Advancing Reservoir Performance

An Integrated Petrophysical Characterization of Shale Gas Reservoirs

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October 2009

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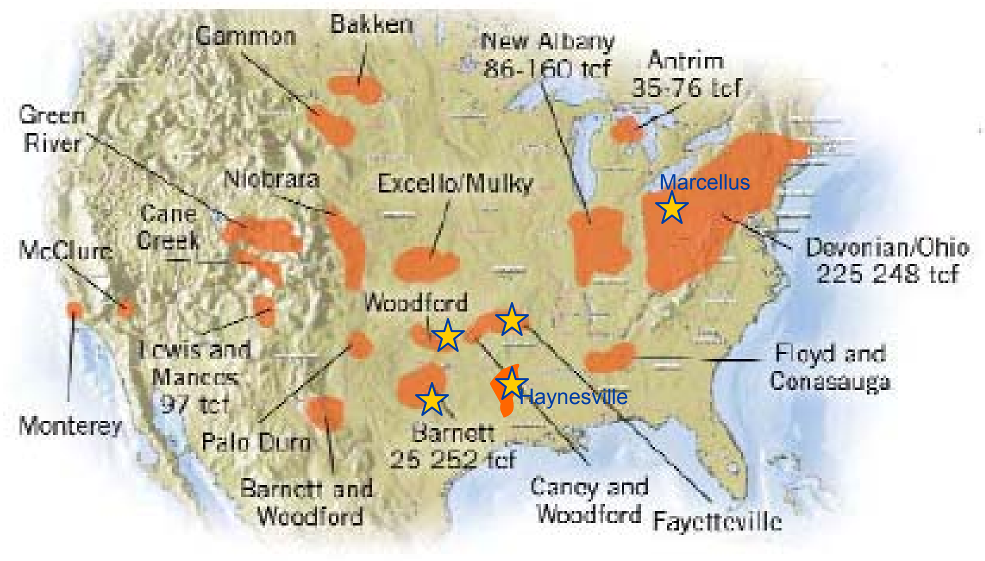
Shale Gas Reservoir Characteristics

-Gas Shales are composed of fine- grained detrital matrices of silt to clay sized fractions of organic matter, quartz, feldspars, clay minerals, calcite, dolomite and other minerals, the amounts of which vary with each play

– The complex matrices serve as both seal, reservoir, and source for the gas

– Must be fracture stimulated to produce at economic rates



Oil and Gas Investor 2007

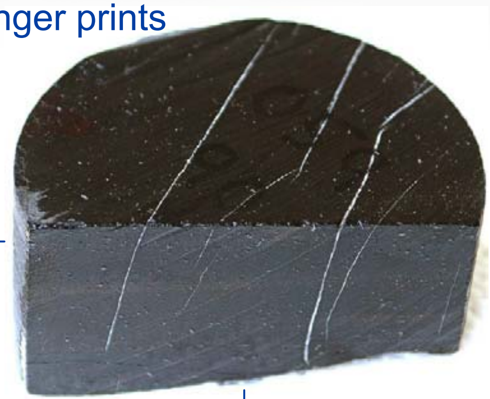
Difficult to predict the success of stimulation strategies → Due to the lack of petrophysical models that can predict the reservoir properties that contribute to the success or failure of stimulation

Shale Gas Reservoir Characteristics

Reservoir properties must be evaluated in terms of......

- Mineralogy
- Total Organic Content (TOC) – Kerogen Type and Maturation
- Porosity
- Permeability – Measured in Nanodarcies
- Total Gas in Place (GIP) – Adsorbed, Free and Absorbed
- Stress regime
- Mechanical Rock Properties
- Open or Mineralized Fractures

Lithofacies are geochemical finger prints



Provenance

Environment of Deposition

Reservoir properties must be understood in reference to…….

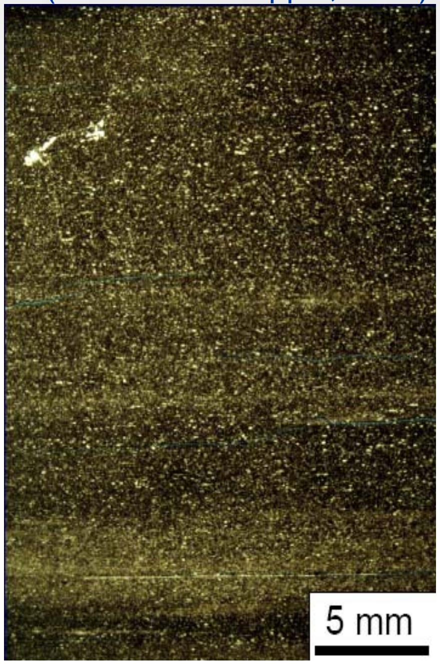
★ **Lithofacies** ★

Contents

- Why is it important in terms of reservoir stimulation strategies to identify lithofacies in Shale Gas reservoirs?
- In addition to identifying lithofacies, what other important properties are needed to develop an integrated petrophysical model?
-
- Introduce the Integrated Petrophysical Model – “Gas Shale Lithofacies Model” developed for characterizing the Barnett Shale
- Show two well examples showing the effectiveness of the model for predicting favorable zones for hydraulic fracturing versus non- favorable - compare accumulative gas production from each
- Goal for the development of the “ Gas Shale Lithofacies Model”
- Conclusion

Identify Lithofacies that Promote Production: Favorable for Recovery of Gas

(Loucks and Ruppel, 2007)



Siliceous Mudstones: Barnett Shale

45% quartz ;
27% illite with very minor smectite;
8% calcite + dolomite;
7% feldspar;
5% organic matter;
5% pyrite;
3% siderite;
and trace amounts of copper and phosphatic materials.

(Bowker, 2002)

Why? Geomechanical properties of these lithofacies are conducive to forming extensive open fracture fairways for recovery of gas.

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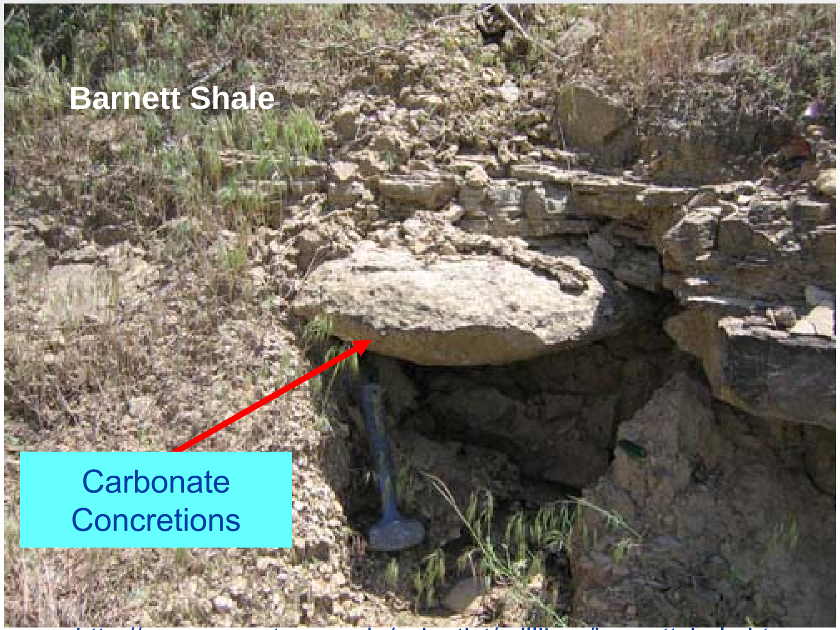
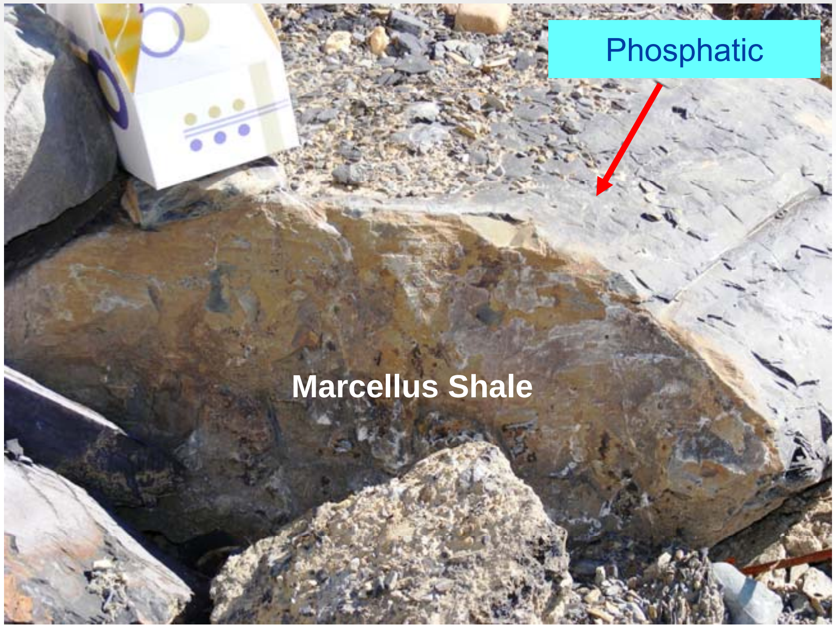
Identify Lithofacies that Influence Completion Strategies: Frac Barriers and Zones of Fracture Attentuation



