

# **Sequence Stratigraphy of the Woodford Shale and Application to Drilling and Production\***

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Search and Discovery Article #50792 (2013)\*\*

Posted June 21, 2013

\*Adapted from oral presentation given at AAPG Woodford Shale Forum, Oklahoma City, OK, April 11, 2013. Authorship includes “several students, Institute of Reservoir Characterization.”

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## **Abstract**

The Woodford Shale in Oklahoma commonly is subdivided into Lower, Middle, and Upper members. Yet, based upon lithologic variability determined from core and/or well logs, the members can be further subdivided, particularly the productive Middle member. Subdivision is readily accomplished within the context of sequence stratigraphy (Slatt and Rodriguez, 2012): the Woodford comprises a 2nd order depositional sequence comprised of several 3rd (and most likely 4th) order (para)sequences. These intervals are verified by a combination of well and core descriptions, and more recently, by palynology (Molinares, in prep.). Such parasequences are correlative and mappable for considerable distances using well logs and 3D seismic (when calibrated with logs) (Amorocho, 2012).

Sequence stratigraphic intervals and their rock properties can be related to geomechanical (as well as geochemical) properties. Geomechanical characterization has led to development of the concept of brittle-ductile couplets, that can be correlated and mapped (Slatt and Abousleiman, 2011). Brittle strata tend to be enriched in biogenic quartz and/or carbonate material and ductile strata tend to be enriched in clays and organic matter.

Because depositional sequences and parasequences occur at a variety of geologic time scales, brittle-ductile couplets also occur at a variety of stratigraphic scales. Thus, there is a natural, predictable link between sequence stratigraphy and geomechanics. The recognition of such couplets can better target landing zones for horizontal drilling and artificial fracturing.

## **Selected References**

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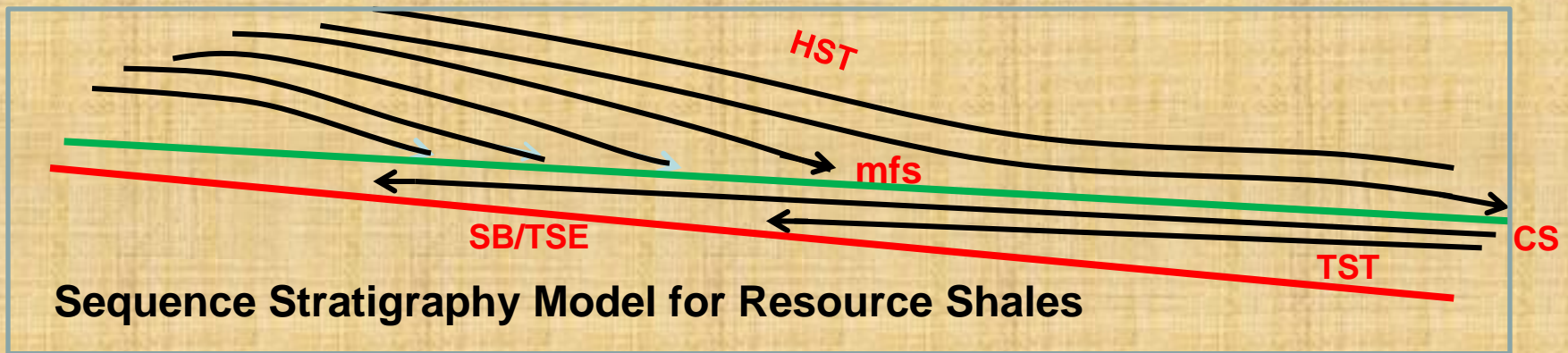
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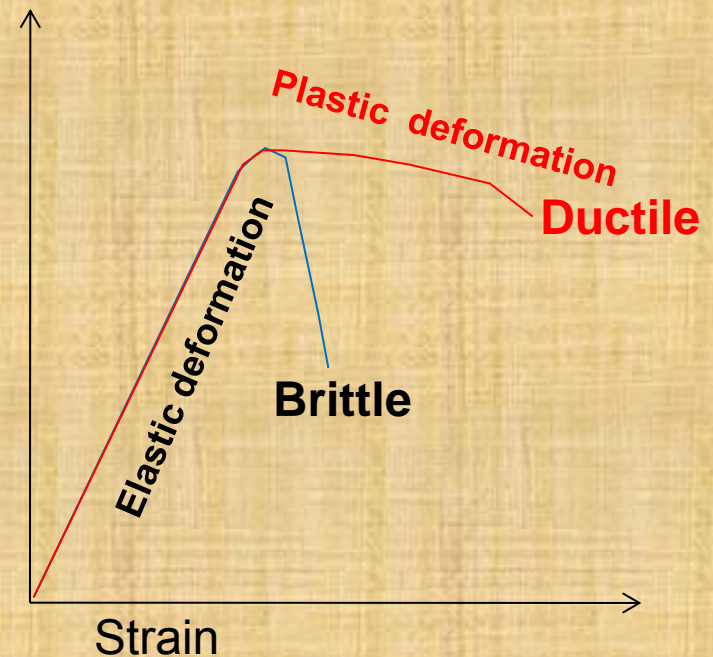
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**Roger M. Slatt**  
and  
**several students**

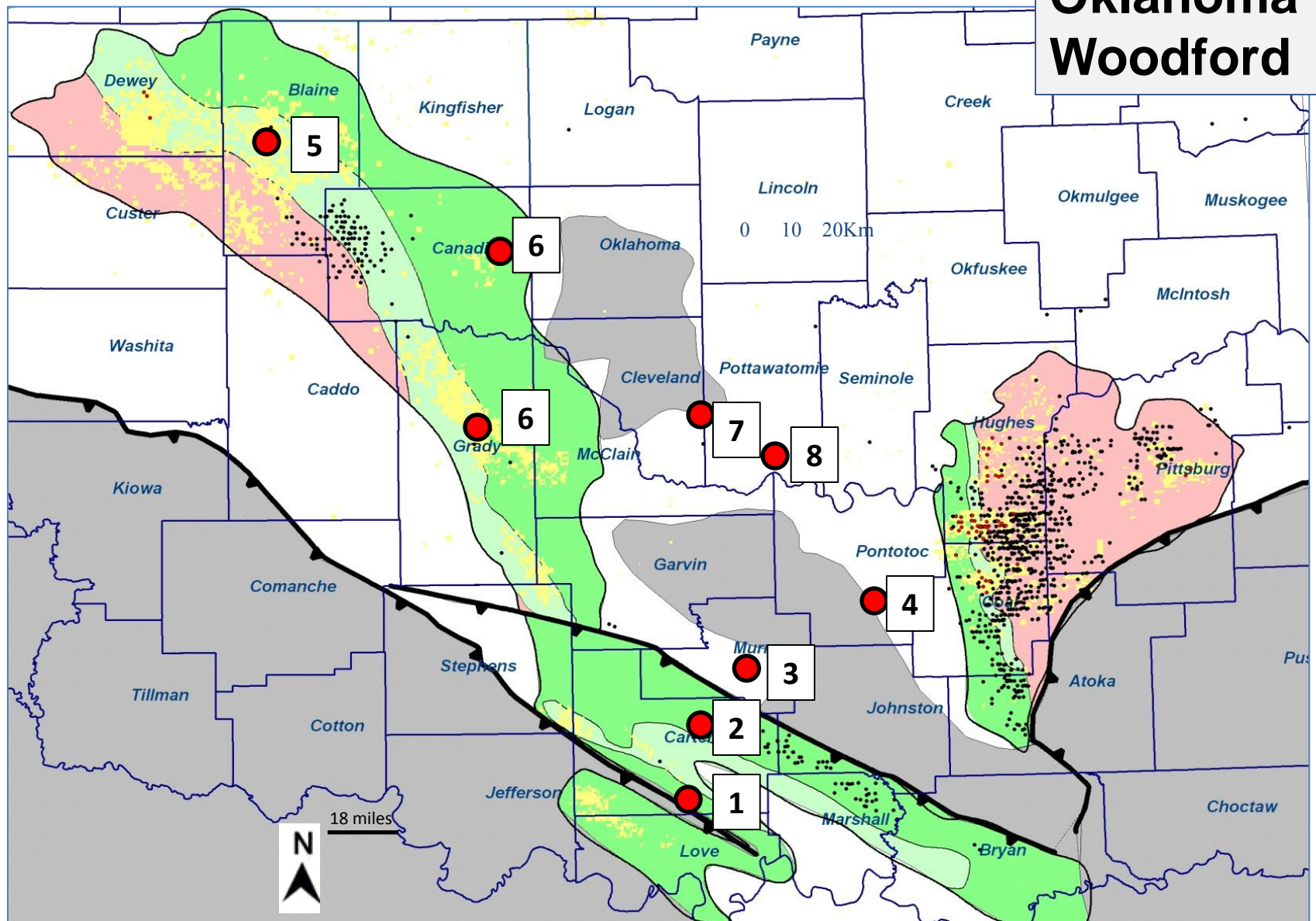
Institute of Reservoir  
Characterization

