PS Multi-scale, Brittle-Ductile Couplets in Unconventional Gas Shales: Merging Sequence Stratigraphy and Geomechanics*

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Abstract

The words “ductile” and “brittle” have emerged as two key descriptors for characterizing unconventional gas shales. The former is usually considered to be relatively organic (TOC)- and clay-mineral rich, while the latter is considered to be more enriched in “silica” (i.e., biogenic and/or detrital quartz)- and/or carbonate (calcite/dolomite) minerals. Our studies of some gas shales have shown that such ductile and brittle rocks occur as alternating „couplets‟ at a variety of scales. At the largest, sequence stratigraphic scale, ductile beds comprise condensed sections (CS) which lie on or stratigraphically near a combined sequence boundary/transgressive surface of erosion (SB/TSE). Detritus-rich beds prograde over the top of the condensed section (i.e., maximum flooding surface) during the ensuing highstand/regressive (HST/RST) depositional phase. The next smaller, temporally-shorter parasequence scale often consists of a ductile CS shale overlain by a „cleaning‟-upward‟ (i.e., on gamma -ray log) HST/RST shale. Vertical stacking of repetitive parasequences gives rise to a series of stacked, ductile-brittle couplets, each couplet bound by a marine flooding surface. At a still-finer, sub-parasequence scale, ductile and brittle couplets are often finely interbedded or interlaminated. It is possible to recognize or predict these different scales of couplets in outcrop, on logs and core, and sometimes on seismic, thus providing a means of predicting stratigraphic variability in geomechanical and other rock properties. Examples include: (1) Fracture Toughness, Young‟s Modulus and Poisson‟s Ratio vary at the sequence and parasequence scales, (2) Microseismic event-intensities vary at the parasequence scale, and (3) rock strength varies with amount of laminations/beds per stratigraphic interval at the sub-parasequence scale. Applications of these findings include (1) predicting the stratigraphic position of a horizontal wellbore for optimal artificial fracturing and penetration of gas/oil-rich horizons, (2) optimizing drilling orientation with respect to bedding and (3) predicting differential retention of fracture proppant.

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Multi-scale brittle-ductile couplets in unconventional gas shales: Merging Sequence Stratigraphy and Geomechanics

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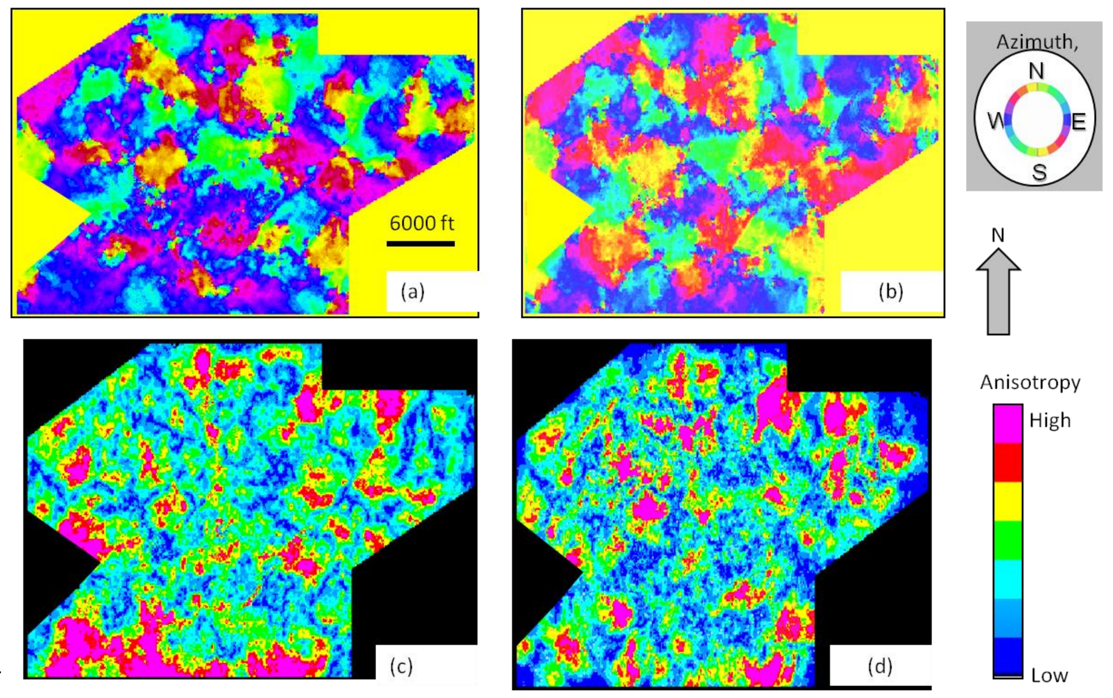
The words "ductile" and "brittle" have emerged as two key descriptors for characterizing unconventional gas shales. The former is usually considered to be relatively organic (TOC)- and clay-mineral rich, while the latter is considered to be more enriched in "silica" (i.e., biogenic and/or detrital quartz) and/or carbonate (calcite/dolomite) minerals. Our studies of some gas shales have shown that such ductile and brittle rocks occur as alternating „couplets" at a variety of scales. At the largest, sequence stratigraphic scale, ductile beds comprise condensed sections (CS) which lie on or stratigraphically near a combined sequence boundary/transgressive surface of erosion (SB/TSE). Detritus-rich beds prograde over the top of the condensed section (i.e., maximum flooding surface) during the ensuing highstand/regressive (HS/RST) depositional phase. The next smaller, temporally-shorter parasequence scale often consists of a ductile CS shale overlain by a „cleaning"-upward" (i.e., on gamma –ray log) HS/RST shale. Vertical stacking of repetitive parasequences gives rise to a series of stacked, ductile-brittle couplets, each couplet bound by a marine flooding surface. At a still-finer, sub-parasequence scale, ductile and brittle couplets are often finely interbedded or interlaminated. It is possible to recognize or predict these different scales of couplets in outcrop and on logs and core, and sometimes on seismic, thus providing a means of predicting stratigraphic variability in geomechanical and other rock properties. Examples include: (1) Fracture Toughness, Young"s Modulus and Poisson"s Ratio vary at the sequence and parasequence scales, (2) Microseismic event-intensities vary at the parasequence scale, and (3) rock strength varies with amount of laminations/beds per stratigraphic interval at the sub-parasequence scale. Applications of these findings include (1) predicting the stratigraphic position of a horizontal wellbore for optimal artificial fracturing and penetration of gas/oil-rich horizons, (2) optimizing drilling orientation with respect to bedding and (3) predicting differential retention of fracture proppant.

WHAT DID KIEL KNOW ABOUT COMPLEX FRACTURE PATTERNS IN SHALES???? .

He must have known stratigraphy, of course!!

Figure 1. From: Ralph W. Veatch, Jr. "A Historical Perspective of HYDRAULIC FRACTURING". 2007 SPE Hydraulic Fracturing Technology Conference, College Station Texas, January 29, 2007.

BARNETT EXAMPLE: POST-HYDRAULIC FRACTURE 3D SEISMIC SURVEY, BARNETT SHALE, CONFIRMS COMPLEX PATTERN OF 'FRACTURE COMPARTMENTS'.