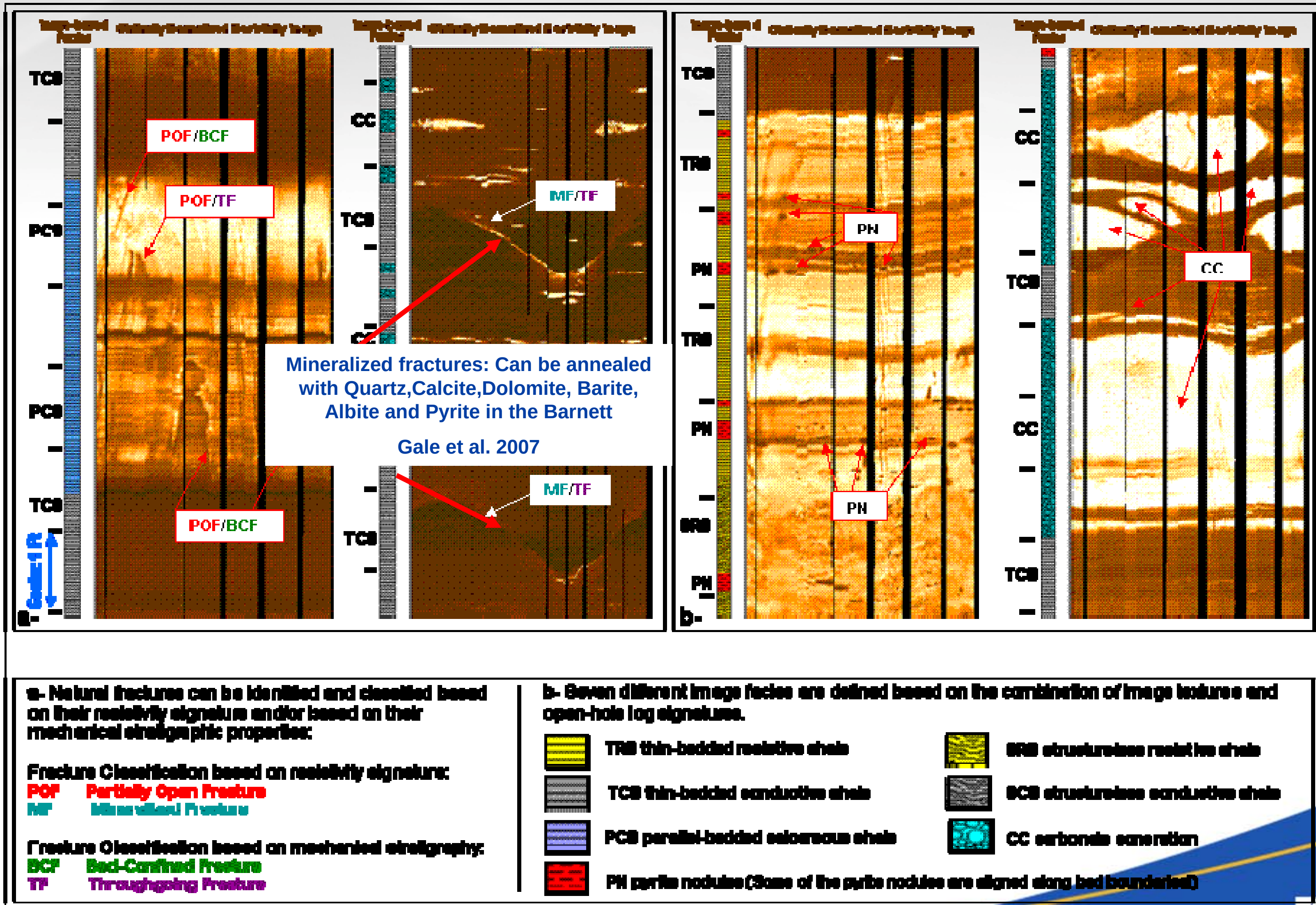
http://www.geo.utexas.edu/scientist/milliken/barnettshale.htm



Phosphatic and carbonate lithofacies are common in many shale gas reservoirs

- **Phosphatic mudstones or concretions are composed of apatite($Ca_5 (PO_4)_3(OH, F, Cl)$ in some reservoirs - occur in condensed organic-rich flooding surfaces, characterized by elevated uranium**
- **In some plays, must avoid fracturing carbonate lithologies that introduce water into the reservoir : Viola and Ellenberger underlying the Barnett Shale**

Lithofacies- Related to Fractures, Pyrite Nodules and Carbonate Zones
Mineralized and Open Fractures can be Important



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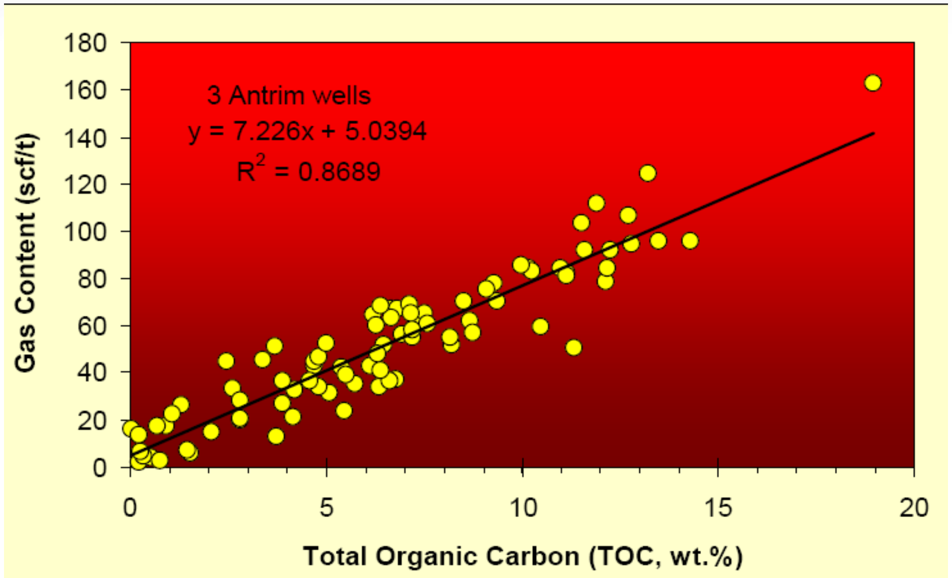
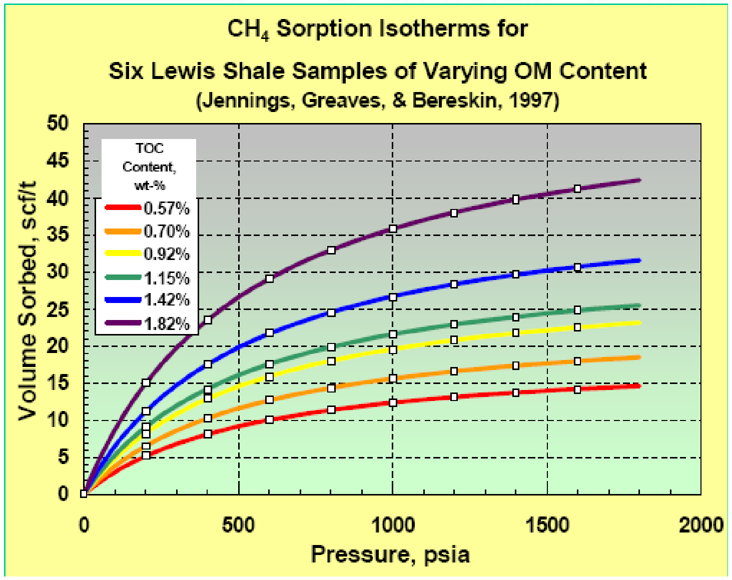
Total Organic Carbon Varies According to Lithofacies

