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Evaluating the Impact of Mineralogy on Reservoir Quality and Completion Quality of Organic Shale Plays

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Abstract

Geochemical logs are fundamental to the evaluation of organic shale plays because they quickly provide continuous mineralogic information that enhances the petrophysical and geological evaluation of these complex reservoirs. Mineralogy impacts both reservoir quality (RQ) and completion quality (CQ), which ultimately governs unconventional well performance. *s*Core is a ternary-based classification scheme for organic mudstones (Fig. 1) that will be used in this paper to define relationships between mineralogy, RQ and CQ within various U.S. shale plays. For details on sCore please refer to the paper by Gamero et al. (2013a, 2013b).

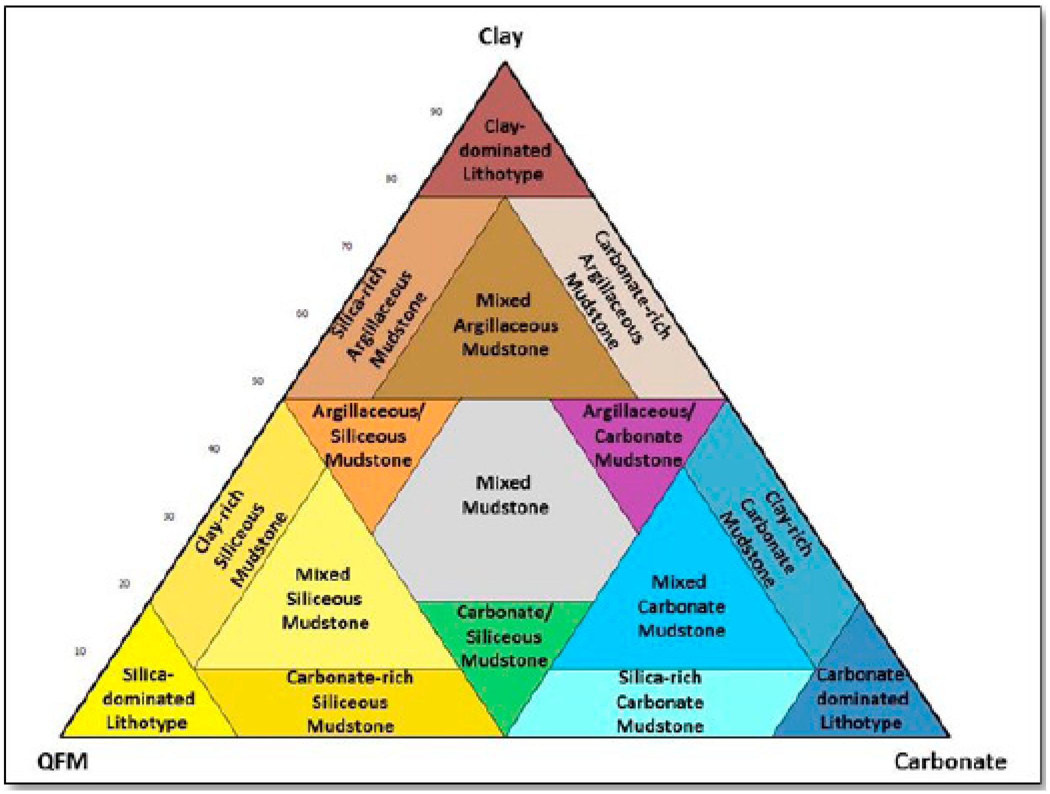
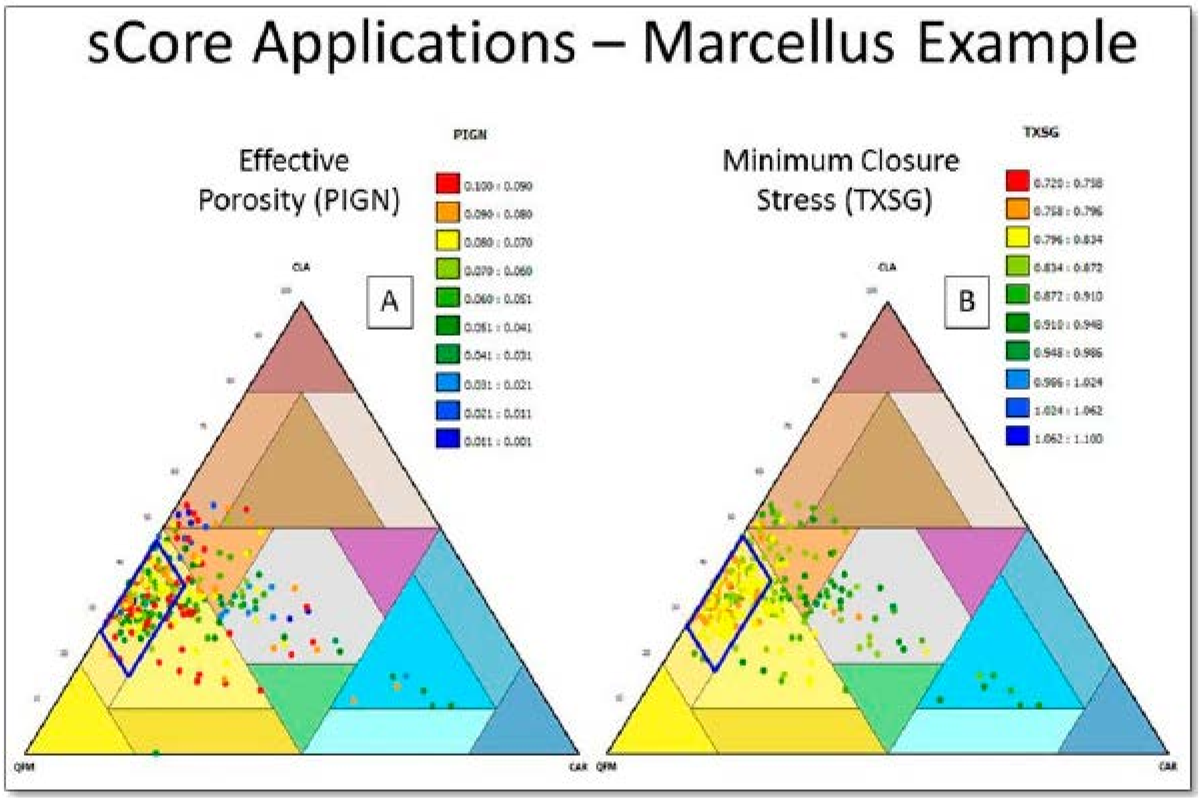


