The Exploration, Appraisal and Development of Unconventional Reservoirs: A New Approach to Petroleum Geology*

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Search and Discovery Article #41115 (2013)**
Posted February 28, 2013

*Adapted from AAPG Distinguished Lecture presented at Tulsa Geological Society Luncheon Meeting, January 29, 2013

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Abstract

The discovery of commercial oil and gas production from shale, or mudstone, reservoirs has dramatically changed how we explore for and develop oil and gas accumulations. In conventional exploration, appraisal and development there is a fairly standard and accepted application of processes and technologies. However, the processes and technologies that are employed in the exploration, appraisal and development of mudstone reservoirs are significantly different, and they are often employed for different reasons and at different stages of the cycle.

Prospect identification is always the initial phase of any exploration project. In most cases in the conventional world, this is a result of the interpretation of seismic data, either 2D and/or 3D, in order to identify the areal extent of the prospect, which would typically be on the order of a few hundred acres or in some instances a few thousand acres. However, in the unconventional world the identification is done at a basin level and is not typically supported by seismic, but rather by detailed analysis of a few key wells and their associated petrophysical attributes. Once those attributes are deemed to have the potential of supporting a commercially productive mudstone reservoir, then the utilization of seismic might be employed to help define the boundaries of the reservoir. However, that would typically be the exception as the reservoir boundaries are generally defined by the configuration of the basin, which is generally fairly well understood and can encompass a million acres or more.

Once the prospect has been identified, the evaluation processes during the exploratory drilling phase are dramatically different. During conventional exploration the validation of the presence, or lack, of hydrocarbons is largely done by the acquisition and interpretation of data from open hole wireline logs. While cores, either whole or sidewall, will often be taken, they are typically acquired not to validate the productivity of the reservoir but rather to supplement the open hole log data. In unconventional exploration, the opposite is the case. While the open hole logs are extremely important once the discovery is made to calibrate the reservoir, the most critical data around the validation of the quality of the reservoir is the detailed analysis of the rock acquired from whole core. While some of the attributes that are measured

from the mudstone core are common to conventional exploration, there are many more measurements that are taken on mudstone reservoirs that are totally unique to this type of reservoir.

As the prospect moves into appraisal and development mode, there are also unique processes and technologies in the unconventional world that are used to more fully understand the reservoir. The most important of those is the calibration, through the use of specific algorithms, of the data acquired from the whole core data to the open hole data that is being acquired from the appraisal and development drilling. Because the cost and time necessary to acquire an extensive collection of whole core data can be prohibitive, there will be a limited number of wells from which whole core is taken in any given field. Therefore, it is critical to be able to calibrate the various measurements from the whole core to the open hole log data that will be available on many more wells. This is also the point during which 3D seismic would be acquired as opposed to the acquisition of that type of data during the identification process. In unconventional development, the primary benefit of the 3D seismic data is not to identify where you want to drill, but where you do not want to drill. Specifically, the horizontal lateral is placed to minimize the effect of faulting on the lateral.

Throughout the entire period of field appraisal and development, the practice of geosteering is critical to the economic success of the field. Because virtually all of the unconventional development is done with the application of horizontal drilling, it is critically important that the drill bit maintain its position within the highest quality reservoir while the lateral is being drilled. Since the drilling operations are performed around the clock, and unexpected changes in dip or the presence of faults can cause the bit to rapidly change its relative stratigraphic position, a Gamma Ray tool is incorporated into the bottom hole drilling assembly in order to provide continuous measured depth Gamma Ray log data, which is then converted to a true vertical depth (TVD) log using software designed specifically for this process. This TVD log data is subsequently correlated with nearby well control to determine where the lateral is positioned stratigraphically at all times during the drilling operation. When the bit has been interpreted to be out of the desired stratigraphic section, or target window, it is the responsibility of the geosteerer to collaborate with the drilling organization to make the necessary changes to get the bit back into the target window.

Reference Cited

Herron, M.M., and S.L. Herron, 1998, Quantitative lithology; open and cased hole application derived from integrated core chemistry and mineralogy database, *in* P.K. Harvey, and M.A. Lovell, (eds.), Core-log integration: Geological Society Special Publications, v. 136, p. 81-95.

“The Exploration, Appraisal and Development of Unconventional Reservoirs: A New Approach to Petroleum Geology”

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BHP Billiton Petroleum
Winter 2013

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Brief History of Shale Exploration

- George Mitchell and Mitchell Energy pioneered shale exploration in the Barnett in the early 1980's

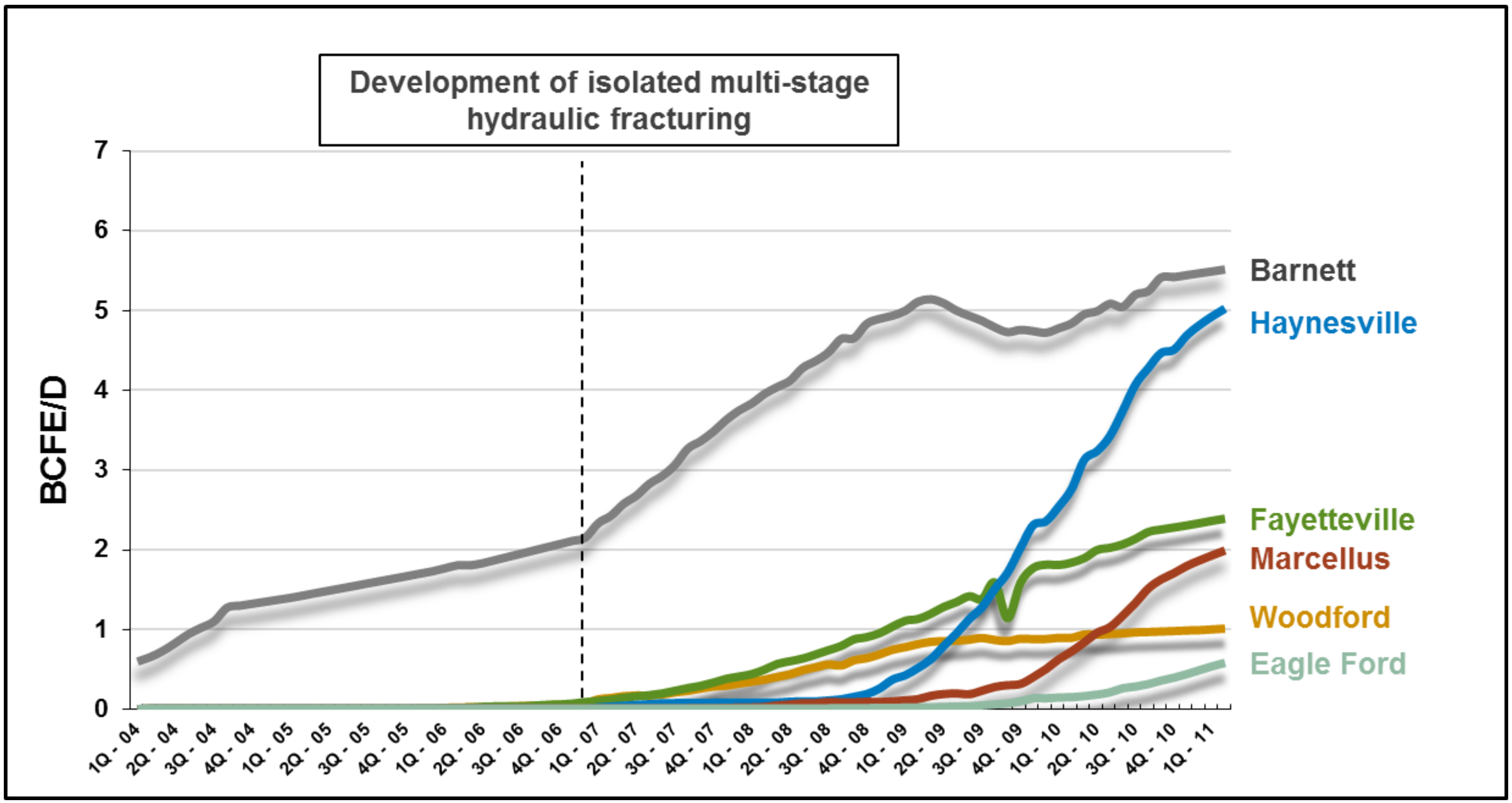
- By the late 1990's they had proven that vertical Barnett wells were commercially viable

- In the early 2000's a move was made to drill horizontally in the Barnett, but completion technology was lagging and results were marginal

- In 2006 the use of isolated multi-stage completions was proven to be successful which was the true game changer for horizontal drilling in shale reservoirs

Growth of North America Shale Production

- The development of isolated multi-stage hydraulic fracturing in 2006 caused a dramatic increase in shale production
- By 2011 the Haynesville Shale surpassed the Barnett as nation's leading shale play



Unconventional Exploration Process

Contrasting the Methodologies of Exploration

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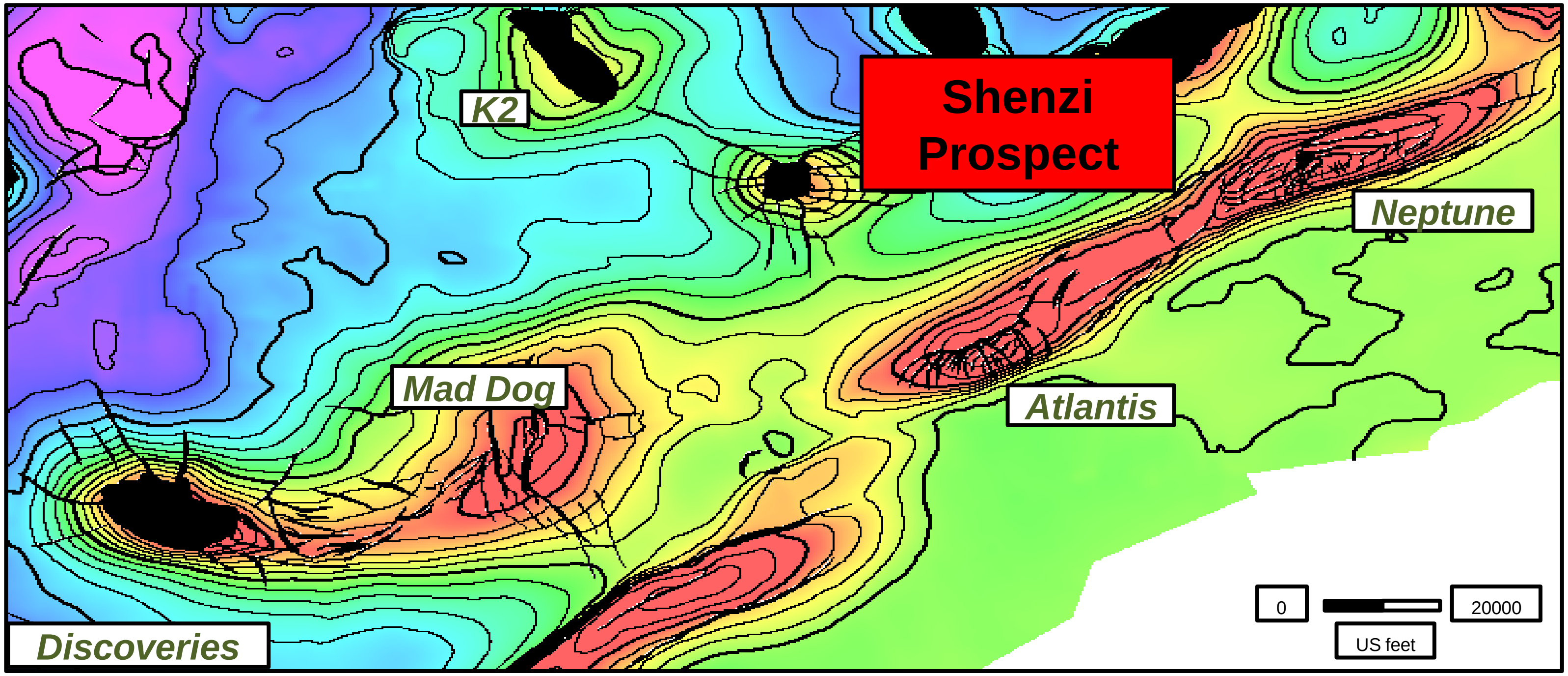
Conventional

- Prospect identification focuses "outside in"
- Seismic control works "outside in"
- Stratigraphic support eventually focuses on facies analysis local to the prospect
- Reservoir quality issues are relegated to the area of the prospect

Unconventional

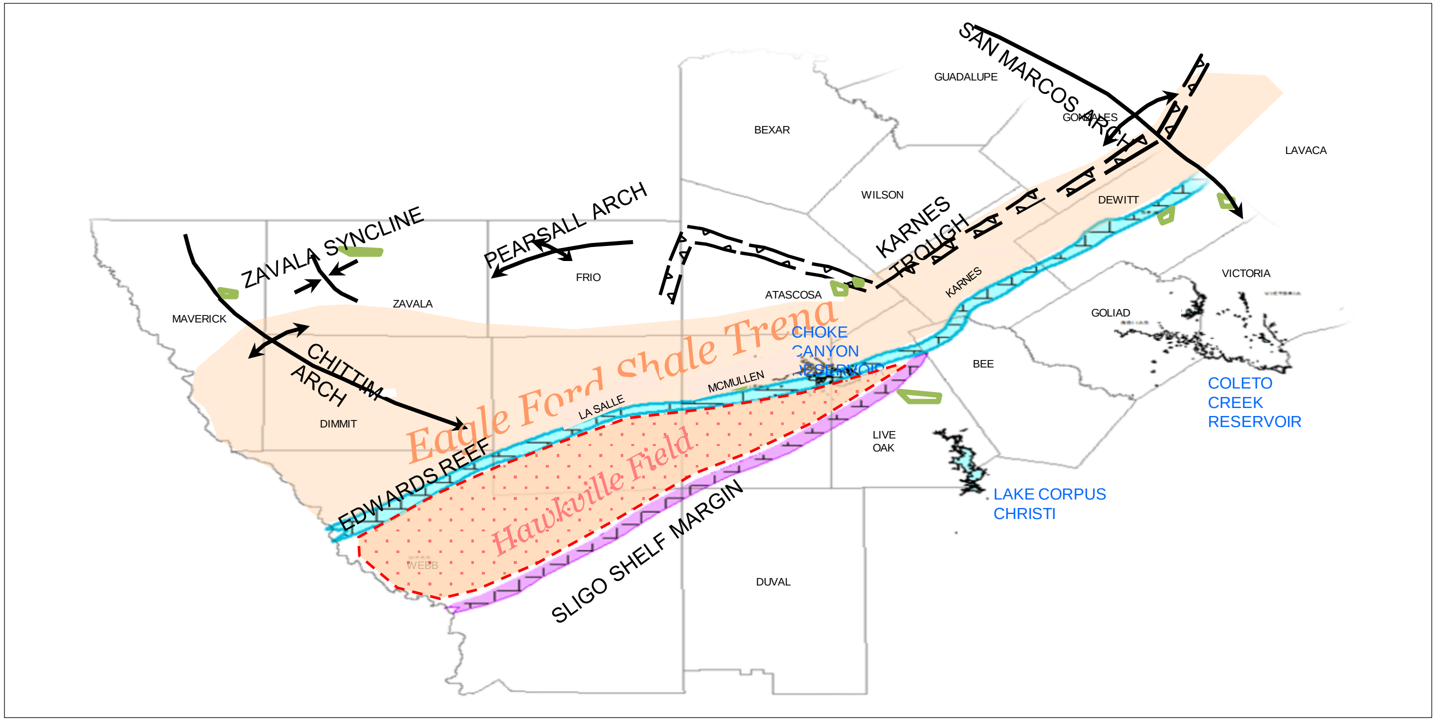
- Project identification focuses "inside out"
- Seismic control works "inside out"
- Stratigraphic support focuses on analysis of the entire basin
- Reservoir quality analysis is required over a very broad area of the basin

Prospect Identification: Conventional Analogy



- Deep Water Gulf of Mexico Prospect
- Structurally controlled and supported by local analogs
- At time of Prospect Identification, there were three significant analogs in the area of the prospect
- The area of the prospect was on the order of 10K acres with Resource Potential in excess of several hundred MMBOE

Prospect Identification: Unconventional Analogy



- Eagle Ford Shale Prospect
- Known regional source rock across large petroliferous basin
- Reservoir quality and geochemical attributes poorly understood
- The area of the prospect was >10 MM acres with high-side Resource Potential of >10 BBOE

