

**PS Thickness Trends and Sequence Stratigraphy of the Middle Devonian Marcellus Shale, Appalachian Basin:
Evidence of the Influence of Basement Structures on Sedimentation Patterns***

Gary G. Lash¹ and Terry Engelder²

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¹Department of Geosciences, State University of New York, Fredonia, NY (lash@fredonia.edu)

²Department of Geosciences, The Pennsylvania State University, University Park, PA (engelder@geosc.psu.edu)

Abstract

Analysis of more than 900 wireline logs indicates that the Middle Devonian Marcellus Shale comprises two third-order depositional sequences, MSS1 and MSS2, in ascending order. Thickness trends of the sequences reflect the interplay of temporal and spatial variations in accommodation space, the influence of recurrent basement structures, eustatic fluctuations, and proximity to Middle Devonian clastic sources. Thickening of both sequences toward the eastern region of the basin preserves a record of greater accommodation space and proximity to clastic sources at this early stage of the Acadian Orogeny. Moreover, organic-lean late MSS2 highstand systems tract deposits prograded to the west. Local variations in the thickness of MSS1 and MSS2 reflect the reactivation of extensional basement structures, including the Rome Trough, most evident in thickness trends of MSS1 highstand systems tract deposits. Lithostratigraphic units and depositional sequences of the Marcellus Shale reveal variable degrees of erosion in western New York and northwestern Pennsylvania, a consequence of intermittent vertical displacement of crustal blocks bounded by both Eocambrian extensional structures and northwest-striking cross-structural discontinuities, including the Tyrone - Mt. Union, Lawrenceville-Attica, Home-Gallitzen, and Pittsburgh-Washington faults. Episodes of block movement induced by Acadian plate convergence gave rise to northeast-southwest-trending regions of starved sedimentation and/or erosion bounded by cross-structural discontinuities. Block movement appears to have initiated in late Early Devonian time, resulting first in local erosion of the Oriskany Sandstone in northwest Pennsylvania. Similarly, depositional and erosional patterns of the Marcellus Shale and the overlying organic-rich Levanna Member of the Skaneateles Formation in New York and western Pennsylvania were controlled by block movement.

THICKNESS TRENDS AND SEQUENCE STRATIGRAPHY OF THE MIDDLE DEVONIAN MARCELLUS SHALE, APPALACHIAN BASIN: EVIDENCE OF THE INFLUENCE OF BASEMENT STRUCTURES ON SEDIMENTATION PATTERNS*

Gary G. Lash
Dept. of Geosciences, SUNY - Fredonia
Fredonia, NY 14063 (Lash@fredonia.edu)

Terry Engelder
Dept. of Geosciences,
The Pennsylvania State University
University Park, PA

ABSTRACT

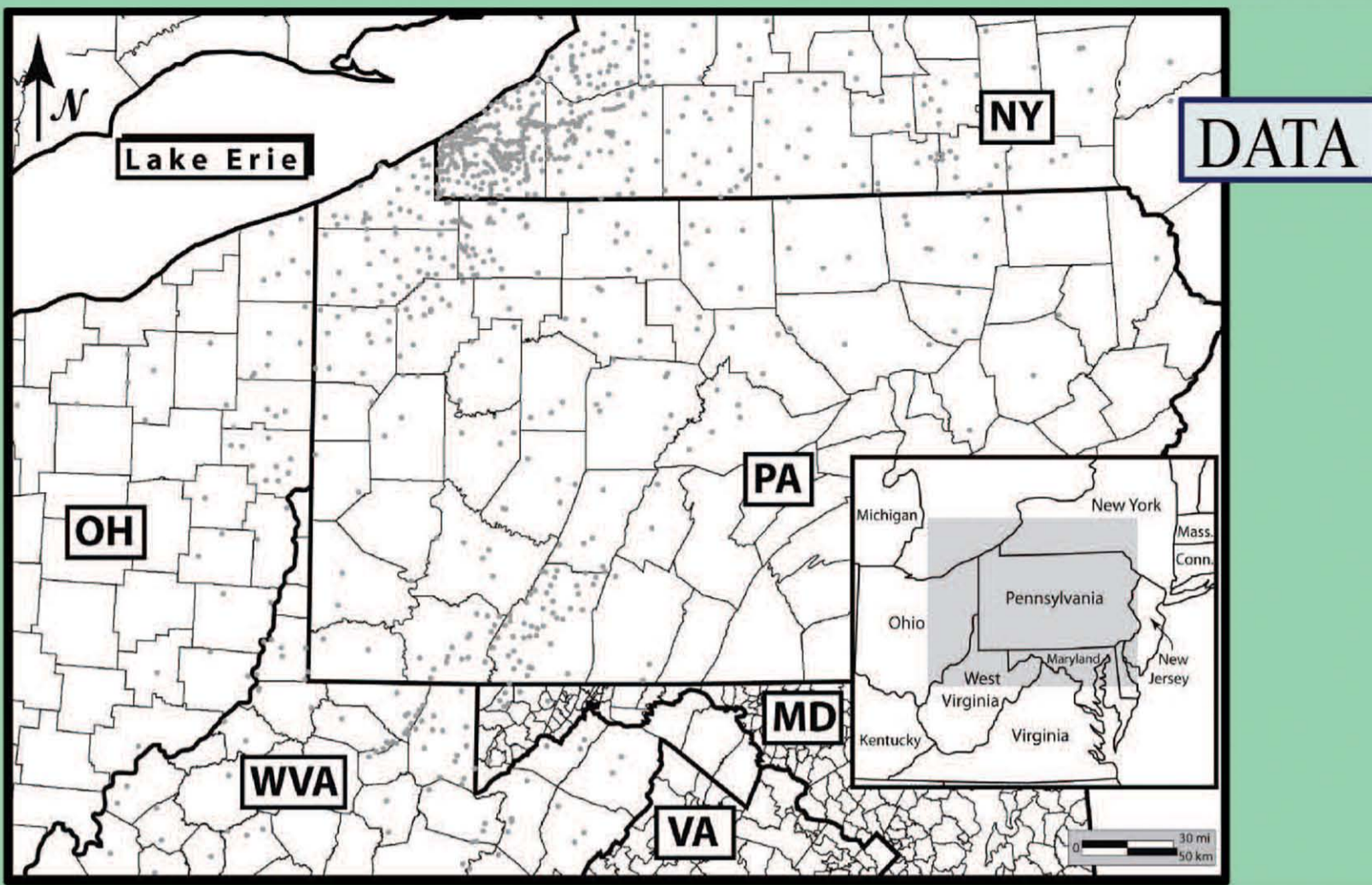
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INTRODUCTION

Results reported on in this paper are based on our analysis of more than 900 wireline logs from the Appalachian Basin of Pennsylvania, New York, northern West Virginia, eastern Ohio, and western Maryland (Figure). We focus on the Appalachian Plateau region of the basin for two reasons: the greater density of available wireline logs and fewer structural complications. Specific points addressed in this study include (1) the distribution and thickness trends of the two black shale members of the Marcellus Formation, (2) the distribution and thickness of the intervening limestone, an interval that could be critical to stimulation and production considerations, and (3) the stratigraphy and distribution of the organic-rich Levanna Member of the Skaneateles Formation, a unit that has been confused for the Marcellus Formation.

