The Pennsylvania State University

The Graduate School

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SEQUENCE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE BURKET MBR., HARRELL FM. AND ASSOCIATED STRATA IN THE NORTHERN APPALACHIAN BASIN

A Thesis in

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By

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Abstract

Organic-carbon-rich shales of the Burket Member, Harrell Formation, were deposited at the toe and basinward of a series of alternately prograding and backstepping clinothems associated with the proto-Catskill Delta complex centered in or around western Susquehanna and Wyoming Counties, Pennsylvania. Distribution of organic-carbon-rich facies was controlled by changes in the delta complex driven by variations in rates of creation of accommodation and by a persistent topographic high centered in the area of western McKean and eastern Warren counties, Pennsylvania. Specifically, I interpret the middle and upper Tully Ls., the Burket Mbr., and the upper Harrell Fm. as comprising a single third order depositional sequence with the lower Tully Ls. being deposited during the falling stage of the preceding third order sequence. The middle Tully LS. represents the lowstand systems tract (LST), whereas the upper Tully Ls. and basal portion of the Burket Mbr. were deposited during the transgressive systems tract (TST). The upper portion of the Burket Mbr. was deposited during the highstand systems tract (HST) and the upper Harrell Fm. was deposited during the falling stage systems tract (FSST). The regional extent of parasequence sets, systems tracts, and the inferred depositional sequences, along with correlations with large scale transgressive sequences in other basins, suggest that base-level fluctuations were largely the result of allogenic forcing – eustacy, climate, or regional thermal uplift or subsidence – rather than autogenic forcing. Geochemical analysis suggests that bottom water conditions were oxic to suboxic at the time of Tully Ls. deposition but that conditions had become anoxic to euxinic by the time of Burket Mbr. deposition.

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Introduction

The development of unconventional drilling technologies in the 1990s, specifically horizontal drilling techniques and hydraulic fracturing, has created a renaissance for hydrocarbon production in the Appalachian Basin. In Pennsylvania alone, over 18,000 drilling permits were issued for unconventional oil and gas wells from 2000 to 2014 (PA Office of Oil and Gas Management 2015). Within the Appalachian Basin there are six organic-carbon-rich black shale intervals that have proven reserves, or may be prospective for unconventional hydrocarbon exploration: The Marcellus Fm., the Utica Fm., the Burket Mbr. of the Harrell Fm, the Middlesex Mbr. of the Sonyea Fm., the Rhinestreet Mbr. of the West Falls Fm., and the Dunkirk Mbr. of the Canadaway Group. The Middle Devonian Marcellus Fm. of Pennsylvania (PA), New York (NY), Ohio (OH), and West Virginia (WV) is the most well-known, was the first to be developed using horizontal drilling and hydraulic fracturing technologies, and now is a proven natural gas resource. By some estimates the Marcellus may contain as much as 500 trillion cubic feet (TCF) of total natural gas and 144.1 TCF of undiscovered hydrocarbons (Engelder and Lash 2008). The Middle Ordovician Utica is the second most promising and is the target of a large amount of development, particularly in central and western Ohio where lower levels of thermal maturity allow for the production of significant quantities of liquid hydrocarbons.

The Burket lies above the Marcellus approximately 100’ in western PA to over 1500’ in northeastern PA and southeastern NY. Isocore thicknesses of the Burket range from zero, in northwestern-most PA and along the Pennsylvania-Ohio border, to approximately 200’ in northeastern PA and southeastern NY. Organic-carbon-rich shales of the Burket were deposited in the central portions of the basin and are coeval with the more proximally deposited organic-carbon-lean siltstones and sandstones of the Harrell and Trimmers Rock Formations. Organic carbon content is generally lower in the Burket than in the Marcellus, but TOC values in the Burket Mbr. of around 4% by weight were measured near the PA outcrop belt as part of this study, while TOC values as high as 5% by weight have been measured in well cuttings from northern PA (Arnold 2010).

While the Burket Mbr. has been studied in outcrop and in central New York and eastern PA (Lash 2007, Arnold 2010, Wilson, Schieber et al. 2010, Wilson 2012), the unit is only cursorily known in the subsurface of PA and south-central NY (David, Lombardi et al. 2004). Herein I demonstrate that the organic-carbon-rich shales of the Burket constitute a prospective unconventional gas reservoir. It was deposited at the distal end of a series of clinothems associated with the alternately prograding and back-stepping proto-Catskill Delta complex as shown primarily through well-to-well correlations of wireline logs. The distribution and thickness of organic-carbon-rich facies of the Burket Mbr. were influenced by shifts in the delta complex, driven by changes in sedimentation and accommodation rates (Ettensohn and Barron 1981). A series of isochore and facies maps predict the prospectivity of the Burket Mbr. in the subsurface of PA and southern NY.

Background

Stratigraphy

Stratigraphic nomenclature of the units discussed in this study is quite complex and varies across the study area (Fig. 1), reflecting over one hundred years of study and interpretation. Recent publications have attempted to resolve and simplify the terminology (Ver Straeten and Brett 2006, Ver Straeten 2007), but correlations into the subsurface from outcrops along the periphery of the basin still result in conflicting terms. Unit names referenced in this study are presented in Figure 2.

The oldest unit in the study interval is the Mahantango Fm., a grey, brown, or olive siltstone and shale, interbedded with fine sandstones. The Mahantango Fm. conformably overlies the Marcellus Formation and unconformably underlies the Tully Limestone (where present), a limestone and calcareous shale. The Marcellus Fm., the Mahantango Fm., and the Tully Ls. constitute the Hamilton Group, a predominantly siliciclastic unit. Some authors have included the Tully Ls. as part of the Mahantango Fm. (Hasson and Dennison 1988, Berg, Dolimpio et al. 1993, de Witt, Roen et al. 1993), whereas more recent workers have treated the Tully as an independent unit of the Hamilton Group (Brett, Baird et al. 2011). For the purposes of this study, I utilize the latter convention due to the sharp break in lithology between the Mahantango Fm. and the Tully Ls., as observed in outcrops, cores, and wireline logs in PA, and I will refer to the Tully Limestone Member as the Tully Ls. and the subjacent siliciclastic facies as the Mahantango Fm. Conditions allowing for the deposition of the Tully Ls. have been attributed to syn-depositional basement structures that acted to sequester clastic sediments proximal to their source area to the east, allowing a carbonate ramp/platform structure to develop across central and southern New York and north central Pennsylvania (Heckel 1973, Woodrow, Dennison et al. 1988). The eastern, proximal equivalent of the Tully Limestone in Pennsylvania and southeastern New York is a sandy siltstone to sandstone known as the Gilboa Formation (Fig. 2); see also (Heckel 1969, Rickard 1989). The lateral contact between the Gilboa and the Tully is quite abrupt (Rickard 1989), and the two interfinger, indicating coeval deposition.

Above the Tully Limestone/Gilboa Fm. in the study area lies an organic-carbon-rich mudstone which is the focus of this study. In central and eastern PA it is known as the Burket Member of the Harrell Formation; in NY and western PA this unit has the status of a formation and is known as the Geneseo Fm., part of the Genesee Group. In northeastern-most PA, where clastic dilution has rendered the basal portion of the Harrell Fm. relatively organic lean, the Burket is not identified. For the purpose of this study I will honor the central PA nomenclature and refer to the organic-carbon-rich, high gamma-ray API mudstone immediately above the Tully Limestone/Gilboa Fm. as the Burket Member of the Harrell Fm., while the overlying or laterally chronostratigraphically equivalent organic-lean mud/siltstone will be referred to as the Harrell Fm.

The Mahantango through Harrell Fms. were deposited during the Givetian-4 and -5 3rd-order sequences of Brett, Baird et al. (2011). It is worth noting that earlier work, including stratigraphic columns published by the Pennsylvania Geologic Survey, have pegged the transition from the Middle to the Late Devonian at the top of the Tully Limestone (Ettensohn 1985, Rickard 1989, Berg, Dolimpio et al. 1993, Bartholomew and Brett 2007), whereas more recent publications have included the Burket and the Harrell in the Middle Devonian, drawing the Middle/Late Devonian boundary at the contact between the Harrell and the Brallier Formations (Brett, Baird et al. 2011). Givetian-4 corresponds to the cycle Ii of the Brett, Baird et al. (2011) sea level curve. The base of Givetian-4 is marked by a widespread pack- to grain-stone unit, the South Lansing Coral Bed/Spezzano Bed of the Upper Windom Member, Moscow Fm. (Brett, Baird et al. 2011). Givetian-5 is analogous to T-R Cycle IIa of Johnson et al., (1985). The start of Givetian-5 is marked by the Taghanic Unconformity (Brett, Baird et al. 2011), and also represents the end of the Lower Kaskaskia Supersequence and the beginning of the Upper Kaskaskia (Sloss 1963). This unconformity was originally thought to occur at the base of the Tully Ls., but is now recognized as a surface in the middle, across which there is a sharp shift in sedimentary facies from highly argillaceous, micritic limestone below to cleaner, fossil rich, wackstone above. The end of the Givetian Stage lies at the upper contact of the Harrell Fm. (Brett, Baird et al. 2011). The absence of definitive dates (such as those from the Tioga Bentonites of the Marcellus Formation) makes constraining the ages of deposition of the Tully and Burket difficult; however, the absolute age of the Givetian has been defined as the interval from 388.1 (± 2.6) Ma to 383.7 (± 3.1) Ma (Kaufmann 2006). The end of Harrell Fm. deposition has been interpreted to coincide with the end of the Givetian (Brett, Baird et al. 2011). Furthermore, the Lower Tully lies roughly in the middle of the *Po. Ansatus* conodont zone and Burket deposition ends just at the boundary between the *S. Hermanni* and *K. Disparilis* zones (Brett, Baird et al. 2011). Recent work has applied absolute ages to these conodont zone boundaries (Kaufmann 2006). It is therefore reasonable to assume that the deposition of the Tully Limestone and Harrell Shale occurred from 386.8 (± 3.2) Ma to 383.7 (± 3.1) Ma. Additional evidence for the absolute age of these formations is provided by the presence and global correlation of the Geneseo/Taghanic Bioevent. Recent work focusing on outcrop exposures in northern Spain, and utilizing previously established conodont zone chronostratigraphy, has placed the timing of the Geneseo Biovent (later portion of the diachronous Taghanic Biocrisis) at between 385.8 Ma to 386.2 Ma (García-Alcalde, Ellwood et al. 2012). Thus I feel confident in asserting that deposition of the Tully Ls. occurred from 386.8 (± 3.2) Ma to 385.5 (± 3.2) Ma and deposition of the Burket Mbr. occurred from 385.5 (± 3.2) Ma to 384.7 (± 3.5) Ma. Thus the Burket Mbr. probably represents less than one million years of sediment accumulation.

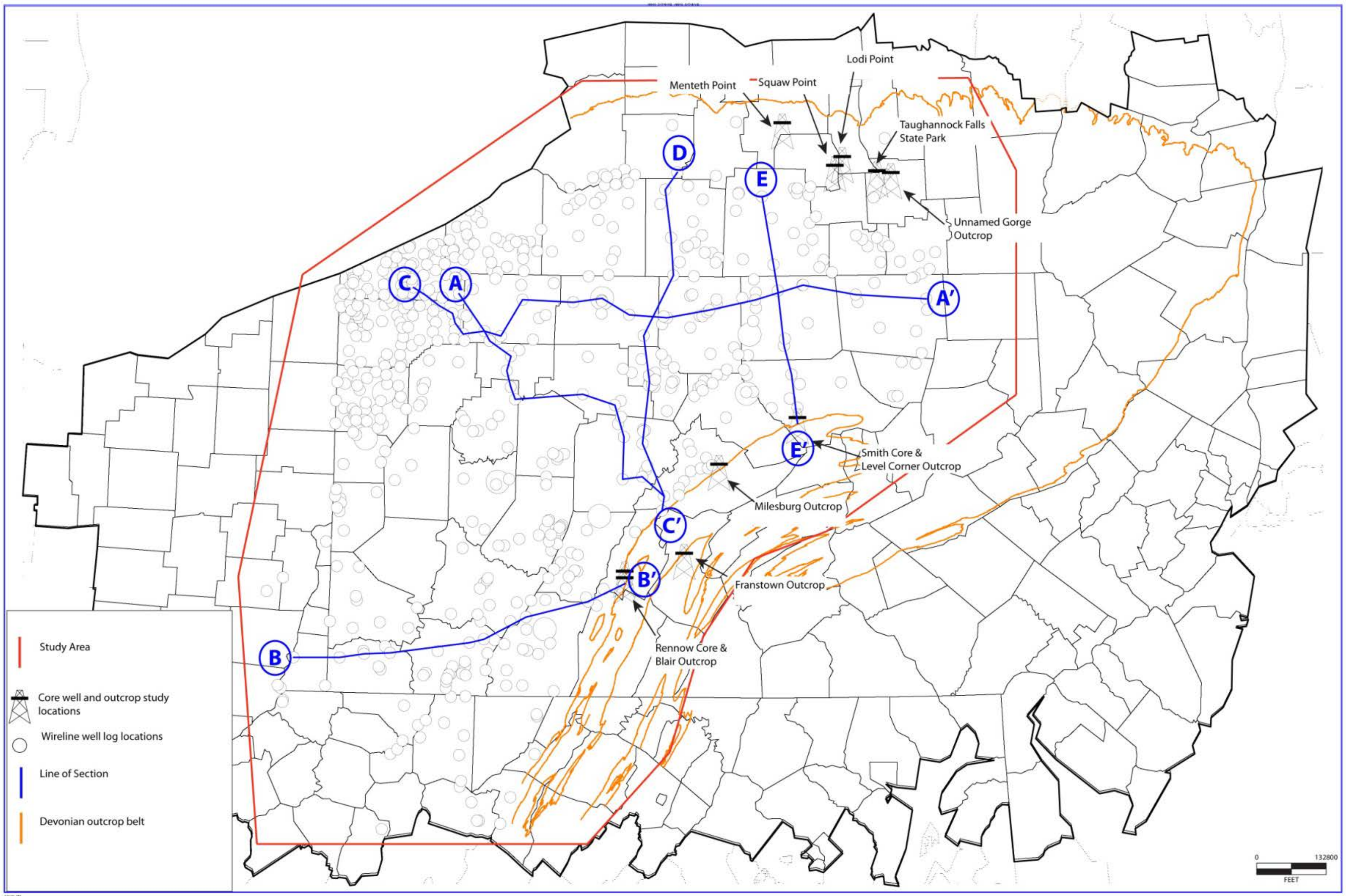


Figure 1 – Study area, well and outcrop study locations, and lines of section.

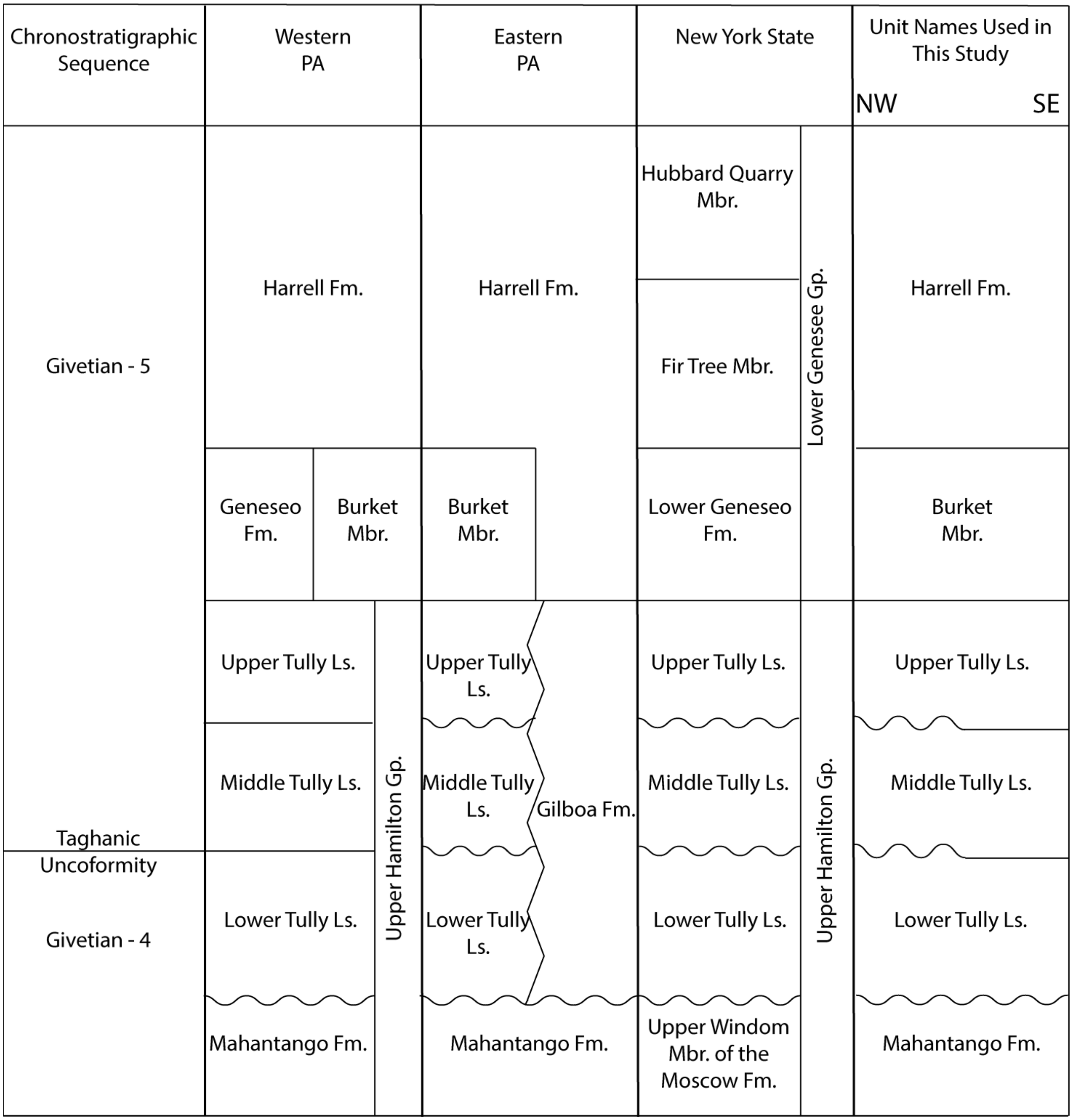


Figure 2 – Stratigraphic nomenclature of the late Middle Devonian (Giv-4 and Giv-5). Columns 2, 3, and 4 after Rickard (1975), Berg, Dolimpio et al. (1993) and Brett, Baird et al. (2011). Column 5 from this study.