University of Oklahoma



**Sequence stratigraphy of the Woodford Shale  
and applications to drilling and production**

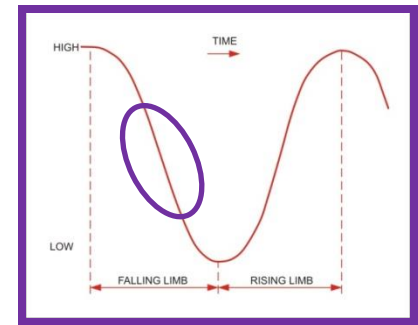
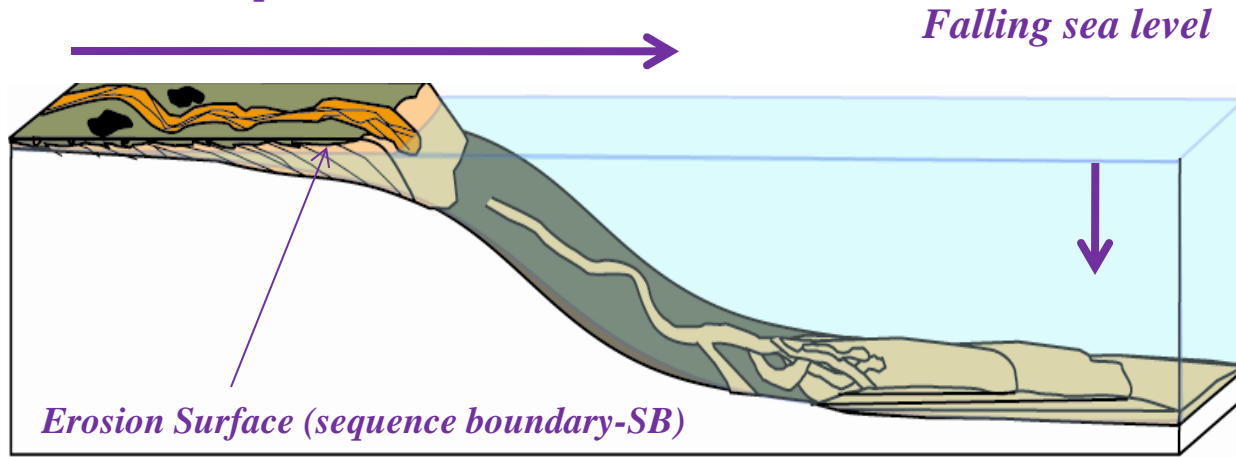
# Oklahoma Woodford



Gas Condensate Oil No Woodford

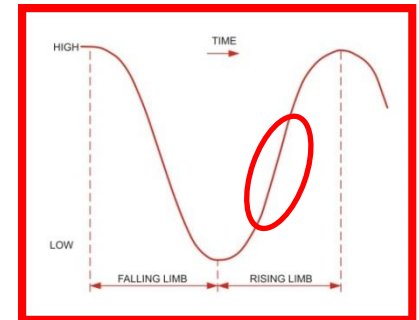
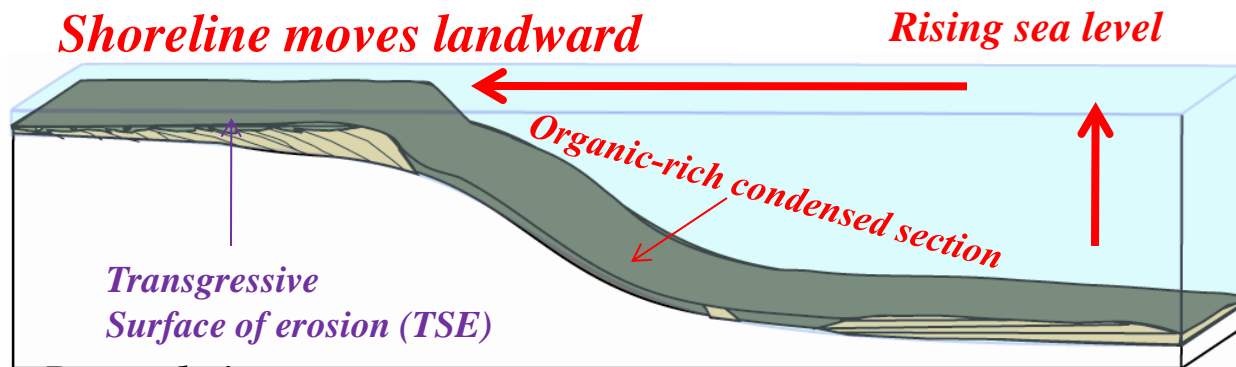
All well and outcrop locations are approximate

*Shoreline moves seaward: shelf becomes exposed and eroded.*



*“Lowstand systems tract”*

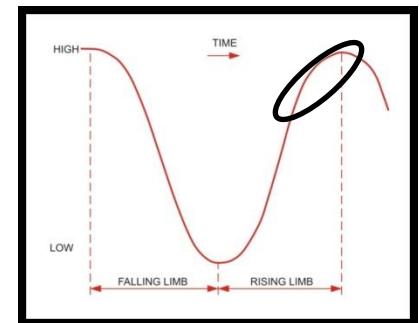
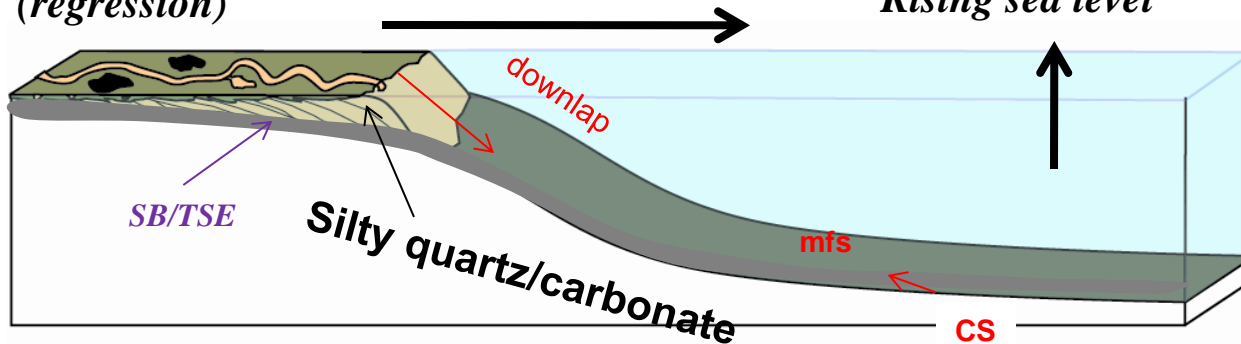
*Shoreline moves landward*



