Sequence Stratigraphy, Geomechanics, Microseismicity, and Geochemistry Relationships in Unconventional Resource Shales*

Roger M. Slatt[1], Carlos Molinares-Blanco[2], Jean D. Amorocho[3], Carlos L. Cabarcas[4], and Emilio Torres-Parada[5]

Search and Discovery Article #80407 (2014)
Posted October 6, 2014

*Adapted from presentation at Tulsa Geological Society luncheon meeting, September 9, 2014. An article with the same title was presented by the authors at URTeC, 2014

[1]Institute of Reservoir Characterization, University of Oklahoma, Norman, OK (rslatt@ou.edu)
[2]ConocoPhillips, Katy, TX
[3]ConocoPhillips, Houston, TX
[4]Hilcorp Energy Co., Houston, TX
[5]Noble Energy Co., Houston Texas

Abstract

Cyclical sedimentation patterns are common in unconventional resource shales, whether they be carbonate- or siliciclastic-dominated. In many resource shales the cyclical patterns have been related to eustatic sea-level fluctuations, even though these fluctuations may sometimes be obscured by tectonic overprint. The cyclicity is reflected in repetitive sedimentation patterns which represent alternating relatively shallow/oxic- and deeper/anoxic-water deposition. Typical cyclicity might occur in the form of alternating clay/organic-rich and quartz/calcite-rich strata. In more carbonate-rich sequences, organic-rich marls might alternate with organic-poor limestones. This cyclicity can occur at a variety of stratigraphic scales and provides a sequence stratigraphic framework for mapping, correlation, and interpretations. Incised valley fill may provide a localized, thicker, more organic-rich stratigraphic section ('sweet spot'), than adjacent areas.

Within the context of geomechanics, these cyclical strata are termed 'brittle-ductile couplets. Using the Barnett and Woodford shales as examples, clay/organic-rich intervals tend to be relatively ductile (relatively low Young's Modulus and high Poisson's ratio), and cleaner quartz/calcite-rich intervals tend to be relatively brittle (relatively high Young's Modulus and low Poisson's ratio). In carbonate-rich deposits, such as the Eagle Ford Formation, re-crystallized, TOC-poor limestones tend to be stronger and more brittle than TOC-rich marls.

Within the context of microseismic, microseisms may be vertically stratified or layered, with some horizons containing more events than other horizons. This stratification has been related to brittle-ductile couplets in at least one area, and placed within a sequence stratigraphic framework.

Within the context of geochemistry, ductile strata tend to contain more TOC and are thus better potential HC source rocks than brittle strata, which contain less TOC. Biomarkers (geochemical fingerprints) are useful for interpreting sources and environments of deposition of organic matter, and ultimately they are used for environmental zonation of shales.

Using these principles and observations, it is possible to build a sequence stratigraphic framework from multiple data sets to map and correlate brittle and ductile strata, organic-/hydrocarbon-rich zones, and more fracturable stratigraphic intervals. A suggested horizontal landing zone is the brittle strata within a brittle-ductile couplet. It is hypothesized that when hydraulically fractured, both brittle and ductile strata become fractured, and hydrocarbons move from the ductile to the brittle zone, whose fractures remain open after proppant emplacement. With time, ductile strata may close around the proppant and become sealed.

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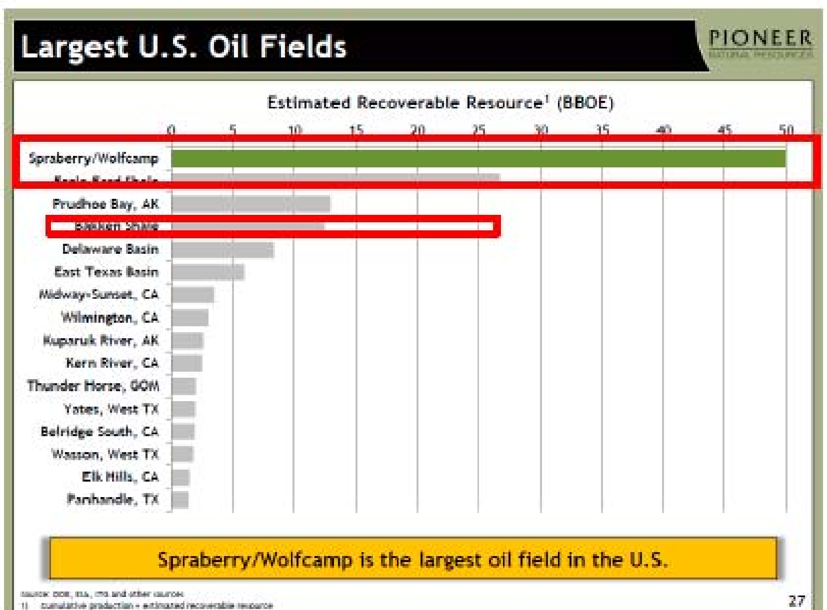
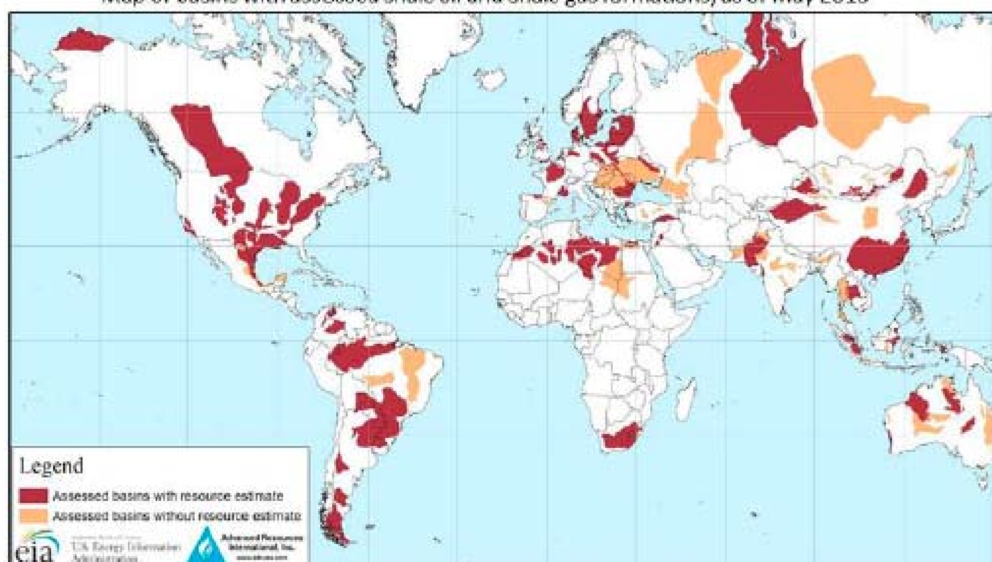
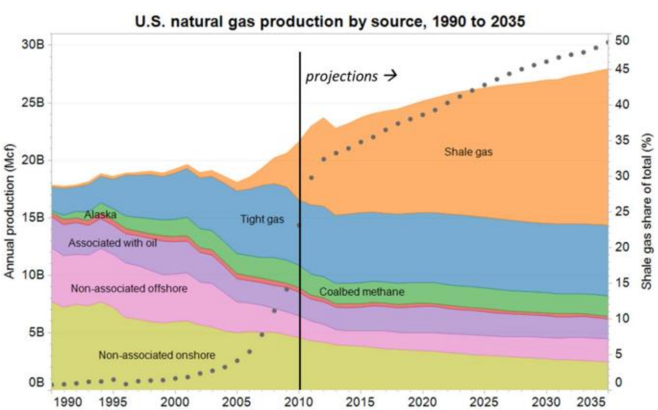


Map of basins with assessed shale oil and shale gas formations, as of May 2013



Source: United States basins from U.S. Energy Information Administration and United States Geological Survey; other basins from ARI based on data from various published studies.

Source U.S. Energy Information Administration based on data from various published studies. Update: May 9, 2011



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E&Y: Unconventional resources largest source of US oil, gas growth in 2013

02/10/2014 Oil and Gas J.

Unconventional resources in the US constituted the oil and gas industry's largest source of growth in 2013—a trend that's expected to continue into 2014, Ernst & Young indicated in its US quarterly outlook. In the next 2-3 years, the US will look to become a net exporter of gas, while dramatically reducing its dependency on oil imports. "The surge of the US energy market really was a game changer in a relatively short time" said Deborah Byers, E&Y oil & gas leader. "And we think those changes will continue to play out in 2014." However, capital may move away from unconventional plays with the possible freeing up of Mexico's energy sector while additional f...

OTC, Houston, May, 2014, "The oil and gas industry continues to unlock greater resources both onshore and offshore— in shale formations and in deepwater. Growing production from these areas, particularly in the US, is the product of continuous innovation and the resources contained in both will play a critical role in meeting growing global energy demand."

Innovation = Technology plus integration

Institute of Reservoir Characterization
2014 - 2015

Dr. Roger M. Slatt
Director

ConocoPhillips
SCHOOL OF GEOLOGY & GEOPHYSICS
The University of Oklahoma

Resource Shale Studies at University of Oklahoma's Institute of Reservoir Characterization: (Dr. R. Slatt)

-School of Geology and Geophysics (Dr. P. Philp)

-External collaborators: Dr. N. O'Brien; New York State Univ., Potsdam
Dr. E. Eslinger; The College of St. Rose, Albany
Mr. R. Davis; Schlumberger

Students Graduated since 2005 from Institute Reservoir Characterization

Students graduated with thesis on Woodford shales:

-Althoff, Brito,Chain, Killian, Portas, Perez, Sierra, Totten, Badra, Amorocho, Molinares, Mann, Serna, Treanton (14)

Students graduated with thesis on other shales:

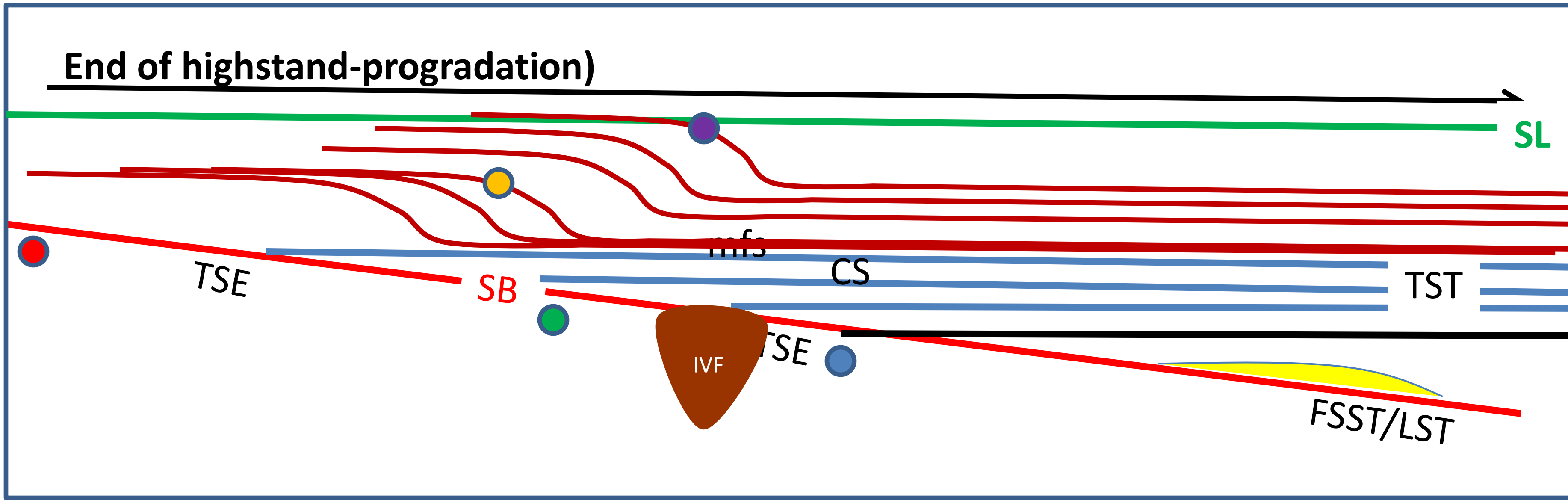
-Baruch, Borges, Gomez-Prada, Guest, Hulsey, Magoon, Parada-Torres, Vallejo, Zheng, Riley,* Singh *(Ph.D.) (11)

Students beginning/working theses on shales (almost all Woodford)

-Ali, McCullough, Klockow, Turner (Ph.D.), Bontemi, Hill, Zou, Cardona, Deng (9)

Additional Graduates (theses in *reservoir characterization* and *turbidites*): 34