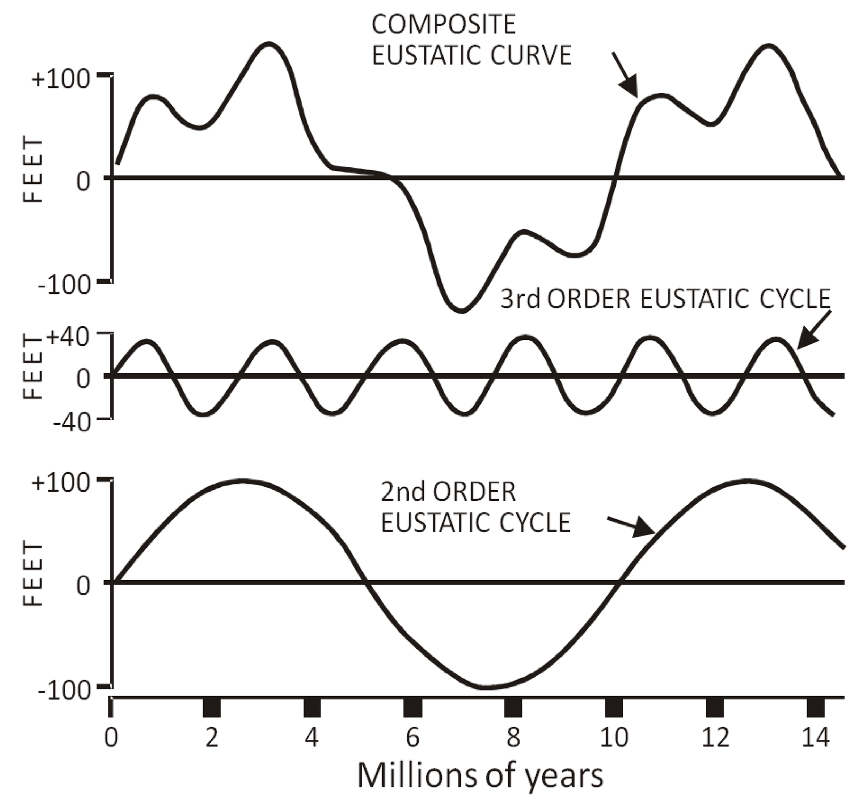


after Kui, 2010, OU Ph.D. dissertation).

Figure. 2. "Phantom horizon slices 10 ms above the Ordovician unconformity of the azimuth of anisotropy, ψ, computed from (a) acoustic impedance and (b) AVAz. Phantom horizons at the same level through the intensity of anisotropy, ε, computed from (c) acoustic impedance and (d) AVAz. Overall, the results are similar. The drilling program consisted of horizontal wells oriented NW-SE to better generate fractures parallel to the maximum horizontal stress oriented NE-SW. **This image refutes this widely accepted hydraulic fracture model and shows the fractures have widely variable orientations, though these orientations remain consistent in what we interpret to be "fracture compartments".** (quote from Kui, 2010, OU Ph.D. dissertation)

SEQUENCE STRATIGRAPHY

INTERACTION OF 2nd AND 3rd ORDER EUSTATIC CYCLES



Sequence Stratigraphy is based upon the premise that through geologic time, the oceans have risen and fallen in a cyclic manner (i.e., rise and fall of sea level). Because of this, strata are deposited in a predictable manner.

Many of the resource shales were deposited as 3rd order sequences superimposed upon a 2nd order sequence as shown by the composite eustatic curve.

The following panels show a generalized sequence stratigraphic model (Fig. 4) that is applicable to many resource shales, with two examples, both showing a higher frequency relative sea-level cyclicity superimposed upon a lower order of cyclicity (Fig. 5). The Barnett Shale consists of 14 3rd order cycles (GRP"s) superimposed upon the 2nd order cycle (Fig. 6). The 2nd order cycle which comprises the Barnett Shale consists of a lower organic-rich interval overlain by a less organic -rich, relatively „cleaner" interval (Fig. 6). The 3rd order cycles consist either of an upward increase in carbonate at the expense of clays/organics, or an upward increase in clays/organics at the expense of carbonate (Fig. 7). At a smaller scale, there is a high degree of primary stratification observable by FMITM log and to a lesser extent by core description (Fig. 8).

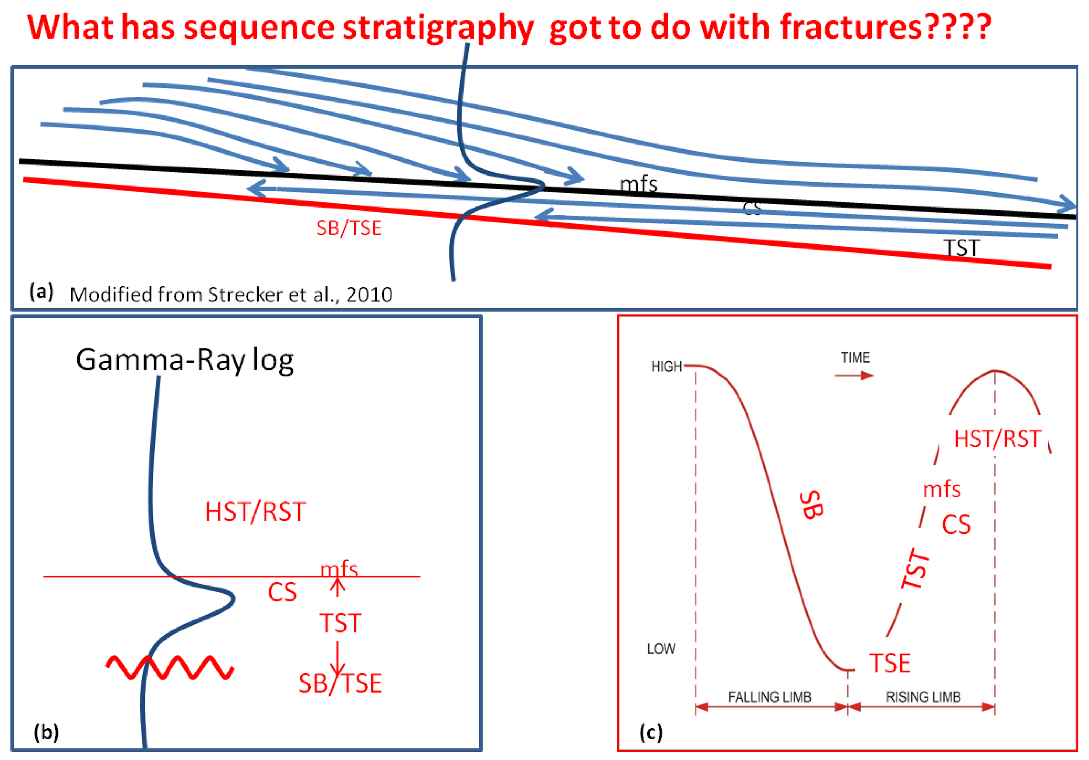


Figure. 4 (a) General sequence stratigraphic model for resource shales (Slatt and Rodriguez, 2010) showing combined lowstand sequence boundary (SB)/transgressive surface of erosion (TSE), overlain by onlapping transgressive systems tract (TST), capped by condensed section (CS) and maximum flooding surface (mfs), with highstand (regressive) systems tract (HST/RST) downlapping onto mfs. (b) Generalized well log showing high gamma ray TST/CS and lower gamma ray HST/RST. (c) stages of development of sequence stratigraphic features within a eustatic sea-level cycle.