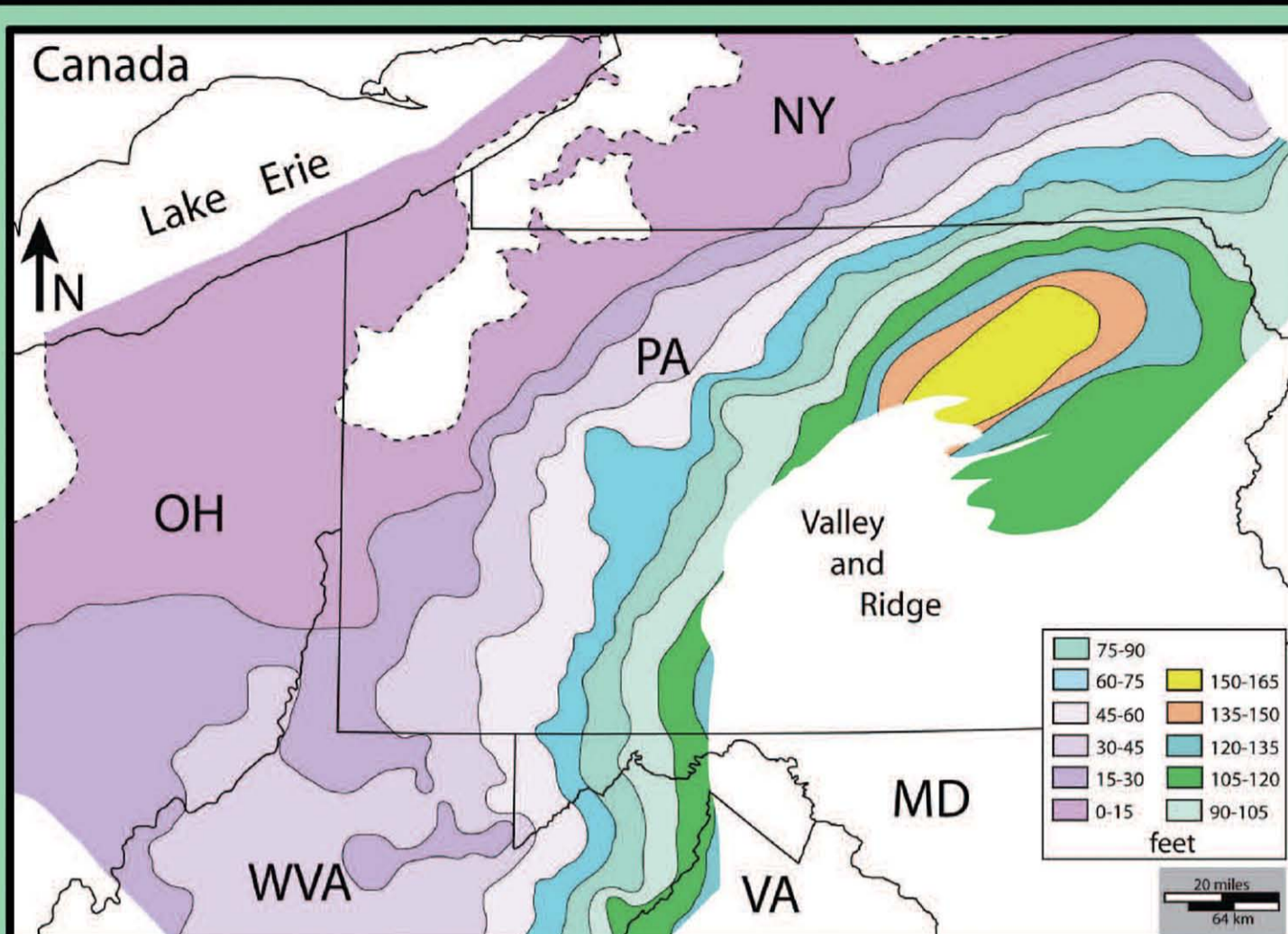
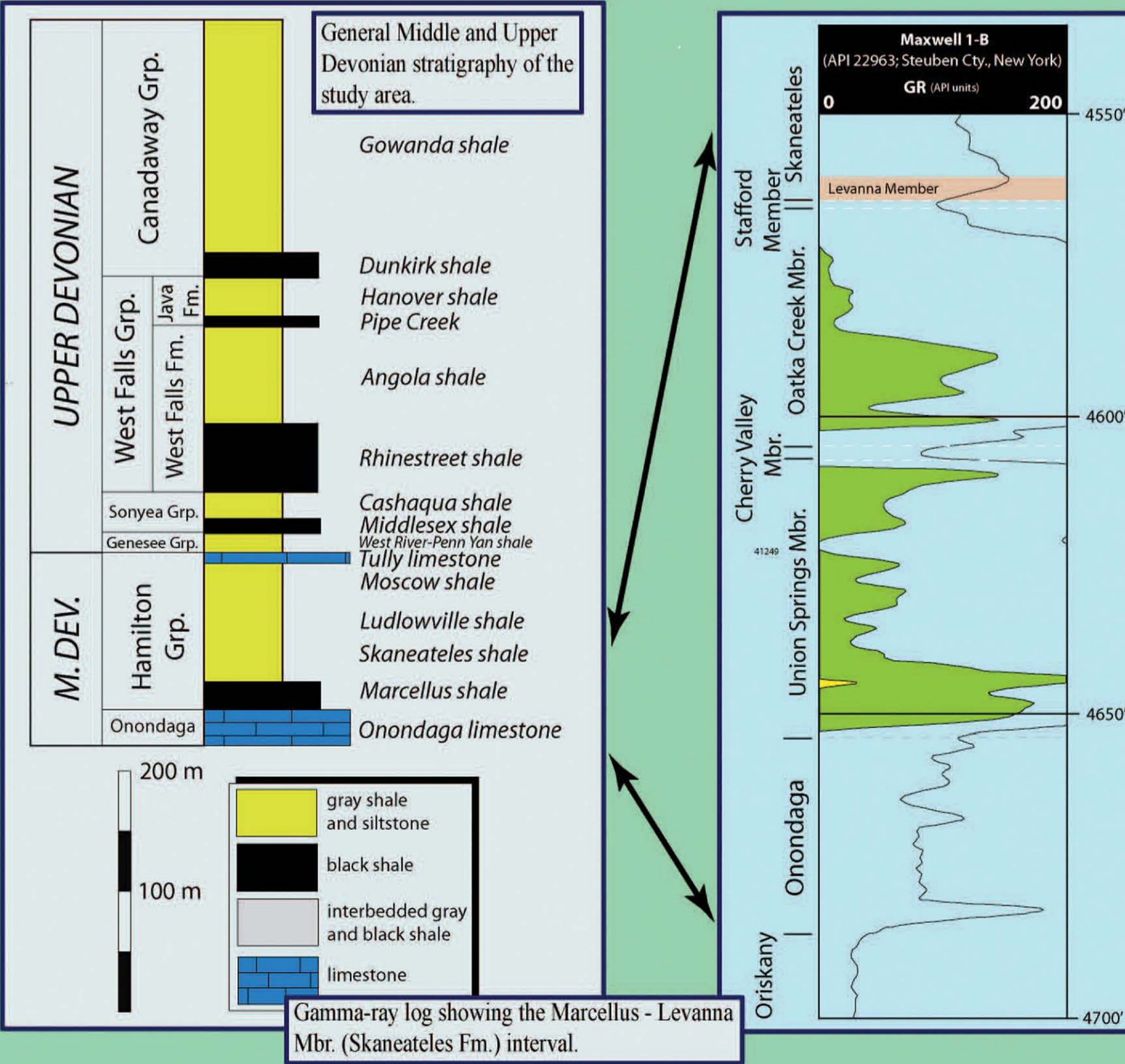
As important as the above points are, however, the more significant contribution of this paper is a sequence stratigraphic framework of the Marcellus Formation based on publicly available wireline logs. Partington et al. (1993) and Emery and Myers (1996), among others, have demonstrated the utility of 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. Thickness trends of lithostratigraphic units and the sequence stratigraphy of the Marcellus Formation reveal a basin that was more tectonically active than heretofore realized. Reactivated extensional basement structures, including Eocambrian faults associated with the Rome Trough, and northwest-striking basement faults (i.e., cross-strike structural discontinuities of Wheeler, 1980), appear to have controlled sedimentation patterns of at least the late Early through early Middle Devonian succession, including the Marcellus Formation, in western New York and northwest Pennsylvania.

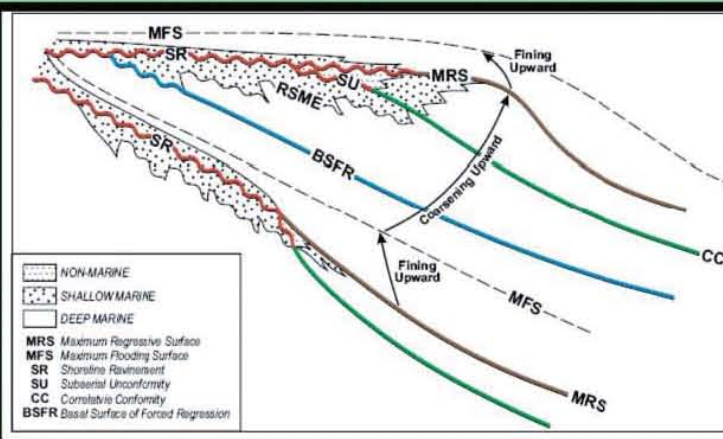
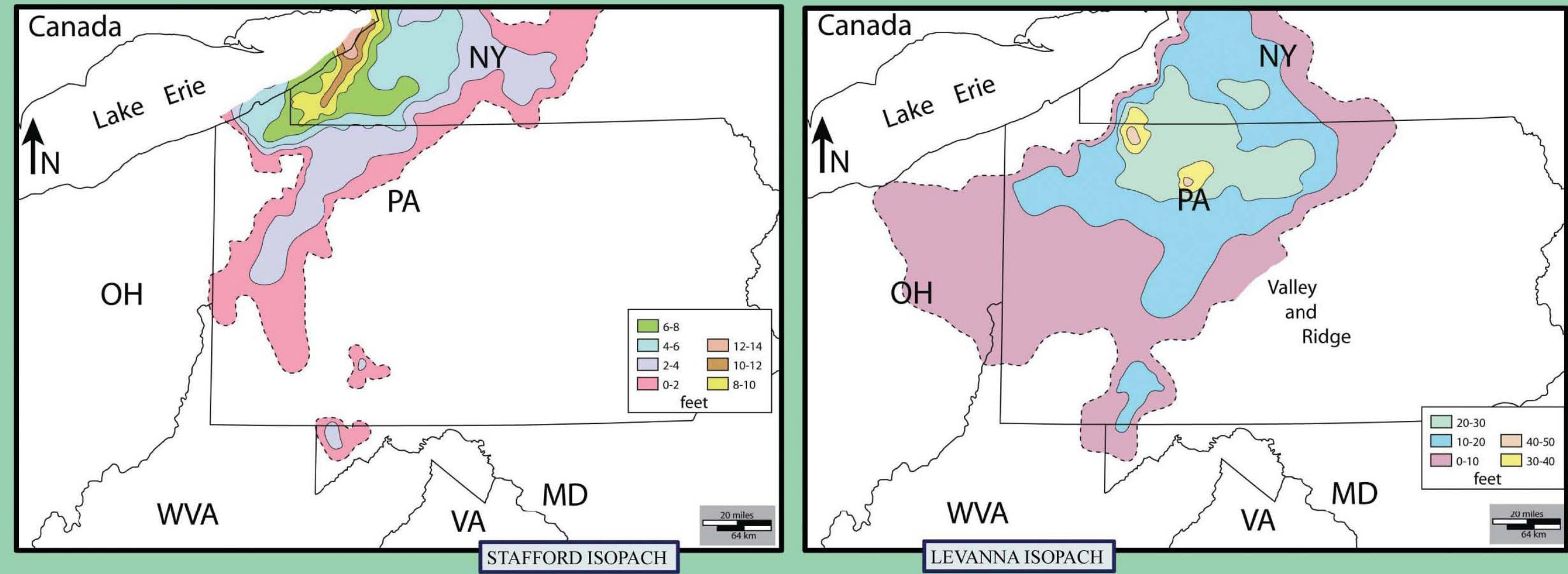
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LITHOSTRATIGRAPHY

In this paper, we adopt a lithostratigraphy in line with that employed by Rickard (1984, 1989) and one that lends itself to subsurface correlation of wireline log signatures. Specifically, we define our basal unit of the Marcellus Formation as the Union Springs Member, a term recognized by the United States Geological Survey Geologic Name Lexicon. The Union Springs Member of this study, which encompasses the Bakoven Member of Ver Straeten and Brett (2006), is overlain by the Cherry Valley Member. Our Cherry Valley Member, which comprises variable amounts of interlayered carbonate, shale, and sandstone, correlates with the Stony Hollow Member of the Union Springs Formation and the Hurley and Cherry Valley members of the Oatka Creek and Mt. Marion formations of Ver Straeten and Brett (2006). Finally, we employ the name Oatka Creek Member, also recognized by Geologic Name Lexicon, for the succession of black and gray shale and lesser siltstone and limestone that underlies the Stafford and Mottville members of the Skaneateles Formation.





