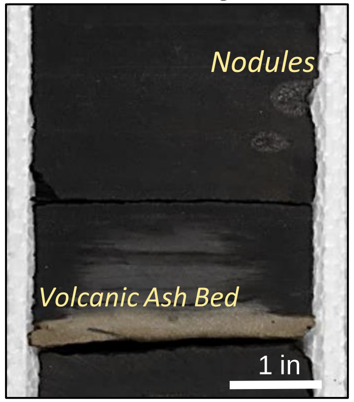


Composition *(n=11)*

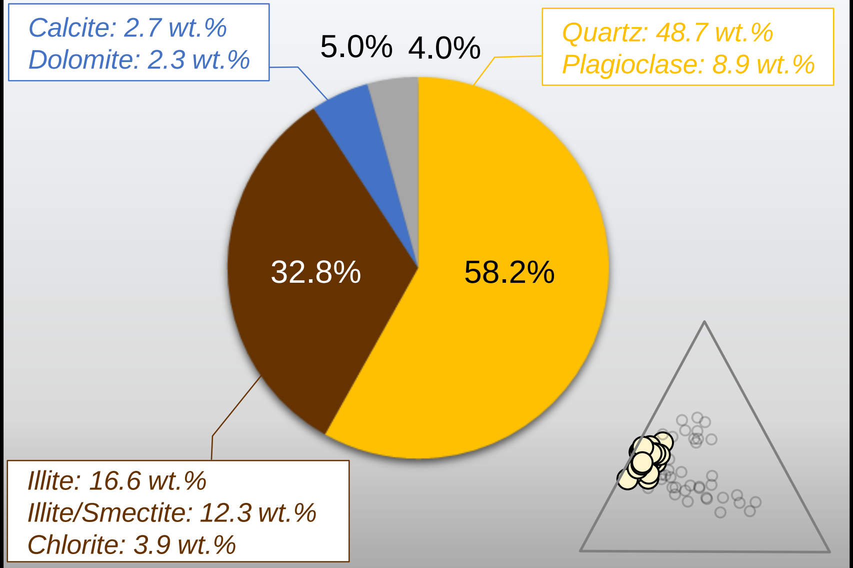


Siliceous Mudstone

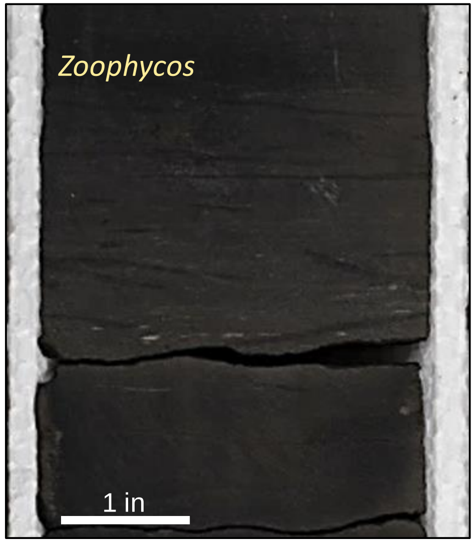
TOC: 2.6 wt.%
Porosity: 9.4 %
Permeability: 58 nD



Composition *(n=26)*

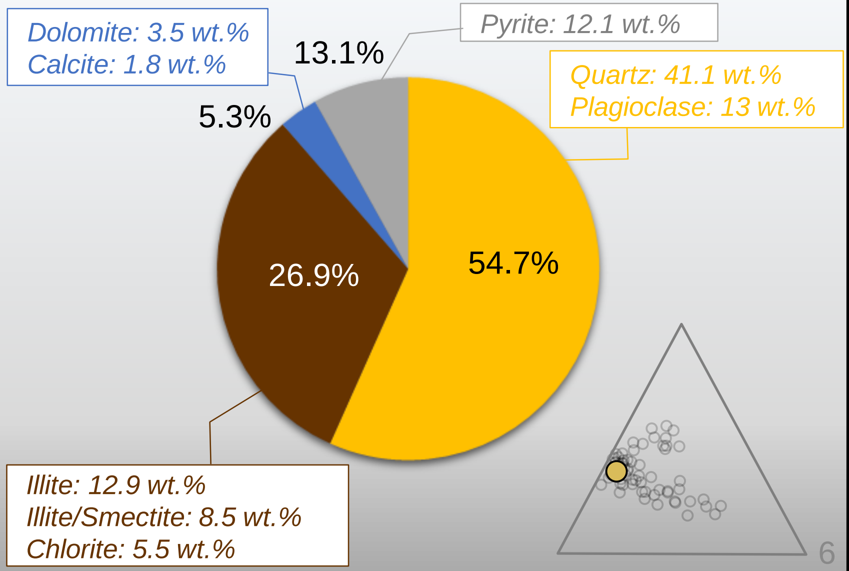


Bioturbated Siliceous Mudstone



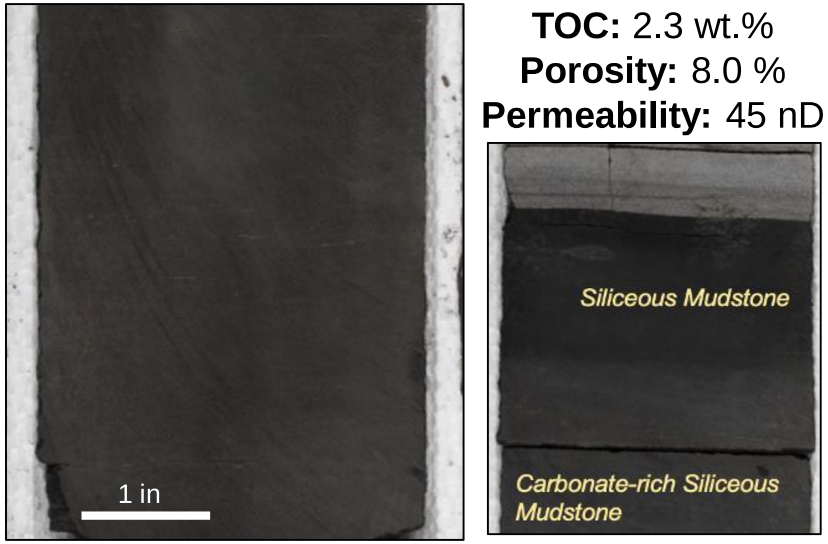
TOC: 1.7 wt.%
Porosity: 8.5 %
Permeability: 108 nD

Composition *(n=1)*



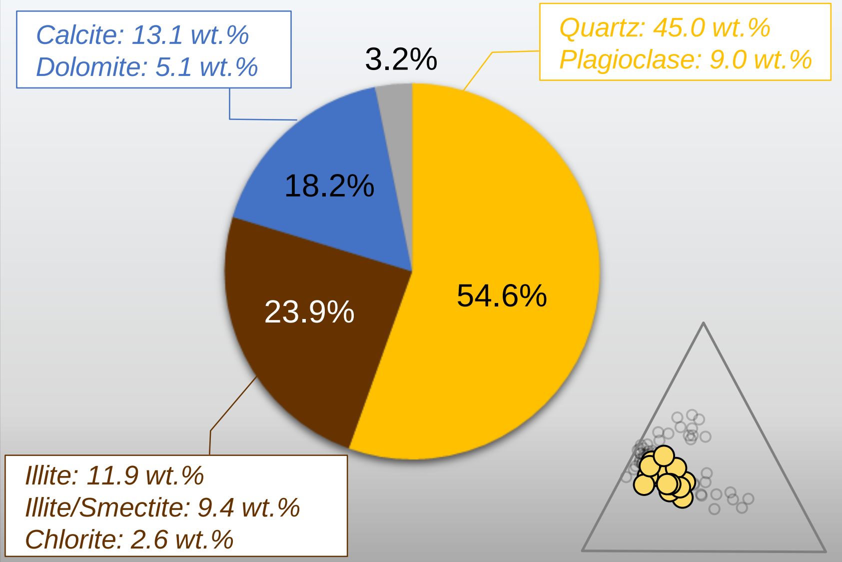
Lithofacies

Carbonate-rich Siliceous Mudstone

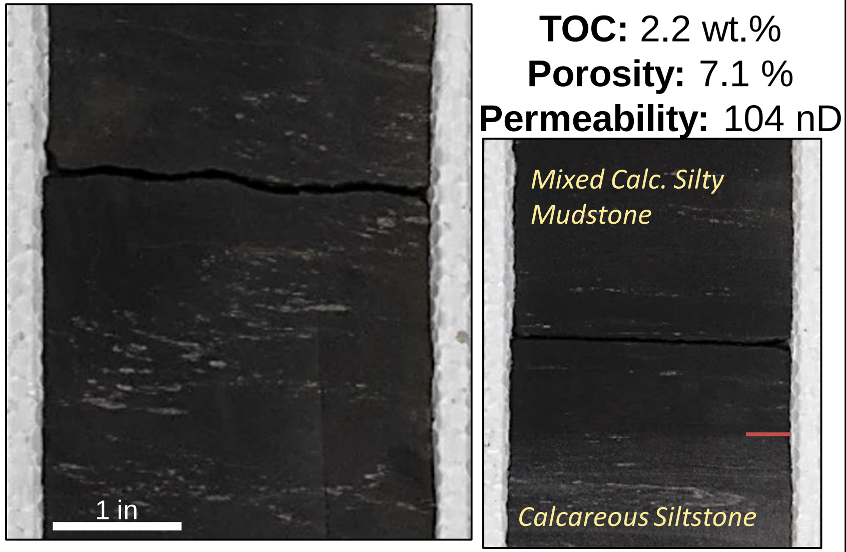


TOC: 2.3 wt.%
Porosity: 8.0 %
Permeability: 45 nD

Composition *(n=17)*

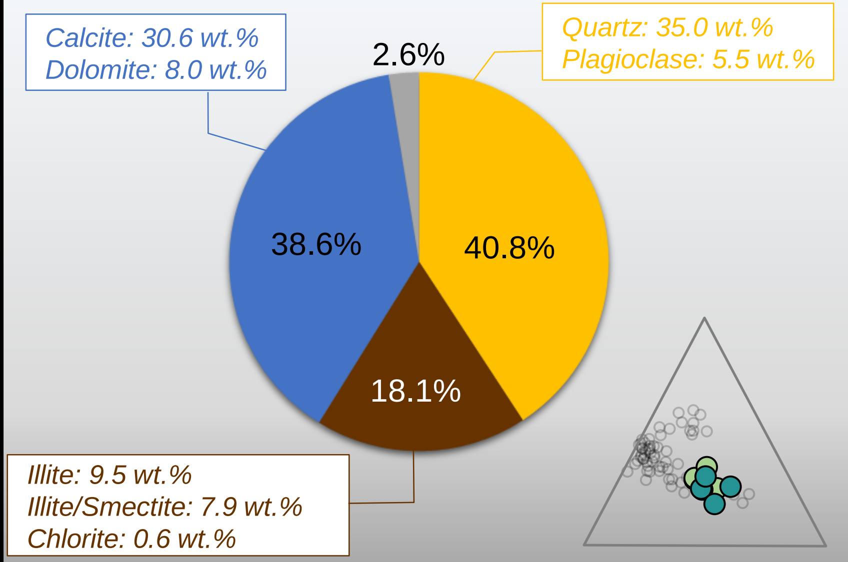


Mixed Calcareous Silty Mudstone

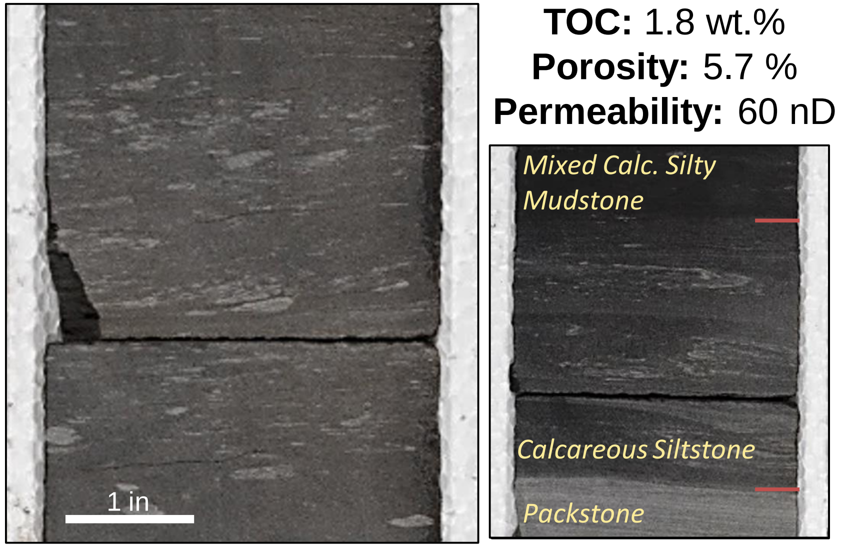


TOC: 2.2 wt.%
Porosity: 7.1 %
Permeability: 104 nD

Composition *(n=9)*

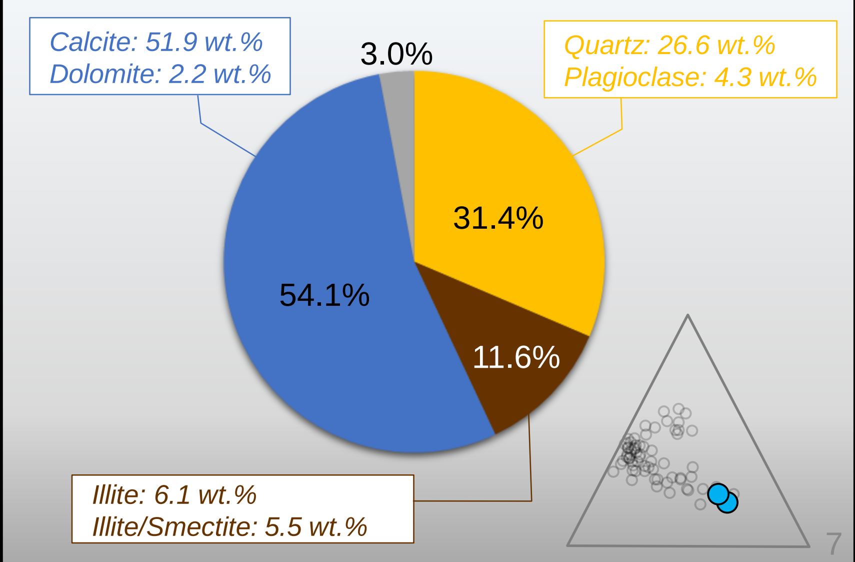


Calcareous Siltstone



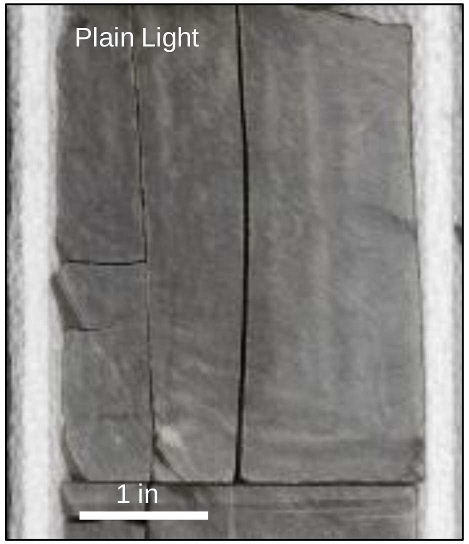
TOC: 1.8 wt.%
Porosity: 5.7 %
Permeability: 60 nD

Composition *(n=2)*

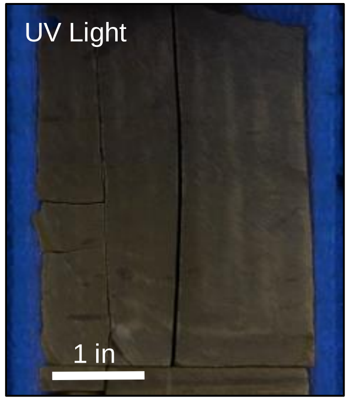


Lithofacies

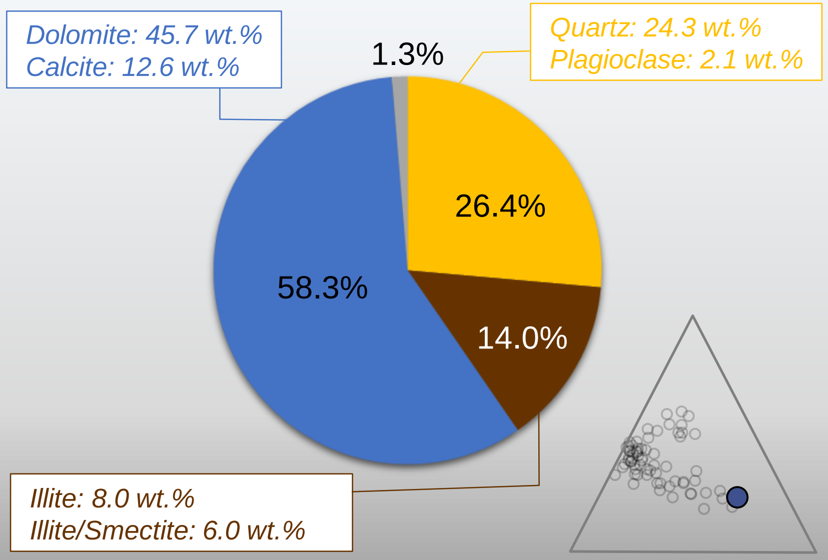
Dolostone



TOC: 0.7 wt.%
Porosity: 6.1 %
Permeability: 11 nD

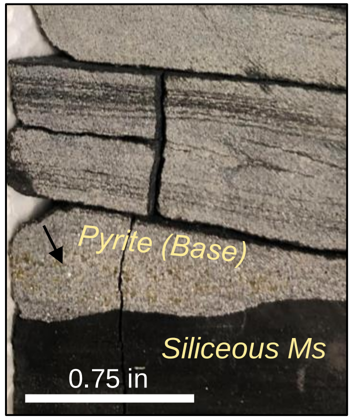


Composition *(n=1)*



Skeletal Packstone

No XRD and RCA Data

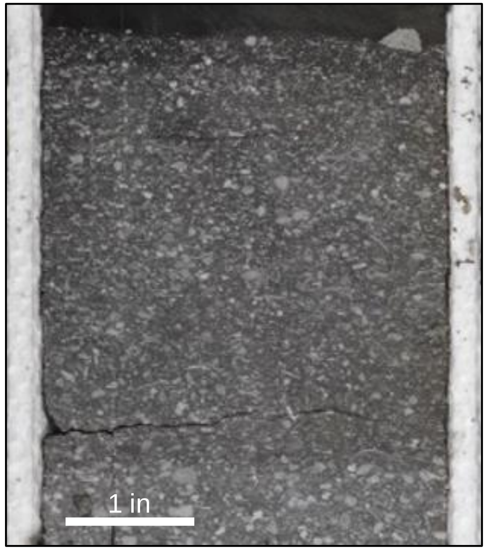


(n=0)

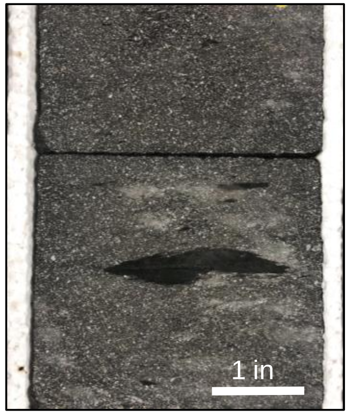
From Wolfcamp literature in the Delaware Basin:

- ***Low TOC*** *(less than 1 wt.%)*
- ***Low porosity*** *(average 2.3%)*
- ***Low clay*** *(less than 4 wt.%)*
- ***Calcite (88 wt.%)***

Wackestone



No XRD and RCA Data



(n=0)

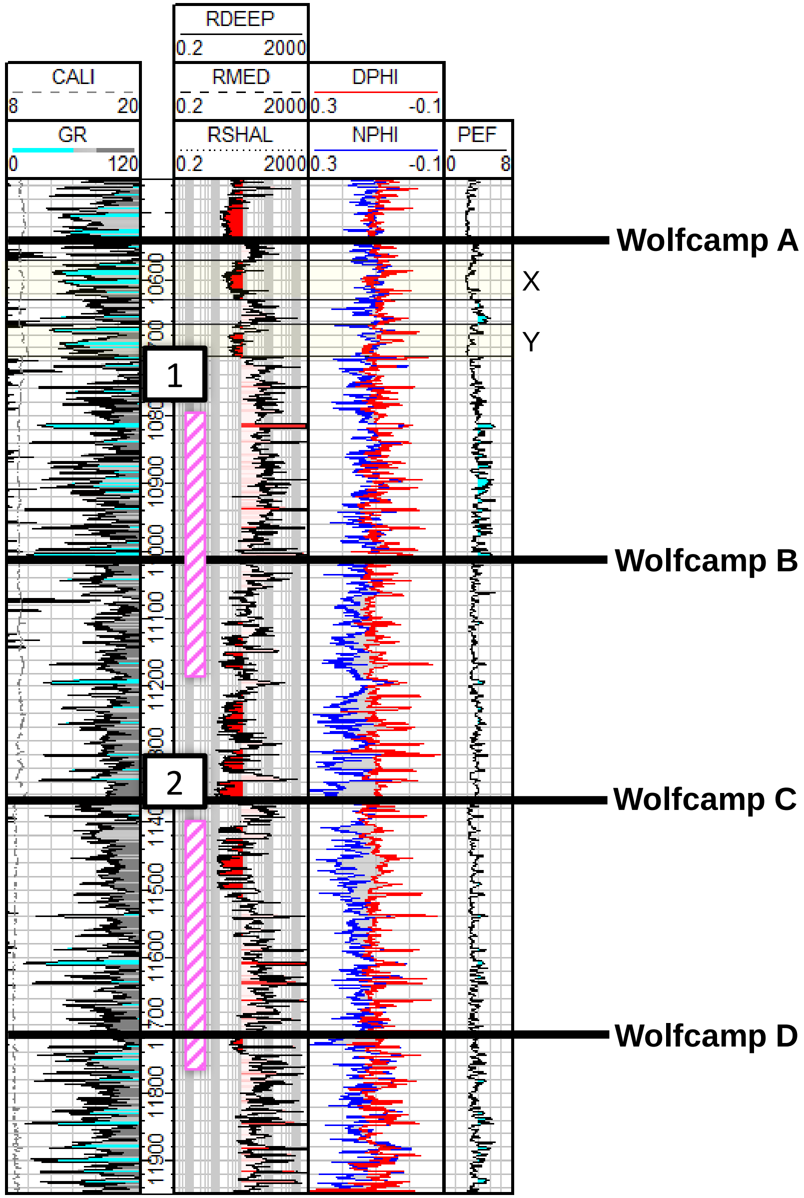
From Wolfcamp literature in the Delaware Basin:

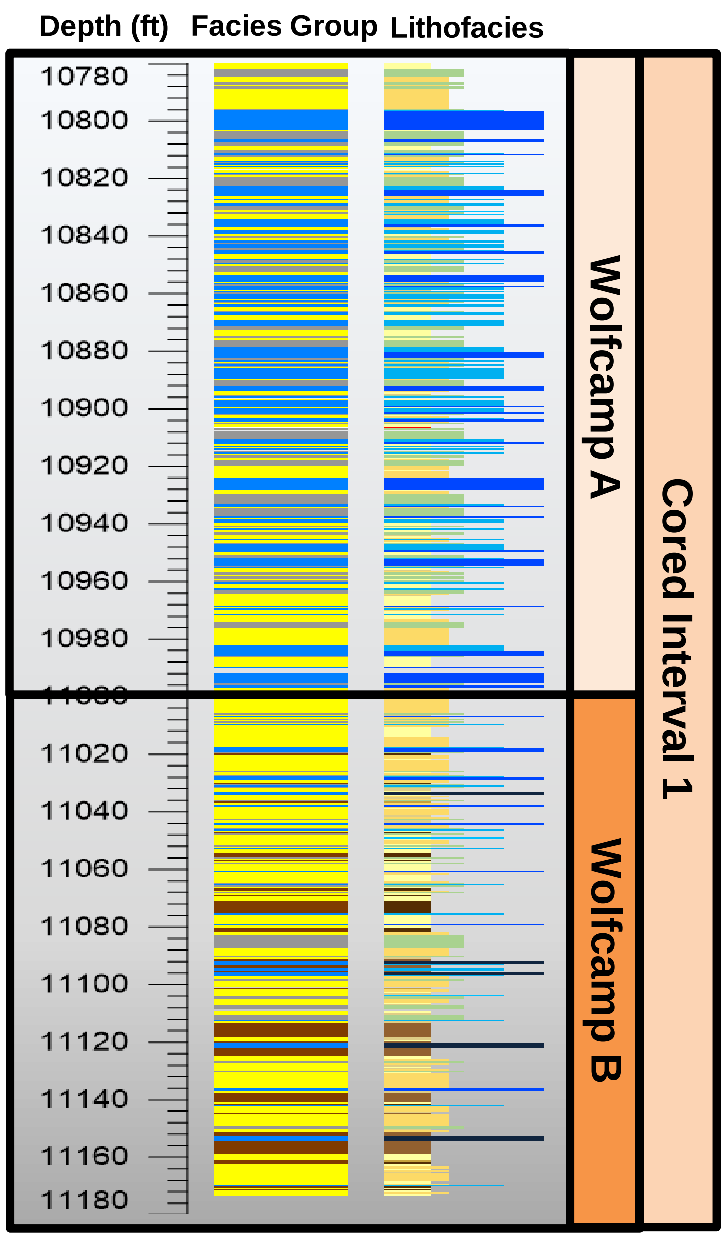
- ***Variable TOC***
- ***Calcite (70 wt.%)****, quartz (21 wt.%), clays (4 wt.%), calcite (2 wt.%)*

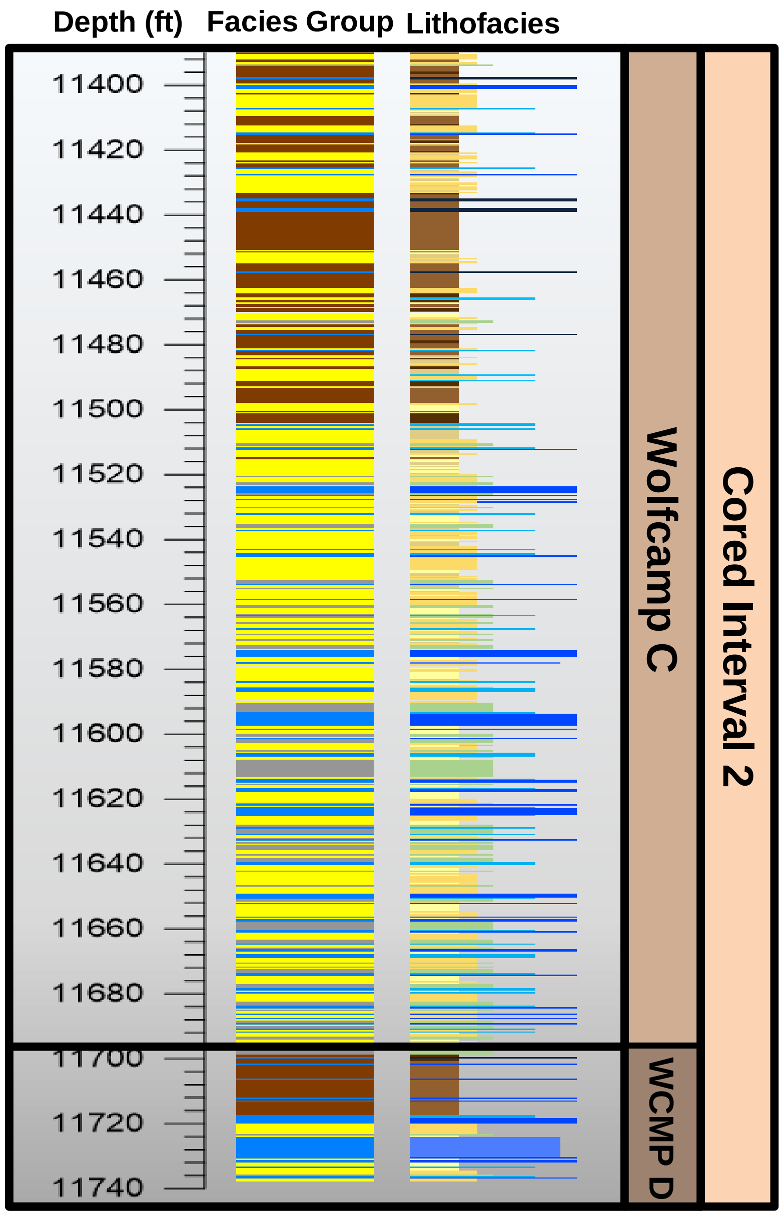
Sources: Kvale et al., 2019; Bievenour, 2019