Woodford Consortium Partners in recently completed project

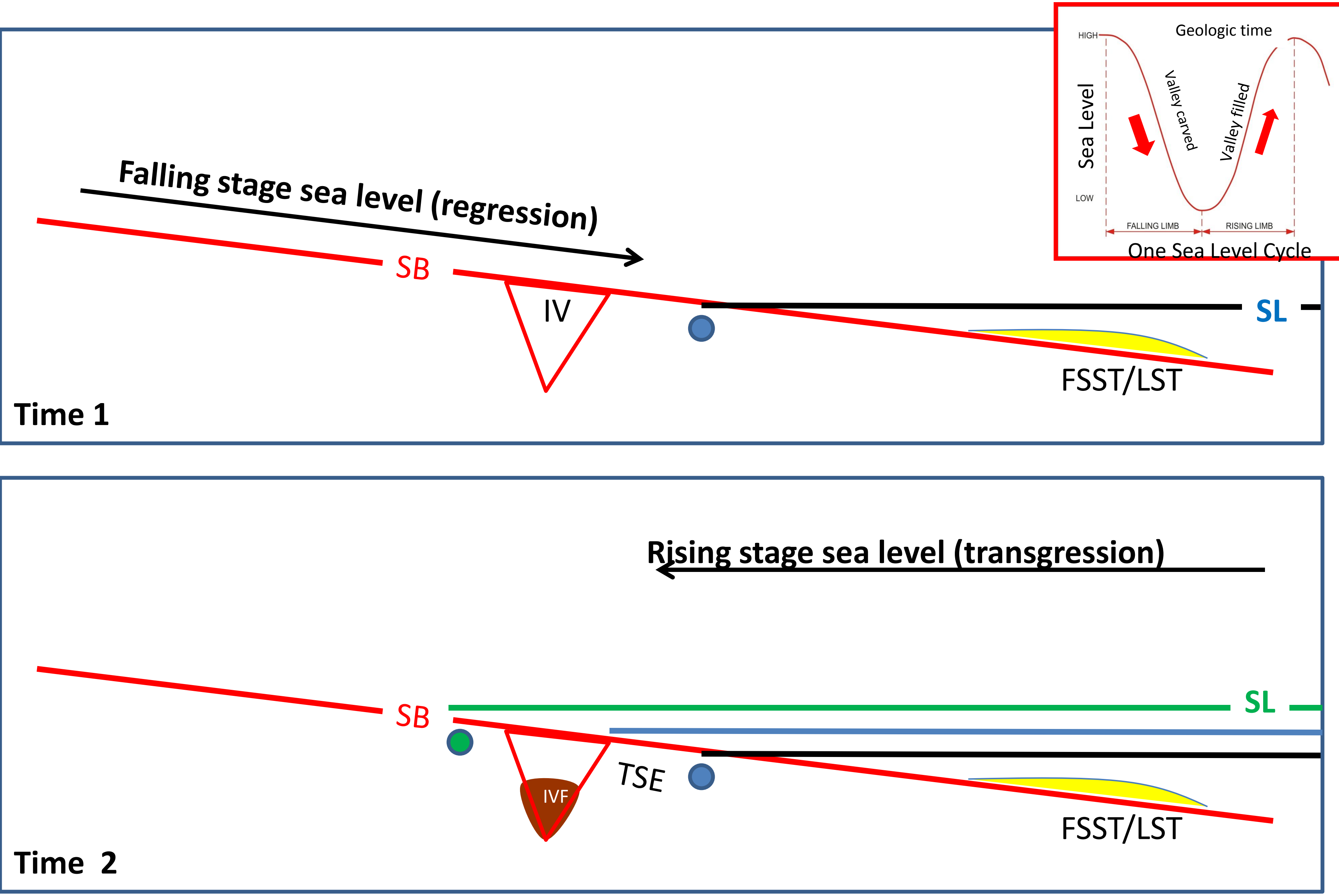


Generalized sequence stratigraphic model for unconventional resource shales

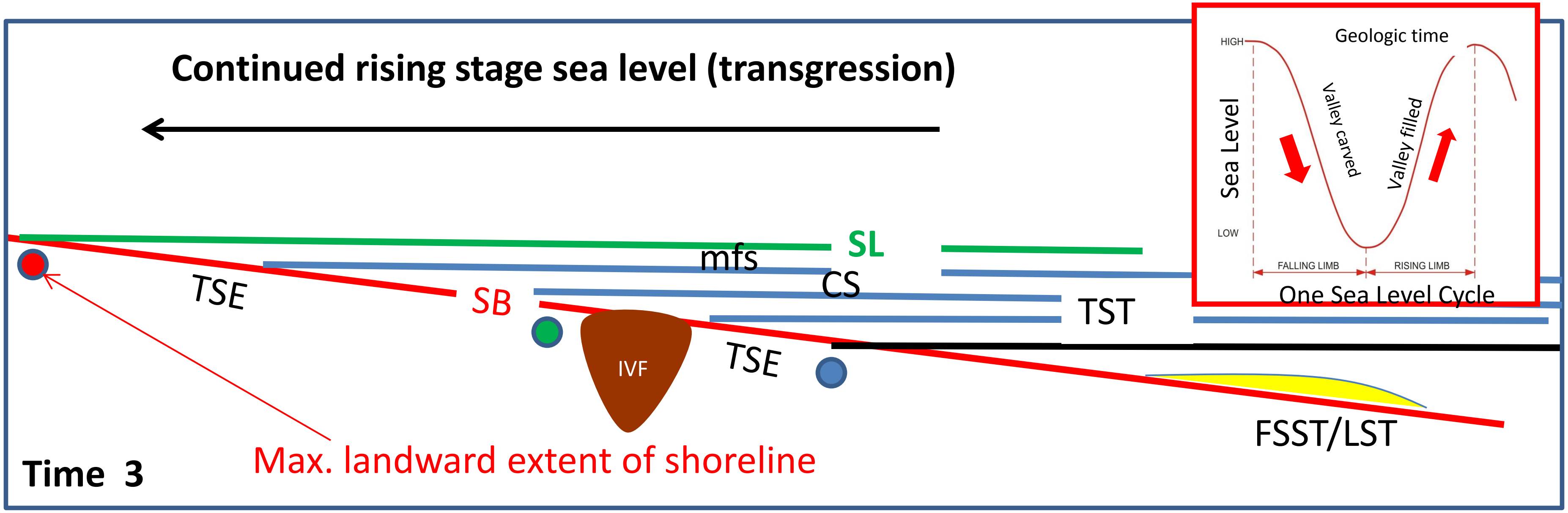
Sequence Stratigraphy

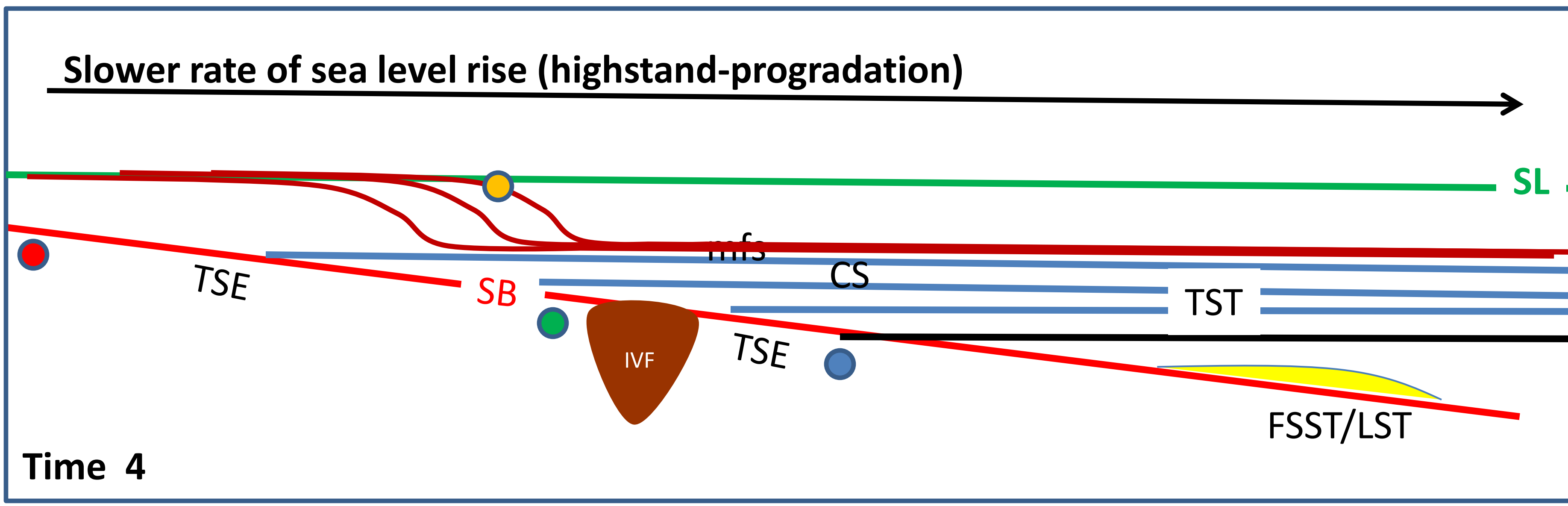
Shales studied (in varying detail) →

Woodford
Eagle Ford
Marcellus
New Albany
Caney
Fayetteville
Horn River
Haynesville
Longmaxi
Barnett
LaLuna
Brown shale

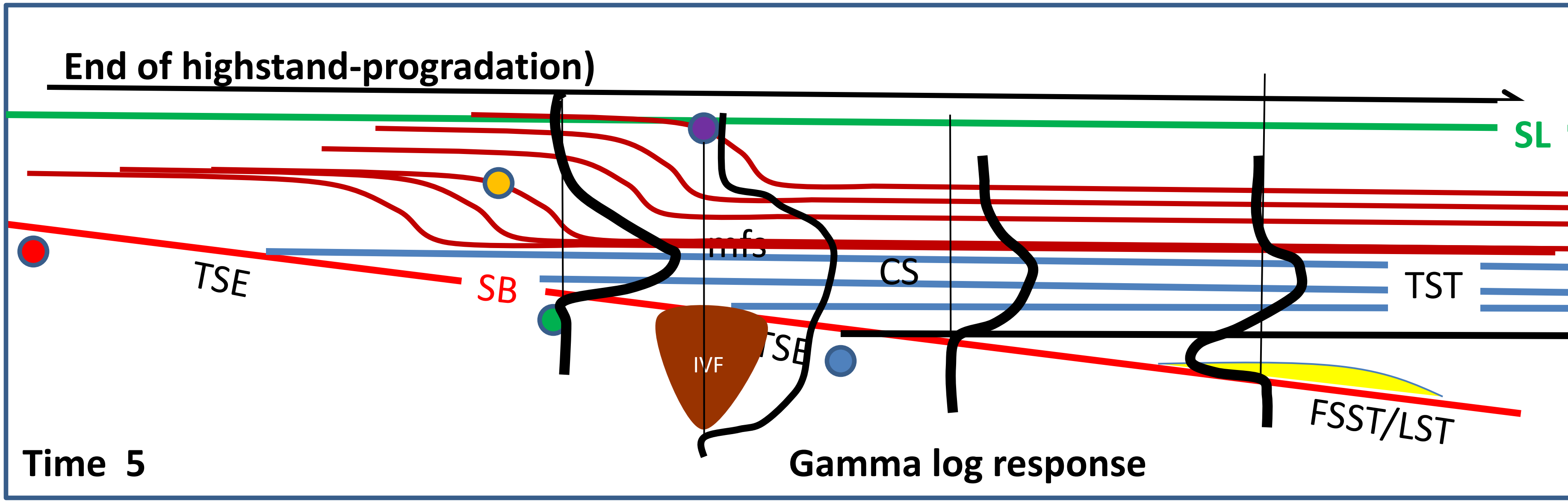


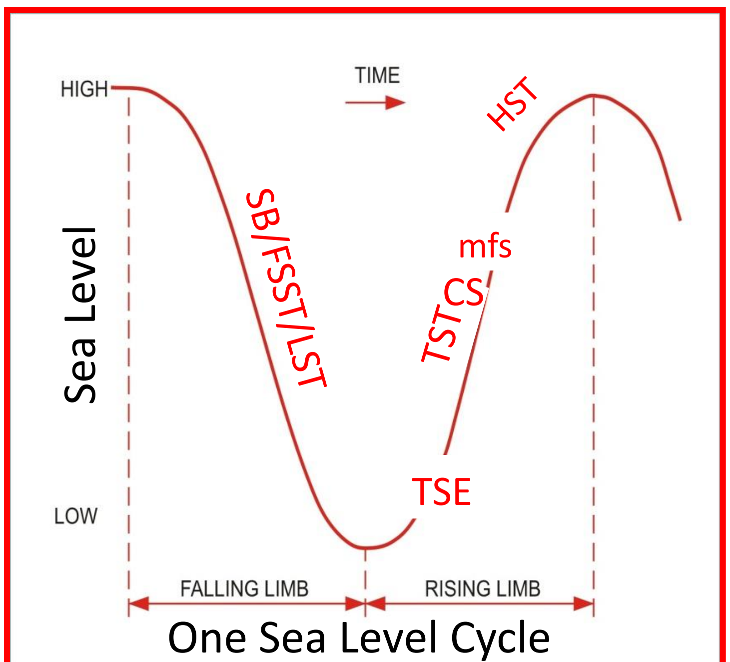
Generalized sequence stratigraphic model for unconventional resource shales

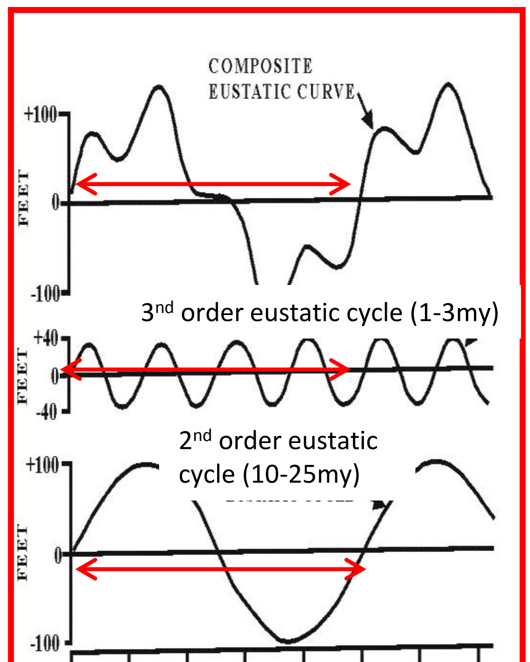




Generalized sequence stratigraphic model for unconventional resource shales







Woodford
Eagle Ford
Marcellus
New Albany
Caney
Fayetteville
Horn River
Haynesville
Longmaxi
Barnett
LaLuna
Brown shale

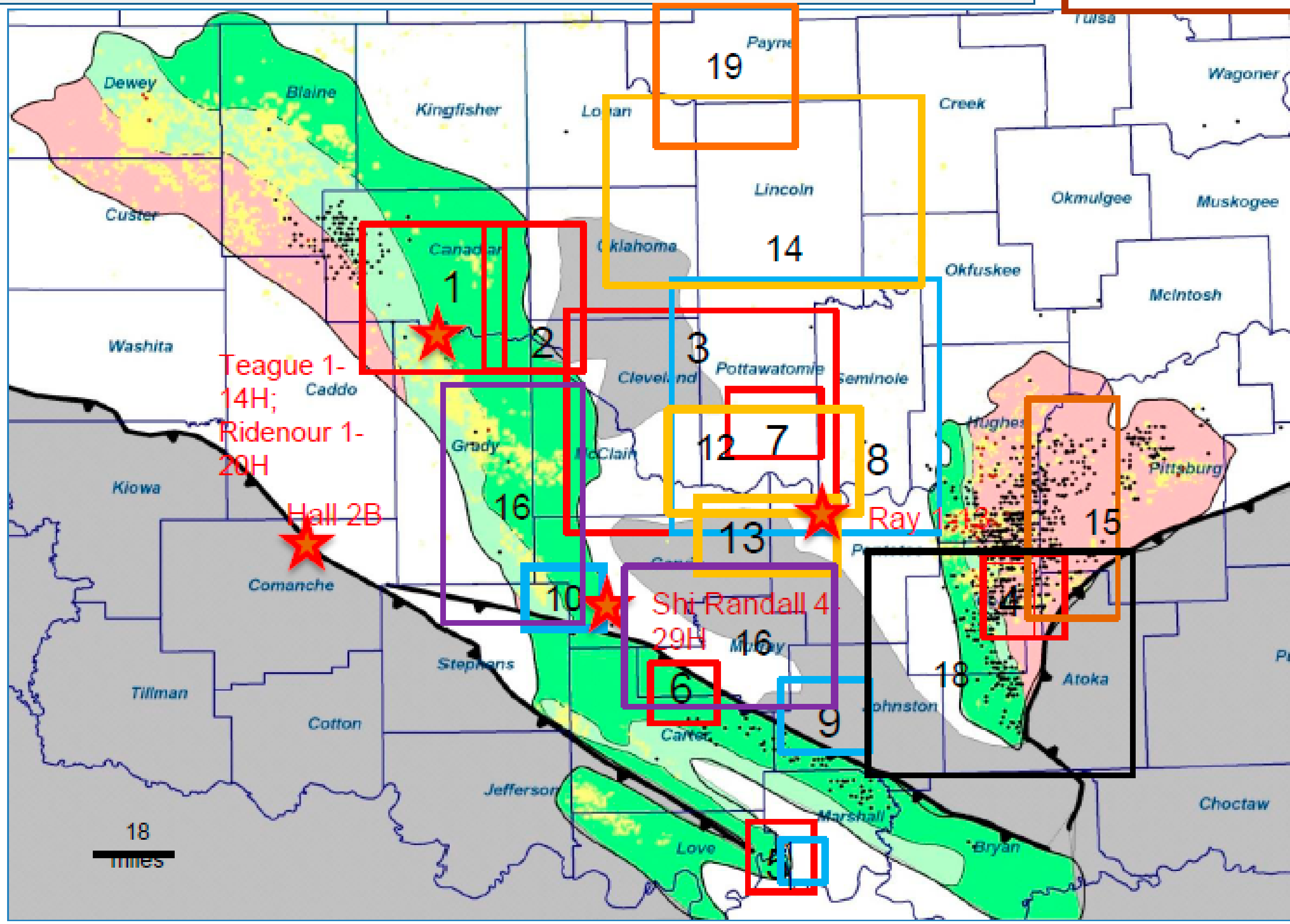
Generalized sequence stratigraphic model for unconventional resource shales

Institute of Reservoir Characterization, OU: Oklahoma Woodford studies

Students

1-Killian
2-Chain
3-Althoff
4-Portas, Molinares
5-Serna
6-Badra
7-Amorocho
8-McCullough
9-Turner, Treanton
10-Mann
11-Klockow
12-Bontempi
13-Cardona
14 - Ali
15-Research Seminar class project
16-Spring 2014
17-S. Hasbrook
18-N. Hasbrook
19. Infante

Anthis 2[17]
(in Washington County)

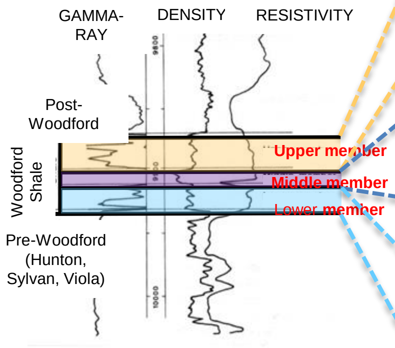


Gas Condensate Oil No Woodford

Marathon Oil Corporation · Pathfinder Exploration, LLC · Longfellow Energy LP · Tip Top Energy LP · bhpbilliton resourcing the future · Chevron · ConocoPhillips · Ward Petroleum · Nostra Terra Oil & Gas Company PLC · Halliburton · Potts-Stephenson Exploration Company · CSE · Chaparral Energy · Vitruvian Exploration II, LLC · Newfield

Woodford Shale Stratigraphy

(Upper Devonian - Lower Mississippian)



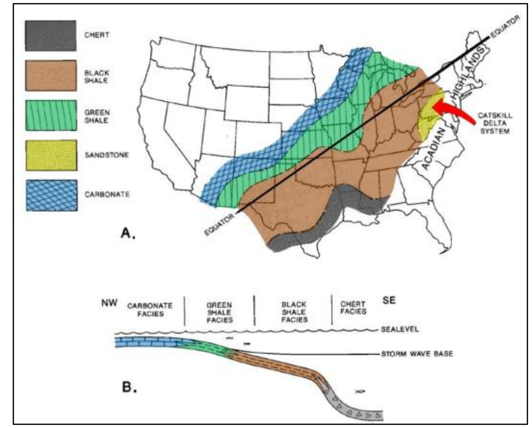
Black shale
Resinous spores and mostly parallel laminae
Phosphate nodules
Intermediate radioactivity