Case Study for Unconventional Exploration: Hawkville Field

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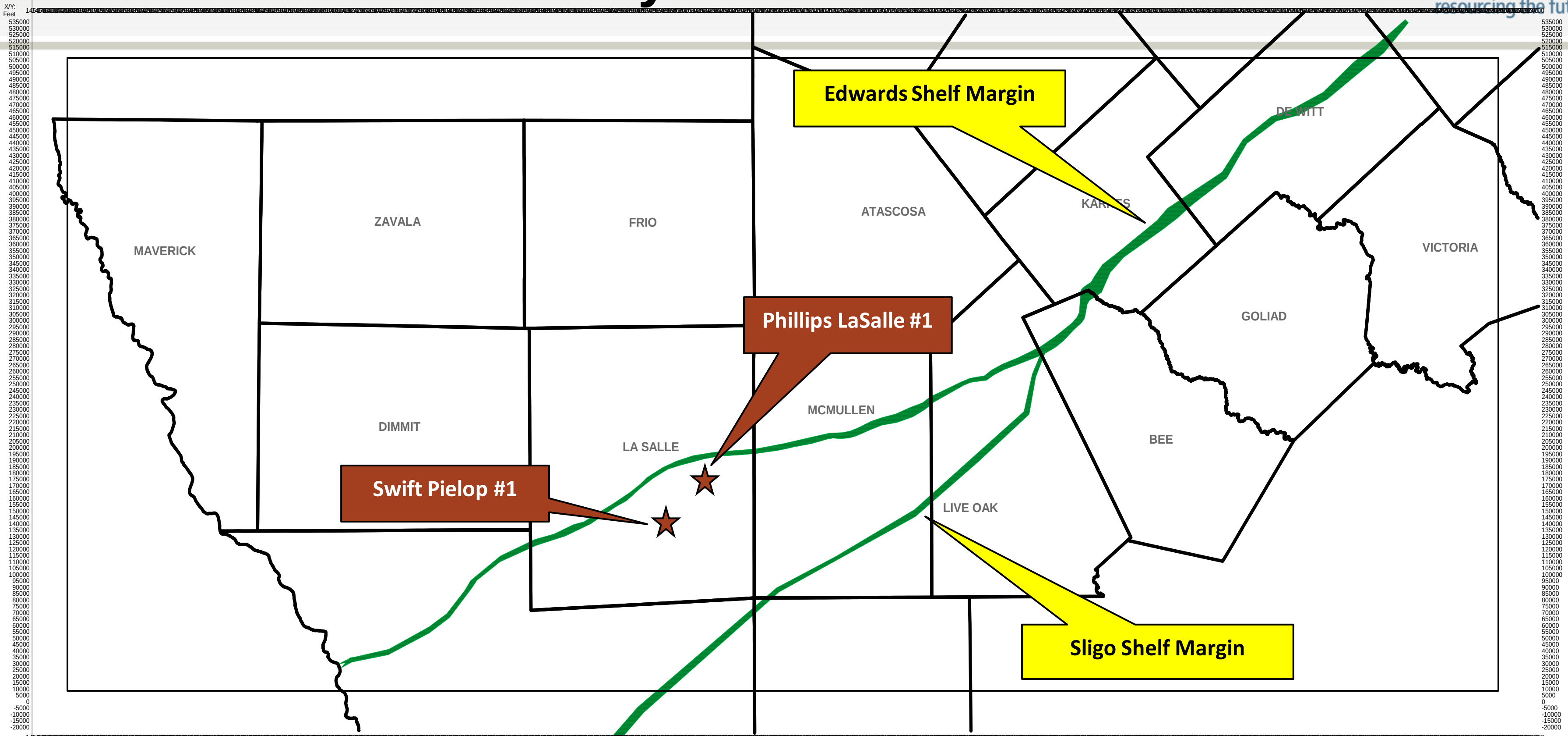
- In early 2008 the CEO of Petrohawk charged the Exploration team to find another "Haynesville-like" play
- We targeted the Eagle Ford Shale based on its significance as a regional source rock
  - Q1: Mapped the Eagle Ford across the entire Gulf Coast Basin and identified an anomalously thick, porous and highly resistive Eagle Ford section in La Salle and McMullen Counties
  - Q2: Acquired Eagle Ford cuttings on a key well and had them analyzed for TOC, VRo and other key parameters
  - Q3: Acquired ~160,000 acres and spudded the initial test well
  - Q4: Completed it in October 2008 for 7.6 Mmcf/d and 251 Bc/d

Hawkville Field in Early 2008

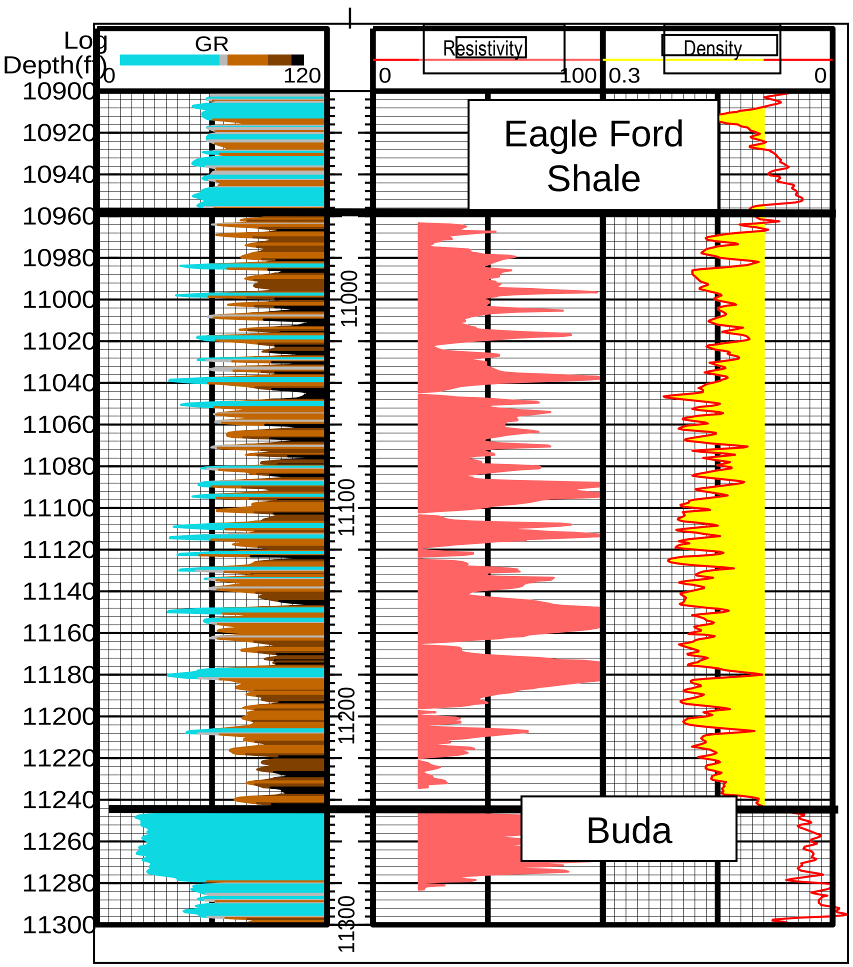


- Very limited well control in prospective area
- Prospect was located in a regional setting between two divergent shelf margins which suggested the presence of a "mini-basin"
- While the geochemical properties were unknown, the depth range (10,000-11,500') suggested a relatively mature source rock

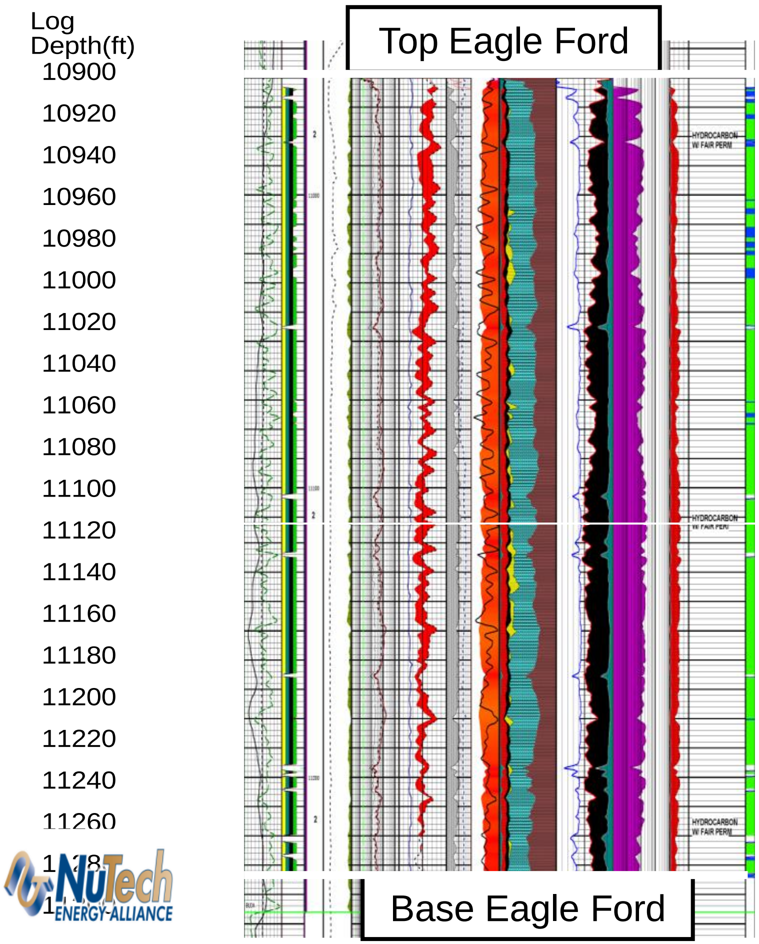
Key Finding #1:
World Class Petrophysical Characteristics

Atascosa_bee_dewitt_gonzales_liveoak_lasalle_maverick_webb_wilson

Swift Pielop 1



Swift Pielop #1



Key Finding #2:
Positive Geochemical Characteristics

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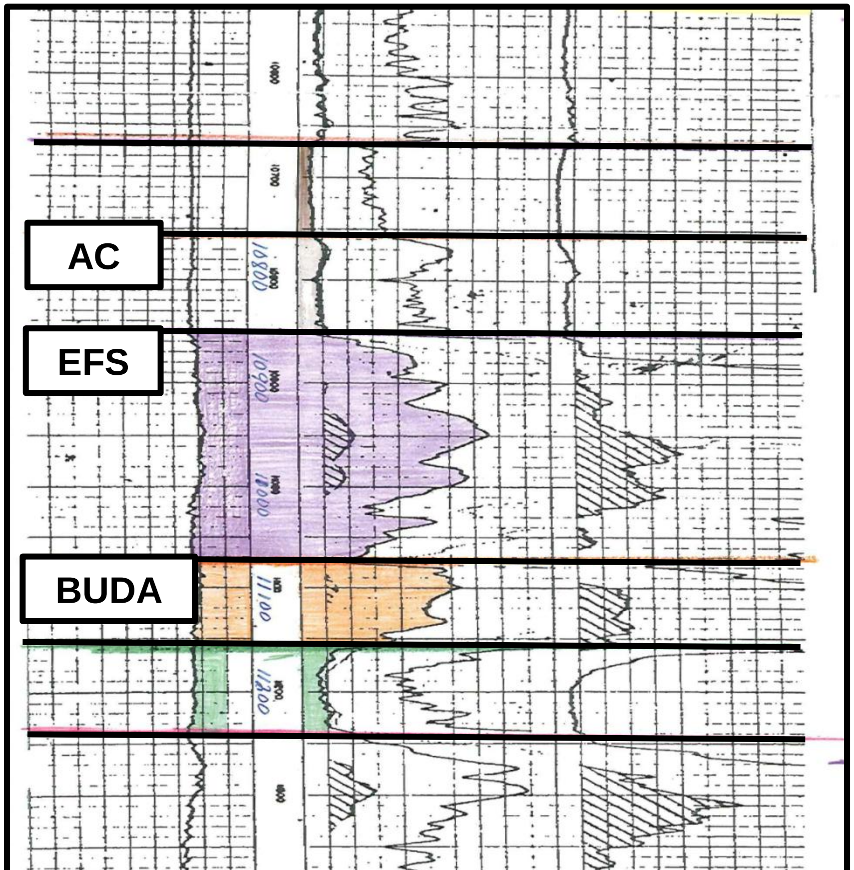
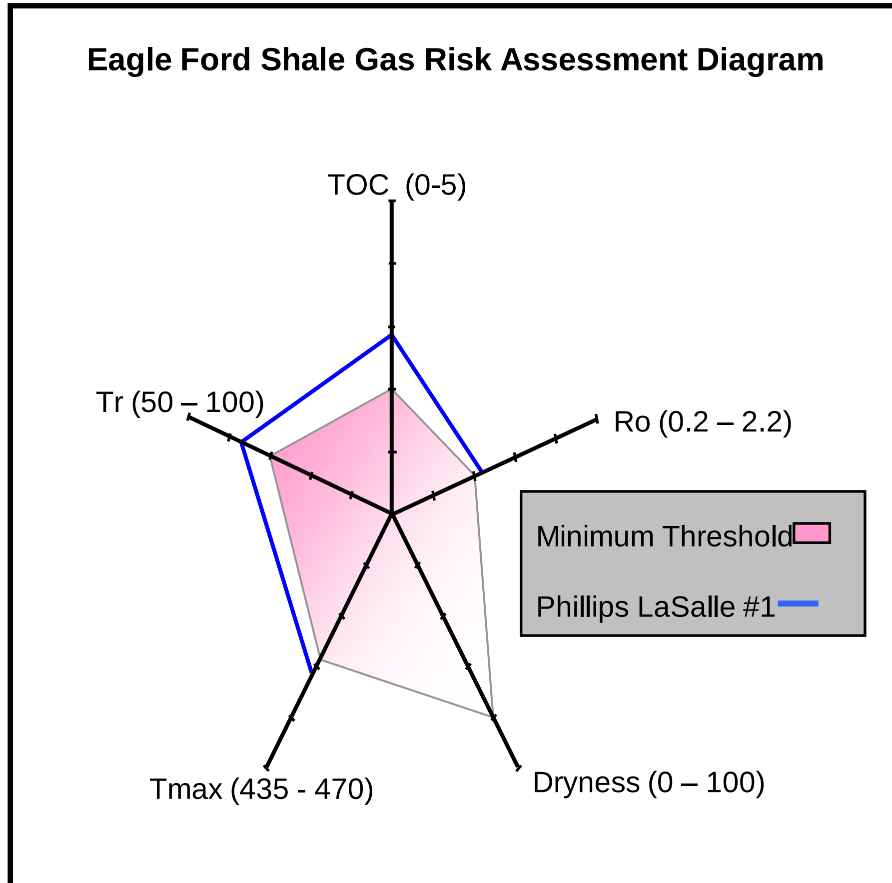
Phillips LaSalle #1
D&A in 1952

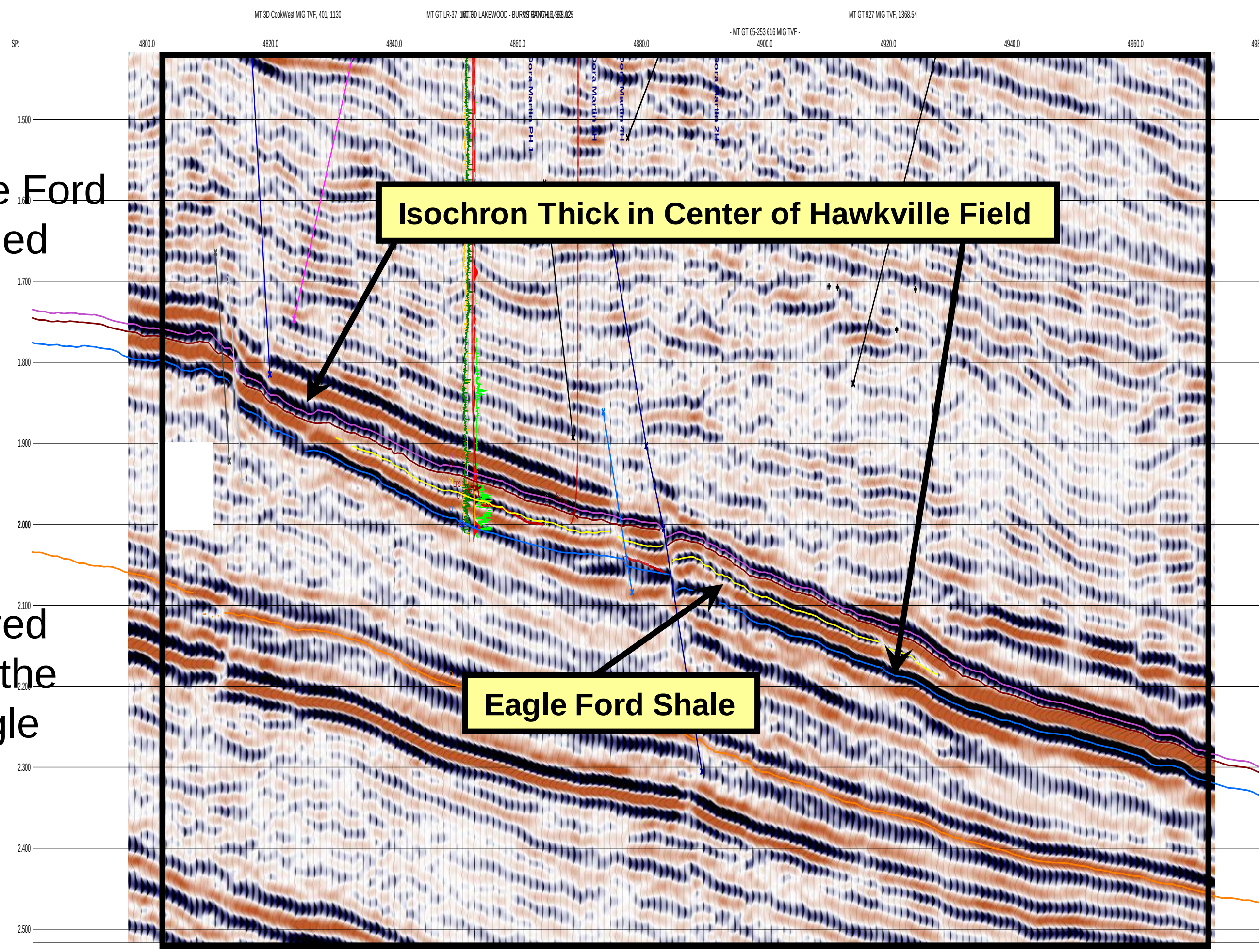




Key Finding #3: Seismic Definition of the Reservoir

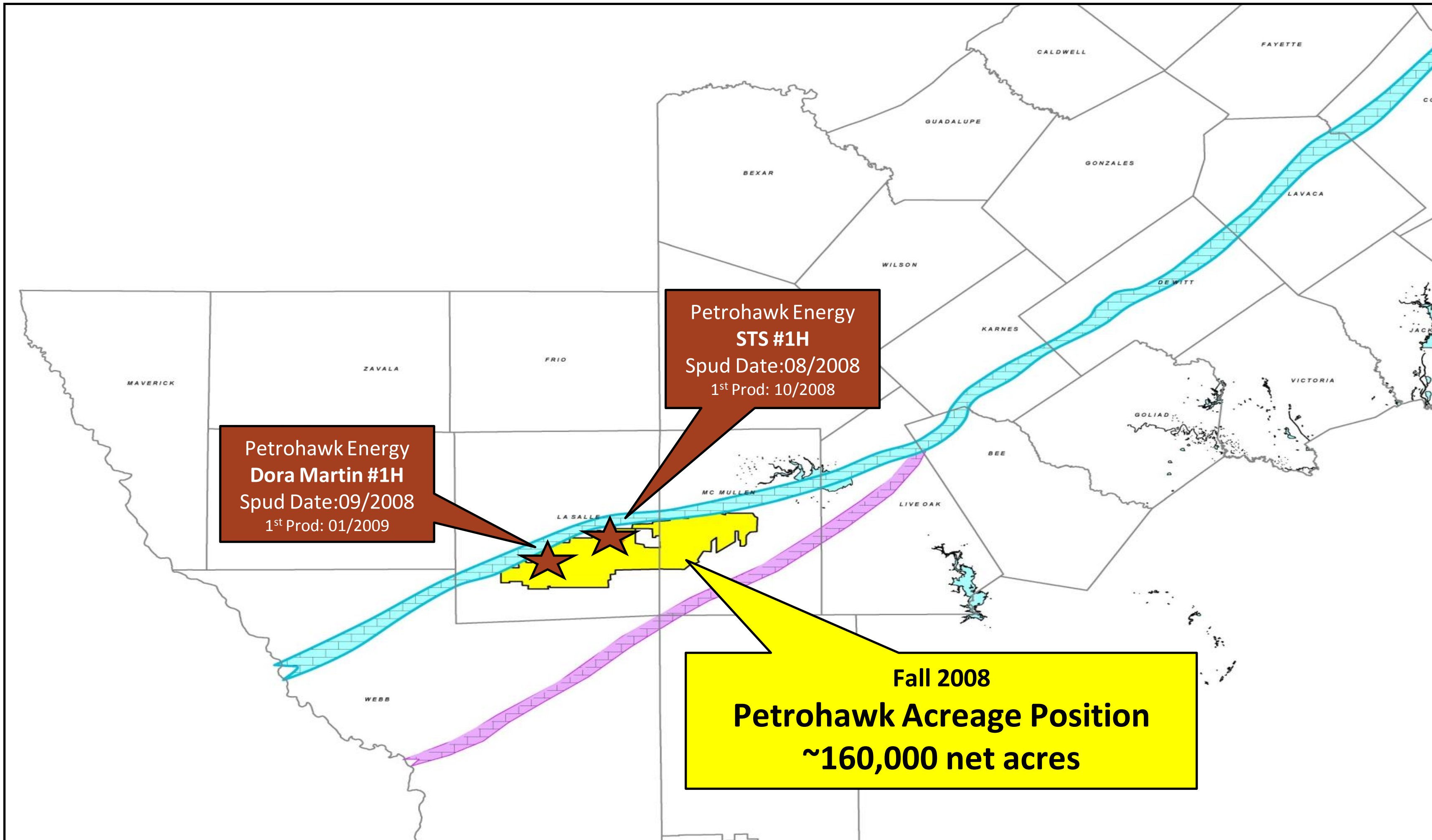
- The anomalously thick Eagle Ford at Hawkville could be identified with 2D seismic data