Wolfcamp Facies Distribution

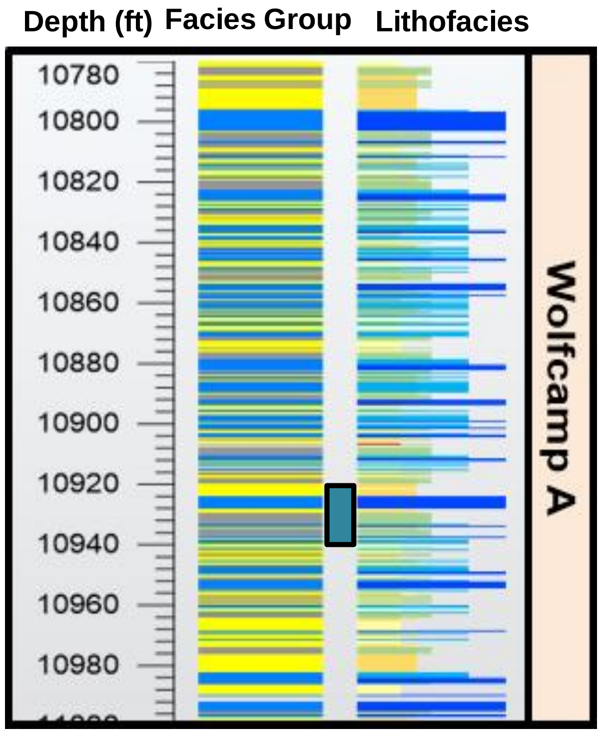
Well Log

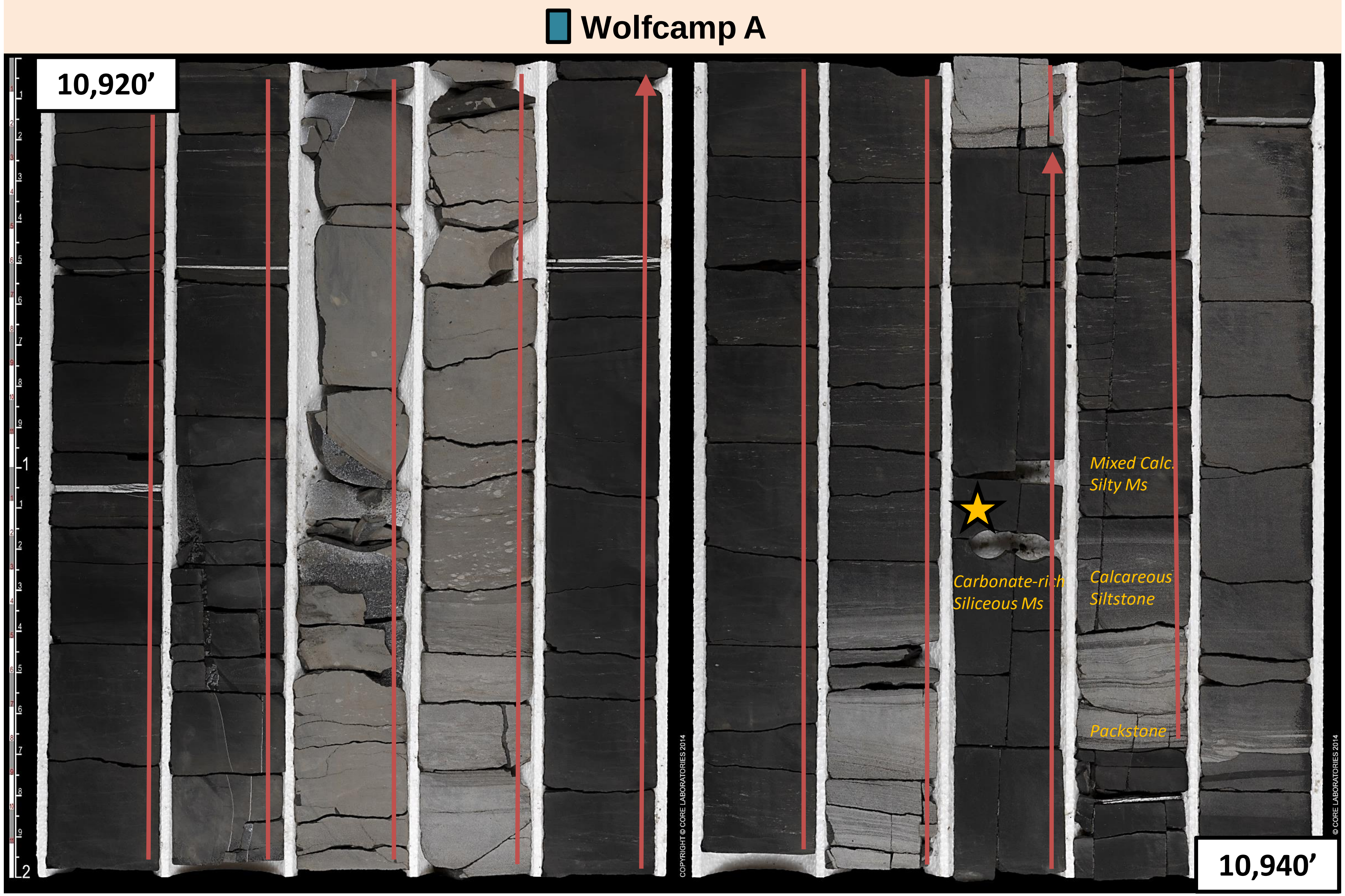




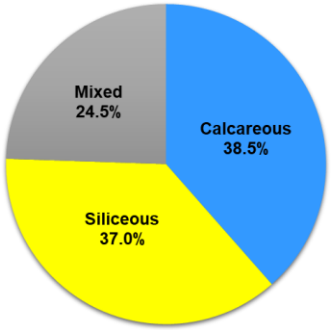


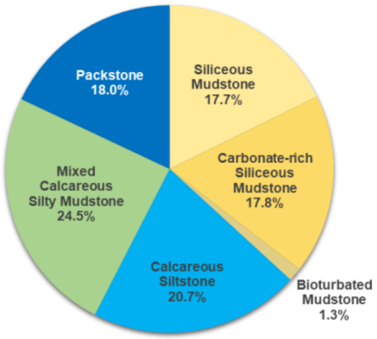
Wolfcamp A Facies Distribution



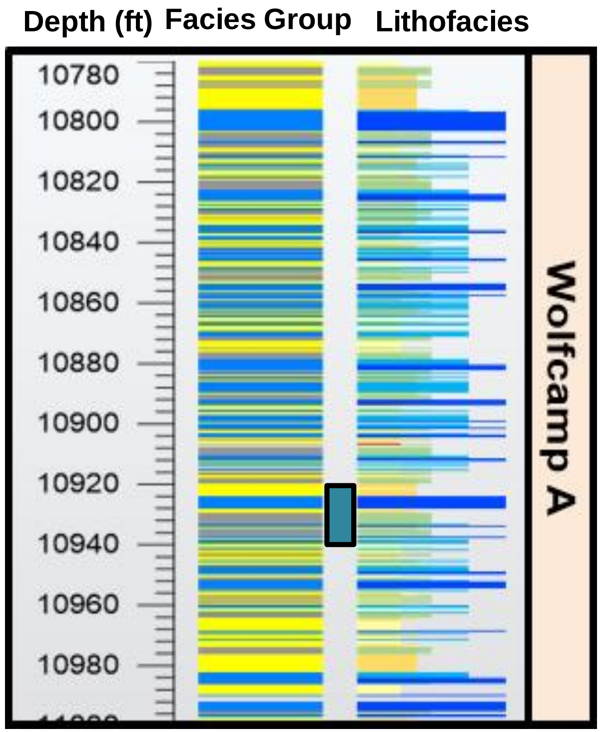


Wolfcamp A

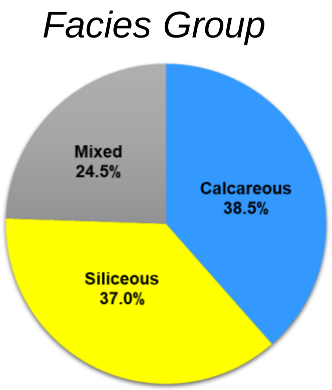


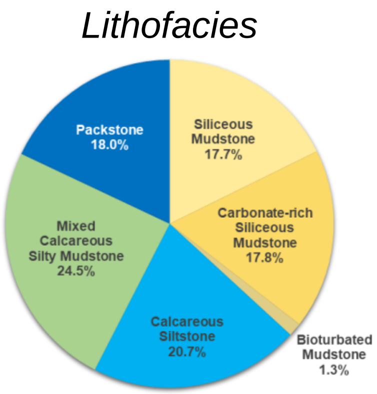


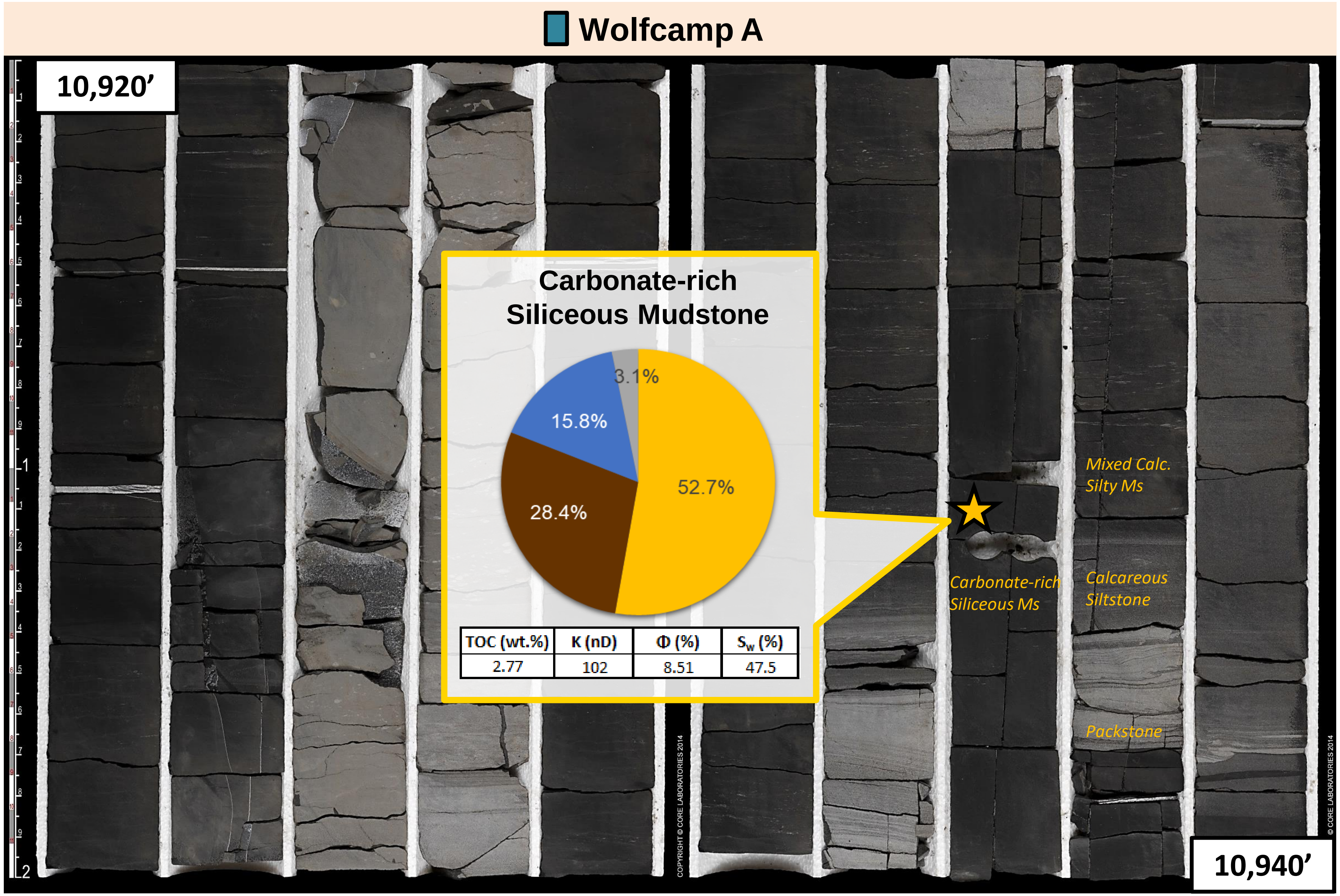
Wolfcamp A Facies Distribution



Wolfcamp A

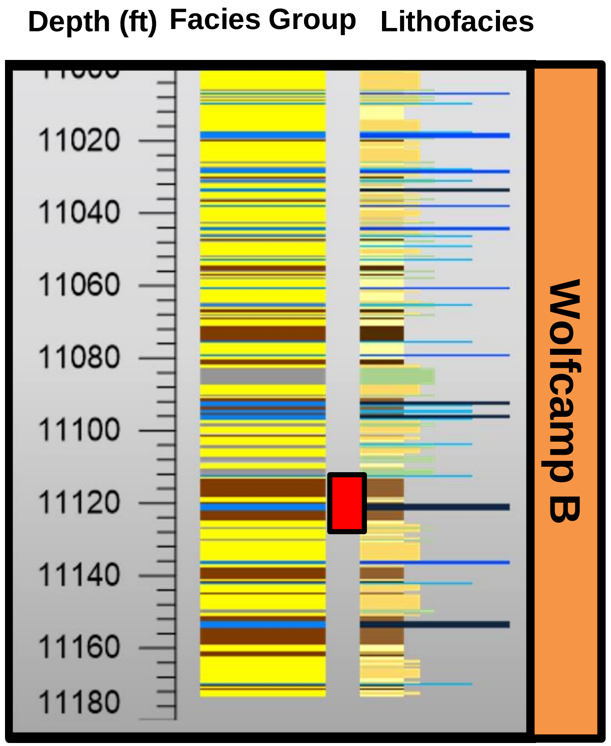




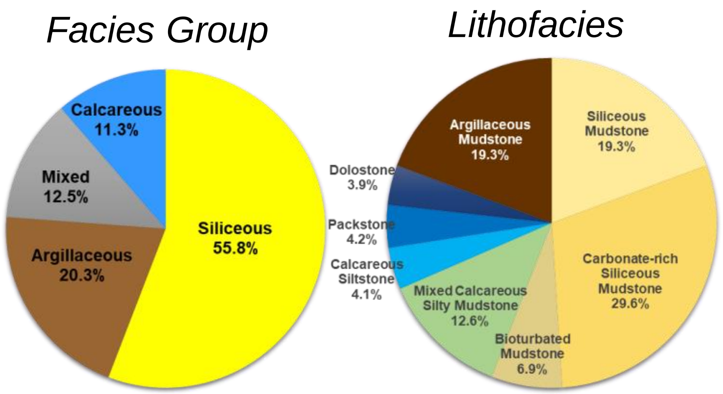


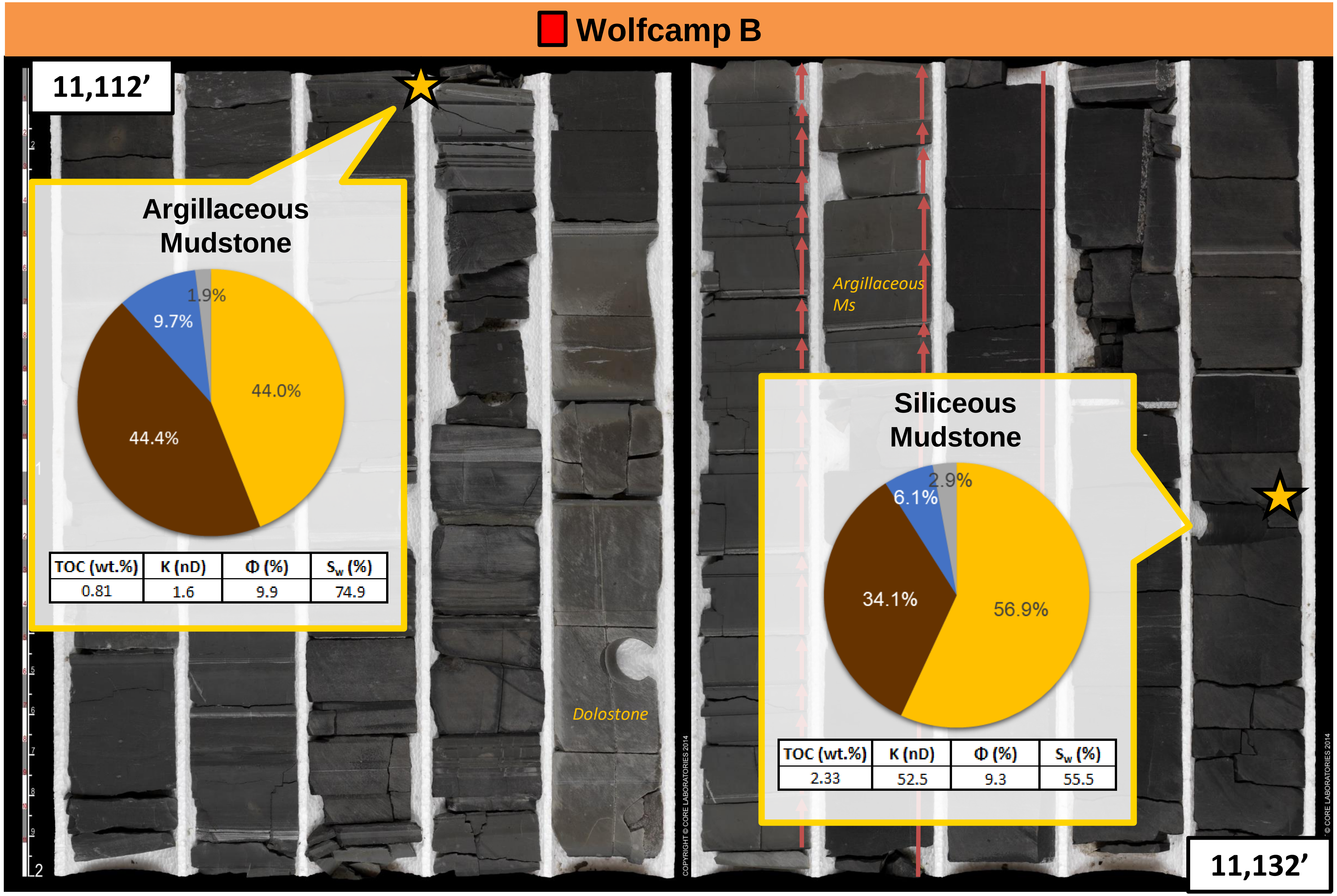
TOC (wt.%)	K (nD)	Φ (%)	S_w (%)
2.77	102	8.51	47.5

Wolfcamp B Facies Distribution



Wolfcamp B





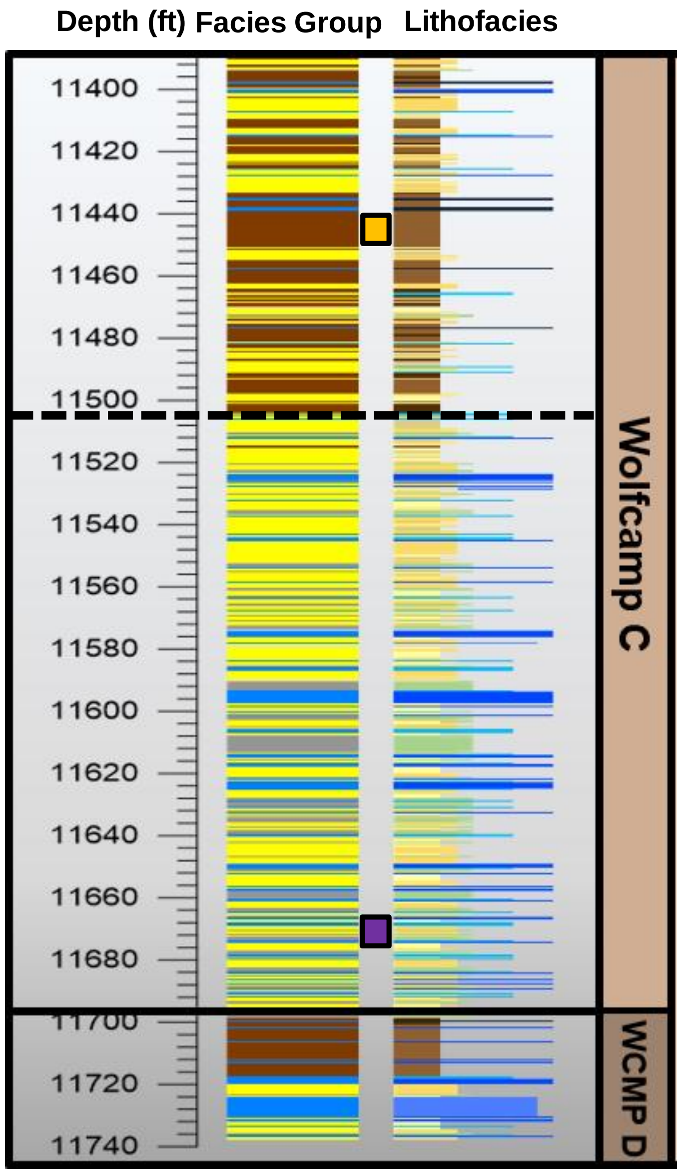
Argillaceous Mudstone

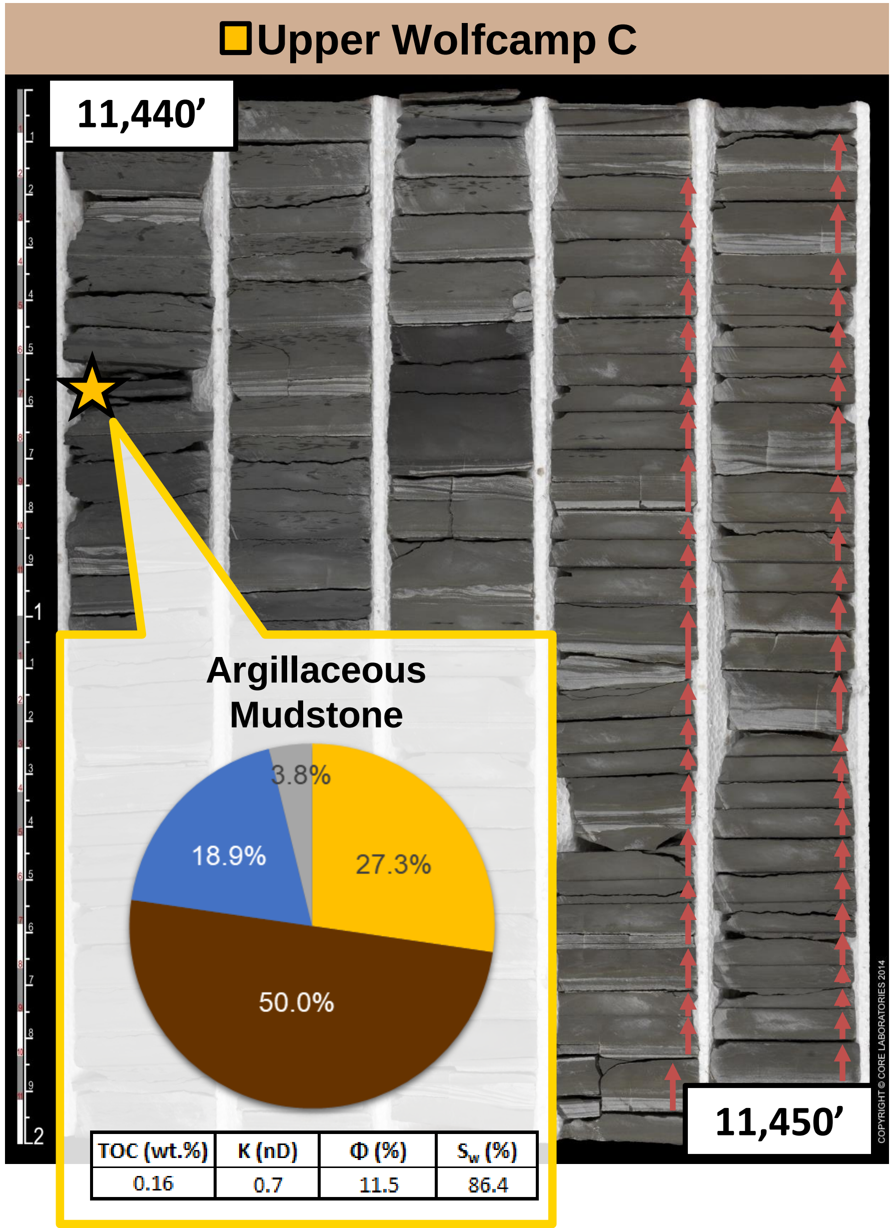
TOC (wt.%)	K (nD)	Φ (%)	S_w (%)
0.81	1.6	9.9	74.9

Siliceous Mudstone

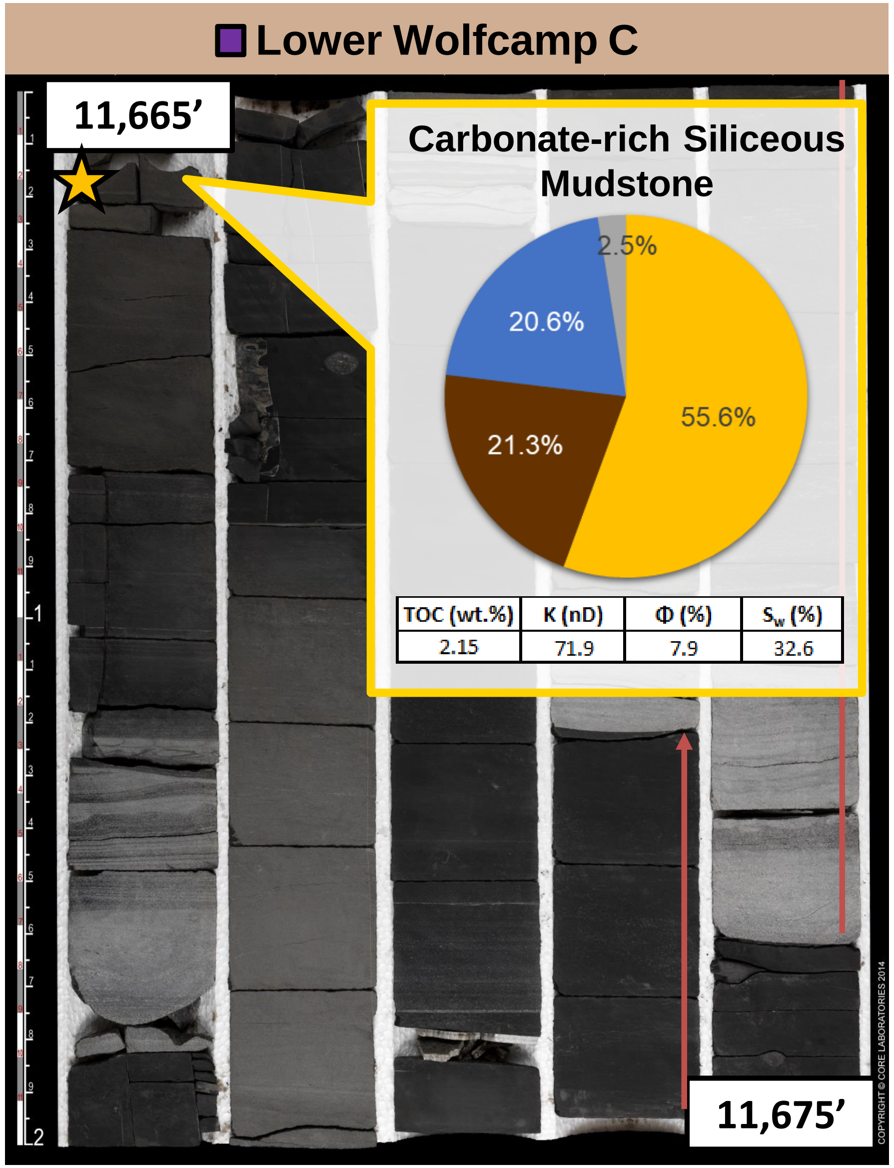
TOC (wt.%)	K (nD)	Φ (%)	S_w (%)
2.33	52.5	9.3	55.5

Wolfcamp C Facies Distribution



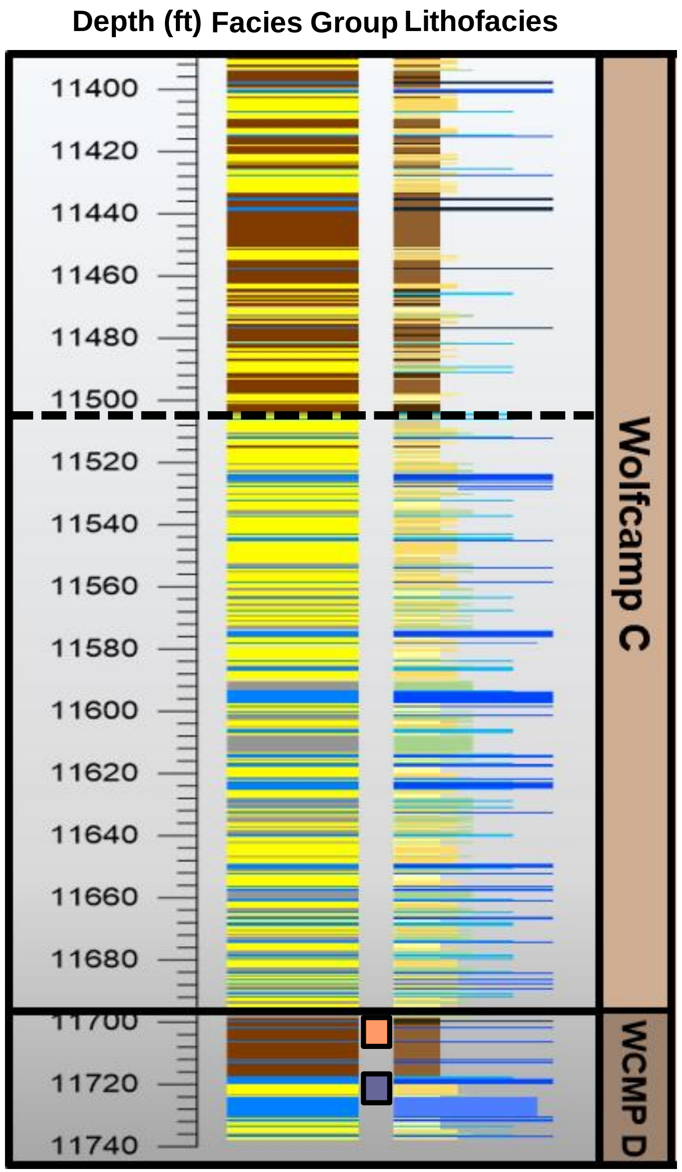


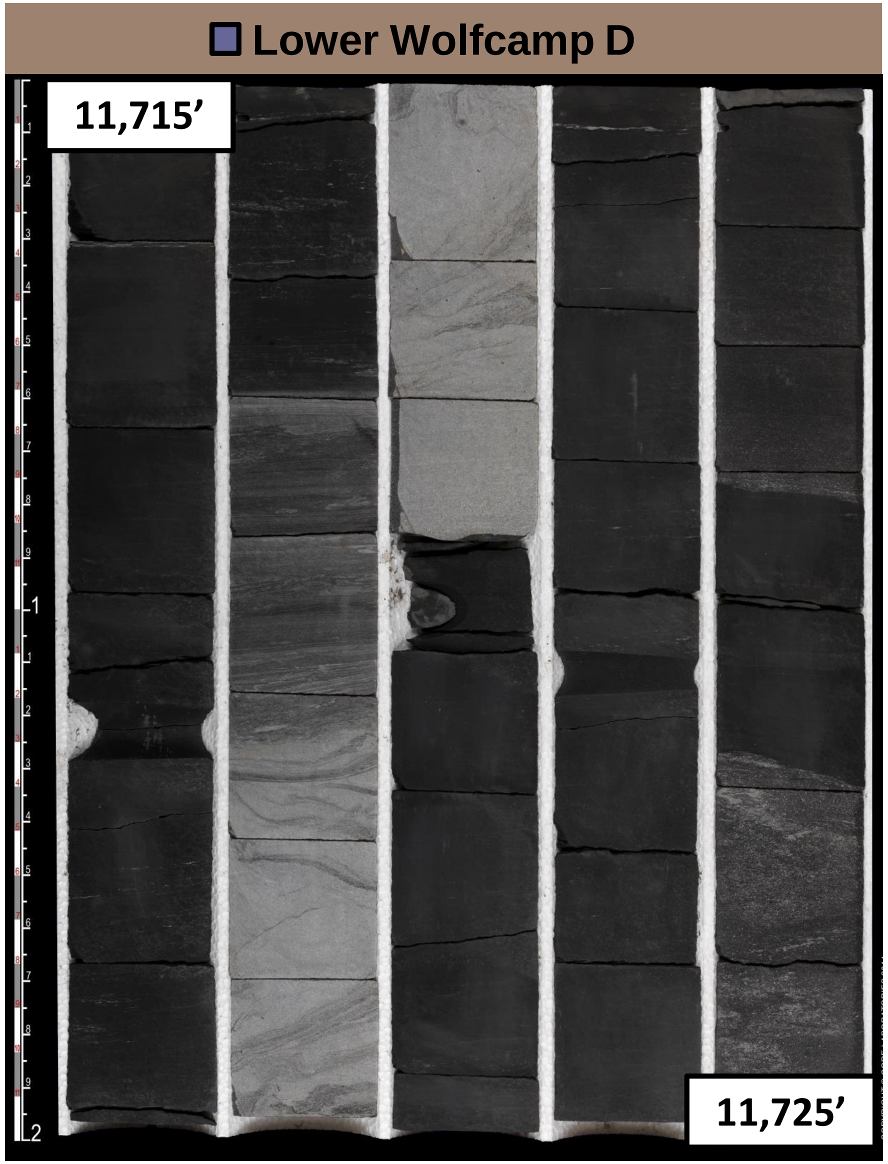
TOC (wt.%)	K (nD)	Φ (%)	S_w (%)
0.16	0.7	11.5	86.4



TOC (wt.%)	K (nD)	Φ (%)	S_w (%)
2.15	71.9	7.9	32.6

Wolfcamp D Facies Distribution





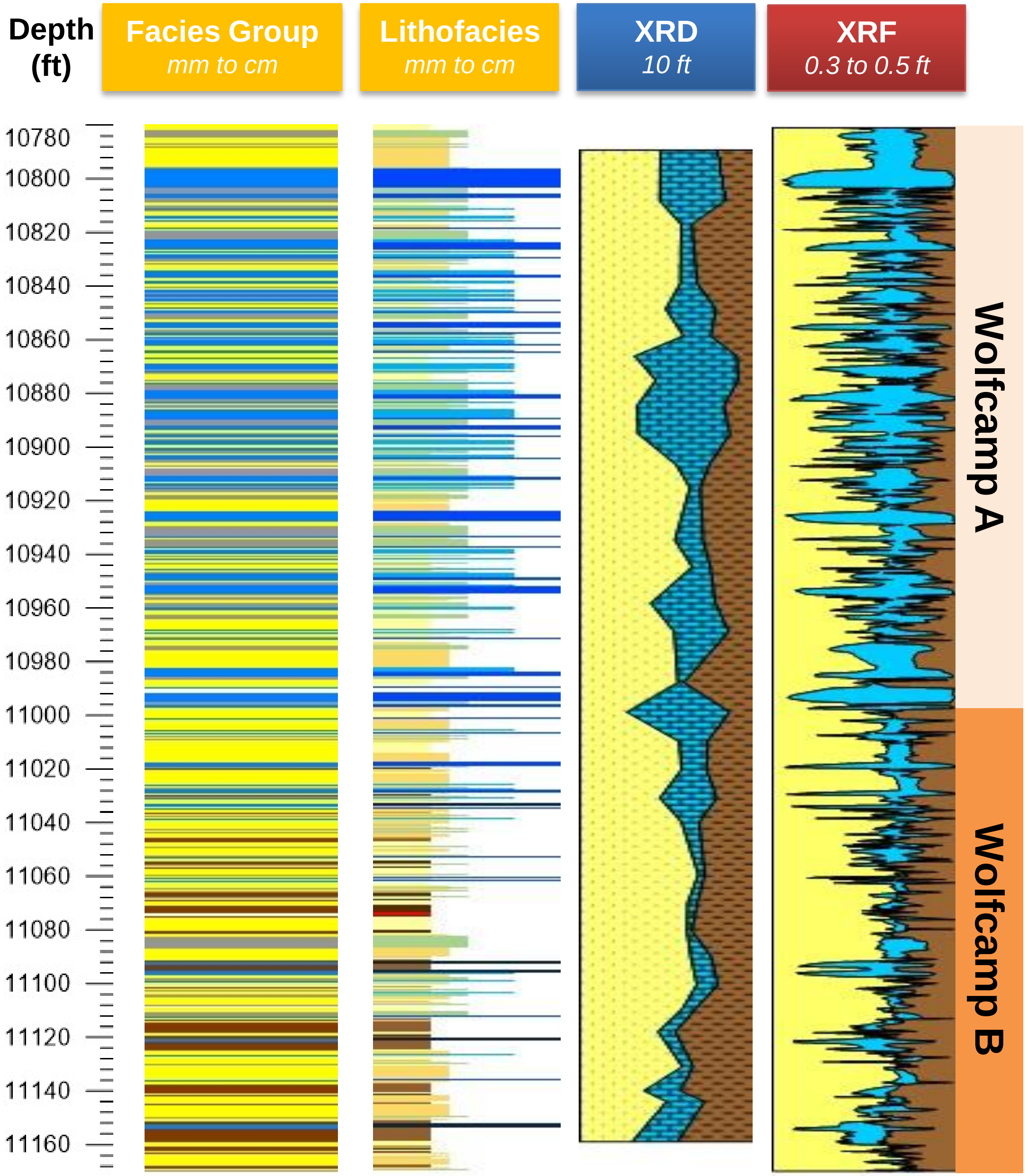
Integration of Elemental Analysis

What have we seen so far?