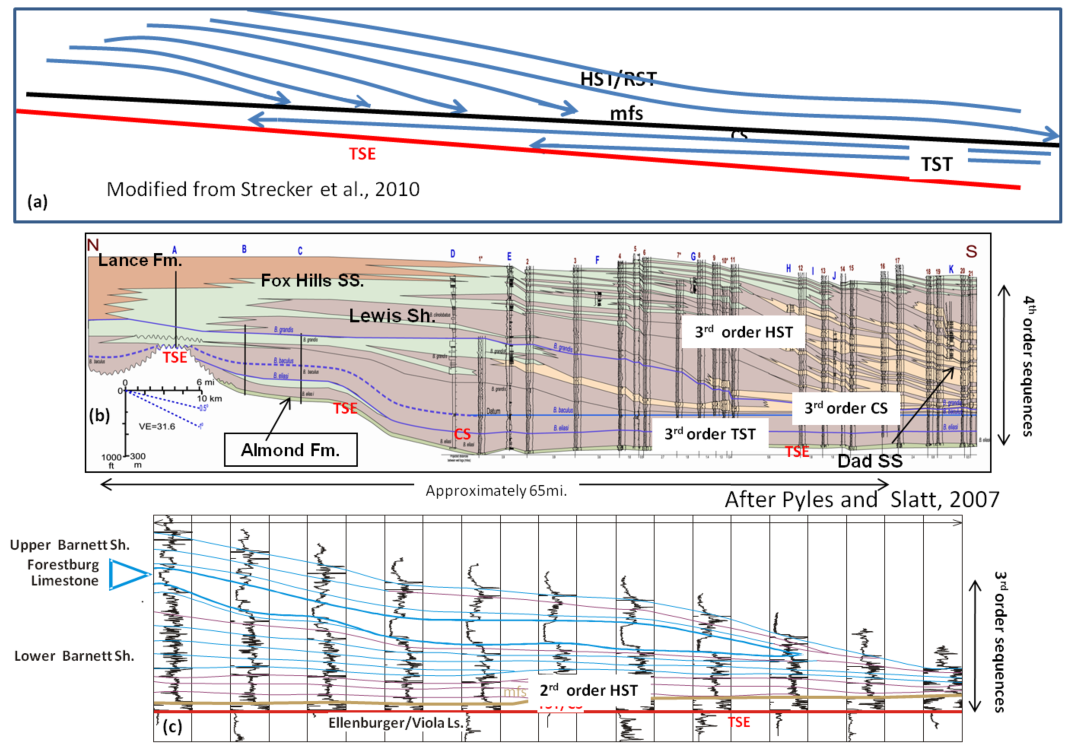


Figure. 5. Examples of the general model (a) include : (b) Cretaceous Lewis Shale and (c) Mississippian Barnett Shale. Lewis Shale 4th order sequences are superimposed on 3rd order transgressive/highstand systems tract; Barnett 3rd order sequences are superimposed upon a 2nd order transgressive / highstand systems tract. Other unconventional resource shales exhibit the same general stratigraphy (Slatt and Rodriguez, 2010).

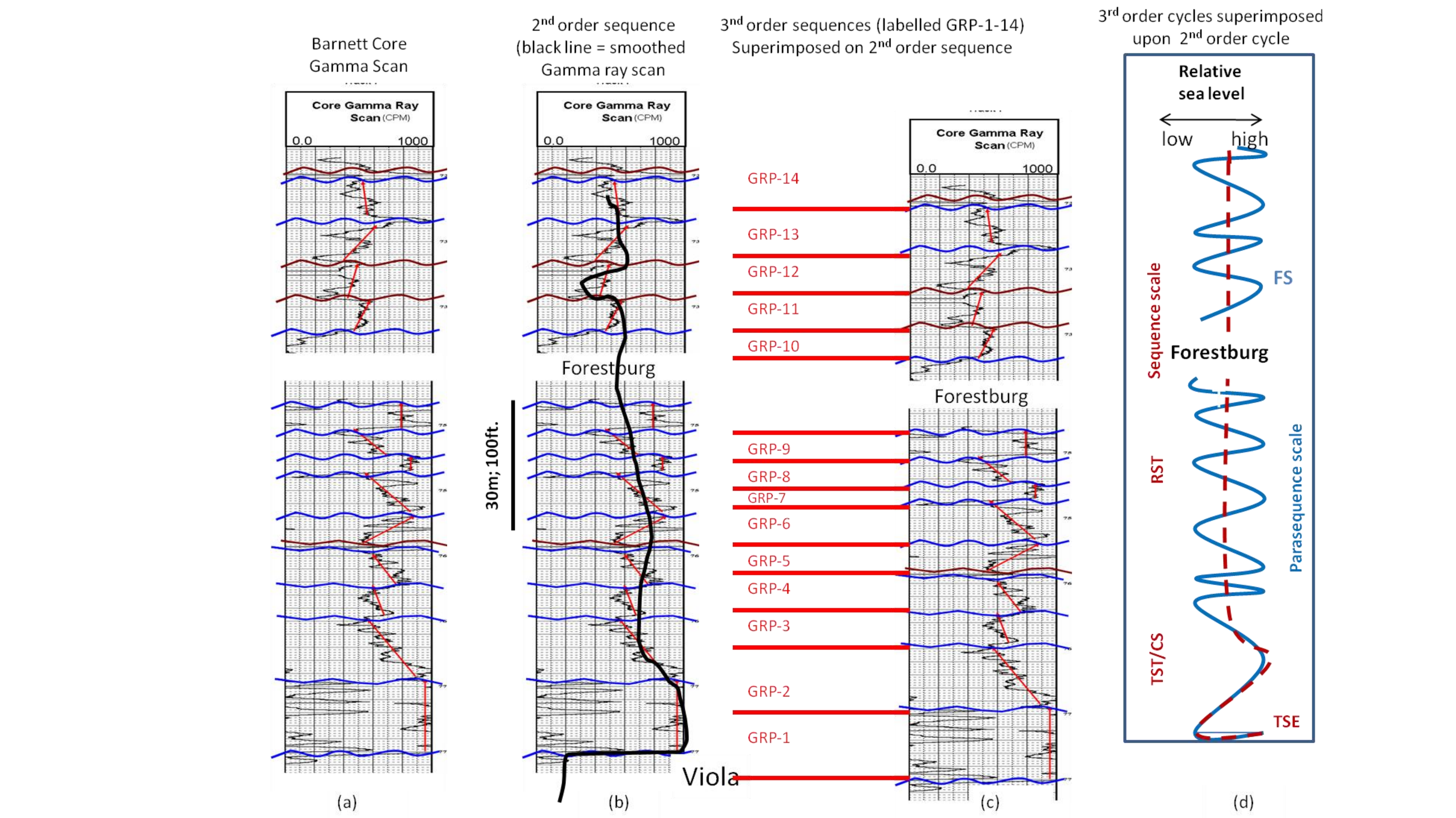


Figure 6. (a) Barnett Shale gamma ray log showing gamma ray patterns (red arrows). (b) Generalized core gamma scan log showing a lower, high API interval and an upper, relatively lower API interval which correspond to intervals of high and low TOC, respectively. This is a 2nd order depositional sequence scale display. (c) 14 3rd order (para)sequences (labeled GRP-), each one exhibiting either an upward increase or an upward decrease in API due to stacking of different lithologies. (d) schematic 2nd order eustatic sea-level cycle (red-dashed curve) with the 14 3rd order cycles (blue solid curve) superimposed.