Most widespread lithofacies
Mainly black shale
Deposition during maximum transgression
Highest TOC, radioactivity, concentrations of pyrite

Black shale - Contains more carbonate, silt and sand than the middle and upper members
Overlies the regional unconformity
Lowest radioactivity

(Anadarko Basin; modified from Hester et al., 1990)

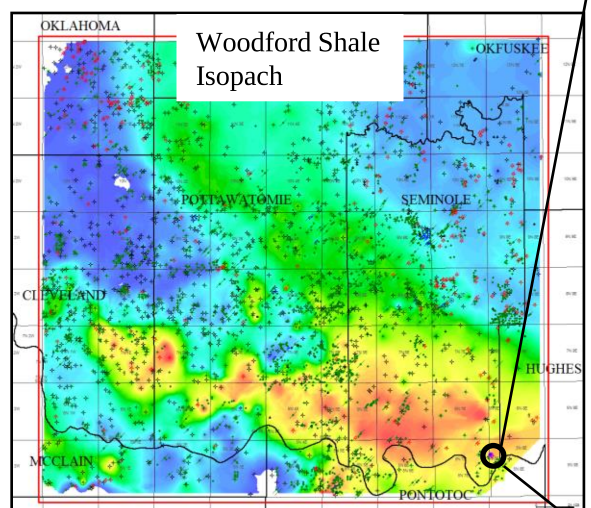
(Lambert, 1993; Comer, 2008)

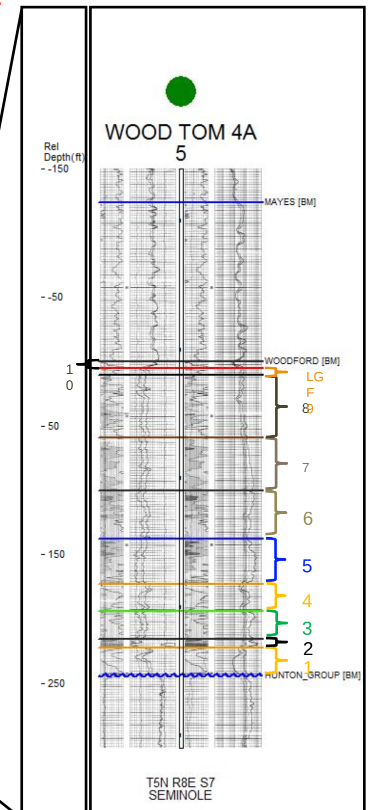


Woodford deposition, and resulting stratigraphy, is much more complex than shown on this map!!

Correlation Standard on Cherokee Platform (from McCullough):

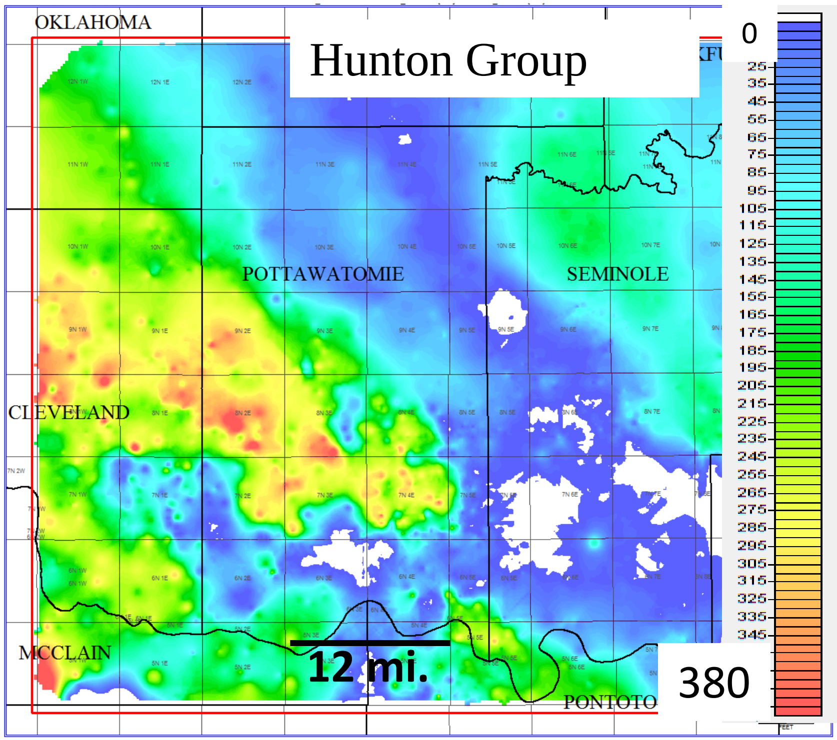
Woodford Shale subdivided into 10 units based on well log profiles (GR, Res, D/N).

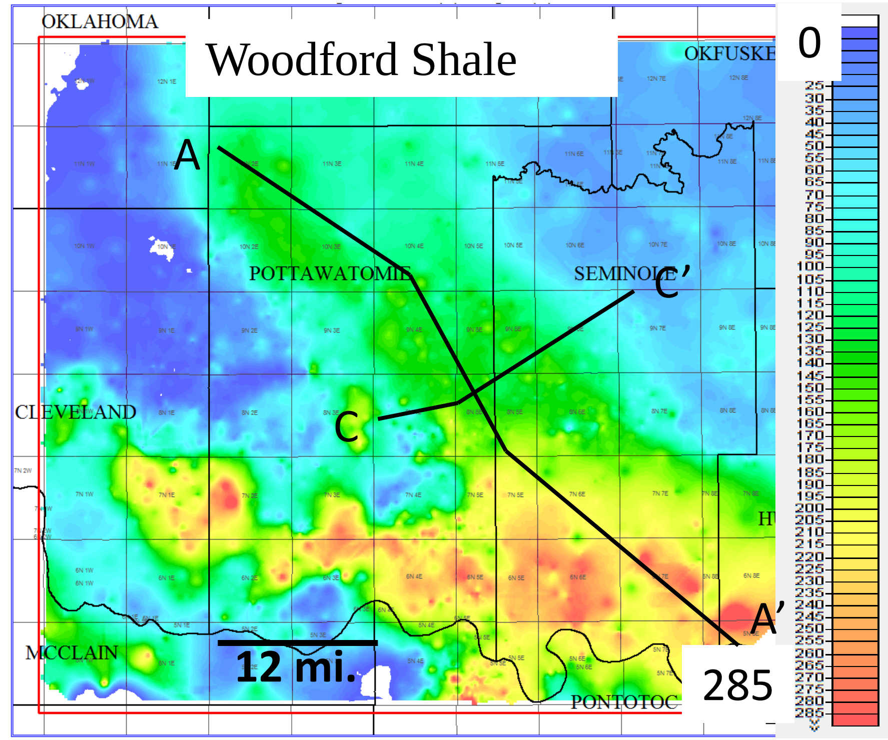


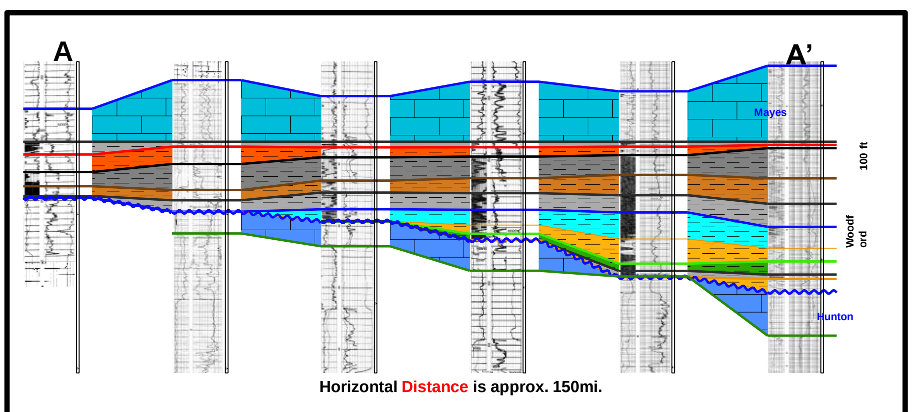


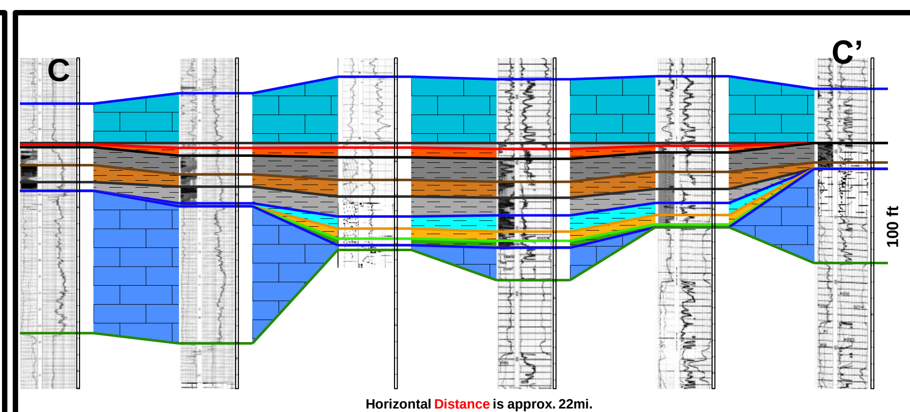
Woodford Incised Valleys

Valley fill is thin where underlying Hunton is thick and vice versa



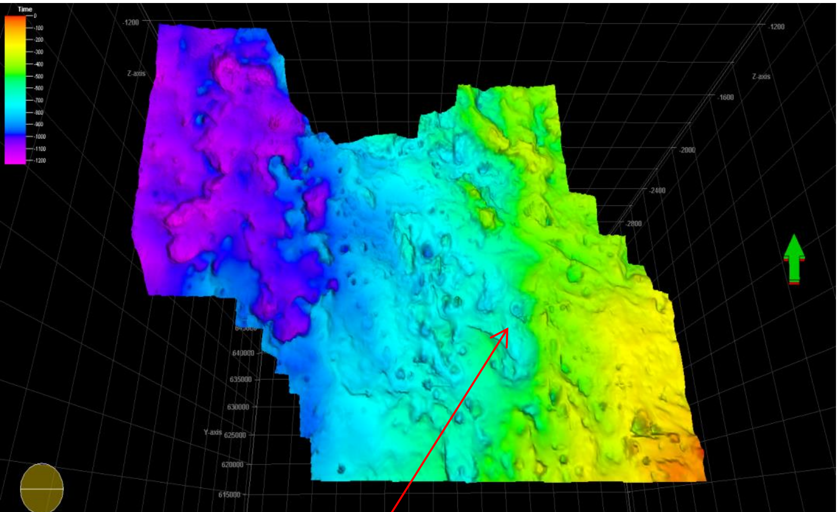


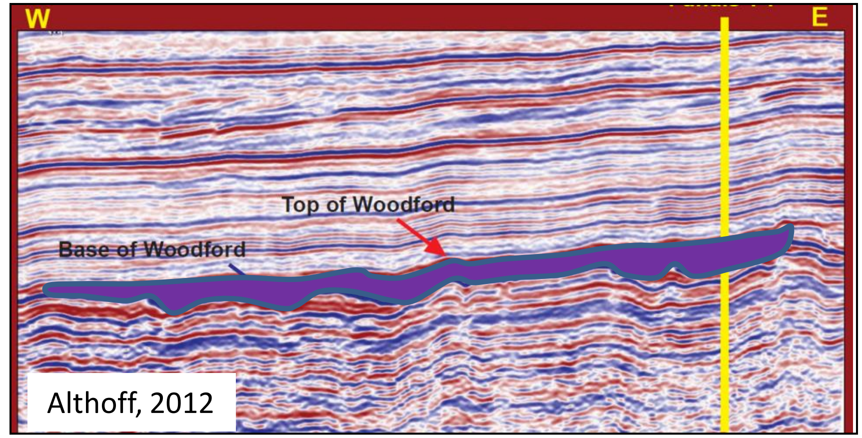


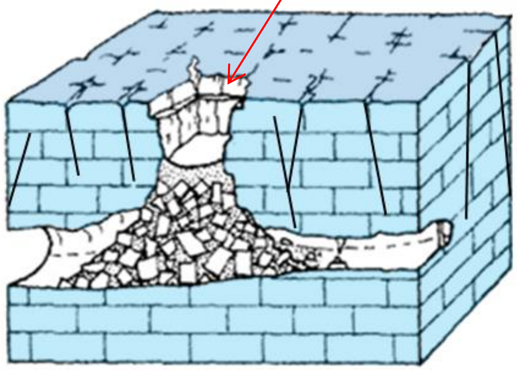


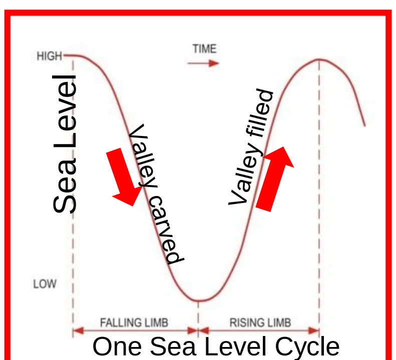
McCullough, 2014

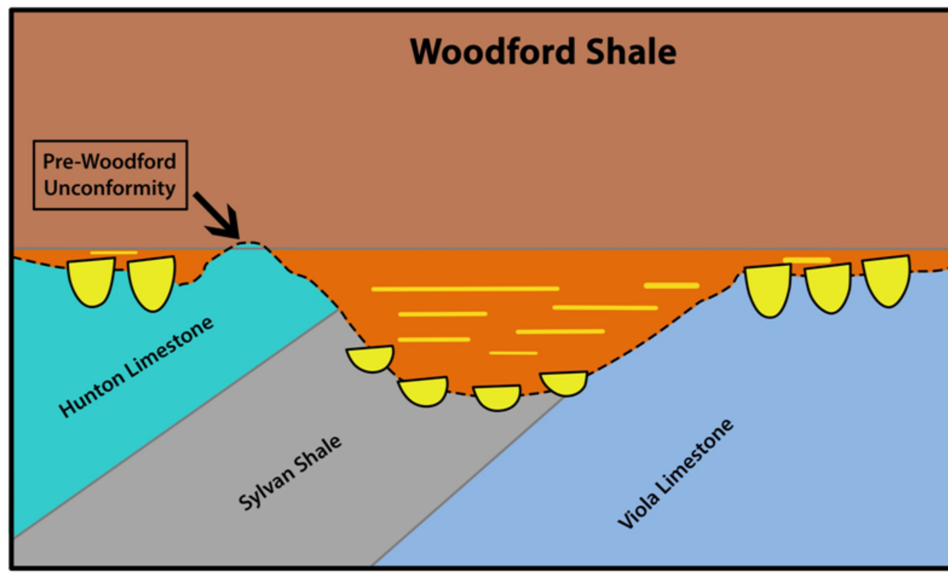
Woodford Incised valley fills and karst fills = potential sweet spots (greater thickness/organic-rich)