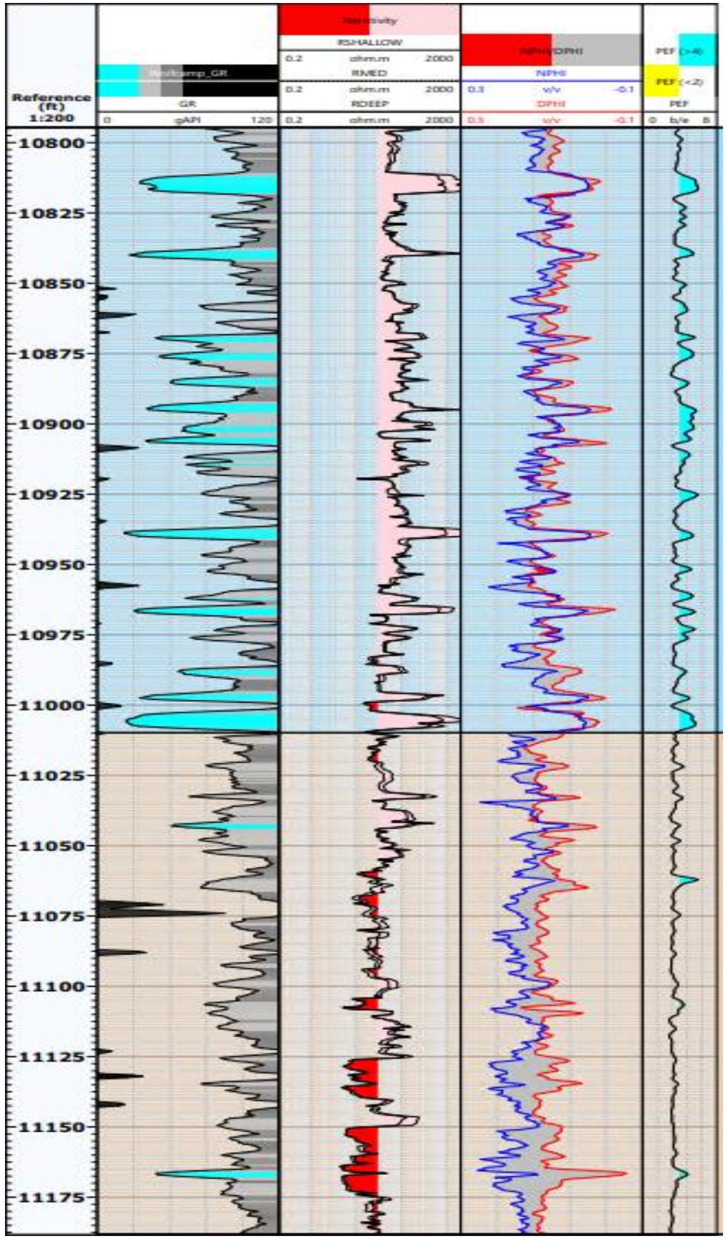
- 4 facies group and 9 lithofacies
- Facies distribution
- X-ray Diffraction and Routine Core Analysis
  - Around 10' intervals
  - Provides insight to mineralogy and reservoir properties at concrete points

To further reservoir characterization:

- High-resolution elemental data from XRF available for Wolfcamp A and B Cored Section (every 6")
- From XRD, three most abundant minerals make up 67% samples (Quartz, Calcite, and Illite)
- Mineral model (Nance and Rowe, 2015) approximates three mineral components based on stoichiometric relationships (Ca, K, and Si)



Bridging Core Calculated XRF GR to Wireline Log GR

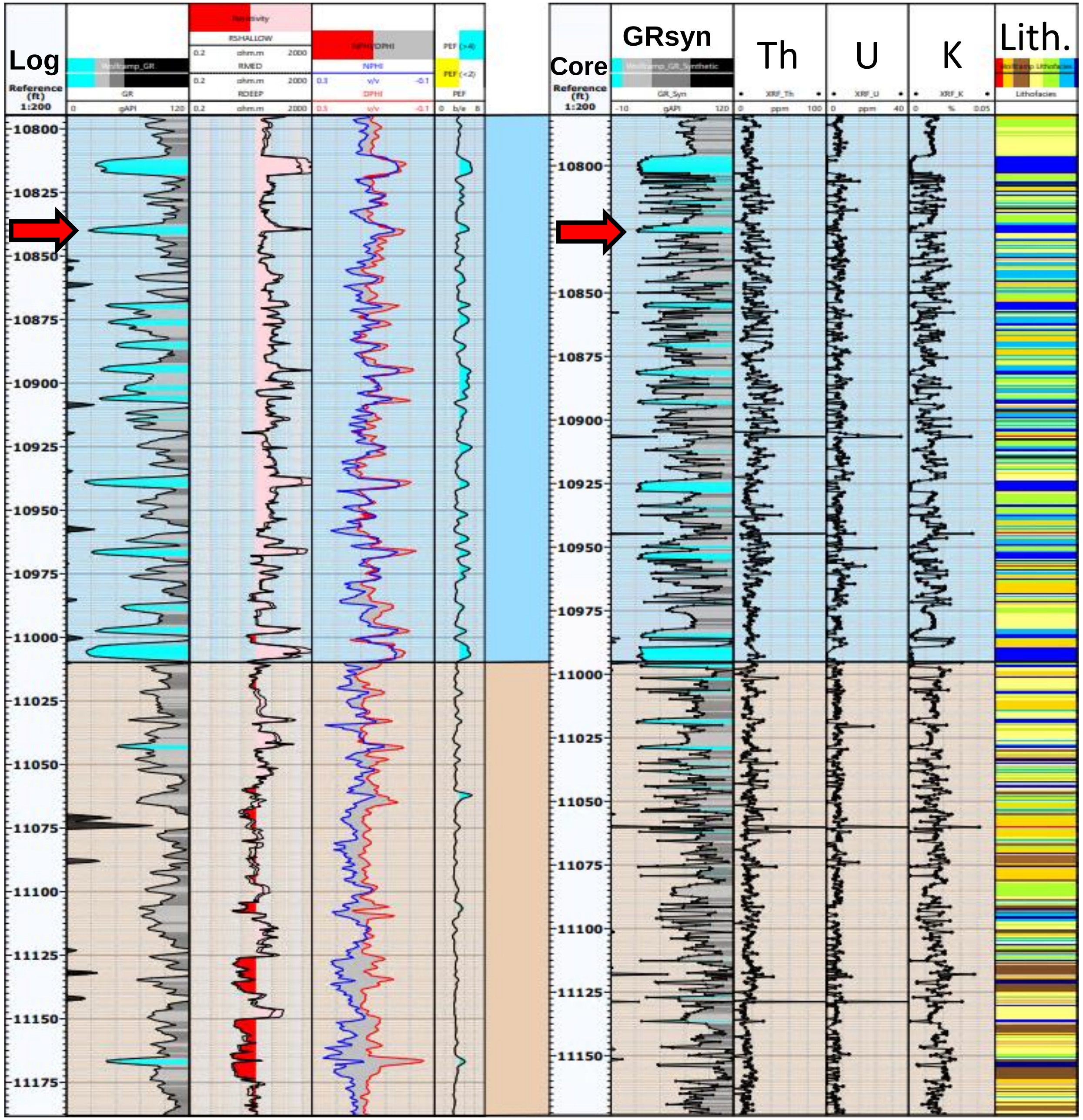


- **Wireline GR most common tool to discern lithology and correlate zones**
- **Standard Wireline GR tool has 12-in vertical resolution and 24-in depth of investigation**
- **Wireline GR prone to "shoulder effects"**

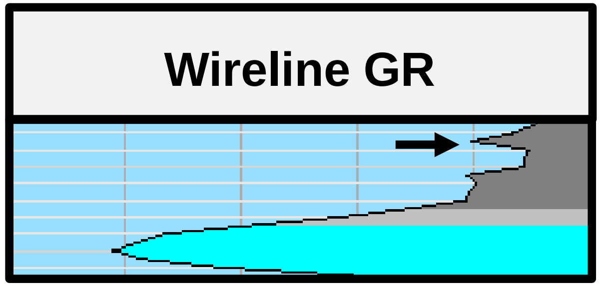
GRsyn calculated from XRF can show higher resolution profile:

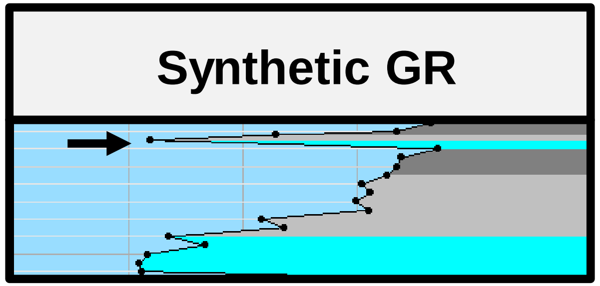
$$GR_{syn} = (3.93 * Th_{ppm}) + (8.09 * U_{ppm}) + (16.32 * K_{\%})$$

Bridging Core Calculated GR to Wireline Log GR



- **Wireline GR captures overall lithology characteristics**
- **Core-derived GRsyn provides insight to more realistic GR profile**

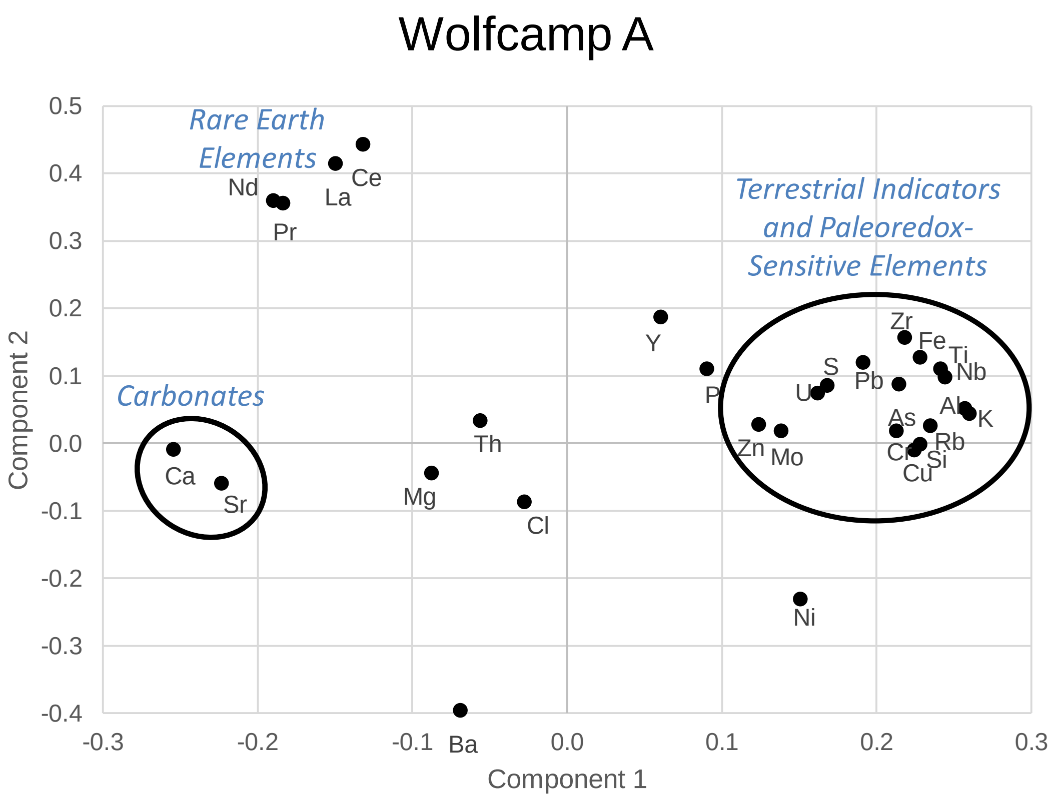


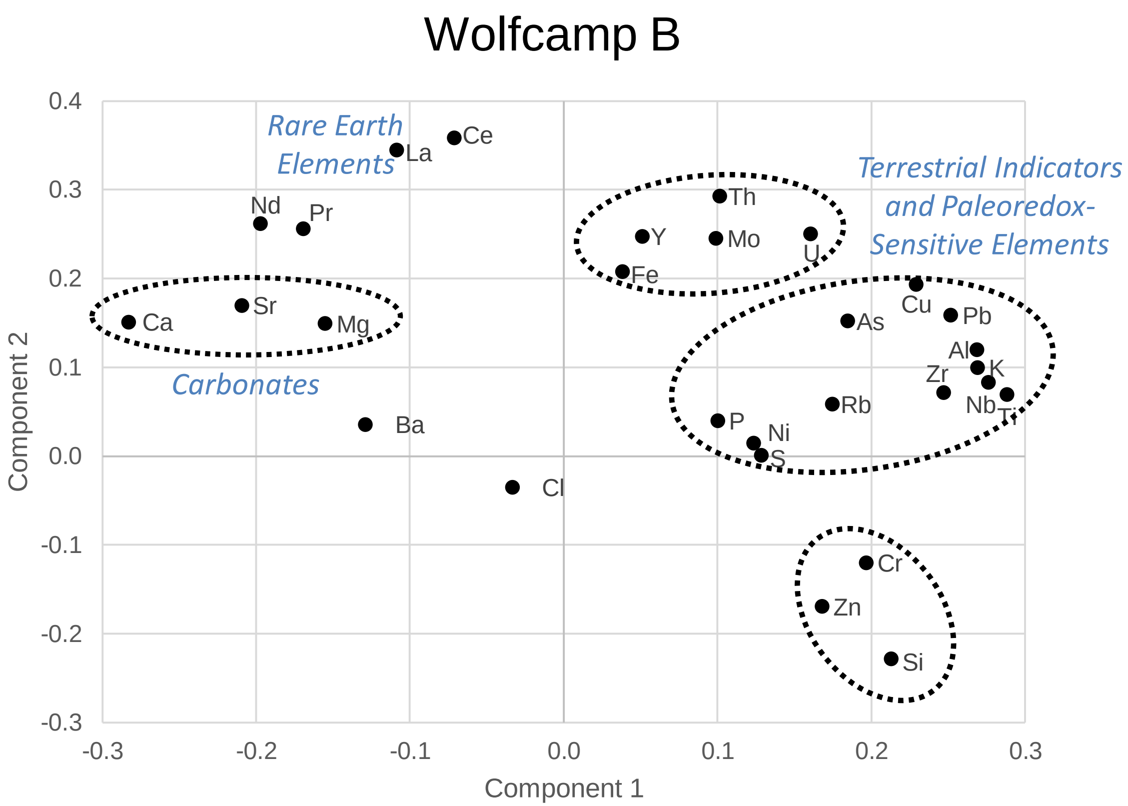


Wireline: Thin beds observed, not fully developed

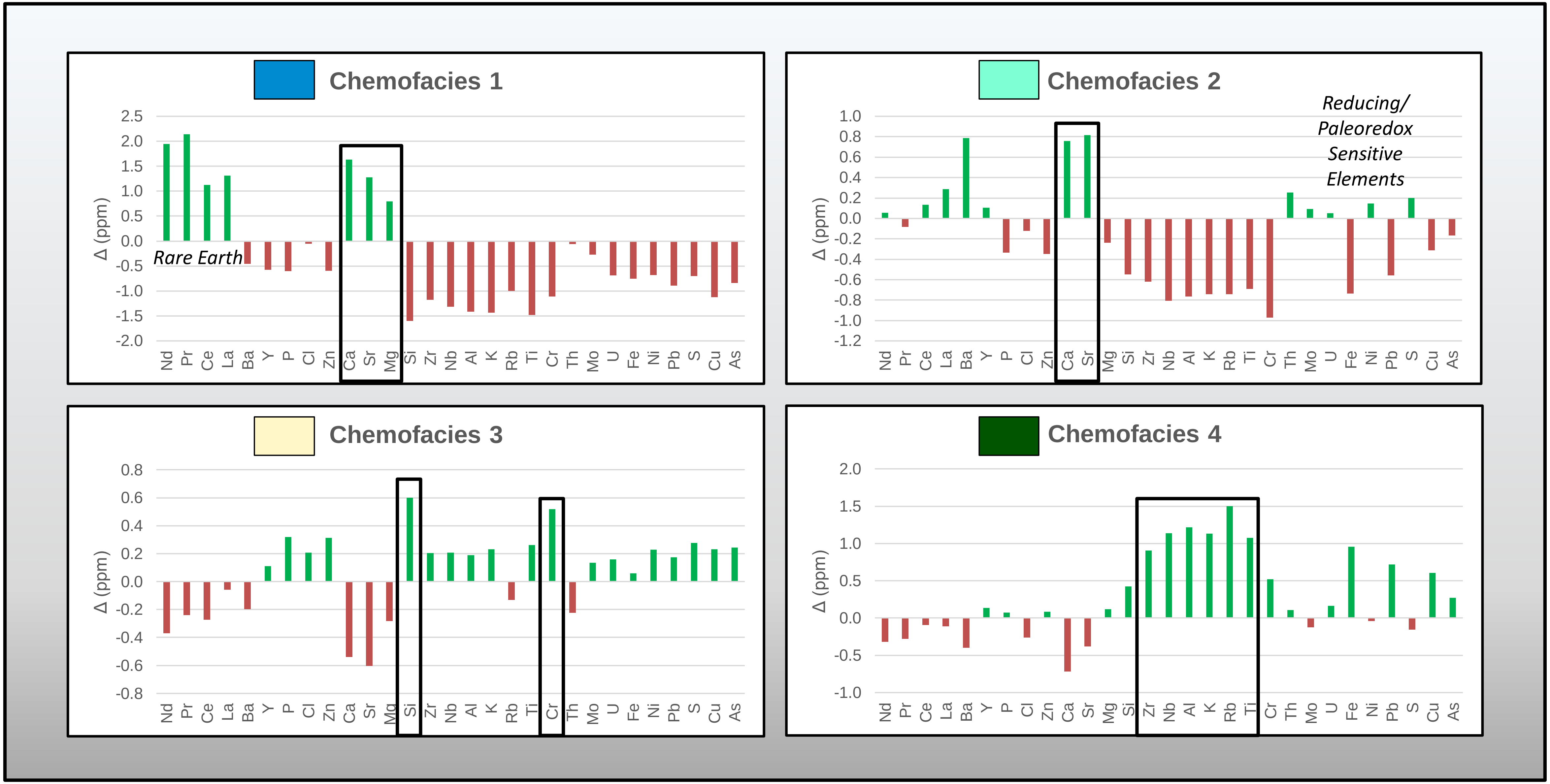
Statistical Methods to Define Chemofacies

- **41 elements analyzed from XRF**
- **Principal component analysis (PCA) and K-mean clustering methods used to find associations in elemental dataset**