Tectonic, Climatic, and Basin Setting

The units examined in this study were deposited in the Middle to Upper Devonian Acadian foreland basin of eastern North America. This basin was elongate, with its major axis trending roughly southwest-northeast. The basin formed due to crustal loading induced by the collision of Laurentia with the Avalonian microcontinent in the Late Silurian through Late Devonian (Ettensohn 1985, Ettensohn 1985). Flexural modeling based on preserved stratal thicknesses indicates that this collision resulted in two km of crustal thickening across eastern PA, New Jersey, and southeastern NY during the Middle Devonian. Thickening continued through the Late Devonian creating an additional ten km of crustal thickness by the Late Devonian (Fig. 3) (see also (Beaumont, Quinlan et al. 1988). Clastic detritus shed west-northwestward from these orogenic highlands constituted the primary clastic input to the Middle and Upper Devonian Acadian Basin (Ettensohn 1985, Beaumont, Quinlan et al. 1988).

Following the Pragian Walbridge Unconformity (Sloss 1963), the basin was flooded from the southwest by marine waters from the Rheic Ocean. Bathymetry in the study area during the Middle and Upper Devonian is poorly constrained, but a general shoaling to the north and northeast is inferred from the fringe of Onondaga and Tully reef deposits of southern and southwestern NY (Mesolella 1978, Edinger, Copper et al. 2002). This interpretation agrees with the hindcast models of Beaumont et al. (1988). The eastern and southeastern margins of the basin were bounded by the Acadian Highlands (Mesolella 1978).

During the Middle Devonian, the northwestern margin of the basin apparently was not bounded by the type of flexural forebulge typically associated with foreland basins (Beaumont, Quinlan et al. 1988, Ver Straeten and Brett 2000, Ver Straeten 2007, Kohl, Slingerland et al.

2014). Instead, the northwestern margin was formed by a paleo-topographic high, previously referred to as the Findley-Algonquin Arch, that resulted from the interaction of crustal loading of the Acadian Highland, Acadian Foredeep, and the intracratonic Michigan basin (Beaumont, Quinlan et al. 1988, Ver Straeten and Brett 2000, Ver Straeten 2007, Kohl, Slingerland et al. 2014). The Michigan basin experienced much higher (up to 2X) sedimentation rates than the Appalachian basin throughout the Middle Devonian (Beaumont, Quinlan et al. 1988). By the Upper Devonian, however, deposition rates in the Appalachian basin far exceeded those in the Michigan basin (by up to 10X) (Beaumont, Quinlan et al. 1988). Stratal thicknesses of the Tully and Burket suggest that the Findley-Algonquin Arch persisted at least through the earliest Upper Devonian. During the Middle and earliest Upper Devonian, the higher sedimentation rates and corresponding increased crustal loading in the Michigan Basin likely acted to dampen the effect of loading in the Acadian Highlands and Foredeep and prevented flexural uplift from forming a true forebulge. The Findley-Algonquin Arch was an area of reduced accommodation during the Middle and earliest Upper Devonian (Beaumont, Quinlan et al. 1988). Therefore, unconformities (specifically the Sub-Tully, Lower Tully or Taghanic, and Upper Tully unconformities) have removed, or caused to not be deposited, the greatest portion of strata from the arch region. These surfaces become generally conformable to the south and east, towards the Acadian Foredeep.

During the Middle to earliest Upper Devonian, Laurentia was located between 25° and 35° south latitude, within a subtropical climate belt (Scotese and McKerrow 1990, Edinger, Copper et al. 2002). This temperature regime promoted production and deposition of carbonates, which, combined with clastic material shed off of the Acadian Highlands, created a mixed clastic-carbonate depositional system (Brett and Baird 1985). Relatively warm water (~25° to 35° C) (Milici and Swezey 2006) promoted the deposition of carbonates, which, combined with the input of clastic detritus shed from the Acadian highlands, produced a mixed clastic-carbonate system (Brett and Baird 1985).

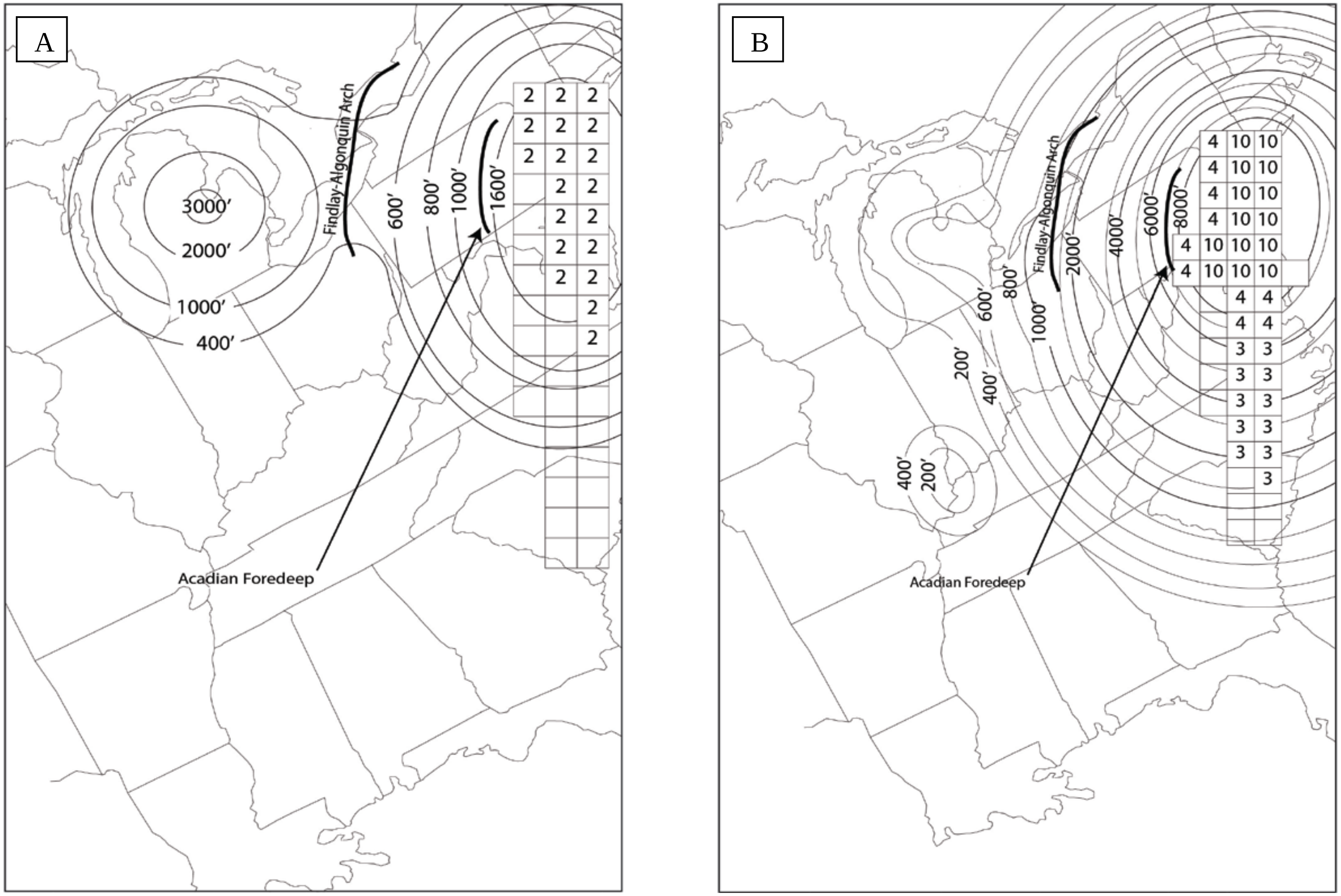


Figure 3 - Flexural model reconstruction of the crustal thickening associated with the Acadian Orogeny and original depositional thicknesses of sediments of the Middle Devonian (A) and Upper Devonian through Lowest Missispian (B). Numbers in boxes indicate additional crustal loads (in km); isopach lines indicate total thickness of sediment deposited (Beaumont, Quinlan et al. 1988).

Methods

Dataset

The dataset for this study consists of: 1) approximately 600 wireline well logs distributed throughout the study area; 2) two well cores, one in Lycoming County, PA, at 41°12'36.25"N 77°12'15.55"W, and one in Blair County, PA, at 40°22'42.36"N 78°26'5.37"W; and 3) 8 outcrop studies, located in Newry (Blair County), Milesburg (Centre County), Level Corner (Lycoming County), PA, and Lansing (Tompkins County) Taghannock Falls State Park (Tompkins County), Lodi (Seneca County), Squaw Point (Yates County), and Menteth Point (Ontario County), NY (Fig. 1) see Appendix A for coordinates of outcrop studies.

The wireline logs used in this study were obtained from publicly available databases in PA (The Pennsylvania Internet Records Imaging System, PA-IRIS), NY (The Empire State Oil and Gas Information System, ESOGIS), WV (The West Virginia "Pipeline" System), and OH (The Risk Based Data Management System, RBDMS). Wireline log analysis was conducted using the PETRA software suite. While a wide array of electric and nuclear logs are present in the well log set, sequence stratigraphic correlations and lithologic interpretations are primarily based on wireline gamma ray (GR) logs and synthetic wireline GR logs produced from outcrop surveys using a handheld spectral scintillometer. It is often the case that older GR logging tools were less sensitive than their modern counterparts, resulting in artificially depressed GR responses that do not correspond well to nearby logs of more recent vintage. For this reason, many of the GR logs used in this study were normalized to a standard response range calculated from a nearby log recorded within the last 20 years following the techniques outlined in Shier (2004). A neighbor-comparison statistical-shift normalization scheme was utilized to correct older logs (Shier 2004). Each of the older GR logs was normalized to the closest (based on surface distance) modern log using a statistical shift based on the P5 and P60 GR response within an interval defined by the base of the Tully and the top of the Harrell (Fig. 4). The P5, a GR value that is higher than 5% of the data points within the normalization interval, approximates the minimum GR response of the Tully Limestone while the P60, a GR value that is higher than 60% of the data points within the normalization interval, approximates the mean GR response of the upper Harrell. For wells in which a significant discrepancy exists between the relative stratal thicknesses of the Tully Ls. and Harrell Fm., additional adjustments to the normalization scheme were necessary to achieve good fits between the low GR of the Tully Ls. intervals and the mid-high GR of the upper Harrell Fm. For example, thickening of the Tully Ls. will tend to cause the P5 and P60 GR values to be lower, whereas thinning will cause the P5 and P60 GR to be higher.

The two cores examined in this study were shallow NX size cores drilled by the Appalachian Basin Black Shale Group (ABBSG) and taken from areas close to outcrops. The cores were first slabbed, then one half was polished using 100 grit emery cloth. Carbonate rich intervals, particularly the Tully Ls. intervals, were washed with 10% HCl to reveal previously undetectable bioturbation. The cores were then described at the decimeter scale and samples were taken for geochemical and mineralogical analyses as well as for thin section preparation. Finally, the cores were scanned using a GeoTek MSCL-S automated core analyzer fitted with XRF, magnetic susceptibility, and natural gamma ray sensors. Core scanner data were sampled at 2.5 cm (.984 in) intervals and are presented as a smoothed curve.

Outcrops were examined and described at the decimeter scale in order to create standard lithic logs. At 7 outcrops we measured GR response using a handheld spectral gamma ray scintillometer (RS-230 BGO Super-Spec from Radiation Solutions). The scintillometer was placed flush to the outcrop face, parallel to bedding, and measurements were taken every 6 inches using a 45 second assay time. Plotting these data produces a spectral gamma ray log similar to, and comparable with, a wireline spectral gamma ray log (Ettensohn, Fulton et al. 1979, Chamberlain 1984, Jordan, Slatt et al. 1991, Svendsen and Hartley 2001). While care was taken to ensure a clean, flat, and unweathered surface for all measurements, sources of error include outcrop surface irregularities and variations in U, Th, and K concentrations due to weathering of exposed surfaces. From core and outcrop observations, individual facies were identified and 16 large-format thin sections were prepared by Spectrum Petrographics to assist with facies descriptions and depositional environment interpretations.

Lithologic facies were mapped to GR log responses, generating idealized siliciclastic and carbonate dominated successions that were then used to inform interpretations of both lithologic and depositional facies interpretations for other wells. Mudstone-dominated rocks were divided into five facies (M1 – M5), consisting of mudstones to muddy siltstones (Fig. 7). These facies represent the distal end-members of both the siliciclastic- and carbonate-dominated successions.

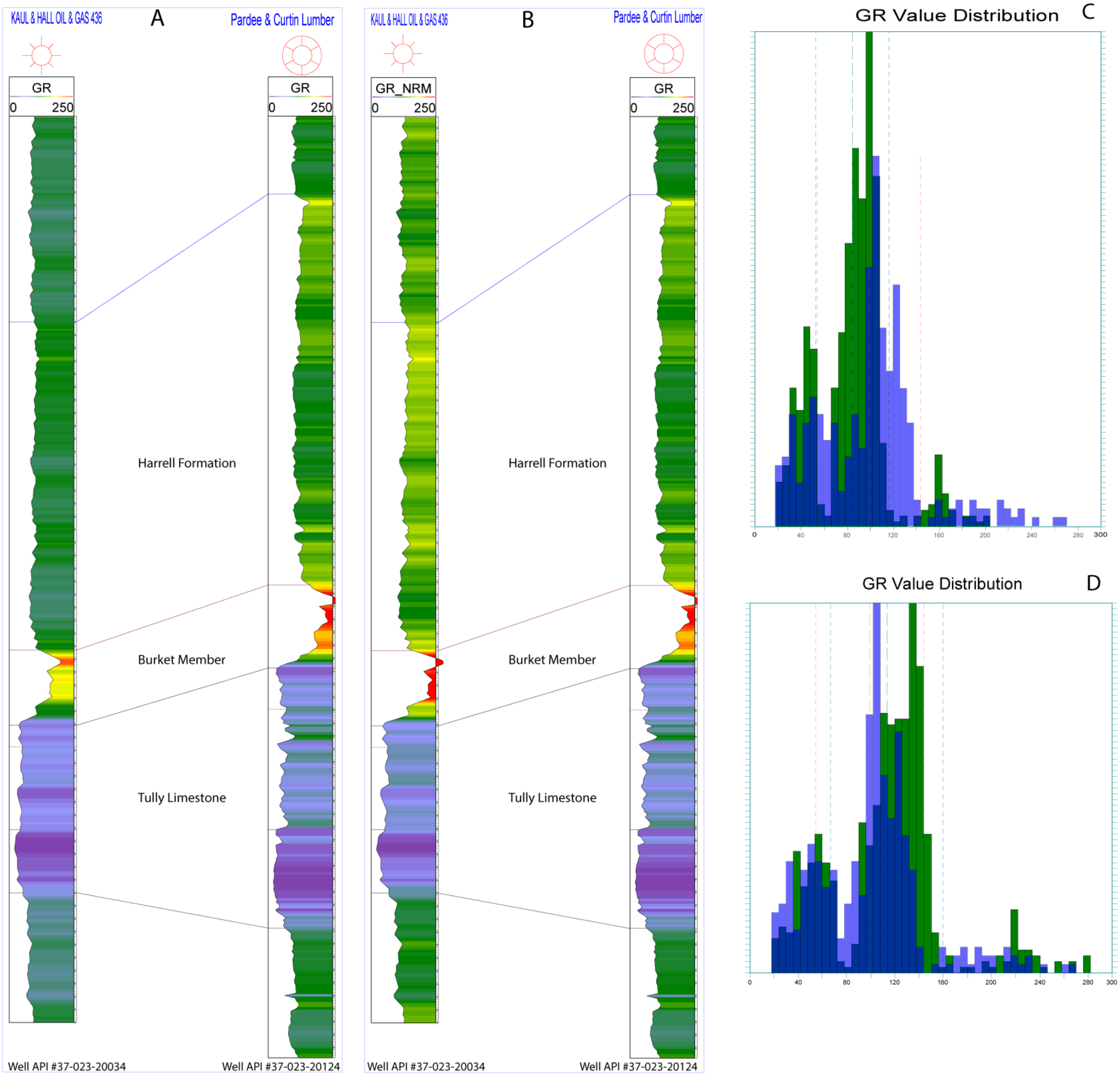


Figure 4 – Example of GR log normalization. GR response from older (left) and more recent (right) logging tools before (A) and after (B) normalization. GR value distribution histogram camparisons between older (green) and recent (blue) logs are shown before (C) and after (D) normalization (overlap appears as dark blue). Note that both the log and the log histogram of the older well more closely resembles that of the newer well after normalization (B and D) than before (A and C). Both wells located in western Cameron County, Pennsylvania.

