Concepts and Methods for the Recognition of Cyclicity in the Middle Devonian Marcellus Shale*

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Abstract

The Marcellus Shale in the Appalachian Basin of the Northeastern United States is part of the Devonian black shale of the Hamilton Group. It is one of the leading gas producing formations in the United States and the prospective play area extends from New York through Pennsylvania into West Virginia and Ohio. However, as this resource play becomes more important, it is clear that there are currently no good methodologies for establishing sequence stratigraphic frameworks in the very fine- to fine-grained mudrocks dominated successions that characterize this play. This is due to the fact that previous attempts to develop good sequence stratigraphic frameworks for the Marcellus Shale (e.g. Lash and Engelder, 2011) have been based on a depositional model that is patterned after the Black Sea depositional model for black shale sedimentation. Such an approach leads to the conclusion that the organic-rich facies of the Marcellus Shale were deposited in permanently anoxic deep basin environments. Recent work discussed in this study, as well as those carried out by others (e.g. Smith and Leone, 2010 and Andrew and Macquaker (2011) suggest, however, that the Marcellus Shale facies may have been deposited in relatively shallower water under more dynamic seafloor conditions than the conventional black shale depositional models suggest. While some of the Marcellus Shale lithofacies may have been deposited by suspension settling out of low-energy buoyant plumes, others were most likely deposited by sediment dispersal mechanisms that involved a combination of storm-winnowing and re-suspension, gravity-driven processes and unidirectional currents in a bathymetrically subdued setting similar to modern day continental shelves. Key controls on black shale sedimentation in such settings would be a combination of changes in salinity, nutrient sourcing of algal blooms, substrate and clastic influx rates, rather than water depth. Given a depositional model that is not driven primarily by sea-level fluctuations, some concepts and methods for defining cyclicity are discussed in this study.

General Stratigraphy of the Marcellus Formation

The Middle Devonian Marcellus Shale is the basal unit of the Hamilton Group in the Appalachian Basin. Throughout much of the basin, the Marcellus Formation consists of two black shale intervals, separated by a sequence of limestone, shale and lesser sandstone of variable thickness (de Witt et al., 1993). It is an organic-rich shale that lies nearly a mile (1.5 km) beneath the surface with thicknesses up to 900 feet (274 m) in places (Lash and Engelder, 2011). It is usually sub-divided into three members: the Union Springs Member, the Cherry Valley Member and the Oatka Creek Member (Lash and Engelder, 2011) in a stratigraphic model that regards the Cherry Valley Limestone Member as the lateral equivalent of the Purcell Limestone. However, authors such as de Witt et al. (1993) suggested that the Purcell Limestone should be regarded as a different limestone unit within the Marcellus Formation. Stratigraphic and sedimentologic evidence from the data used in this study also suggest that the Purcell Limestone is a different and younger stratigraphic unit than the Cherry Valley Limestone. In this study, the two Marcellus Shale members were, therefore, separated in a revised stratigraphic section.

The Union Springs Member is the organic-rich black shale that overlies the Onondaga Limestone with which it has either a gradational and/or sharp basal contact. It is the basal unit of the Marcellus Formation and is overlain by the Cherry Valley Member, which is composed of variable amounts of interlayered carbonate, shale and sandstone. The Cherry Valley Member is overlain by the Oatka Creek Member, which is a succession of black and gray shale, lesser siltstones, and limestone that underlies the Stafford and Mottville members of the Skaneateles Formation. The Purcell Limestone Member is composed of a grey silty shale and mudrock, as well as some beds of siltstone, an abundance of limestone nodules, and a scattering of barite nodules about 1 to 2 inches (2 to 5 m) in diameter (de Witt et al., 1993). It separates the black shale successions of the Lower Oatka Creek Member from the grey shale successions of the Upper Oatka Creek Member. In some parts of the basin, the Purcell Limestone and the Cherry Valley Limestone are either too thin or altogether absent.

Recognition of Cyclicity

Proper recognition of cyclicity can enhance our ability to predict the deposition or non-deposition of organic-rich mudrocks lithofacies in the Marcellus Shale succession. By integrating sedimentologic and stratigraphic information with geochemical and mineralogical data, proxies for determining organic richness and delineating stratigraphic sequences and their component systems tracts can be identified (Figure 1). Sedimentologic, stratigraphic and geochemical proxies have been used in the past by many authors, including Creaney and Passey (1993) and Singh et al. (2008) to carry out sequence stratigraphic interpretations in organic-rich shale sequences. When these proxies are integrated with appropriately-scaled electrical wireline logs (Figure 2) and detailed geologic description of core data (Figure 3) they can be used to produce sequence stratigraphy type sections that can be used for basinwide correlations to develop a sequence stratigraphic framework for the Marcellus Shale (Figure 4).