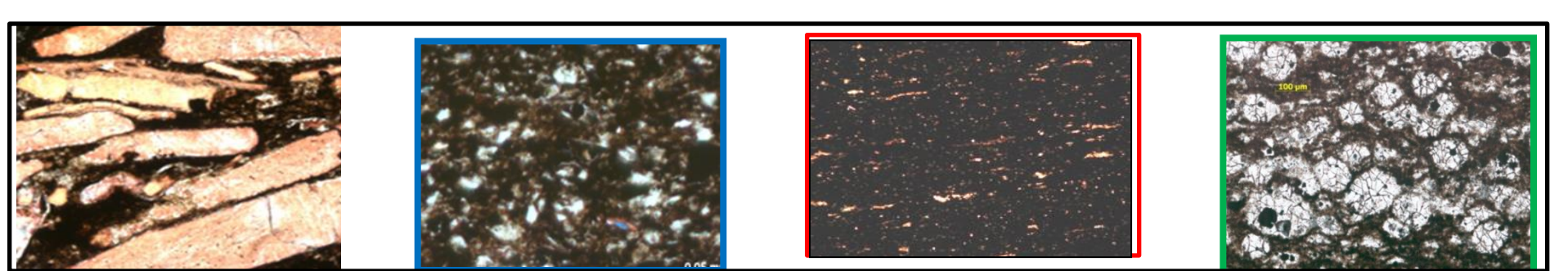
*“Transgressive systems tract”*

*Progradation (regression)*

*Shoreline moves seaward*



*“Regressive/Highstand systems tract”*

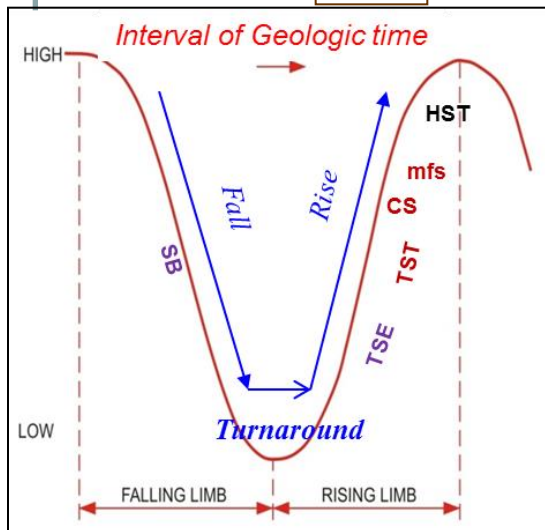
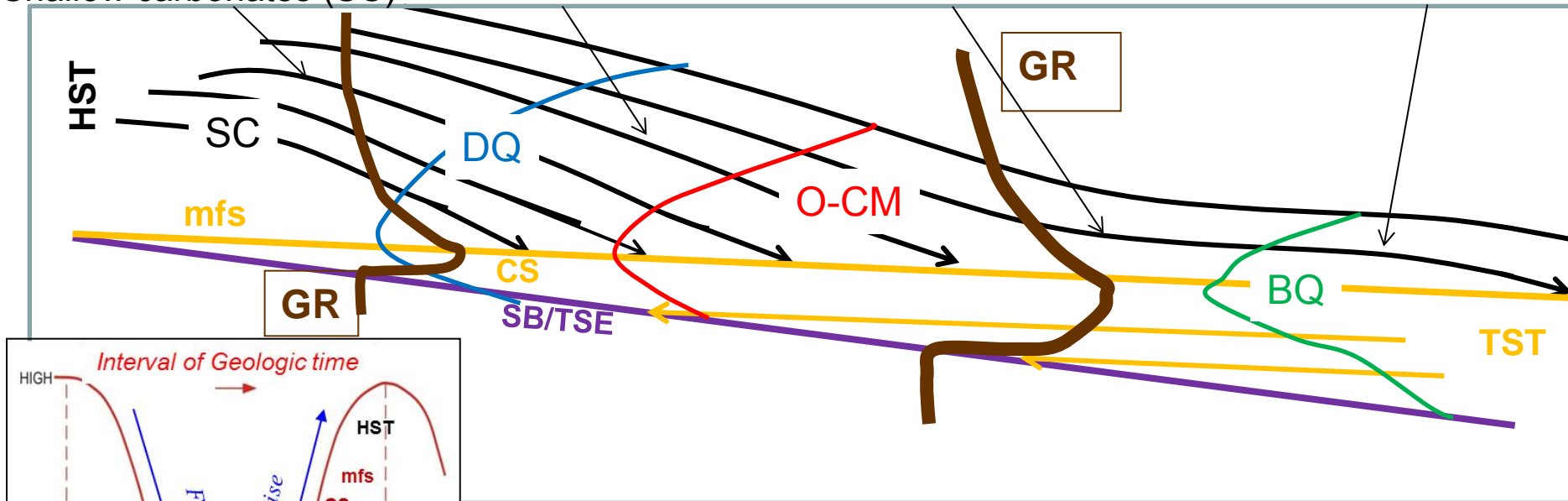


Shallow carbonates (SC)

Detrital quartz (DQ)

Organic/clay mudstone (O-CM)

Biogenic quartz (BQ)



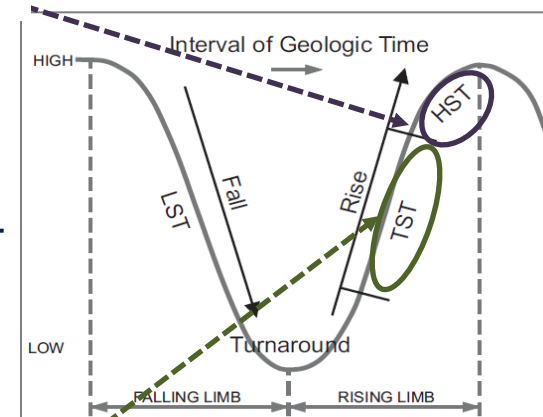
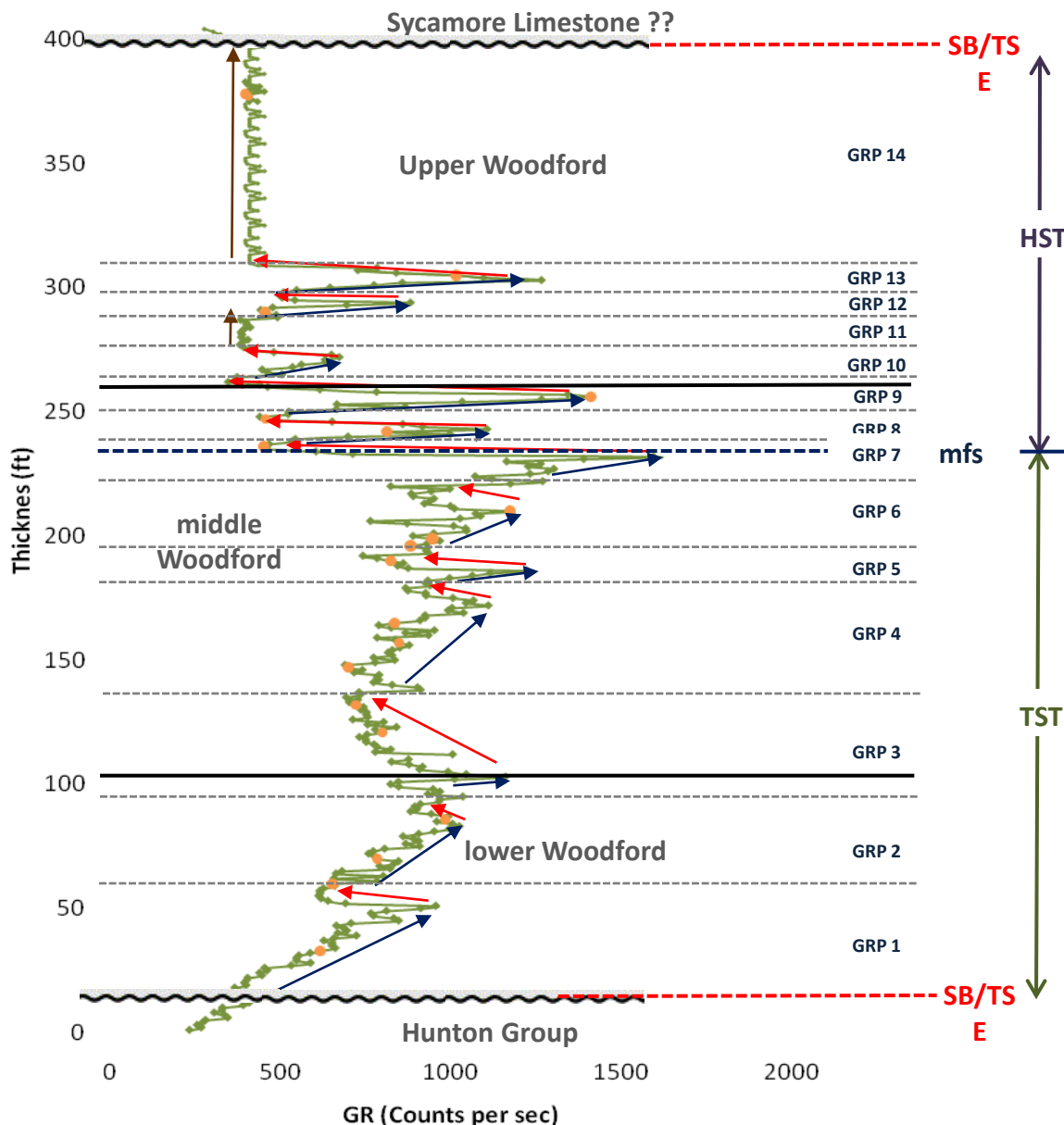
**Global (eustatic) cycle: *Intervals of geologic time***

- 2<sup>nd</sup> order—10 -25 Ma
- 3<sup>rd</sup> order-- - 1- 5 Ma
- 4<sup>th</sup> order.... 0.1-0.5 Ma