- A grid of 2D data was acquired that allowed the mapping of the entire extent of the thick Eagle Ford reservoir

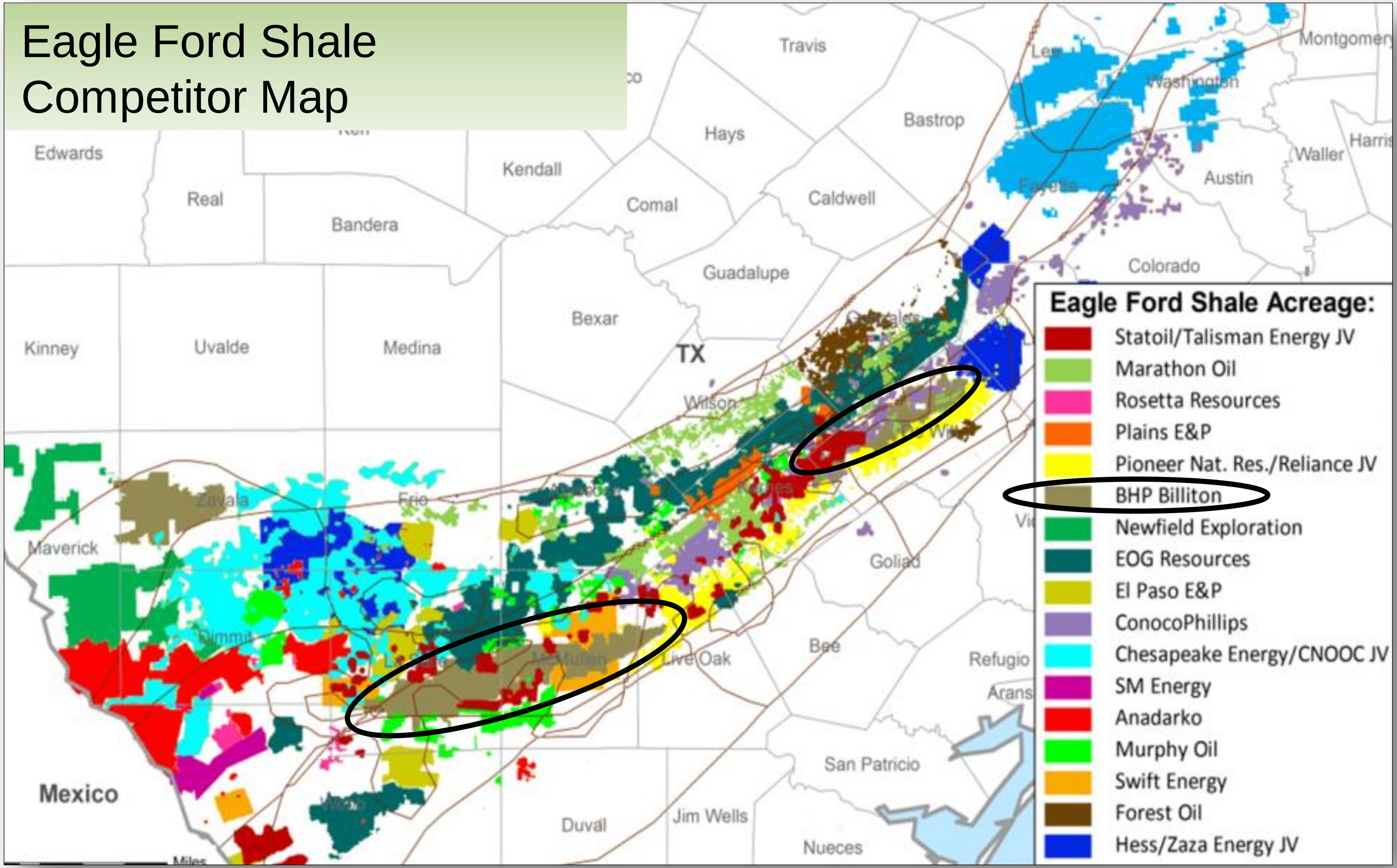


Data Courtesy of Seitel, Inc.

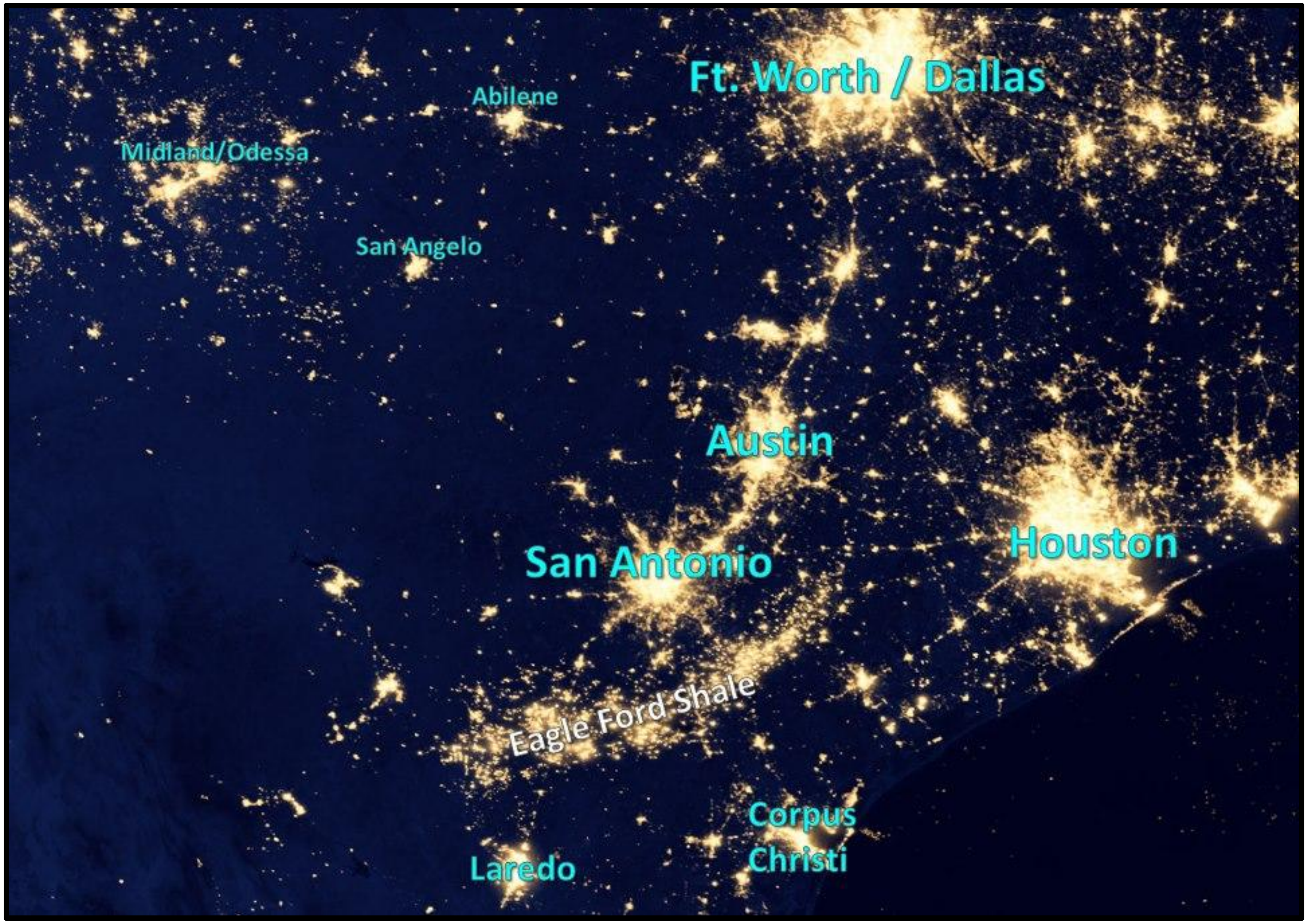
Hawkville Field in Late 2008



The Eagle Ford Shale in 2012



Night View of Texas by Satellite



Unconventional Appraisal Process

Critical Data for Effective Appraisal Program: Core Data and "Core to Log" Data

- **There is nothing more critical to the evaluation of a shale resource than the extensive data gathered from whole core analysis:**
  - Measurement of "conventional" reservoir attributes such as Porosity, Sw, Permeability, etc.
  - Identify and measure the mineralogy, specifically clay minerals versus "coarse-grained" constituents
  - Measurement of key geochemical (TOC, Thermal Maturity, etc.) and geomechanical attributes (Young's Modulus and Poisson's Ratio)
  - Most importantly, calibrate core measurements to conventional open hole log suites, therefore expanding knowledge regarding reservoir characterization, formation evaluation (OGIP, Recovery and EUR) and optimization of the hydraulic fracture stimulation

Pilot Wells During Appraisal Process

- Essential to acquire acceptable “grid” of open hole data subsequent to discovery
- Percentage of wells with pilot holes with complete data suite (core plus full complement of open hole logs) is low, but it is critical to have adequate baseline of core data
- Collective data set will enhance:
    - Reservoir characterization
    - Identify optimum stratigraphic target for lateral
    - Help determine the optimum stimulation “recipe” (fluid compatibility , geomechanics, stress regime, fracture density, etc.)
    - **Provide basis for creating algorithms that translate core data to log data**

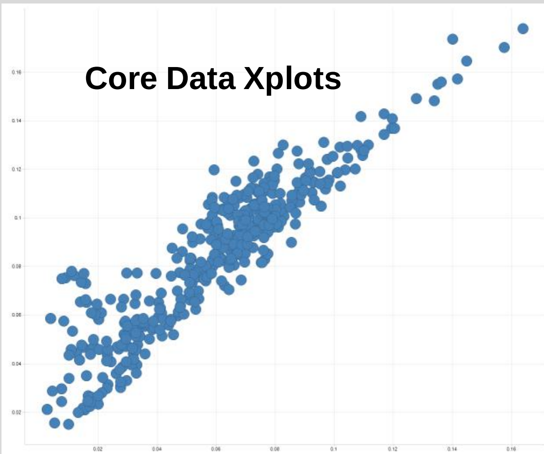
Analytical Process from Core

- Complete Cored Interval
  - Spectral Core Gamma
  - Fracture & Sedimentological Description
  - Core Photography
- Basic Rock Properties
  - Porosity characterization (GRI method)
  - Steady-state nano-permeability (CT-Scan plugs)
- Reservoir Geology & Geochemistry
  - Geochemistry (TOC, Pyrolysis, Vitrinite Reflectance)
  - Thin Section Petrography & FIB SEM
  - X-Ray Diffraction

Analytical Process from Core (continued)

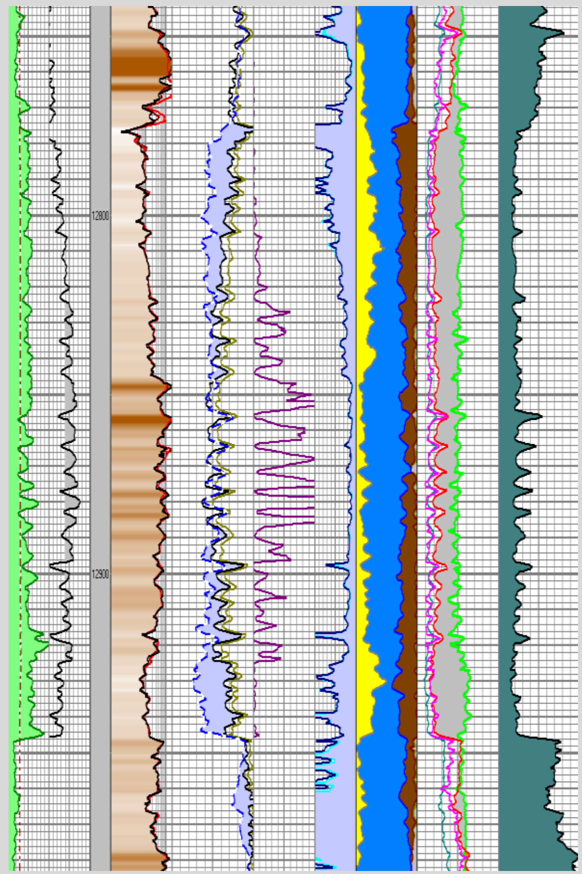
- Adsorption & Desorption
  - Desorbed gas content & composition
  - Adsorption isotherm
  - Isotope Analysis
- Completion & Stimulation
  - Geomechanical Properties (Single-State & Multi-Stage)
  - Proppant Embedment and Fracture Conductivity
  - Capillary Suction (CST) and Roller-Oven Testing

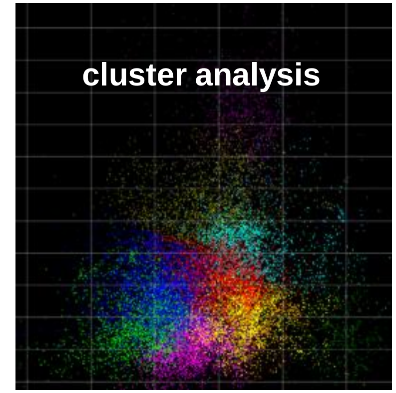
Basic Petrophysical Workflow

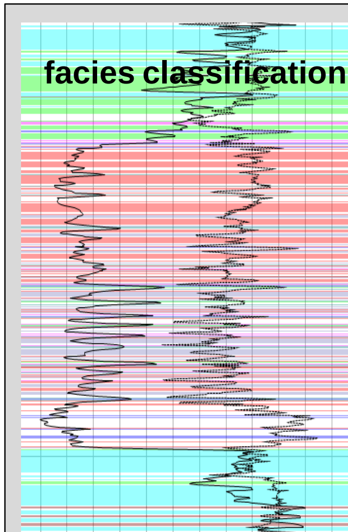


TOC
Porosity
Permeability
Saturation
Lithology
Geomechanics
ALGORITHMS

INTERPRETED
LOG CURVES

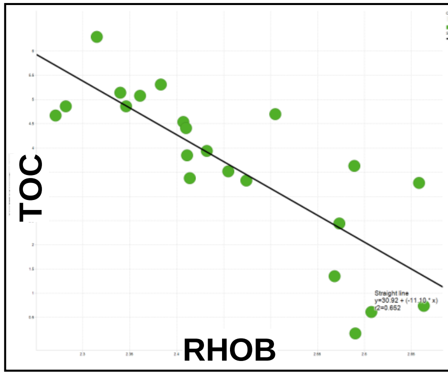




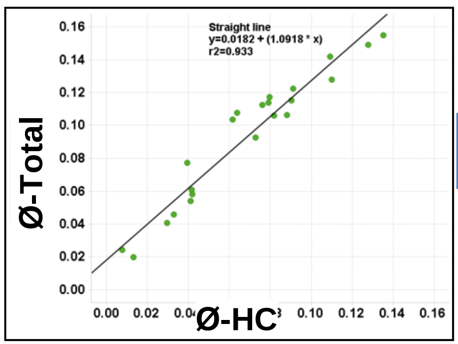


Core to Log Calibration: TOC-Porosity-Permeability-Saturation

Triple Combo

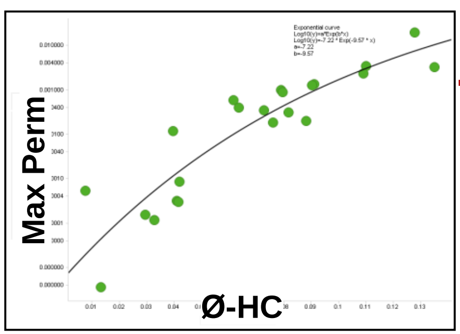


TOC
Fair correlation coefficient
$r^2 \sim 0.65$

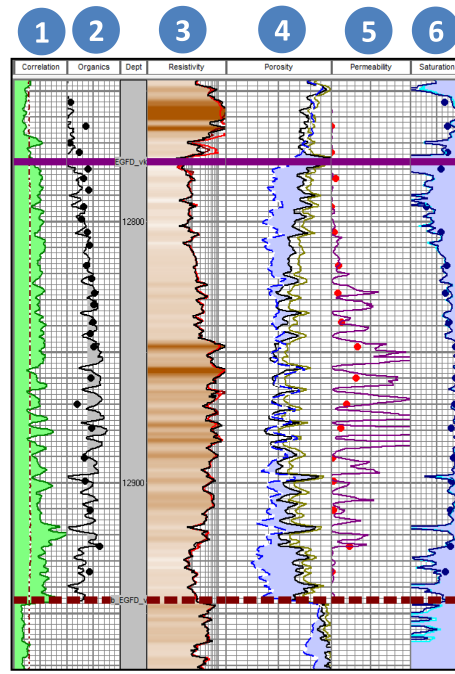


Hydrocarbon-filled Porosity
Highest correlation coefficient
$r^2 \sim 0.93$

Total porosity → HC-filled porosity → 4



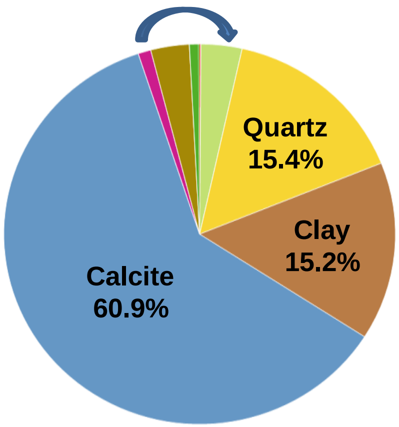
Permeability
Least dependable of the algorithms
(use qualitatively and in localized zones)