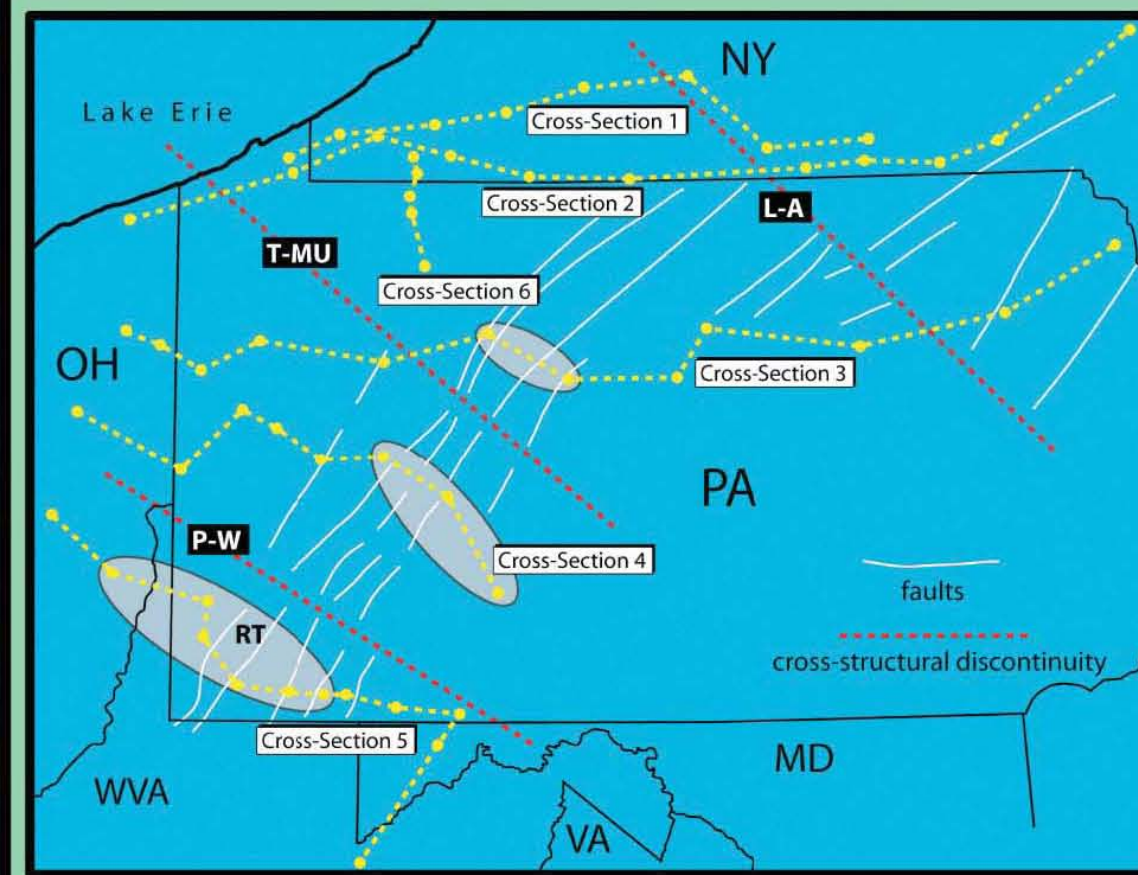
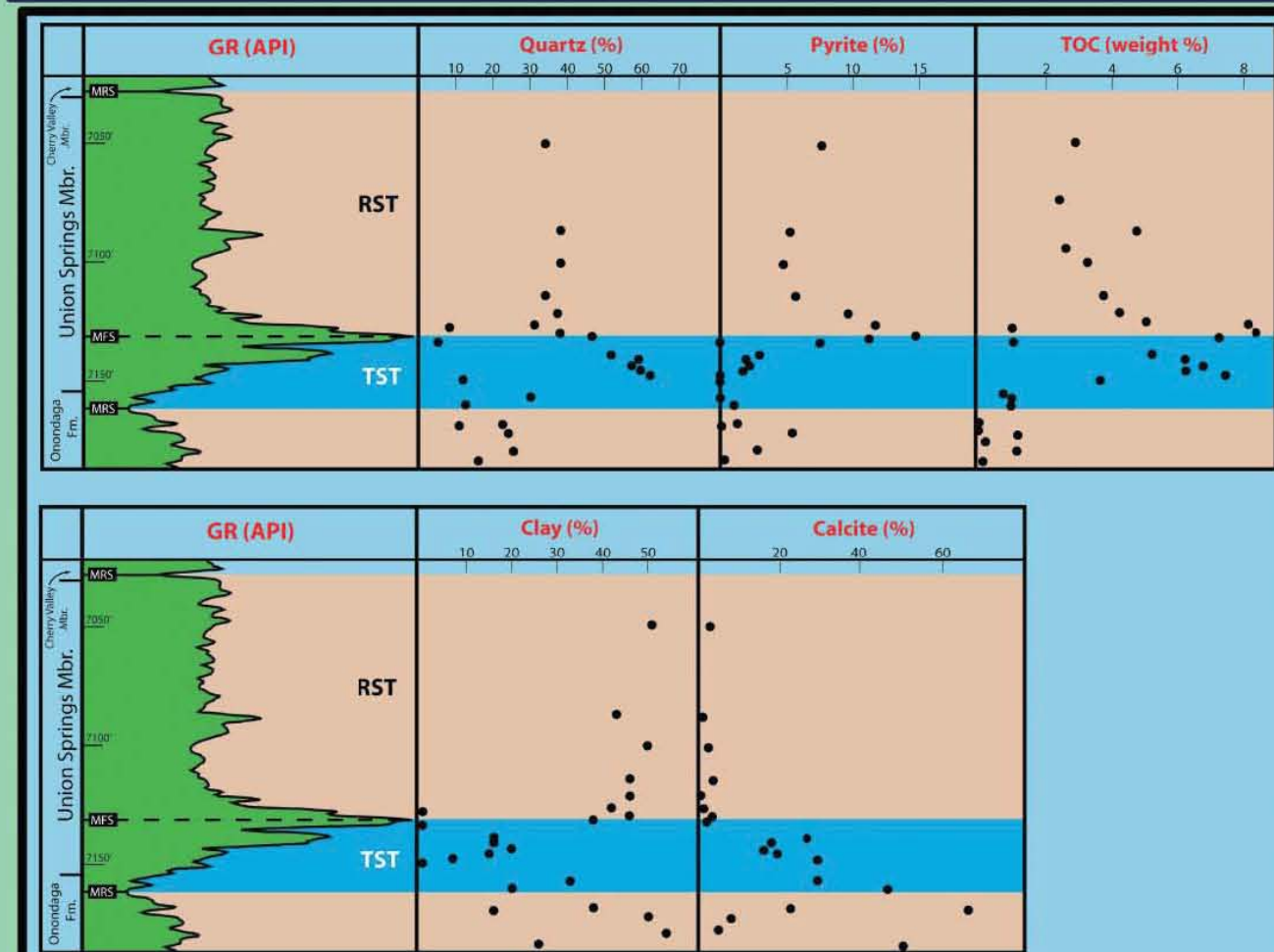
Sequence stratigraphic elements of the T-R sequence of Embry and Johannessen (1992) (on right). The maximum regressive surface is the basinward equivalent of the subaerial unconformity and shoreline ravinement - unconformity.

Composite wireline log and sequence stratigraphic "type section" of the Marcellus Formation (below) generated as per Brown et al. (2005).

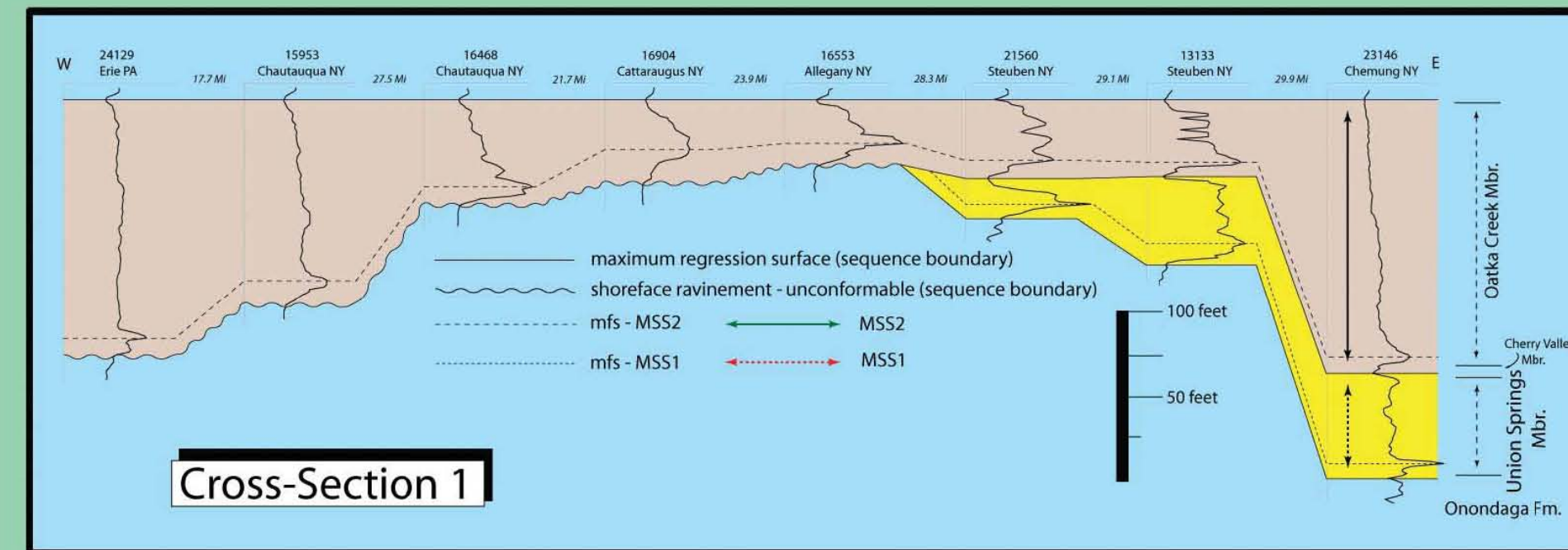
SEQUENCE STRATIGRAPHY

We adopt the transgressive-regressive (T-R) sequence described by Johnson et al. (1985) and Embry and Johannessen (1992) and further refined by Embry (2002). Indeed, Johnson et al. (1985) first applied the T-R sequence concept to the Devonian succession of the Appalachian Basin a quarter of a century ago. T-R sequences comprise 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, 1993, 2002). Recognition of T-R sequences is dependent upon the identification of minimally diachronous sequence boundary surfaces (Embry, 2002). Embry (2002) has demonstrated that those surfaces most conducive to defining T-R sequences include the subaerial unconformity, the shoreface ravinement-unconformable and -conformable, and the maximum regressive surface.