TOC is Related to Gas Content



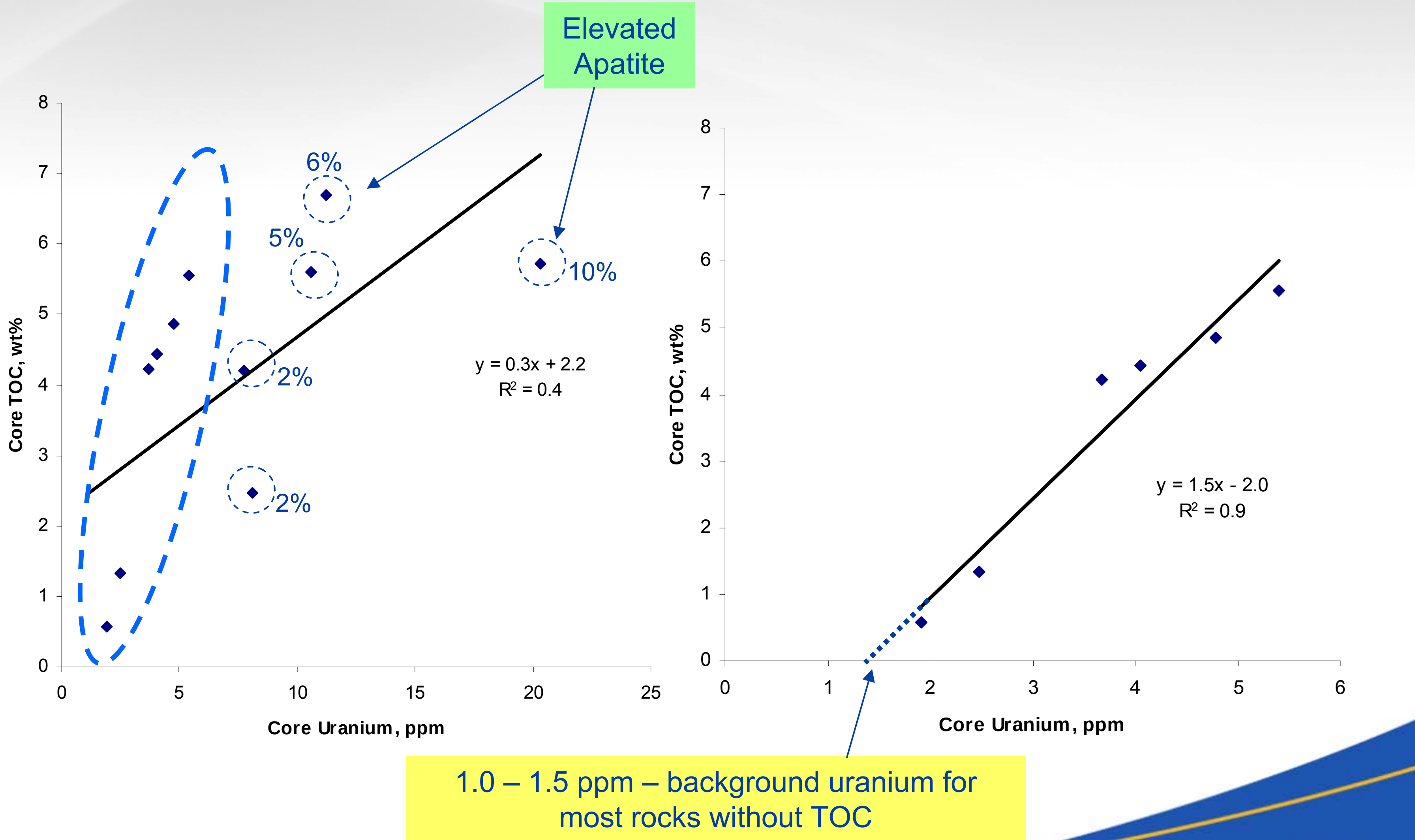
Predicts Total Gas



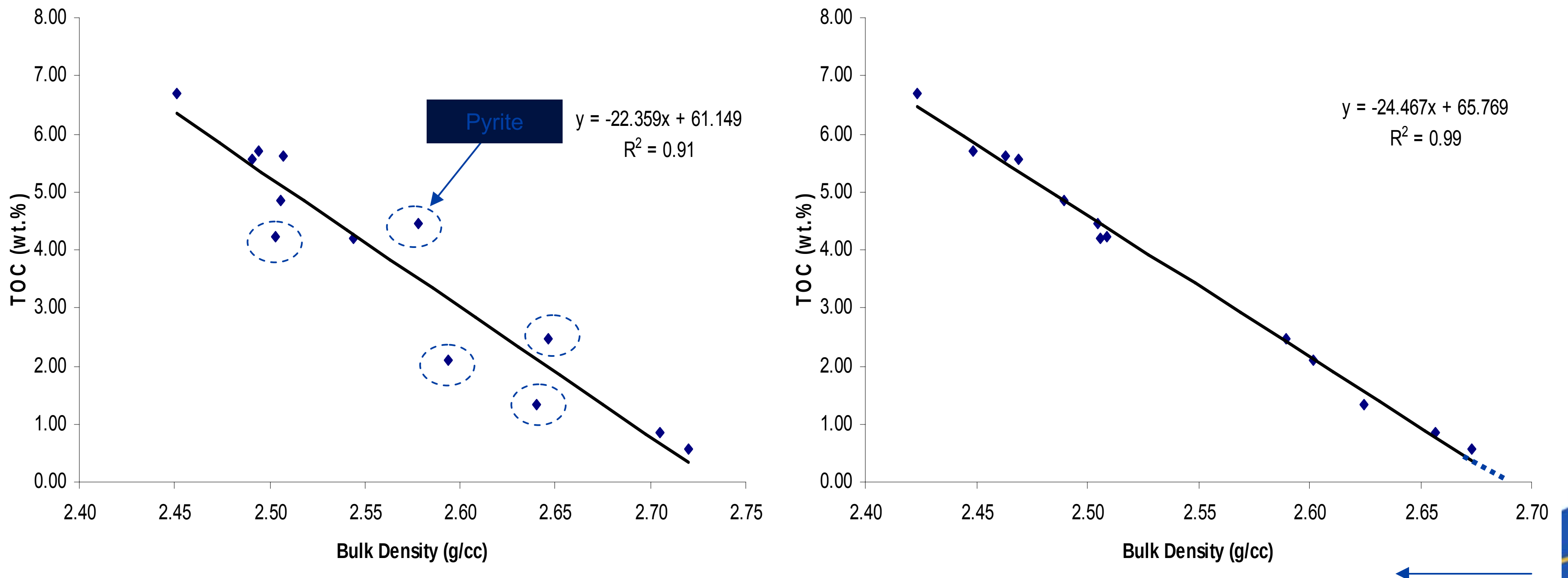
Predicts Probability of Adsorbed Gas

From Jarvie, 2007 AAPG Southwest Section Meeting

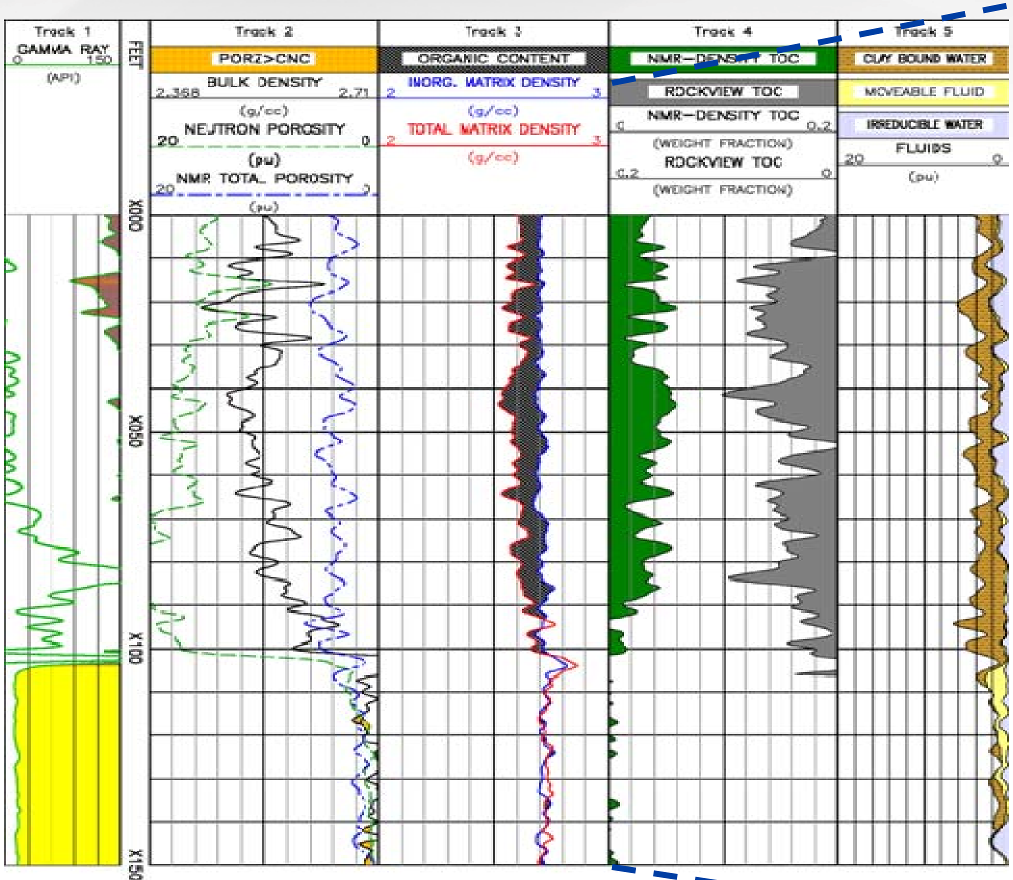
Empirical Correlations: Uranium versus TOC – Effects of Apatite in Organic Mudstones