Sw based on default Rw ~ 0.025

Core to Log Calibration: Lithology

Dolomite 1.1%
Pyrite 3.1%
Plagioclase 3.2%



* Key Element to Mineral Conversions

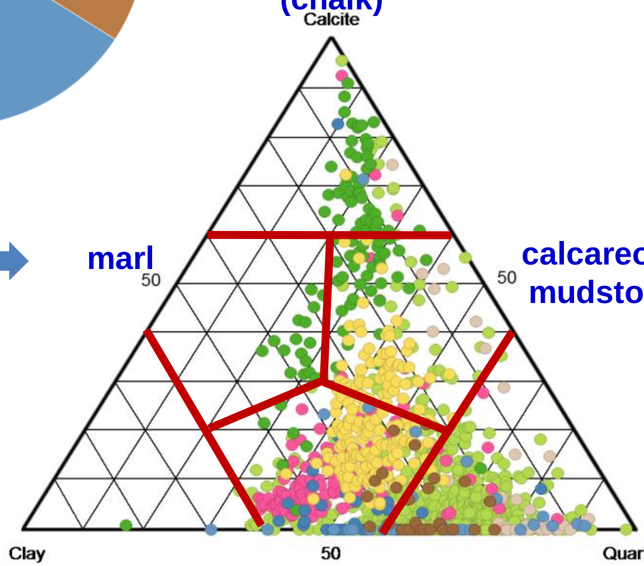
QFM ~ 2.139 * Si
Calcite ~ 2.497 Ca
Calcite + Dolomite ~ -7.5 + 2.69 (Ca + 1.455 Mg)
Pyrite = 1.8709 S
Kerogen ~ 0.83 /TOC
Clay ~ (1- sum of above)

(Source : Herron and Herron, 1998)

Carbonate (chalk)

marl

calcareous mudstone



clay-rich mudstone

argillaceous mudstone

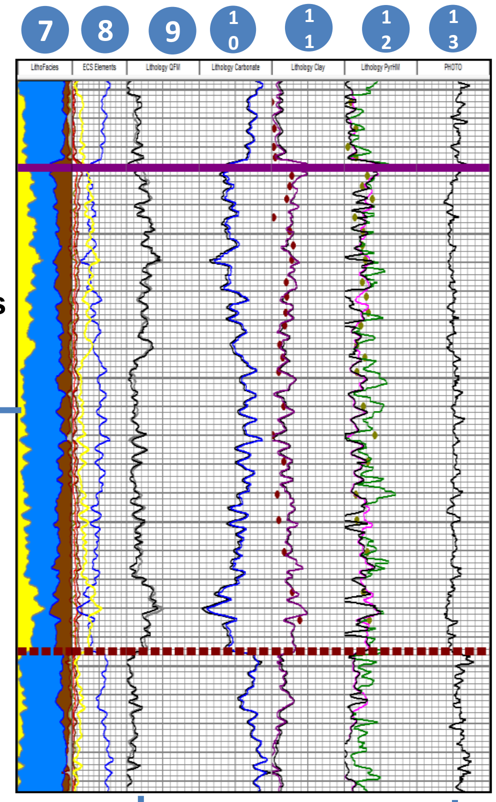
siliceous mudstone

element data from ECS-type logs

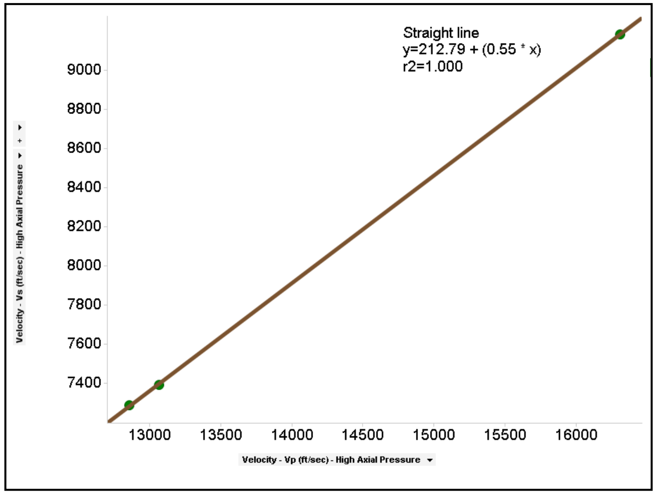
element to mineral conversion *

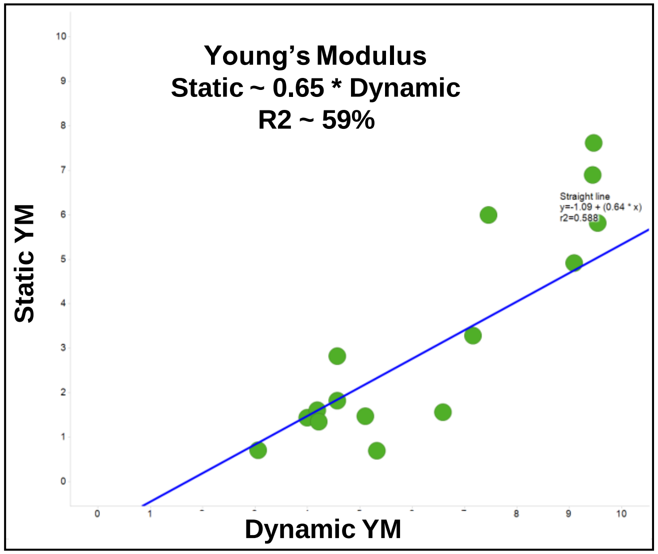
PEF check

composite lithofacies display



Core to Log Calibration: Geomechanics





Use as a "proxy" for estimating Vs | DTS when dipole or sonic scanner data is unavailable

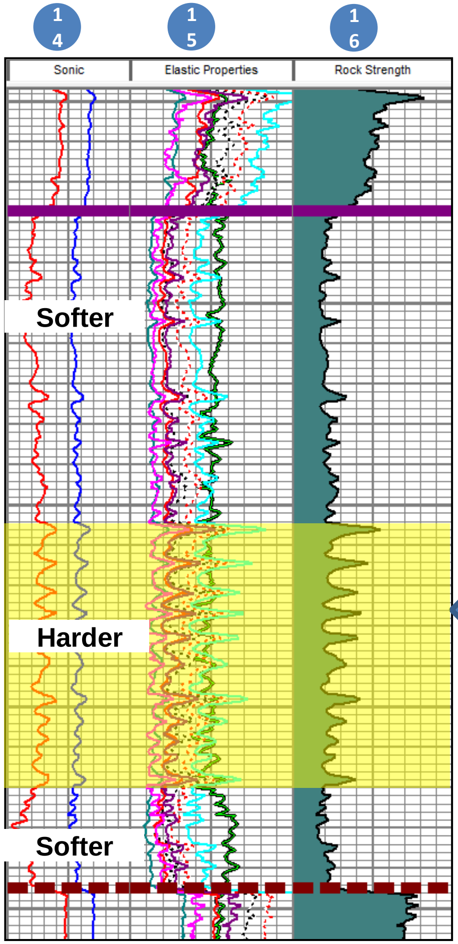
r^2 ~ 0.94 | **Track 14**

1. Use industry standard algorithms to calculate dynamic elastic modulii (Vp, Vs, RhoB)

Lambda
Mu
Bulk Modulus
P-wave Modulus
Poisson's Ratio
Young's Modulus

2. Convert from dynamic to static modulii for fracture propagation modeling

Dynamic-static relationships are derived from multi-stage Triaxial testing where both static and dynamic measurements are collected simultaneously



Uniaxial Compressive Strength (UCS *) from DTC or Vp

Core to Log: QC and Interpretation

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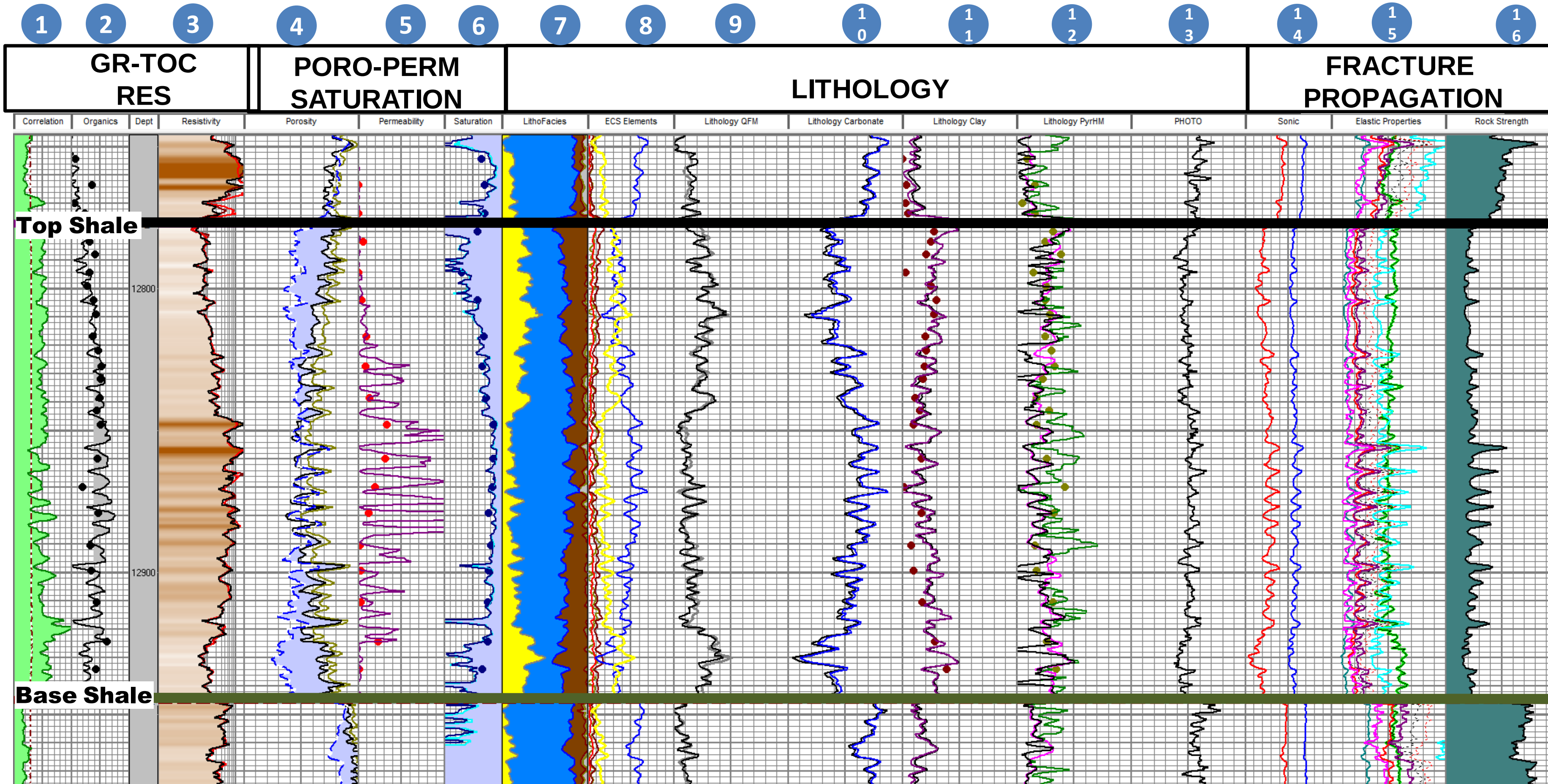
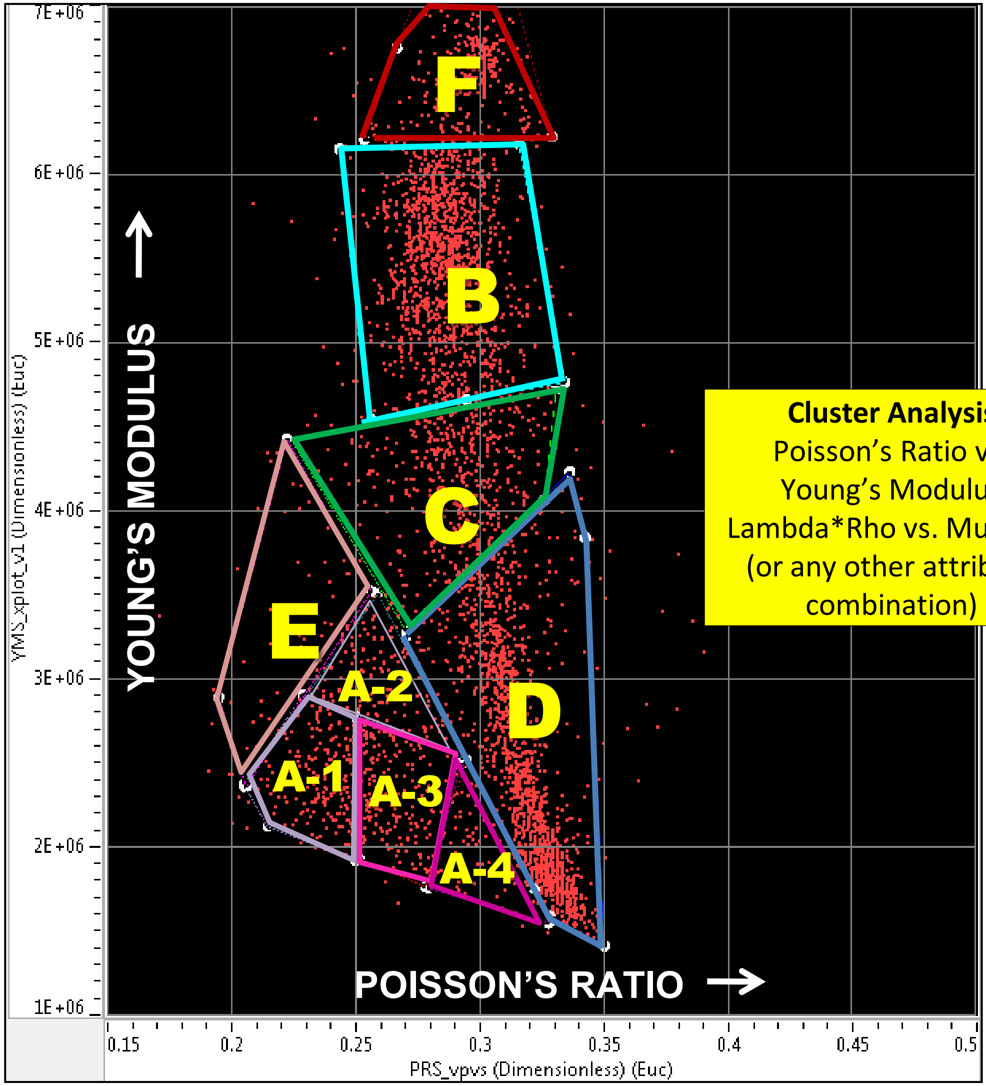


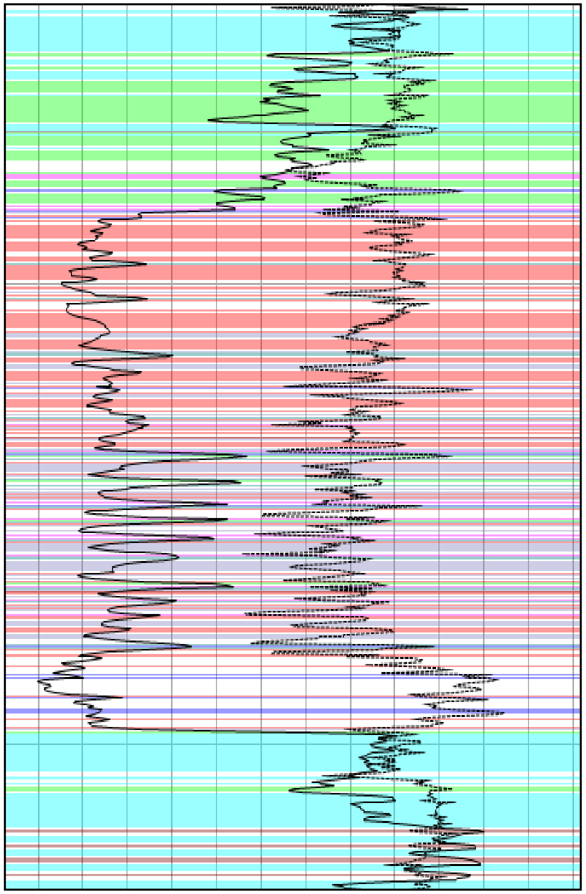
TOC distribution	Sweetspot screening	Rock properties from ECS-type tool should dovetail with geomechanical descriptions	Frac properties from DTC-DTS