Figure 1. The sCore ternary diagram displays 16 organic mudstone lithofacies (Gamero et al, 2013). The end members represent dry-weights of the main components of organic mudstone—clay (WCLA), carbonate (WCAR) and quartz, feldspar and mica (WQFM).

Ternary plots are useful for discriminating rock types based on normalized proportions of three main end members: i) clay; ii) carbonate; and iii) quartz, feldspar, and mica. When shale RQ parameters, such as effective porosity (PIGN), total organic car-bon (TOC) content, matrix permeability, hydrocarbon saturation, etc., or CQ parameters, such as minimum closure stress, Thomsen’s gamma, etc. are plotted on an *s*Core ternary diagram, one can make observations on how mineralogy impacts RQ and CQ in a particular shale play. The identification of lithofacies having superior RQ and CQ is important information for identifying “sweet spots” and targeting both vertical and horizontal well completions. Figs. 2A and 2B illustrate how mineralogy correlates with effective porosity, and minimum closure stress in a Marcellus Shale example. There is a moderate correlation between RQ and mineralogy, and the clay-rich siliceous mudstones appear to have better reservoir quality, assuming permeability and organic parameters were also good. CQ, more specifically minimum closure stress, also has a strong correlation with mineralogy. The clay-rich siliceous mudstones appear to have the lowest stress and hence good completion quality. In this case, the high porosity and minimum closure stress regions overlap, suggesting this is an area of good RQ and CQ assuming permeability and thermal maturity are also consistent and should be targeted during drilling and completion.



