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

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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.

**Selected References**


Torres-Parada, Emilio, 2013, Unconventional gas shale assessment of LaLuna Formation in the central and south areas of the Middle Magdalena Valley basin, Colombia: M.S. thesis, University of Oklahoma.


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Roger M. Slatt, Carlos Molinares-Blanco, Jean D. Amorosco, Carlos L Cabarcas, and Emilio Torres-Prada
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
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
- Marcellus
- Caney
- Fayetteville
- Horn River
- Haynesville
- Barnett
- LaLuna
- Brown shale
- Eagle Ford
- New Albany
- Fayetteville
- Longmaxi
Generalized sequence stratigraphic model for unconventional resource shales
Continued rising stage sea level (transgression)

Max. landward extent of shoreline

Slower rate of sea level rise (highstand-progradation)

Generalized sequence stratigraphic model for unconventional resource shales
End of highstand-progradation)

One Sea Level Cycle

Time 5

Gamma log response

Generalized sequence stratigraphic model for unconventional resource shales
Institute of Reservoir Characterization, OU: Oklahoma Woodford studies

1-Killian
2-Chain
3-Althoff
4-Portas, Molinares
5-Serna
6-Badra
7-Amorcho
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

Map showing locations of well measurements with specific locations highlighted:
- Teague 1-14H; Ridenour 1-20H
- Hall 2B
- Shi Randall 429H

Legend:
- Pink: Gas
- Green: Condensate
- Yellow: Oil
- Gray: No Woodford

Companies and logos at the bottom of the page.
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

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
Falling stage of sea level

Early stage of sea level rise

Continued sea level rise

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

Effect of erosional paleotopography on valley filling

SB (due to subaerial exposure)

Stagnant/hypersaline/lake?

Marine encroachment

TSE

Modified from Althoff, 2012

One Sea Level Cycle
**WHAT IS BRITTLENESS???

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.

\[
BI = \frac{\sigma_c}{\sigma_t}
\]

\(\sigma_c\) = Compressive strength
\(\sigma_t\) = Tensile strength
An interval is classified (by drillers) to be:

- **Ductile**
  - High E and low V = Brittle
  - A lot of pumping to break
  - High fracture gradient

- **Brittle**
  - Low E and high V = Ductile
  - Not as much pumping as the “ductile” intervals
  - Lower fracture gradient

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

\[ BI = \frac{(Q + Dol + Lm)}{(Q + Dol + Lm + Cl + TOC)} \]

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

**Geomechanical Measures of rock deformation**

- Decreasing stiffness/ability to propagate a fracture
- Young's Modulus
- Poisson's Ratio

**Brittle Rock**

**Ductile Rock**

(Bustin et al., 2009)
**Mineralogic affect on rock fracturability (brittleness)**

\[ BI = \frac{(Q + Dol)}{(Q + Dol + Lm + Cl + TOC)} \]

Where BI = brittleness index

- **Q** = quartz
- **Cl** = clay
- **Dol** = dolomite
- **Lm** = limestone (calcite)
- **TOC** = Total organic carbon

(Wang and Gale, 2009)
Upward-decreasing Gamma Ray = water depth of deposition must be decreasing with time, as rocks are deposited.

- **Core Gamma Ray (Cpm)**
  - Increasing gamma ray = decreasing depth.
  - Decreasing gamma ray = increasing depth.

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

- **Surface Layer:**
  - Aerobic, oxygen abundant.

- **Pycnocline:**
  - Dysaerobic with rapid downward decrease in dissolved oxygen.

- **Bottom Layer:**
  - Anaerobic with very little or no oxygen.

- **Pyrite nodule:**
  - 

- **Calcareaous concretions:**
  - 

- **Pyritic nodules:**
  - 

- **Marine depositional environment**
  - Diverse benthic, shelly epifauna.
  - Bioturbation with some pelagic fossils possible; may contain pelagic fossils; benthic epifauna absent.
  - No bioturbation; pelagic fossils only. Laminated organic-rich mud.

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

- **Shallow water**
  - High amount of detrital quartz in the matrix.
Ductile-Brittle Couplets: Barnett Shale example

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

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

Slatt and Abousleiman, 2011

Singh, 2008
(DT) X (RHOB) = Al

Youngs modulus $\varepsilon$ and Poissons Ratio (PR)

Fracture Gradient (MPa/m)

Couplets at the parasequence scale

$\varepsilon$-PR crossover

High $\varepsilon$, low PR

Brittle

Ductile

Molinares-Blanco, 2013
Amorocho, 2012
EagleFord, S. Texas

Breyer et al., 2014
“Brittle-Ductile Couplets”
(Slatt and Abousleiman, 2011)

Brittle = biogenic quartz rich
(reservoir rock)
Ductile= clay-organic rich
(HC source rock)

Core

Outcrop

Vertical fracture

Thin Sections

Brittle

Ductile

Shattered, recrystallized radiolaria

Homogenous clay

Althoff, 2012
Apply natural fracture distribution to hydraulic fracturing?

- 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.

Modified from Terracina et al., 2010.
Bedding/Lamination planes are depositional, thus planes of weakness.
Brazilian Tensile strength Test

Modified from Sierra et al., 2010

Modified from Sierra et al., 2010

12.6MPa Tensile strength to breakage

7.1MPa tensile strength to breakage

Load Parallel

Load perpendicular

Less force req’d to break along planes

More force req’d to break perpendicular to planes

Sample 1 = 3%

Sample 2 = 7%

Sample 3 = 20%

Sample 4 = 38%

Tensile Strength (MPa)

Carbonate (%)
Experimental *Microseismic Survey*

(Cabarcas and Slatt, 2014, *Interpretation*)

Not Woodford

(Warpinski, 2009)
Single stage, experimental fracture and microseismic job

Gamma ray log

fs = flooding surface
mfs = maximum flooding surface
SB = sequence boundary

Treatment well

(Cabarcas and Slatt, 2014)

80 ft.

= brittle

= ductile
Barnett Microseismic

- Top Barnett
- Upper Barnett
- Forestburg Limestone (Fracture Barrier)
- Fault repeat?

Cored well for calibration

- GRP9?
- GRP8
- GRP7
- GRP6
- GRP5
- GRP4
- GRP3
- GRP2
- GRP1

Key

- Siliceous Non-Calcarenous mudstone
- Siliceous Calcarenous mudstone with high calcite
- Siliceous Calcarenous mudstone with low calcite
- Micritic/Limy mudstone
- Dolomitic mudstone
- Phosphatic deposit
- Fossiliferous deposit
- Concretion
- Different Fossil Assemblage
- Alternating silt/shaly (wavy) bed deposit
- Calcarenous laminae
- Brittle
- Ductile

Monitoring

Injection Well

Well
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

Wet gas

Crude Oil

CH₄; methane

C₁₇
Pristane

C₃₅
Phytane

General formula: [(Cn)(H(2n) + 2)]
Example: Propane = C₃H₈
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 evaluation 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.
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