Facies Extraction Using Geomechanical Data



Cluster Analysis
Poisson's Ratio vs. Young's Modulus
Lambda*Rho vs. Mu*Rho
(or any other attribute combination)

Facies extracted from Crossplot

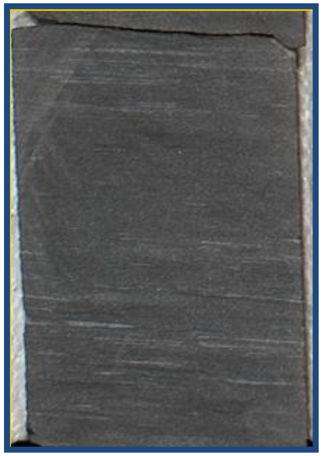


The Whole Core Itself:
Macro Observations From the Eagle Ford

Marl

Foraminifer Marl

Foram-Rich Marl



Limestone

Calcareous Shale

Ash Beds/Bentonite

Courtesy of Core Laboratories

The Relationship of Eagle Ford Core to Gamma Ray Showing Significant Vertical Heterogeneity

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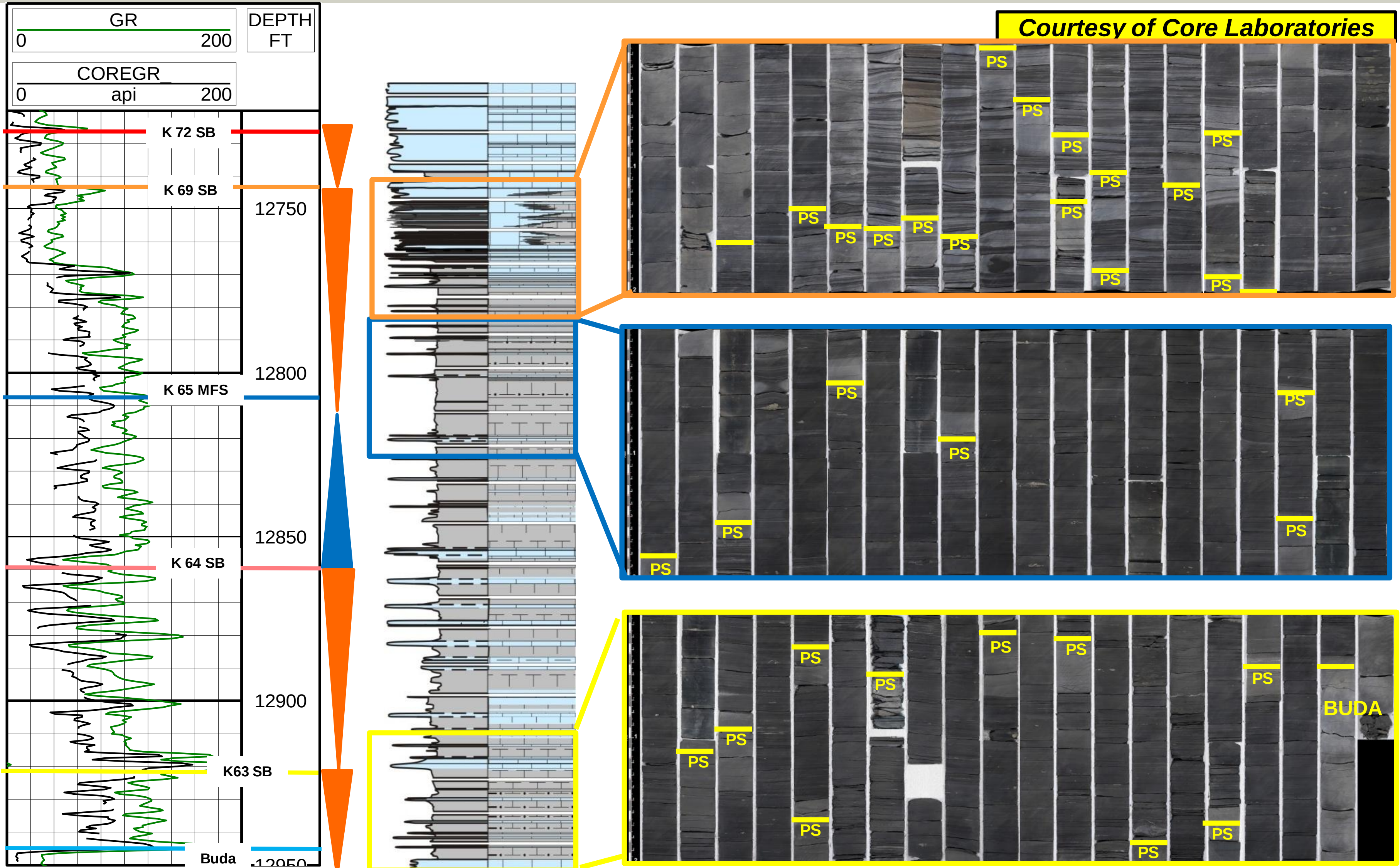
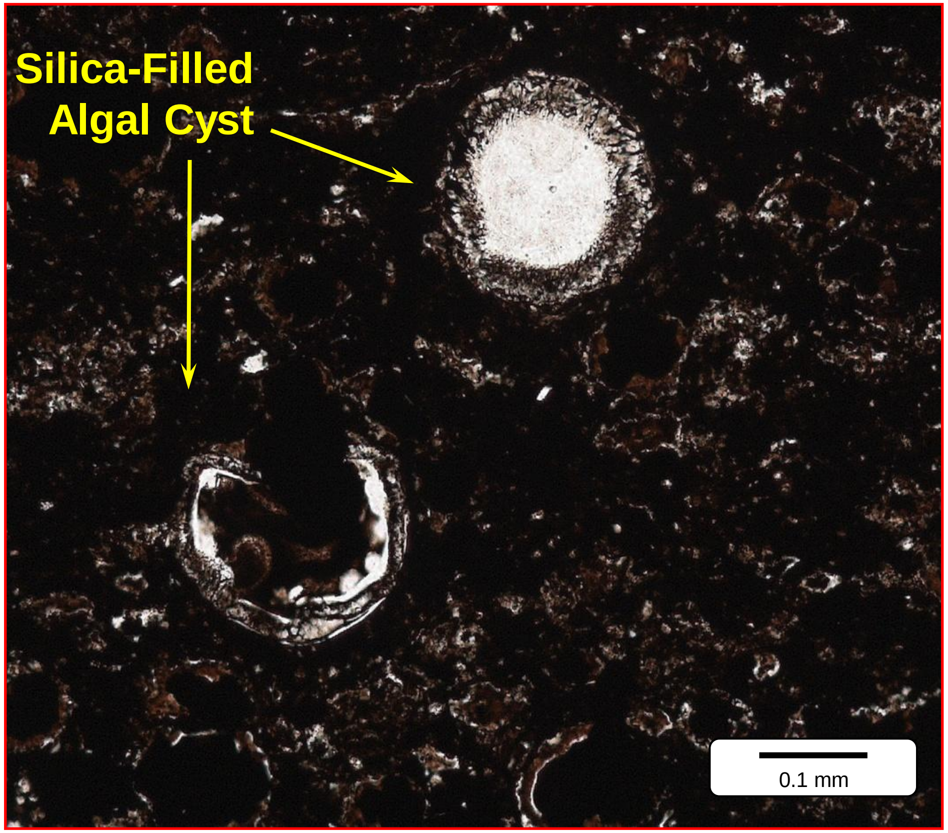


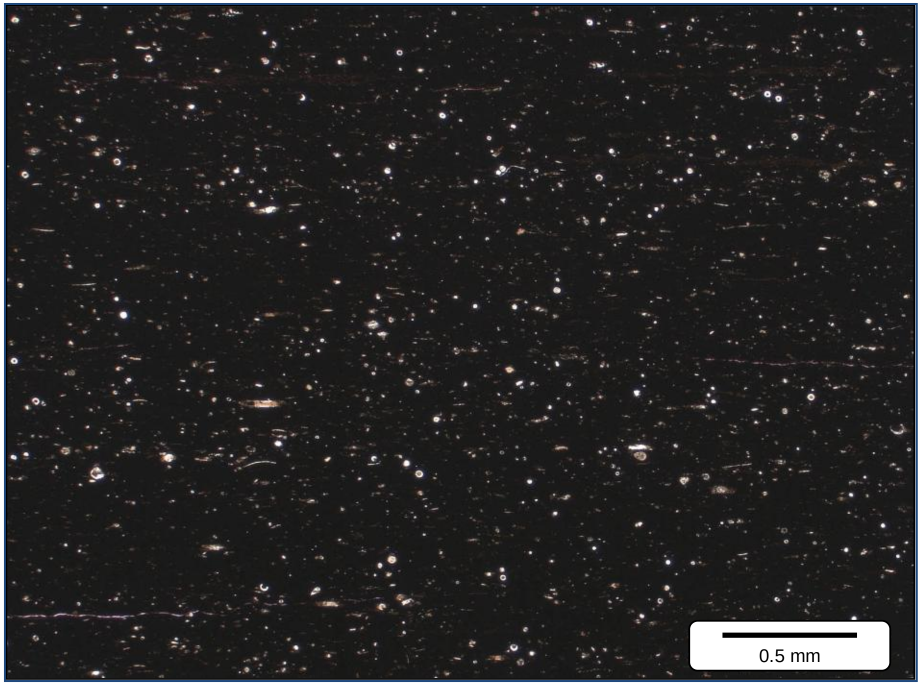
Mineralogical Analysis: Relationship of Texture and Composition to Shale Reservoir Quality

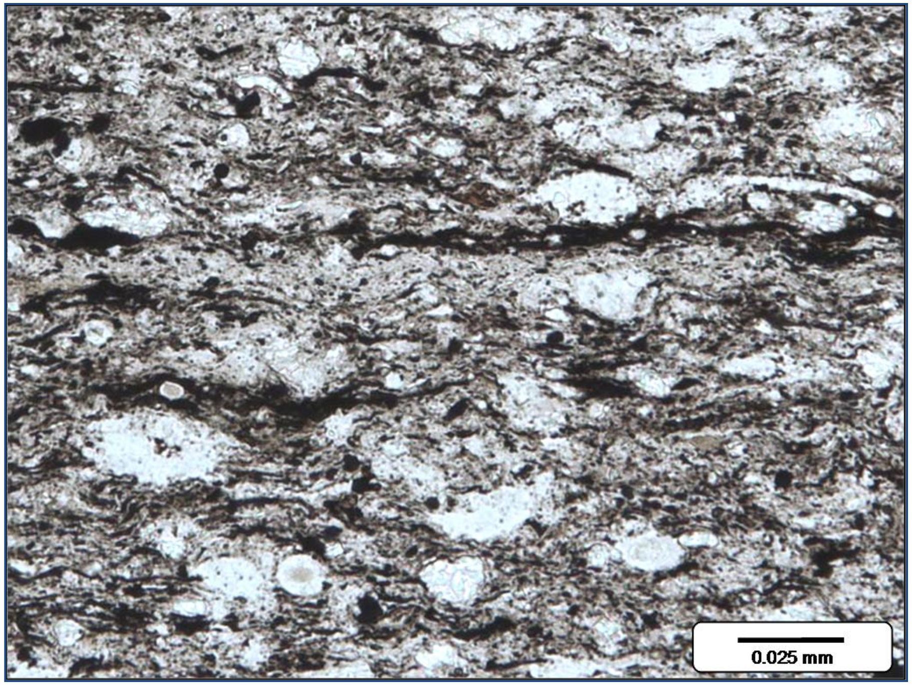
- Epi-fluorescence Petrography
  - Lithology
  - Rock Type
  - Mineralogy
  - Micro-Fractures
- X-ray Diffraction Analysis
  - Mineralogy
  - V Clay
- SEM Analysis



Courtesy of Core Laboratories

Micro-Textural Relationships: The Importance of Scale to Proper Reservoir Identification



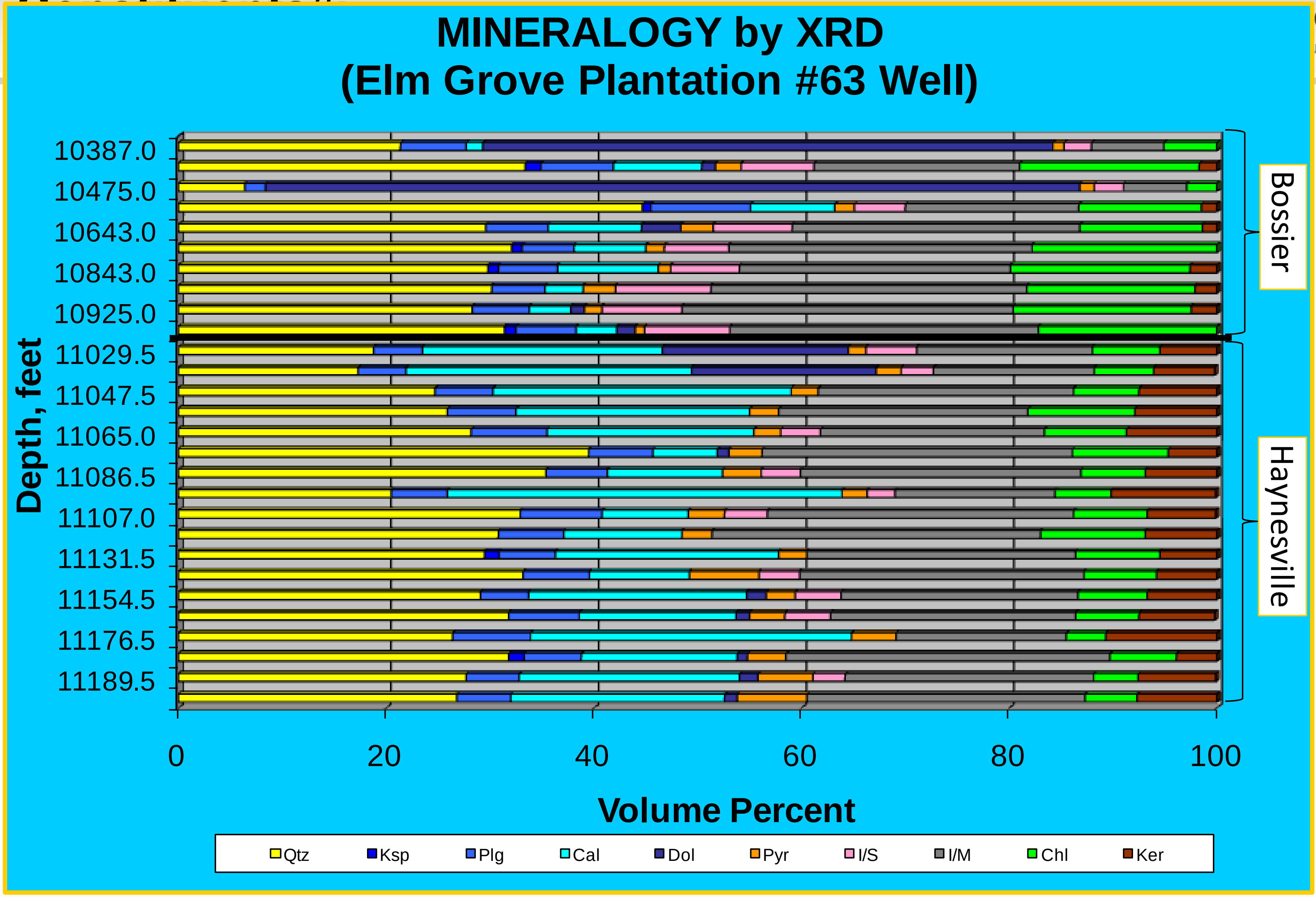


Standard 30-micron-thick slide:
No apparent grain support which would suggest poor reservoir quality

Ultra-Thin (20-micron) slide:
Significant grain support which leads to better reservoir quality

Courtesy of Core Laboratories

The Importance of "Coarse-Grained Constituents"



