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.
Selected References


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 organic-rich (TOC) and clay-mineral rich, while the latter is considered to be more enriched in “alicyclic” (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/capping” (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 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??

BARNETT EXAMPLE: POST-HYDRAULIC FRACTURE 3D SEISMIC SURVEY, BARNETT SHALE, CONTAINS COMPLEX NETWORK OF FRACTURE COMPARTMENTS

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 2nd 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 (OPs) 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 “clean” interval (Fig. 6). The 3rd order cycles consist either of an increase in carbonate at the expense of clays/or ganies, or an upward increase in clays/or ganies at the expense of carbonate (Fig. 7). At a smaller scale, there is a high degree of stratigraphic variability observable by FMI log and a lesser extent by core description (Fig. 8).

Figure 1. 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 parasequences (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 2. Barnett Shale gamma ray log highlighting an upward-increasing GRP and an upward-decreasing 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 3. 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.
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FRACATURES AND GEOMECHANICS (Continued from first panel)

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) beds/laminar sets (inches); (d) beds/laminar sets (< inch).

3. Natural fractures also occur at a variety of scales, including the sequence and (para)sequence scales, beds, 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:

- **Aperture scales**
  - Upper scale: Laminar fracture (e.g., bed fracture) (Fig. 19). The fracture offset in (b) may be due to dissipation of fracture energy through the more porous and ductile (paras)sequences than the overlying and underlying siliceous mudstone bed. The alignment of tensional fractures shown in (c) and (d) suggest a crystal structure effect on orientation of the small-scale tensional fractures. (Fig. 19).

- **Numerical scale**
  - Provides opportunities for understanding and managing more (para)sequences and their associated adjacent brittle rocks.

- **Bedform/fracture scales**
  - Brittle fracture (e.g., bed fracture) for each interval on this scale is (Fig. 19).

- **Multi-scale brittle-ductile couplet**
  - For example, the Barnett Shale, a brittle-ductile couplet (Fig. 20).

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

The results presented here...

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