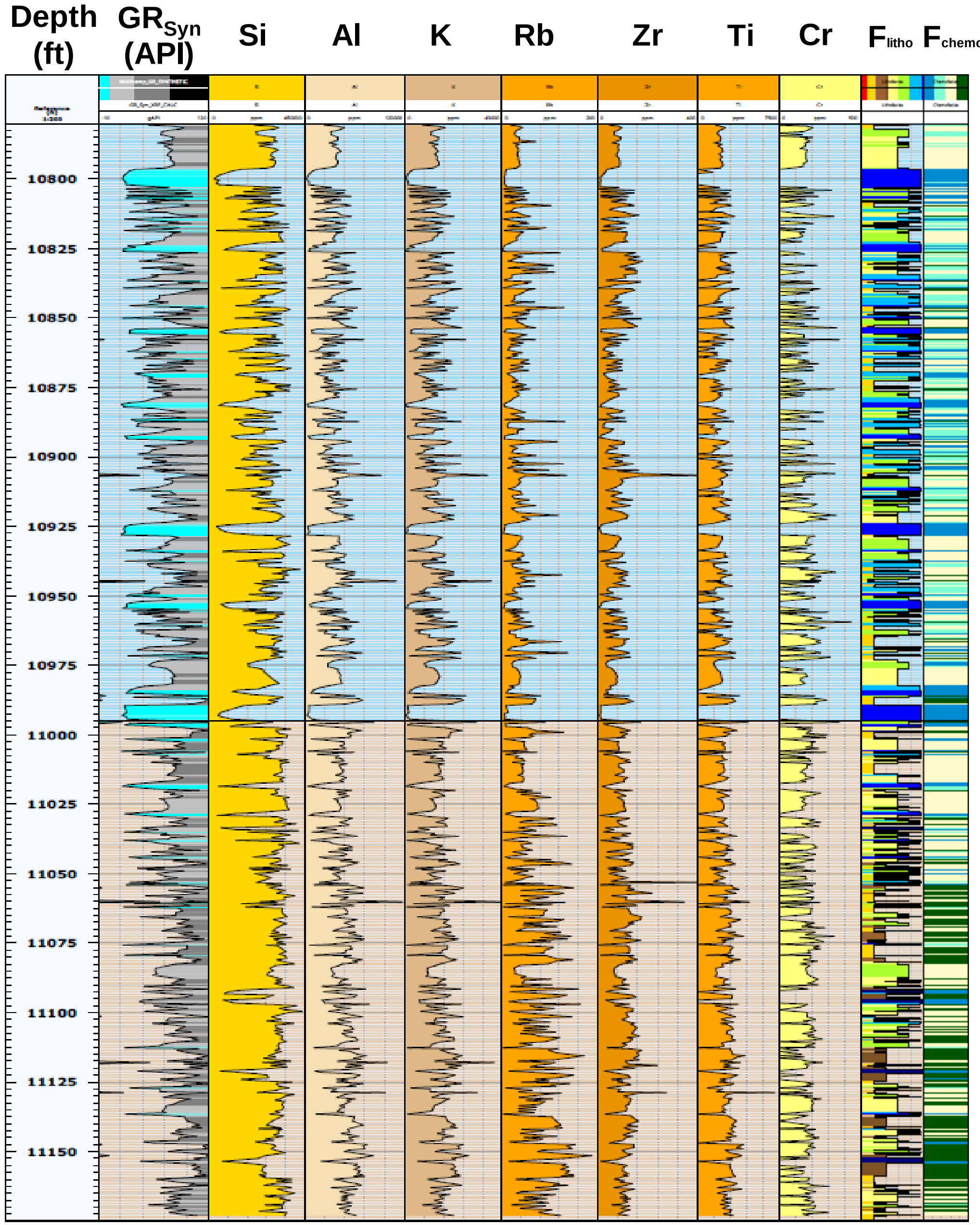




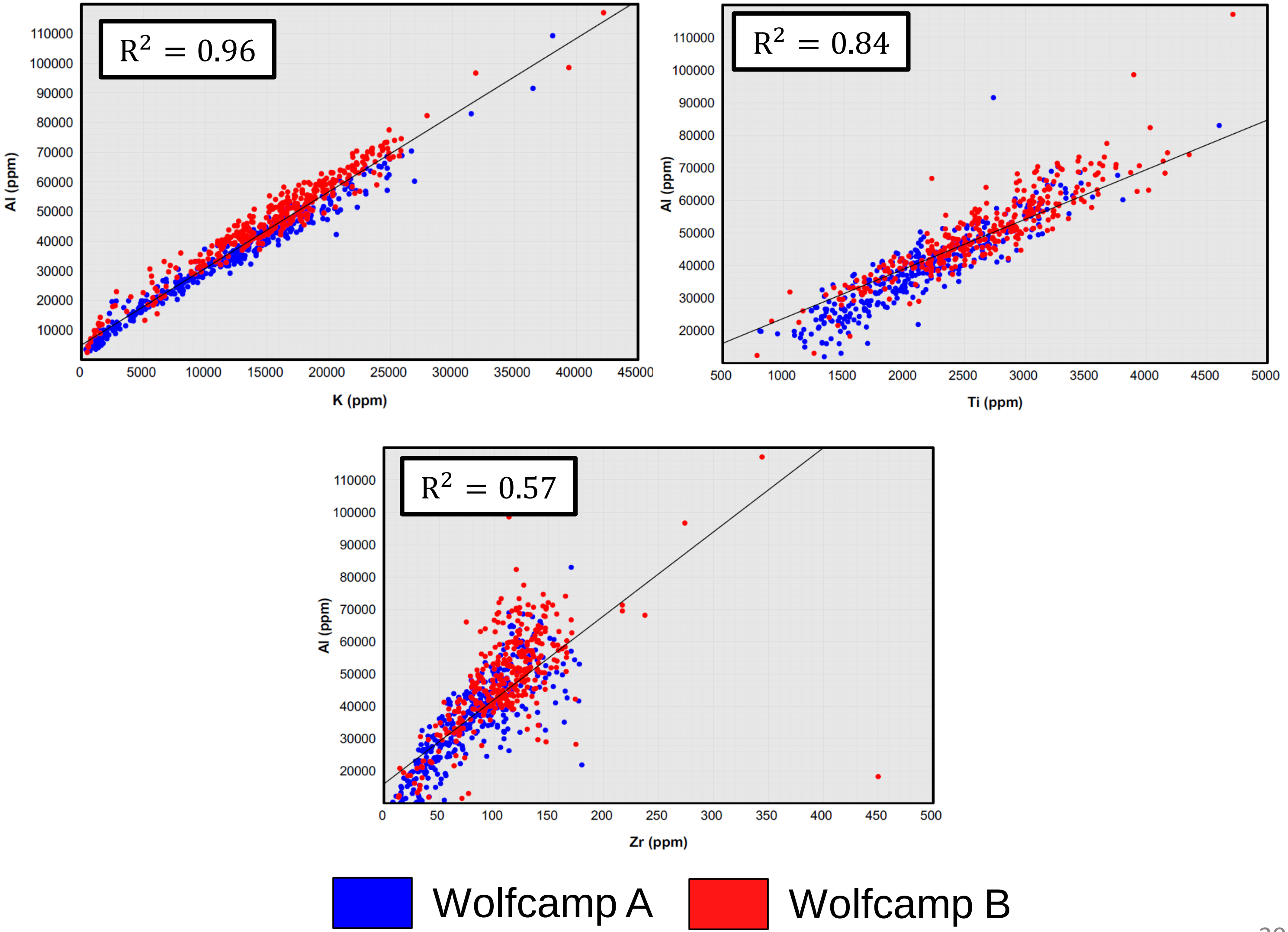
Statistical Methods to Define Chemofacies



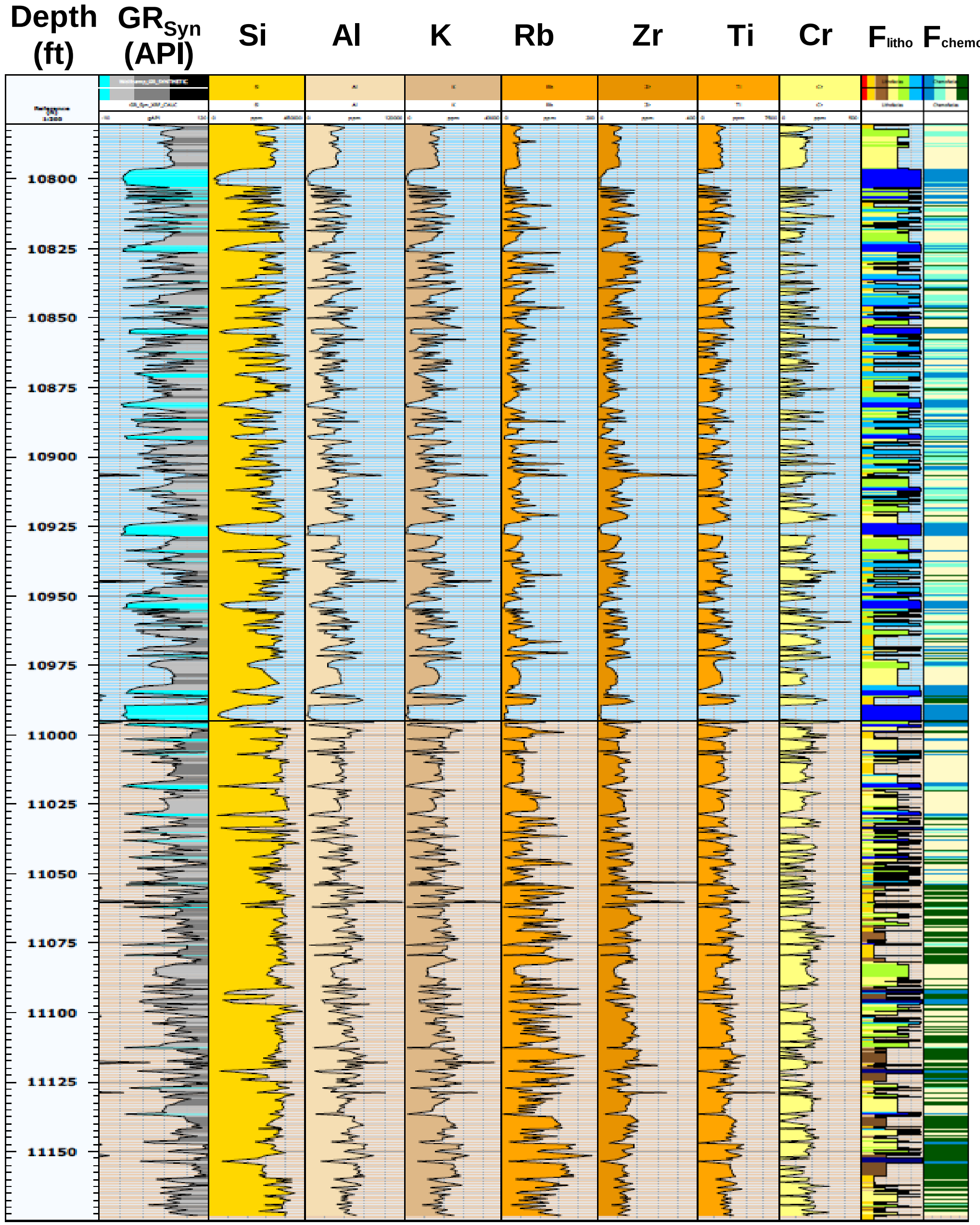
Terrestrial Indicators



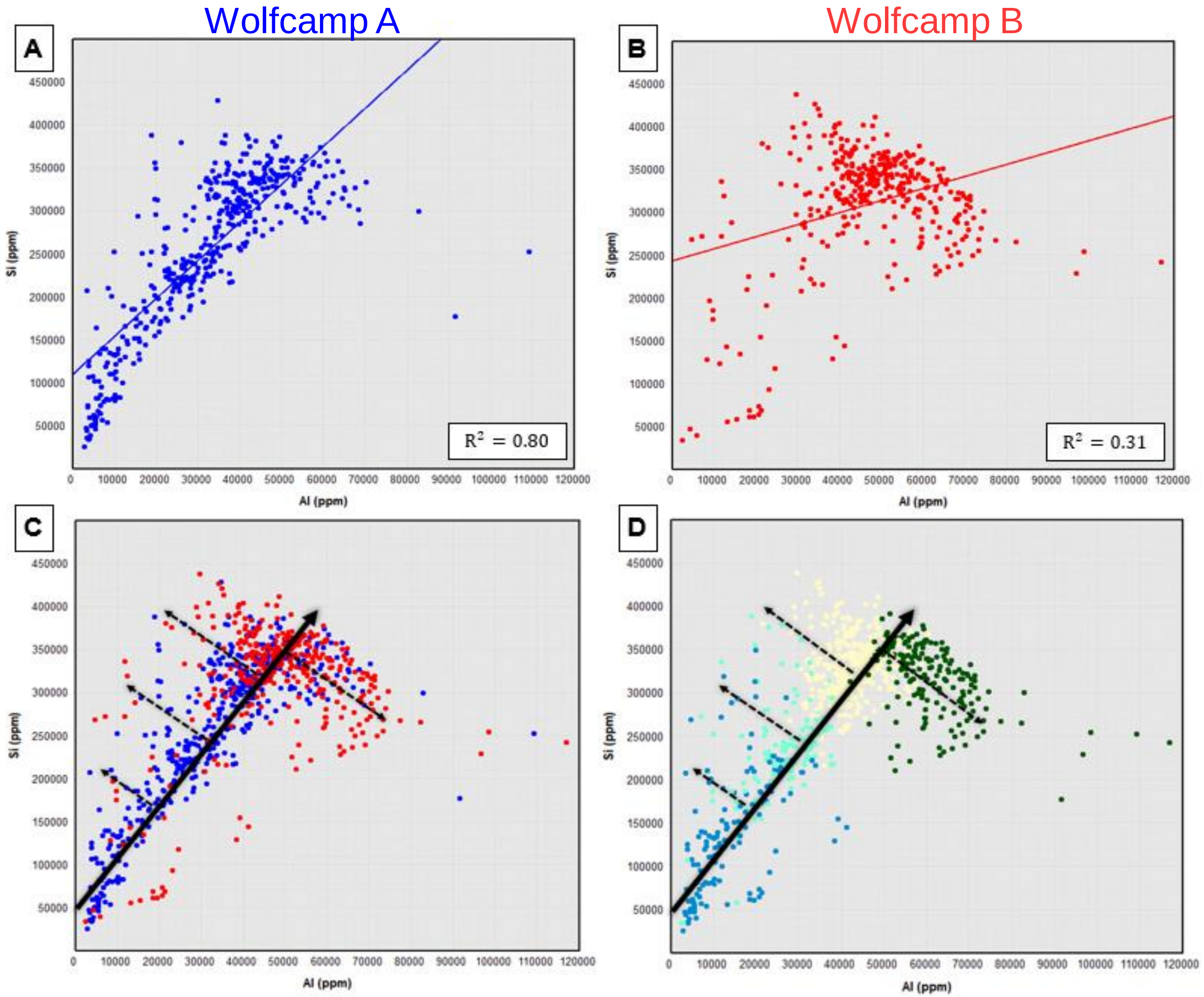
- **Moderate to strong correlations were observed for elements K, Ti, Zr, Rb, and Cr to Al for both Wolfcamp A and B**



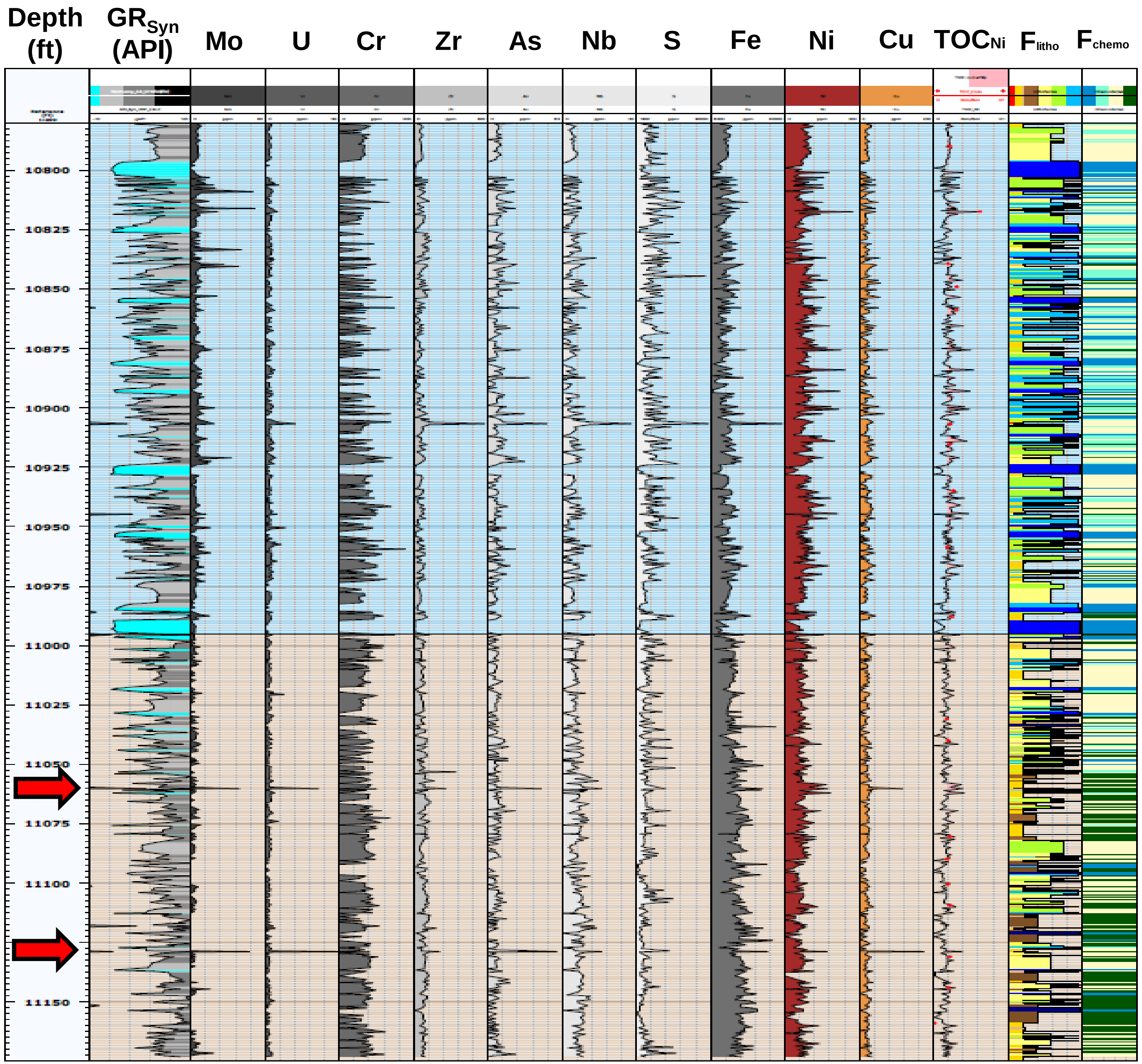
Terrestrial Indicators



- **Moderate to strong correlations were observed for elements K, Ti, Zr, Rb, and Cr to Al for both Wolfcamp A and B**
- **Si shows both detrital and authigenic/biogenic sources**



Paleoredox-Sensitive Elements

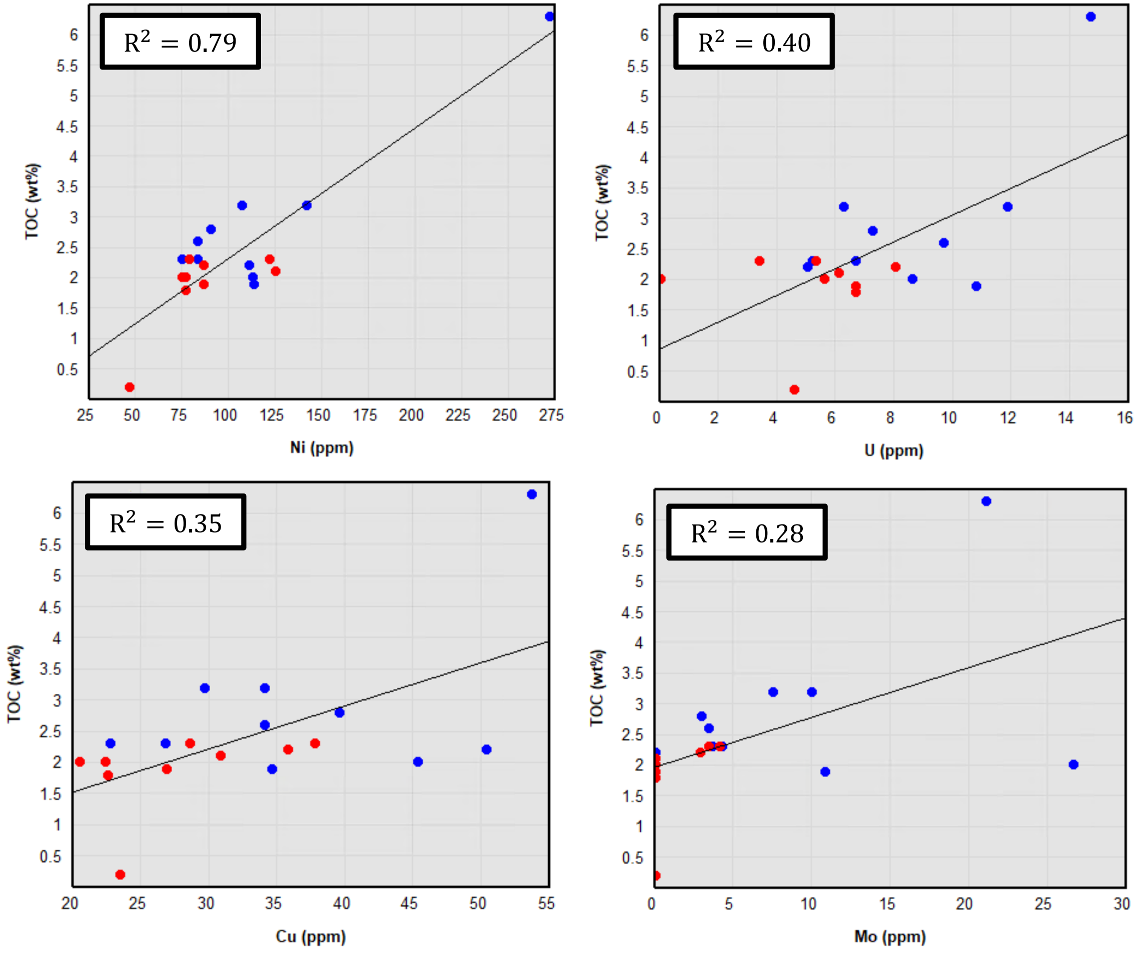


- **Pulses of elevated paleoredox-sensitive elements (no prolonged interval)**
- **Highest increases coincide with the Siliceous Mudstone lithofacies**