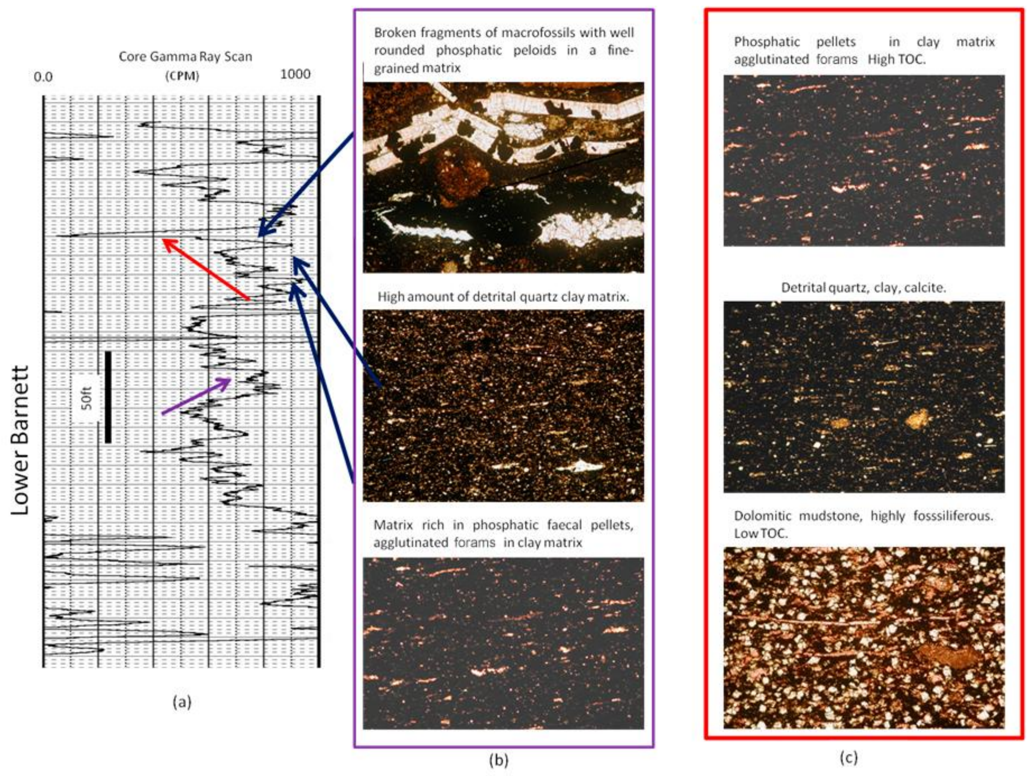


Figure 7. (a) Barnett Shale gamma ray log highlighting an upward-decreasing GRP and an upward-increasing GRP. (b) shows thin sections of the three facies comprising the upward-decreasing GRP. (c) shows thin sections of the three facies comprising the upward-increasing GRP.

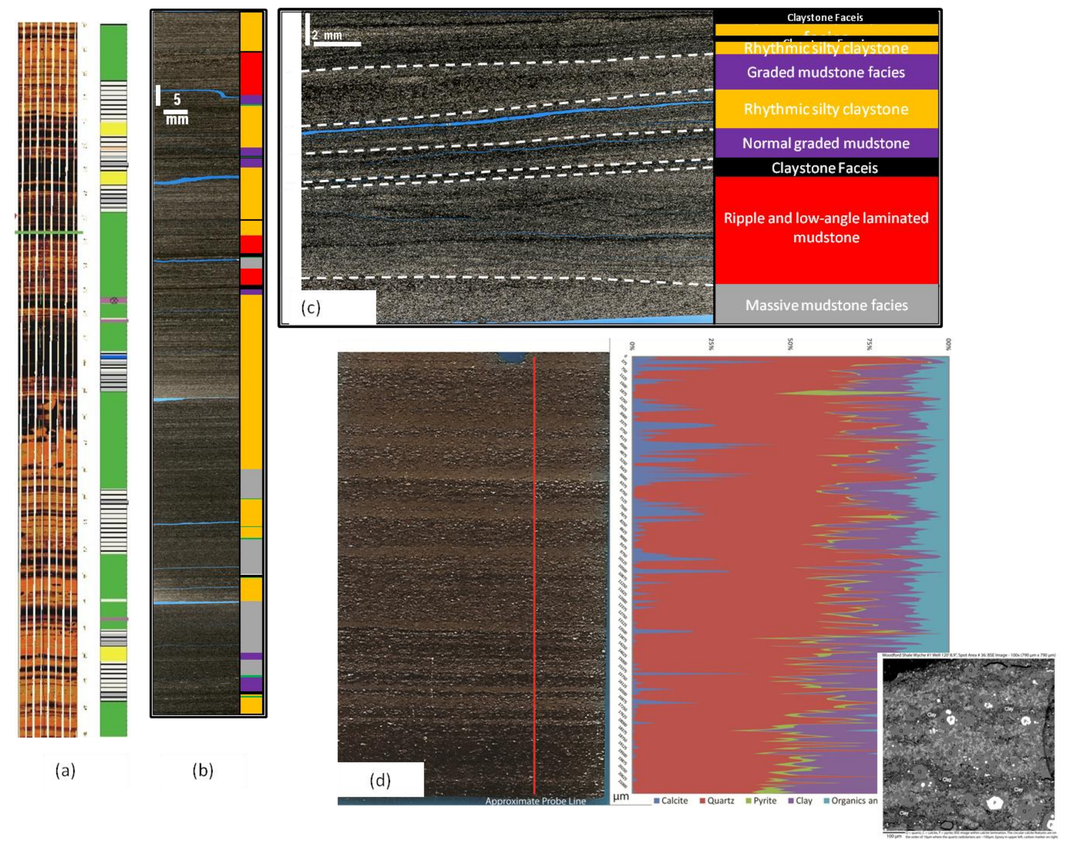


Figure 8. Bedsets /laminae sets and beds/laminations. (a) FMI™ log and core description, Woodford Shale, showing high degree of interbedding, particularly as seen on the FMI™ log. (b) Shows fine-scale laminations and beds in the Barnett Shale core. (c) Shows different micro-facies within a Barnett Shale core. (d) Electron Microprobe scan of thin section and mineralogical composition determined from microprobe elemental analysis. Note the fine-scale interbedding of calcite-rich and calcite-poor laminae. Each analyzed data point is separated from the next by 75μm. The calcite-rich laminae (inset in lower right corner) are composed of recrystallized radiolaria cemented by crystalline calcite. The calcite-poor laminae are clay-rich. Microprobe analysis provided by M. Totten as part of his M.S. thesis research at OU.