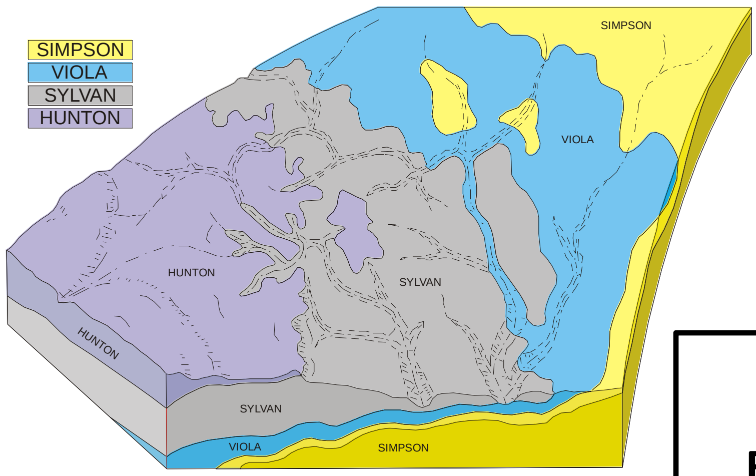




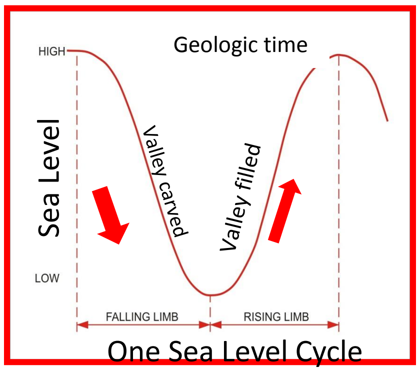


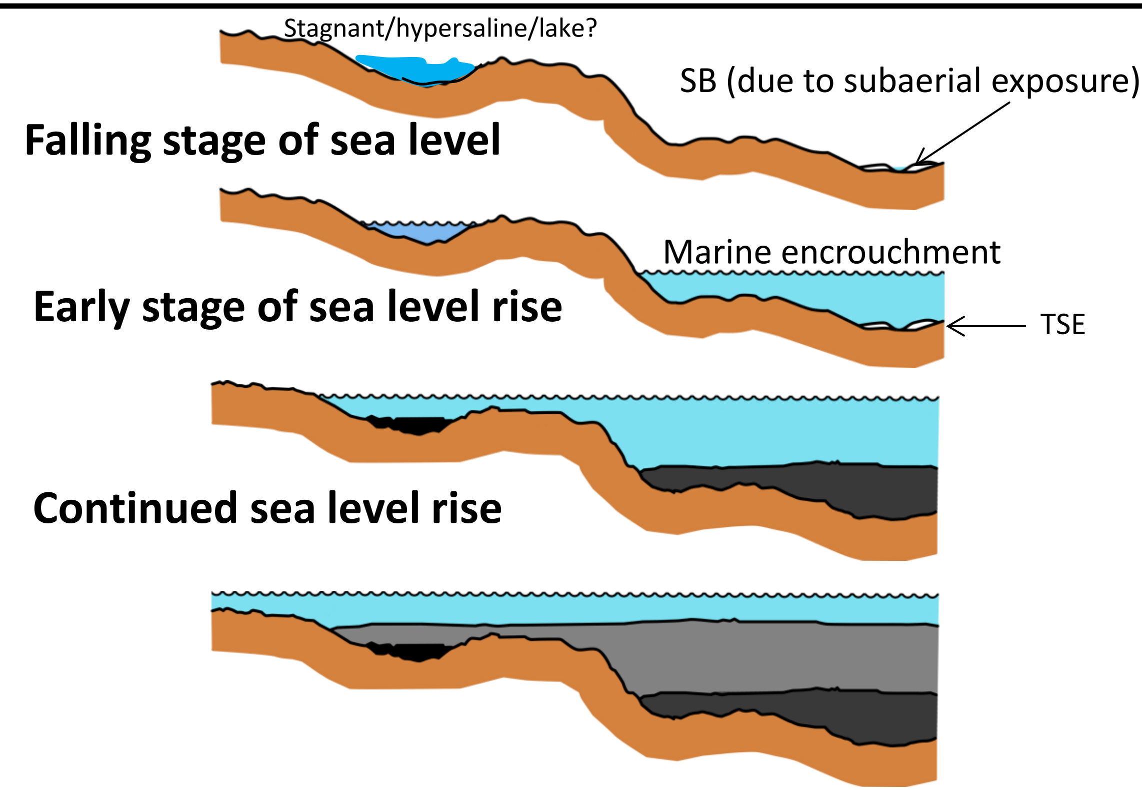
Dutton, T., Longfellow Energy LP, Emerging Shale Plays Conference – April 25, 2013

Effect of erosional paleotopography on valley filling



Modified from Althoff, 2012





Continued sea level rise to give gray marine shales over black shales

Geomechanics

WHAT IS BRITTLENESS???

BRITTLE

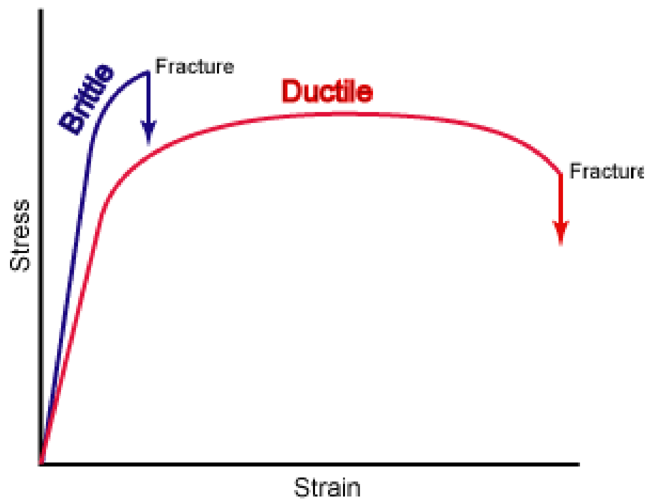
BRITTLENESS is the measurement of stored energy before failure, and is function of:

- Rock strength
- lithology
- texture
- effective stress
- temperature
- fluid type
- diagenesis
- TOC

BRITTLENESS INDEX (BI) is the most widely used parameter for the quantification of rock brittleness.

$$BI = \frac{\sigma_c}{\sigma_t}.$$

σ_c = Compressive strength
σ_t = Tensile strength



DUCTILE

An interval is classified (by drillers) to be:

Ductile → A lot of pumping to break → High fracture gradient

Brittle → Not as much pumping as the "ductile" intervals → Lower fracture gradient

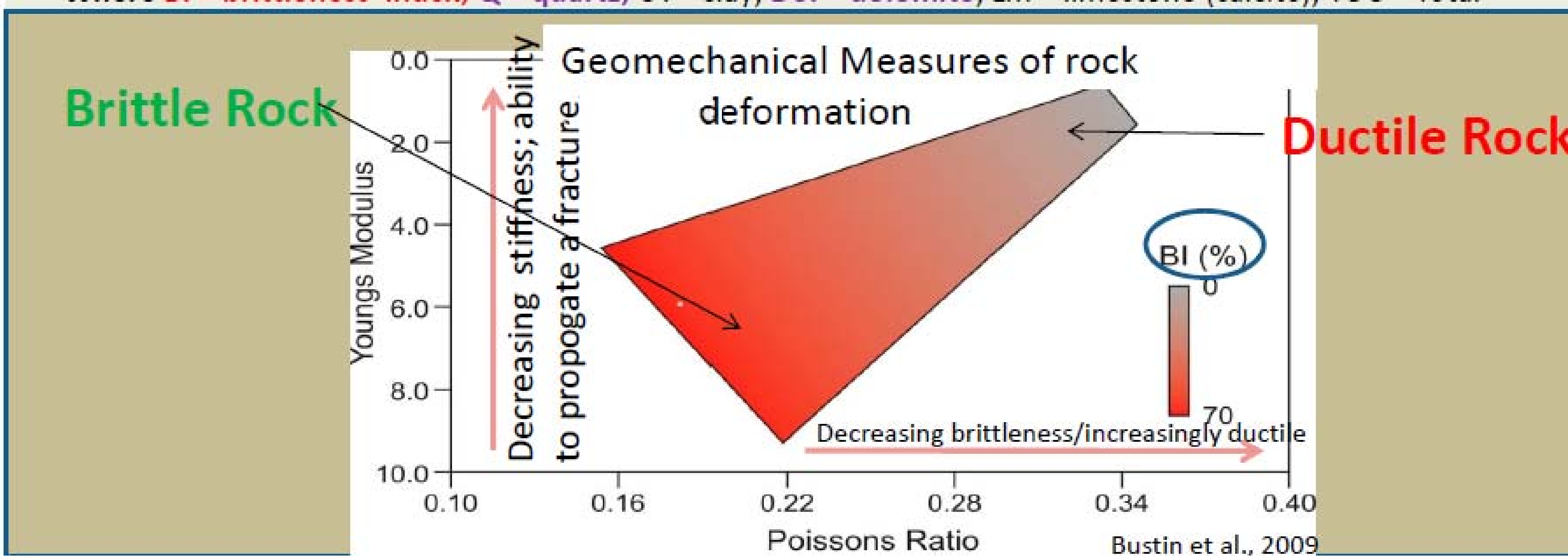
High E and low V = Brittle

Low E and high V = Ductile

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

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

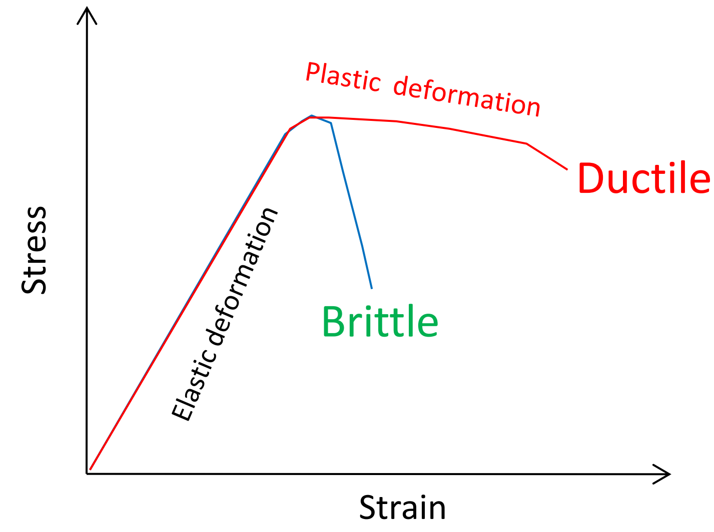
Where BI = brittleness index; Q = quartz; C l = clay; **Dol = dolomite**; Lm = limestone (calcite); TOC = Total



Mineralogic affect on rock fracturability (brittleness)

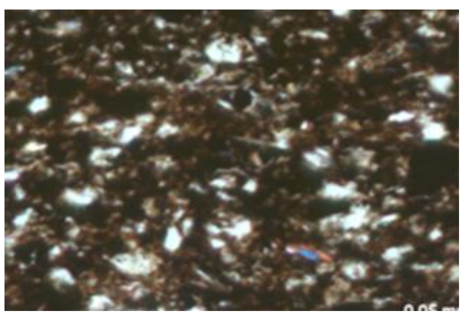
BI = (Q + Dol)/ (Q + Dol + Lm + Cl + TOC)

Where BI = brittleness index
Q = quartz
C l = clay
Dol = dolomite
Lm = limestone (calcite)
TOC = Total organic carbon
(Wang and Gale, 2009)

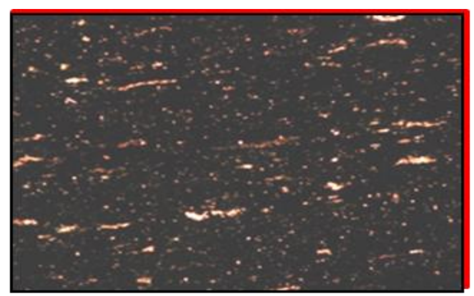


Carbonate

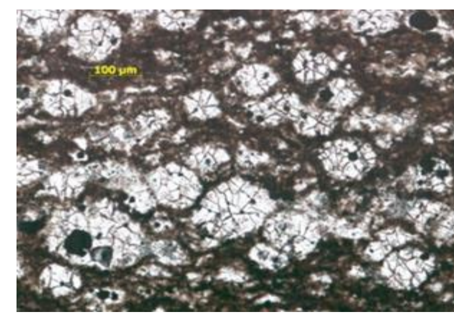
Detrital quartz/clay

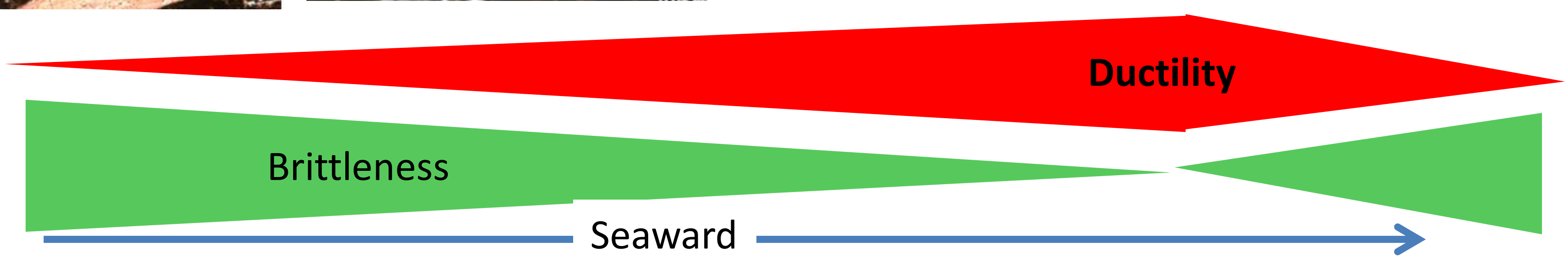


Organic/clay mudstone

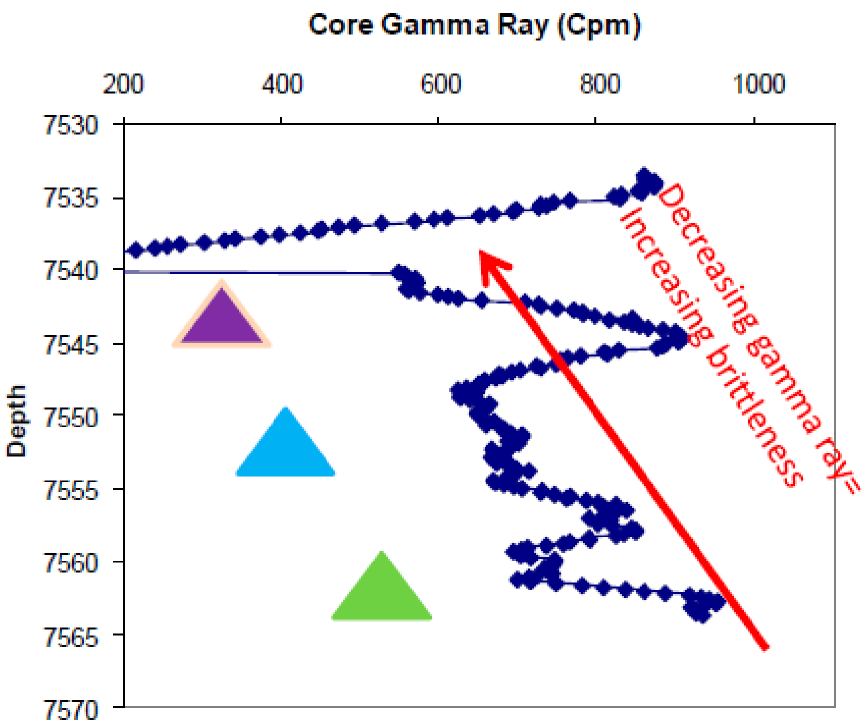


Biogenic quartz

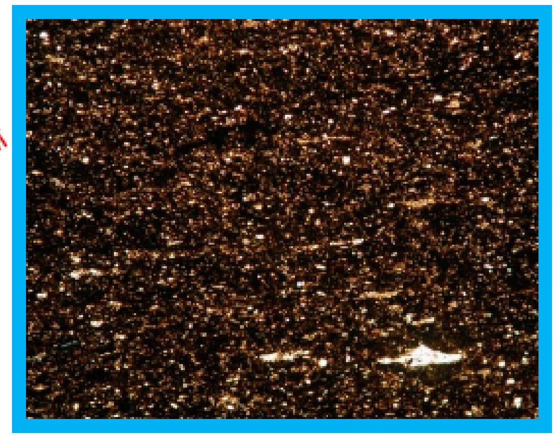




Upward-decreasing Gamma Ray = water depth of deposition must be decreasing with time, as rocks are deposited

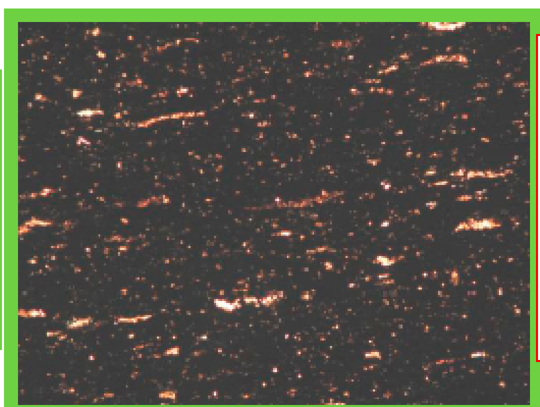


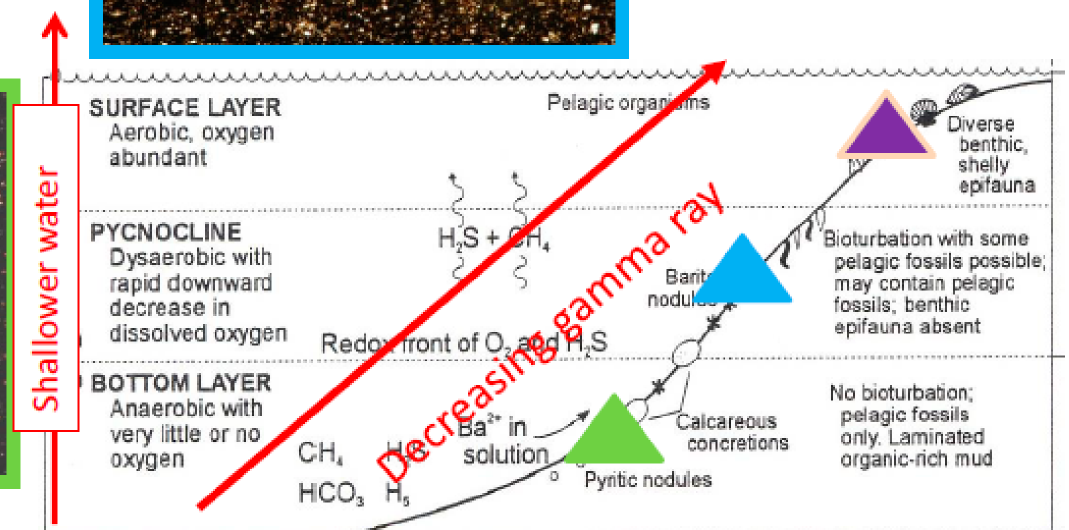
Top of the parasequence: Broken fragments of macrofossils and with well reounded phosphatic peloids comprising the high energy deposit: Fossiliferous deposit



High amount of detrital quartz in the matrix.