Courtesy of Core Laboratories

The Importance of "Coarse-Grained Constituents": Marcellus Shale

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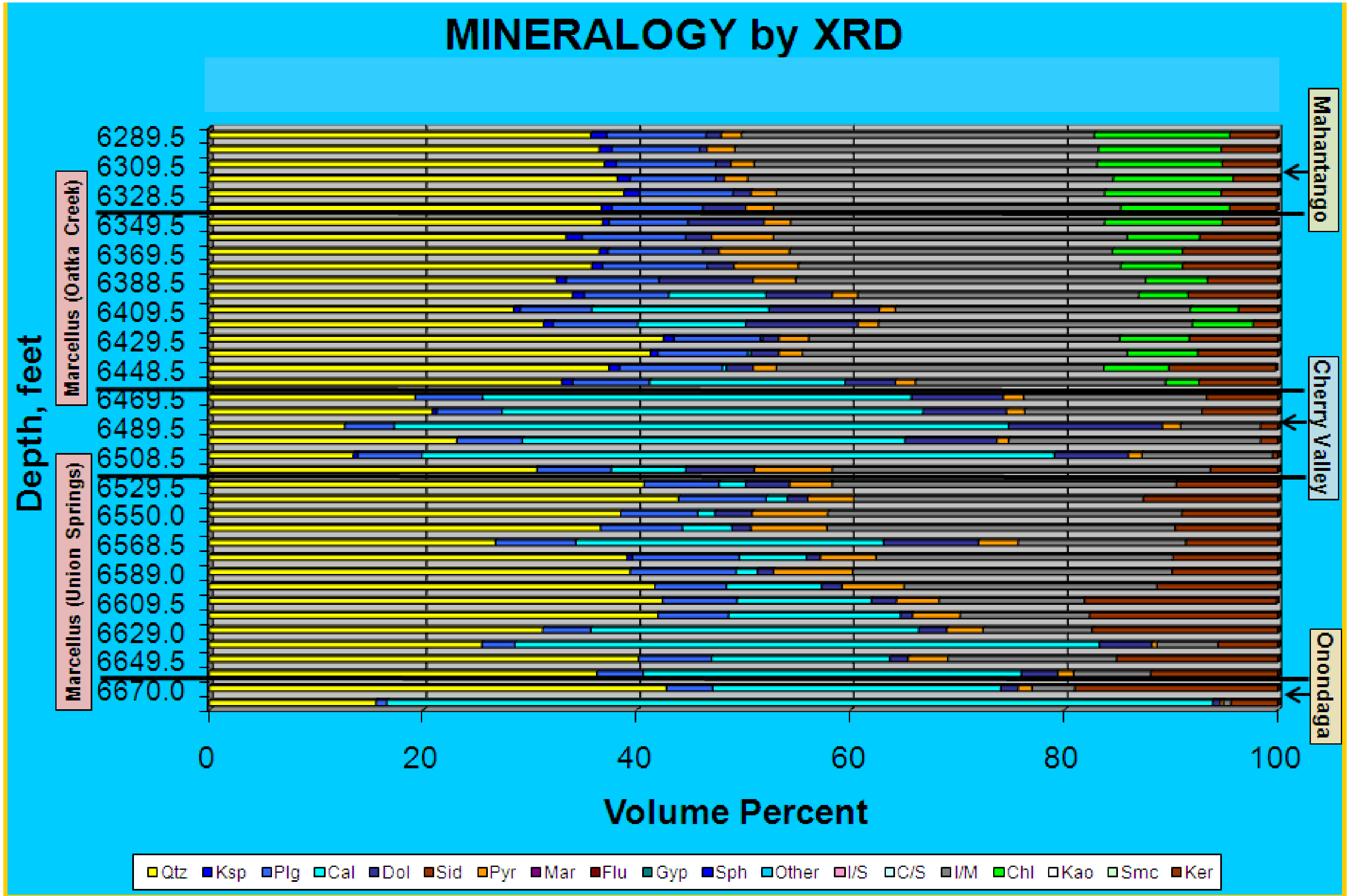
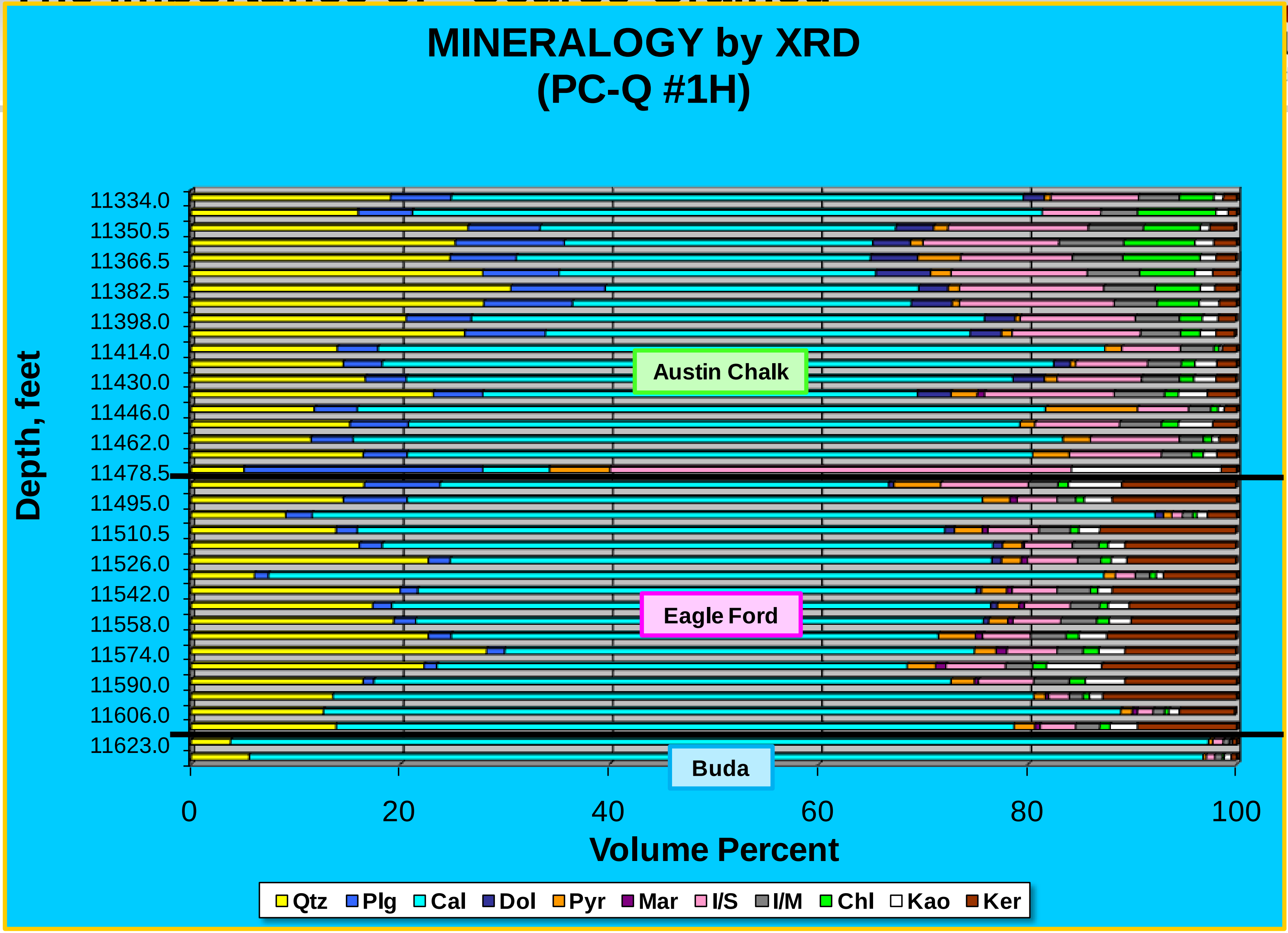


Courtesy of Core Laboratories

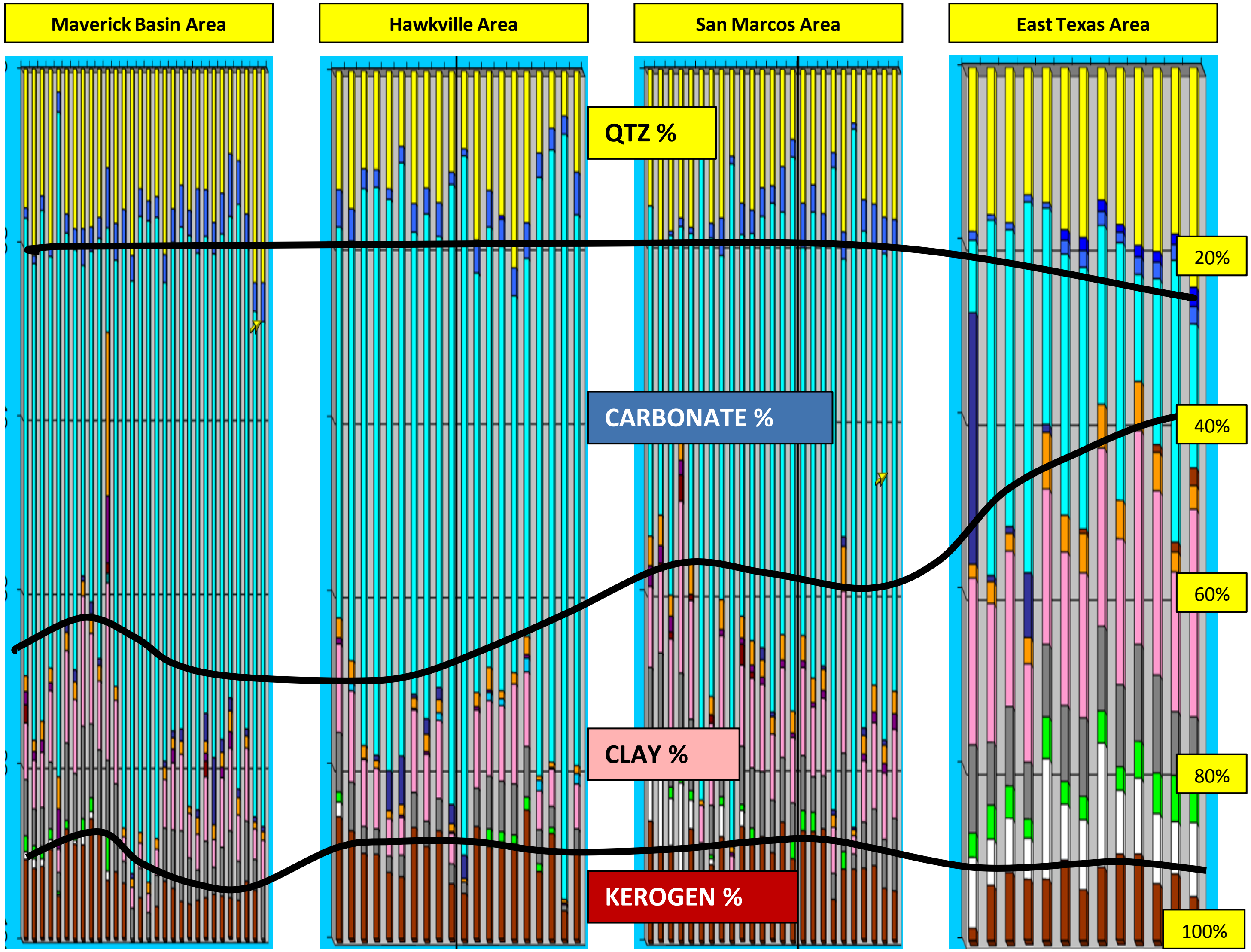
The Importance of "Coarse-Grained



Courtesy of Core Laboratories

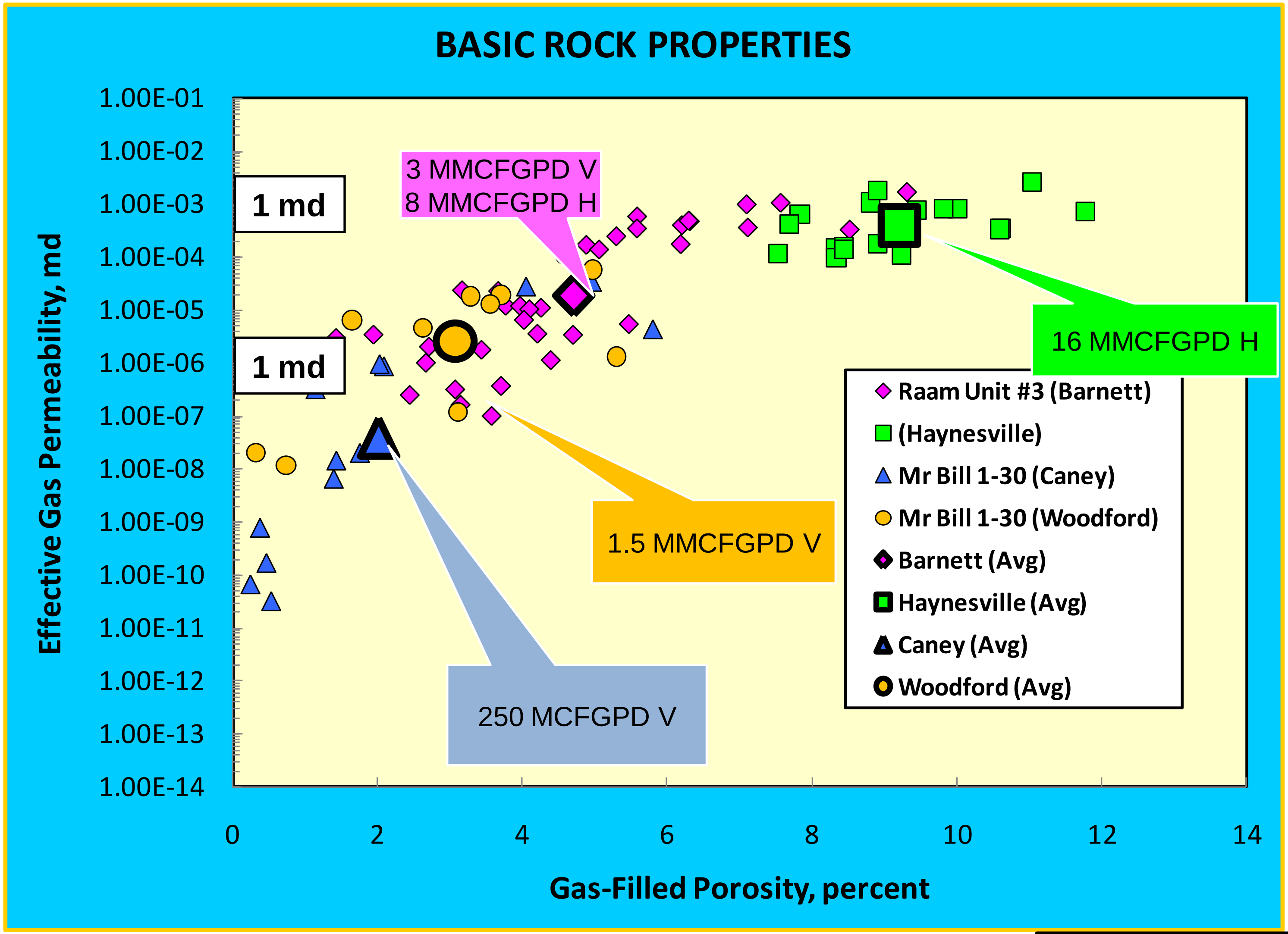
Eagle Ford: Mineralogical Variation Across the Trend

- Clay content increases from west to east
- Kerogen content remains relatively constant
- Increase in clay resultant from clastic influence of the East Texas Basin



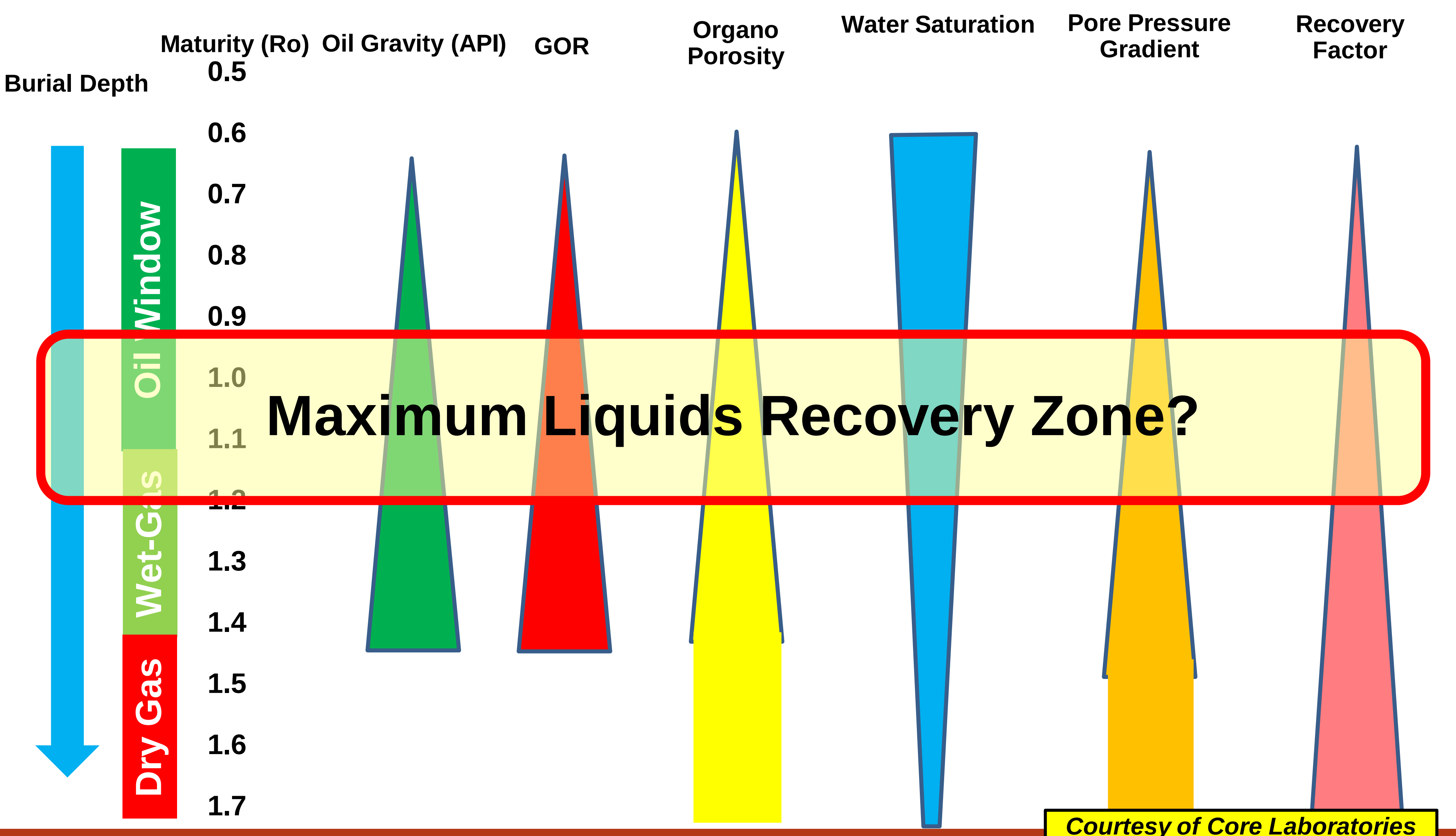
XRD Data from Core Lab

The Relationship of Porosity and Permeability to Mineralogy: Can't Have One Without the Other

