Sequence Stratigraphy Manifested in Source and Reservoir Properties of Shale Successions – Examples from the Middle Devonian Marcellus Formation, Appalachian Basin

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Introduction

Most shale gas reservoir properties reflect a history of base level fluctuations that can be cast in terms of a predictive sequence stratigraphic famework. Indeed, Partington et al. (1993) and Emery and Myers (1996), among others, have demonstrated the utility of some of the more common wireline log suites to the interpretation of sedimentary successions in terms of such sequence stratigraphic elements as sequence boundaries, systems tracts, condensed sections, and maximum flooding surfaces. Such an approach serves as a means by which basin fill can be organized into unconformity (or equivalent conformable surface) bounded packages of strata that provide a framework for predictive reservoir assessment and correlation into regions of minimal or poor data control. Ongoing sequence stratigraphic investigations of the Middle and Upper Devonian shale succession of the Appalachian Basin involving field and subsurface study, including the collection of XRF, XRD, and organic geochemical data, reveal a robust link between base level history and various reservoir and source rock properties. This talk draws upon our present understanding of the sequence stratigraphy of the Middle Devonian Marcellus Formation of the Appalachian Basin. Emphasis is placed on vertical changes in those compositional attributes that affect shale reservoir quality. However, we also recognize that the impress of sequence stratigraphy can be recognized in trace element chemostratigraphy and perhaps even thermal maturity indices, including Rock-Eval parameters and %Ro.

Sequence Stratigraphic Paradigm

Our approach to the sequence stratigraphy of the Devonian gas shale succession of the Appalachian Basin is grounded in the transgressive-regressive (T-R) sequence concept, outlined by Embry and Johannessen (1992) and further refined by Embry (2002). Indeed, Johnson et al. (1985) first applied the T-R sequence concept to the Devonan succession of the Appalachian Basin a quarter of a century ago. A T-R sequence comprises a transgressive systems tract, a deepening-up succession that records rising base level, overlain by regressive systems tract deposits that accumulated during falling base level and consequent reduced accommodation space (Embry and Johannessen, 1992; Embry, 2002). Delimiting T-R sequences requires the identification of minimally diachronous sequence boundary surfaces (Embry, 2002).