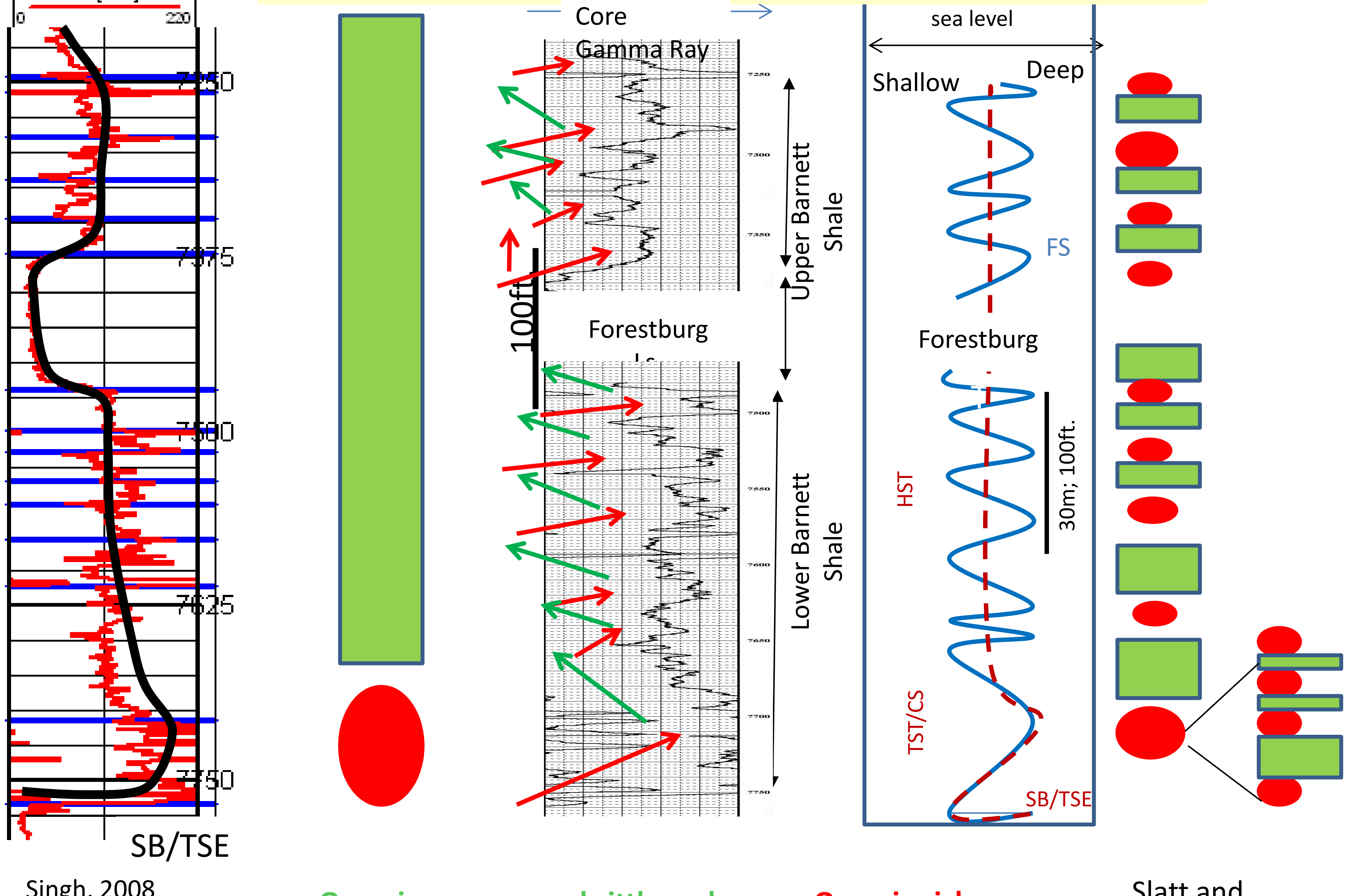
Matrix rich in phosphatic faecal pellets suggesting low sedimentation; higher agglutinated forams.





Marine depositional environment

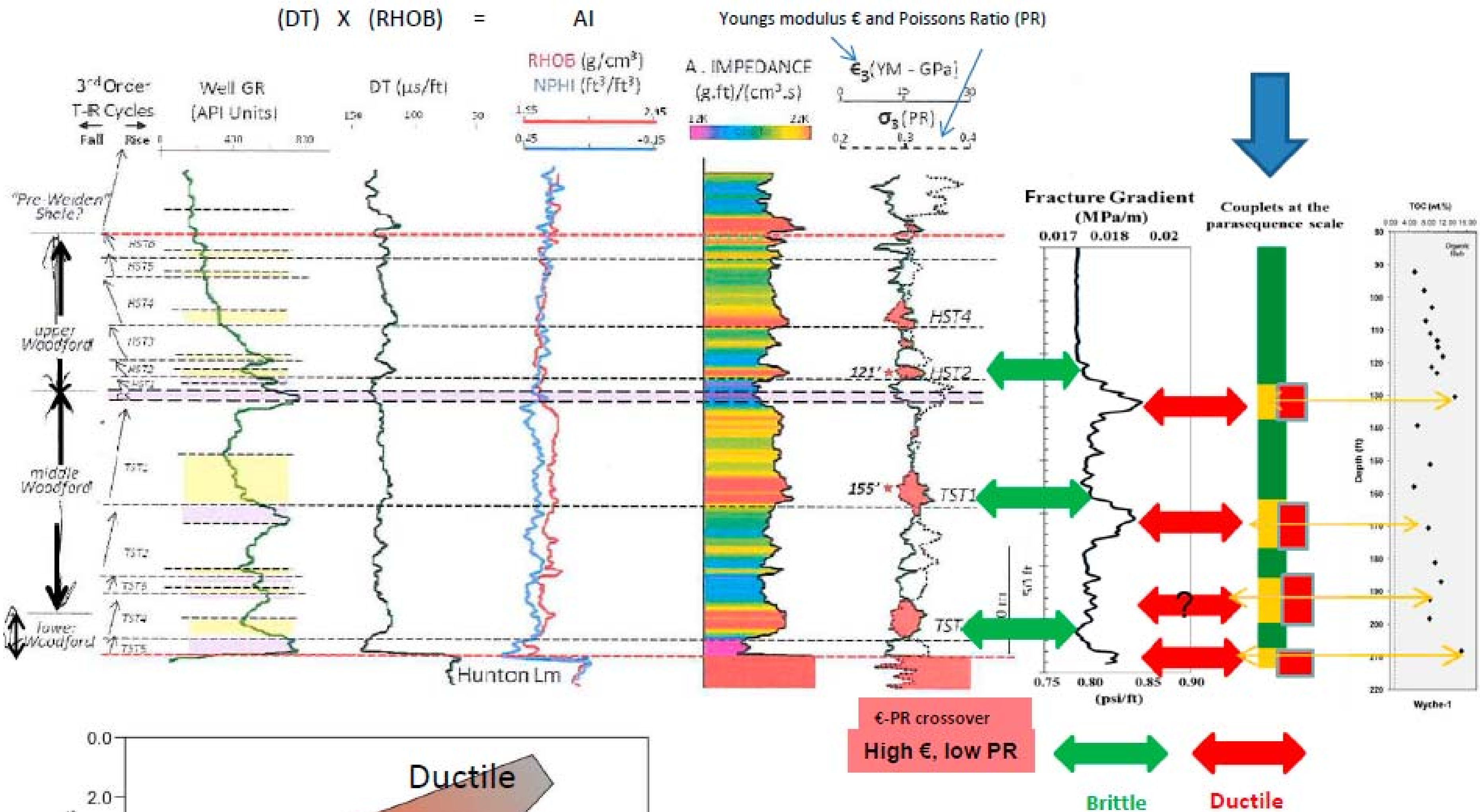
Ductile-Brittle Couplets: Barnett Shale example

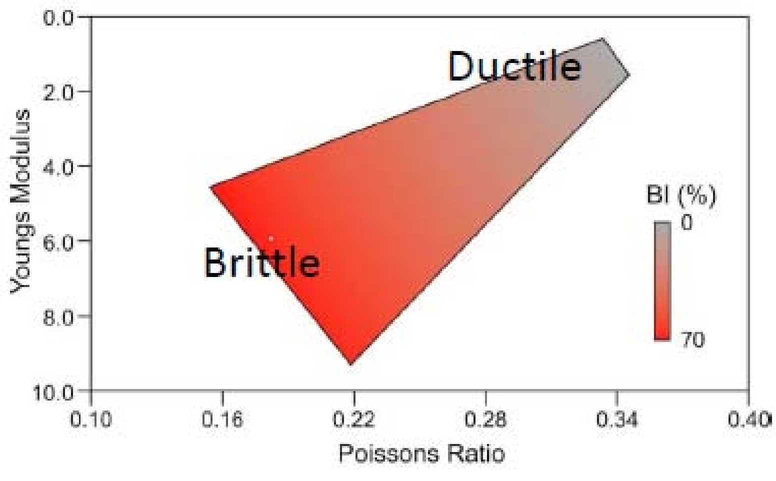


Organic-poor, more brittle rocks (quartz/carbonates)

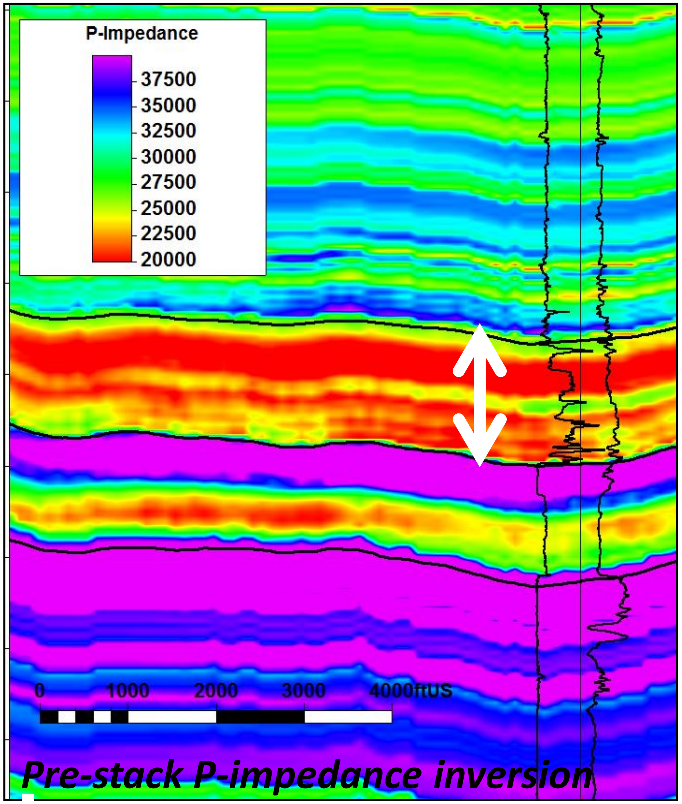
Organic-rich, more ductile rocks (clay/TOC)