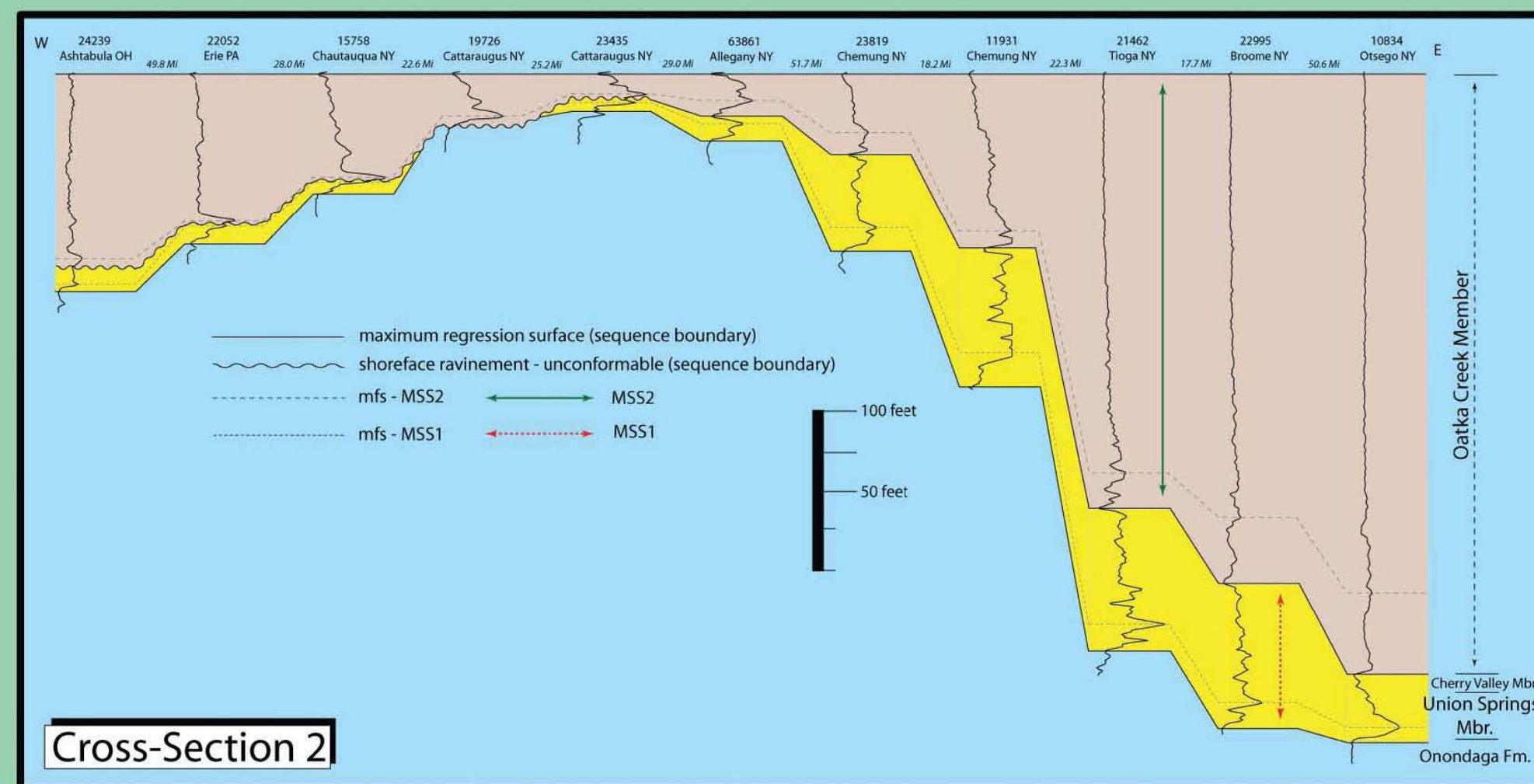
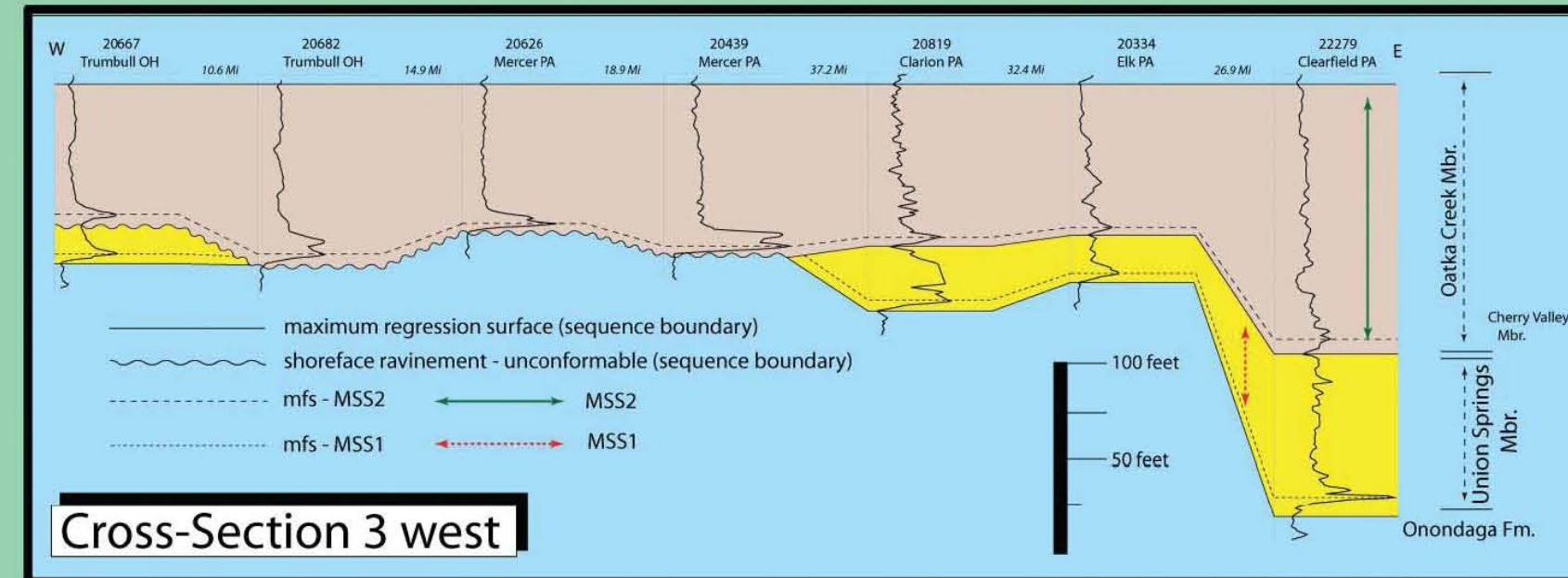
Mineralogy and TOC trends through the MSS1 depositional sequence. Data based on a suite of sidewall core samples recovered from a Marcellus Formation well; the location is proprietary.



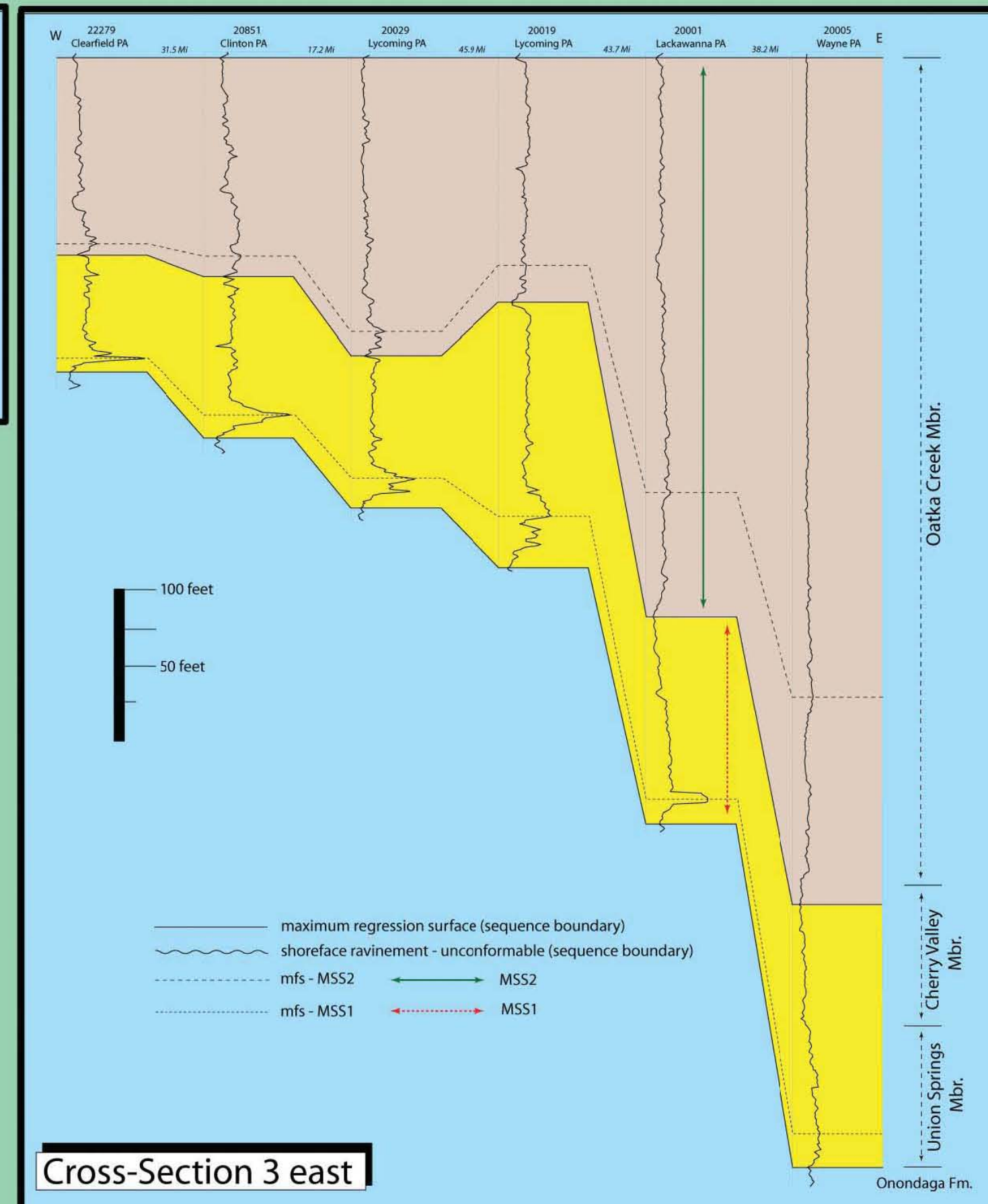
Map showing basement structural elements (modified from Alexander et al., 2005) and location of sequence stratigraphic cross-sections (B - G) across the core region of the Marcellus Formation basin; RT = Rome Trough; L-A = Lawrenceville-Attica cross-structural discontinuity; T-MU = Tyrone-Mt. Union cross-structural discontinuity; P-W = Pittsburgh-Washington cross-structural discontinuity. Cross-sections are hung on the top of the MSS2 T-R sequence. Shaded ovals on the map denote cross-section segments that display evidence of syndepositional faulting. Logs are gamma-ray logs; maximum API count = 700.