The data used in this study include over 100 thin sections, scanning electron microscopy (SEM) and x-ray diffraction (XRD) analyses of 100 samples from over 1000 feet of core from eight regionally distributed wells, information from field studies of Marcellus Shale exposures in 12 locations in New York and Pennsylvania, as well as more than 800 electrical wireline logs. To avoid using conventional sequence stratigraphic terms that suggest eustatic fluctuations as the primary control on black shale deposition, new terms were introduced to mark the deposition or non-deposition of organic matter-rich mudrocks and to describe important surfaces or boundaries that define cycles/sequences and the systems tracts they contain. These terms are: (1) Preservation Shutdown Surface - PSS, (2) Preservation Initiation Surface - PIS, (3) Maximum Preservation Surface - MPS, (4) Shutdown Systems Tract - SST, (5) Initiation Systems Tract – IST, and (6) Preservation Systems Tract - PST. These terms are similar, but not the same as the conventional terms used in depositional sequences to describe important sequence stratigraphic surfaces and systems tracts. The first three terms describe stratigraphic surfaces in organic-rich mudrocks and are similar to the surfaces used in depositional sequence, i.e. sequence boundaries, transgressive surface and maximum flooding surface, respectively. The last three terms describe the systems tracts that are contained by these surfaces and are also similar to lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST), respectively.

The preservation shutdown surface (PSS) is the surface at or zone within which the rate of production and/or preservation of organic matter reduce drastically or organic matter production and preservation ceases altogether, resulting in low total organic carbon content of the sediments immediately above this surface. In the Marcellus Shale, this surface is characterized by the deposition of widespread and thin calcareous intervals with high diversity faunas dominated by filter feeders and micro-carnivores laid down during times of low sediment supply rates and during periods of low re-suspension. The surface can be identified by minimum or low gamma radioactivity (<120 API), low TOC (<1%), high density (>=2.6 gcc), lower neutron porosity (<=0.15 v/v), dramatically increased calcite content, reduced quartz and pyrite content as well as increased clay content (Figure 1 and Figure 4). The sediments deposited above the preservation shutdown surface are referred to as the shutdown systems tract (SST) and are capped by the preservation initiation surface. The preservation initiation surface (PIS) marks the onset or the reestablishment of organic-rich mudrock deposition as a result of the rejuvenation of sediment input due to tectonics, climate change and/or algal bloom resulting from increased nutrient influx. In the Marcellus Shale, the surface also coincides with a modest rise in base level as a result of increased subsidence/uplift. It can be identified by an increase in gamma radioactivity (>120 API), increased TOC (>2%), lower density (<=2.55 gcc), decreasing calcite content, increased quartz and pyrite content as well as reduced clay content (Figure 1 and Figure 4). In the Marcellus Formation, the PIS is usually followed by the deposition of laminated organic-rich non-calcareous mudstone, pyritic non-calcareous mudstone and siliceous mudstone sediments as well as carbonate concretions of varying sizes. These sediments are referred to as initiation systems tract (IST) and are capped by the maximum preservation surface (MPS). The Maximum Preservation Surface (MPS) marks the highest level of organic matter production, preservation and least clastic dilution (sediment starvation) in a given depositional cycle. Thus, it is characterized by high TOC, high pyrite content, thin carbonate concretion layers and the deposition of virtually barren non-calcareous to very mildly calcareous, black laminated organic-rich mudrock under widespread euxinic conditions in relatively shallow water. This surface is essentially related to the period of highest level of seasonal anoxia coincidental with the period of highest base level rise due to subsidence/uplift and maximum sediment starvation. The sediments deposited above this surface are regarded as the preservation systems tract (PST) and they are capped by the preservation shutdown surface of the next cycle. The MPS may or may not be a condensed section depending on its location within the basin. PST sediments usually comprise a series of upward coarsening packages similar to Singh et al.'s (2008) upward decreasing gamma ray parasequence (Figure 3).