Sequence Stratigraphy

This study employs the sequence stratigraphic terminology and techniques of Catuneanu (2006) and Catuneanu et al. (2009). Systems tracts, genetically related packages of sediment linked to a shoreline trajectory, are grouped together to form a depositional sequence. System tracts are divided into parasequences, defined as “a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces” (Van Wagoner, Mitchum et al. 1990). Parasequences are typically identifiable in GR logs by an upward-decreasing GR response followed by an abrupt shift to a higher GR facies (Van Wagoner, Mitchum et al. 1990). Singh (2008) showed in a study of the Barnett Shale that fluctuations of GR signature correspond to small scale coarsening- or calcifying-upward sequences in that organic-rich mudstone. Similar patterns are observed in the Burket, and are therefore used to correlate well logs, cores, and outcrops.

Consistent with practices articulated in Catuneanu (2006) and Catuneanu et al. (2009), parasequence stacking patterns are utilized to identify systems tracts. Retrogradational stacking patterns indicate that the rate of creation of accommodation (Å) exceeds the rate of sediment supply (Q_s) and the parasequence set is interpreted as representing the transgressive systems tract (TST). Normal regressive stacking patterns indicate that Q_s is greater than Å and the parasequence(s) are interpreted as forming either a highstand systems tract (HST) or lowstand systems tract (LST). These are differentiated by the changes in the ratio of Q_s/Å. During lowstand one would expect to see a progradational ($Q_s >$ Å) to aggradational ($Q_s \approx$ Å) stacking pattern, whereas during highstand the stacking pattern will tend to be aggradational to progradational (Neal and Abreu 2009). A forced regressive stacking pattern, identifiable by a sudden basinward shift of facies and the erosion of proximal strata, indicates a period of base level fall in which Å < 0, and the parasequence(s) are interpreted as part of the falling stage systems tract (FSST).

I identified four significant stratigraphic surfaces: the sequence boundary (SB), the maximum regressive surface (MRS), the maximum flooding surface (MFS), and the basal surface of forced regression (BSFR) (Catuneanu 2006, Catuneanu, Abreu et al. 2009). The SB is a surface of subaerial erosion or its correlative conformity (Catuneanu 2006, Catuneanu, Abreu et al. 2009) and is used to define the end of one depositional sequence and the beginning of the next. The SB can typically be identified in GR logs either by a sharp GR discontinuity, indicative of an erosional unconformity, or by the top of an interval of rapidly decreasing upward GR response and the onset of relatively stable GR response. The MRS marks the shift from shoreline regression to transgression and defines the base of the TST (Catuneanu 2006, Catuneanu, Abreu et al. 2009). The MRS can typically be identified in GR logs as the top of a relatively stable GR interval immediately below an increasing upwards interval. The MFS marks the most landward migration of the shoreline and the transition from retrogradational to progradational strata (Posamentier and Vail 1988, Van Wagoner, Mitchum et al. 1990, Catuneanu 2006) and is typically represented in GR logs as the highest peak. The BSFR marks the onset of base level fall and approximates the paleo-seafloor or ravinement surface where subaqueous erosion occurred due to the downward shifting wave profile. In GR logs the BSFR is typically identified by the onset of a rapidly decreasing upward response.

Choice of Datum

In two of the lines of section presented later in this study I utilize the Taghanic Unconformity as a datum. The Taghanic Unconformity represents the sequence boundary between the Givetian-4 and Givetian-5 third order sequences of Brett and Baird (2011). I have chosen to stand the cross sections on the Taghanic Unconformity rather than hang them from an upper unit, because the former results in a basin stratal architecture more consistent with the paleo-environmental interpretations of the facies. Standing the sections on the Taghanic Unconformity indicates that the New York and northwestern PA portions of the basin were the shallowest areas of the basin, while central and west central PA were the deepest portions. If I were to hang the section from an upper surface, the Tully Ls. of southern New York and northwestern PA, where the greatest amount of erosion or non-deposition has occurred, would become one of the deeper portions of the basin. This is inconsistent with its biota and wave-influenced bedforms. I acknowledge that using the Taghonic Unconformity and its correlative conformity as the datum fails to account for any bathymetric features that may have been present at the time of this surface as well as for erosional truncation and sediment bypass, both of which were especially pronounced along the northern margin of the basin and, at times, in the eastern portion of the study area. It further fails to account for the presumably significantly higher subsidence rates in the eastern portion of the basin, proximal to the Taghanic Highland.

In the cross sections from C to C', D to C', and E to E' I have chosen to hang the sections on a datum marking the onset of rapid transgression and the beginning of Burket Mbr. deposition. I have utilized this surface because sections D to C' and E to E' are predominantly parallel to the strike of the clinothems and this convention preserves the presumably relatively flat lying geometry of the Burket Mbr. beds. Furthermore, all three of these lines of section run across the Rome Trough and using a datum surface above the Tully Ls. most accurately represents the thickening of the Tully Ls. due to increased accommodation through this bathymetric feature.

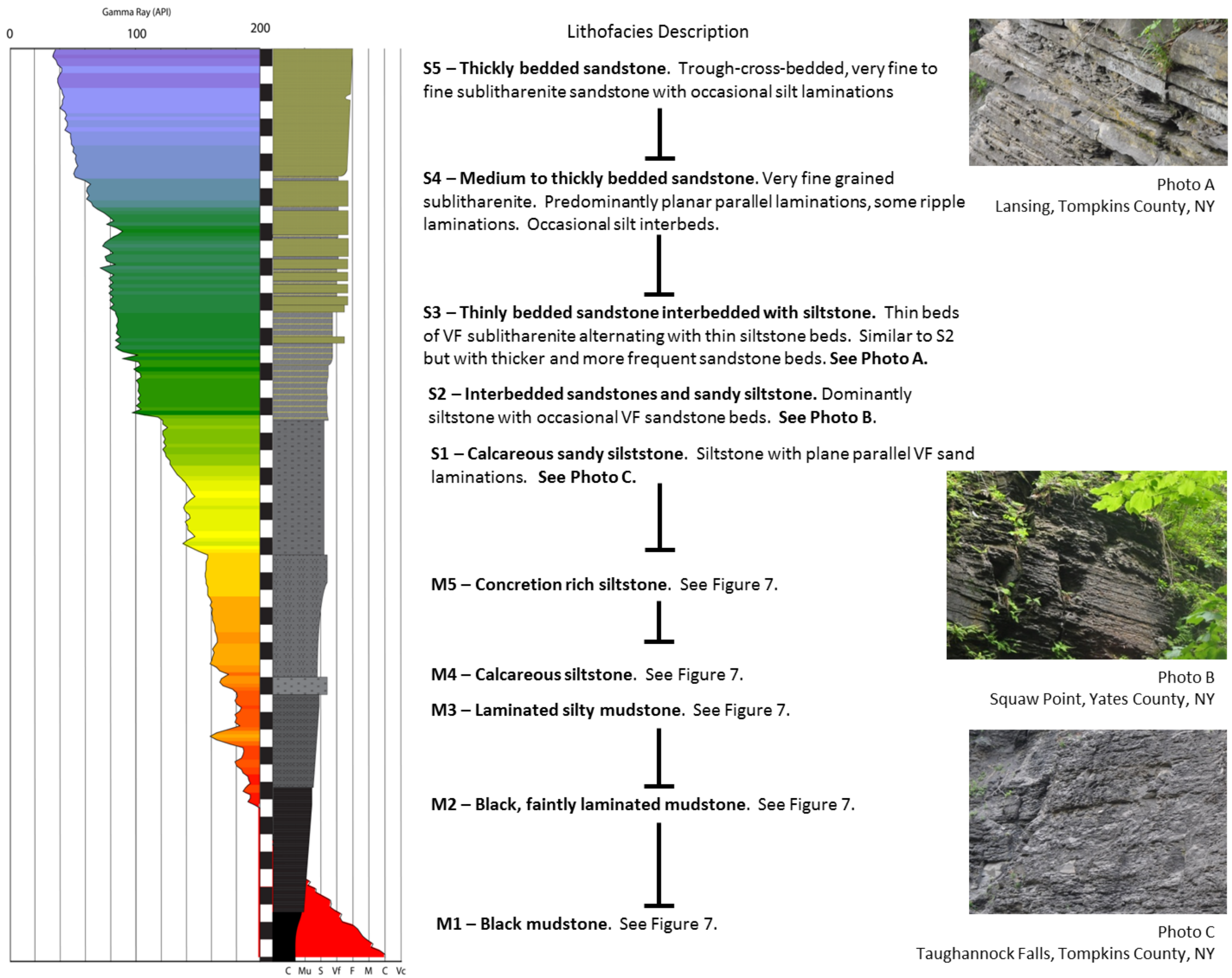
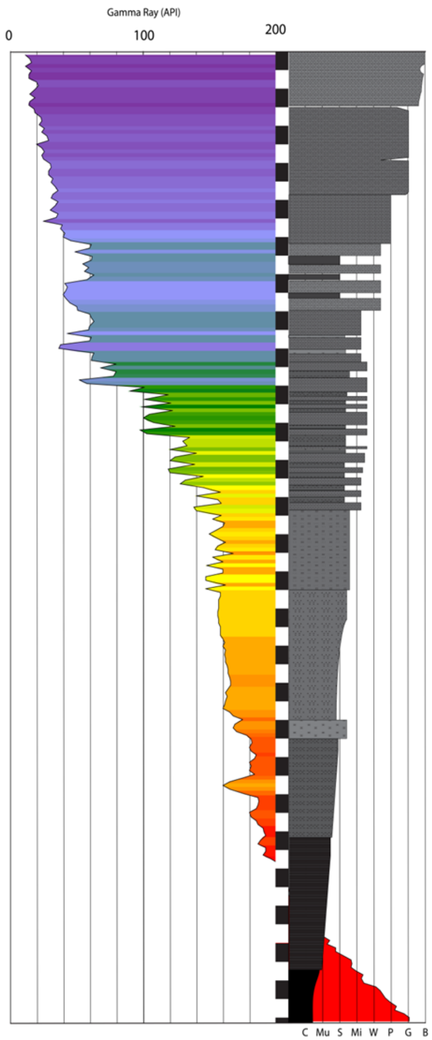


Figure 5 – Idealized clastic facies succession mapped to GR response



Lithofacies Description

C6 – Biostromal, biohermal facies. Rugose corals forming reef mounds with onlapping crinoidal grainstones.

C5 – Crinoidal grainstone. Grainstone composed primarily of crinoid columnals. Brachiopods and rugosians are common.

C4 – Packstone dominated facies. Fossiliferous light to medium grey packstone. **See Photo A.**

C3 – Wackstone dominated facies. Dark grey to grey wackstone. Grains predominantly composed of small scale calcite fragments and shell (brachiopod, gastropod and bivalve) fragments. **See Photo B.**

C2 – Micrite dominated facies. Light grey micritic limestone . Typically heavily bioturbated. **See Photo C.**

C1 – Calcareous fossiliferous siltstone. Dark grey calcisiltite. **See Photo D.**

M5 – Concretion rich siltstone. See Figure 7.

M4 – Calcareous siltstone. See Figure 7.

M3 – Laminated silty mudstone. See Figure 7.

M2 – Black, faintly laminated mudstone. See Figure 7.

M1 – Black mudstone. See Figure 7.

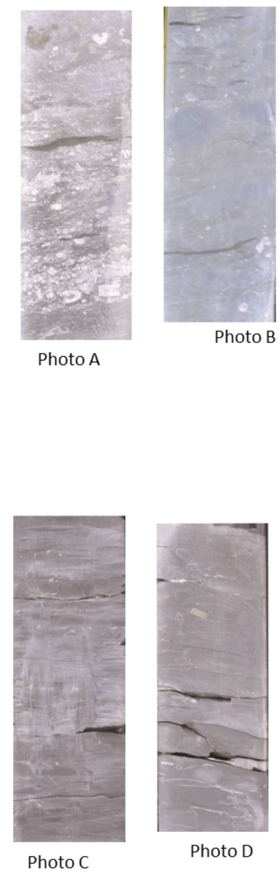


Photo A from Rennow Well, Blair County, PA
Photos B, C, and D from Smith Well, Lycoming County, PA

Figure 6 – Idealized carbonate dominated facies succession mapped to GR response

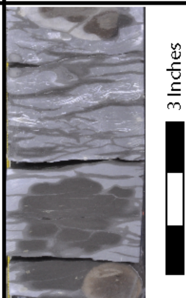
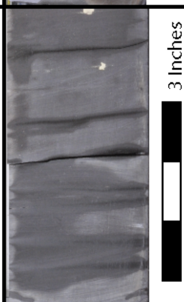
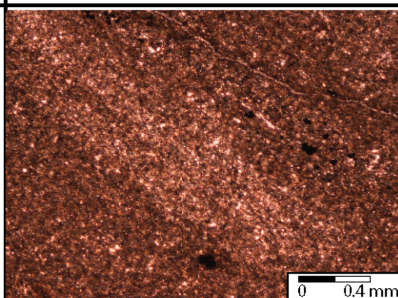
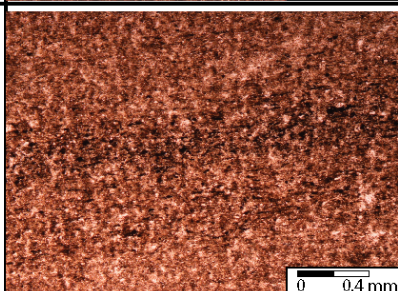
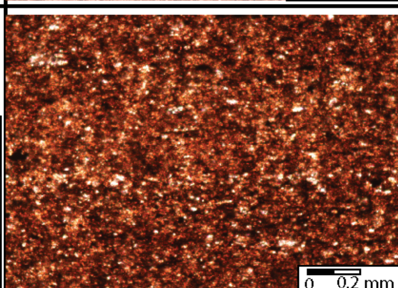
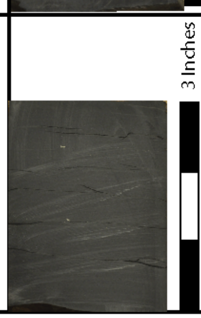
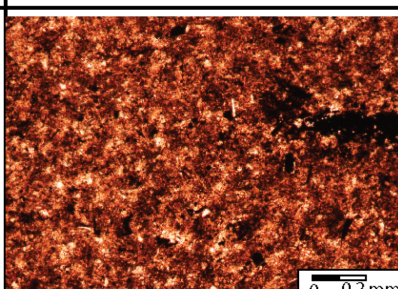
Facies	Core Photo	Thin Section Photo	Description
M5		No Thin Section	Medium grey to dark grey siltstone. Carbonate concretions common. Concretions range in size from tens of millimeters to 30 or 40 centimeters in diameter. Plane parallel laminations are typically distorted by differential compaction.
M4			Dark grey, calcareous siltstone. Generally plane parallel laminations. Carbonate is generally present as micritic mud and shell fragments. Carbonate content is generally 20-30%
M3			Dark grey, silt-rich mudstone with thin to thick plane parallel laminations. Pyrite is common as framboids and nodules. Carbonate content varies from 8% to as high as 15%
M2			Black mudstone with thin, faint, plane parallel laminations. Pyrite is observed as both nodules and framboids. Silt sized quartz grains constitute approximately 30-40% of the matrix. Carbonate content is generally in the range of 6-8%
M1			Black, organic-rich mudstone. Generally massive to faintly laminated. Pyrite present primarily as framboids, though some nodules are observed. Framboids are generally small (<12 μm). Silt sized quartz grains generally constitute less than 30% of the matrix. Carbonate content is generally in the range of 6-8%.

Figure 7 – Mudstone dominated facies in thin section and hand sample

Results

Tully Limestone

First I will briefly discuss the Eifelian and Givetian strata that underlie the Tully Limestone in order to understand the paleogeography at the onset of Tully Ls. deposition. The Sub-Onondaga Unconformity and its correlative conformity form the base of the Eifelian sequence. The Onondaga Fm. overlies this sequence boundary (Inners 1975, Ver Straeten 1996, Ver Straeten 2007) in northeastern and western PA and southern New York. The Onondaga Fm. grades into its lateral equivalent the Selinsgrove Mbr. of the Needmore Fm. in central and southern PA (Inners 1975, Ver Straeten 1996, Ver Straeten 2007). The Onondaga Fm. is a carbonate-dominated unit that consists of facies ranging from fossiliferous reef deposits to black calcareous mudstones (Inners 1975, Ver Straeten 1996, Ver Straeten 2007). The Selinsgrove Mbr. is composed primarily of argillaceous wackstone and micrite limestones interbedded with calcareous shales and represents the deeper water facies of the coeval Onondaga Fm. (Inners 1975, Ver Straeten 1996, Ver Straeten 2007). The Onondaga and its equivalents comprise the Eif-1 and the TST of the Eif-2 third order sequences of Brett, Baird et al (2011). The Marcellus Fm. conformably overlies the Onondaga Fm. and is composed of three members: the basal Union Springs Mbr., the middle Purcell Mbr., and the upper Oatka Creek Mbr. (Ver Straeten 1996). The Union Springs and Oatka Creek Mbrs. consist primarily of fine-grained, organic-carbon-rich shales and mudstones interpreted to have been deposited under anoxic to euxinic conditions during periods of elevated base level (Brett, Baird et al. 2011, Ver Straeten, Brett et al. 2011, Kohl, Slingerland et al. 2014). The Purcell Mbr. is a calcareous interval consisting of facies ranging from micritic skeletal wackstone to argillaceous black micrite and grades eastward into the sandstone dominated Turkey Ridge Member (Kohl, Slingerland et al. 2014). The Marcellus Fm. comprises the remainder of the Eif-2 (above the MFS) and the Eif-Giv sequence of Brett, Baird et al (2011). The Marcellus Fm. is conformably overlain by the Mahantango Formation, a clastic dominated succession which is composed of three generally coarsening and thickening upward succession of silty mudstones with thin sand laminations to cross bedded sandstones representing third order depositional sequences (Willard 1935, Willard 1935, Duke and Prave 1991, Prave, Duke et al. 1996, Brett, Baird et al. 2011, Ver Straeten, Brett et al. 2011). In western New York, the three third order cycles equivalent to the Mahantango Formation are each assigned Formation status and are referred to as the Skaneateles, the Ludlowville, and the Moscow Formations (Rickard 1975, Brett, Baird et al. 2011). In summary, at the onset of Tully Ls. deposition the northern Appalchian Basin was of moderate depth with the deepest area occupying a roughly northeast to southwest trend from central to southwestern Pennsylvania. Water depth shoaled gradually northward across a carbonate ramp/platform from northern Pennsylvania to central New York. There is no indication of water column stratification or significant sea-floor anoxia at the onset of Tully Ls. deposition.