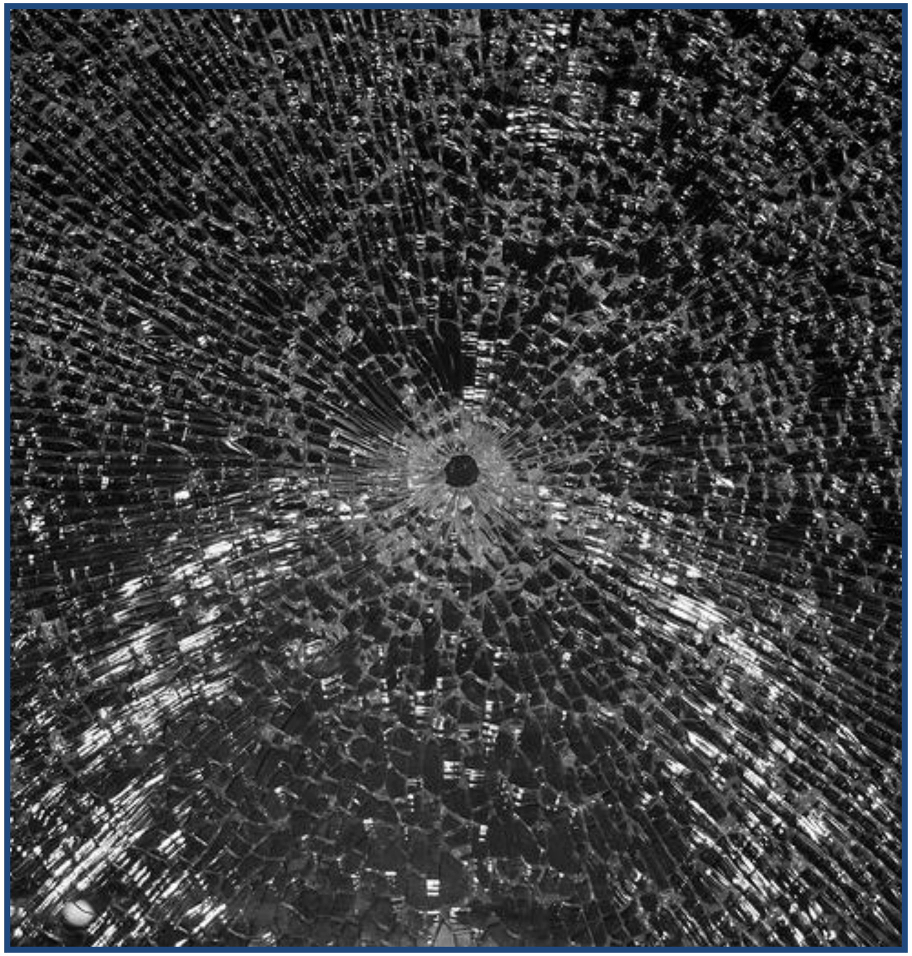


Courtesy of Core Laboratories

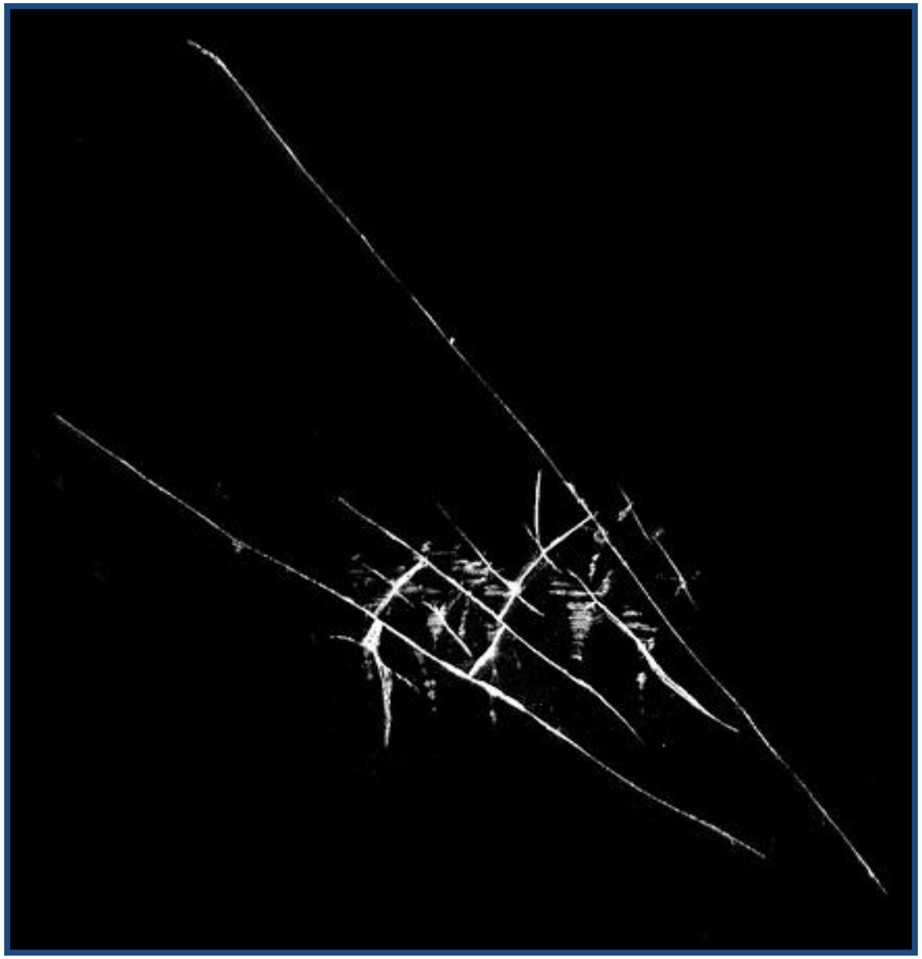
Source Rock Reservoirs: Observed Maturity Effects



The Importance of Stress



Isotropic ‘Tempered’ Glass



Anisotropic ‘Natural’ Glass

Courtesy of Core Laboratories

Measuring Stress: Essential to Understand Geomechanics of the Reservoir

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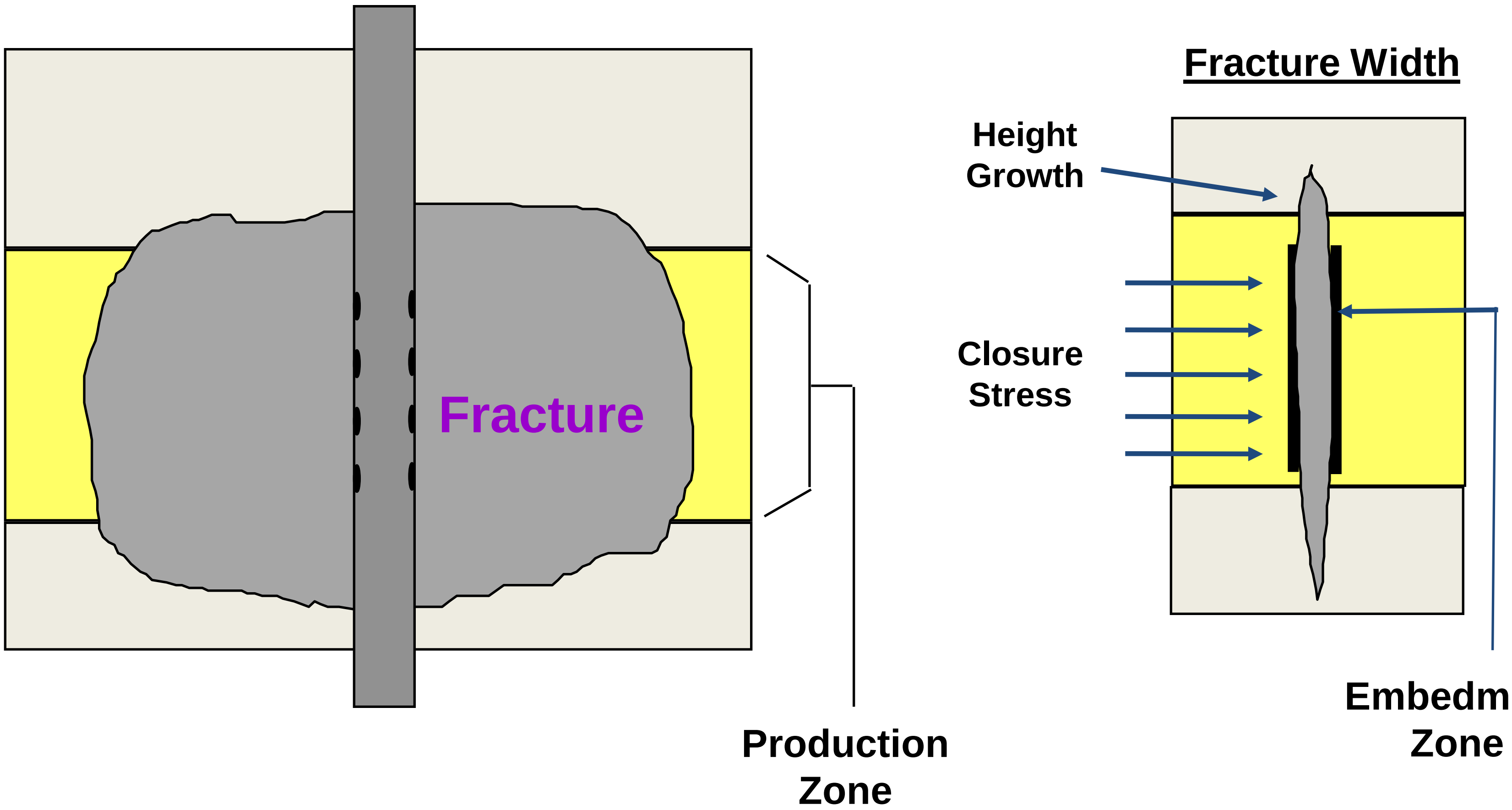
- Laboratory Measurement
  - Static and Dynamic Measurements on Core Samples (Young’s Modulus)
- Log Data
  - Full-Waveform Acoustic Logs (Dipole Sonic)
  - Bulk density
  - Lithology

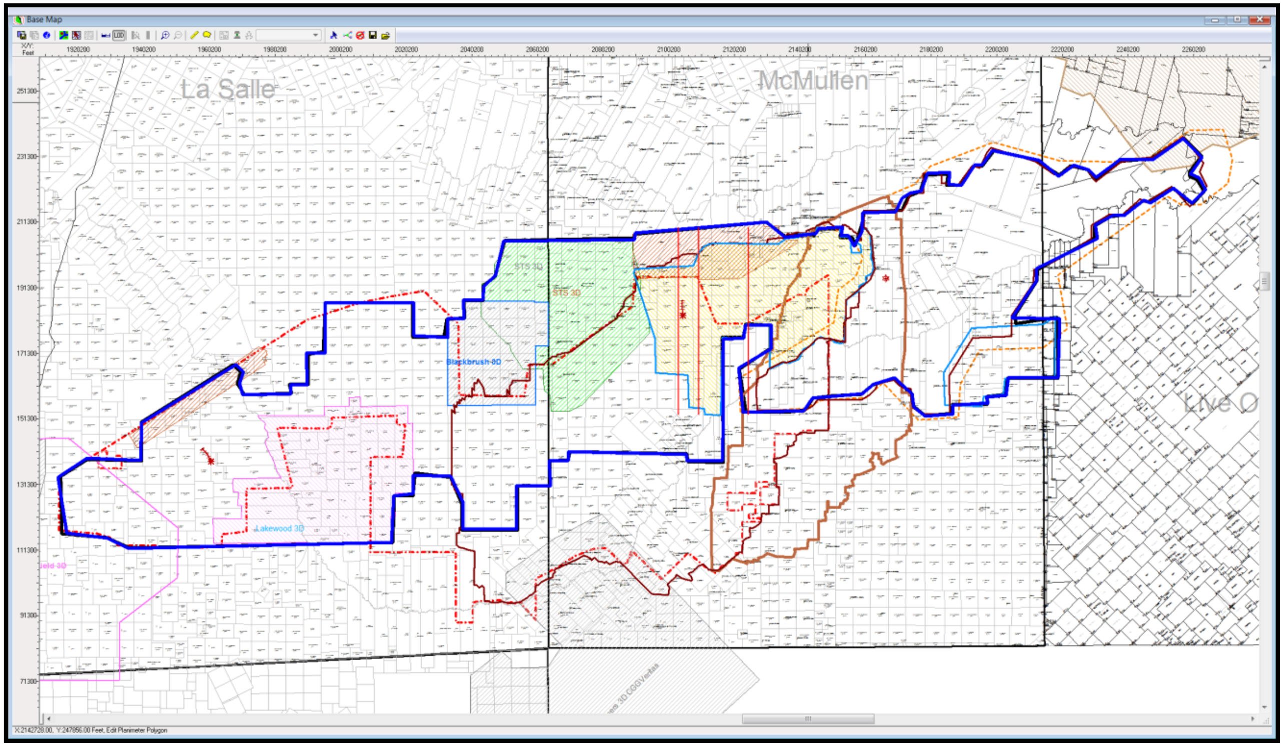
Definition of Fracture Geometry



Courtesy of Core Laboratories

Unconventional Development Process

3D Seismic Data: Critical to a Successful Development Program

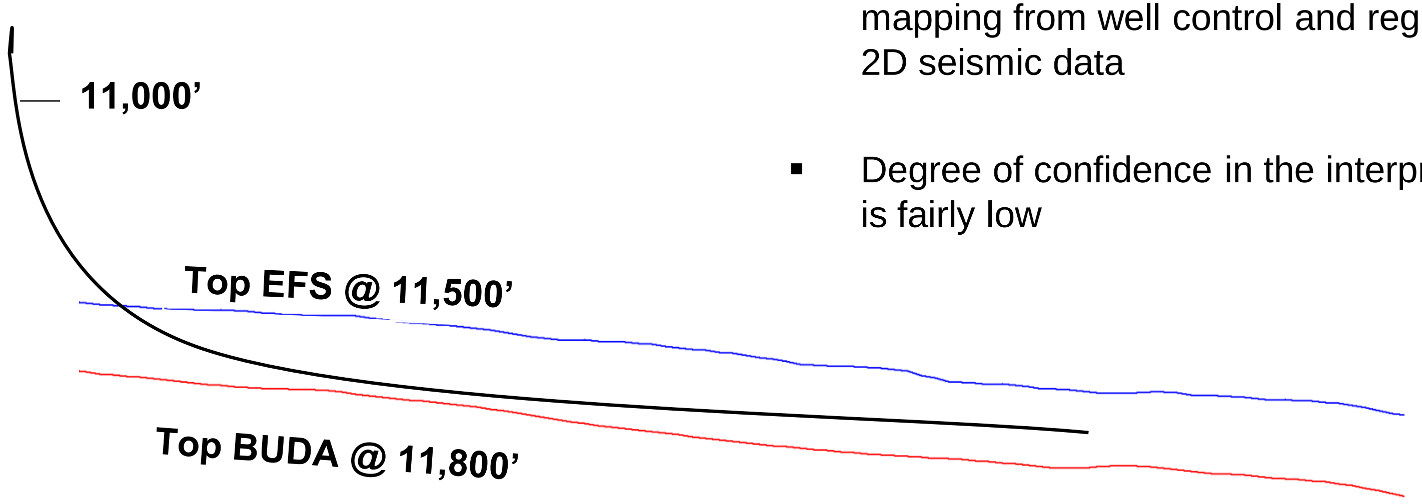


- The cost of 3D seismic data is minimal in the total field development cost
- 3D seismic data is critical in identifying faults and dip changes that could compromise the stratigraphic targeting of a horizontal wellbore
- Merged ~650 square miles of acquired proprietary data and licensed data in Hawkville Field

Geo-Steering: An Important New Geoscience Skill Set

- Horizontal drilling creates significant ***geological*** challenges
- Unforeseen dip changes and/or faults can cause a well to be out of zone for a large portion of a lateral
- The combination of utilizing 3D seismic data and Measured Depth (MD) to True Vertical Depth (TVD) Gamma Ray correlation allows the geologist to direct the ***drilling*** operation to allow the well to stay within the target window
- The post-drill geologic interpretation of the wellbore also provides insight into the completion design and can cause the ***completion*** engineer to vary certain stages of the hydraulic fracture stimulation depending on the inferred reservoir quality within each stage

Pre-Drill Well Plan Prior to 3D Seismic Data Acquisition

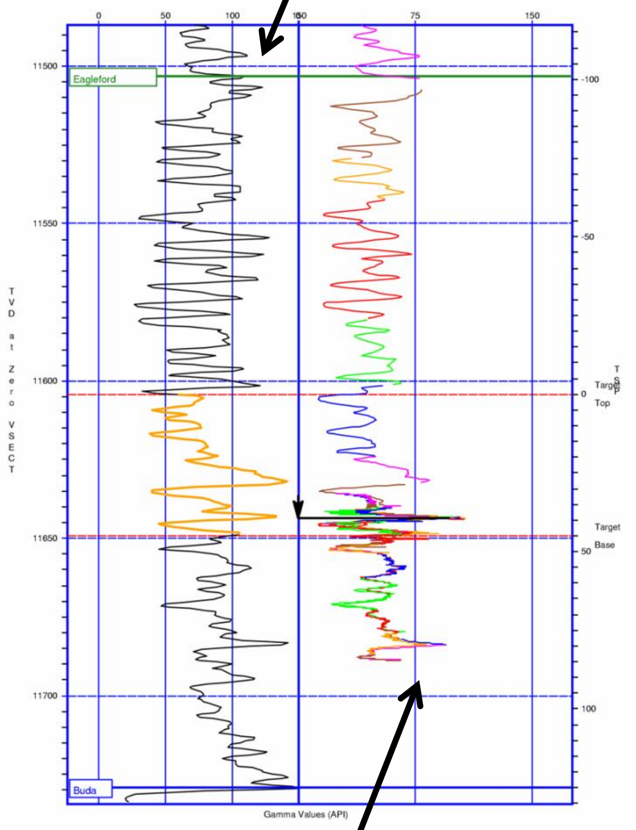


- Well plan is designed using subsurface mapping from well control and regional 2D seismic data
- Degree of confidence in the interpretation is fairly low