Conclusion

In all, four cycles were recognized from the Selinsgrove Member of the Onondaga Limestone to the base of the Stafford Limestone Member below the Mahantango Shale (Figure 4). These cycles are referred to as Marcellus Cycle 1, Marcellus Cycle 2, Marcellus Cycle 3 and Marcellus Cycle 4 respectively (i.e. MC1, MC2, MC3 and MC4), with MC1 being the oldest cycle and MC4 representing the youngest cycle. MC1 and MC2 are highly organic-rich and show varying thicknesses across the basin. These variations are interpreted to be due to localized erosional activities or non-deposition in topographically high areas. MC1 and MC2 are separated by the Cherry Valley Limestone, which has a variable thickness over much of the basin. MC3 and MC4 on their own part are not as organic rich and may be composed of only negligible thicknesses of IST or PST deposits over parts of the basin. MC2 and MC3 are separated by usually thin (1 to 2 feet thick) bioturbated dolomitic mudstone and wackestone with abundant colonies of diminutive organisms, brachiopods, pelecypods and some other undifferentiated bivalves. MC1 approximates equivalents of cycle 1c and the middle part of cycle 1d, MC1 and MC2 fall within the upper part of cycle 1d while MC4 approximates the lower part of cycle 1e of Johnson et al.'s (1985) transgressive-regressive (T-R) cycles. The four cycles recognized in this study are based on a depositional model that is not primarily driven by sea-level fluctuations and, with limited age-datable fossils, it is difficult to establish an absolute age-based, high resolution chronostratigraphic framework for the cycles. This work shows that it is possible to define cyclicity in organic matter-rich mudrock-dominated successions without bias towards the deep basin depositional model.

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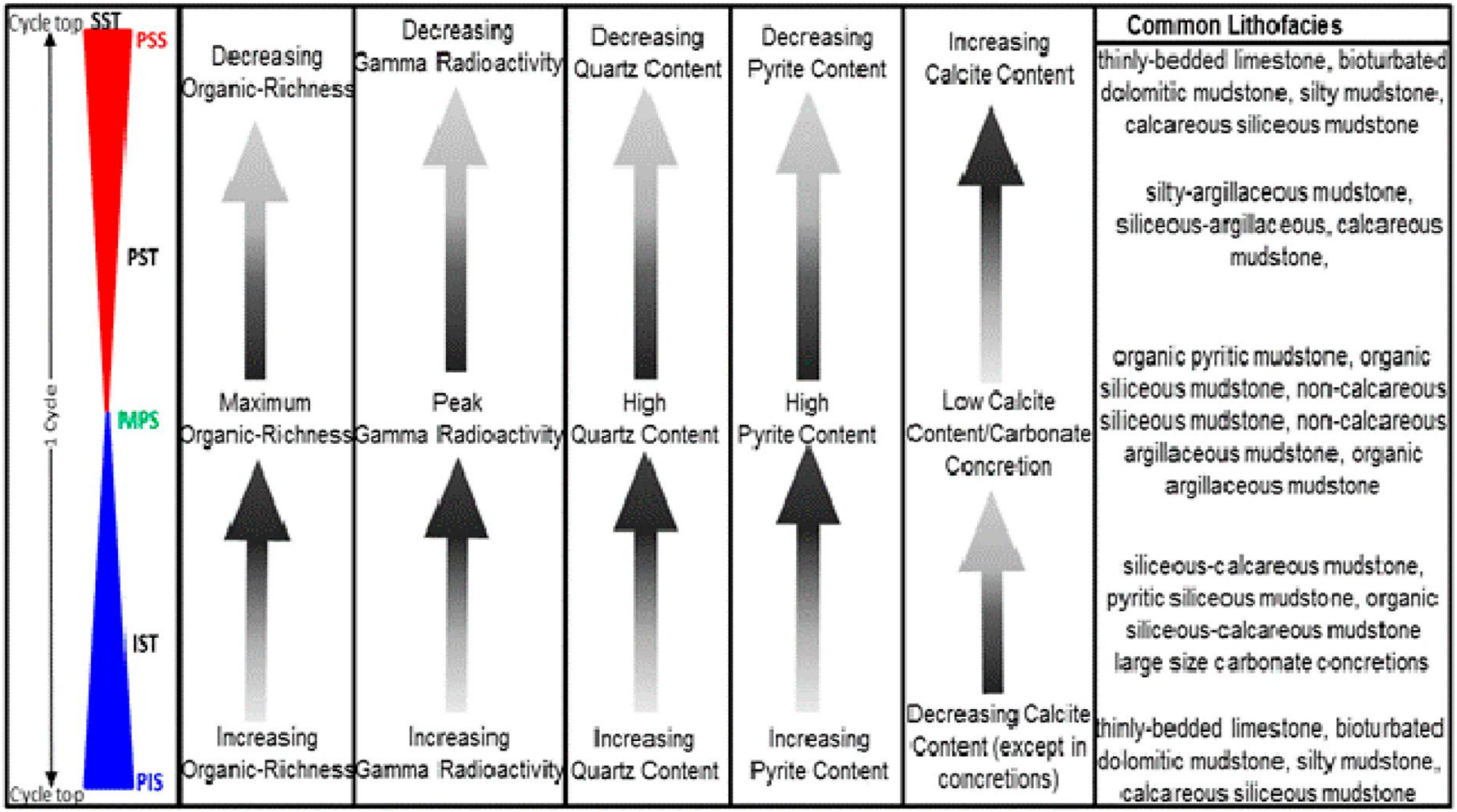