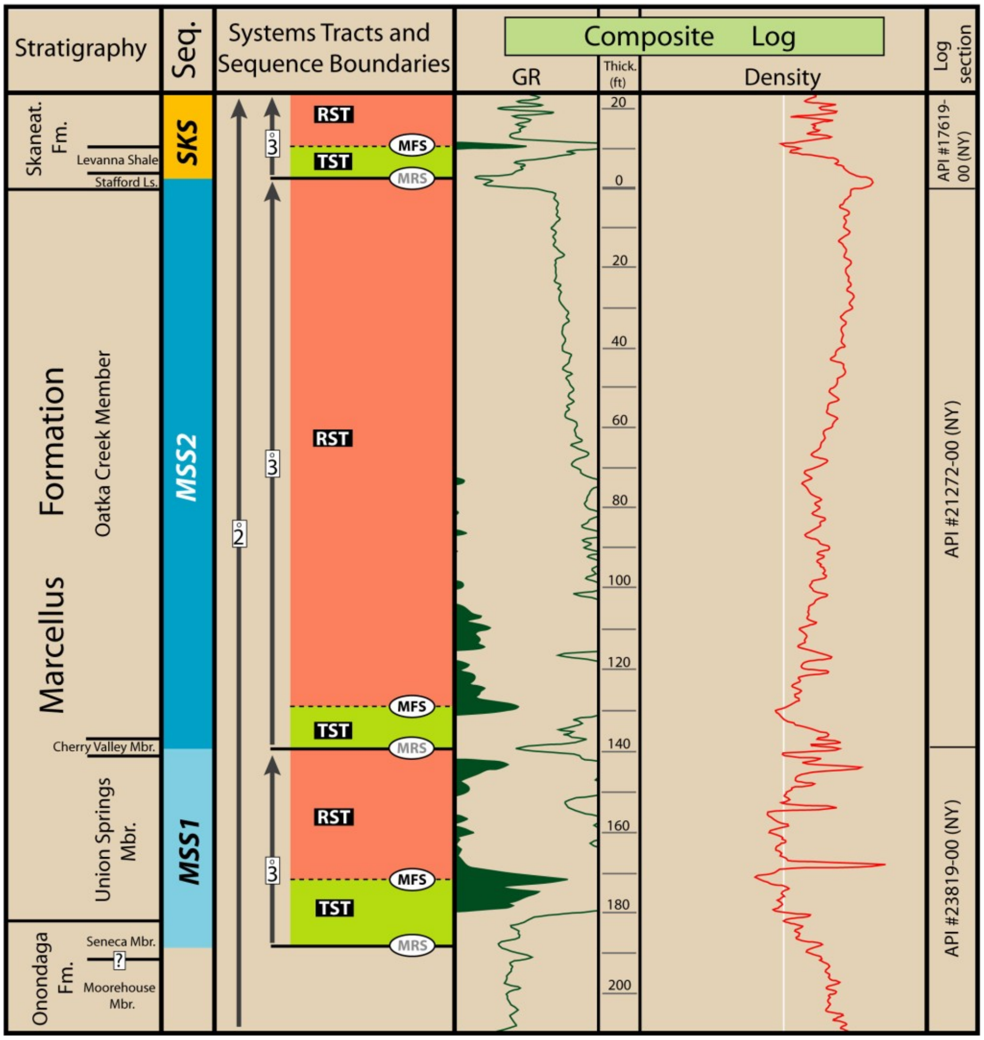

Figure 1: Sequence stratigraphic "type section" of the Marcellus Formation that encompasses the upper part of the underlying Onondaga Formation and the lower interval of the Skaneateles Formation; TST = transgressive systems tract; RST = regressive systems tract; mfs = maximum flooding surface; mrs = maximum regressive surface (refer to Lash and Engelder (2011) for discussion).

Those surface most conducive to defining T-R sequences include the subaerial unconformity, the unconformable shoreline ravinement, and the maximum regressive surface (Embry, 2002). A single T-R sequence comprises transgressive systems tract deposits overlain by a regressive systems tract succession, the contact being a maximum flooding surface; the sequence is bounded on top and bottom by maximum regressive surfaces (MRS) or equivalent ravinement surfaces.

Discussion

The Marcellus Formation encompasses the bulk of two T-R sequences herein referred to as MSS1 and MSS2, in ascending order (Fig. 1). These sequences, approximate equivalents of Johnson et al.'s (1985) T-R Cycles Id and Ie and Ver Straeten's (2007) Eif-2 and Eif-3 sequences, span ~1.8 MY, extending from the upper *costatus* conodont zone through the *hemiansat.* zone (Kaufmann, 2006; Ver Straeten, 2007). The relatively short duration of MSS1 and MSS2 is consistent with their reflecting third-order base level cycles that occurred within a second order cycle encompassing much of the Middle and part of the Upper Devonian succession. Details of the sequence stratigraphy of the Marcellus Formation can be found in Lash and Engelder (2011). The top of the MSS1 transgressive systems tract, the maximum flooding surface, is placed at a gamma-ray peak a short distance above the maximum regressive surface that defines the base of the sequence (Fig. 1). The maximum flooding surface is roughly coincident with a condensed section defined by abundant pyrite and thin carbonate layers, both evident in bulk density and photoelectric index wireline logs as well as in core. XRD analysis of a suite of sidewall core samples recovered from MSS1 transgressive systems tract deposits reveals an abundance of quartz well in excess of that observed in overlying regressive systems tract deposits (Fig. 2). Elevated abundances of quartz are also revealed by increasing Si/Al ratios based on XRF analysis of Marcellus transgressive systems tract deposits. Similarly, XRD data illustrates a markedly reduced clay content in the Si-rich transgressive systems tract deposit (Fig. 2), likely a reflection of the rapid landward shift of marine environments at this time. Thin section and scanning electron microscopic examination reveals that the bulk of the quartz in the MSS1 transgressive systems tract/condensed section is microcrystalline, likely derived from the dissolution of silica tests (e.g., Schieber et al., 2000). Much of the quartz lines pore throats or forms irregular microcrystalline aggregates that coat detrital clay grains (Fig. 3). Occasional angular detrital quartz and feldspar grains are probably windblown detritus. Occasional excursions in Ti/Al probably record an eolian contribution. Calcite is as much as three-times as abundant in transgressive systems tract deposits as in the overlying regressive systems tract (Fig. 2). Most calcite occurs as single crystals or patches of microspar and microcrystalline aggregates that originated from styliolinid fragments.