**Sequence Stratigraphy Model for resource shales**

# Woodford in McAlester Cemetary Quarry

Serna-Bernal, 2013



Modified from Slatt and Rodriguez, 2012

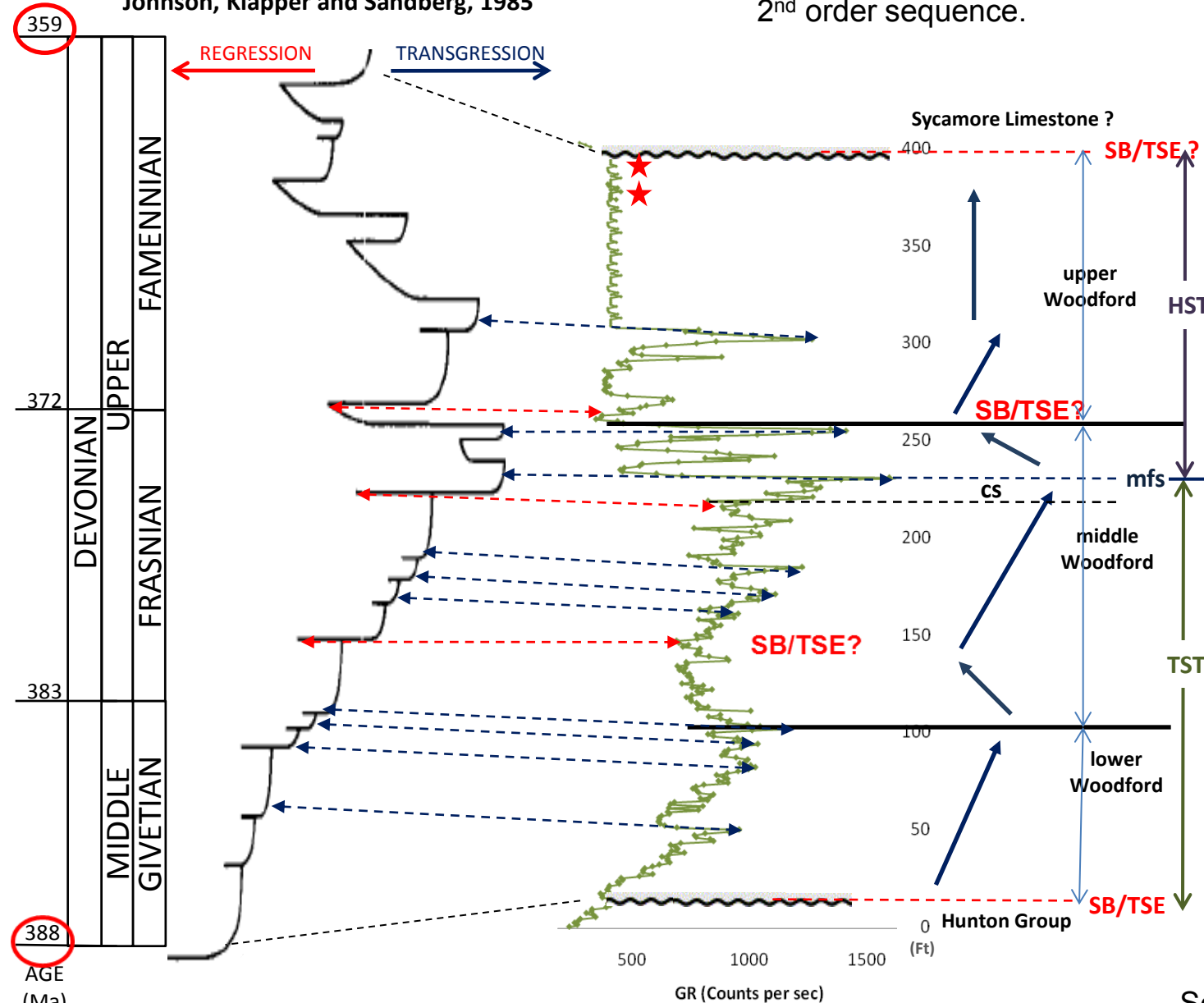
## GAMMA RAY PARASEQUENCE

- Upward Decreasing GRP
- Upward Increasing GRP
- Constant GRP
- Sample

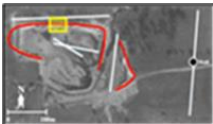
mfs: Maximum Flooding surface  
 SB: Sequence boundary  
 TSE: Transgressive surface of erosion  
 LST: Lowstand system tract  
 TST: Transgressive system tract  
 HST: Highstand system tract

Age of Woodford = 388-359my = 29my = “2<sup>nd</sup> order sequence”. Several 3<sup>rd</sup> order (1-5my) sequences within 2<sup>nd</sup> order sequence.

GLOBAL SEA LEVEL CURVE  
Johnson, Klapper and Sandberg, 1985



Serna-Bernal, 2013



# Wyche Farm Quarry

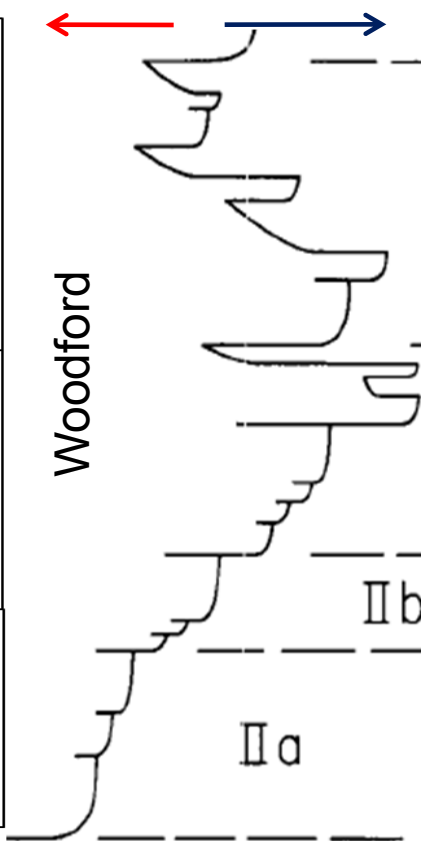
Molinares, 2013



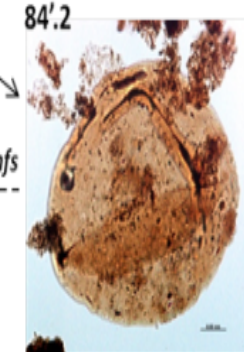
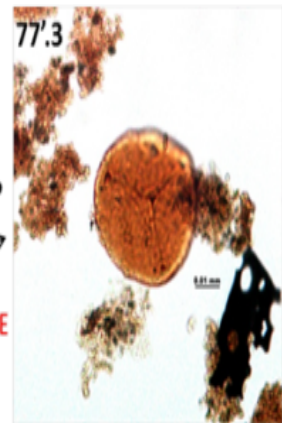
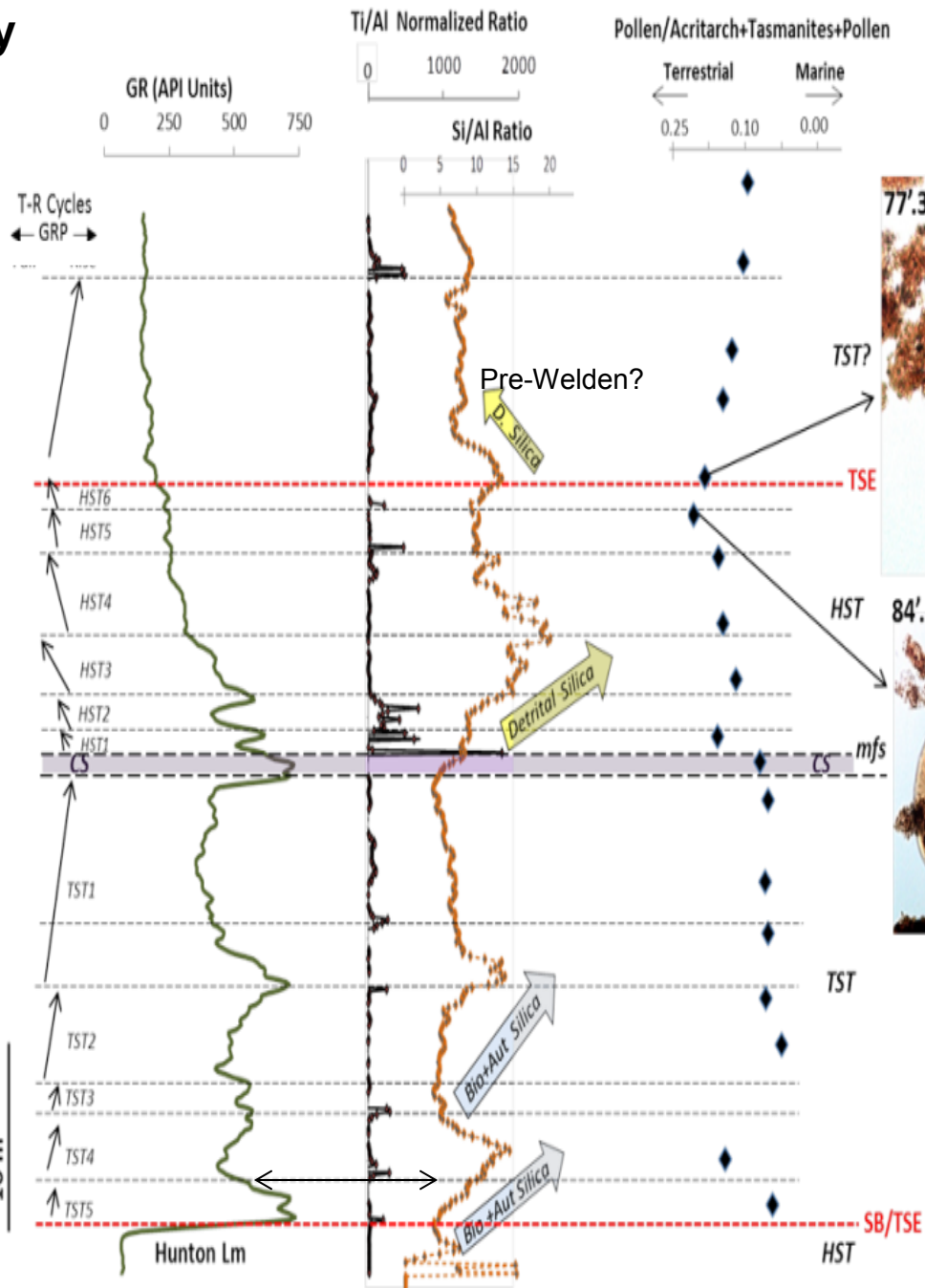
359			
			FAMENNIAN
	DEVONIAN	UPPER	
372			FRASNIAN
	MIDDLE	GIVETIAN	
383			
388			
AGE (Ma)			