Figure 1. Proxies for defining cyclicity in the Marcellus Shale.

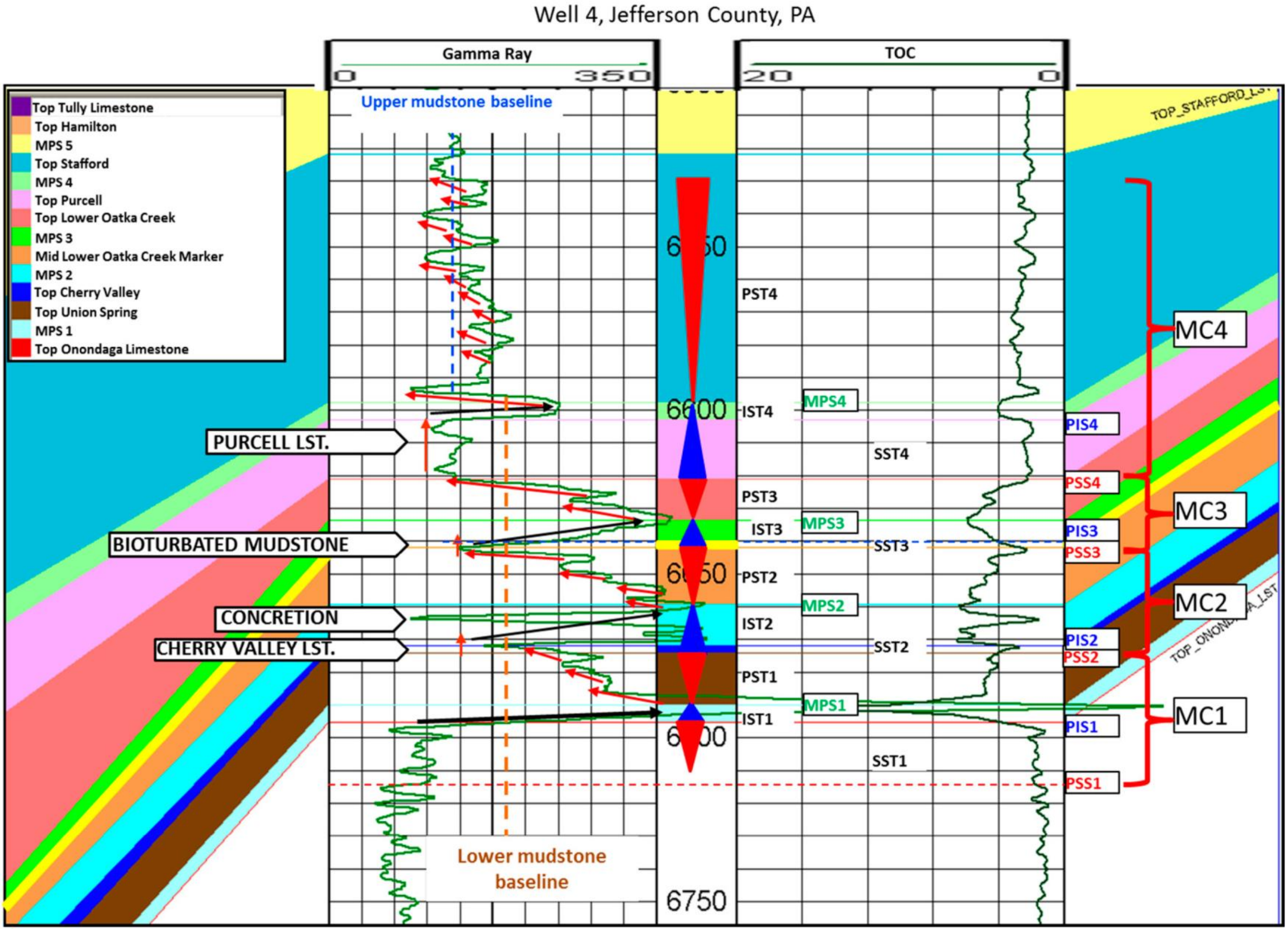

Figure 2. Sequence stratigraphy type section for the Marcellus Shale.