Peaks in pyrite and TOC are coincident with the inferred maximum flooding surface (Fig. 2). It was at this time that conditions conducive to the preservation of organic matter, perhaps fully euxinic bottom conditions related to salinity/density stratification of the water column (e.g., Ettensohn and Elam, 1985; Werne et al., 2002), were established. Alternatively, the relatively rapid rate of sedimentation during Marcellus time, perhaps enhanced by a basin shallower than generally presumed, may have combined to diminish the rate of oxidation of organic matter in the water column. Pyrite occurs as euhedral crystallites and framboids, most less than 5 µm in diameter. Locally, framboids comprise polyframboidal masses, which preserves some degree of porosity (Fig. 4). Organic matter, most abundant close to the maximum flooding surface (Fig. 2), is an important component of these deposits beyond its role as a source of hydrocarbons. At low thermal maturity, perhaps to a maximum level of $\%R_o \approx 1.0$, organic grains illustrate a very ductile behavior that, during burial-related compression occluded pore throats resulting in reduced porosity and permeability of organic-rich intervals (Fig. 5). Indeed, heavily bioturbated organic-lean gray shale is normally more porous (Fig. 5) and, judging from dated obtained by mercury injection capillary pressure analysis, much more permeable (e.g., 0.00028 md versus 0.00528 md). At higher levels of thermal stress ($\%Ro > \approx 1.1$), however, organic matter illustrates the development of nanoporosity thereby enhancing the gas storage potential of the most organic-rich interval of the succession (e.g., Loucks et al., 2009). Data from several thermally