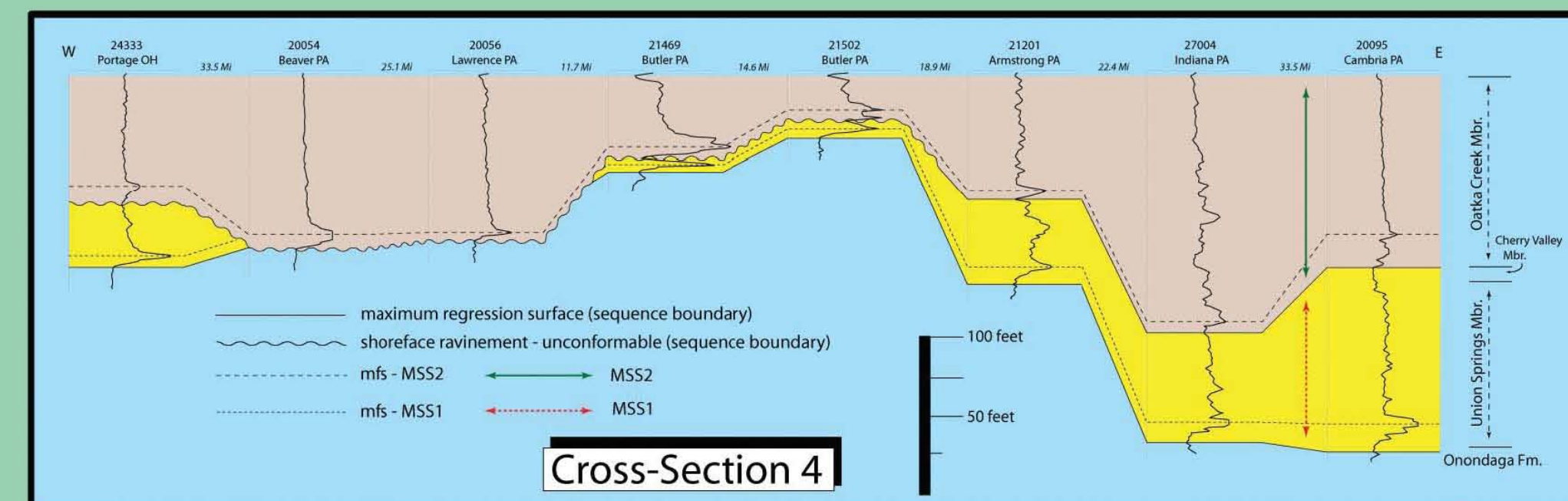
A series of sequence stratigraphic cross-sections through the core region of the basin reveals several significant aspects of the stratigraphic architecture of the Marcellus Formation. MSS1 is thickest in northeastern Pennsylvania and southeastern New York where a thick regressive systems tract interval includes arenaceous limestone. Similarly, depositional sequence MSS2 thickens toward the northeastern region of the basin, the bulk of the thickening restricted to the regressive systems tract. Moreover, gamma-ray log responses suggest that transgressive systems tract deposits are less organic-rich in this region of the basin, a likely reflection of the dilution of these deposits by a high clastic flux derived from the Acadian highland source region.

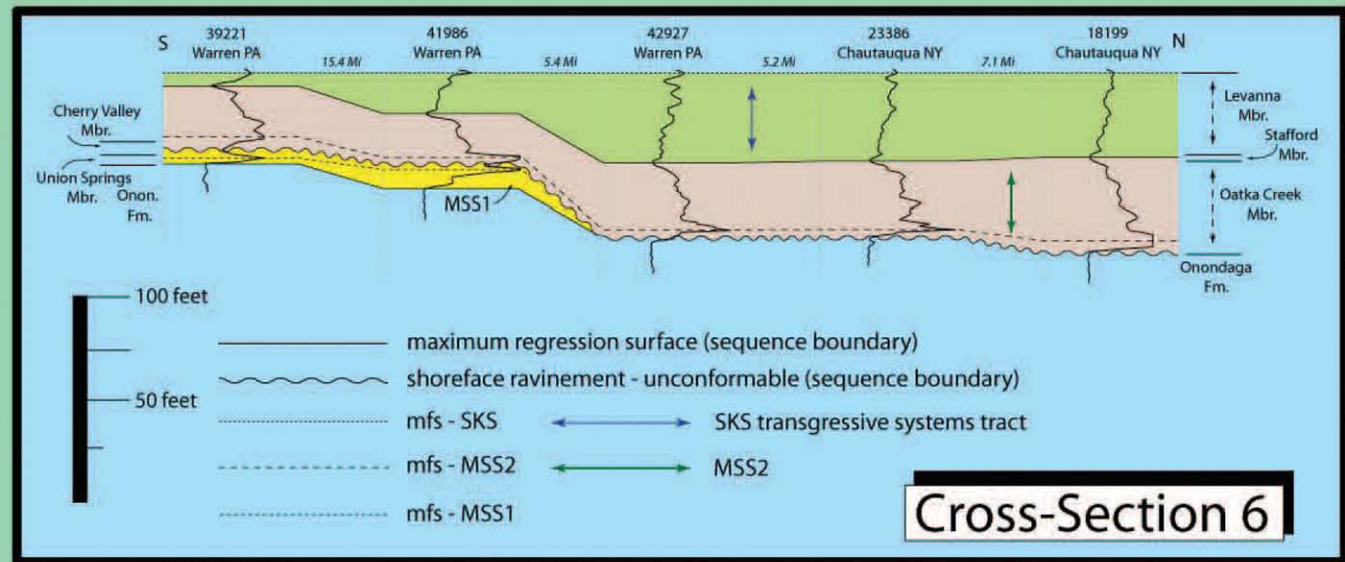
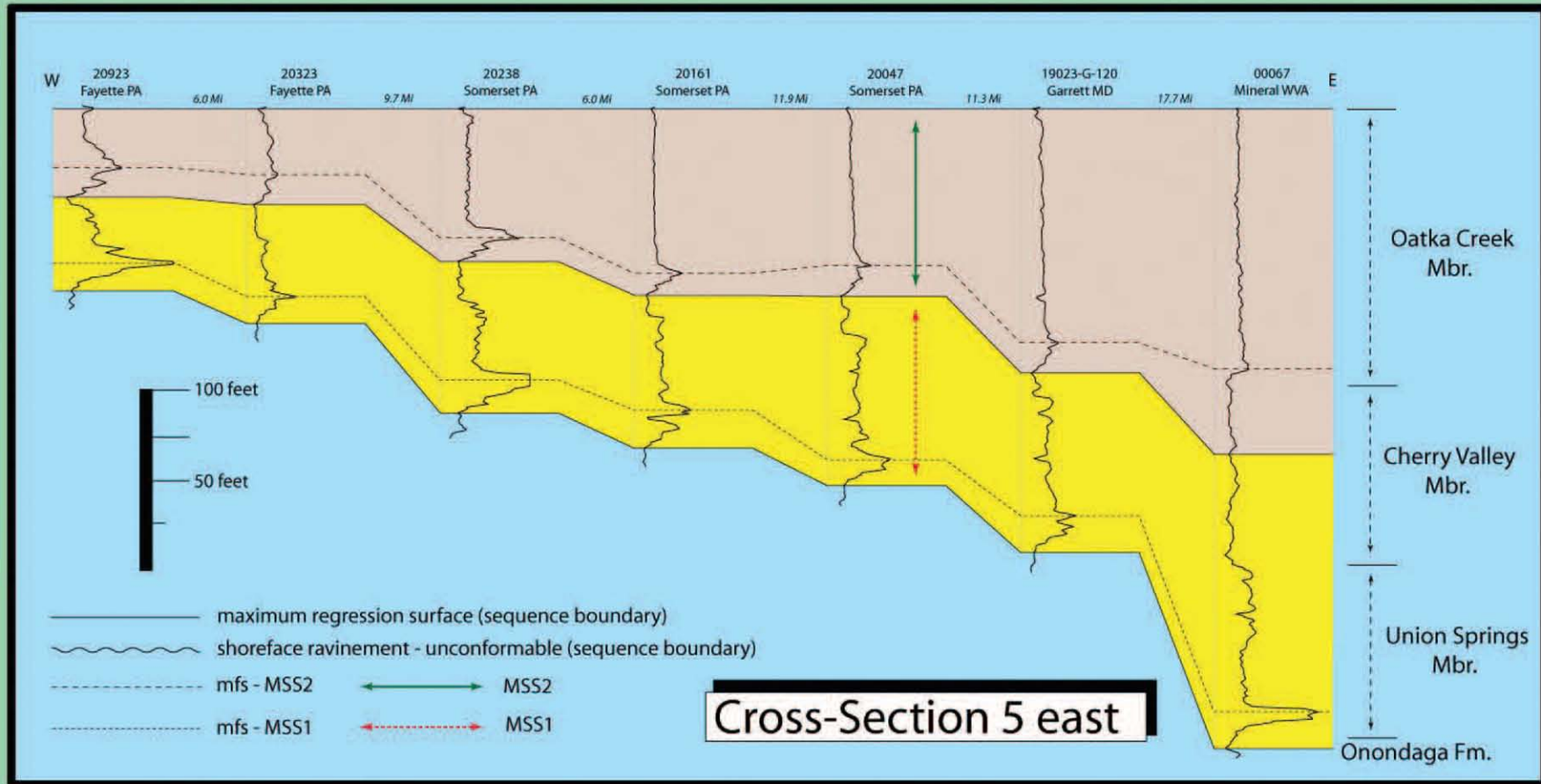
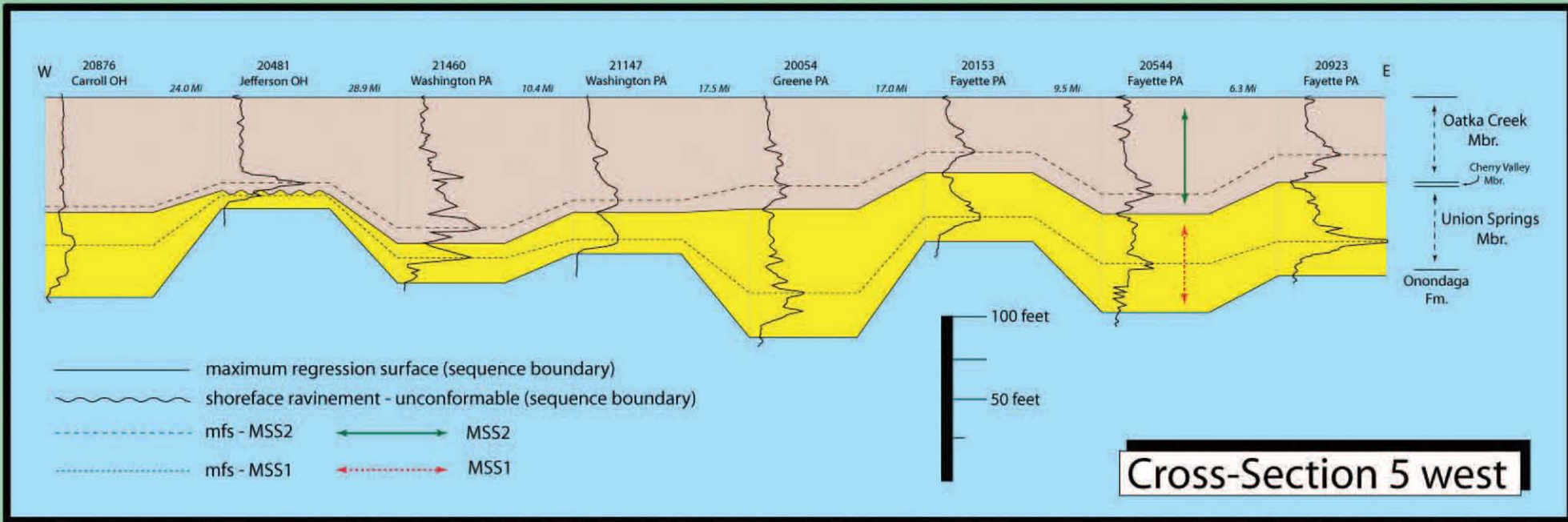