The Tully Ls. is defined in this study by picking its base at the onset of a coarsening/calcifying-upward sequence at the top of the Manantango Fm. that is represented in the GR logs by a gradual decline in GR response. Its top is placed at the onset of a rapid fining/decalcifying-upward sequence that is represented in the GR logs by rapidly increasing GR response (Fig. 8). Consistent with the interpretations of Brett, Baird, et al. (2011), I have divided the Tully Ls. into three sub-units, the Lower, Middle, and Upper Tully Ls. Earlier work on the Tully Ls., focusing on the New York outcrop belt, divided the Tully Ls. into an upper and lower unit (Heckel 1969, Heckel 1973, Rickard 1975, Rickard 1989, Brett and Baird 1996), but I have chosen to use the more recent convention. Individual parasequences are extremely difficult to correlate within the Tully Ls. due to the drastic differences in thickness and the amount of material that was likely removed by erosion (discussed later in this section). For that reason I have chosen to describe the Tully Ls. based on the three subunits rather than by discussing each parasequence individually.

The Lower Tully Ls. consists of a coarsening/calcifying upward succession (Fig. 8). In GR logs, this interval begins with the onset of a gradual decrease in GR response and ends with the onset of a thick succession of relatively stable, low GR response. This succession of relatively constant GR response is often preceded by a slight GR “kick”. In the New York outcrop belt the upper surface of this interval is recognized as the Taghonic Unconformity (Brett, Baird et al. 2011). The Lower Tully Ls. is absent or thinned in large portions of the study area, especially in western and central New York, due to tectonic uplift and erosion forming the Taghonic Unconformity (Fig. 9) (Heckel 1973, Baird and Brett 2003, Baird and Brett 2008, Ettensohn 2008, Brett, Baird et al. 2011). Lithologically, the Lower Tully Ls. grades from a calcareous mud/siltstone in eastern New York to a slightly argillaceous calcilutite in central New York before thinning to zero in west central New York and along the Pennsylvania/Ohio border (Figs. 9 and 10). Southward from the New York outcrop belt, the Lower Tully thickens and grades into calcareous shale throughout Pennsylvania ((Heckel 1969, Brett, Baird et al. 2011).

The Middle Tully Ls. is recognized in GR logs as a thick, relatively homogeneous interval of low GR response with an upper boundary defined by the onset of a fining/decalcifing upward sequence (Fig. 8). In areas where the Lower Tully Ls. has been removed by the Taghonic

Unconformity, the Middle Tully Ls. rests directly on earlier Mahantango Fm. deposits and is recognizable as an abrupt drop in GR response. GR response of the Middle Tully Ls. is extremely low, typically < 50 API, in southern New York and northern PA. GR response and thickness increase southward into the central portion of the study area (Figs. 11, 12, and 13). The Middle Tully Ls., as described in this study, is synonymous with the Lower Tully Ls. of Heckel (1969 & 1973), Rickard (1975 & 1989), and Brett and Baird (1996). Lithologically it consists of muddy/silty calcilutite at the eastern extent of the formation, where it laterally contacts the Gilboa Fm., grading to the north and west into clean calcilutite (Heckel 1969).

The lower surface of the Upper Tully Ls. is defined in this study by a fining/decalcifying upward succession recognized in GR logs by a gradually increasing GR response. The upper surface of the Upper Tully Ls. is marked by the onset of rapid transgression which accompanied the start of Burket Mbr. deposition and is recognized in GR logs by an abrupt increase in GR response Fig. 8).

Examination of the isochore thicknesses of the three Tully Ls. subdivisions (Figs. 14, 15, and 16) shows very different depositional patterns for the three units. Deposition of the Lower Tully Ls. (Fig. 14) was concentrated in the central basin, especially along a southwest to northeast trend which roughly corresponds to the Rome Trough (Lash and Engelder 2011). This suggests that both clastic and detrital carbonate material was bypassing shelf and slope areas more proximal to the sources and that deposition was largely controlled by accommodation. Deposition of the Middle Tully Ls. shows a markedly different pattern (Fig. 15). The thickest accumulations of Middle Tully Ls. occur in eastern and northwestern PA, areas close to the sources of clastic and carbonate material respectively while only moderate thickening is observed along the Rome Trough. This indicates that sediment supply, rather than accommodation, was the primary control on Middle Tully Ls. deposition. Upper Tully Ls. deposition (Fig. 16) is relatively uniform, with only slight thickening apparent along the Rome Trough and moderate thickening in the east and northwestern portions of the study area. I interpret this to indicate that 1) increasing accommodation closer to the sources of clastic and carbonate material (east of and north of the study area) was acting to sequester significant quantities of sediment, and 2) additional accommodation created by reactivation of basement faults of the Rome Trough was largely filled by the end of Tully Ls. deposition.

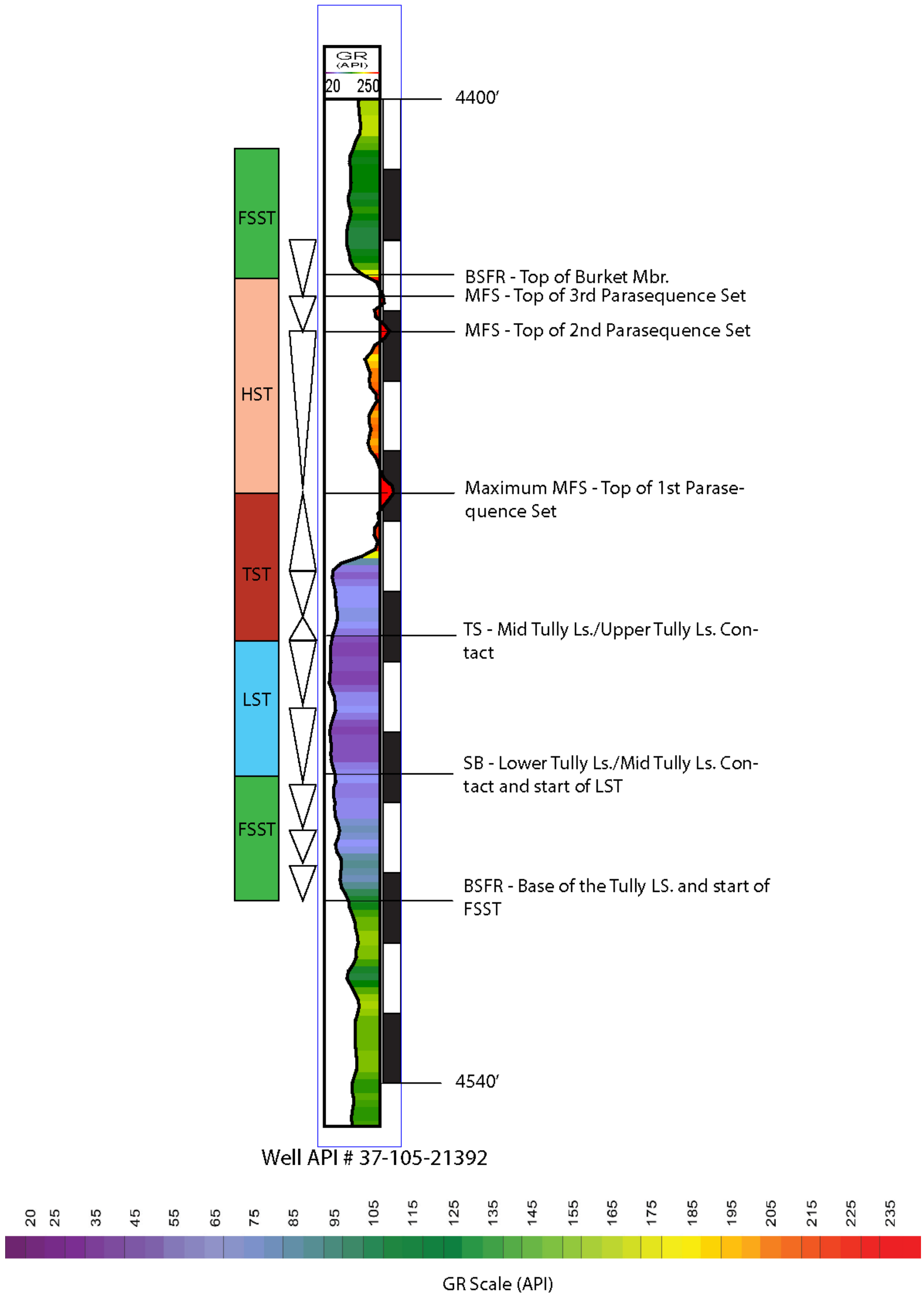


Figure 8 - Type GR log for the Tully Ls. to Burket Mbr. interval with sequence stratigraphic interpretations. Middle column identifies coarsening and fining intervals. Well located in western Potter County, PA.

Burket Shale Member

Stratigraphy

The Burket Member of the Harrell Formation lies conformably above the Tully Limestone. Its base is defined in this study as the start of a rapidly fining/decalcifying interval above the Tully Ls., recognizable in GR logs by a rapid increase in GR response. Its top is defined by a rapidly coarsening/calcifying upward interval recognizable in logs by a rapid decrease in GR response (Fig. 8).

Three parasequence sets (PSS-01 – PSS-03) were identified in the Burket Mbr (Fig. 8) in sections of the study area proximal to the source of Burket clastic material. In more distal portions of the study area, condensation of the Burket Mbr. interval is so pronounced that the three parasequence sets are indistinguishable; the entire Burket Mbr. Interval there consists of a single GR peak (Figs. 9, 10, and 11). The stacking pattern present within the PSS-01 parasequence set is retrogradational (Fig. 17) and I have therefore labelled PSS-01 as the Transgressive Systems Tract (TST). PSS-02 displays a largely aggradational stacking pattern while the stacking pattern of PSS-03 is progradational (Fig. 13). This aggradational to progradational type of stacking is indicative of the High-Stand Systems Tract (HST).

The contact between the Tully Ls. and the Burket Mbr. varies significantly from the central basin to the periphery. In the central and eastern portions of the study area the transition is represented by a gradational increase in GR response across approximately 10-15 feet of section, and where observed in outcrop at the eastern end of the New York outcrop belt it consists of interfingered black mudstone and shaley limestone (Plate 1A). In the western and northwestern portions of the study area the contact is much more sharply defined.

In the northern portion of the basin, the Burket Mbr. consists of interbedded grey silty mudstone and thinly laminated, grey-black to black mudstone containing frequent silt drapes that display evidence of minor bioturbation (Wilson 2012). Pyrite is prevalent as both burrow fill, especially within the silty-grey mudstone, and as large (>12 µm) disseminated framboids (Wilson 2012). Large concretions, up to 40 cm in diameter, are common, especially at exposures in Tompkins County, NY (Plate 1B). Burket Mbr. samples from central and southern Pennsylvania are generally much finer and darker, consisting of massive black mudstone interbedded with faintly laminated, silty, black mudstone. Pyrite is common in PA samples, typically as disseminated framboids of less than 12 µm.

Depositional patterns through the Burket Mbr. (Figs. 18, 19, and 20) are quite similar. Throughout the Burket Mbr. interval deposition was concentrated in the eastern, proximal portion of the study area with thicknesses rapidly decreasing to the west.

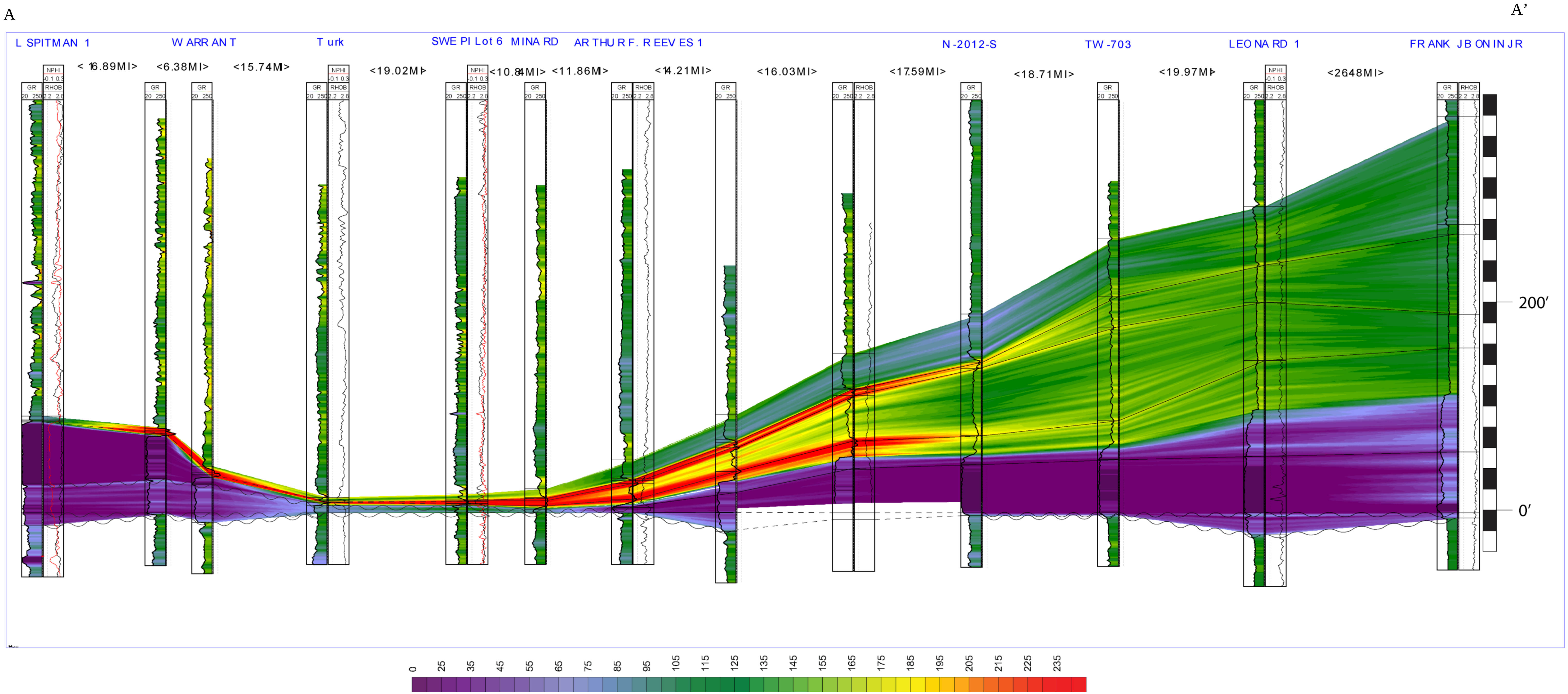


Figure 9 – Cross section A to A' – East to west GR cross section across northern Pennsylvania. Color bar shows gamma response in API units. Left hand log tracks show GR in API units, color bar shown above. Right hand log tracks show bulk density (black, scale 2.2 to 2.8 g/cm^3) and neutron porosity (red, scale -10% to 30%) where available. See Figure 1 for location.

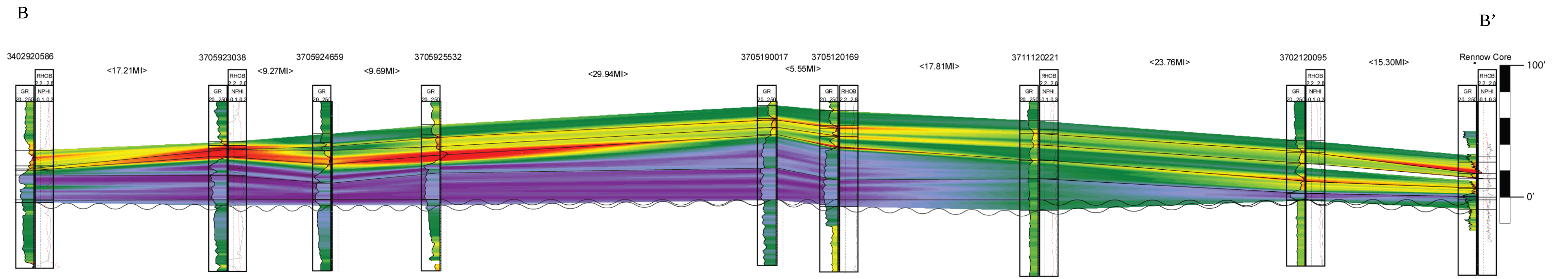


Figure 10 – Cross section B to B' – East to west cross section across southwestern and south-central PA. See Figure 9 for color bar and log track descriptions. See Figure 1 for location. See Figure 1 for location.