Slatt and Abousleiman, 2011

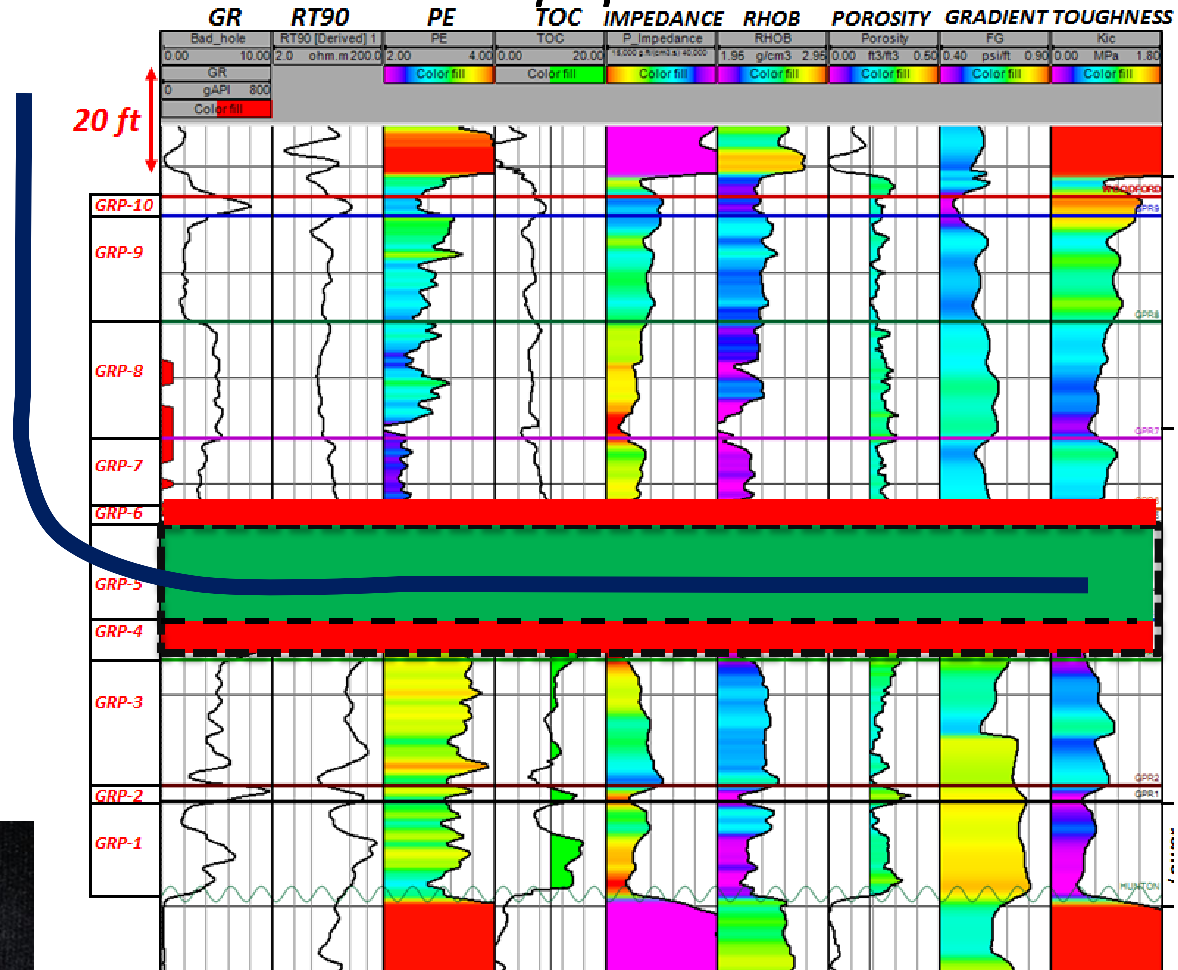


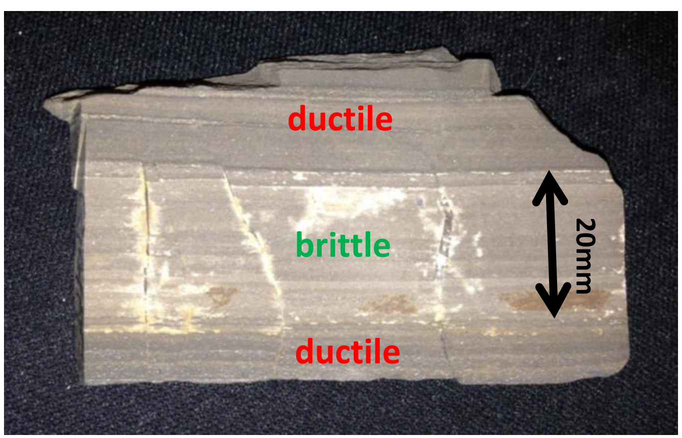


Molinares-Blanco, 2013

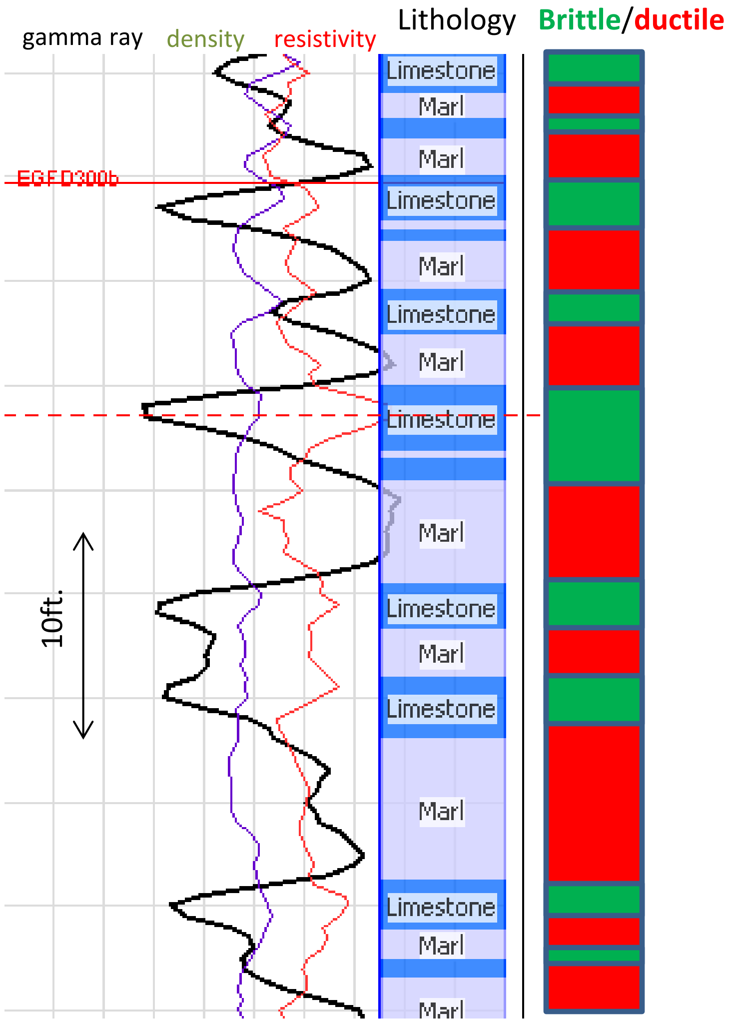


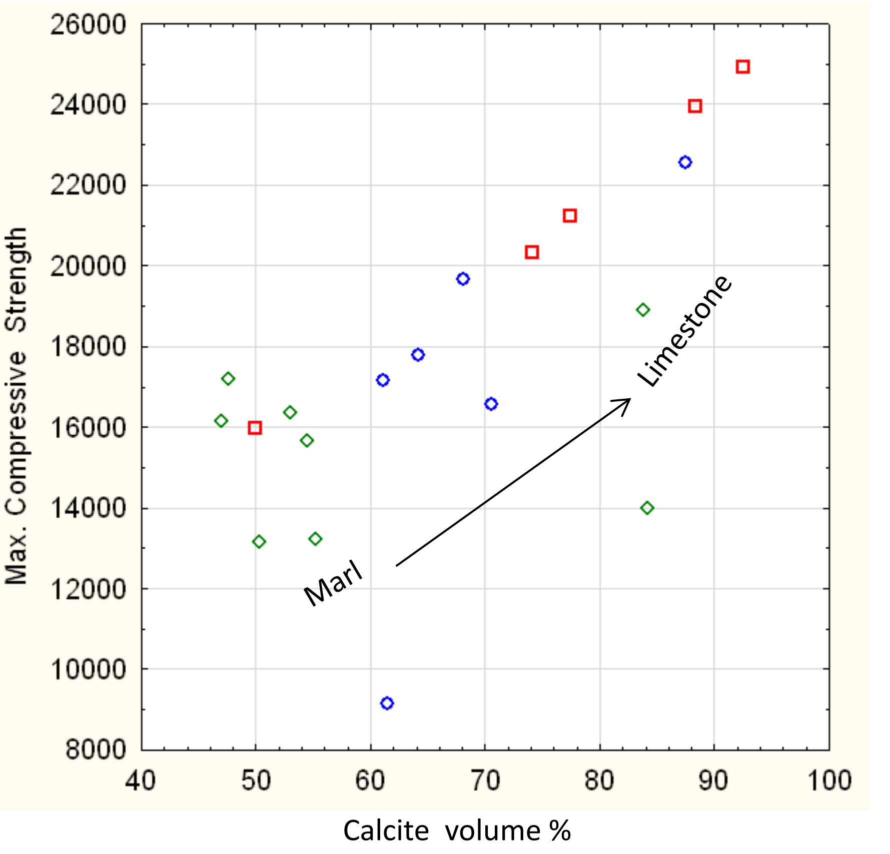
Well properties





Amorocho, 2012





EagleFord, S. Texas

Breyer et al., 2014

"Brittle-Ductile Couplets"
(Slatt and Abousleiman, 2011)

Core

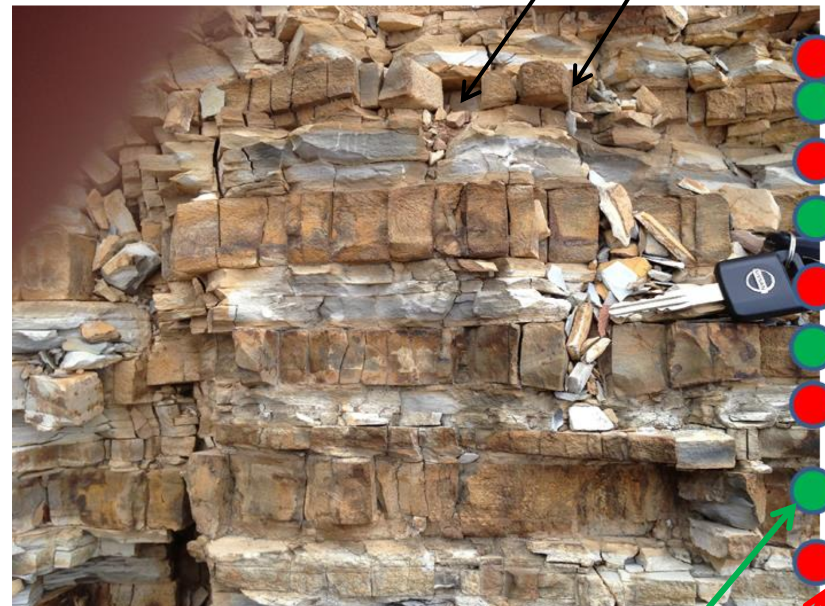
Core

Brittle = biogenic quartz rich ***(reservoir rock)***

Ductile= clay-organic rich ***(HC source rock)***

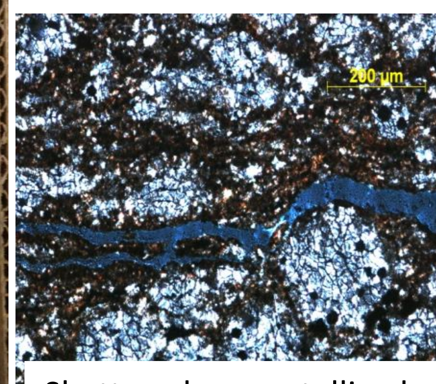
Outcrop

Vertical fracture

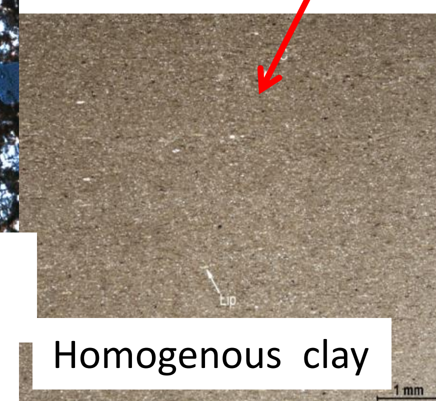


Badra, 2011

Thin Sections



Shattered, recrystallized radiolaria



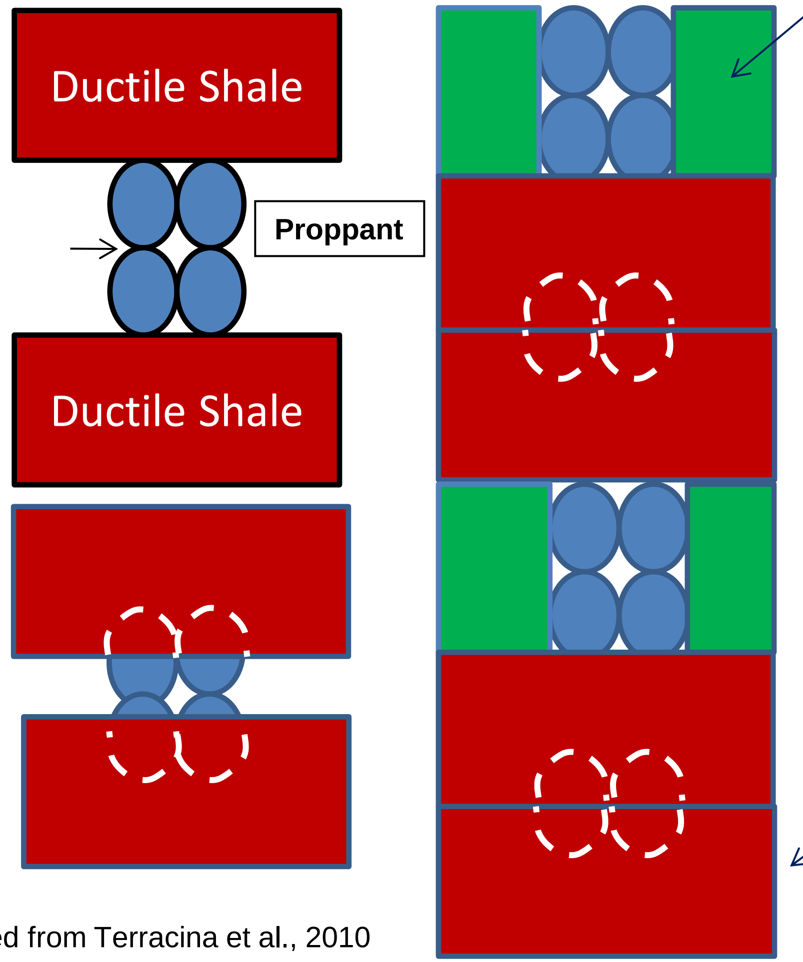
Homogenous clay

Brittle

Ductile

Althoff, 2012

Apply natural fracture distribution to hydraulic fracturing??



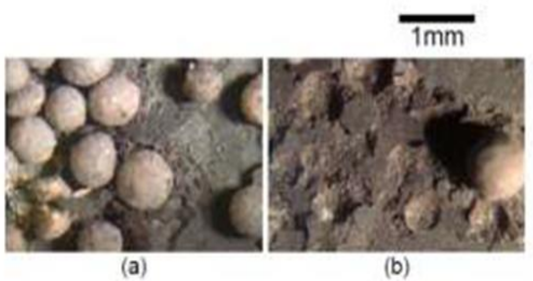
Modified from Terracina et al., 2010

Brittle Rock

Ductile Rock

Proppant embedment in high clay content shale

(Howes, 2013, from Chang and Zoback, 2012)



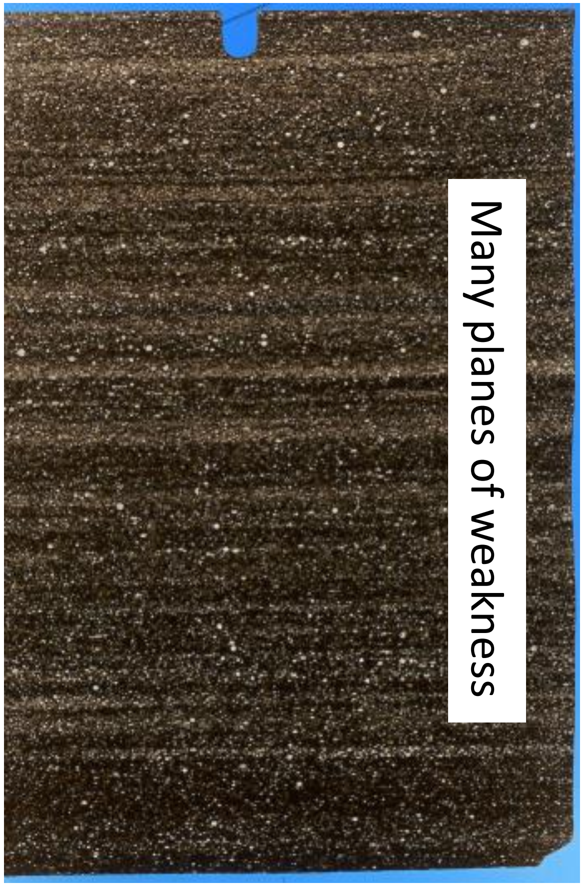
-Hydraulic fractures propagate through brittle chert and ductile clay?

-Proppant goes into both brittle chert and ductile clay

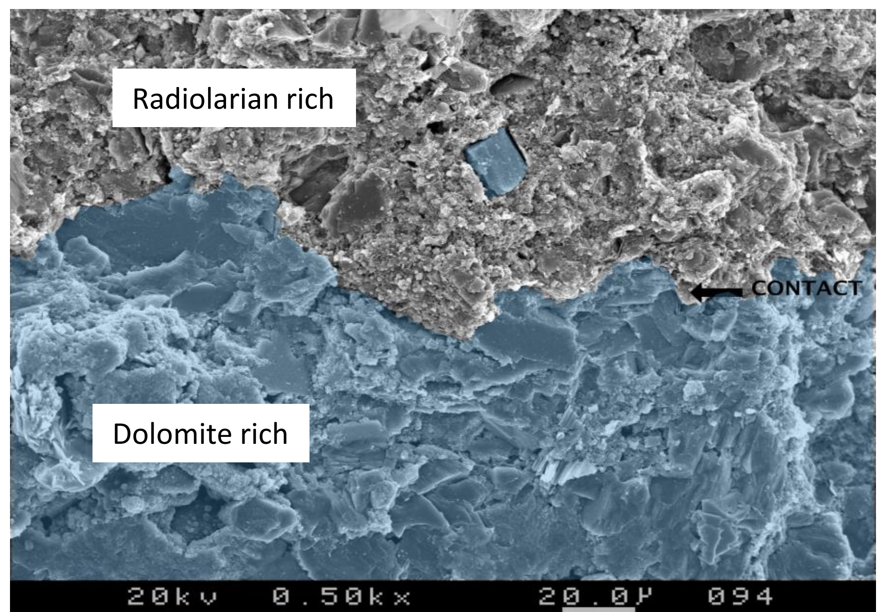
-After fracturing, the fractures in chert remain propped open

-But with time, the ductile beds encase proppant and close??