Figures 2A and 2B. Relationship between mineralogy, RQ and CQ in the Marcellus Shale Play. 2A displays the relationship between mineralogy and effective porosity (PIGN), which is an indication of RQ. Hotter colors represent higher effective porosity. Facies with better RQ fall in the clay-rich siliceous mudstone area. 2B displays the relationship between mineralogy and minimum closure stress (TXSG), where hotter colors represent lower stress values and higher CQ. Facies with better CQ also fall under the clay-rich siliceous mud-stones corner (enclosed area).

In other cases, the correlation between mineralogy and RQ may not be as strong as that observed between mineralogy and CQ. RQ is a function of the original mineral composition, organic type and richness, and the effect of diagenesis and catagenesis (thermal maturation) processes; resulting in highly heterogeneous mudstones with variable properties in both the vertical and horizontal directions. RQ, as determined by other data types, can be compared to the sCore ternary to aid in interpretation of sediment source and sequence stratigraphy. Converting the sCore ternary to a vertical stratigraphic plot allows sCore data to be compared with spectral gamma ray, effective porosity and continuous inorganic geochemistry so that sedimentologic and diagenetic components of the matrix can be resolved (Fig. 3). In other words how much of the Quartz-Feldspar-Mica (QFM) component is in the matrix occur as detrital vs. biogenic grains floating in the matrix will affect RQ and CQ. Unfortunately, interpreting textural information for organic mudstones from our current logging suite is extremely complex and challenging. Therefore, it is a challenge to scale textural and mineralogical variations observed in thin sections to wireline interpretations. However, plotting PIGN, on top of the ternary plot can be used as an indirect proxy for textural and digenetic variations of organic mudstones.

In addition, sCore can be plotted alongside wireline logs to help elucidate depositional and diagenetic components of the mudstones as well as the recognition of significant surfaces in sequence stratigraphy (Fig 3). Flooding events (red arrow, cyan blue horizontal lines) record strata deposited in deeper water, dominated by pelagic deposition, with high organic con-tent and high kerogen-hosted porosity. The blue arrow shows increasing terrigenous or transported material, evidenced by a reduction in organic content and kerogen-hosted porosity, capped by cemented zones with no preservation of organic matter and no porosity. The cemented zones and concretions bed can be identified because they are highly resistive and appear as white colors in high resolution borehole images. Additionally, the sCore display shows rocks with similar composition (siliceous mudstones, orange color with pattern) and different reservoir properties reflecting subtle changes in texture and more importantly diagenetic/catagenetic effects on rock properties. Milliken et al. (2012) found that diagenesis had a profound effect on RQ in a study of the Barnett Shale, rather than variations in primary textures and composition.

Geochemical data may also provide information about the source of minerals within a mudstone and can complement sCore as well as other log responses (Bohacs, 1998; Wright et al., 2010). Ratios like Si/Ti (silica / titanium) might provide information regarding the origin of the silica, indicating if it is biogenic, authigenic or detrital. High Si/Ti ratio may imply higher abundance of biogenic silica. Other ratios like Th/U, K/U and U are good indicators of terrigenous influence and paleo-redox conditions (last three tracks in Fig. 3). In organic mud-stones uranium (U) is associated to organic matter and phosphates, thorium (Th) to ash beds and heavy minerals and potassium (K) to clays and potassium feldspars (Bohacs et al., 1998).