REGRESSION ←      → TRANSGRESSION

Woodford



50 ft  
10 m



An interval is classified (by drillers) to be:

**Ductile**

A lot of pumping to break

High fracture gradient

**Brittle**

Not as much as the “ductile” intervals

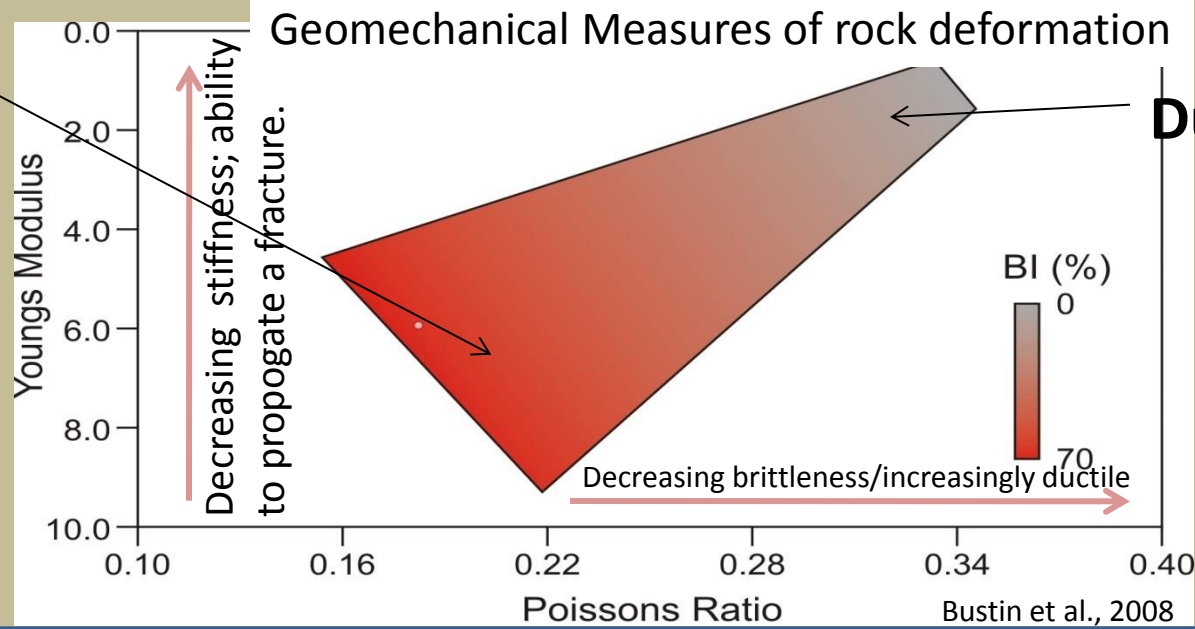
Lower fracture gradient

## Mineralogic affect on rock fracturability (brittleness) (Wang and Gale, 2009)

$$BI = (Q + Dol + Lm) / (Q + Dol + Lm + Cl + TOC)$$

Where **BI** = brittleness index; **Q** = quartz; **Cl** = clay; **Dol** = dolomite; **Lm** = limestone (calcite); **TOC** = Total organic carbon

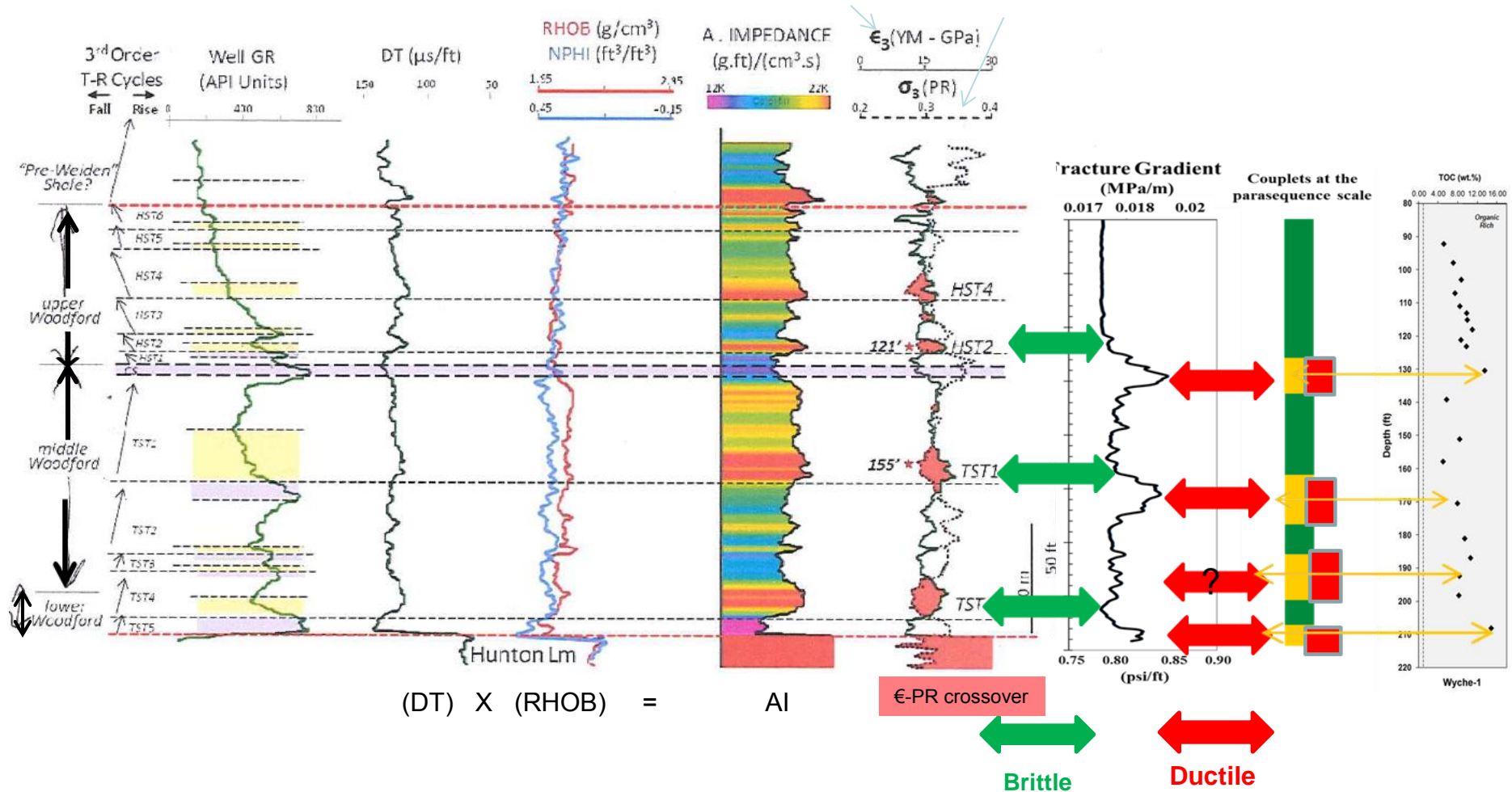
**Brittle Rock**



**Ductile Rock**

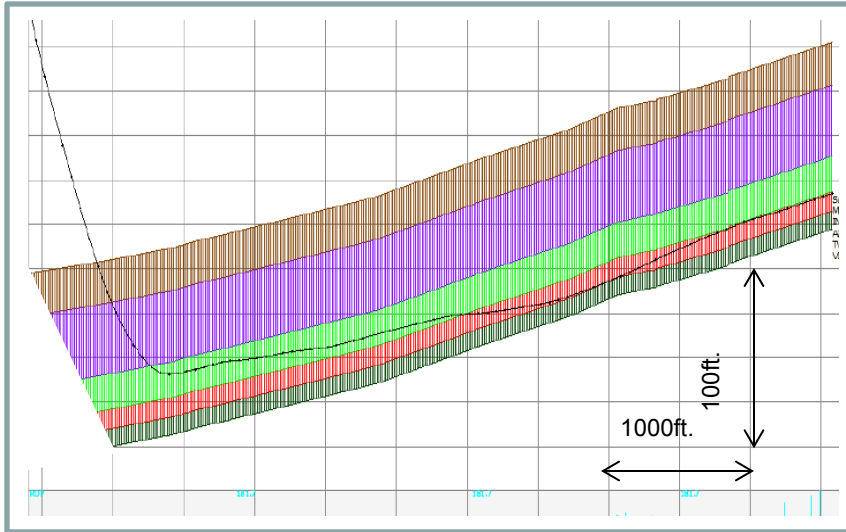
# High frequency sequences and geomechanical properties

Young's modulus  $E$  and Poisson's Ratio (PR)