Multi-scale brittle-ductile couplets in unconventional gas shales: Merging Sequence Stratigraphy and Geomechanics

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FRACTURES AND GEOMECHANICS (Continued from first panel)

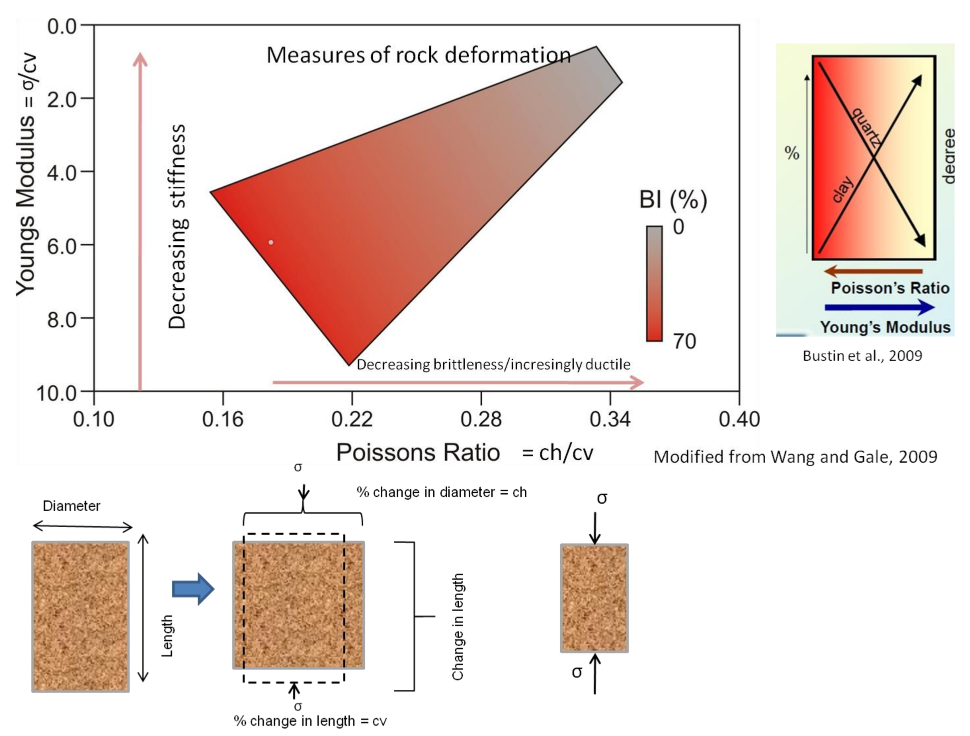


Figure 9. In this presentation, we qualitatively refer to shales as brittle or ductile, depending upon their ability to fracture and propagate a fracture. Young's Modulus and Poisson's Ratio are shown in this figure. A brittle rock will be expressed on a stress-strain diagram as breaking cleanly when stress is applied. A ductile rock undergoes plastic deformation before breaking. Mineralogic analysis (Fig. 10) can be used to calculate a 'brittleness index', but mineralogic analysis does not measure stratification, which we deem important to fracturability. Natural fractures occur at a variety of scales and rock toughness varies with rock properties (Figs. 11-14). Laboratory tests demonstrate that laminated shale is prone to break more easily when stress is applied parallel to the laminations then when stress is applied perpendicular to laminations (Fig. 15). Boundaries between laminae are not chemically bonded, but rather are the product of discrete depositional processes, so are prone to be planes of weakness (Fig. 15). The type, amount, and distribution of shale pores (Fig. 16) also will affect fracturability.

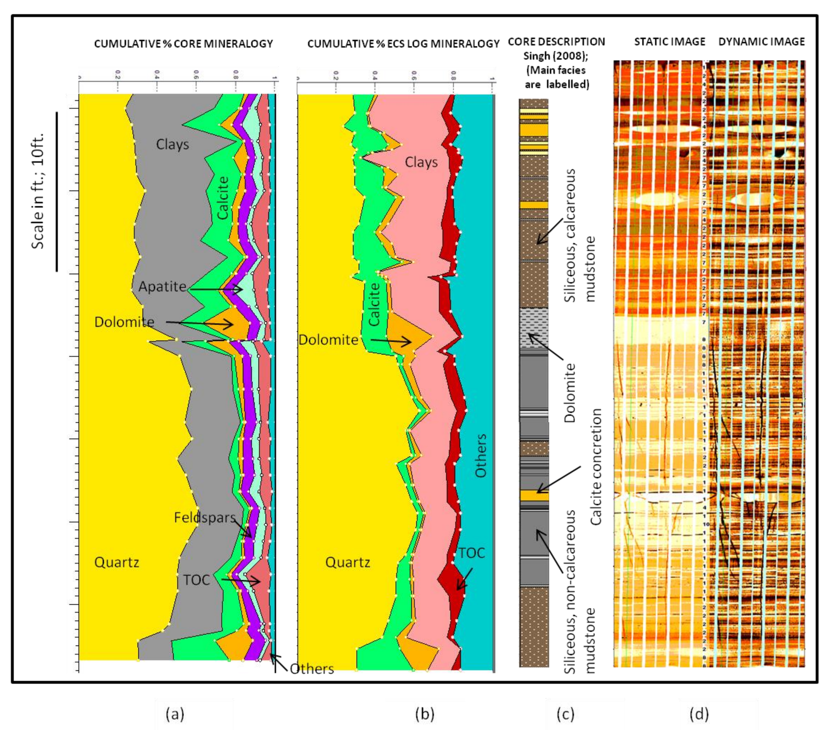


Figure 10. Often the degree of brittleness or ductility of a resource shale will be defined upon the basis of its mineralogic composition, using an equation like that below.

Brittleness Index

$$\frac{(\%Quartz + \%Dolomite)}{(Quartz + Dolomite + Calcite + Clays + TOC)}$$

This figure shows (a) X-ray diffraction mineralogical analysis of a core interval of Barnett Shale compared with (b) mineralogical analysis from a ECS^{TM} log. The results are comparable. (c) is a core description of the same interval. (d) shows the greater degree of fine-scale lamination as shown on the FMI^{TM} log. ECS^{TM} log analysis. We feel that the fine-scale stratification inherent to many resource shales plays a significant role in the fracture potential of a rock. Neither X-ray diffraction analysis nor the ECS^{TM} log provide any indication of stratification.