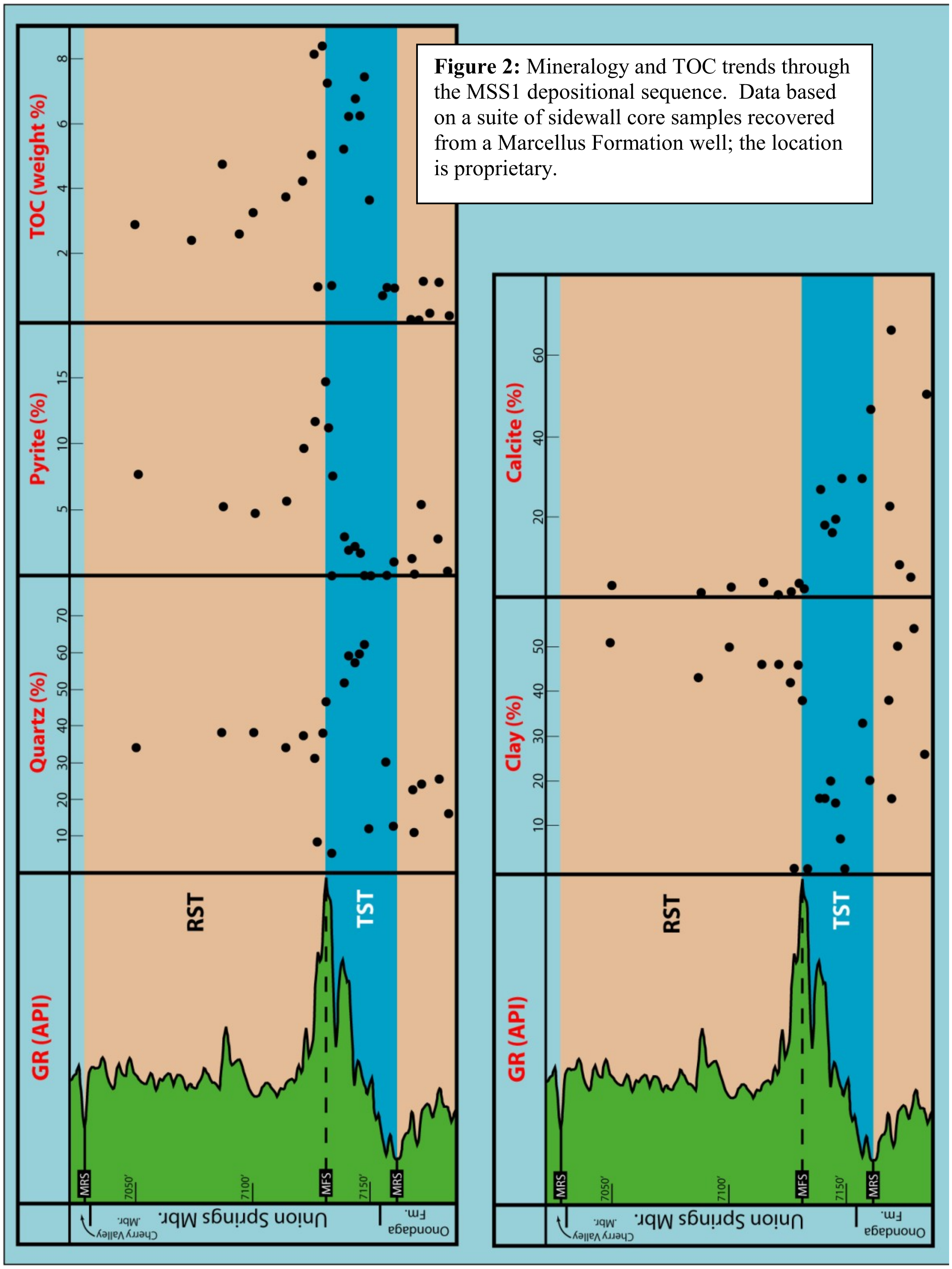

Figure 2: Mineralogy and TOC trends through the MSS1 depositional sequence. Data based on a suite of sidewall core samples recovered from a Marcellus Formation well; the location is proprietary.

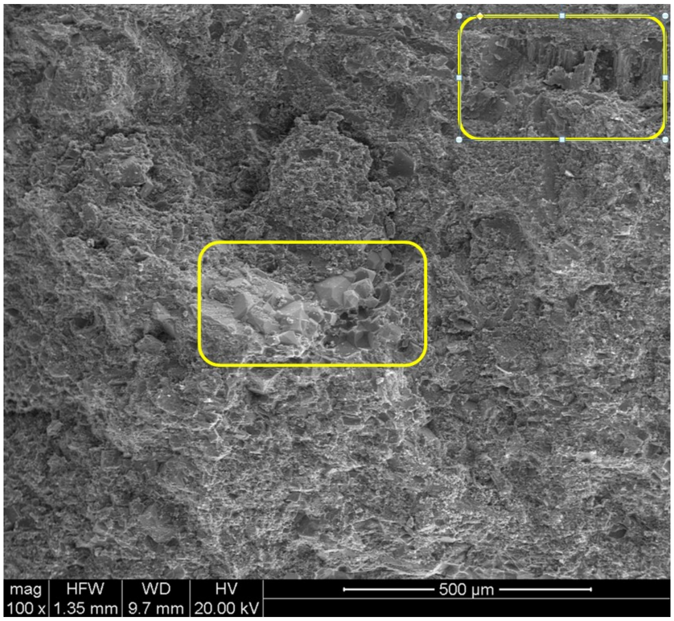

Figure 3: SEM image of a transgressive systems track sample from the Marcellus Formation. Note the general lack of a shale microfabric. Yellow rectangles denote masses of diagenetic quartz.