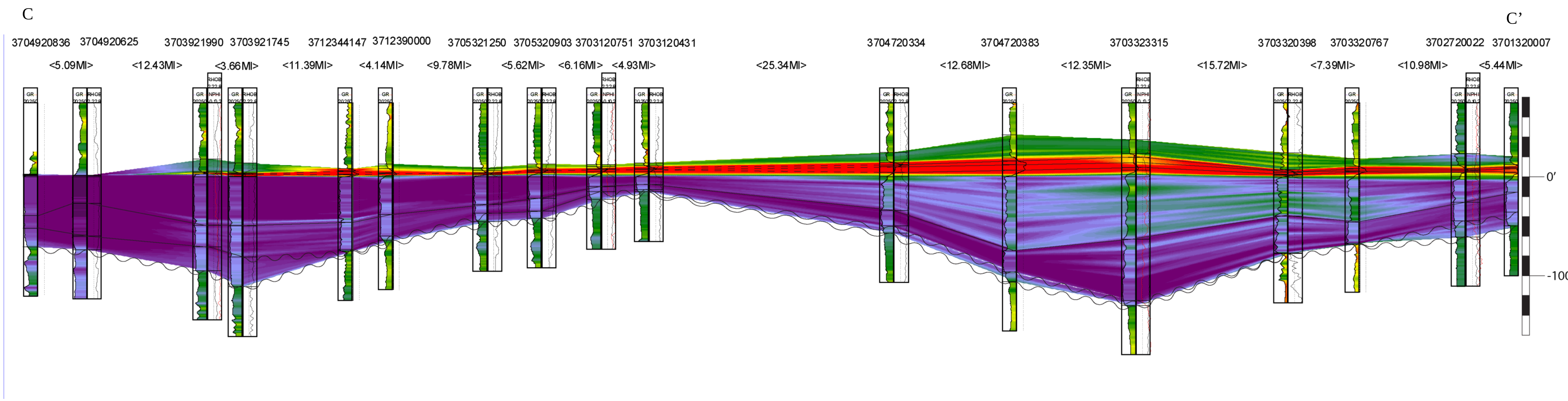


Figure 11 – Cross section C to C' – Northwest to southeast cross section across central and northwestern PA. See Figure 9 for color bar and log track descriptions. See Figure 1 for location.

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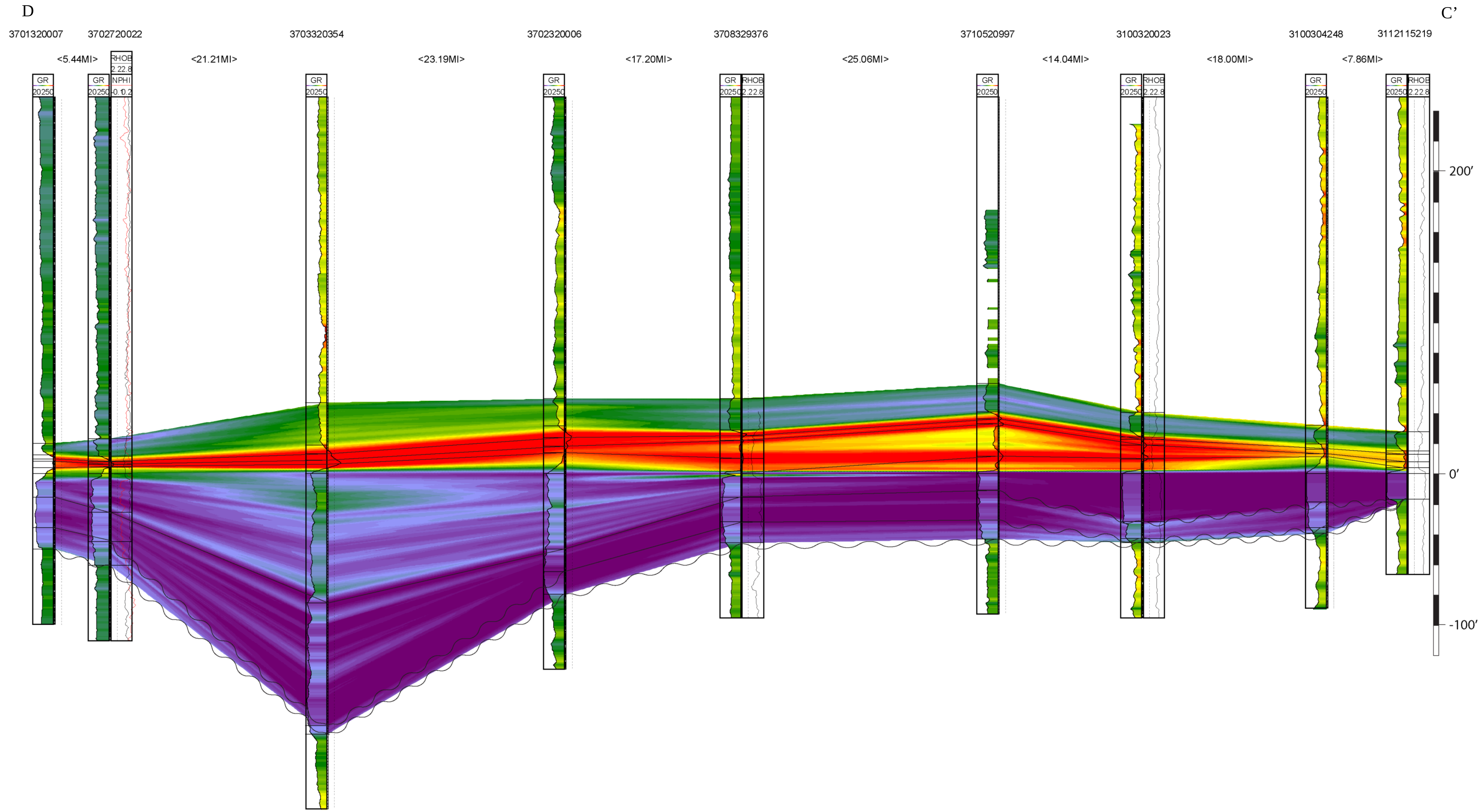


Figure 12 – Cross section D to C’ – North to south cross section across north-central PA and south-central NY. See Figure 9 for color bar and log track descriptions. See Figure 1 for location.

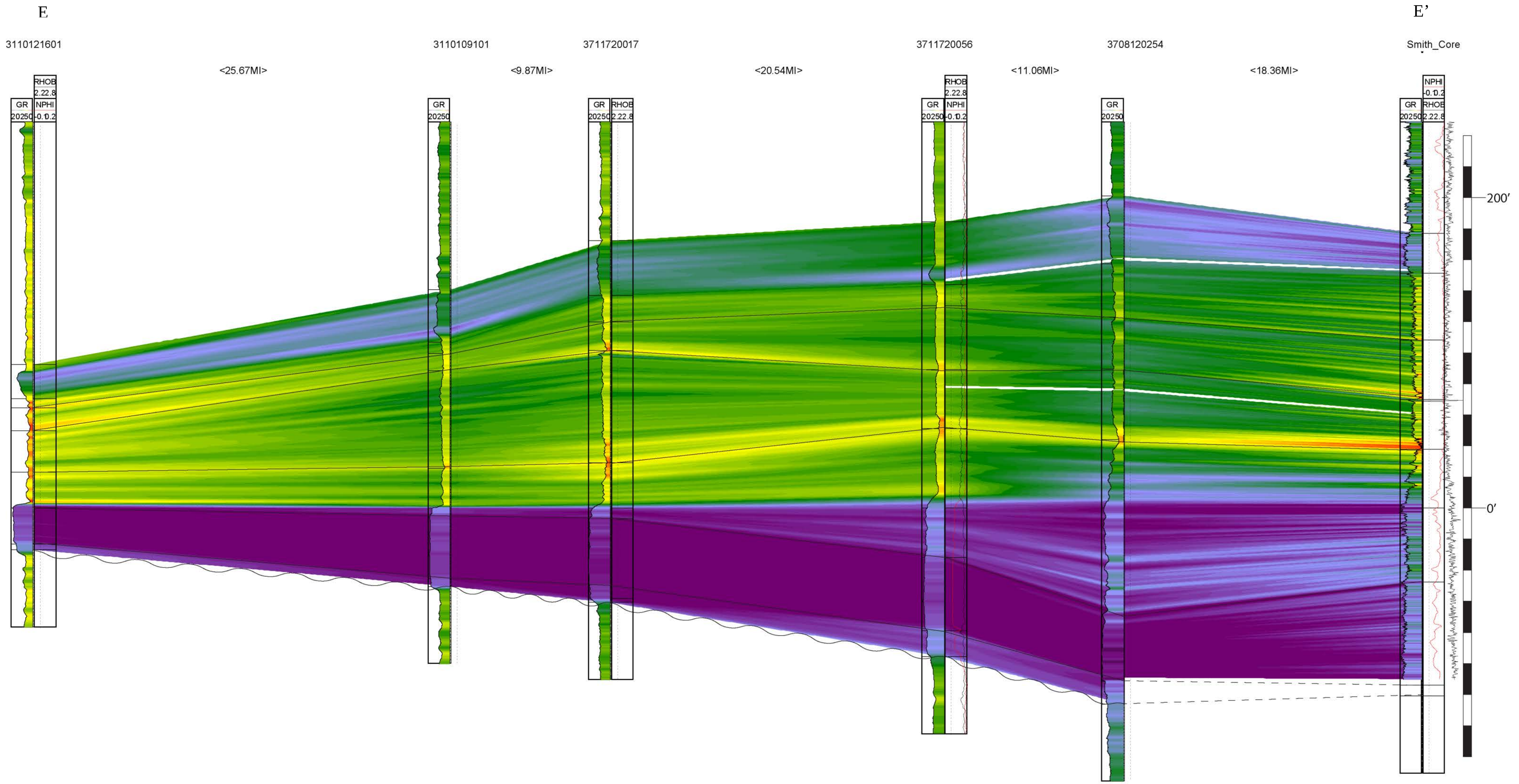


Figure 13 – Cross section E to E' – North to south cross section across northeastern PA and southeastern NY. See Figure 9 for color bar and log track descriptions. See Figure 1 for location.

Geochemistry

Key elemental concentrations and elemental ratios were measured in the Smith and Rennow cores to determine changes in organic material production, dilution, or preservation (TOC%), redox conditions (Mo, Fe/Al, Mn), primary organic production (Ni and Cu), and detrital input (K/Mg+Fe, Ti/Al) (Figs. 24 and 25)

TOC and Fe/Al are relatively high between 163 and 298 ft in the Smith core and between 27 and 50 ft in the Rennow well. Across the same interval Mo concentrations are elevated in the Rennow core. Mo concentrations in the Harrell Fm., the Tully Ls., and the Mahantango Fm are below the detection limit of approximately 13 ppm imposed by the combination of the XRF device and 45 second assay time used to obtain elemental concentration data. In the same intervals within the Burket Mbr. TOC varies between 2 and 4.5 wt% with a peak value of 5.8 wt% recorded at the PSS-02 MFS in the Smith core. Lower TOC values within this interval generally correspond to siltier or more calcareous horizons.

The high TOC values are interpreted to result from enhanced preservation of organic material under anoxic/euxinic bottom water conditions by analogy with Holocene sediments of the Black Sea (Wendt, Arthur et al. in press). Studies of Holocene sediments deposited under euxinic conditions in the Black Sea (Wilkin and Arthur 2001) indicate that much of the pyrite there was formed in the water column as framboids diameter was typically less than 12 µm. Mo concentrations in Black Sea typically show a strong correlation with TOC, and both are heavily influenced by clastic dilution. However, Mo concentrations are generally higher in deep-water masses and Mo is more readily sequestered in organic-carbon rich sediments under anoxic or euxinic conditions. Geochemical analysis of Holocene Black Sea sediments indicate that a significant percentage of the Mo content is preserved in the sedimentary pyrite fraction. In the Smith and Rennow cores there is a prevalence of small (<12 μm) pyrite framboids and a dramatic Mo enrichment in the Rennow well that correlate strongly with TOC (Fig. 26). Generally low Mn values are observed across the same intervals and, at smaller scale, decreases in Mn concentration correlate strongly with increases in TOC. Elevated Uranium concentrations, as indicated in the synthetic spectral GR log of the Milesburg, PA outcrop, are the primary cause of the observed higher bulk GR response of this interval (>250 API) (Fig 27). The Fe/Al ratio is generally slightly elevated in the Burket Mbr. interval relative to the Harrell Fm. and markedly higher relative to the Tully Ls. interval. Peaks in Fe/Al correspond to parasequence flooding surfaces defined by GR response and horizons of macroscopically visible pyrite beds containing abundant, small, pyrite framboids. Taken together, and in light of the Black Sea study, these observations suggest that the Burket Mbr was deposited under a euxinic (anoxic and sulfidic) water mass in the study area. A similar interpretation of redox conditions was offered by Sageman et al. for TOC-rich shales in the Upper Devonian of New York State (Sageman, Murphy et al. 2003, Arthur and Sageman 2005) and by Wendt et al. for the middle Devonian Marcellus Fm. (Wendt, Arthur et al. in press).

Analysis of the detrital indicators suggests low rates of clastic input during deposition of the Burket Mbr. Low K/Mg+Fe ratios suggest that clay minerals consist primarily of mixed layer illite-smectite as opposed to K-micas or pure illite, and that K-feldspar is rare. The Ti/Al signal is much less clear cut. In the Smith core, the Ti/Al ratio in the Burket Mbr. interval is highly variable but shows a general increase when compared to the Tully Ls. and Mahantango Fm. This suggests an increase in detrital silt input bearing minerals such as rutilated quartz and titanomagnetite. The Ti/Al ratio is generally lower in the Burket Mbr. than in the Harrell Fm. and pronounced decreases in the Ti/Al ratio acompany the parasequence flooding surfaces. In the Rennow well, on the other hand, the Ti/Al ratios in the Burket Mbr. are generally lower than those in either the Harrell or Manantango Formations and further decreases in Ti/Al occur at the parasequence flooding surfaces. The mixed signal observed in the data from the Smith well is likely the result of that location being much more proximal to the Givetian clastic depocenter.

Previous authors (Wilson, Schieber et al. 2010, Wilson 2012) have suggested enhanced primary production as a possible explanation for the higher TOC levels observed in black shales, both generally and specifically in the Burket Mbr. To test this hypothesis I measured Ni and Cu because they are generally regarded as excellent proxies for primary production (Tribovillard, Algeo et al. 2006). Elemental concentrations of Ni and Cu measured in the Rennow well does show a significant increase across the Burket Mbr. interval. There are two possible explanations: 1) biologic production increased during Burket Mbr. deposition, or 2) Cu and Ni enrichment is due to a constant flux of organic material coupled with a decreased rate of clastic sediment accumulation/dilution. The latter interpretation is supported by the absence of any significant increase in Cu or Ni concentrations across the Burket Mbr. interval in the Smith core. In fact there seems to be no correlation between the Cu and Ni concentrations and the TOC content of the Smith core.