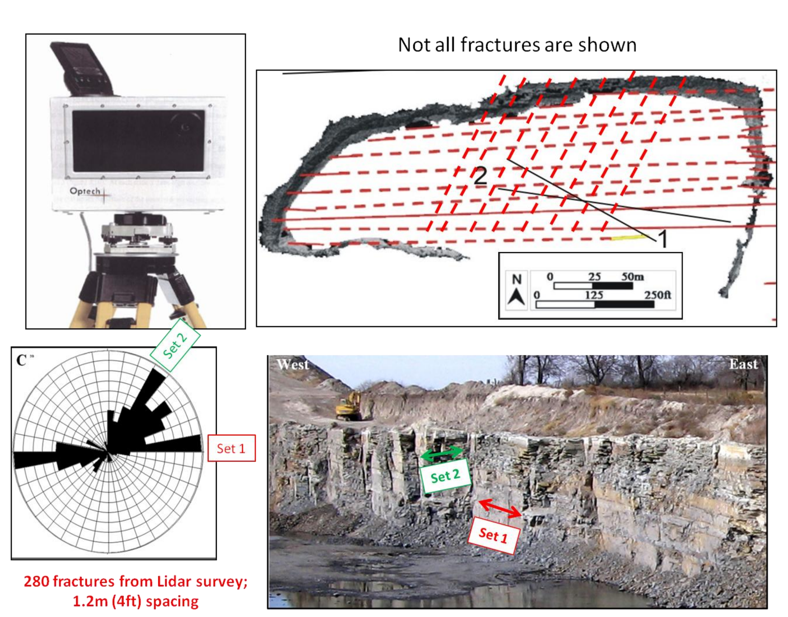


Figure 11..Fractures occur at different scales. This picture shows the results of a LiDAR survey within a Woodford Quarry (Portas, 2009; Slatt et al., 2011). Two sets of large fractures were identified based upon measurement of 280 fractures. Set 2 is parallel to the modern stress field.

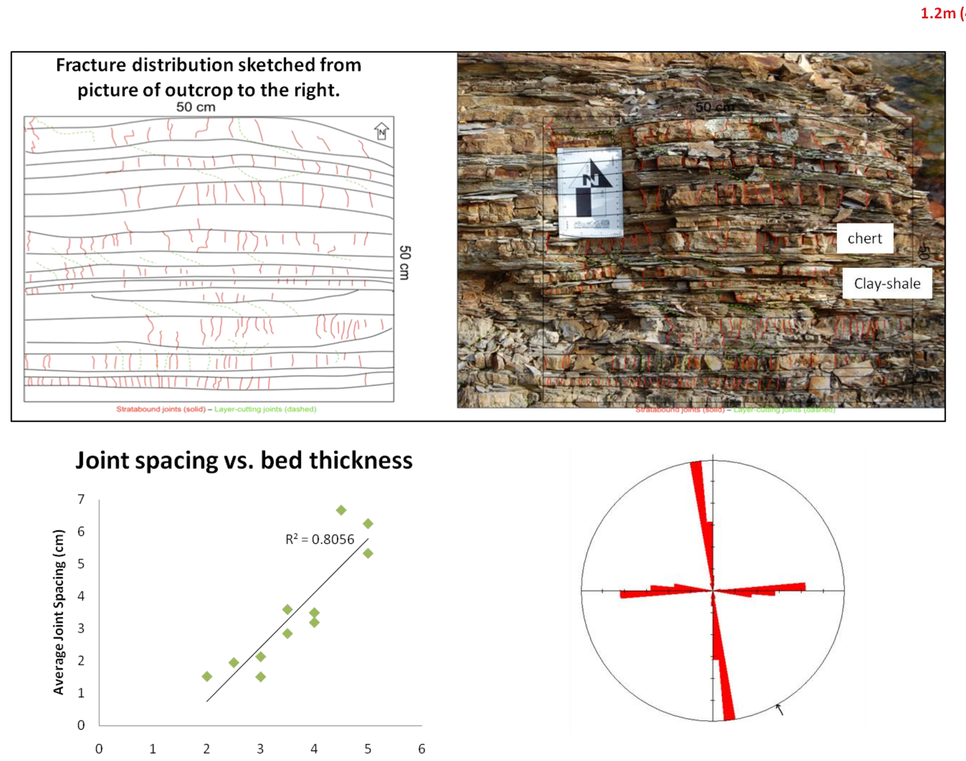


Figure 12. This figure shows an outcrop of the Woodford Shale with natural vertical fractures within chert beds, but not extending into adjacent clay-shale beds. Either the fractures never did propagate through the shales during deformation, or the fractures closed sometime after deformation and pressure reduction. Fracture spacing increases with the thickness of individual chert beds, so bed thickness is a factor in fracture propagation.
In this outcrop, two perpendicular fracture sets were measured, one corresponding to the modern stress regime.
Do the rocks exhibit the same characteristics during artificial fracturing: i.e., do induced- fractures in shale close around proppant once pressure is reduced???

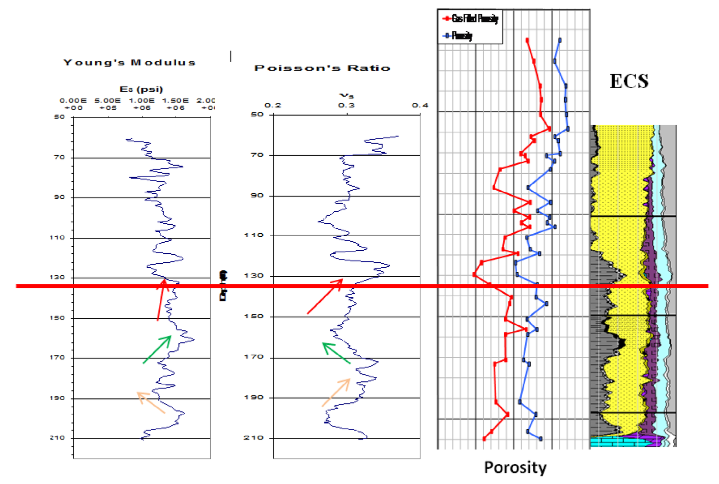


Figure 13. This figure shows the results of fracture toughness measurements on Woodford Shale core samples from the same quarry (Abousleiman, 2010). The ECS^{TM} log shows a higher quartz content in the Upper Woodford, which is a 'tougher' rock than the Middle Woodford.

Formation	Depth meters (ft)	Max. Load (N)	Frac. Toughness (MPavm)
Upper Woodford	33.81 (110.93)	489.00	1.17
	36.85 (120.90)	133.00	1.15
Middle Woodford	41.36 (135.70)	83.00	0.65
	44.28 (145.28)	89.00	0.74
Lower Woodford	50.59 (165.98)	89.00	0.74