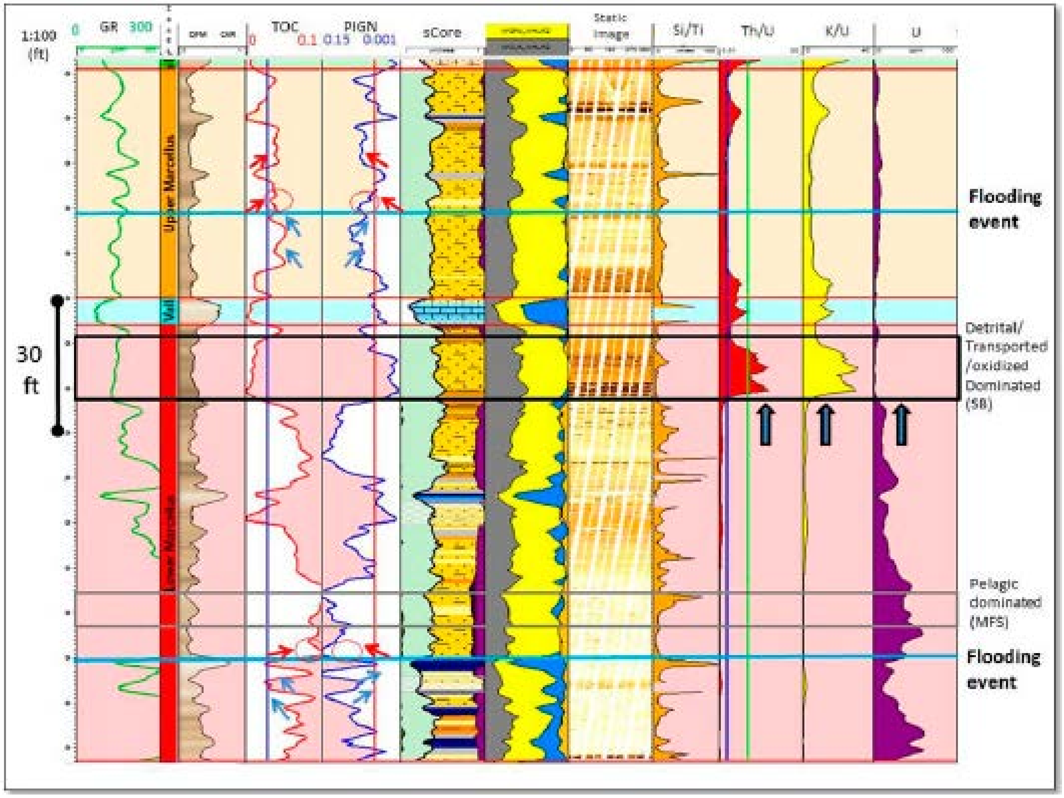
The typical observations that one would make to determine the environment of deposition and recognition of important surfaces in sequence stratigraphy are shown in the following table 1:

Environment	Si/Ti	Th/U, K/U	U	PIG N	TXS G
Pelagic	High	Low	High	High	Low
Terrigeneous/	Low	High	Low	Low	High

More importantly, Adams and Weaver (1985) and Dolenec (2005) indicated that the Th/U ratio will suggest paleoredox conditions. It was found that during full anoxic conditions the Th/U ratio will be under 2, dysoxic conditions the Th/U ratio will be between 2 and 7, and fully oxic conditions the ratio will over 7, as indicated in the following table 2.

Environment	Paleoredox
Anoxic conditions	Th/U < 2
Dysoxic marine	2 > Th/U > 7
Oxic marine	Th/U > 7

The shape of the Th/U curve in combination with the U curve (Fig. 3) in the Marcellus example indicate a rapid change on the redox conditions resulting in oxygen-rich conditions (black arrow). This may indicate a possible change in the source and a possible sequence boundary. This exercise has been applied successfully to multiple shales.



Figures 3. An example of the vertical sCore ternary converted into a vertical stratigraphic section. Track 1: depth, 30ft for scale. Track2: spectral gamma ray in API units (0-300). Track 3: Marcellus Shale zones. Track 4: changes in the proportion of QFM and CAR and the brown shading represent the clay content (dark colors implies high clay content and light colors low clay content. Track 5: total organic carbon (TOC) in, the blue vertical line represents a TOC value of 0.02 Track 6: effective porosity (PIGN) in ft3/ft3, the red vertical line represents a PIGN value of 0.04. Track 7: sCore display. Track 8: geochemical log processing results displayed as normalized total clay (in gray), QFM (yellow), CAR (blue) and pyrite (orange). Track 9: static normalized electrical image. Tracks: 10, 11, 12 and 13 shows inorganic geochemical ratios (Si/Ti, Th/U, K/U and U). Track 11: Th/U ratio, two vertical lines represents a Th/U value of 2 (blue) and a Th/U value of 7 (green). Cyan blue horizontal lines represent flooding surfaces identified as an increase in TOC and PIGN just above a carbonate bed or carbonate concretions. The blue and red arrows represent progradation and transgression, respectively. Gray box (lower) shows a siliceous mudstone with high PIGN and TOC that may be pelagic in origin. Black box (upper) shows siliceous mudstones with low TOC and PIGN that may be detrital or transported dominated.