Impressed upon the northeastward thickening trends of both MSS1 and MSS2 are local variations in thickness that may reflect the effects of basement tectonics (e.g., Harper, 1989). Indeed, the imprint of Rome Trough-related extensional tectonics in southwestern Pennsylvania appears to be manifested by variations in the thickness of MSS1 between Washington and Fayette counties. Further, thickness variations in thickness of Marcellus Formation T-R sequences are found in the western region of Pennsylvania, proximal to the projected region of Rome Trough-related faulting.



Variations in the thickness of MSS1 regressive systems tract deposits are suggestive of local erosion. Notably, the base of MSS2 cuts progressively deeper into MSS1 westward from eastern New York. Moreover, the absence of MSS1 from some regions of the basin indicates that erosion has occurred. In this case, the base of MSS2 is interpreted to be a shoreface ravinement-unconformable that passes laterally into a maximum regressive surface in the conformable succession. Elsewhere, the MSS2 maximum flooding surface is no more than a few meters or so above the MSS1 maximum flooding surface, again, indicative of erosion. The thinning and/or local absence of MSS1 in western New York and Pennsylvania may reflect the effects of both local uplift and concomitant lowering base level.





The Stafford and overlying Levanna members of the Skaneateles Formation comprise the transgressive systems tract of T-R sequence SKS. Rising base level is manifested by upward-increasing gamma-ray response and decreasing bulk density; the SKS maximum flooding surface is placed at the gamma-ray peak/bulk density minimum within the organic-rich Levanna Member. It is noteworthy that the SKS maximum flooding surface in central-western New York is only ~ 20 ft above the upper maximum regressive surface of T-R sequence MSS2, whereas farther to the west, the SKS maximum flooding surface is ~ 60 ft above the base of SKS. Similarly, the SKS maximum flooding surface in northwestern Pennsylvania is only ~ 8 ft above the top of MSS2. However, in western New York, the same surfaces are separated by ~ 35 ft. These relationships reflect the onlapping of SKS transgressive systems tract deposits to the west and north.

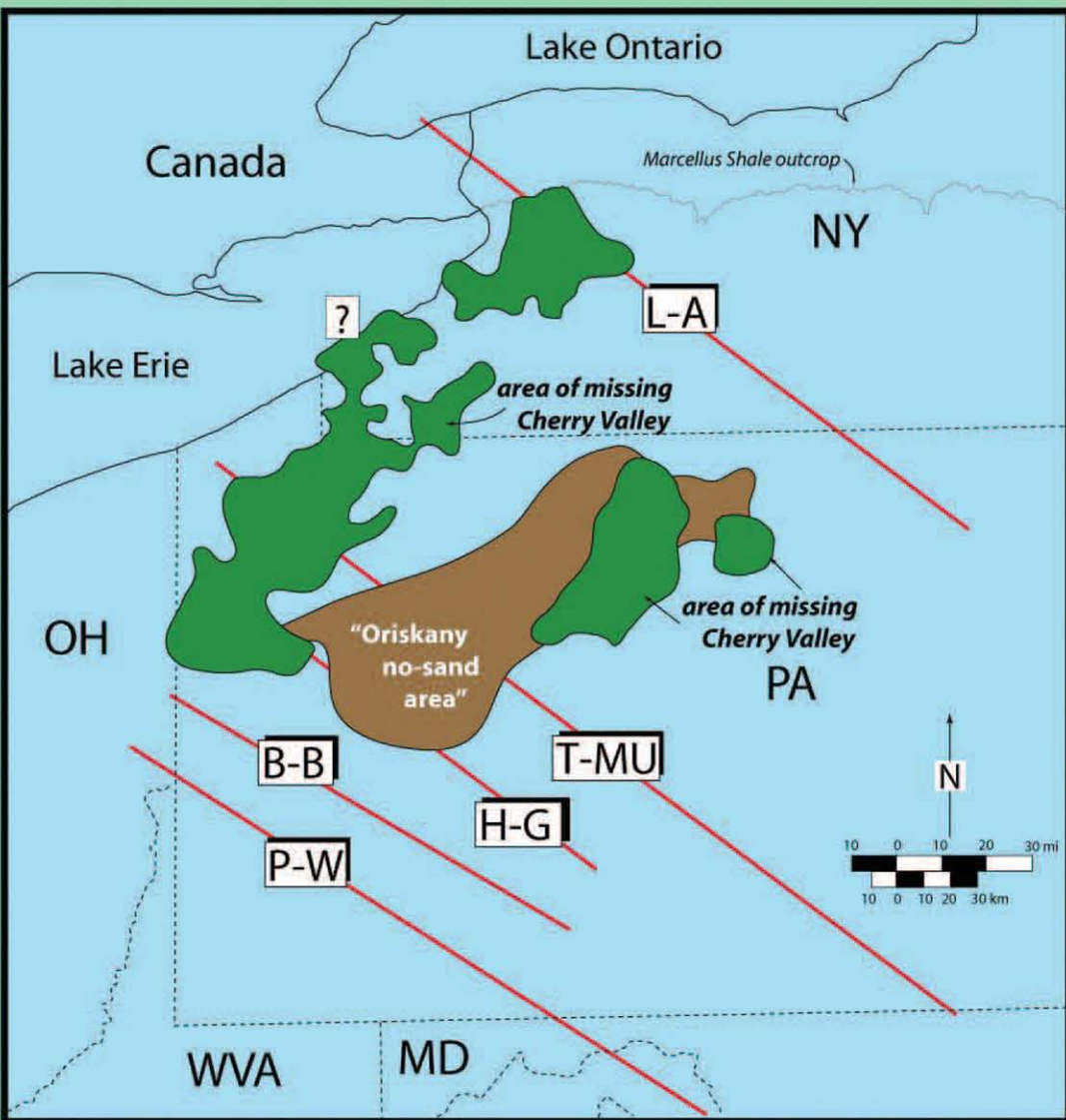
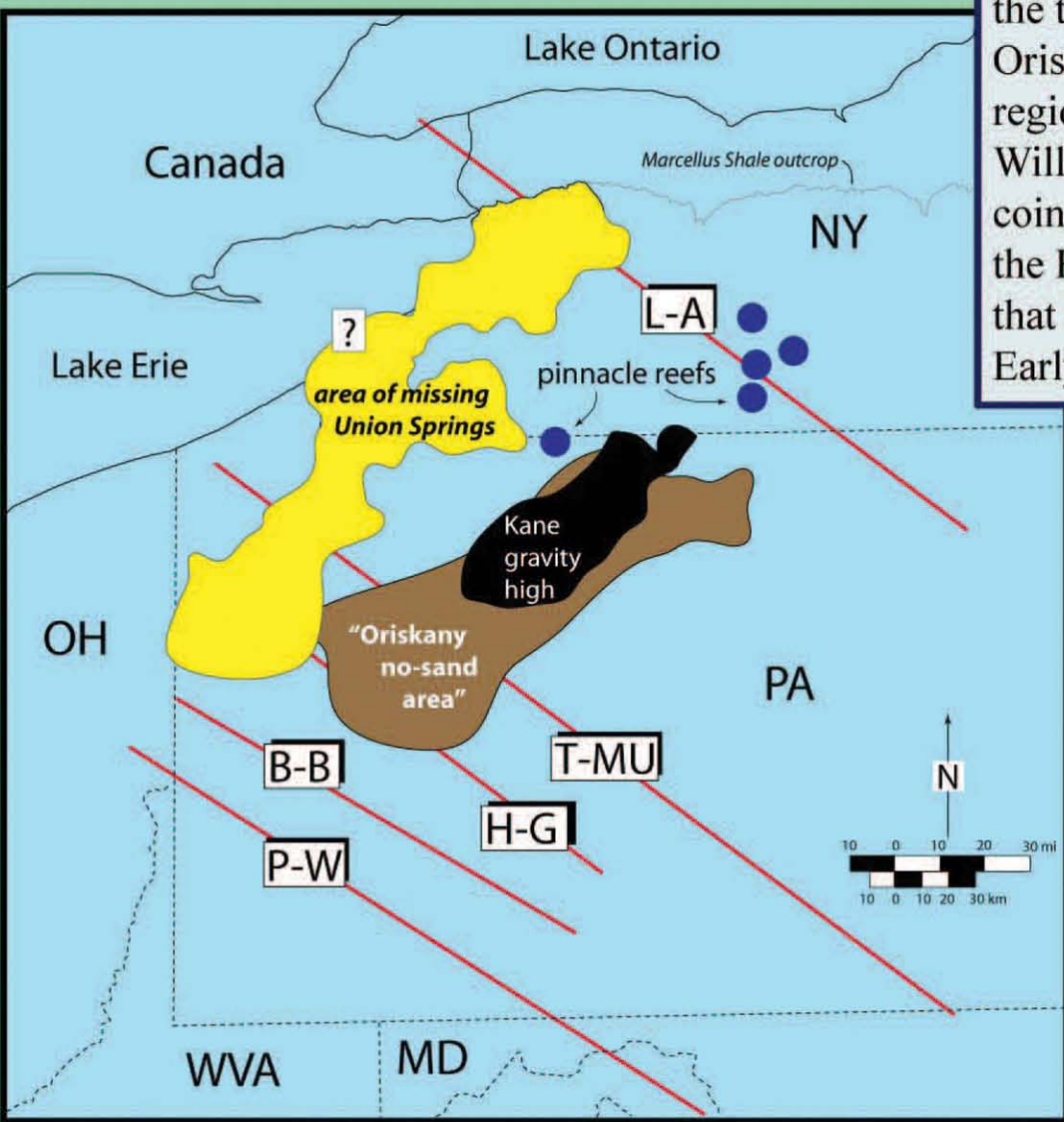
THE ROLE OF BASEMENT STRUCTURES ON MARCELLUS FORMATION SEDIMENTATION PATTERNS