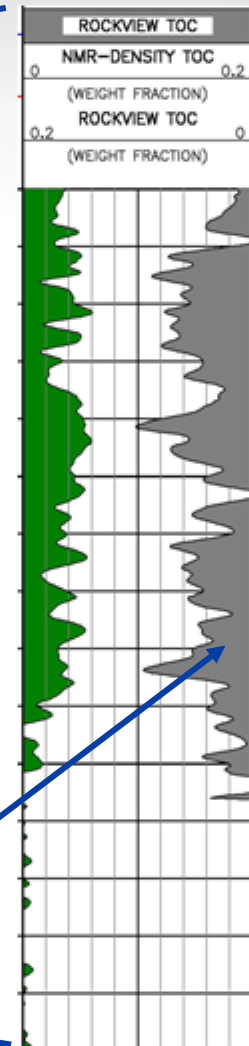


Bulk Density Used to Determine TOC – The Effects of Pyrite and Apatite



A Measurement of Carbon From the Wellbore Environment is Preferred to Compute a TOC





TOC = $[C_{total} - C_{calcite} - C_{Dolomite} - C_{Siderite}]$

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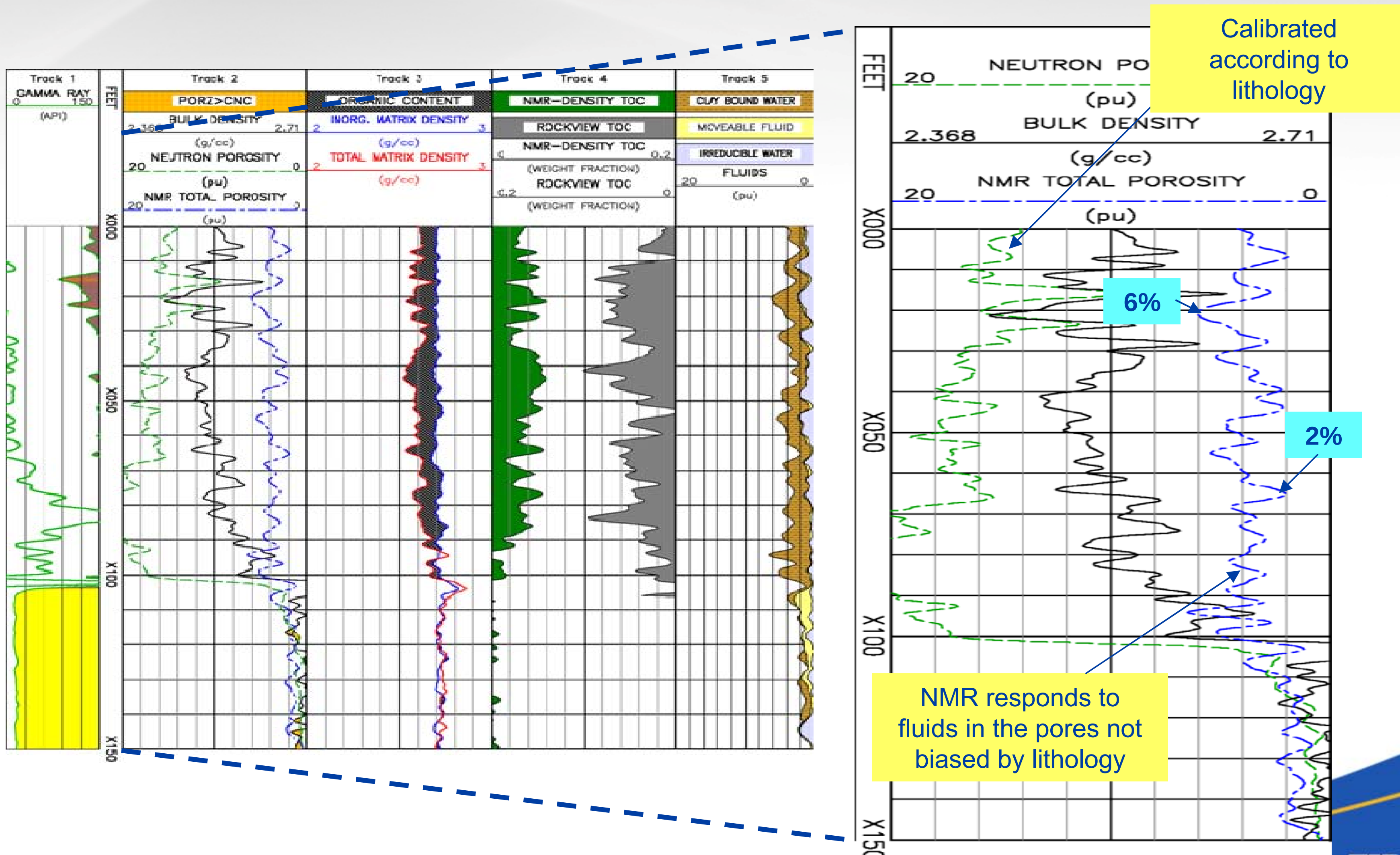
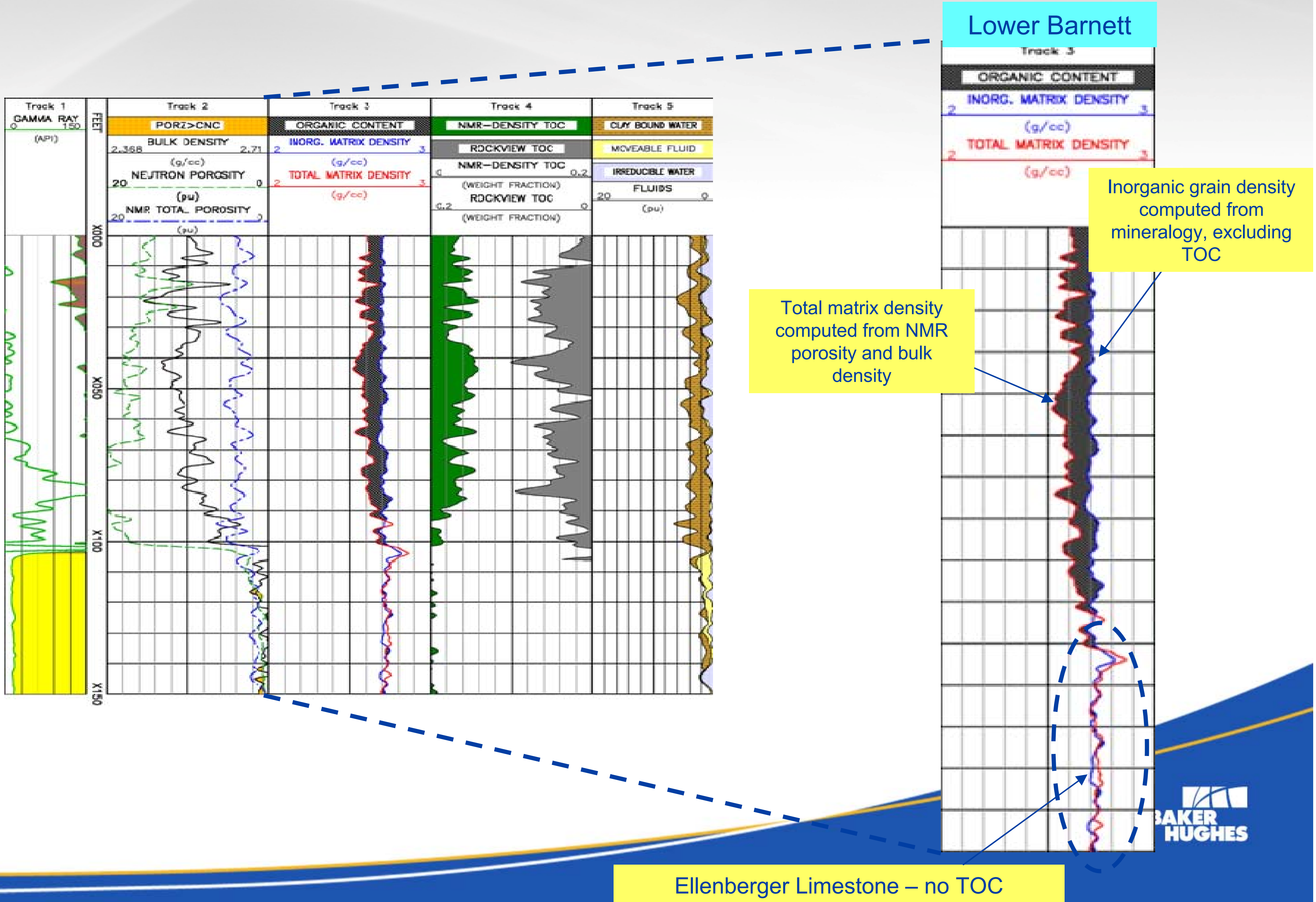
Porosity Lithofacies Dependent: Determining Porosity Using Neutron-Density is Challenging due to Lithofacies Changes