*Some applications, concepts,  
results*

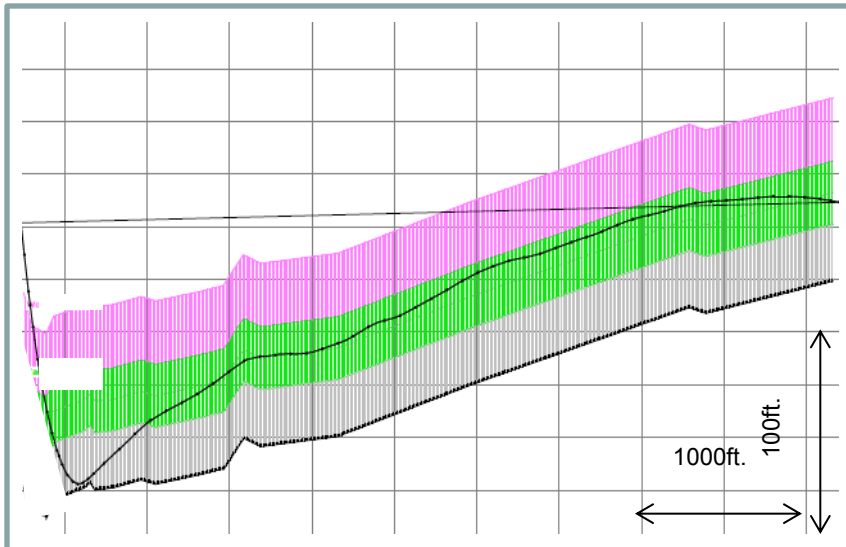
## Stratigraphically targeted drilling



Green is target (oil) zone  
(relatively high silica)  
Red is drilling hazard (relatively  
high clay content)

Well dipped into **Red (ductile)** and could not  
come back into **Green (brittle)**.  
**Result: Uneconomic well**

## Brittle-Ductile Couplet

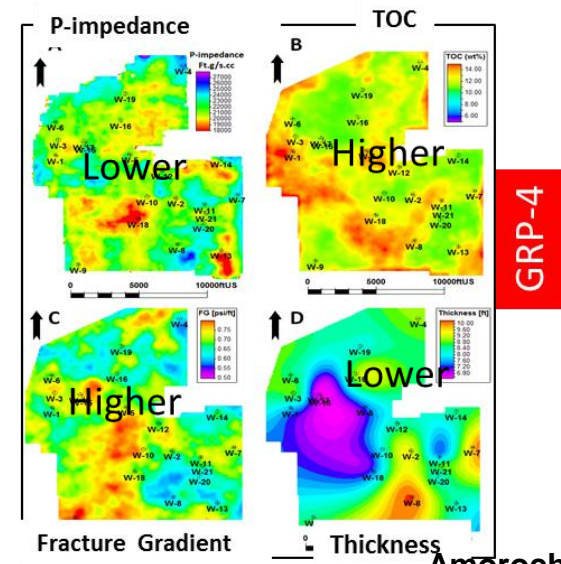
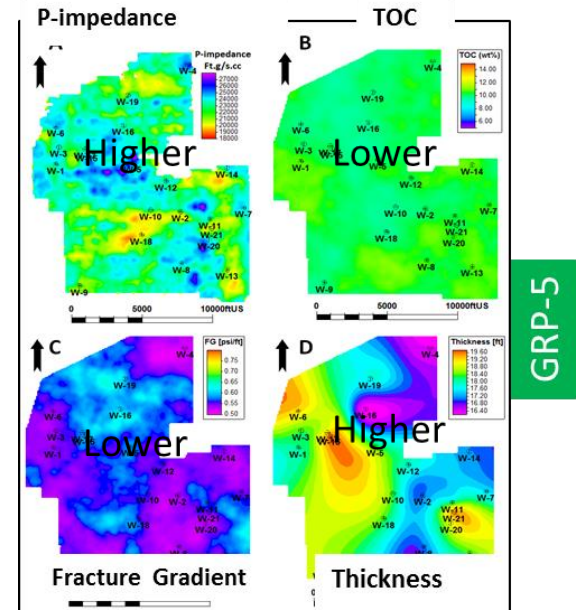
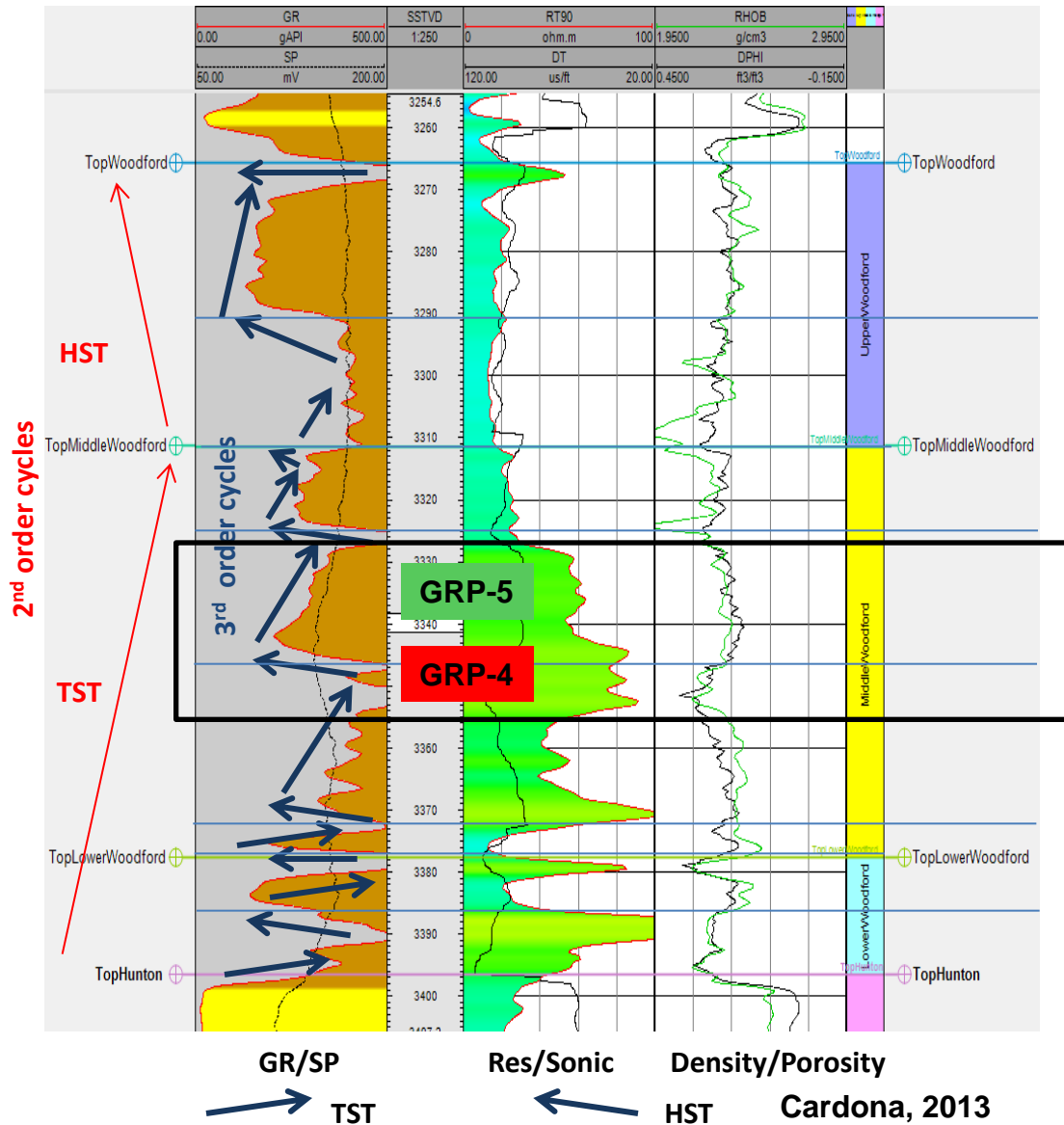


Well landed low, but came back  
into **Green (brittle)**  
target zone and  
stayed.