Tougher — Lower TOC higher quartz; Higher TOC higher clay

Modified from Tran, 2009

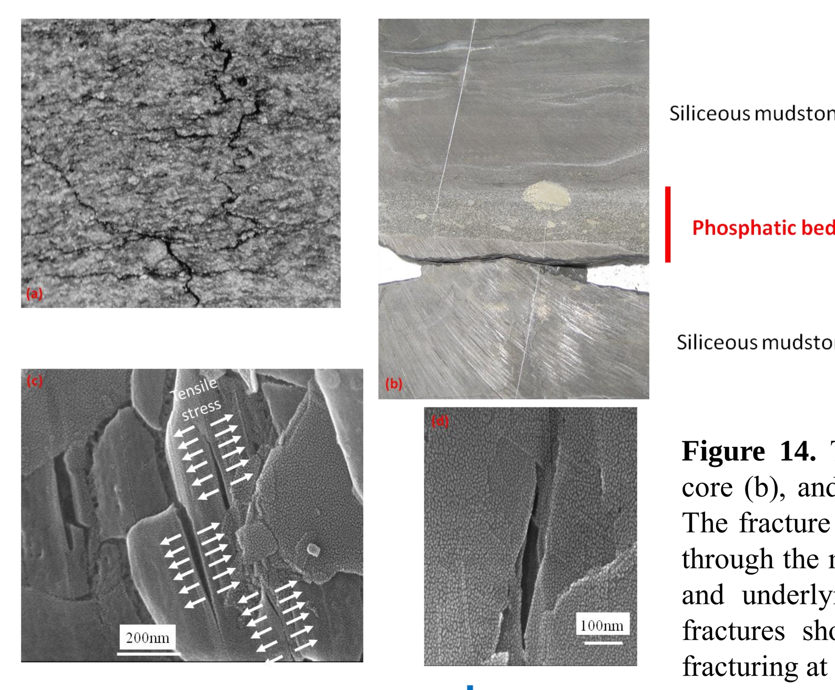


Figure 14. This figure shows smaller-scale fractures in outcrop (a), core (b), and high-resolution scanning electron microscopy (c and d). The fracture offset in (b) may be due to dissipation of fracture energy through the more porous and ductile phosphatic bed than the overlying and underlying siliceous mudstone bed. The alignment of tension fractures shown in c and d suggest a crystal structure effect on fracturing at that small scale.

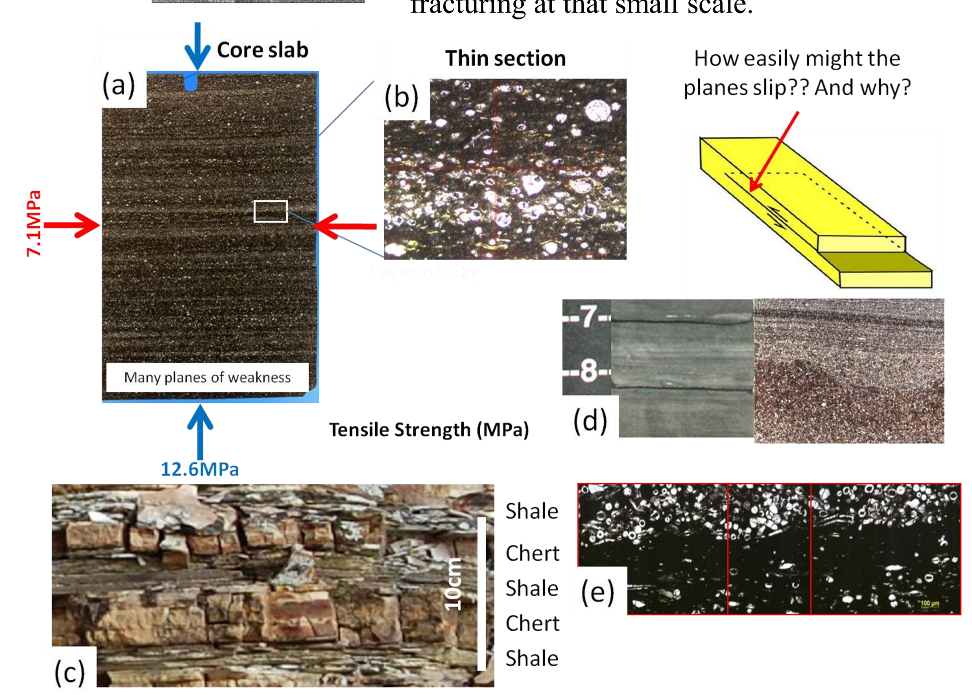


Figure 15. (a) Is a laminated shale from which tensile strength was measured in both perpendicular and parallel orientations with respect to the laminae. The tensile strength of the rock is less in the parallel (7.1 Mpa) orientation than in the perpendicular (12.6MPa) orientation, indicating the planes between the laminae are planes of weakness. Most planes of weakness are not chemically bonded between laminae, so would be expected to be susceptible to breakage along them. Such planes include those between sponge spicule-rich and clay-rich laminae (b and e) ; between brittle chert and ductile clay-shale laminae (c); and micro-scours between beds (d). Thus, there is a depositional effect on shale strength.

Figure 16. A number of different pore types have been documented by Slatt and O'Brien (in press), as summarized in this Table. The type, abundance and distribution of these pores within a resource shale will also affect rock strength.

Pore Type	Image	Distinctive Features
Porous Floccules		Clumps of electrostatically charged clay flakes arranged in edge-face or edge-edge cardhouse structure. Pores up to 10's of microns in diameter. Pores may be connected.
Organo-porosity		Pores in smooth surfaces of organic flakes or kerogen. Pore diameters are at nanometer scale. Pores are generally isolated. Porous organic coatings can also be adsorbed on clays.
Fecal Pellets		Spheres/ellipsoids with randomly oriented internal particles, giving rise to intrapellet pores. Pellets are sand-size and may be aligned into laminae.
Fossil Fragments		Porous fossil particles, including sponge spicules, radiolaria, and spores (Tasmanites?). Interior chamber may be open or filled with detrital or authigenic minerals.
Intraparticle Grains/Pores		Porous grains, such as pyrite framboids which have internal pores between micro-crystals. Grains are of secondary origin, and are usually dispersed within the shale matrix.
Microchannels and Microfractures		Linear nano-micrometer-sized openings that often cross-cuts bedding planes. Occur at nano-meter and larger scales.

Symbols used: Clay Flake; Organic; Silt grain; Fossil fragment; Gas; Gas migration; Microchannel microfracture

MERGING SEQUENCE STRATIGRAPHY AND GEOMECHANICS FOR FRACTURE CHARACTERIZATION AND PREDICTION (?)