The Middle and Upper Devonian succession of the Appalachian Basin records the cratonward advance of the Catskill Delta complex in response to the Acadian oblique collision of the Avalonia microplate and Laurentia (Ettensohn, 1987). Rapid eastward thickening of MSS1 and MSS2 toward the Acadian fold and thrust belt is characteristic of foreland basin deposits (DeCelles and Giles, 1996).

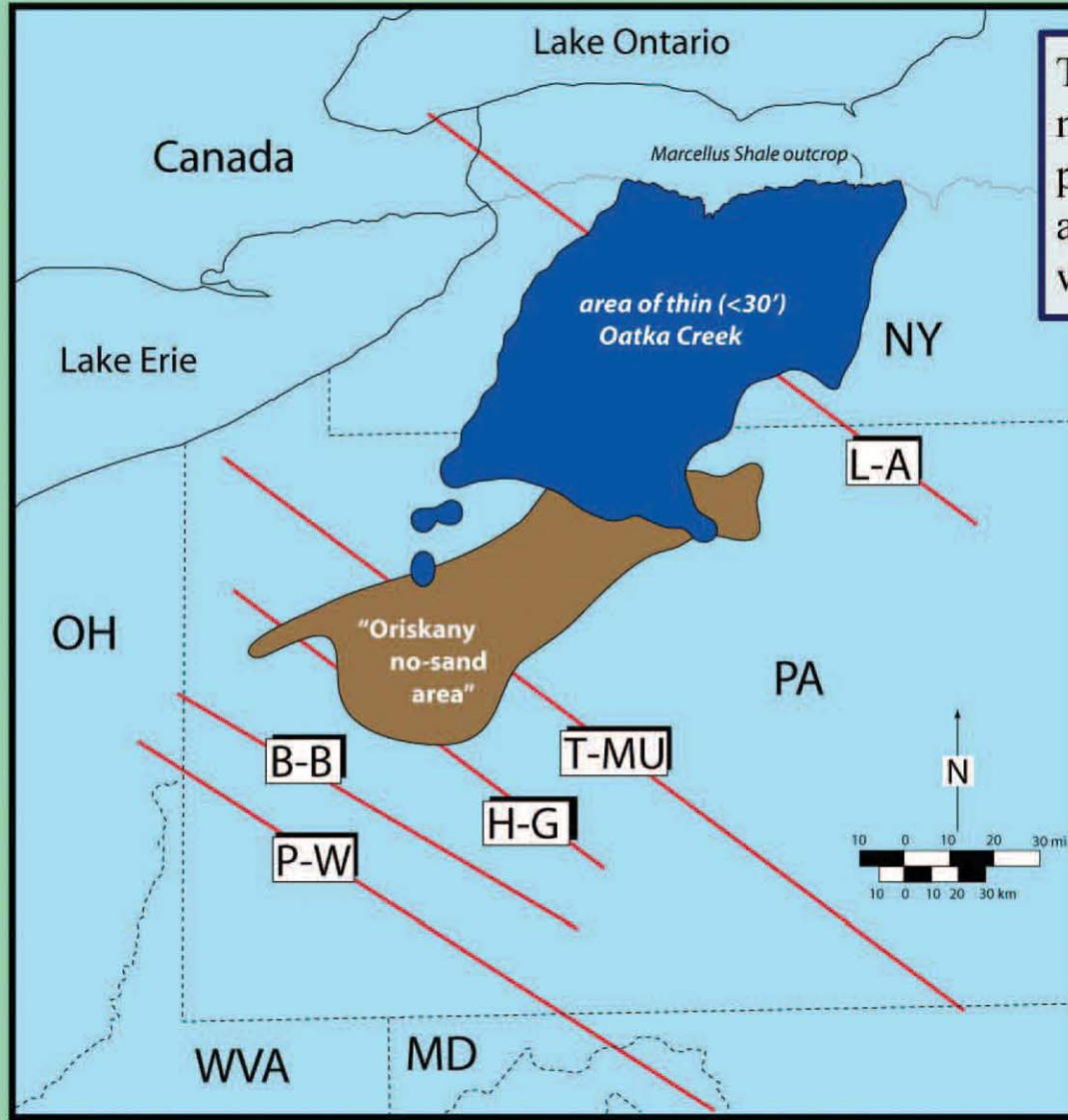
Although the regional architecture of the Acadian foreland basin was a consequence of load-induced subsidence, it is difficult to imagine that inherited basement structures, including the Rome Trough and northwest-striking wrench faults (cross-structural discontinuities), did not, in some way, affect foreland basin evolution and sedimentation patterns during the Acadian Orogeny. Indeed, reactivation of pre-existing faults during foreland flexure can partition the basin into regions of fault-controlled uplift and depocenters.

An early indicator of forebulge-like dynamics induced by Acadian convergence in the Appalachian Basin is the thinning and local absence of the upper Lower Devonian Oriskany Sandstone along a northeast-southwest-trending region of north-central and northwestern Pennsylvania. Williams and Bragonier (1974), commenting on the coincidence of the so-called “Oriskany no-sand area” with the Kane gravity high (Parrish and Lavin, 1982), speculated that the local absence of the Oriskany was a consequence of Early Devonian basement uplift.

It is noteworthy that the elongate “Oriskany no-sand area” and Kane gravity high are roughly centered between the Lawrenceville-Attica and Home-Gallitzen CSDs. Further, Onondaga pinnacle reef development appears to have terminated close to the Lawrenceville-Attica CSD. It is an intriguing possibility that thickness trends of the Lower Devonian Oriskany Sandstone and Onondaga reef development in this region of the basin reflect episodes of vertical displacement of crustal blocks bounded by the Home-Gallitzen, Tyrone-Mt. Union, and Lawrenceville-Attica CSDs. Such block displacement, which would have overprinted smooth elastic forebulge dynamics, partitioned the foredeep basin into subtle ridges and depocenters.