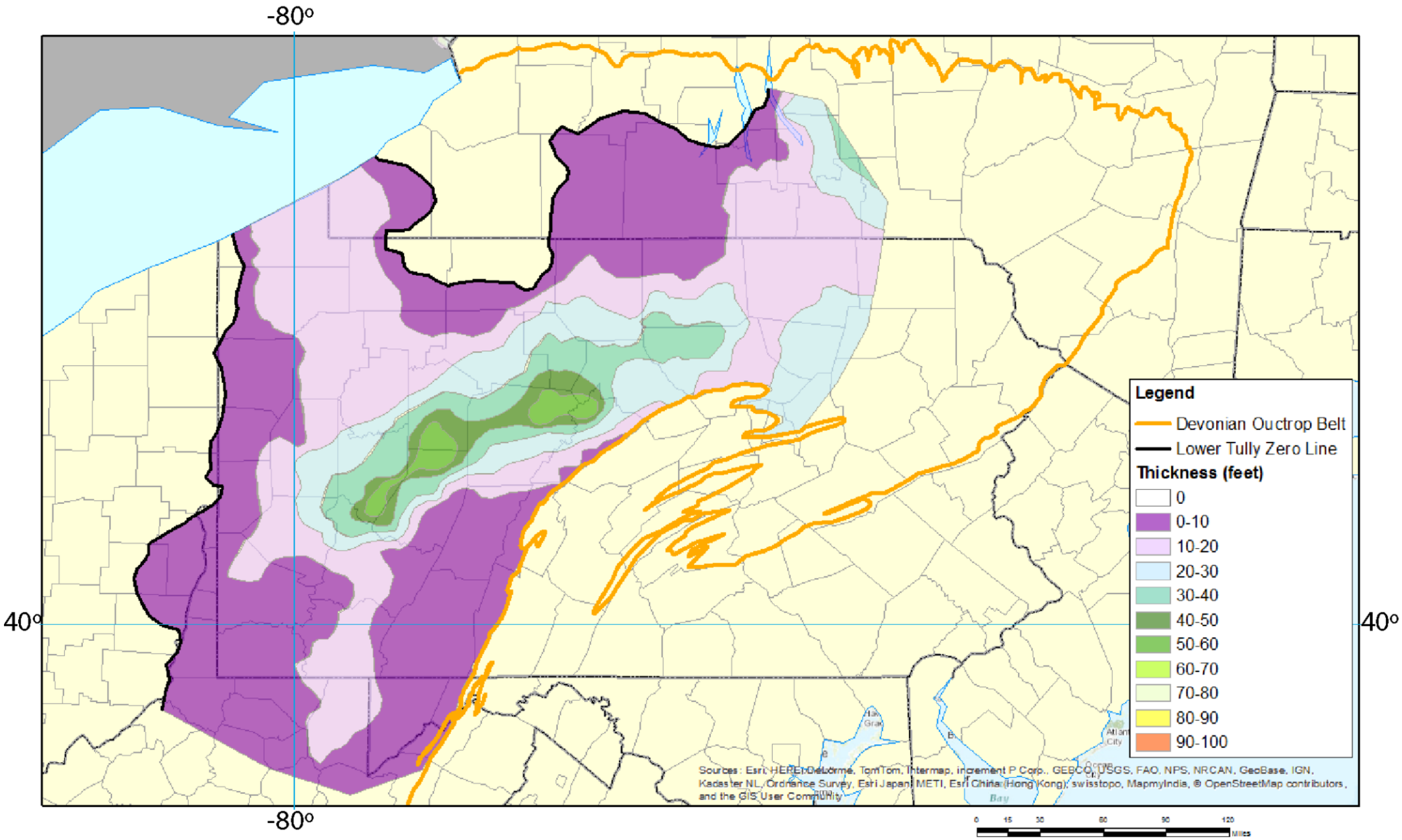


Figure 14 – Lower Tully LS. Isochore

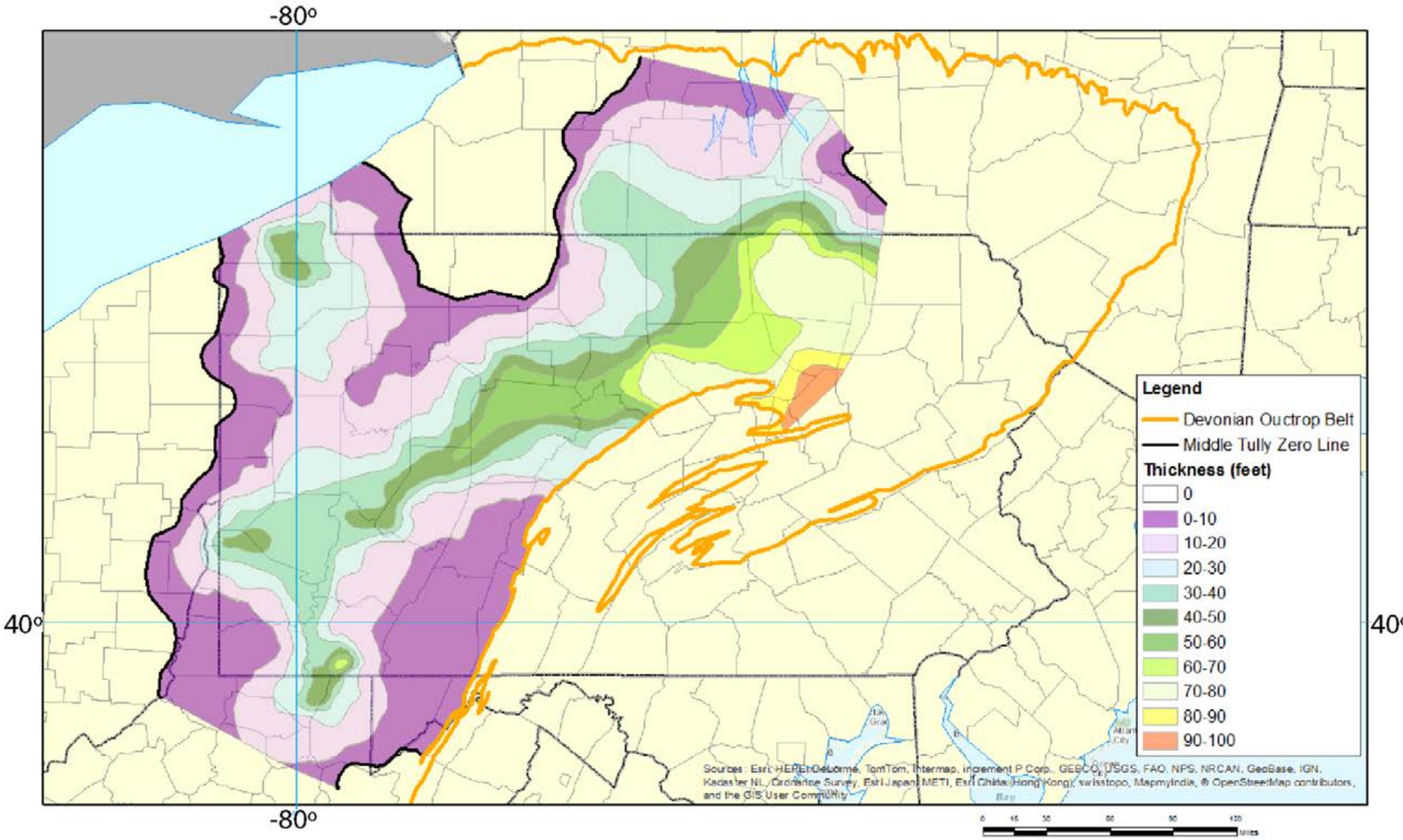


Figure 15 – Middle Tully LS. Isochore

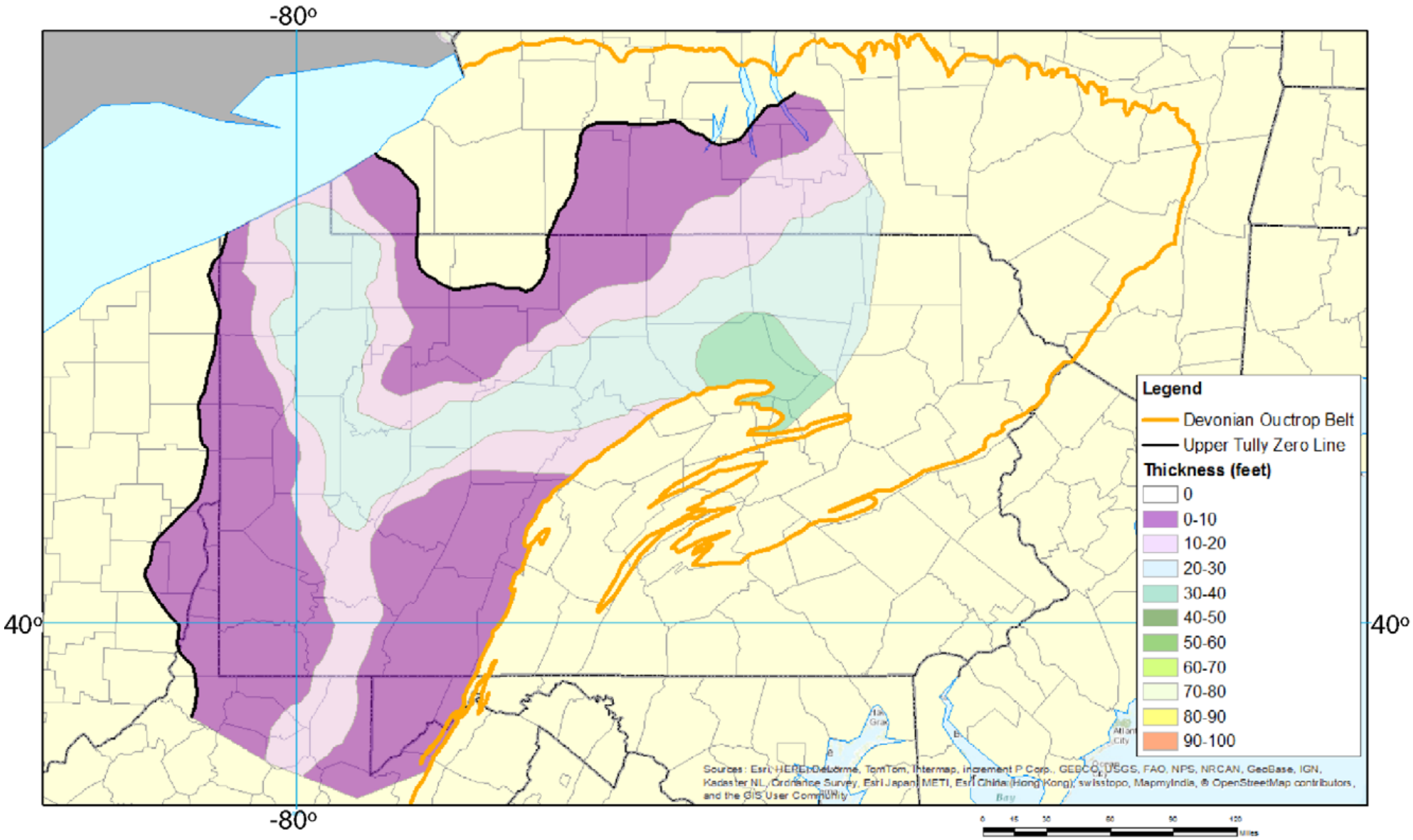


Figure 16 Upper Tully LS. Isochore

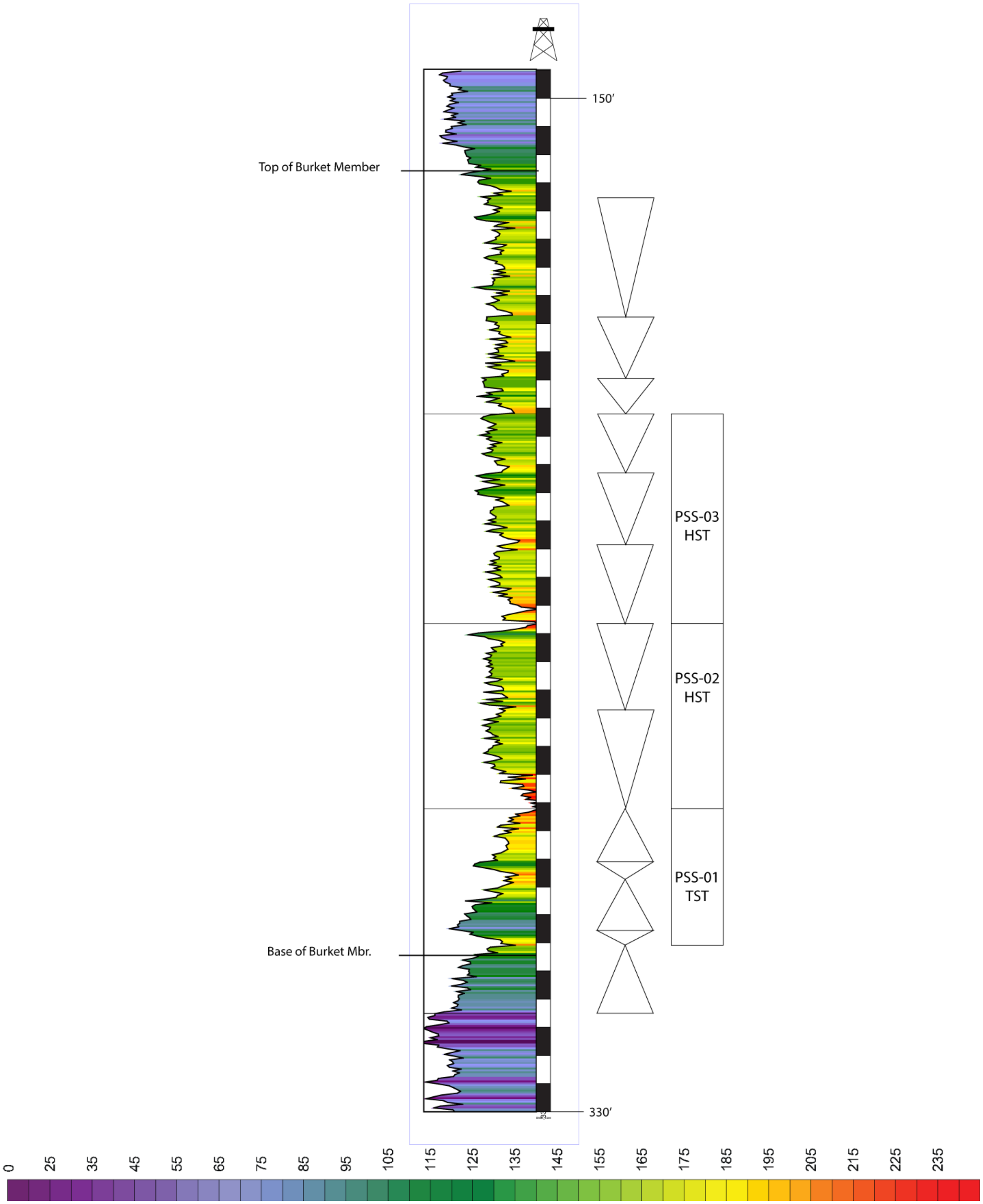


Figure 17 – Expanded view of Burket Mbr. PSS-1 showing individual parasequences in the Smith Core, Lycoming County, PA.