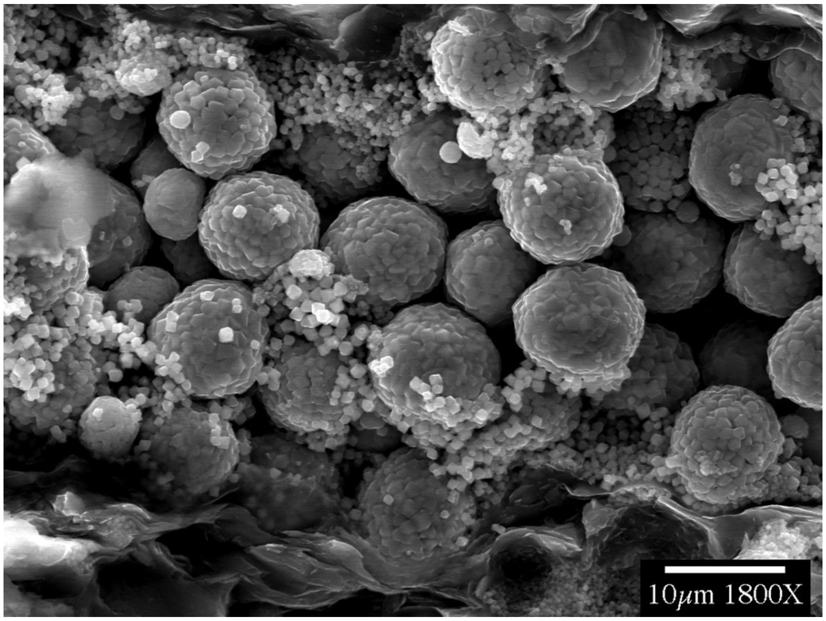

Figure 4: SEM image of a polyframboid in a sample collected from the top of a transgressive systems tract sequence, Marcellus Formation.

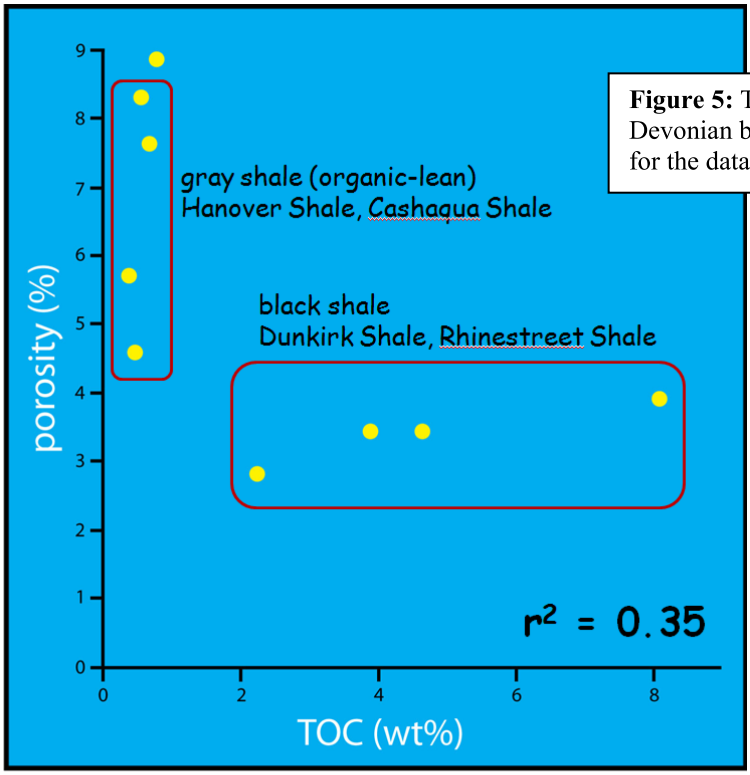

Figure 5: TOC vs. porosity data for Upper Devonian black and gray shale samples. %Ro for the dataset ranges from 0.64-0.82%.