Target Line: 11578' TVD @ Zero Vertical Section Assuming Average 2 degree dip

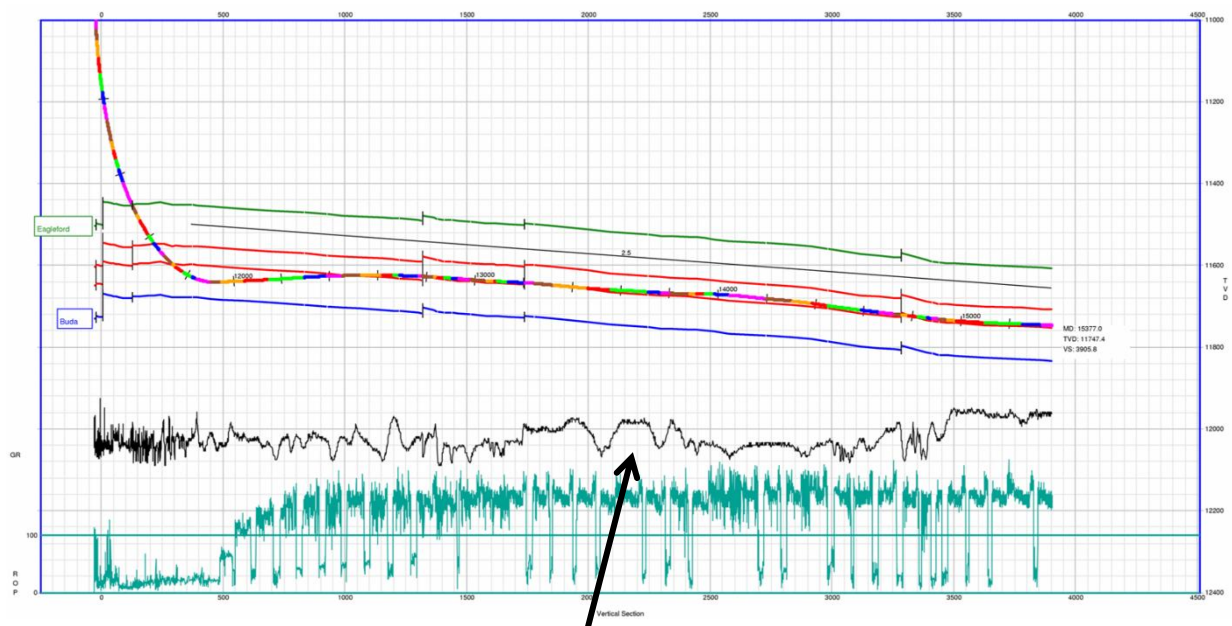
Pre-Seismic Geosteering Interpretation at TD

Pilot Hole Gamma Ray



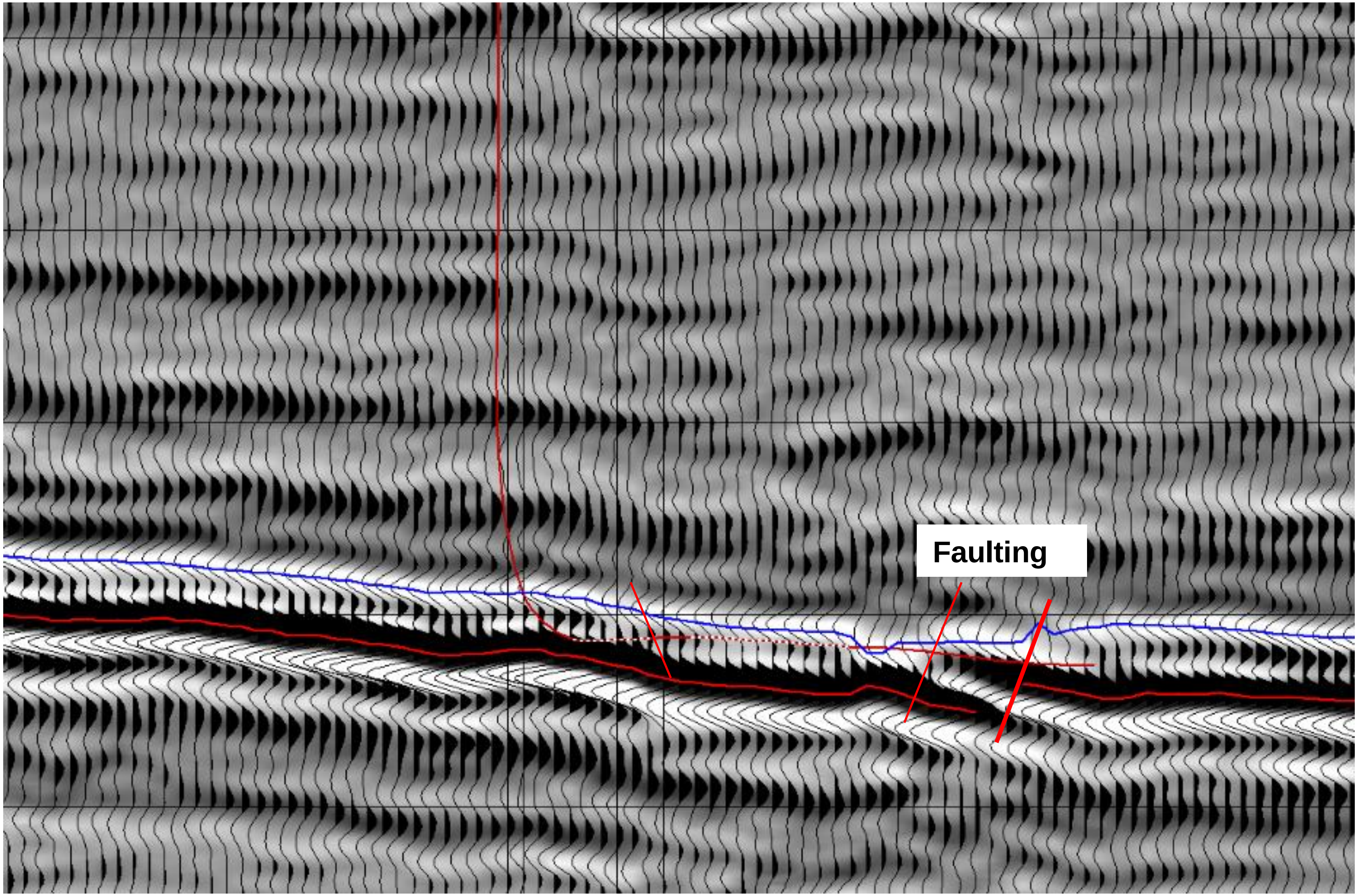
Horizontal Hole TVD Gamma Ray

Vertical Section Montage



Horizontal Hole MD Gamma Ray

3D Seismic Acquired After Completion



Geosteering Interpretation Using 3D Seismic Data

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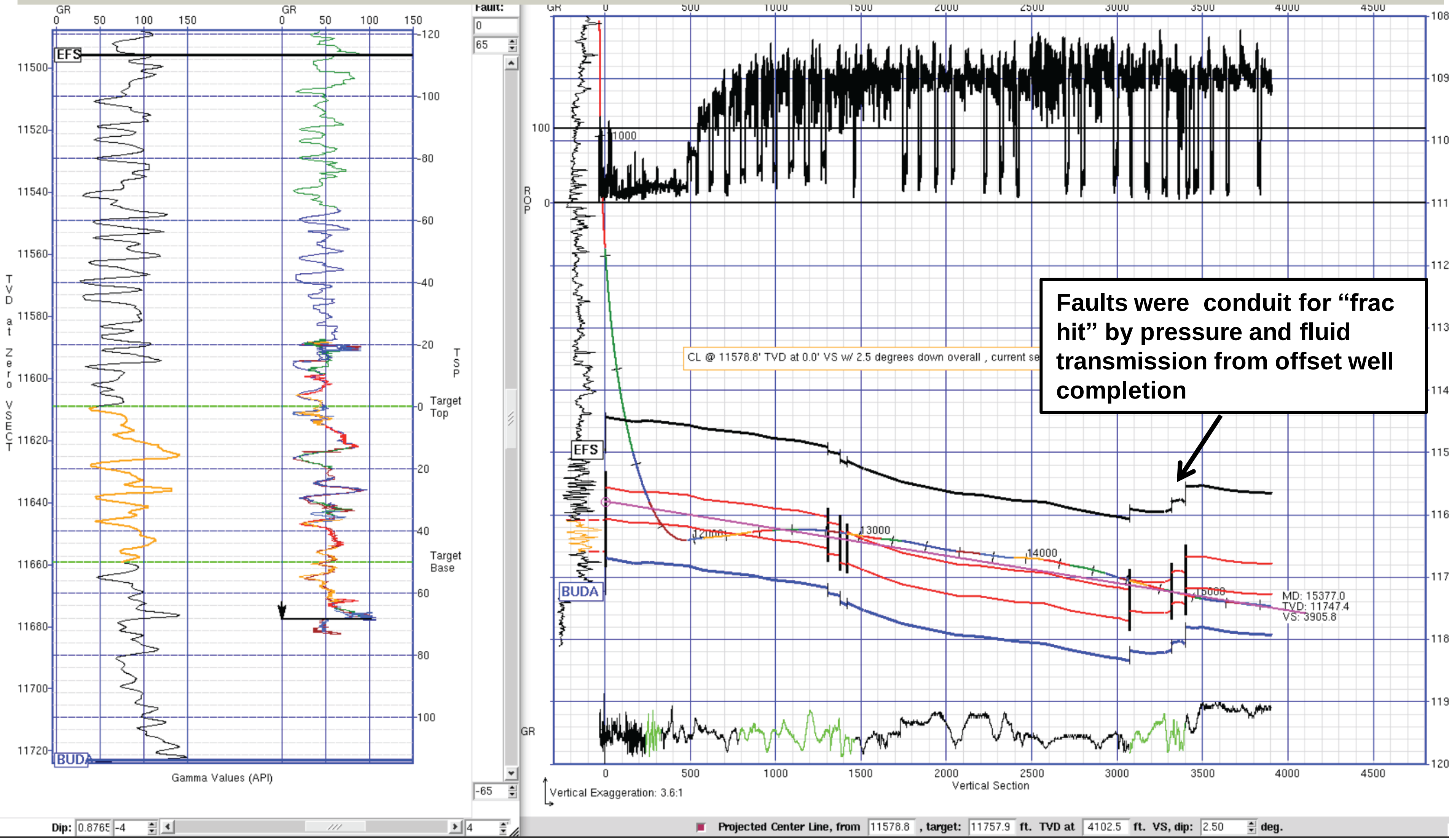
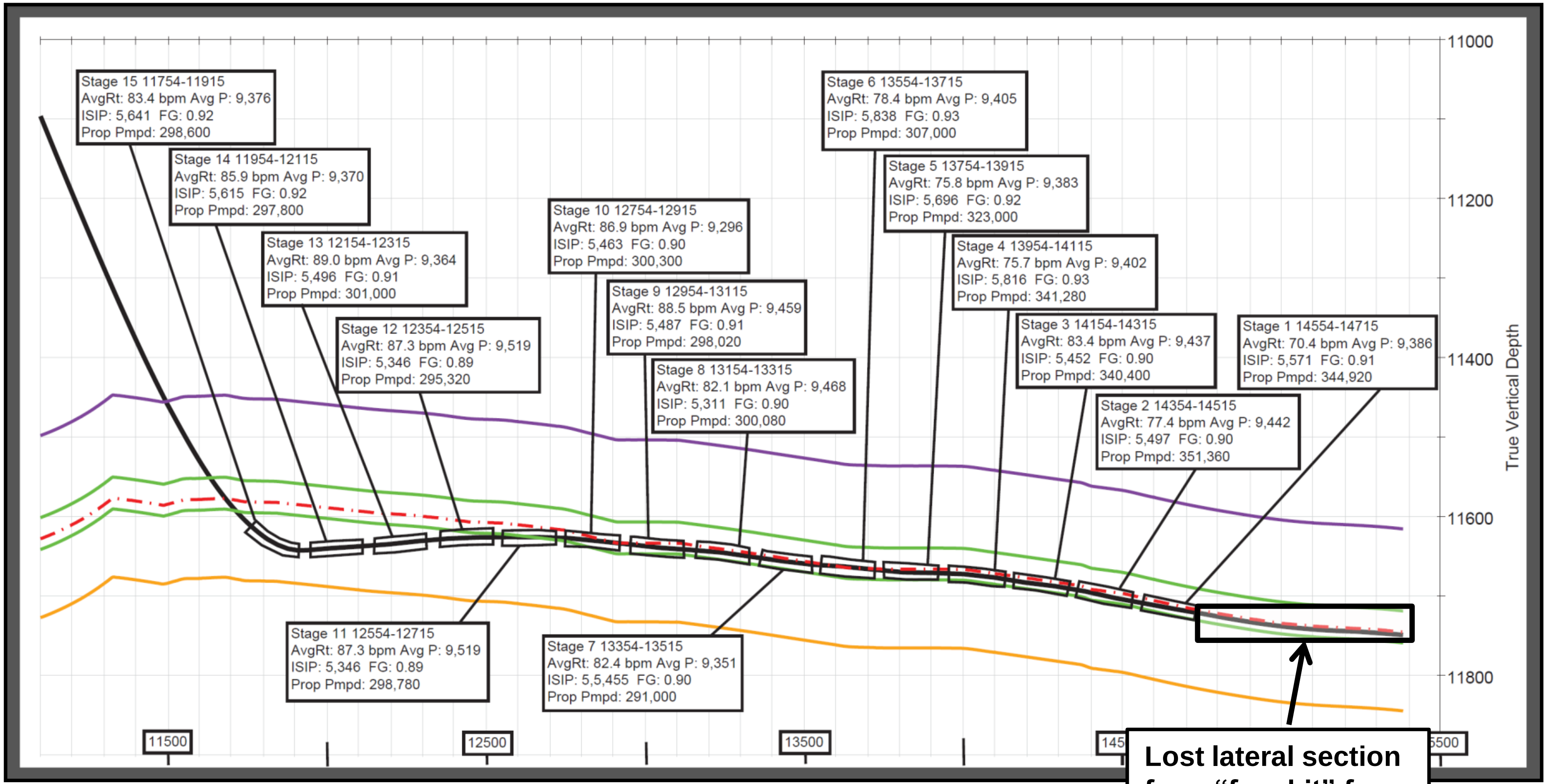
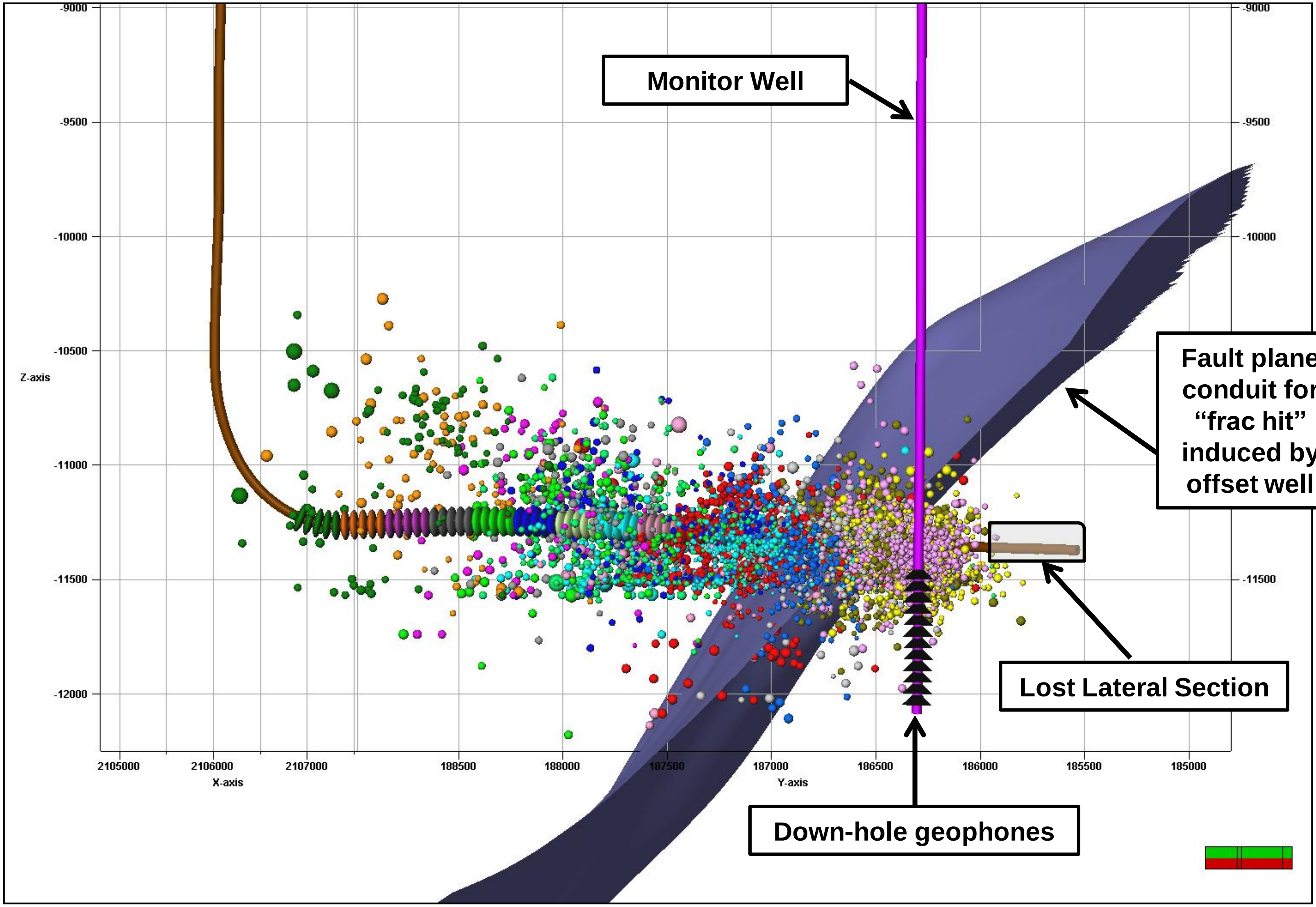


Stage by Stage Fracture Stimulation Montage



Lost lateral section from "frac hit" from offset well

Microseismic Data: Down-Hole View of Fracture Geometry



Conclusions

- The geologic aspects of the Exploration process in shale reservoirs require an “inverted” thought process as compared to conventional exploration and usually is done with insufficient knowledge of reservoir quality

- The geologic aspects of the Appraisal process in shale reservoirs are highly dependent on an understanding of the “nano” elements of the reservoir and require a tremendous amount of data gathering and analysis over an extremely large area

- The geologic aspects of the Development process in shale reservoirs have generated a new set of skills, the most prominent being geo-steering, which is exciting, challenging and cross functional with several engineering disciplines

Acknowledgments

- BHP Billiton Petroleum colleagues, specifically Vanon Sun Chee Fore, Terry Gebhardt, John Goss, Alan Frink, Andy Pepper, Melissa Florian and Kelley O'Brien

- Core Laboratories, specifically Randy Miller

- Seitel, Inc.