Bedding/Lamination planes are depositional, thus planes of weakness

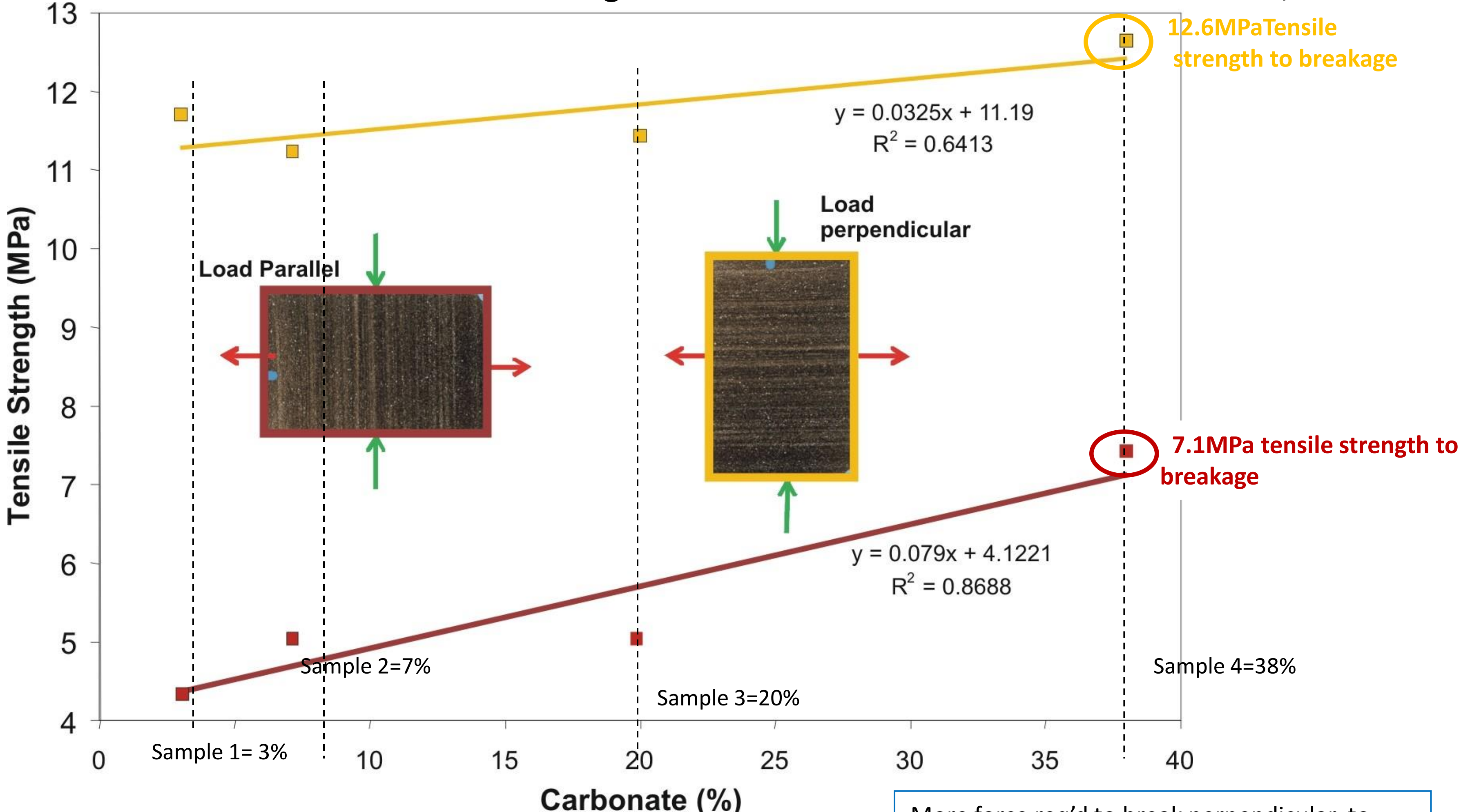


Laminae

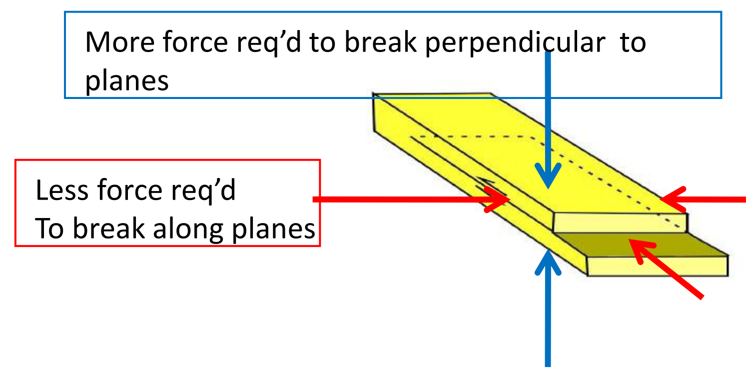


Woodford

Brazilian Tensile strength Test — Modified from Sierra et al., 2010

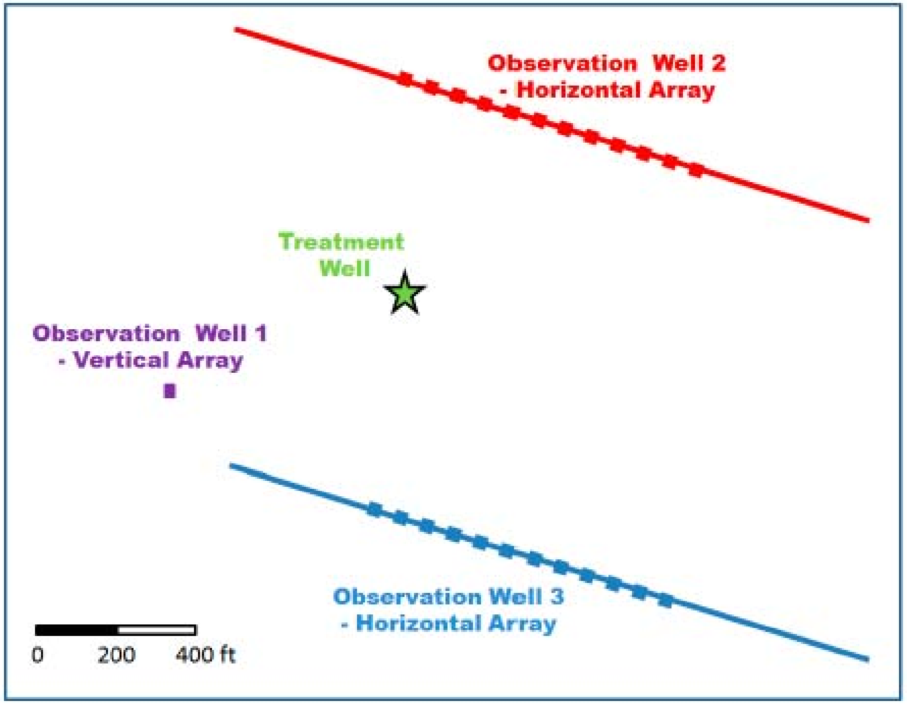


Modified from Sierra et al., 2010

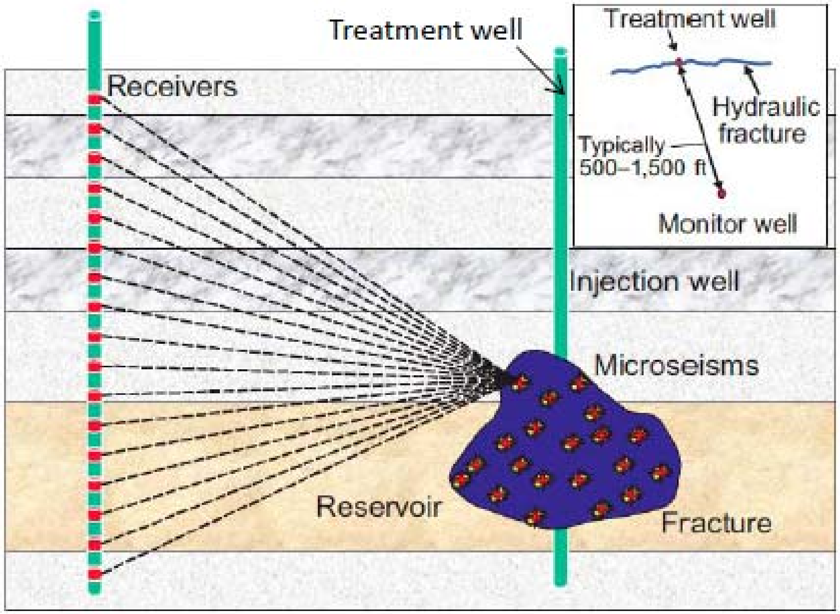


Experimental *Microseismic* Survey

(Cabarcas and Slatt, 2014 , *Interpretation*)

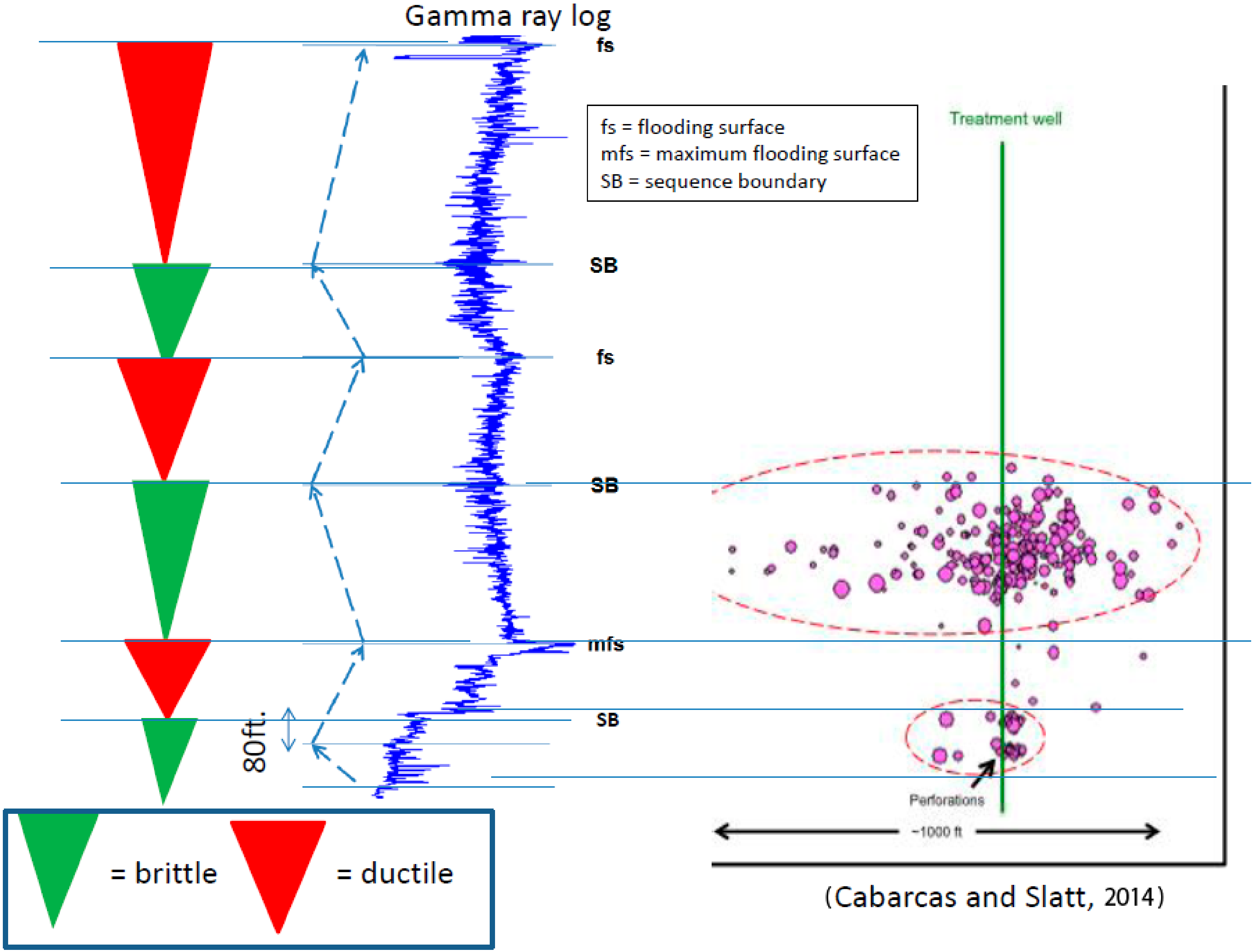


Not Woodford



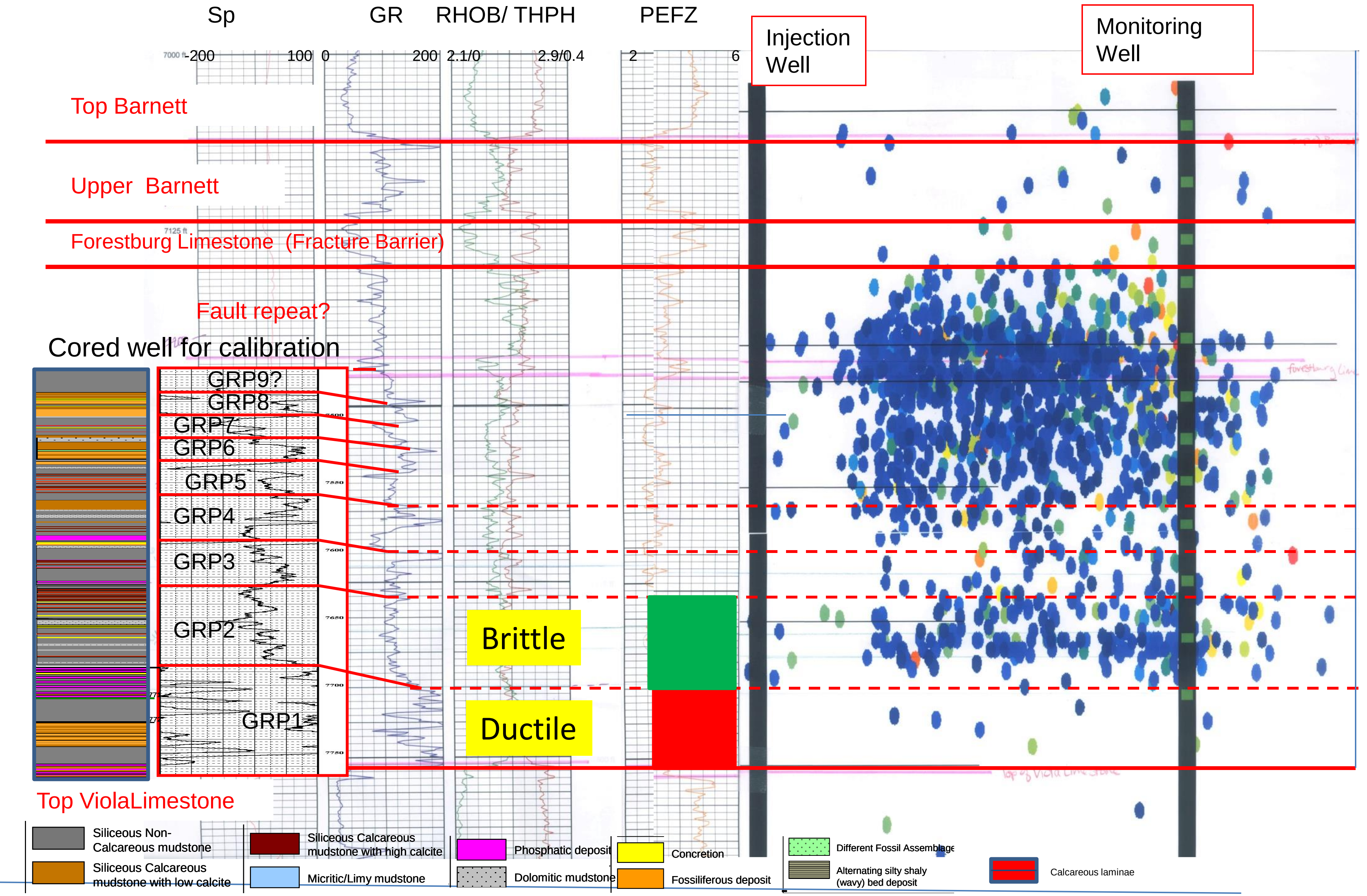
(Warpinski, 2009)