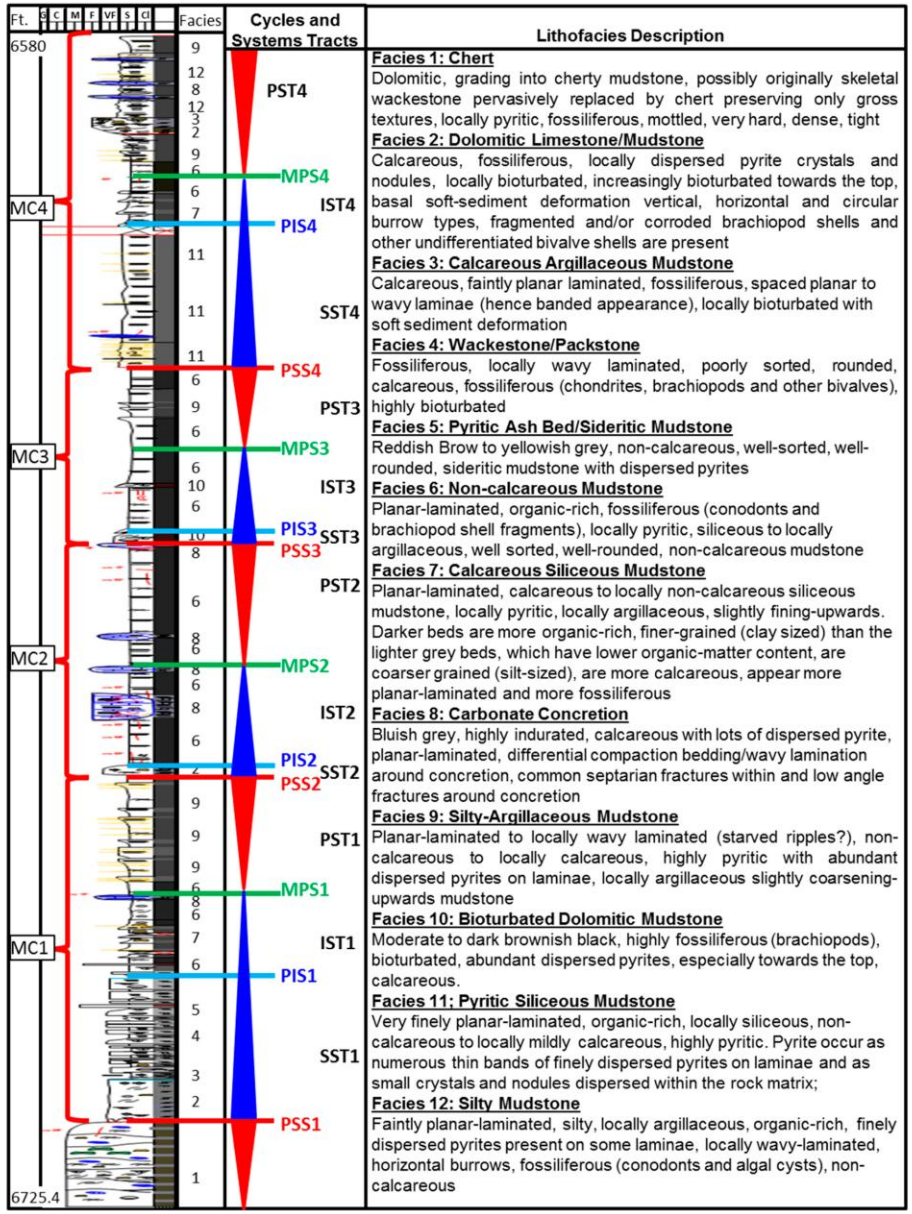

Figure 3. Identification of cyclicity in a Marcellus well. Results from geological description of core data petrographic analysis of 120 thin sections, X-ray diffraction analysis, scanning electron microscopy examination of over 100 samples and geochemical data (TOC) have been integrated with electrical wireline logs to define the cycles. See text for the description of abbreviations.