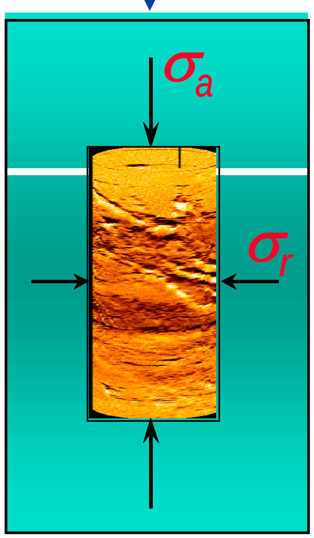


Using NMR for Computing TOC



Derive Geomechanical Properties of the Reservoir Rock

Lithofacies - Acoustic Data, Porosity, Mineralogy and TOC



Static Mechanical Properties:
Rock Strength, Elastic Moduli
Poisson's Ratio, Compressibilities

Compute Horizontal Stress for Each Lithofacies

Summary of Observations and Investigations Concerning the Characteristics of Shale Gas Reservoirs :

Problem: <u>No</u> single log measurement used alone can provide *in situ* answers to characterize the complexity of shale gas reservoirs

- **A method to distinguish between gas shale lithofacies that are favorable for hydraulic fracturing versus those which are considered non-favorable is essential.**
- **A quanitification of the mineralogy associated with each lithofacies is needed**
- **An *in situ* carbon measurement for determining kerogen content from the wellbore is needed to estimate GIP**
- **Porosity estimate using conventional tools is significantly challenged due to complex lithologies - NMR**
- **Quantifying the geomechanical properties of lithofacies is also essential for developing effective completion strategies.**
- **Fracture identification can also be crucial information for developing stimulation strategies**

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Shale Gas Reservoir Evaluation Requires An Integrated Petrophysical Method

FLEX

Geochemistry

Lithology

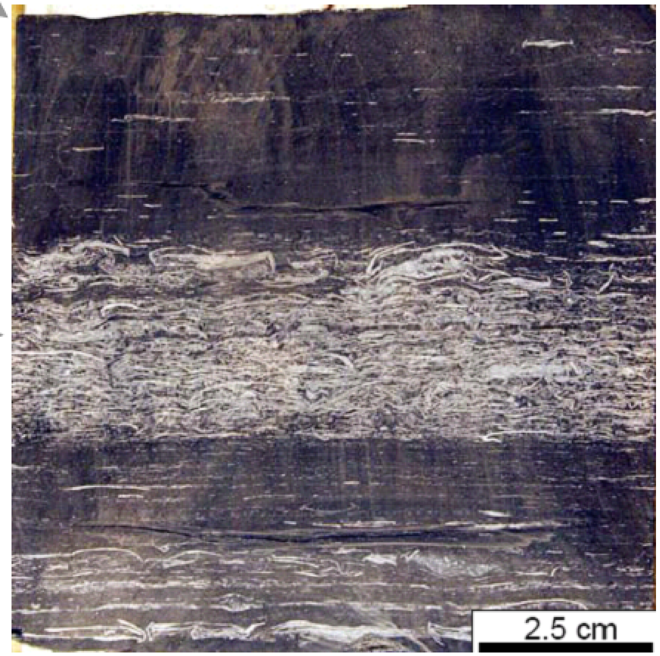
Mineralogy

and Total Organic Carbon

Density-Neutron

MREX

Porosity and an independent estimate of TOC



(Loucks and Ruppel, 2007)

SLII

Th/U used to determine presence of kerogen versus oil with total organic carbon from FLEX

XMAC

Compute geomechanical properties from the FLEX mineralogy

Image correlation with lithology and facies determined using FLEX

STAR

Fracture detection

Barnett Shale Facies

Papazis (2005)

1. Black shale
2. Calcite-rich
3. Silt-rich black shale (phosphatic)
4. Coarse-grain accumulations
5. Concretions (pyrite)

Jarvie (2004)

1. Black shale
2. Calcareous black shale
3. Phosphatic black shale
4. Limey grainstones
5. Dolomitic black shales

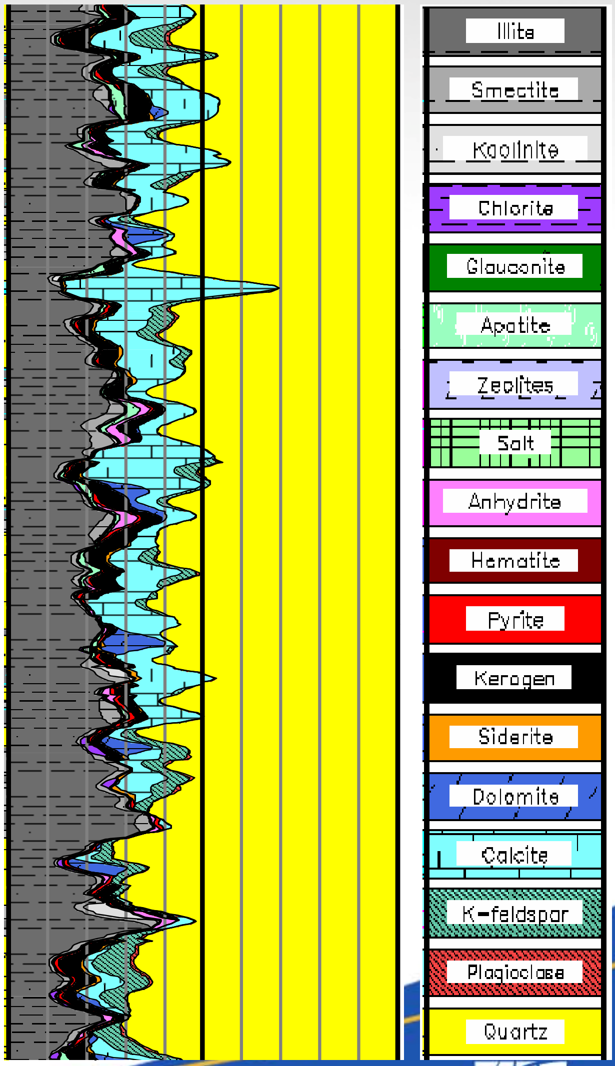
Hickey and Henk (2006) identified 6 lithofacies in Barnett shale; Deep water sedimentation with periodic bedforms indicating intrabasinal mud and debris flows.

Singh et al (2007) found 9 lithofacies in Barnett shale: Deposition influenced by high energy and low energy environments due to eustatic events (sea level changes)

Formation Chemistry is Needed to Detect Lithofacies and Compute Mineralogy and TOC

Pulsed Neutron Geochemical and Spectral Gamma Ray Tool

Element	Capture Spectrum	Inelastic Spectrum	Natural Spectrum
Aluminum		Al	
Calcium	Ca		
Carbon		C	
Chlorine	Cl		
Hydrogen	H		
Iron	Fe		
Magnesium		Mg	
Oxygen		O	
Potassium			K
Silicon	Si	Si	
Sulfur	S		
Thorium			Th
Titanium	Ti		
Uranium			U



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The Relationship of Th/U to Depositional Environment

•How can we detect variations in **depositional facies** in the Barnett Shale?

•Are paleoenvironmental facies changes markers that indicate preservation and amount of accumulated **organic carbon**?

Th/U ratio useful for determining depositional environment (Adam and Weaver, 1958)