**Result: Very economic well**

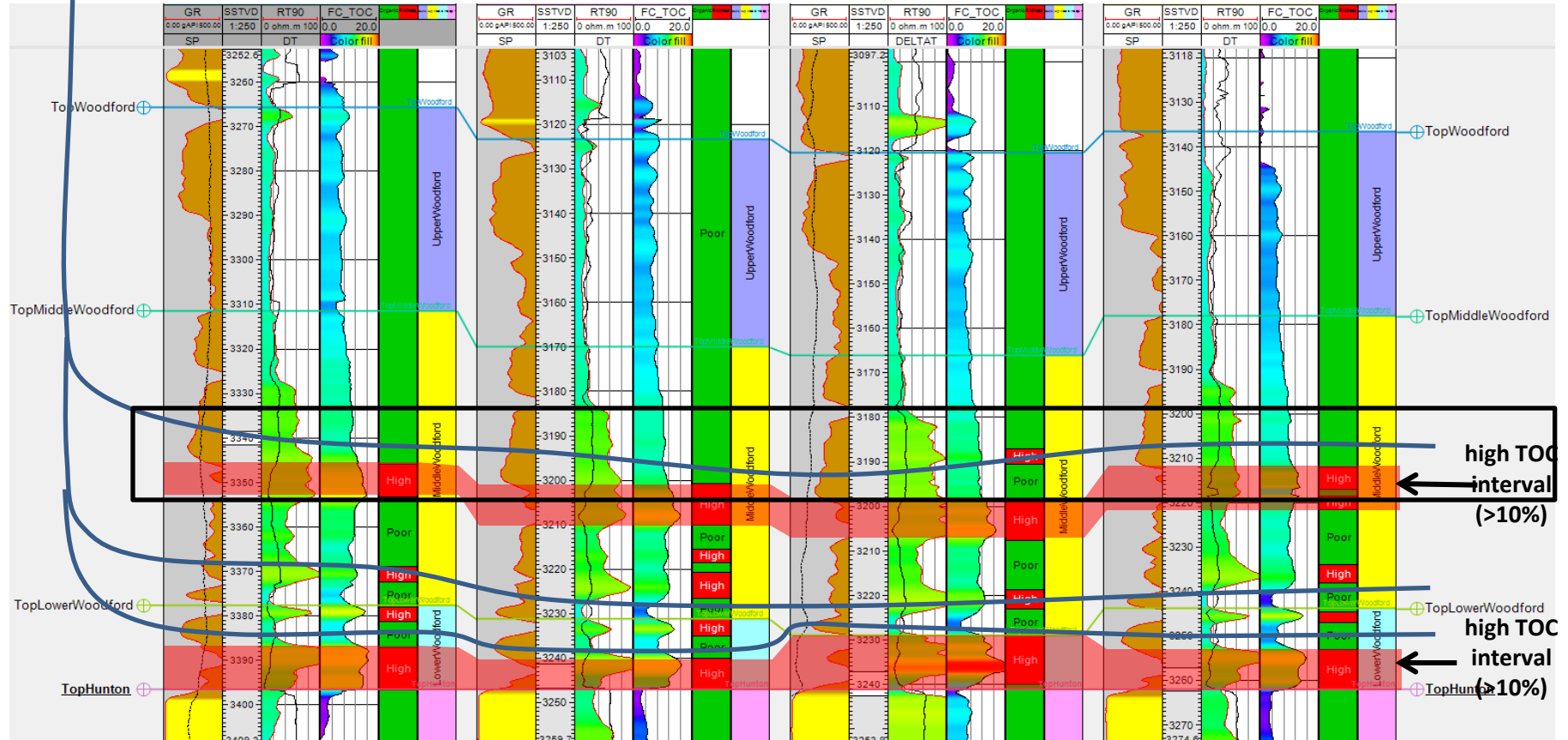
# Woodford in 3D seismic area

10 GRP's identified



Amorocho, 2012

# Drilling opportunities??



Cardona, 2013

TOC calculated using Passey method

# Kincaid 1 #8H with Ridenour 1 20 Type Log

WDFD

MW4

MW2

MW1C

MW1B

MW1A

QTZ

CLAY

TOC%

Chain, 2012

21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

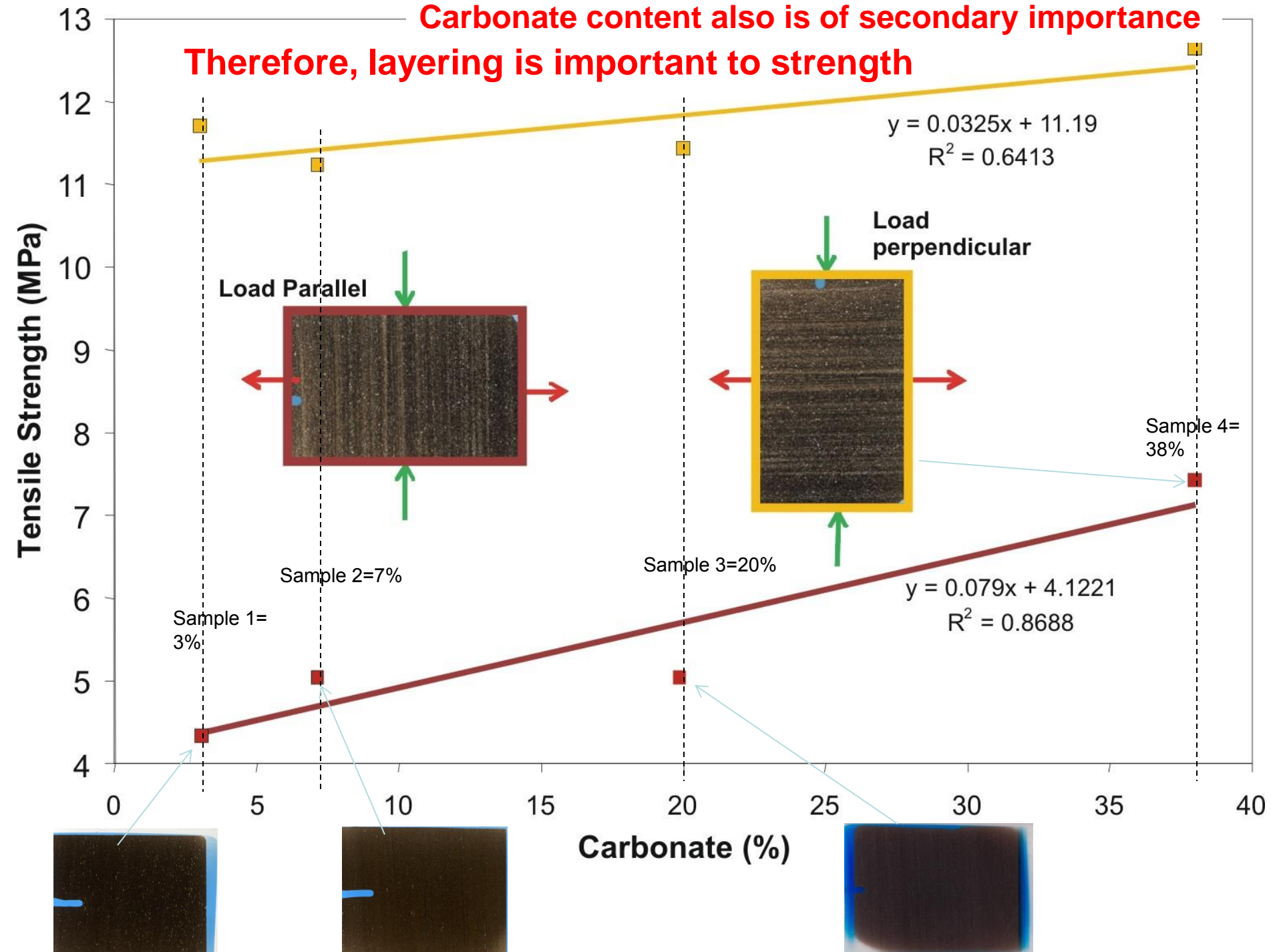
250000  
200000  
150000  
100000  
50000  
0

15000  
14000  
13000  
12000  
11000  
10000  
9000  
8000

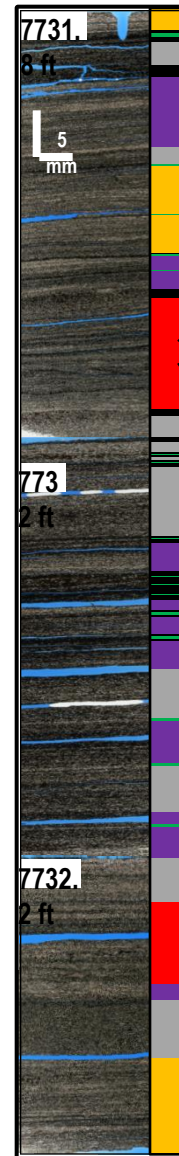
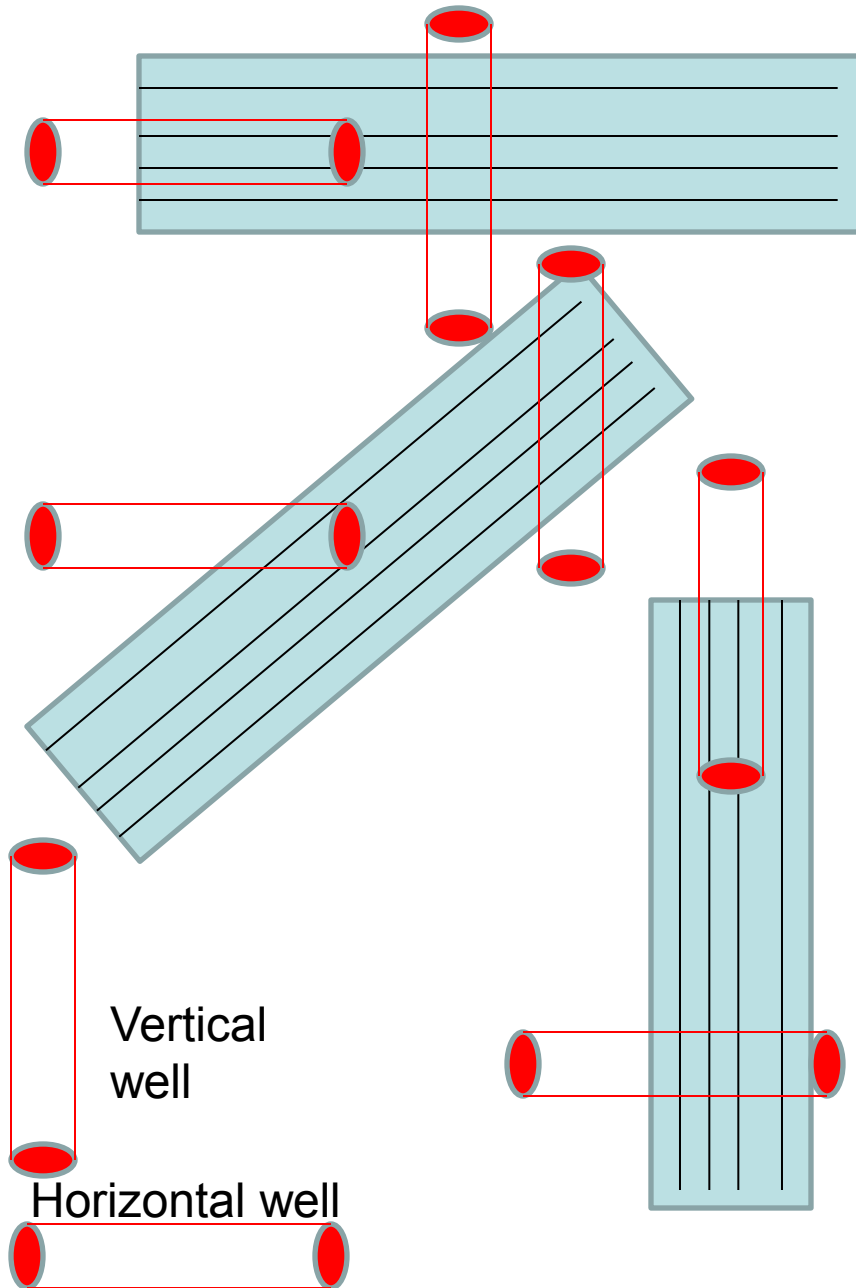
Caldwell, 2011