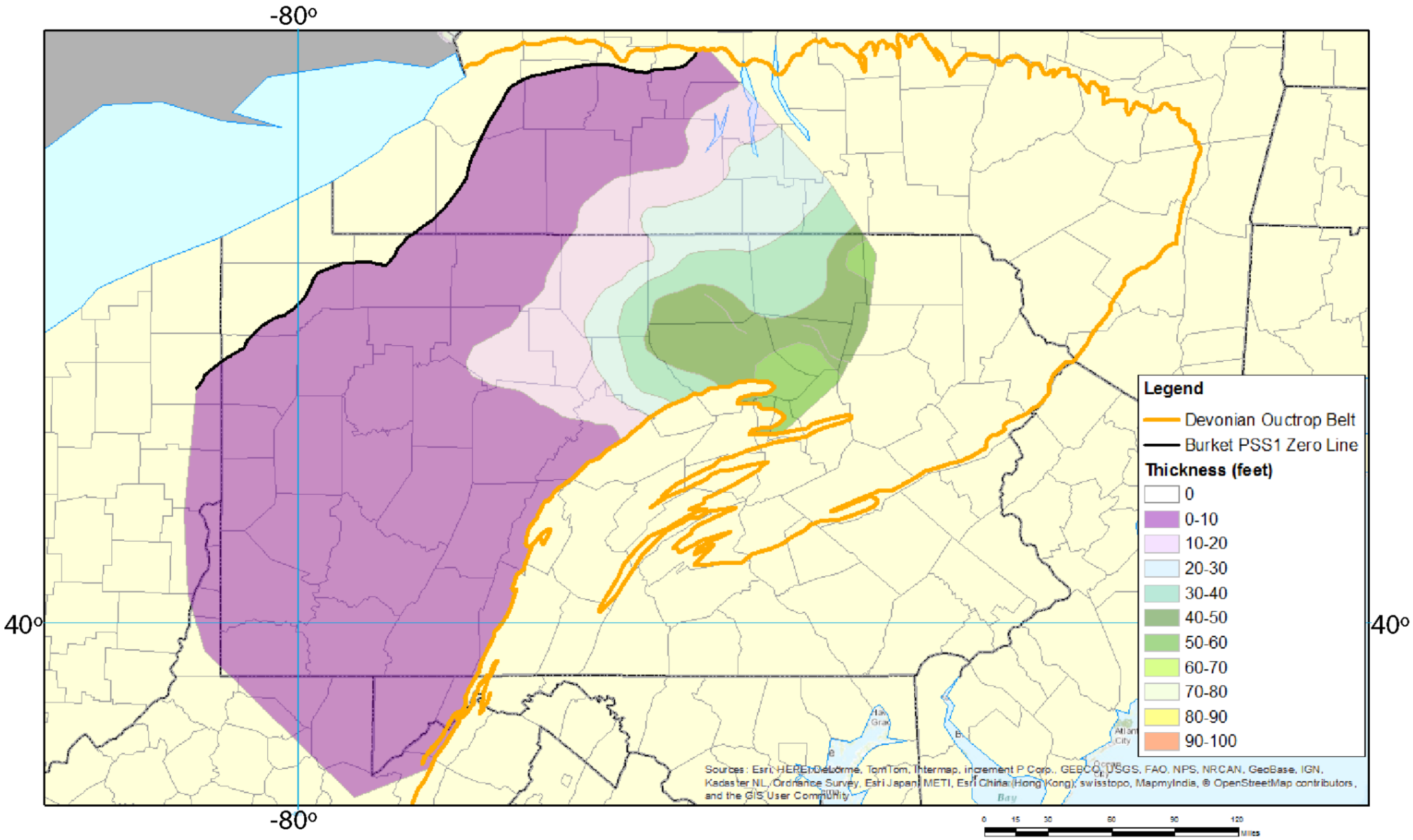


Figure 18 - Burket Mbr. PSS1 Isochore

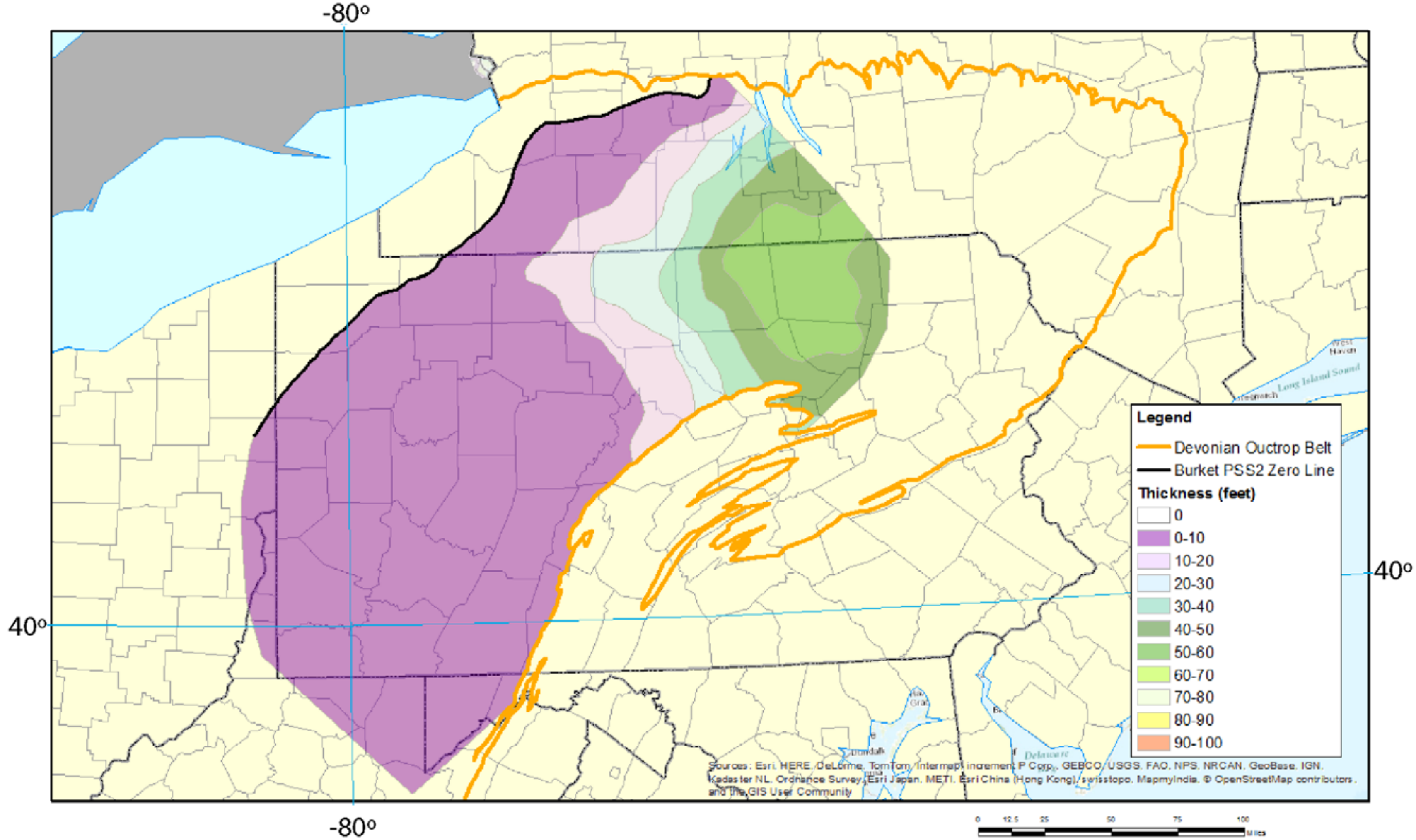


Figure 19 - Burket Mbr. PSS2 Isochore

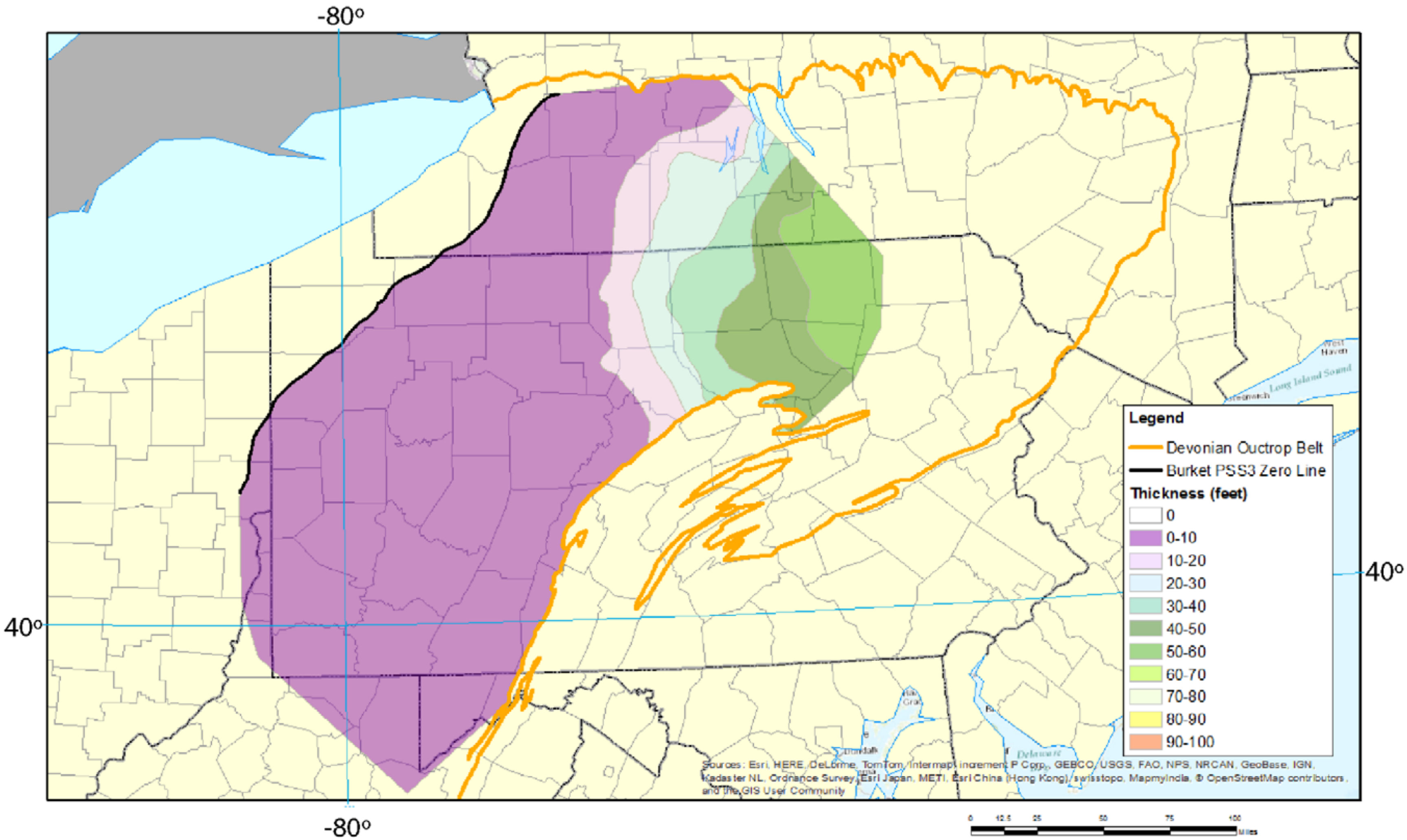
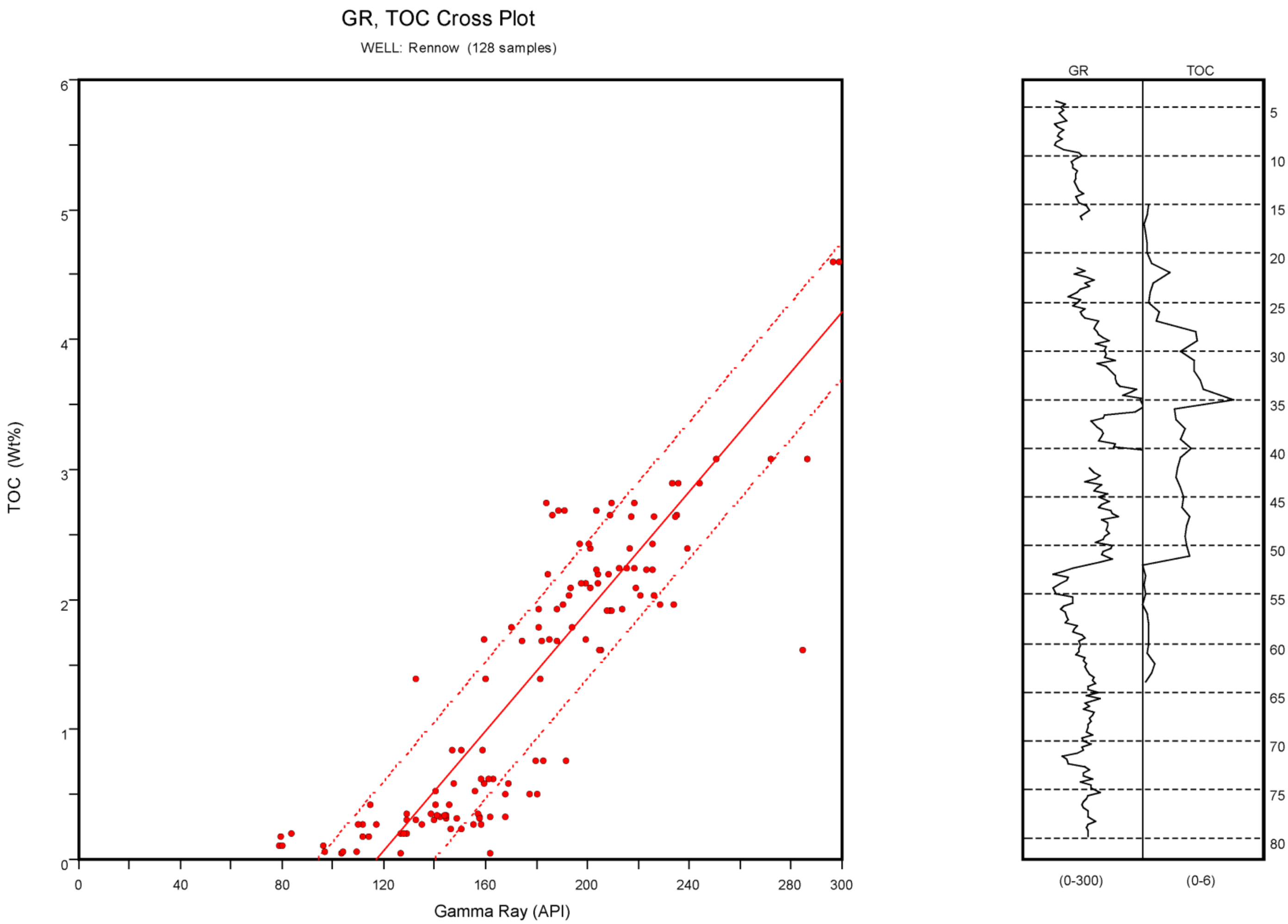


Figure 20 - Burket Mbr. PSS3 Isochore



TOC = 0.0230612*GR - 2.7061 Corr=0.877 StdErr=0.5287

Figure 21 – Covariance of TOC (wt%) and GR (API) in Burket Mbr. and upper Tully Ls. interval. Rennow Core, Blair County, PA.

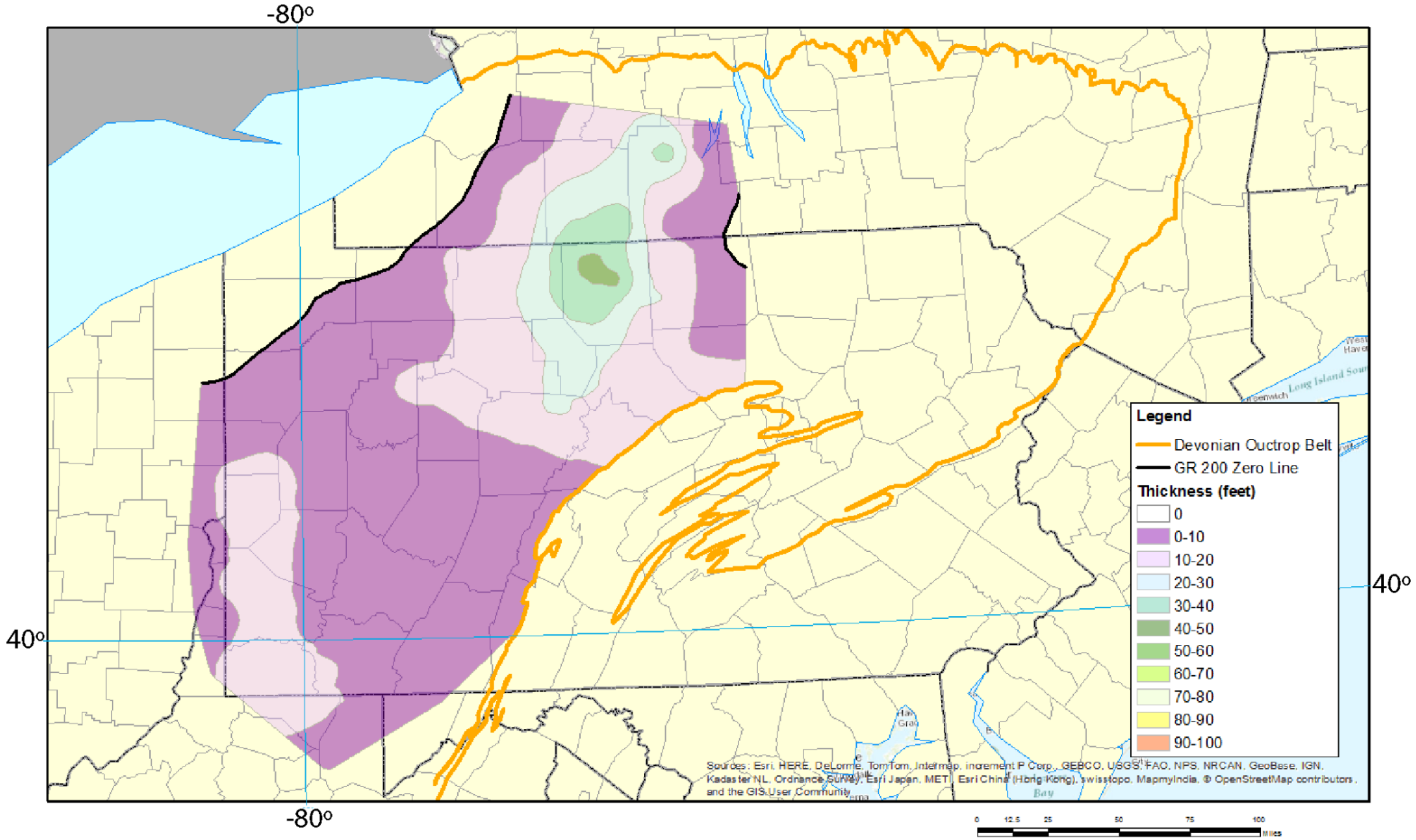


Figure 22 - Burket Mbr. GR 200 Isochore

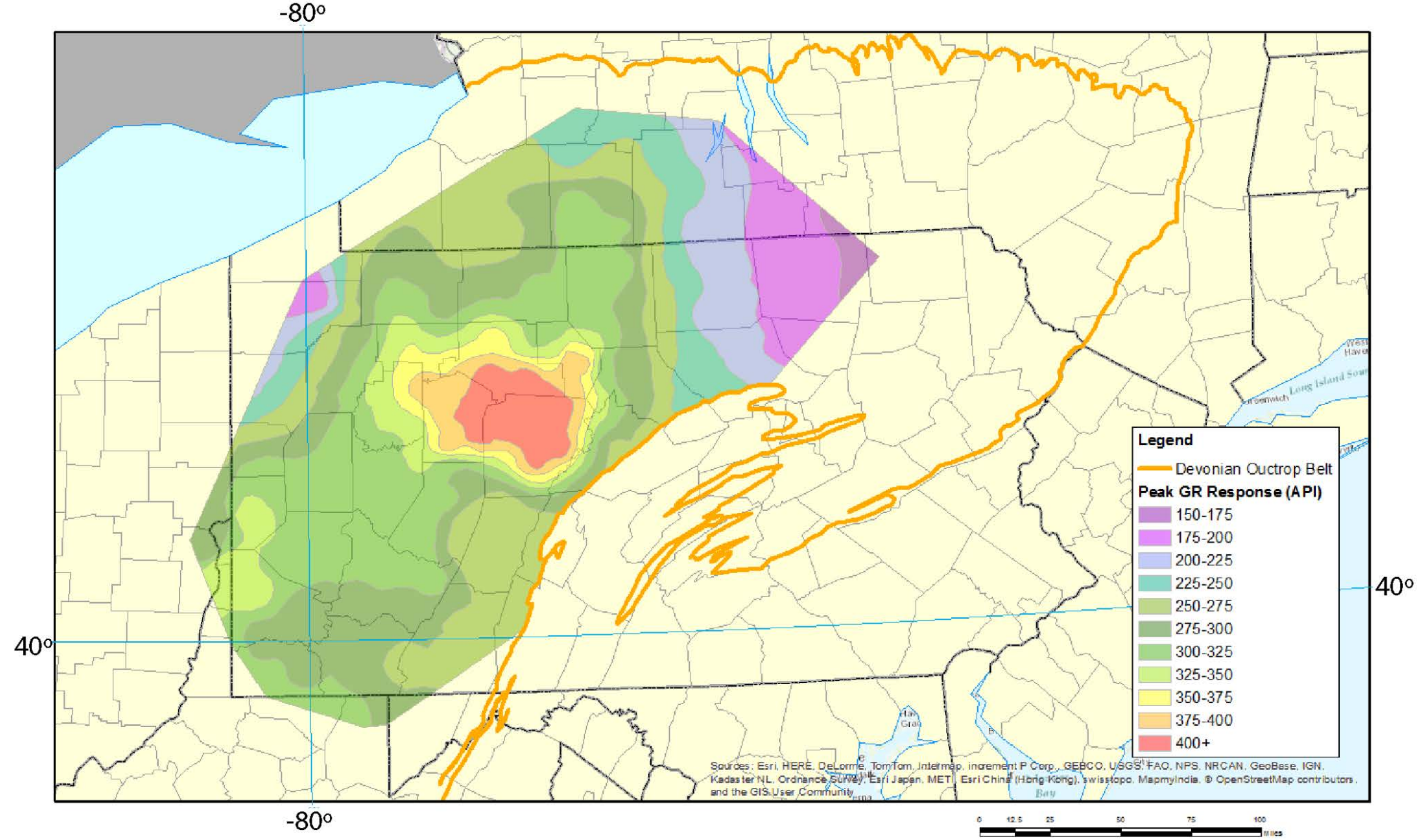


Figure 23 - Burket Mbr. Peak GR response (API)

Discussion

Controls of Organic Matter Distribution

Isovals of the maximum GR response in each well define a roughly southwest to northeast trending area across central Pennsylvania (Fig. 23) while the area of greatest thickness of high GR (> 200 API) occurs along a roughly north to south trend from central New York to north-central Pennsylvania (Fig. 22). Geochemical analysis from one study well suggests a strong positive correlation between GR response and TOC (Fig. 21). While the covariance of TOC and GR response is based on only a single location, the line of best fit suggests that a GR response of 200 API or greater roughly corresponds to a TOC of 2 wt% or greater. I contend that this central portion of the basin, with the highest GR response, represents the deepest portion as well as the most distal from sources of clastic sediment to the east and detrital carbonate to the north and northwest. If so, then the primary controls on the distribution of preserved TOC are organic matter preservation and clastic dilution.