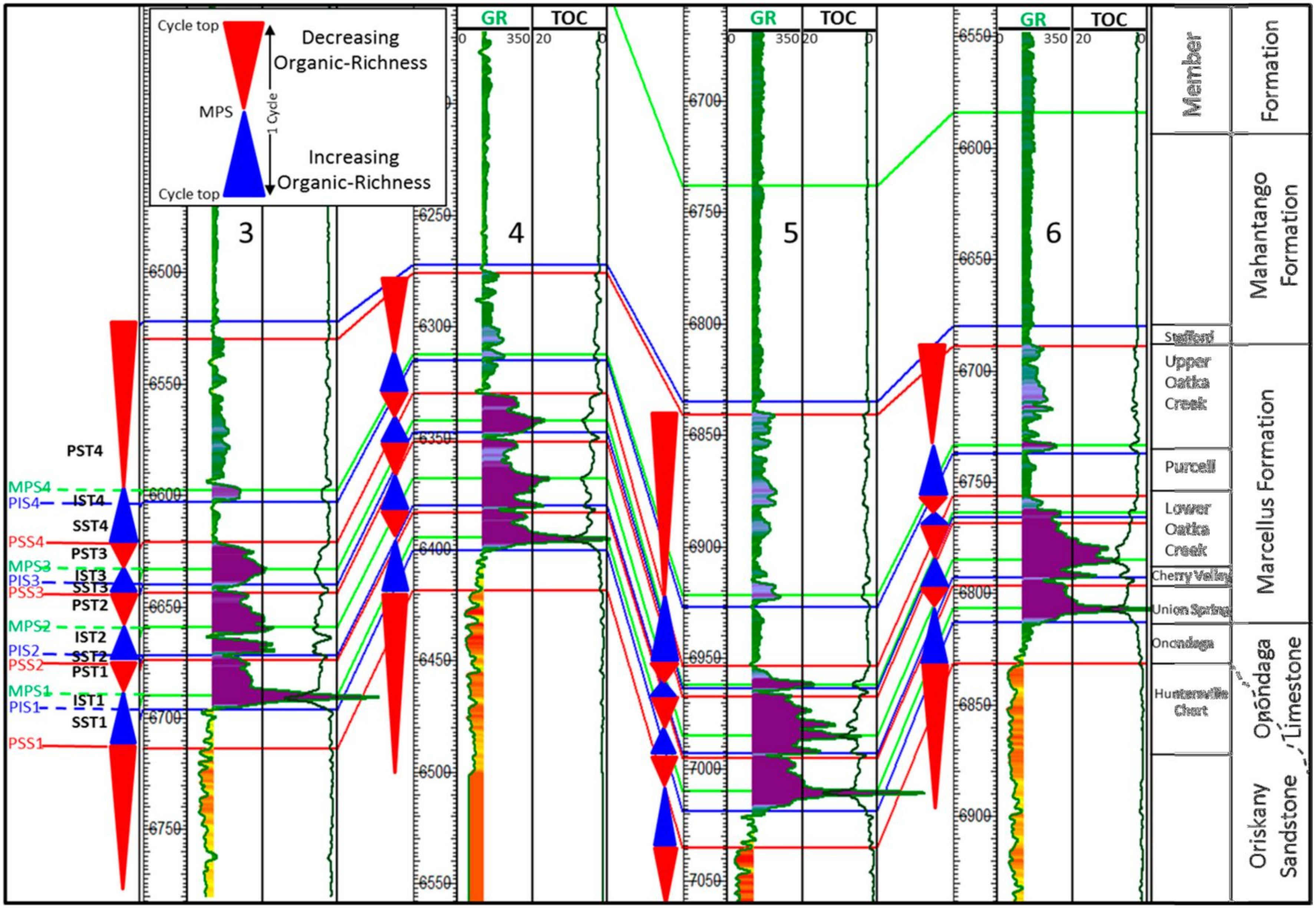

Figure 4. Stratigraphic section showing cyclicity in the Marcellus Shale. Four cycles can be recognized. PSS = Preservation Shutdown Surface, PIS = Preservation Initiation Surface, MPS = Maximum Preservation Surface, SST = Shutdown Systems Tract, IST = Initiation Systems Tract, PST = Preservation Systems Tract, GR= Gamma Ray, TOC = Total Organic Carbon Content. Numbers represent wells.