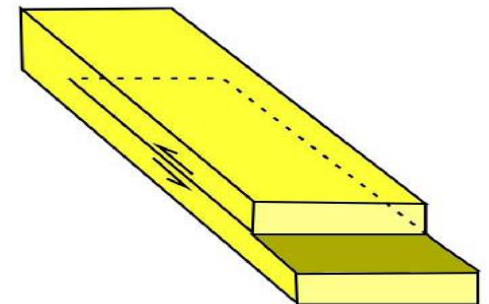
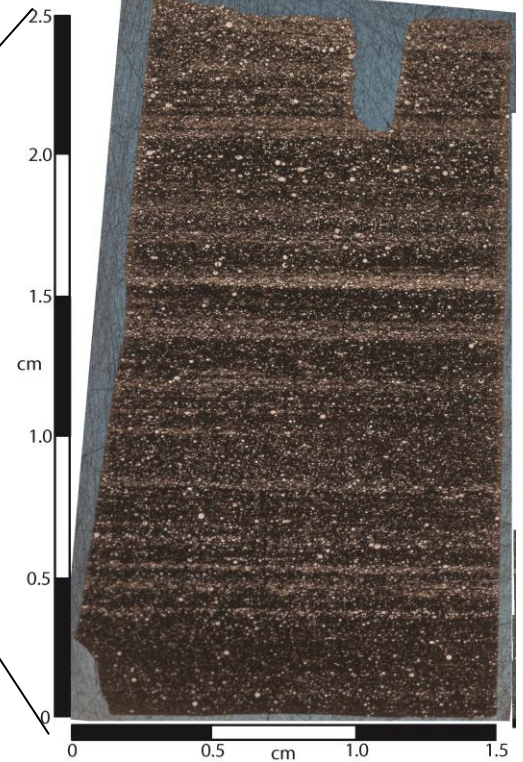
**Carbonate content also is of secondary importance  
Therefore, layering is important to strength**



# Upscaling stratigraphy and geomechanics



Petrographic Thin Section



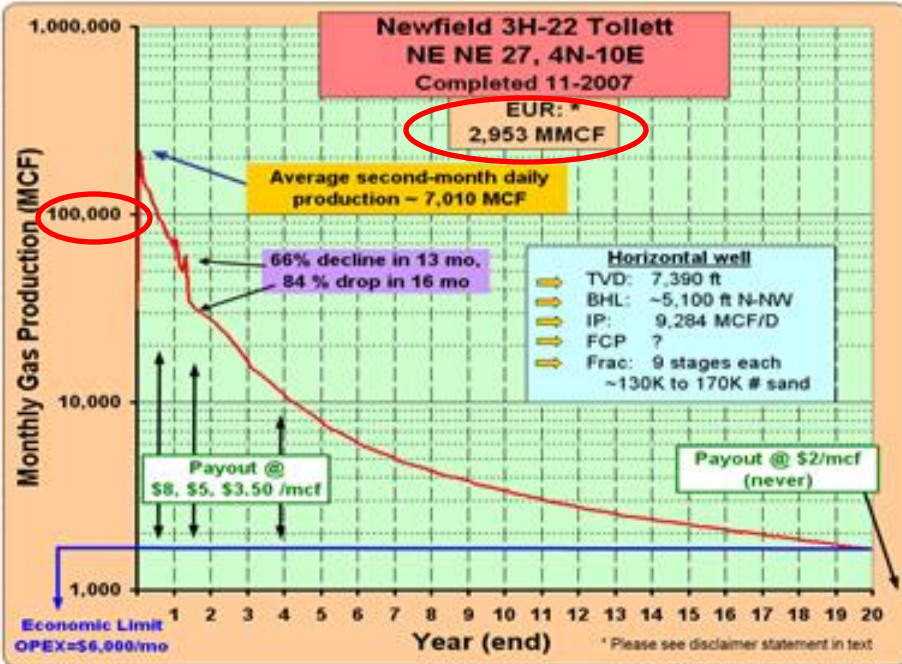


Figure 19. Twenty-year production decline curve of the Newfield 3H-22 Tollett well. Production data from IHS Energy, 2009.

Why different initial production,  
Decline curves, and payouts??

Geologic factors?? How to  
Optimize these factors??

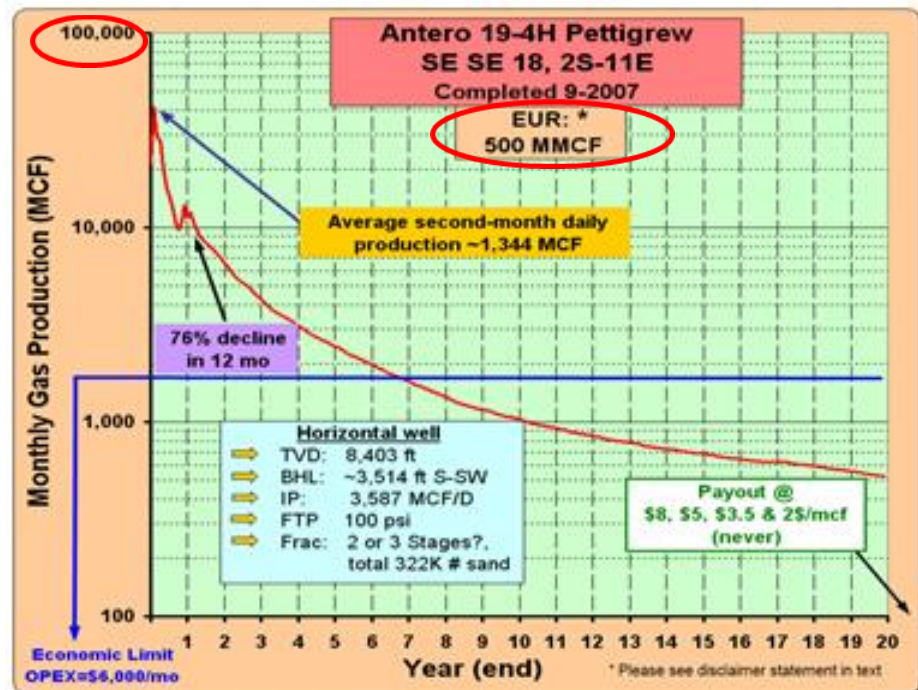
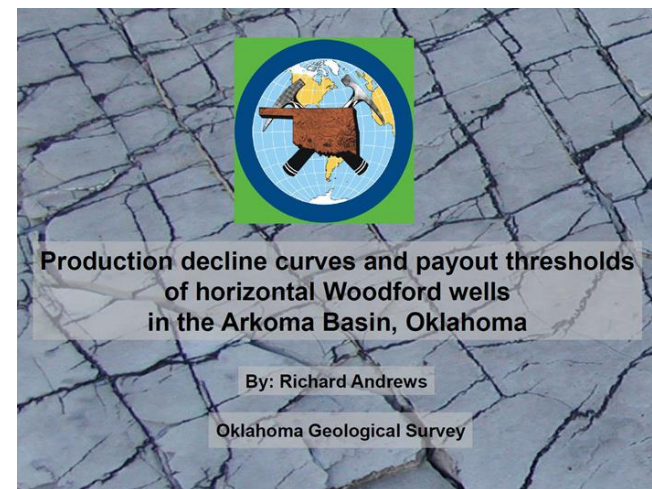


Figure 17. Twenty-year production decline curve of the Antero 19-4H Pettigrew well. Production data from IHS Energy, 2009.