Uranium is redox sensitive - $U^{4+} \leftrightarrow U^{6+} + 2e-$

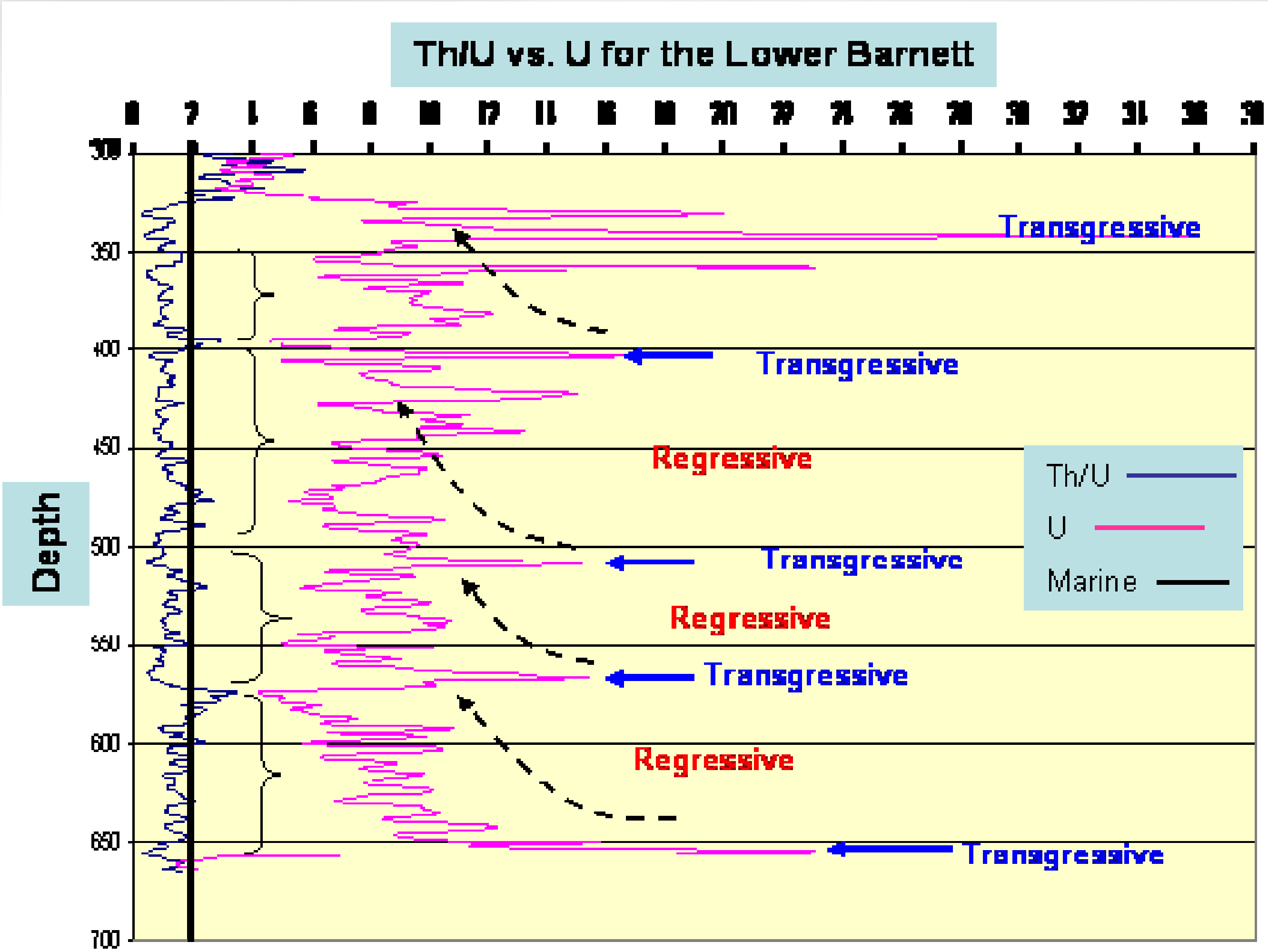
$U^{4+} \leftrightarrow U^{6+} + 2e-$

Insoluble	*Reducing* ↔ *Oxidizing*		Soluble
Organic	*Immobile* ↔ *Mobile*		CO_3^{2-} PO_4^{3-}

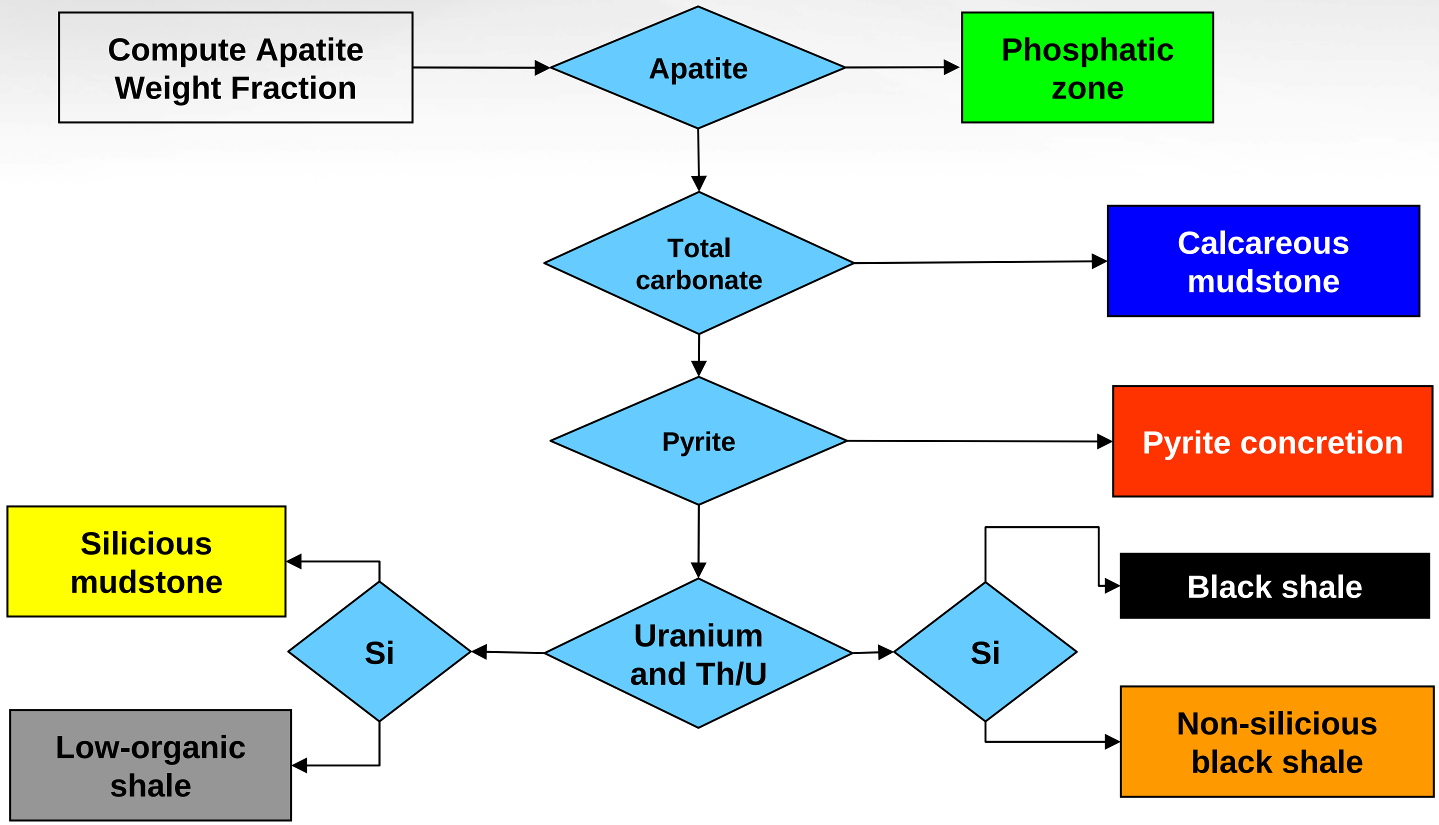
Thorium is not redox sensitive - Th^{4+} - Immobile - Insoluble

Fixed Marine	**Th/U** → **Transition**	**Mobile Continental**
2		7

Role of Th/U Versus U for Developing Gas Shale Facies Model



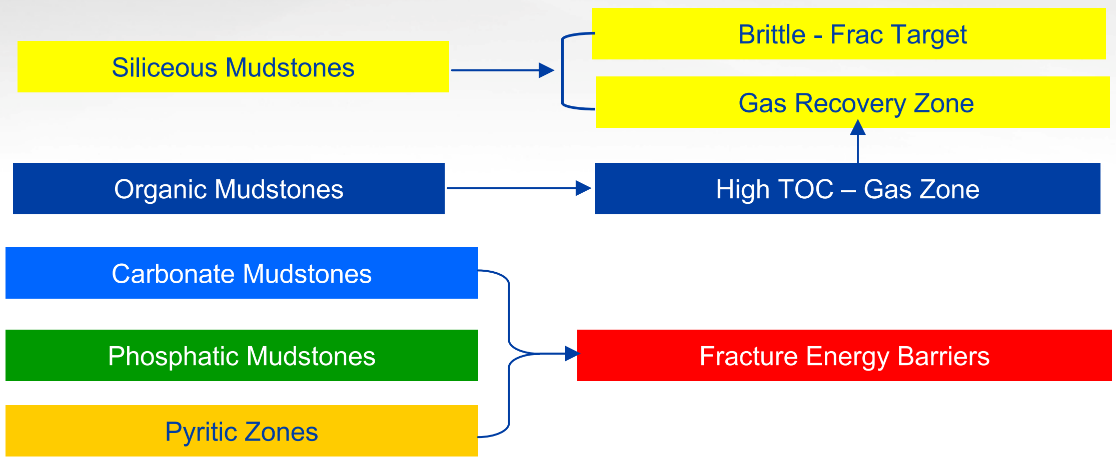
Gas Shale Facies Model Determines 7 Lithofacies from the Barnett Shale



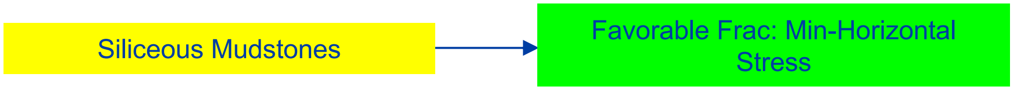
$$TOC = [C_{total} - C_{calcite} - C_{Dolomite} - C_{Siderite}]$$

Gas Shale Facies Model: Barnett

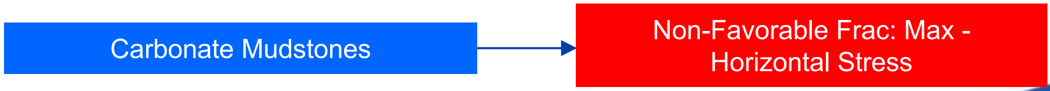
Barnett Shale Strategy: Establish Lithofacies



Use geochemical logs to locate silceous lithofacies favorable for hydraulic fracture. Use lithofacies, mineralogy, TOC, NMR porosity, and acoustic data to compute horizontal stress.