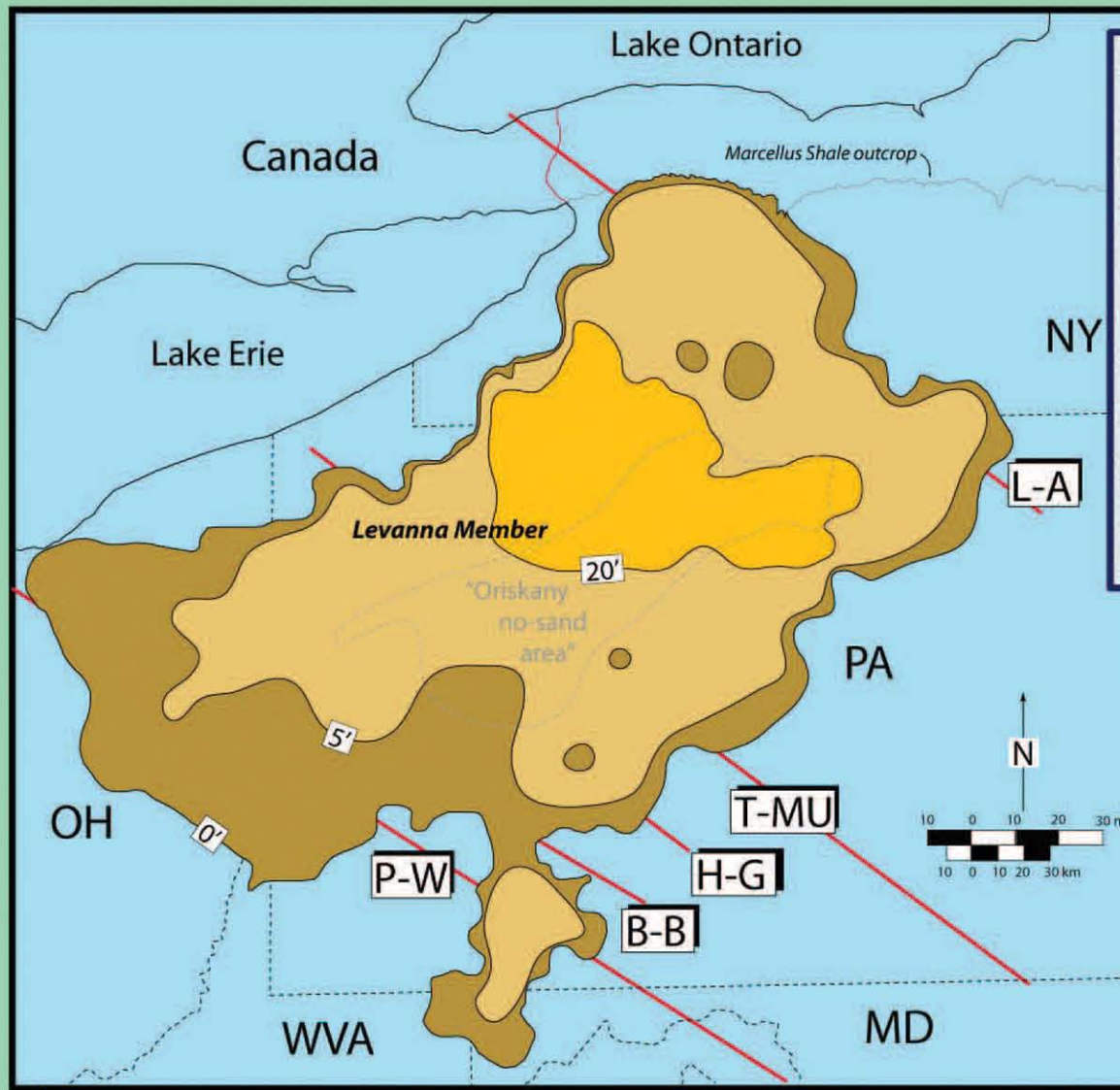
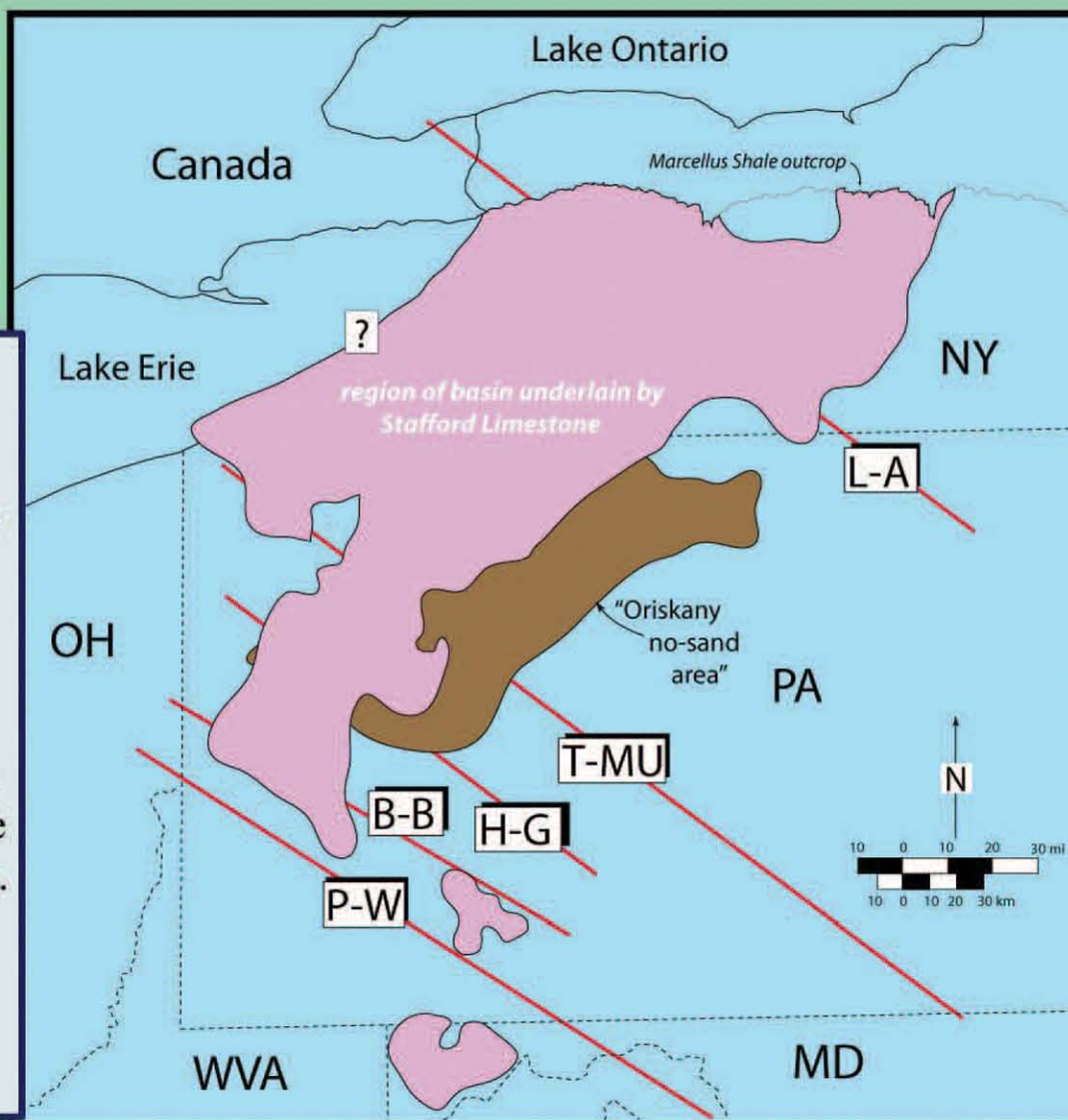


The Union Springs Member, which comprises the bulk of MSS1 transgressive and regressive systems tract deposits, as well as the Cherry Valley Member, much of which encompasses the upper part of the MSS1 regressive systems tract, are absent along a northeast-southwest-oriented region of western New York and northwest Pennsylvania that parallels the “Oriskany no-sand area” to the south. As with the “Oriskany no-sand area,” the western and eastern limits of the region absent the Union Springs and Cherry Valley (MSS1) deposits are roughly coincident with the Home-Gallitzen and Lawrenceville-Attica CSDs, respectively. It is unlikely that the thinning and local absence of MSS1 deposits was solely a consequence of reduced base level. Instead, we suggest that thickness trends of these deposits are reflective of differential uplift of the crustal block bounded by the Lawrenceville-Attica and Home-Gallitzen CSDs soon after the MSS1 base level maximum resulting in local warping or flexing of the basin and consequent reduction of base level.



The region of thin MSS2 deposits, notably the Oatka Creek Member parallels the “Oriskany no-sand area” and is roughly bounded on the west by the Tyrone-Mt. Union CSD.

The Stafford Member of the Skaneateles Formation records the base level minimum at the top of the MSS2 T-R sequence. The isopach pattern of the Stafford Member of the Skaneateles Formation, which records the base level minimum at the top of the MSS2 T-R sequence, may reflect the influence of fault-induced warping of the basin. That is, the southwestern edge of the Stafford Member zeroes close to the inferred trace of the Tyrone-Mt. Union CSD; to the east, the Lawrenceville-Attica CSD appears to have exerted little, if any, control on accumulation of the carbonate lowstand deposits. The southwestern extent of the Stafford may reflect the influence of the Blairsville-Broadtop CSD. It is conceivable that a complex displacement history on both the Tyrone-Mt. Union and Blairsville-Broadtop CSDs influenced sedimentation patterns at the western edge of the Stafford depocenter.



Relatively rapid thinning of the organic-rich Levanna to the east is suggestive of down-to-west displacement along the Lawrenceville-Attica fault creating a black shale depocenter. The western limit of the Levanna is more gradual. The thicker region of the Levanna (20 ft isopach) terminates close to the Tyrone-Mt. Union CSD. However, the effects of this fault on basin morphology appear not to have been great enough to preclude accumulation of carbonaceous sediment well to the southwest of the Tyrone-Mt. Union CSD. The southwestern limit of Levanna sedimentation may have been influenced by down-to-east displacement on the Pittsburgh-Washington CSD. Progressive subsidence of the crustal block defined by the Lawrenceville-Attica and Tyrone-Mt. Union CSDs in tandem with rising base level is indicated by westward and northward onlapping of the most organic-rich facies of the Levanna Member.

CONCLUSIONS

The Marcellus 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 presented in this study demonstrates that transgressive systems tract and early regressive systems tract deposits contain the greatest abundance of malleable organic matter. These same deposits are enriched in those components that enhance brittleness, including quartz, calcite, and pyrite.

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