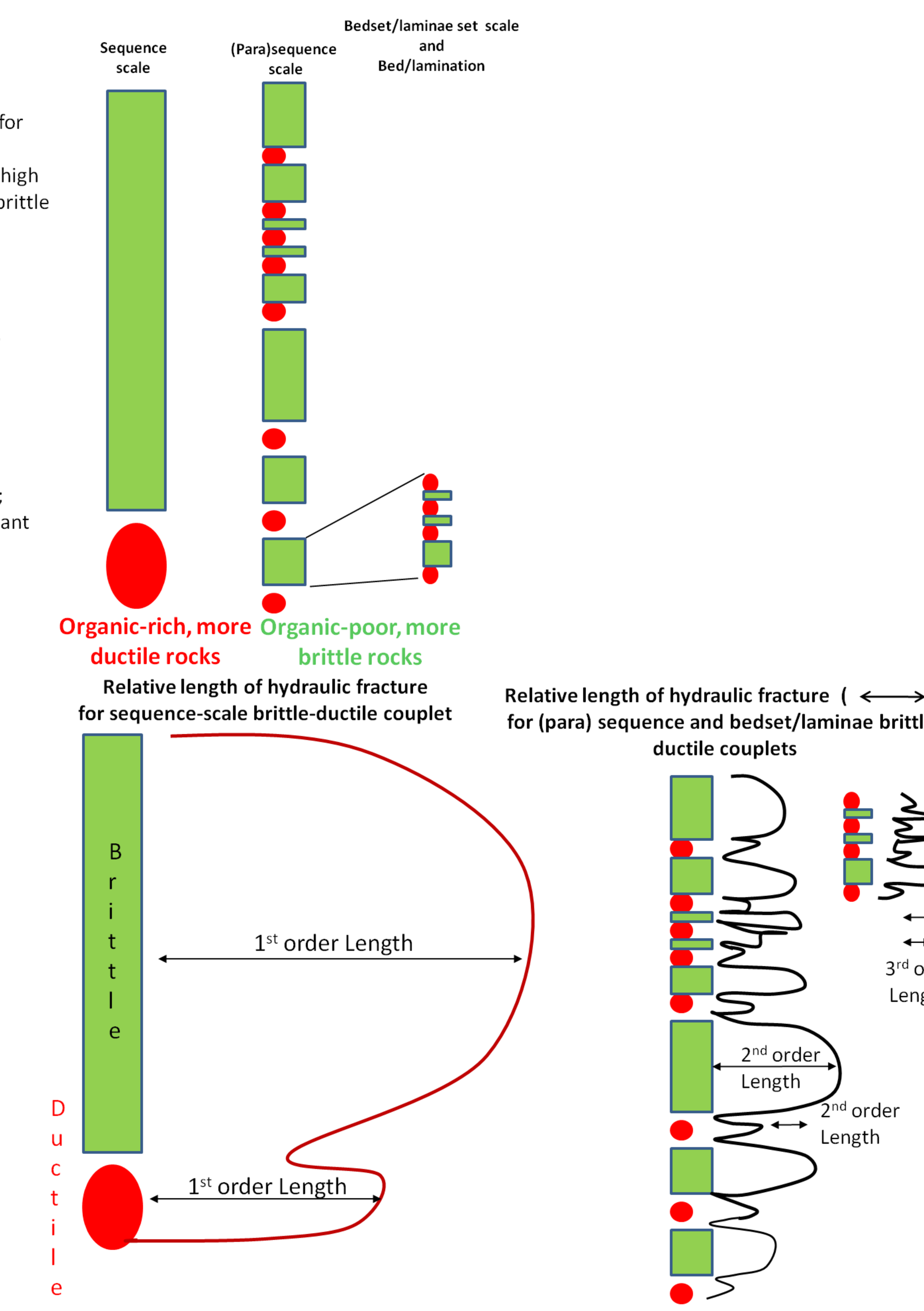
The results presented here…….

1. Depositional sequences within the resource shales exhibit a systematic, predictable stratigraphy with higher-order eustatic sea level cycles superimposed upon a lower-order cycle (usually 3rd order superimposed upon 2nd order sequences for Paleozoic shales).
2. Four predictable scales of stratification are present in the shales: (a) depositional sequence scale (10 inches -100 inches); (b) higher-frequency (para)sequences (10 inches); (c) bedsets/laminae sets (inches); (d) beds/laminations (< inch).
3. Natural fractures also occur at a variety of scales, including the sequence and (para) sequence scales, bedsets, and laminae sets.
4. In addition to mineral composition (i.e., 'silica' content, etc.), other factors that will affect fracturability include degree and scale of stratification and porosity.
5. Rocks comprising these lithologic scales can be classed as either brittle or ductile (in the relative sense).
6. Multi-scale sequence stratigraphy provides a methodology for predicting and mapping brittle and ductile zones in resource shale strata (Fig. 18).
7. Because of the different scales and types of features which affect shale fracturability, it is not surprising that artificial fracture length and orientation is more complex than standard models predict (Figs. 19 and 20).

Scales of brittle-ductile couplets:

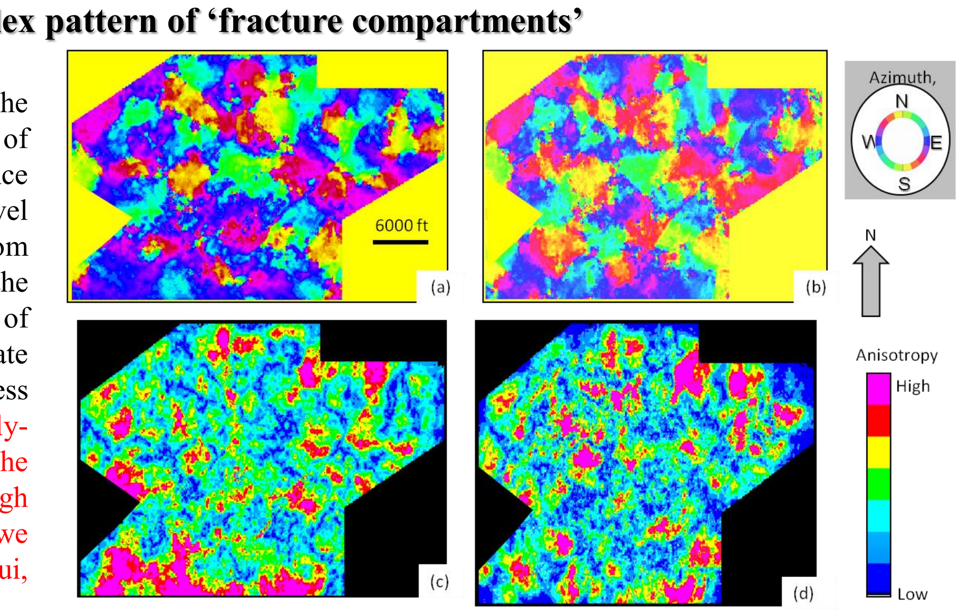
Applications:

- Sequence scale — Lower ductile interval best for horizontal well (if no water encroachment) because of high organics with interbeds of brittle rocks;
- Parasequence scale — Provides opportunities for identifying and mapping more organic-rich intervals associated with adjacent brittle rocks;
- Bedset/laminae scale — Provides intervals with interbeds of organic rich and brittle rocks for fracing; Do ductile rocks hold proppant as well as brittle rocks?? Where does proppant go??



BARNETT EXAMPLE: Post-hydraulic fracture 3D seismic survey, Barnett Shale, confirms complex pattern of 'fracture compartments'

Figure 20. Phantom horizon slices 10 ms above the Ordovician unconformity of the azimuth of anisotropy, ψ, computed from (a) acoustic impedance and (b) AVAz. Phantom horizons at the same level through the intensity of anisotropy, ε, computed from (c) acoustic impedance and (d) AVAz. Overall, the results are similar. The drilling program consisted of horizontal wells oriented NW-SE to better generate fractures parallel to the maximum horizontal stress oriented NE-SW. This image refutes this widely-accepted hydraulic fracture model and shows the fractures have widely variable orientations, though these orientations remain consistent in what we interpret to be "fracture compartments". (after Kui, 2010, OU Ph.D. dissertation).



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