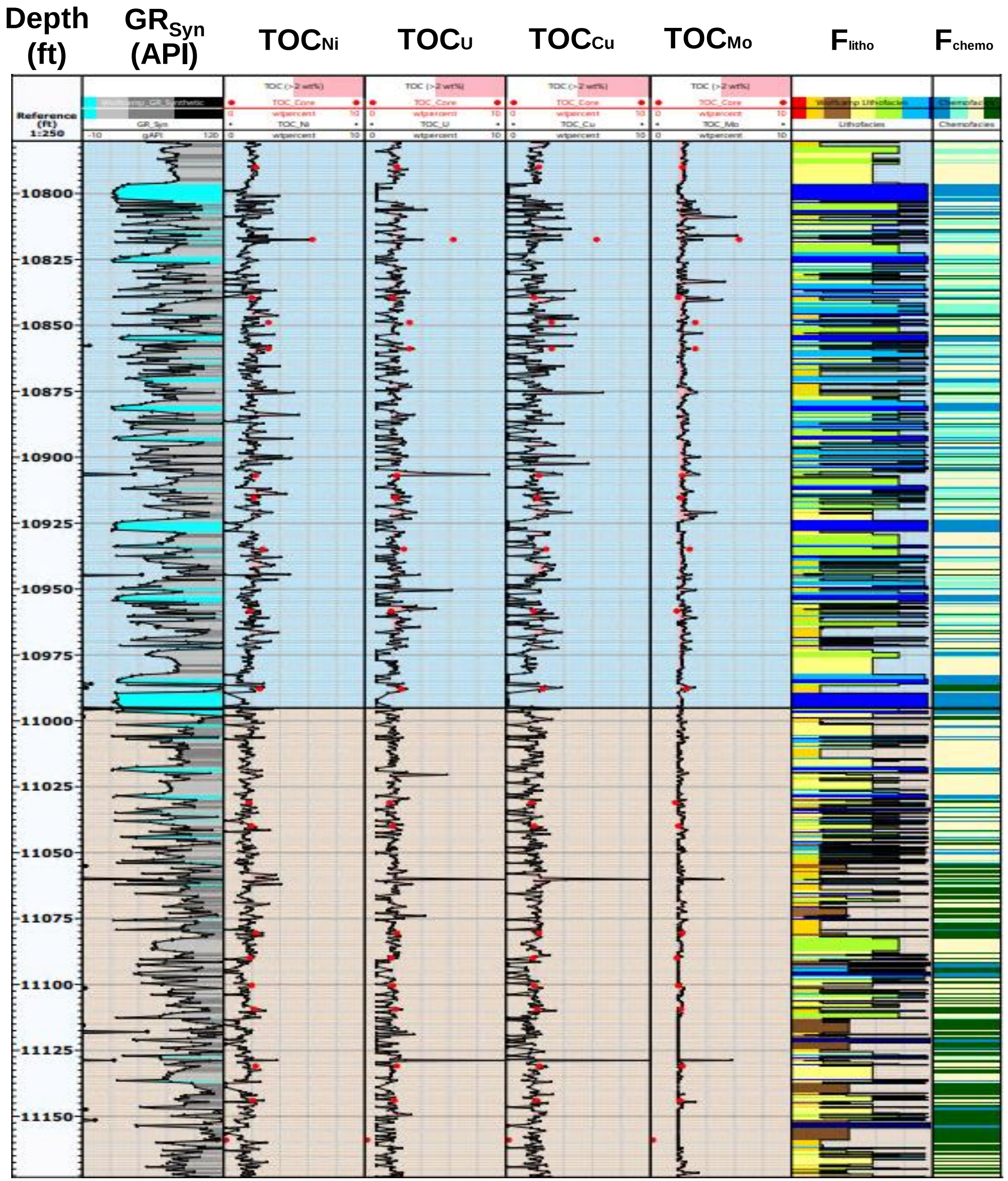
XRD confirms at 11,059.5 – Siliceous Mudstone
LECO TOC: 3.96 wt.%

Elements to TOC Associations

- **For sample depths with LECO TOC, paleoredox-sensitive elements and elements broadly associated with TOC were investigated**

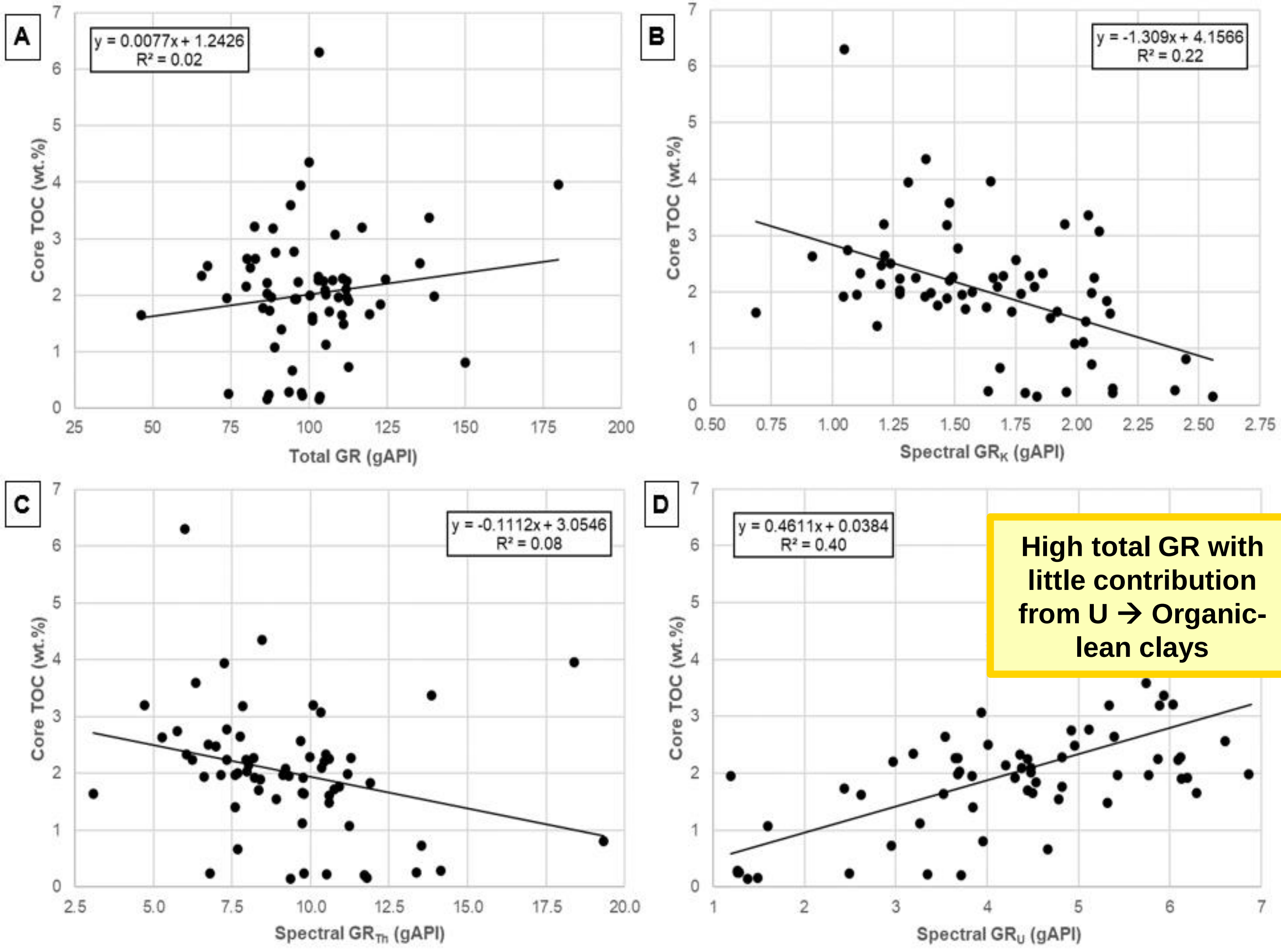


Wolfcamp A Wolfcamp B

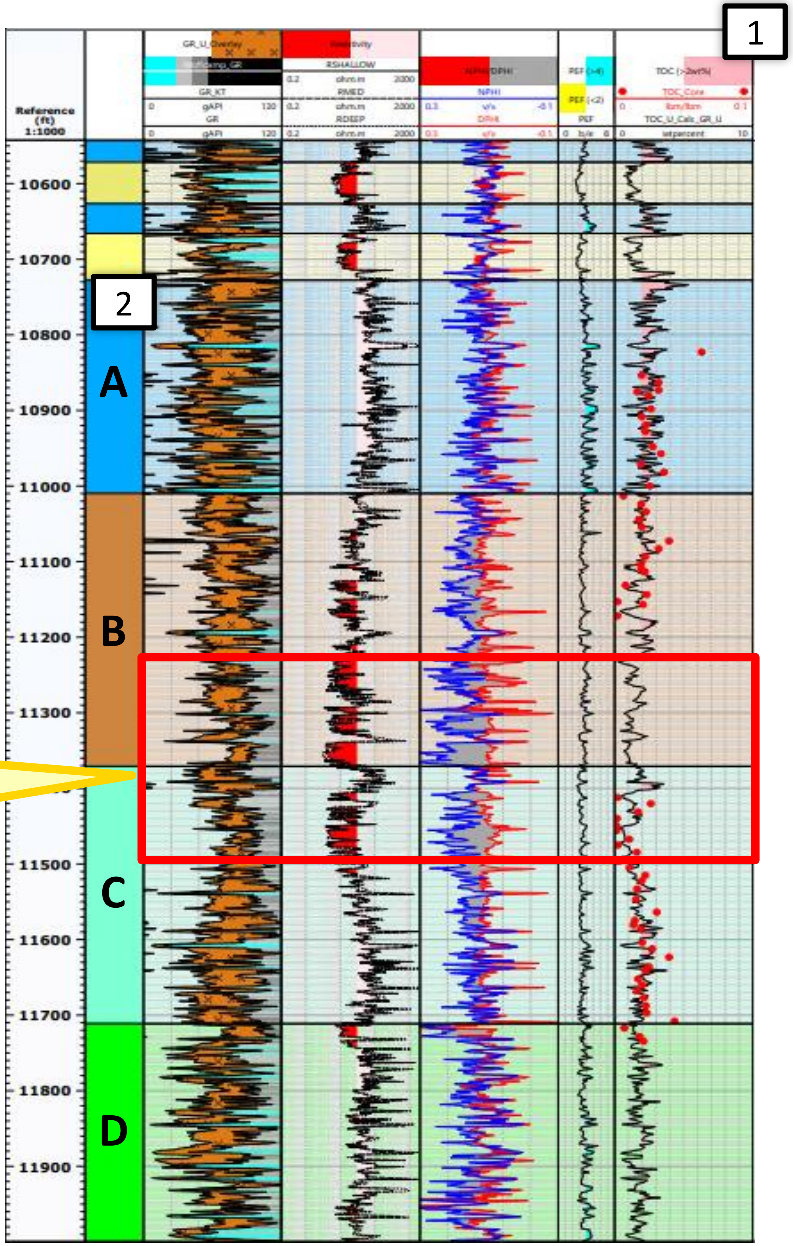


Wireline Spectral Gamma Ray Associations to TOC

- **Similar to Uranium (U) from XRF, Spectral GRU from wireline showed moderate correlation to TOC**



High total GR with little contribution from U → Organic-lean clays



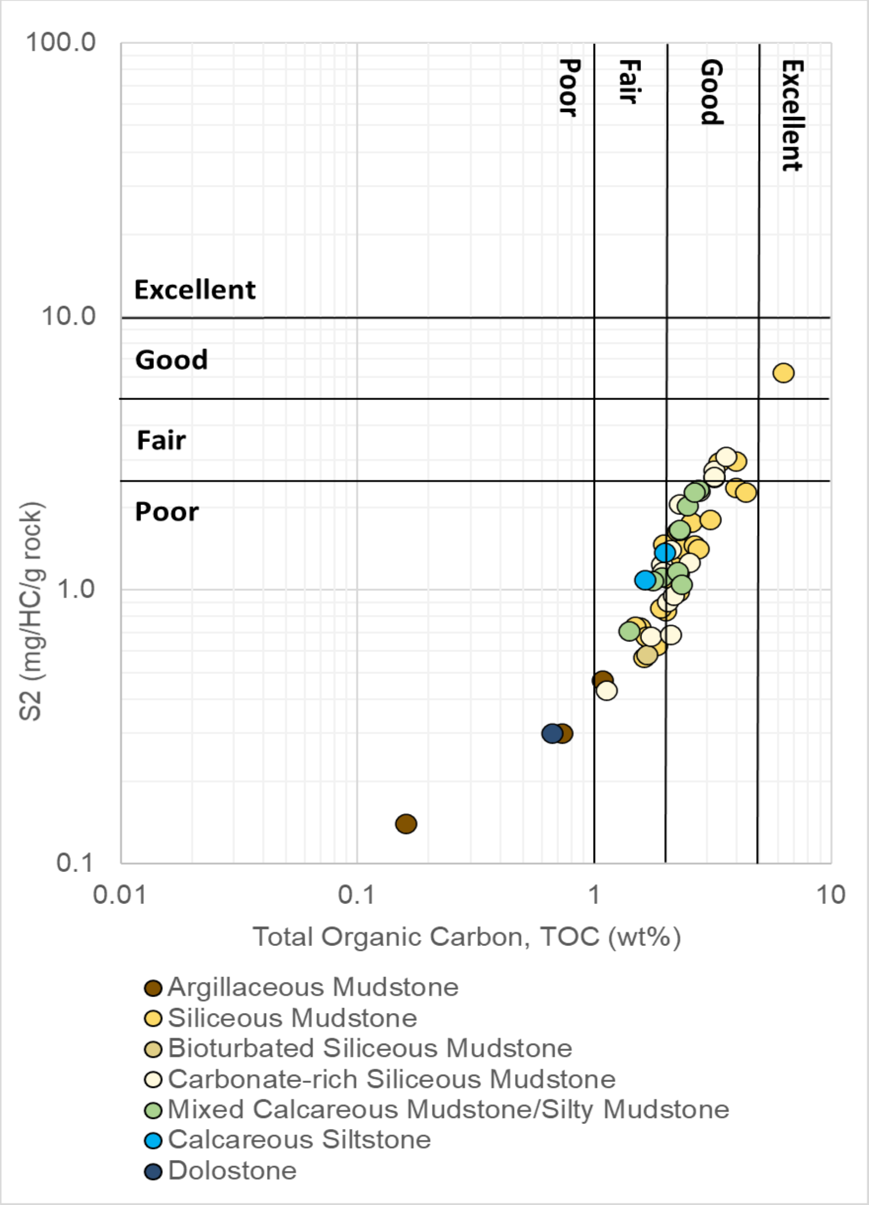
Quantity and Generative Potential of Organic Matter

- **Amount of organic matter quantified through total organic carbon (TOC)**

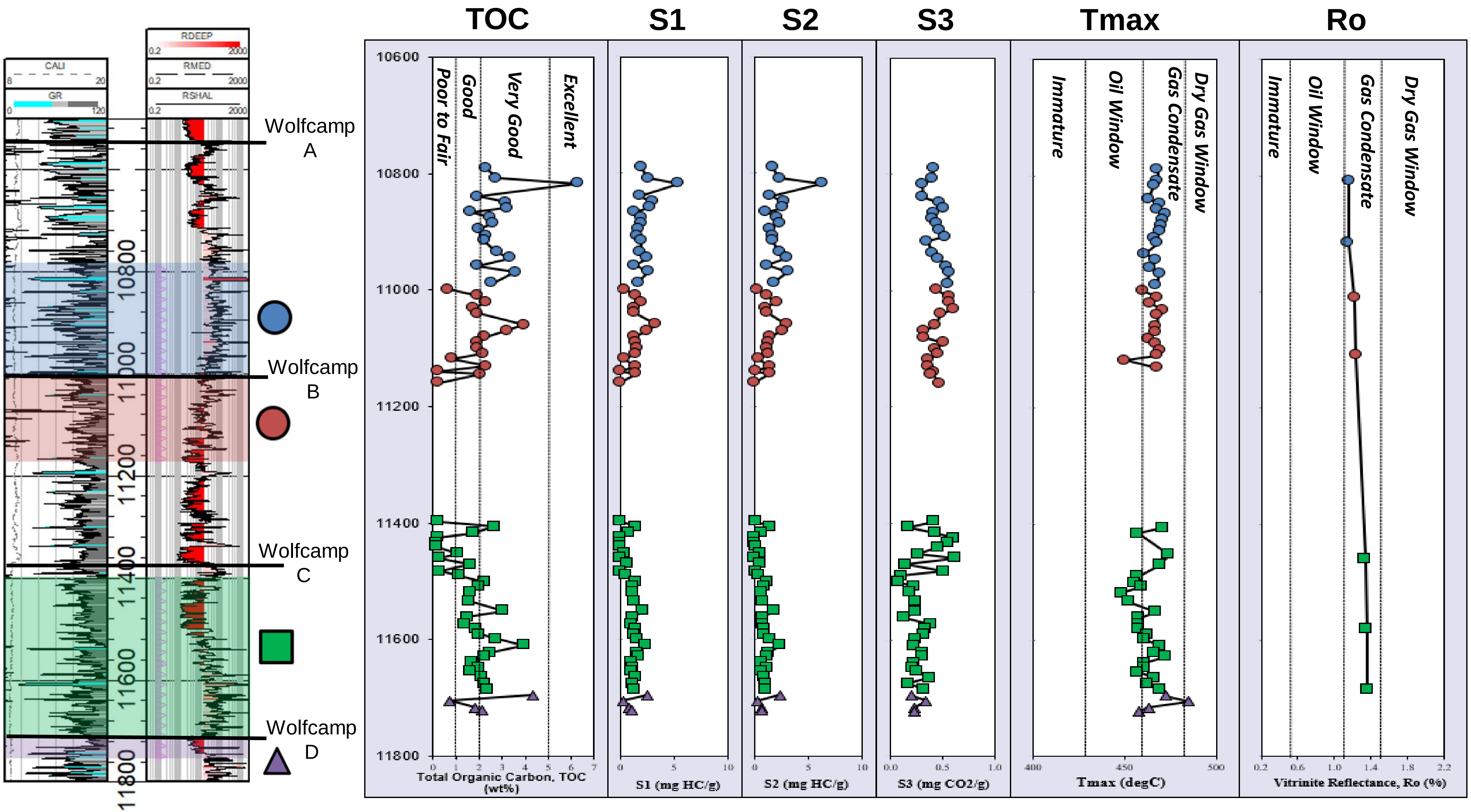
- **LECO TOC provided for 67 samples**

Lithofacies	Total Organic Carbon, TOC (wt.%)			Count, n (-)
	Minimum	Maximum	Average	
Siliceous Mudstone	1.5	6.3	2.6	26
Carbonate-rich Siliceous Mudstone	1.1	3.6	2.3	17
Mixed Calcareous Mudstone/Silty Mudstone	1.4	2.7	2.2	9
Calcareous Siltstone	1.6	2.0	1.8	2
Bioturbated Siliceous Mudstone	1.7	1.7	1.7	1
Dolostone	0.7	0.7	0.7	1
Argillaceous Mudstone	0.2	1.1	0.4	11

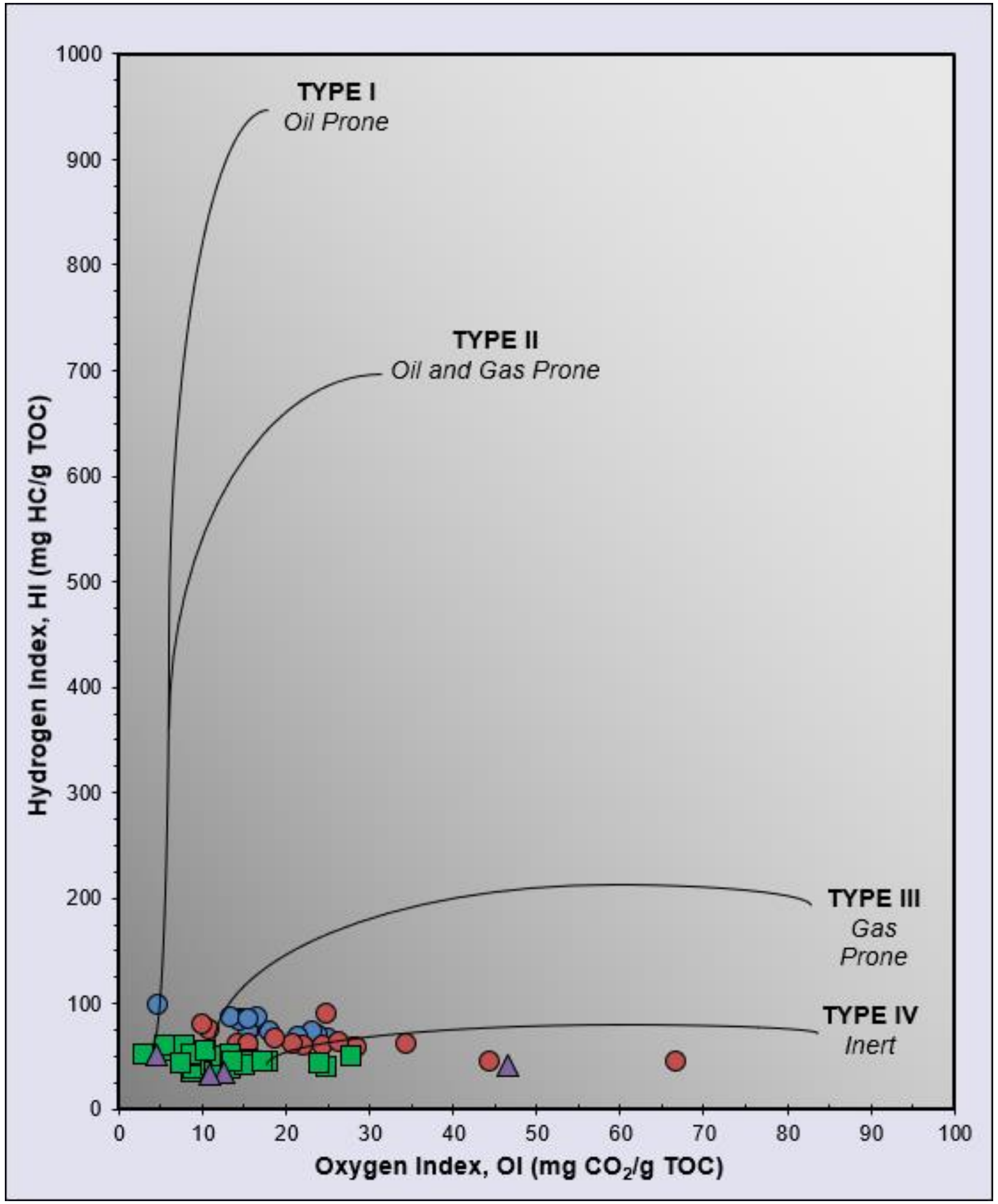
- **Rock-Eval S2 peak from pyrolysis (hydrocarbon generative potential)**