A strong correlation exists between mineralogy and CQ in most U.S. shale plays. Figure 4 depicts the strong correlation between mineralogy and minimum closure stress. In the Wolfcamp example the minimum closure stress changes as a function of clay volume. Waters et al. (2011) indicates that most of the U.S. Basins are within an extensional tectonic set-ting so that in situ stress will vary as a function of clay content. This high stress state diminishes CQ, particularly with respect to hydraulic fracture initiation and proppant embedment. CQ in most U.S shale plays appears to be driven by the mineralogy of organic mudstones. By combining sCore with geochemical parameters and wireline measurements, lithologic differences begin to emerge between mineralogically similar strata. This enables us to identify stratigraphic areas of interest as well as shales of superior CQ and RQ.

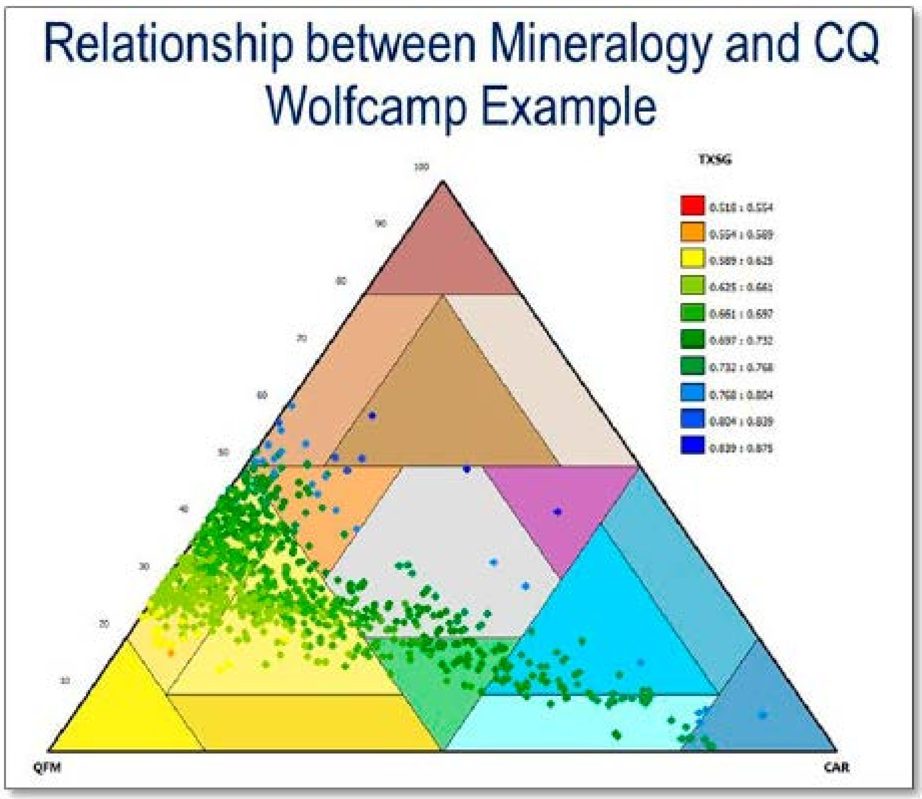


Figure 4. This Wolfcamp example shows a good correlation between mineralogy/composition and CQ. Minimum closure stress (TXSG) is driven by clay and carbonate content.