Must also locate lithofacies that are hydraulic fracture energy barriers. Use mineralogy, TOC, porosity, and acoustic data to compute horizontal stress



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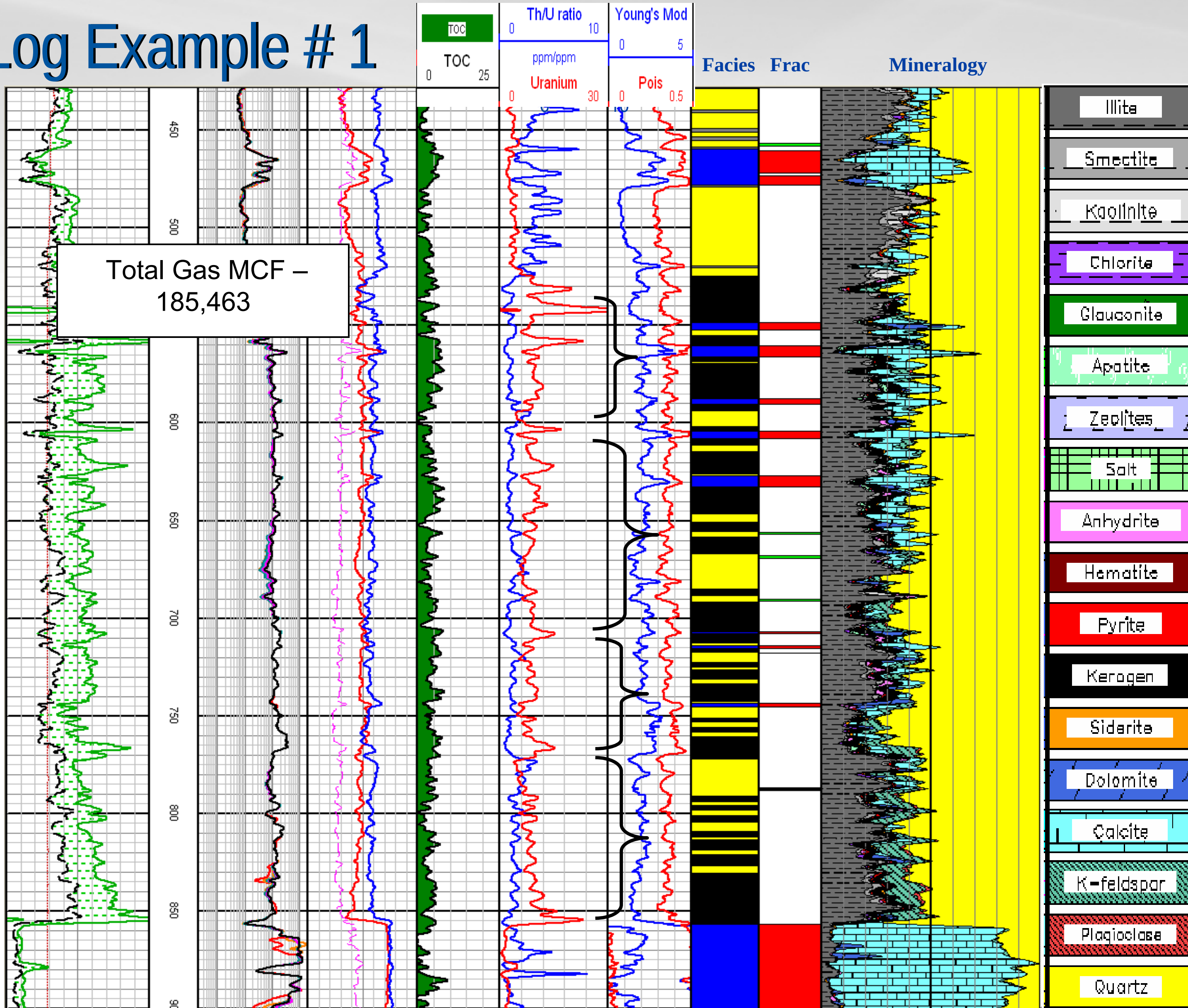
Log Example # 1



Facies Legend

Siliceous Mudstones

Organic Mudstones

Carbonate Mudstones

Siliceous Mudstones

Accumulative thickness-102'

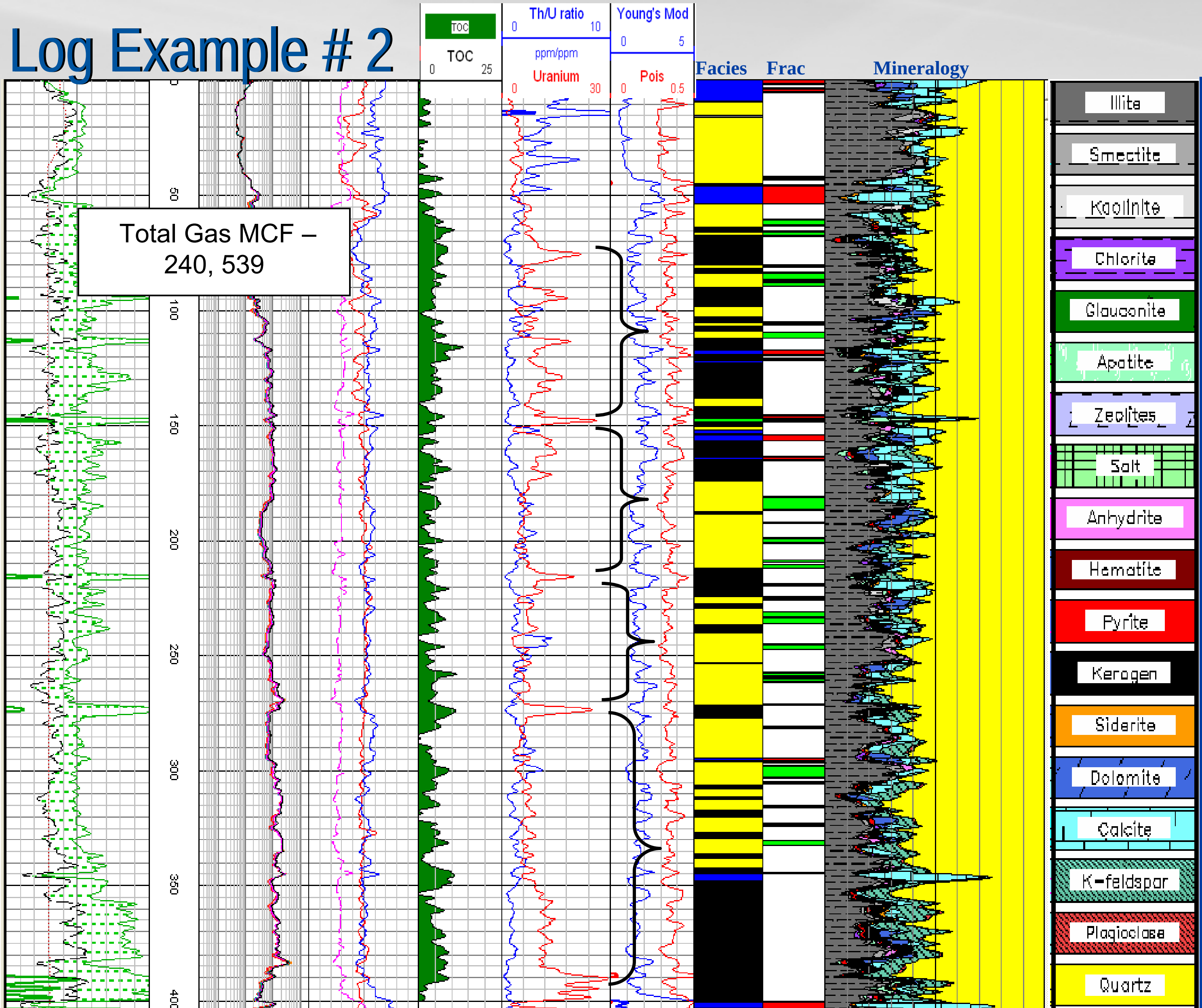
Favorable Frac: Min-Horizontal Stress

Accumulative thickness -8'