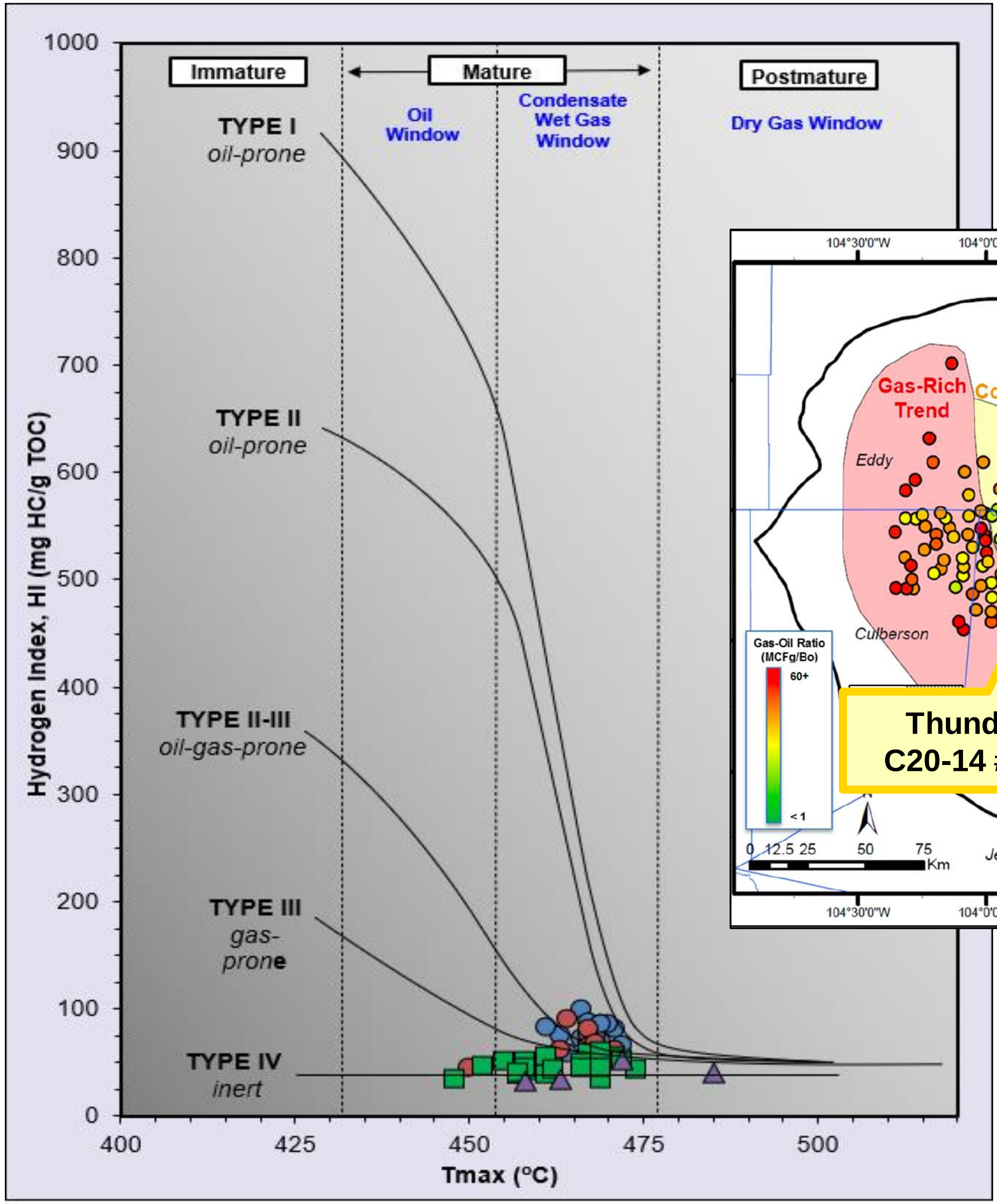


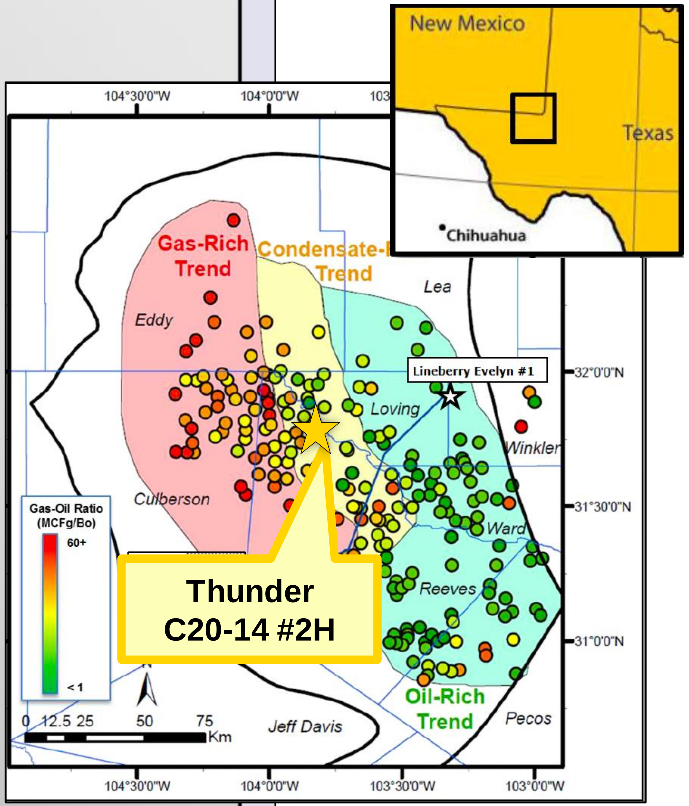
Source Rock Analysis



Kerogen Type and Maturity







Manos and Perez (2018)

Rock Strength (UCS)

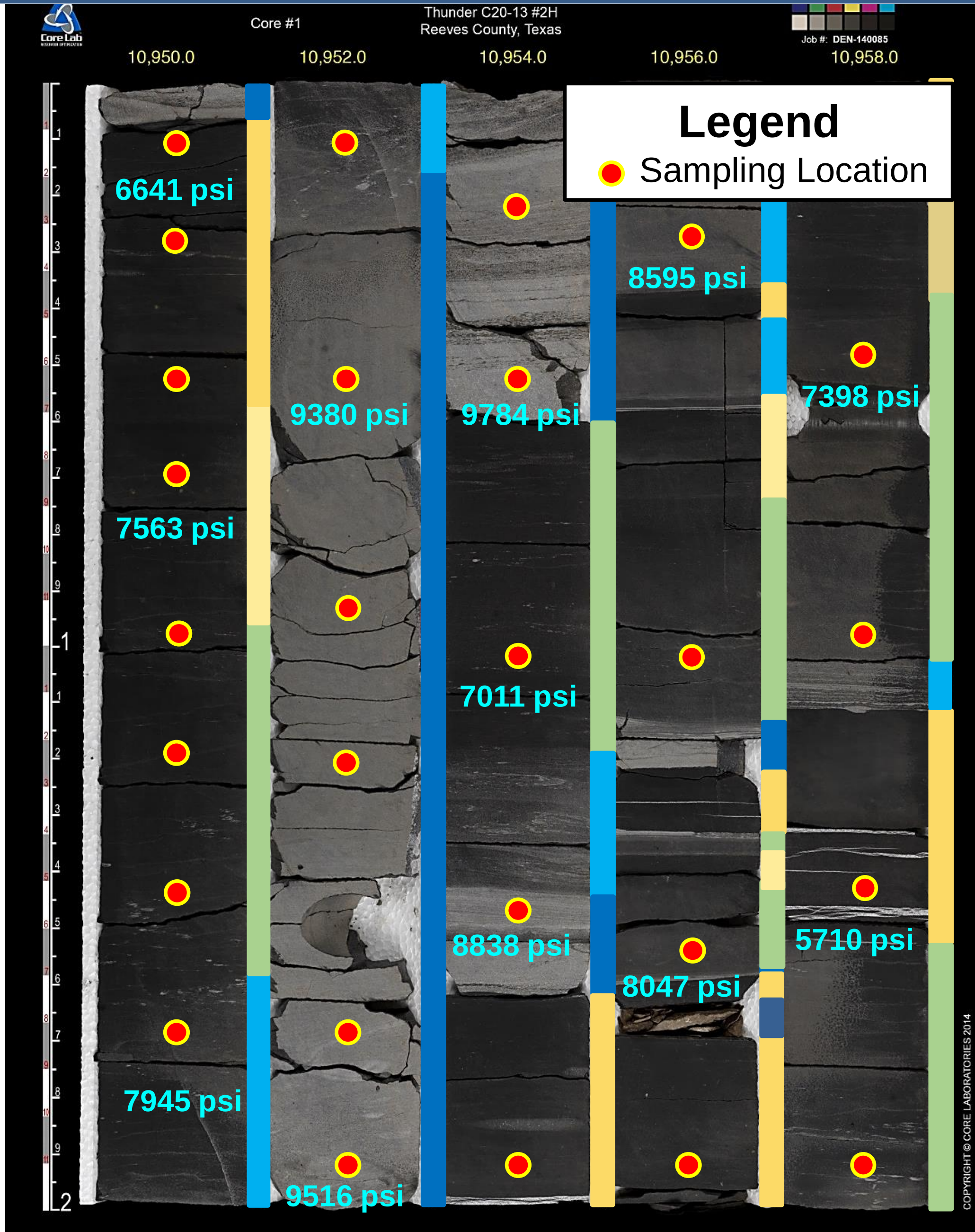
To evaluate the reservoir properties, analyses include:

- **SRA**
- **LECO TOC**
- **Porosity**
- **Permeability**
- **Water and HC saturations**
- **Rock strength (Unconfined Compressive Strength)**

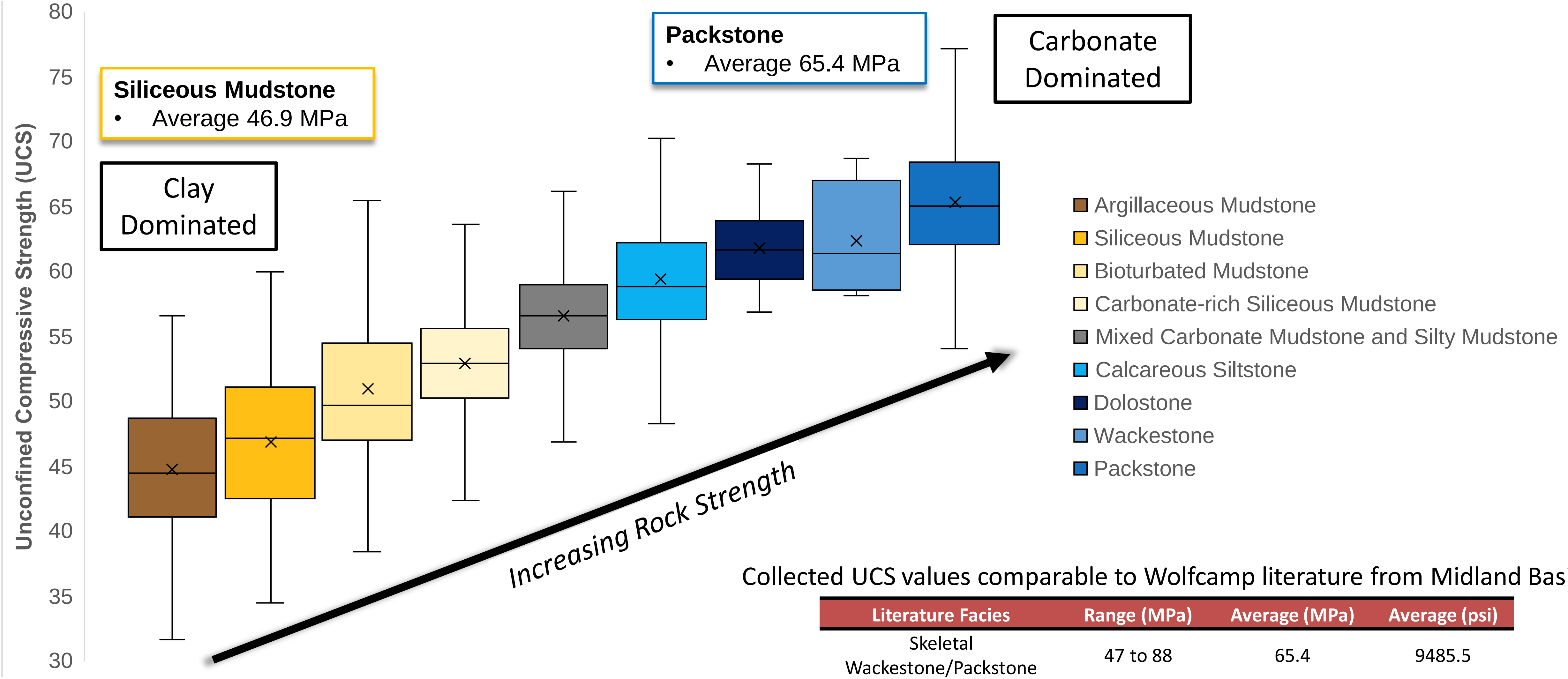
1,277 Depth Points Analyzed
(2- to 5-inch increments)

Why rock strength?

- **Important factor in fracture development (natural and hydraulically induced)**
- **Geomechanical properties to build geologic and frac models most often obtained from sonic scanner logging tools (Vertical resolution 2-5')**
- **Data acquired from core using a hand-held micro-rebound hammer can provide higher-resolution mechanical profile**



Rock Strength by Facies



Collected UCS values comparable to Wolfcamp literature from Midland Basin

Literature Facies	Range (MPa)	Average (MPa)	Average (psi)
Skeletal Wackestone/Packstone	47 to 88	65.4	9485.5
Siliceous Mudrocks	30 to 59	44.1	6396.2

Baumgardner and Others (2016)

Reservoir Quality by Facies

Depositional Facies	TOC (wt.%) (0–3)	Porosity (%) (0–12)	Permeability (nD) (0–110)	UCS (MPa) (40–66)	Reservoir/ Nonreservoir Designations
	Reservoir Properties Summary				
Siliceous Mudstone	2.6	9.4	57.9	46.9	Source/Reservoir
Bioturbated Siliceous Mudstone	1.7	8.5	108.0	50.9	Reservoir
Carbonate-rich Siliceous Mudstone	2.3	8.0	44.8	53.0	Reservoir
Mixed Calcareous Silty Mudstone	2.2	7.1	103.7	56.5	Reservoir
Calcareous Siltstone	1.8	5.7	59.7	59.2	Nonreservoir
Dolostone	0.7	6.1	11.2	61.8	Nonreservoir
Packstone				65.4	Nonreservoir
Argillaceous Mudstone	0.4	9.9	1.3	44.7	Nonreservoir

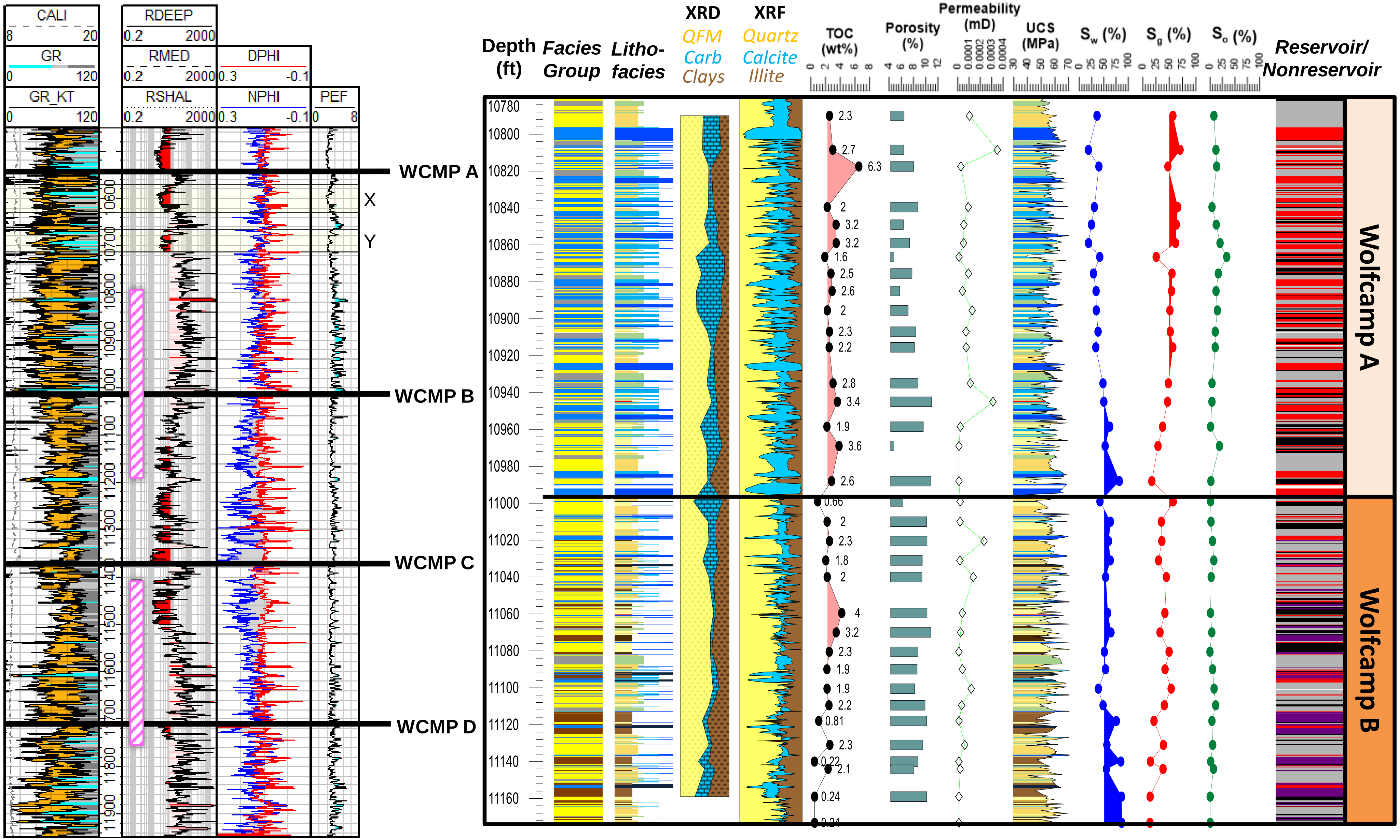
Source/Reservoir
- Highest TOC (up to 6.3 wt.%)
- Low Rock Strength
- High Porosity

Reservoir
- Good TOC (mostly >2 wt.%)
- Good Porosity
- Intermediate Rock Strength

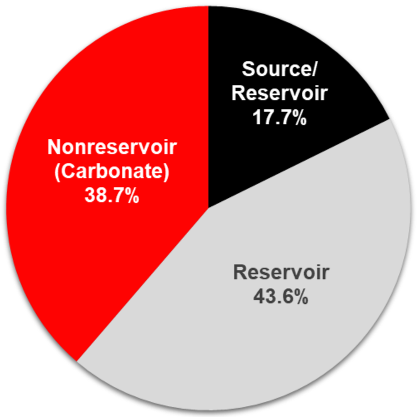
Nonreservoir (Carbonate)
- Low TOC
- High Rock Strength
- Potential Seal/Baffle

Nonreservoir (Argillaceous)
- Lowest TOC and Permeability
- Low Rock Strength
- High Water Saturation

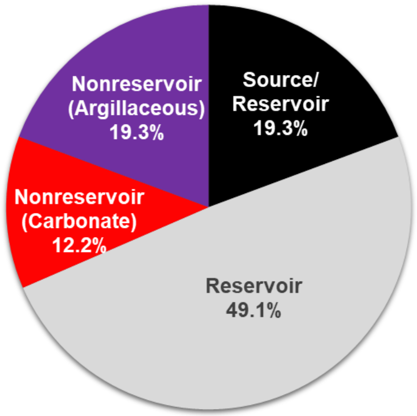
Wolfcamp A and B Reservoir Characterization