Single stage, experimental fracture and microseismic job

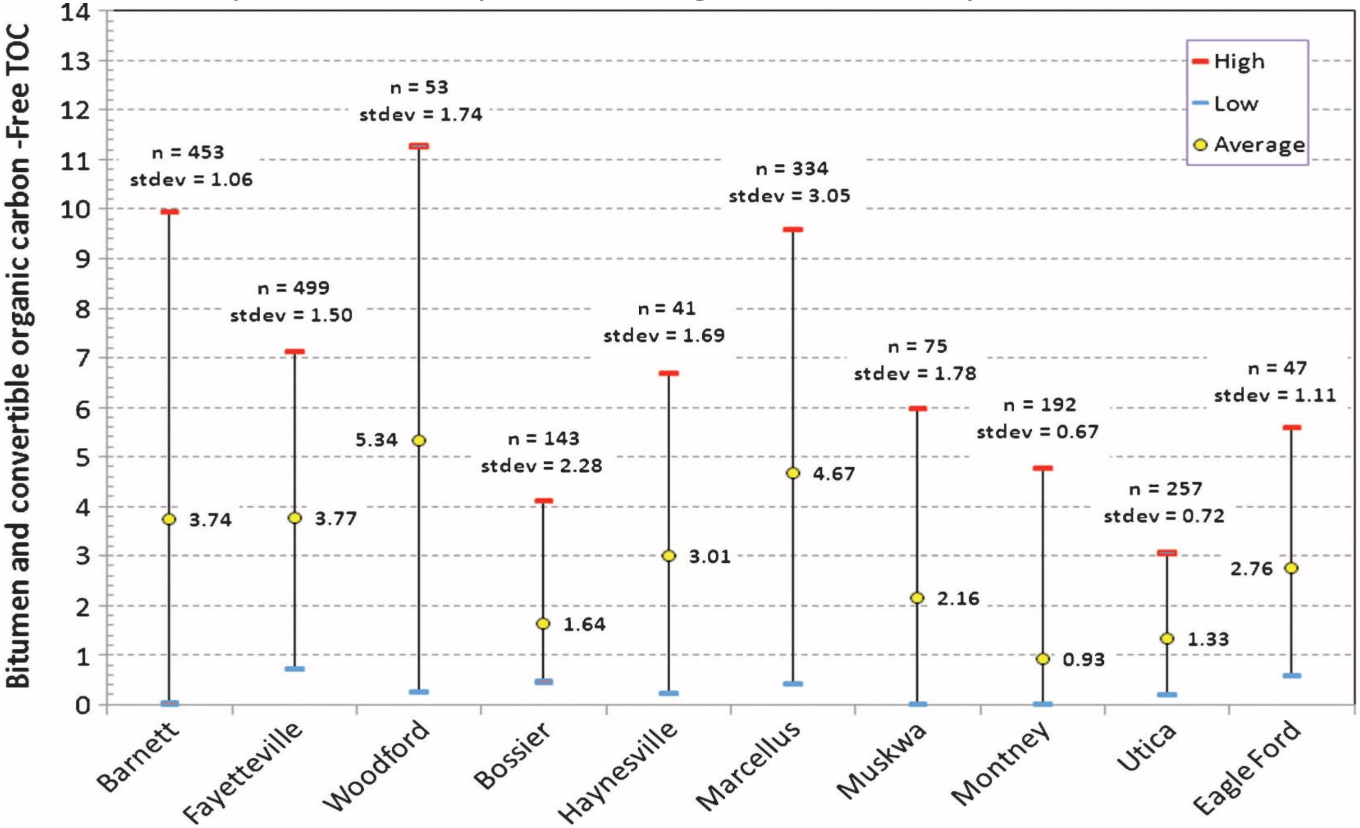


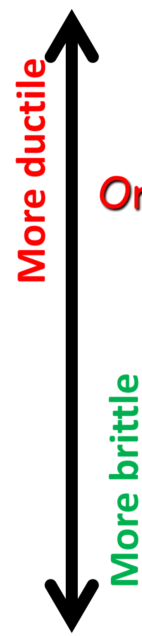
(Cabarcas and Slatt, 2014)

Barnett Microseismic



The TOCpd for the top 10 shale-gas resource systems. Jarvie, 2012





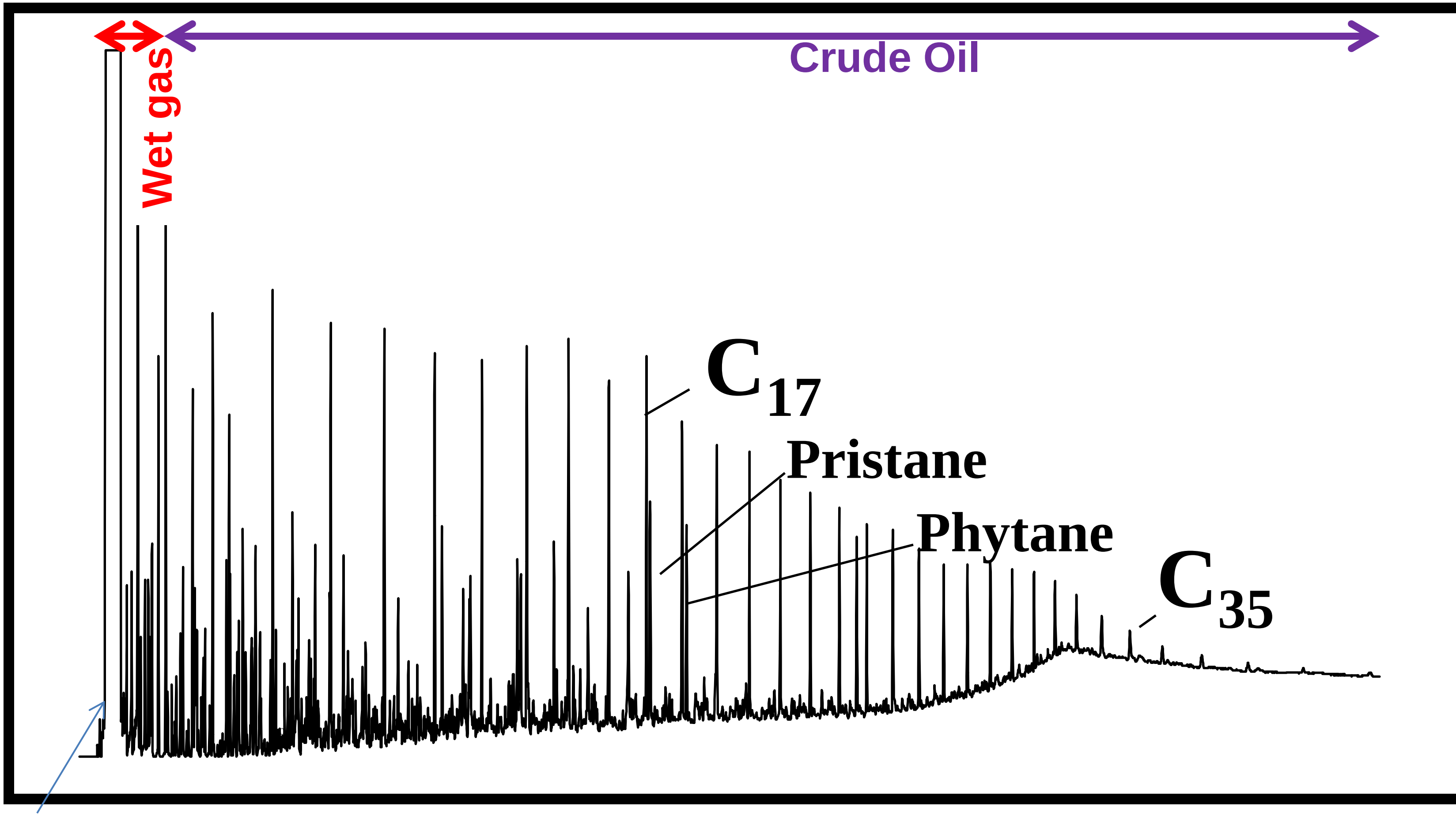
Organic matter quantity is determined by the total organic carbon (%TOC) content (whole-rock basis).

These data show the average TOCpd (present day) values for each system with the range of values, standard deviation, and number of samples. Given the high thermal maturity of these shales, these values are indicative of the nongenerative organic carbon (NGOC) values. TOCpd = present-day total organic carbon; stdev = standard deviation; n = number of samples.

Organic Geochemistry

Natural Gas (and oil)

Crude Oil Chromatogram

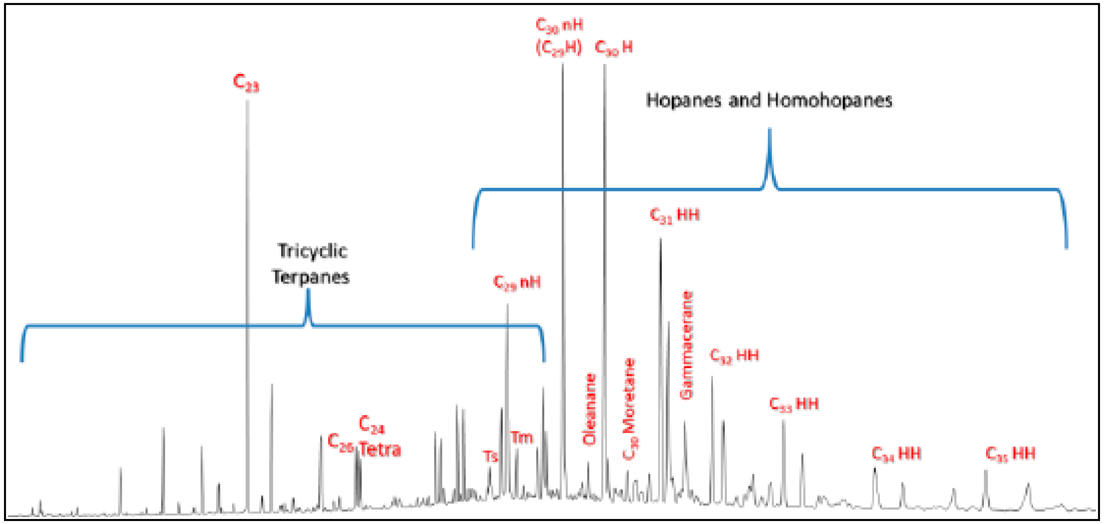


CH4; methane

General formula: [(Cn)(H(2n) + 2)]

Example: Propane = C_3H_8

Chromatogram showing different terpanes. After Torres-Parada, 2013

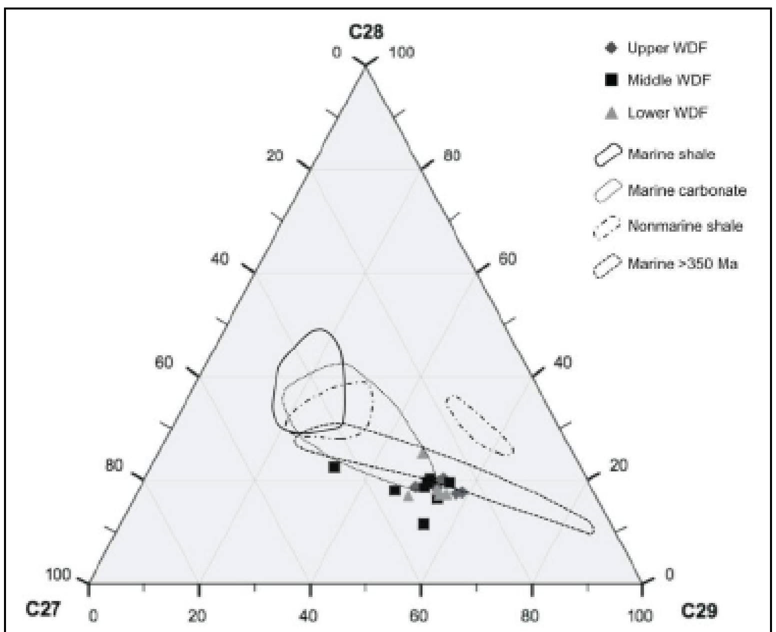


Chromatogram showing different terpanes (bacterial, blue green algae, plants), etc.

Terpanes are a group of compounds derived from bacteria, blue-green algae and plants. A chromatogram of the variety of terpanes is shown in top figure. Terpanes can be used for typing organic matter and depositional environment.

Steranes are used for évaluation of organic matter source, maturity, and for correlations. They are derived from algae and higher plants. Figure below is a C26-C28 ternary diagram containing data from the Woodford (WDF) Formation, indicating a marine source.

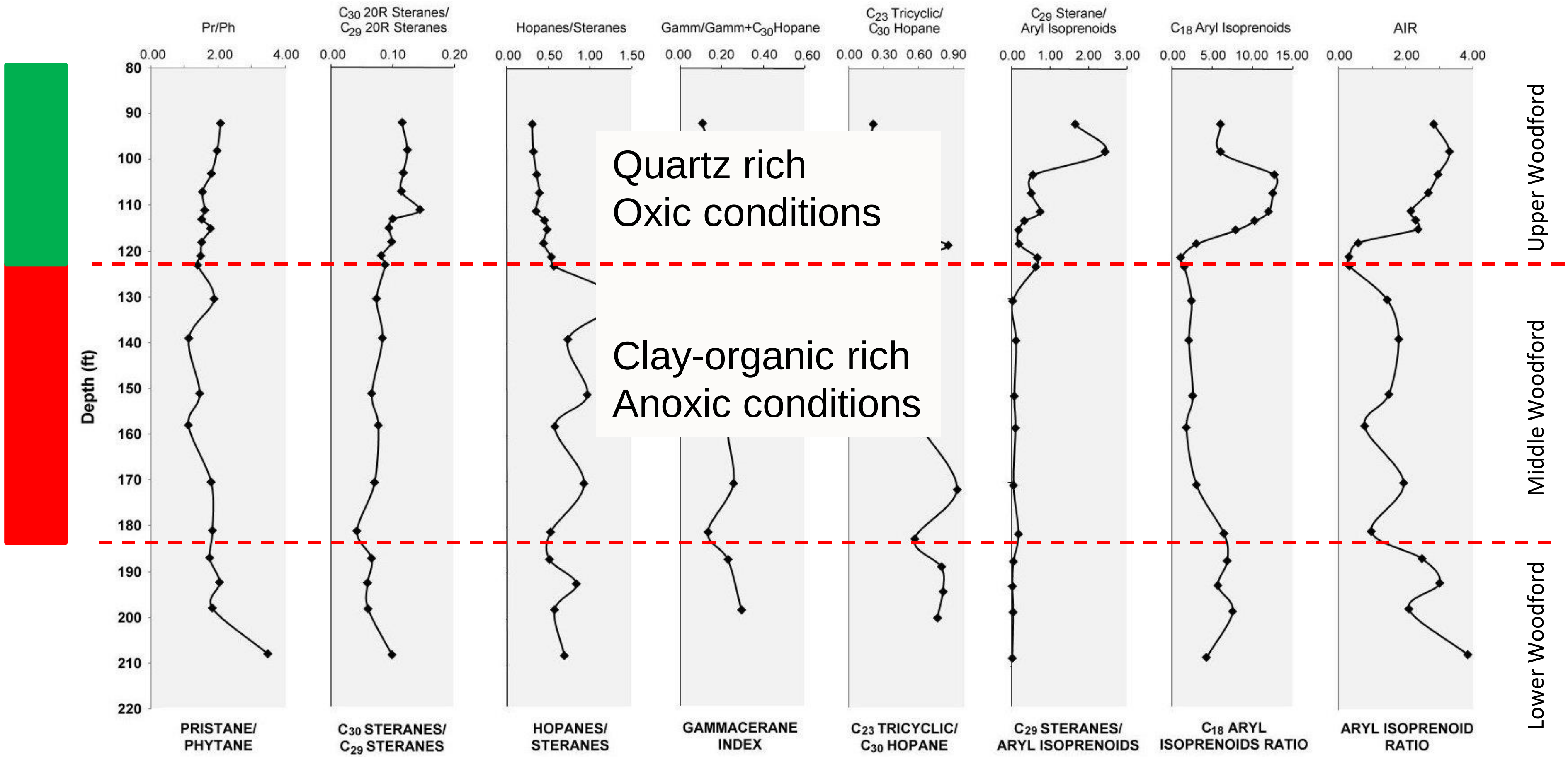
Torres-Parada, 2013



Ternary diagram of key steranes which provide an indicator of source rock and depositional environment

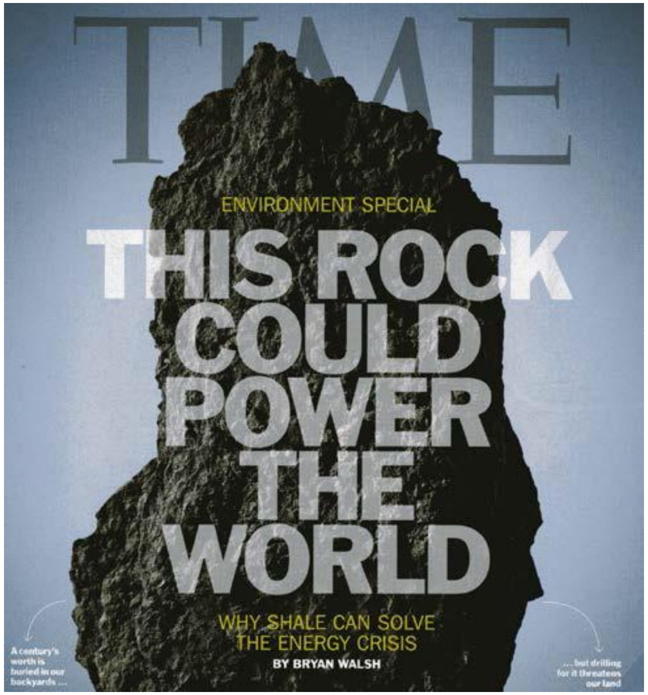
Miceli-Romero, 2010

Geochemical Biomarkers for paleoenvironmental interpretation: Woodford Shale



Geochemical logs showing different biomarker ratios for the quarry well (AIR = (C_{13}-C_{17})/(C_{18}-C_{22}) 2,3,6-trimethyl substituted aryl isoprenoids).

Biomarkers can be used to indicate oxic vs. anoxic bottom water conditions during deposition



Sequence stratigraphy, geomechanics, microseismicity, and geochemistry relationships in unconventional resource shales

Roger M. Slatt, Carlos Molinares-Blanco, Jean D. Amorocho, Carlos L Cabarcas, and Emilio Torres-Prada