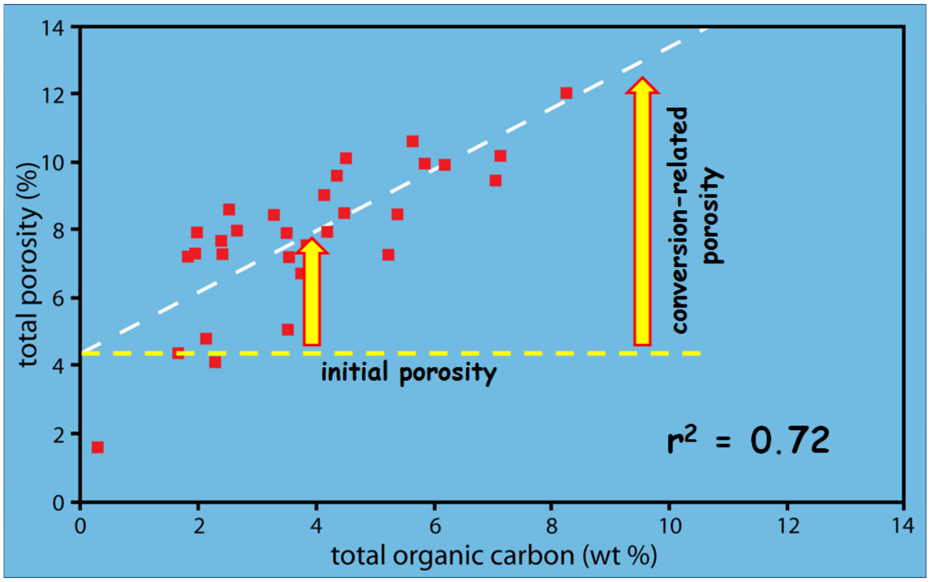

Figure 6: TOC vs. porosity data for a Marcellus Formation data set. %Ro for the dataset >2.0%.

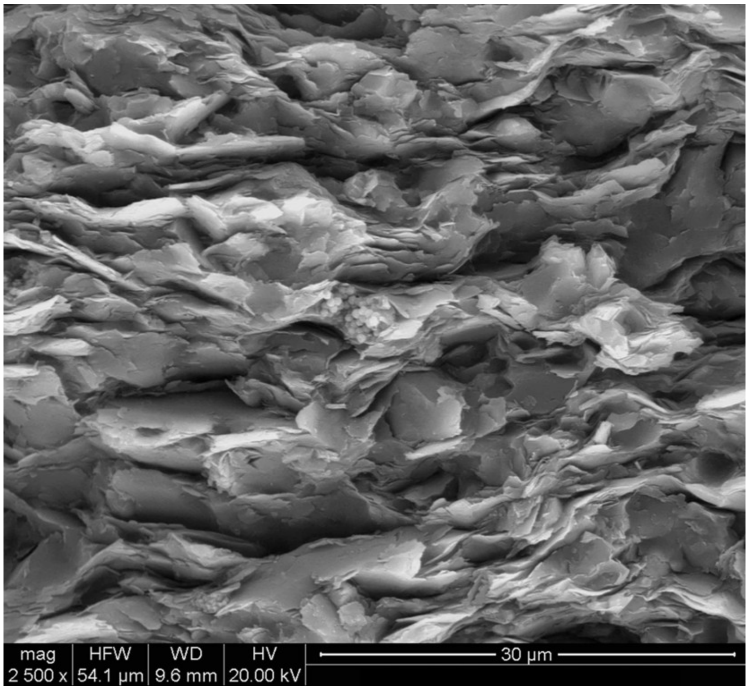

Figure 7: SEM image of a clay-rich regressive systems tract sample from the Marcellus Formation illustrating a strongly oriented clay grain microfabric.

mature (dry gas window) Marcellus wells (Fig. 6) show a strong correlation between porosity and TOC, seemingly confirming an increase in porosity as a consequence of catagenesis. Thus, assuming that thermal maturity has attained a certain threshold level ($\%R_o>\approx1.1$, depending on organic matter kinetics), transgressive systems tract/condensed interval deposits, in addition to being organic-rich, may also have an especially high natural gas storage potential.