Non-Favorable Frac: Max -Horizontal Stress

Accumulative thickness -25'

Log Example # 2



Facies Legend

- Siliceous Mudstones
- Organic Mudstones
- Carbonate Mudstones
- Phosphatic Mudstones

Siliceous Mudstones

Accumulative thickness-148’

Favorable Frac: Min-Horizontal Stress

Accumulative thickness -50’

Non-Favorable Frac: Max -Horizontal Stress

Accumulative thickness -9’

Well # 1was completed a year earlier than Well #2

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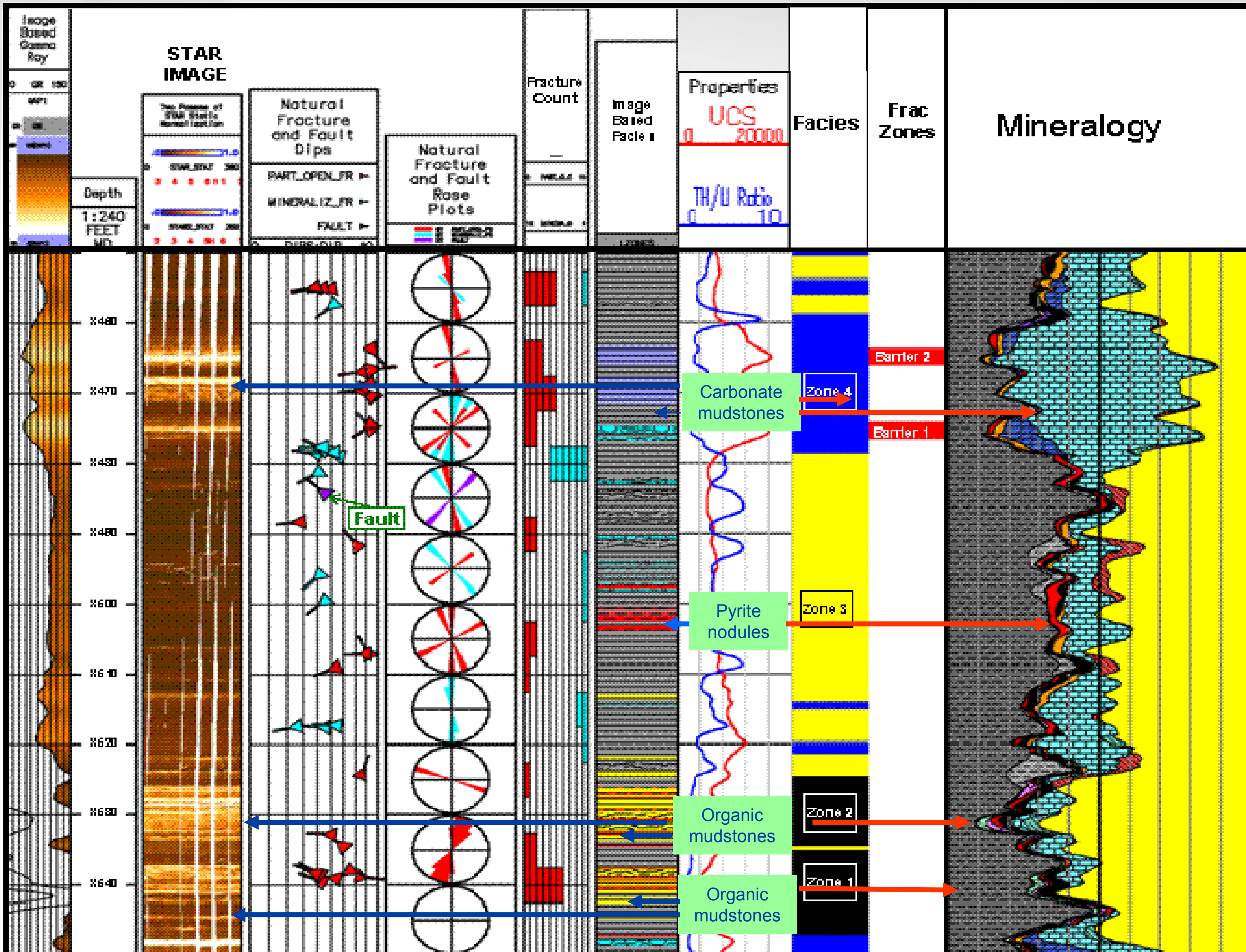
Detailed Interpretation of Image Logs Using Facies Model for Barnett



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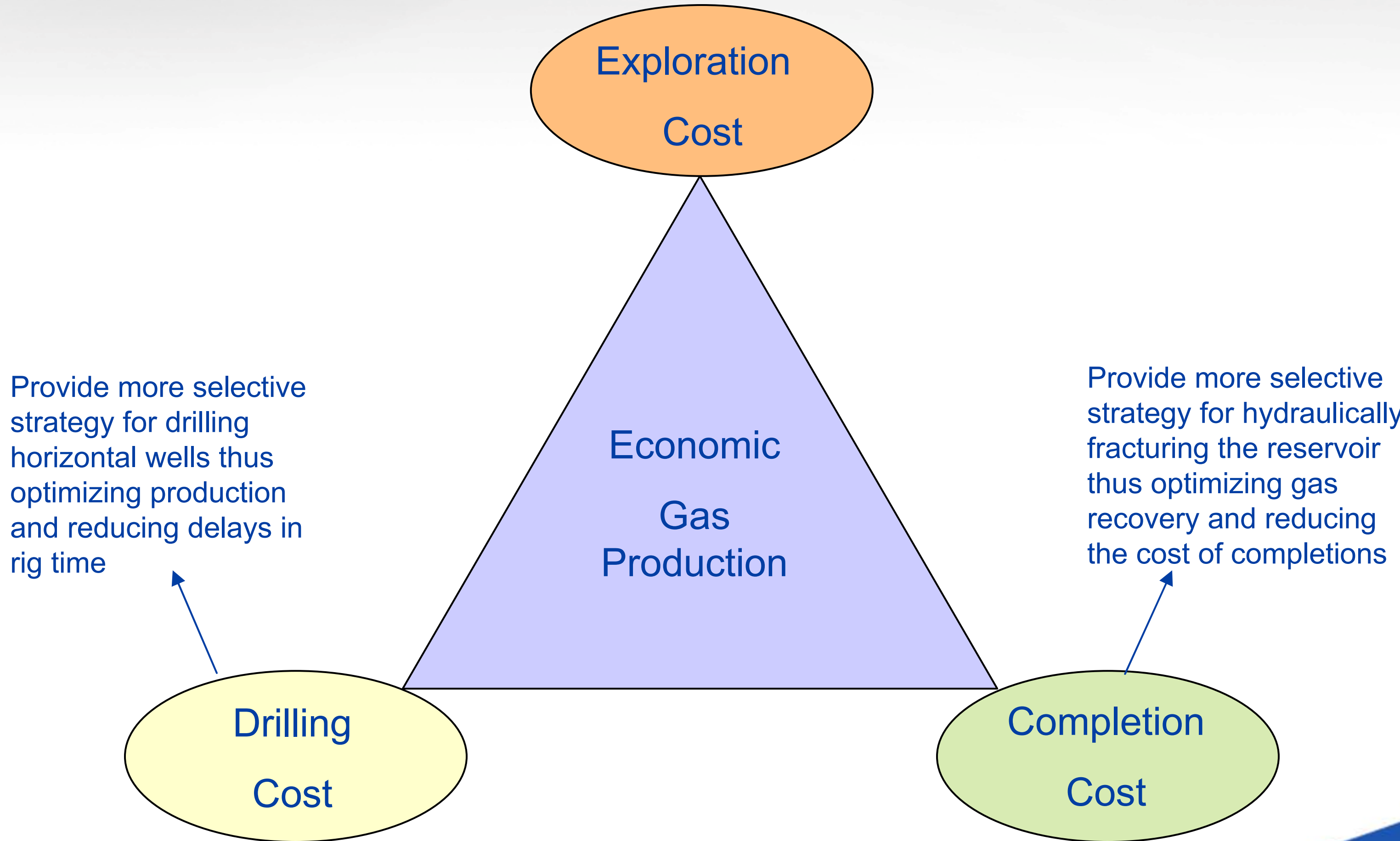
Implications and the Goal of the Integrated Petrophysical Model



Conclusion:

An “Integrated Petrophysical Method” has the capability of reducing cost involved in developing and completing shale gas prospects

Gas Shale Facies Model is effective for detecting variations in Lithofacies in reservoirs and predicting which facies are favorable vs. non-favorable for hydraulic fracturing

We have demonstrated the effectiveness of the model for the Barnett and are currrenty working on similar models for the Haynesville, Marcellus, and the Woodford Shale

Future models for other prospects will also be developed as core data becomes available

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Acknowledgements

Phillip Shoemaker, Shoemaker Exploration Company