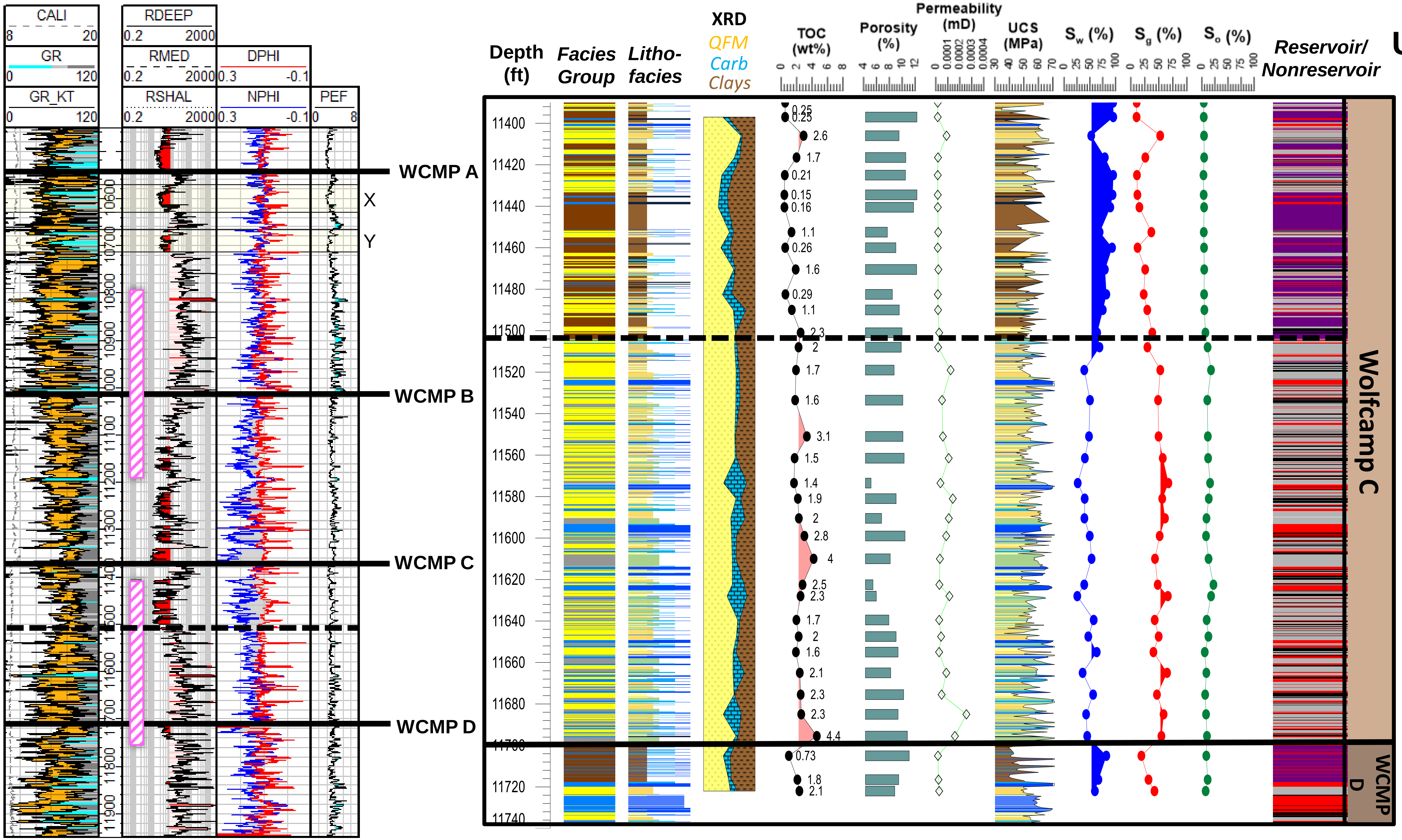
Wolfcamp A



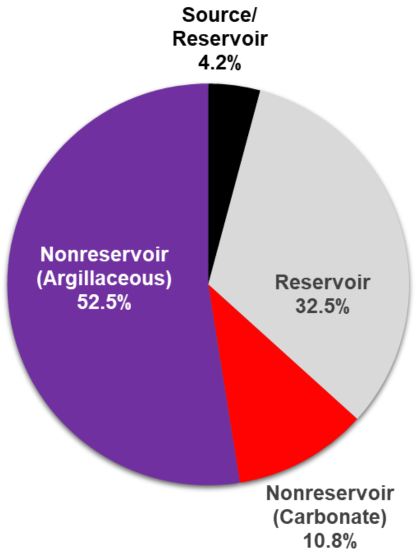
Wolfcamp B



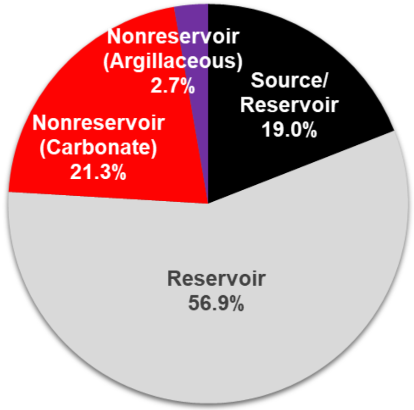
Wolfcamp C Reservoir Characterization



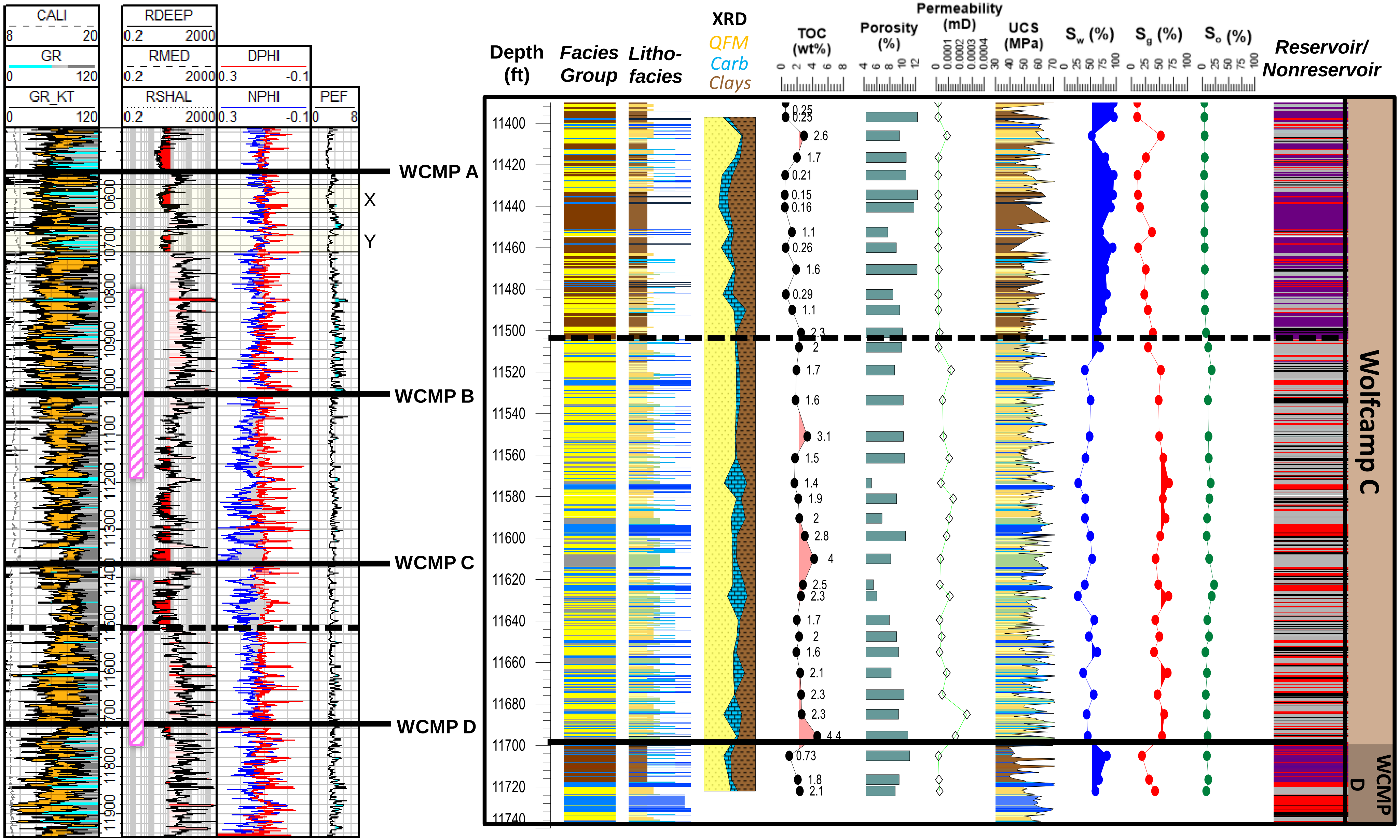
Upper Wolfcamp C



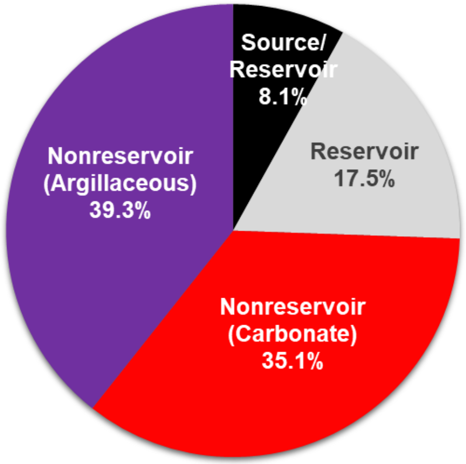
Middle to Lower Wolfcamp C



Wolfcamp D Reservoir Characterization



Wolfcamp D



- Highly stratified
- Reservoir facies abundant
  - WCMP A (61%)
  - WCMP B (70%)
  - WCMP C Upper (37%)
  - WCMP C Lower (76%)
  - WCMP D (26%)
- Variation in nonreservoir facies

Conclusions

- **From core description, 4 facies group and 9 lithofacies were defined and described**
- **Facies distribution for Wolfcamp A, B, C, and D show carbonate- and siliciclastic-dominated zones within intervals**
- **High abundances of paleoredox-sensitive indicators found in interbedded in both Wolfcamp A and B, associated with siliceous mudstones (very fine grain size, high TOC, phosphate nodules and beef fractures)**
- **Elements with most correlated to Core TOC are Ni, U and Cu**
- **U from spectral GR can be used to approximate organic richness from ties to core analysis**
- **Wolfcamp A through top of D in the location of the Thunder in northeast Reeves county is in the gas condensate window**

Conclusions

- **Four designations of source/reservoir, reservoir and two nonreservoir based on reservoir properties**

- **Cored intervals showed reservoir facies are abundant:**
    - **Wolfcamp A (61%)**
    - **Wolfcamp B (70%)**
    - **Wolfcamp C – Middle to Lower (75.9%)**

- **Zones that are potential baffles with high nonreservoir facies:**
    - **Wolfcamp B – Lower (not cored)**
    - **Wolfcamp C – Upper**

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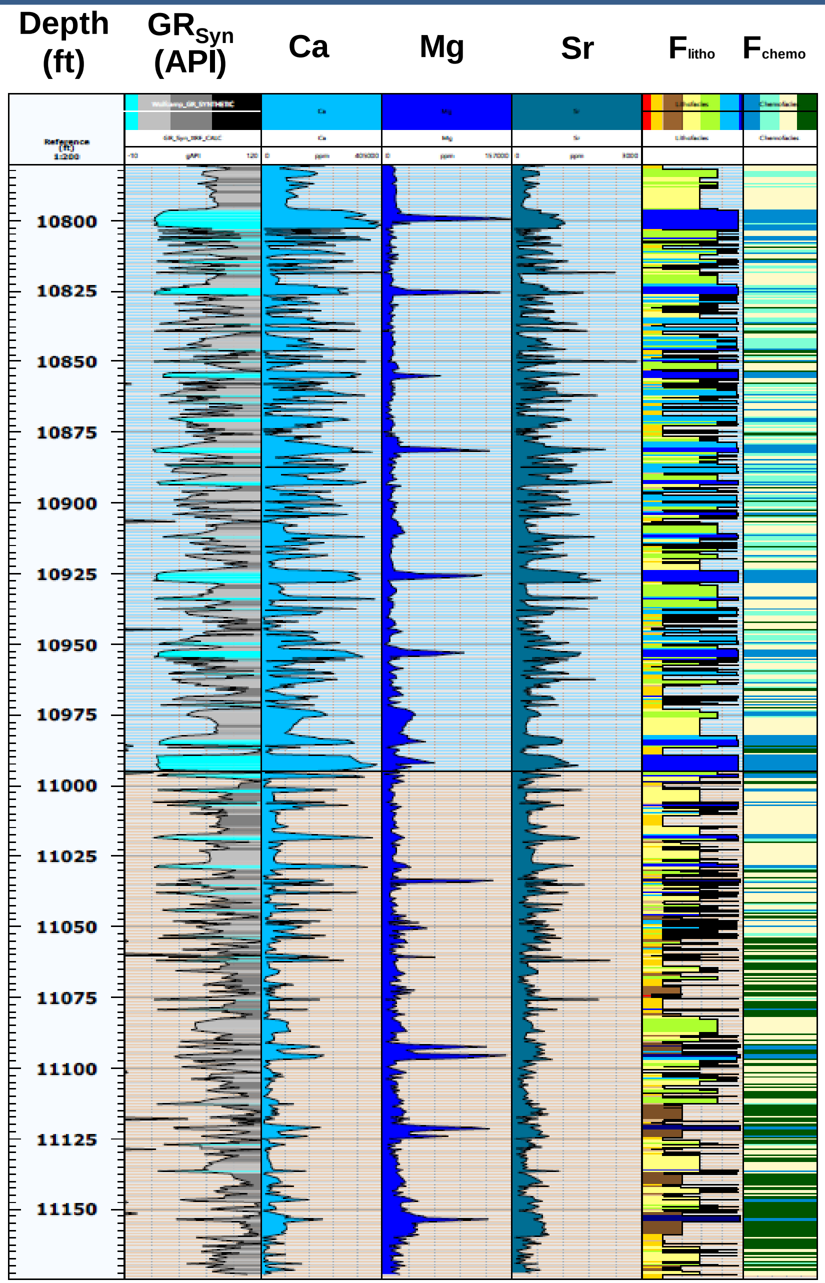
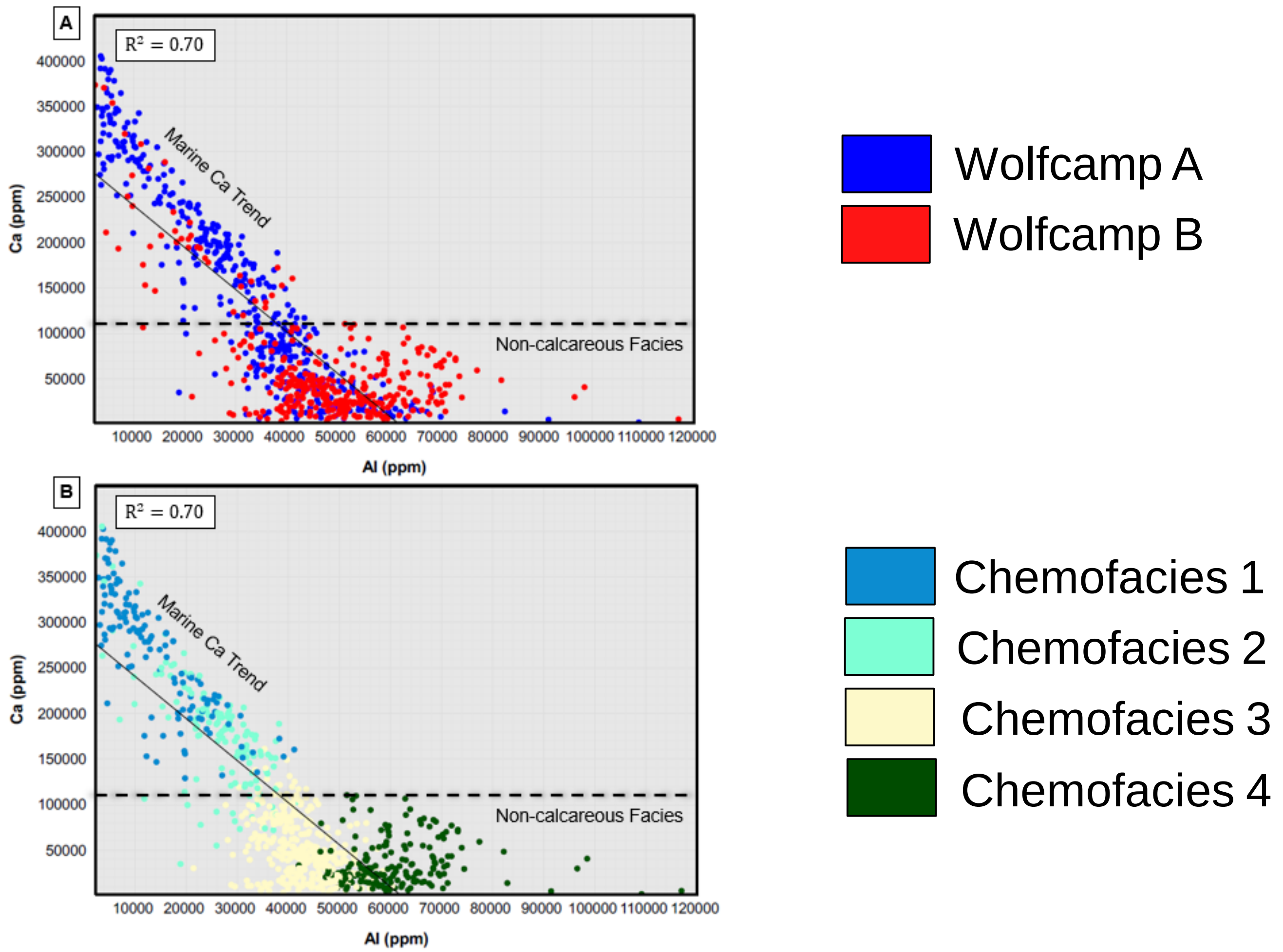
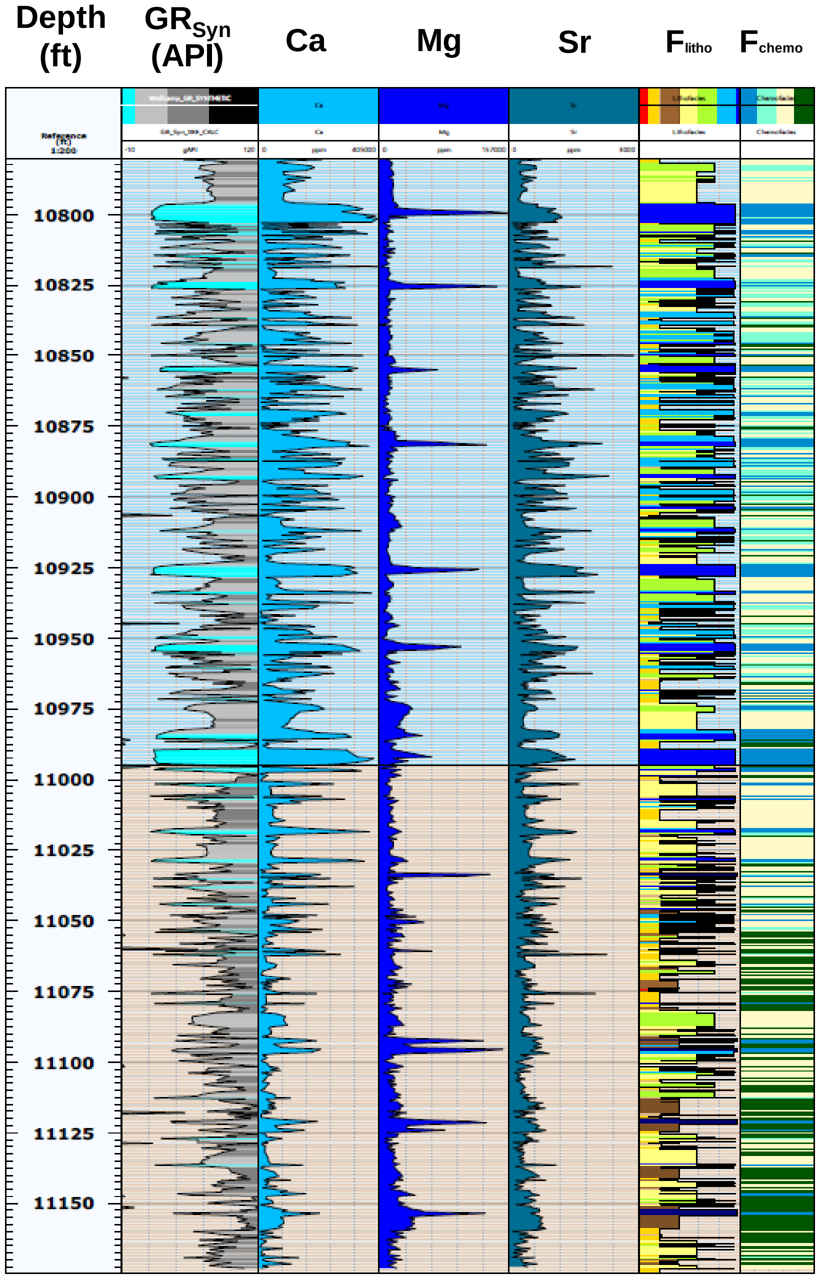


- **Elements associated with carbonate influx: Ca, Sr and Mg**
- **Ca primary cation for calcite and dolomite (can also be detrital from anorthite $CaAl_2Si_2O_8$ → not found to be in this case)**



Carbonate Indicators



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