Overlying regressive systems tract deposits record the reduction of base level and/or increased clastic flux relative to base level rise (Fig. 1). These deposits display a gradual increase in bulk density and reduced gamma-ray response (Fig. 1) reflecting reduced organic carbon and increasing clay content (Fig. 2). Such a behavior is also revealed by XRF data as marked increases in Al% and K% as well as elevated Th/U ratios on spectral gamma-ray logs. Diminished total quartz (Fig. 2) probably records dilution of the biogenic contribution by increasing amounts of clastic detritus, principally clay, as nearshore environments were displaced seaward and accommodation space diminished. The increased abundance of clay, principally illite, in the case of the Marcellus Formation, is accompanied by a more frequent occurrence of a strongly aligned clay grain fabric that imparts a strength anisotropy to the rock (Fig. 7). Further, the increased clay content of regressive systems tract deposits can also result in greater amounts of bound water, which has been recognized in laterologs.

Conclusions

The Marcellus Formation sequence stratigraphy offers a predictive framework for reservoir assessment that can be extrapolated into areas of poor data control. Compositional attributes that influence such critical reservoir properties as porosity and brittleness, including quartz, carbonate, clay, and pyrite, vary predictably as a consequence of base level oscillations. The sequence stratigraphic framework of the Marcellus Formation presented in this study demonstrates that transgressive systems tract and early regressive systems tract deposits comprise the greatest abundance of malleable organic matter. At the same time, however, these deposits also contain relatively abundant amounts of those components that enhance the brittleness of these deposits, including quartz, calcite and pyrite. Further, whereas organic matter appears to reduce porosity and permeability in those organic-rich deposits that have been subjected to thermal stress levels as high as the bottom of the oil window, rocks that have attained the dry gas window display increased porosity in the most organic-rich intervals as a consequence of generation-induced nanoporosity. There is no doubt that considerations of the sequence stratigraphic signature on seemingly monotonous shale successions should be a major component of any exploration/production program.

References

Embry, A., 2002, Transgressive-regressive (T-R) sequence stratigraphy, *in* J. Armentrout and N. Rosen, eds., Gulf Coast SEPM Conference Proceedings, Houston, 151-172.

Embry, A., and E. Johannessen, 1992, T-R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada, *in* T. Vorren et al., eds., Arctic geology and petroleum potential: Norwegian Petroleum Society Special Publication 2, 121-146.

Emery, D., and K.J. Myers, 1996, Sequence stratigraphy: Blackwell Science, Oxford, 297 p.

Ettensohn, F.R., and T.D. Elam, 1985, Defining the nature and location of a Late Devonian-Early Mississippian pycnocline in eastern Kentucky: Geological Society of America Bulletin, 96, 1313-1321.

Johnson, J. G., G. Klapper, and C.A. Sandberg, 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America Bulletin, 96, 567-587.

Kaufmann, B., 2006, Calibrating the Devonian time scale: a synthesis of U-Pb ID-TIMS ages and conodont stratigraphy: Earth-Science Reviews, 75, 175-190.

Loucks, R.G., Reed, R.M., Ruppel, S.C., and Jarvie, D.M., 2009, Moprhology, genesis, and distribution of nanometer-scale pores in siliceous mudstones of the Mississippian Barnett Shale: Journal of Sedimentary Research, 79, 848-861.

Partington, M. A., B.C. Mitchener, N.J. Milton, and A.J. Fraser, 1993, Genetic sequence stratigraphy for the North Sea Late Jurassic and Early Cretaceous: distribution and prediction of Kimmeridgian — Late Ryazanian reservoirs in the North Sea and adjacent areas, *in* J.R. Parker, ed., Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference: Geological Society of London, 347–370.

Schieber, J., Krinsley, D., and Riciputi, L., 2000, Diagenetic origin of quartz silt in mudstones and implications for silica cycling: Nature, 406, 981-985.

Ver Straeten, C.A., 2007, Basinwide stratigraphic synthesis and sequence stratigraphy, upper Pragian, Emsian and Eifelian stages (Lower to Middle Devonian), Appalachian Basin, *in* R.T. Becker W.T. Kirchgasser, eds., Devonian events and correlations: Geological Society, London, Special Publications, 278, 39-81.

Werne, J.P., B.B. Sageman, T.W. Lyons, and D.J. Hollander, 2002, An integrated assessment of a" type euxinic" deposit: evidence for multiple controls on black shale deposition in the middle Devonian Oatka Creek formation: American Journal of Science**,** 302, 110-143.