Controls on Sequence Stratigraphy

Different authors have suggested a wide array of forcing mechanisms to explain fluctuations in base level and accommodation in the Middle Devonian Appalachian Basin. Several authors (Ettensohn and Barron 1981, Ettensohn 1985, Ver Straeten and Brett 2000) have suggested that stratal patterns result from the interplay of thrust-load-induced subsidence or uplift, tectonic rebound, and forebulge migration. Other models have invoked eustacy in conjunction with climatic forcing (Dennison and Head 1975, Johnson, Klapper et al. 1985, Brett, Baird et al. 2011). Recently, Brett, Baird, et al. (2011) proposed a revised sea level curve and correlated the stratigraphy of the Appalachian Basin with that of other North American intracratonic (Illinois and Michigan) basins. Their conclusion was that eustacy and climate were the primary drivers of Middle Devonian stratigraphic sequences. Results presented herein agree with the interpretation of Brett, Baird et al. (2011) suggesting that Givetian 3rd order sequences (Tully Ls., Burket Mbr., and Harrel Fm.) are principally controlled by eustatic forcing. The global correlatability of late Givetian base level rise, as shown by Garcia-Alcalde, Brooks et al. (2011) lends further credence to this eustatic interpretation. Higher frequency parasequences within the 3rd order Givetian sequences, however, could be related to a variety of factors including Acadian tectonics, isostatic forces, and/or climate.

Isochore thickness maps of the Burket Mbr. (Figs. 18, 19, and 20) suggest that inherited bathymetry on top of the Tully Ls. had little or no influence on the distribution of sediment during Burket Mbr. deposition and that the primary control on Burket Mbr. thickness was distance from sources of clastic and detrital carbonate material. Tully Ls. isochore maps (Figs. 14, 15, and 16) however, suggest that bathymetry underlying the Tully Ls exerted significant influence on the thickness and distribution of the Tully Ls. A roughly northeast to southwest trending thickening noted in all three subsections of the Tully Ls., though far more pronounced in the Lower and Middle Tully Ls. then in the Upper, is herein interpreted as the Rome Trough, a faulted Cambrian graben structure(Gao, Shumaker et al. 2000).

Conclusions

The thickness and distribution of the facies associated with the Tully Ls. and Burket Mbr. and their associated strata were controlled by base level fluctuations and, in the case of the Tully Ls., topography inherited from the underlying Mahantango Fm. The Lower Tully Ls. represents the falling stage of a 3rd order depositional sequence (Giv-4), while the Middle Tully Ls., the Burket Mbr., and the Harrell Fm. represent the entirety of the next 3rd order sequence (Giv-5).

Prior to deposition of the Burket Mbr. falling base level coupled with a structural feature which acted to block clastic material from the shallow water areas of southern and central New York State, channeling clastic material southward toward central Pennsylvania, created conditions which allowed for the development of an extensive carbonate platform/ramp extending from central New York to the Pennsylvania border and in northwestern Pennsylvania. Detrital carbonate shed off of the platform/ramp mixed with clastic material shed off of the Acadian highlands to the east and southeast to form thick deposits of muddy limestone to calcareous siltstone in the central Appalachian basin and Rome Trough areas. This process continued through the following low stand systems tract with deposition rates in the central basin Rome Trough exceeding those on the northern carbonate platform/ramp. During the late low stand systems tract, more clastic material was sequestered close to its source as the rate of creation of accommodation space increased resulting in greatly reduced sedimentation rates in the central basin and Rome Tough. With the onset of the transgressive systems tract, carbonate production rapidly ceased, and fine grained muds began accumulating throughout the central and western basin as well as the former carbonate ramp of southern New York. Deepening water also allowed for water column stratification and the deposition and preservation of significant quantities of organic material. This transgressive interval was followed by a relatively brief high stand systems tract during which the majority of the coarse clastic material continued to be sequestered close to the shoreline with relatively fine grained rocks (silty mudstones to muddy siltstones) deposited throughout the central/western basin and across the relict New York carbonate ramp. Overall shallower water across central New York resulted in intermittent oxic conditions as indicated by occasional burrowed horizons. Subsequent base level fall resulted in the delivery of much greater quantities of coarse clastic material into the central/western basin.

Highest peak GR values, which should correspond with the highest peak TOC, occur in a roughly northeast to southwest trend from southwestern to north central Pennsylvania with the absolute highest values clustered in a roughly circular area in west central PA. This area corresponds to the deepest portion of the basin furthest from sources of both clastic and detrital carbonate material. The thickest accumulations of high organic-carbon-rich Burket Mbr. occur in a roughly north to south trend across north central Pennsylvania and south central New York.

A variety of forcing mechanisms can be invoked to explain the changes in relative base level and the resultant changes in lithostratographic facies within the study interval. The widespread 3^{rd} order sequences which constitute the primary controls on deposition in the late Givetian Age, given their correlibility across North American basins and with international basins, are almost certainly the result of eustatic forcing. Higher order parasequences are less regionally extensive and therefore may result from eustatic, climatic, or tectonic influences.

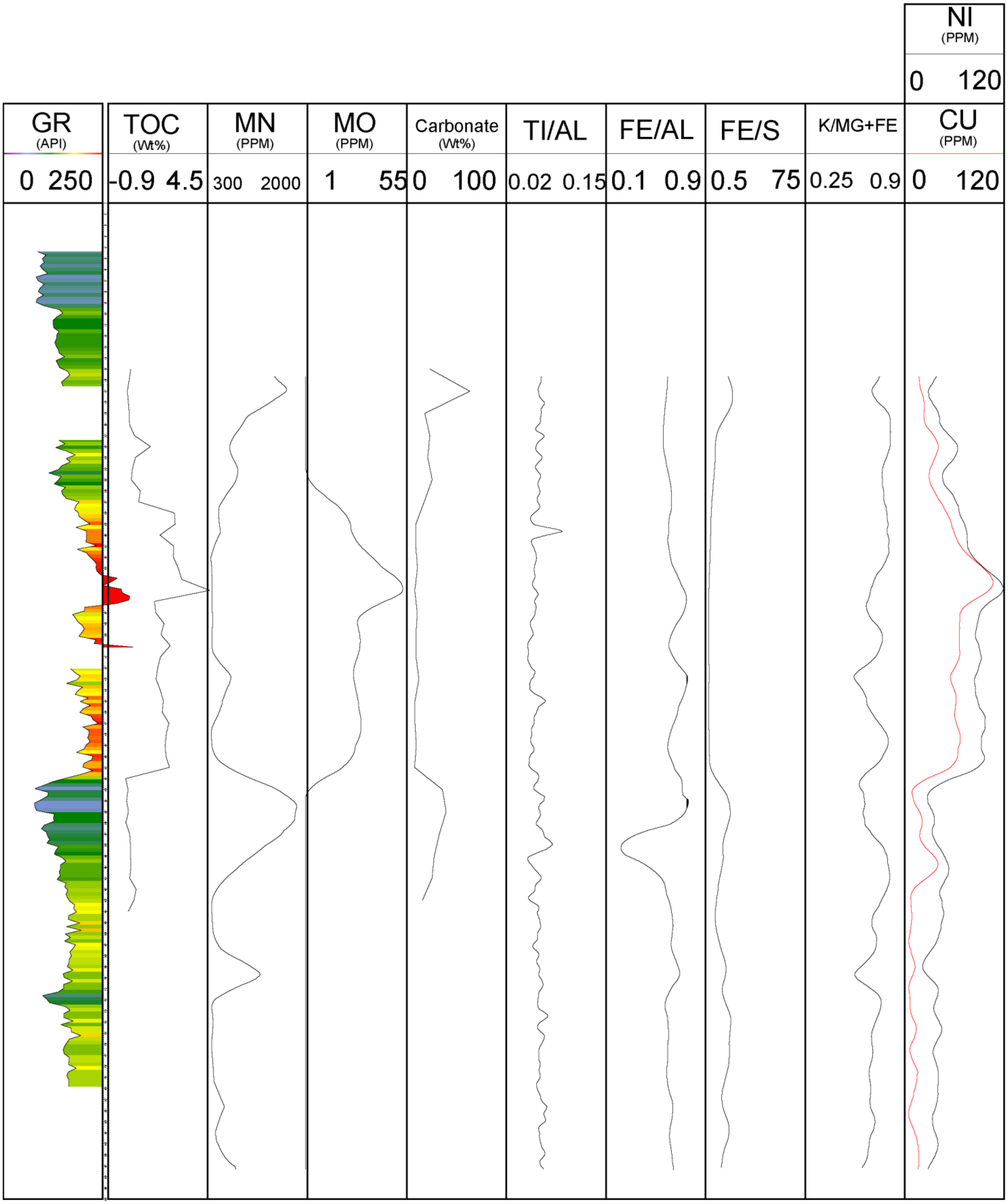


Figure 24 – Selected elemental concentrations and ratios in the Rennow Well, Blair County, Pennsylvania

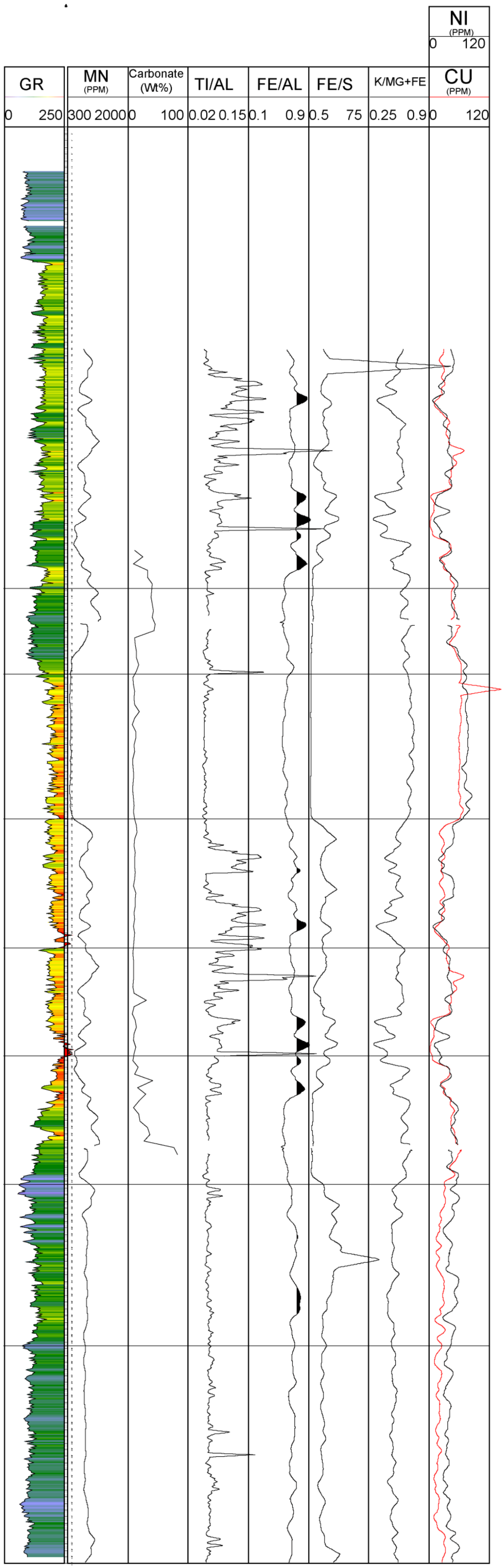


Figure 25 – Selected elemental concentrations and ratios in the Smith Well, Lycoming County, Pennsylvania

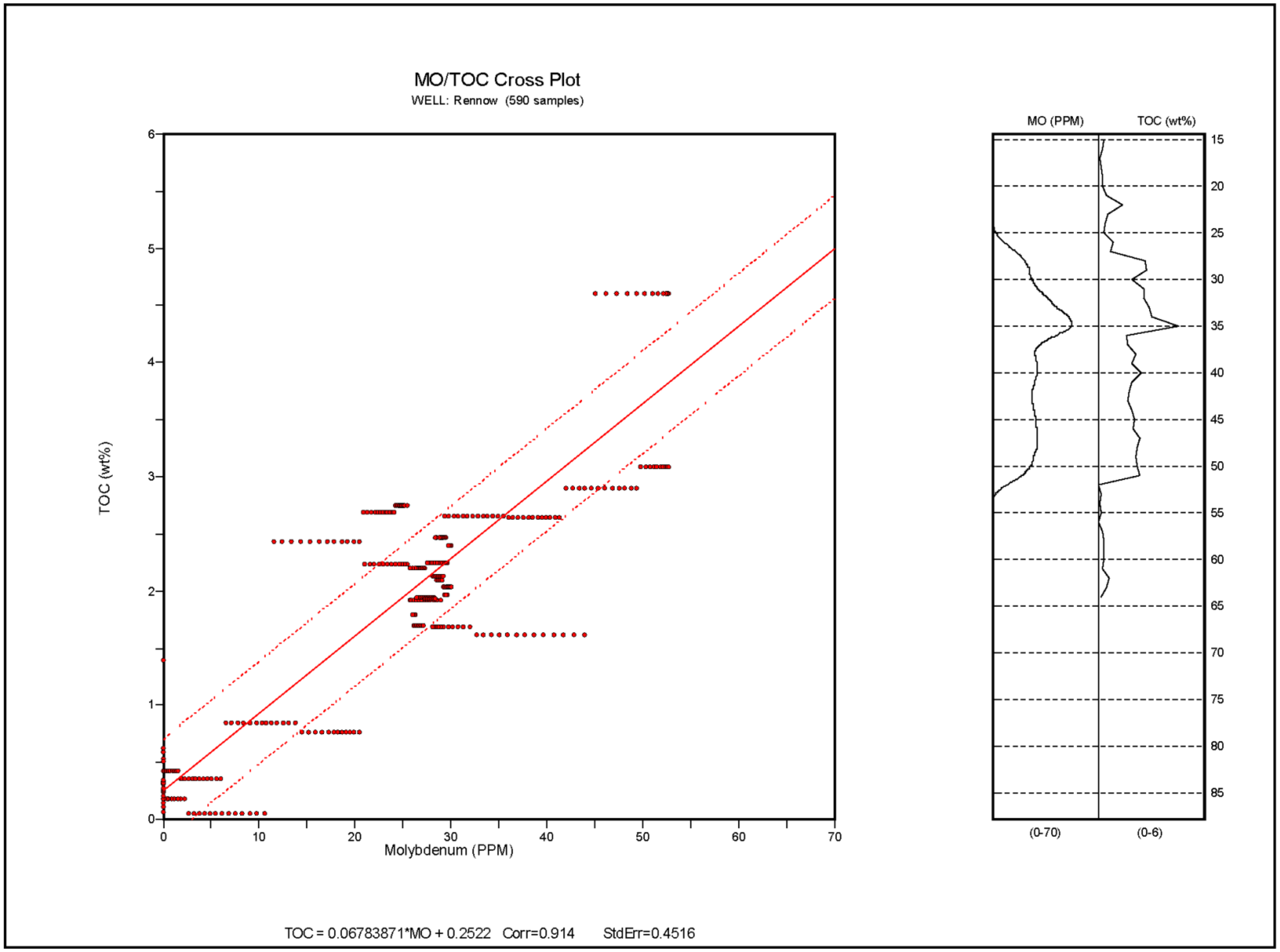


Figure 26 – Cross correlation of TOC and Mo concentrations in the Rennow well, Blair County, Pennsylvania.

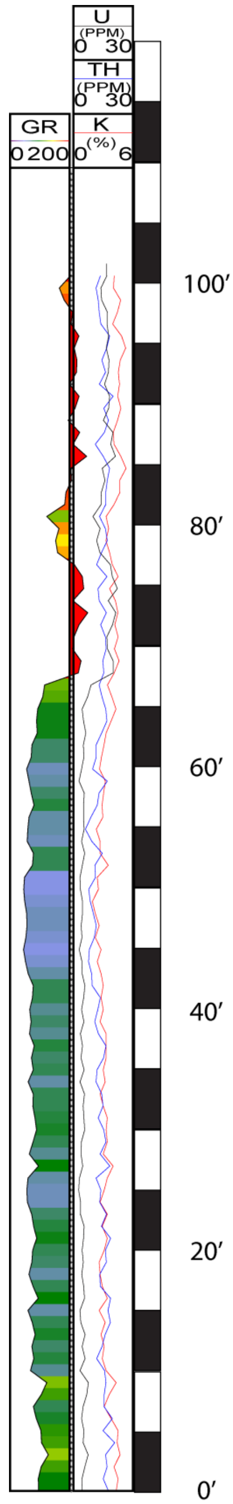


Figure 27 – Synthetic spectral GR log of Milesburg, PA outcrop

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Plate 1

Plate 1 A – Interbedded Tully Ls. and Burket Mbr. Shales. Unnamed gorge, Lansing New York.

Plate 1 B – Carbonate concretion in dark grey silty mudstone. Taghannock Falls State Park, Trumansburg, New York.

Plate 1 C – Joint sets in Burket Mbr. Taughanock Falls State Park, Trumansburg New York.

Plate 1 D – Lower Burket Mbr. Taughannock Falls State Park, Trumansburg, New York

Appendix A – Outcrop Study Locations

Newry, Blair County, PA outcrop

40°22’51.9”N 78°26’02.9”W

Raystown, Huntingdon County, PA outcrop

40°28’41.0”N 78°00’44.7”W

Milesburg, Centre County, PA outcrop

40°57’34.9”N 77°46’00.6”W

Level Corner, Blair County, PA outcrop

41°12’36.2”N 77°12’15.5”W

Lansing, Tompkins County, NY outcrop

42°31’31.2”N 76°30’33.3”W

Taughannock Falls State Park, Tompkins County, NY outcrop

42°32’16.4”N 76°36’29.7”W

Lodi, Seneca County, NY outcrop

42°36’51.2”N 76°36’29.7”W

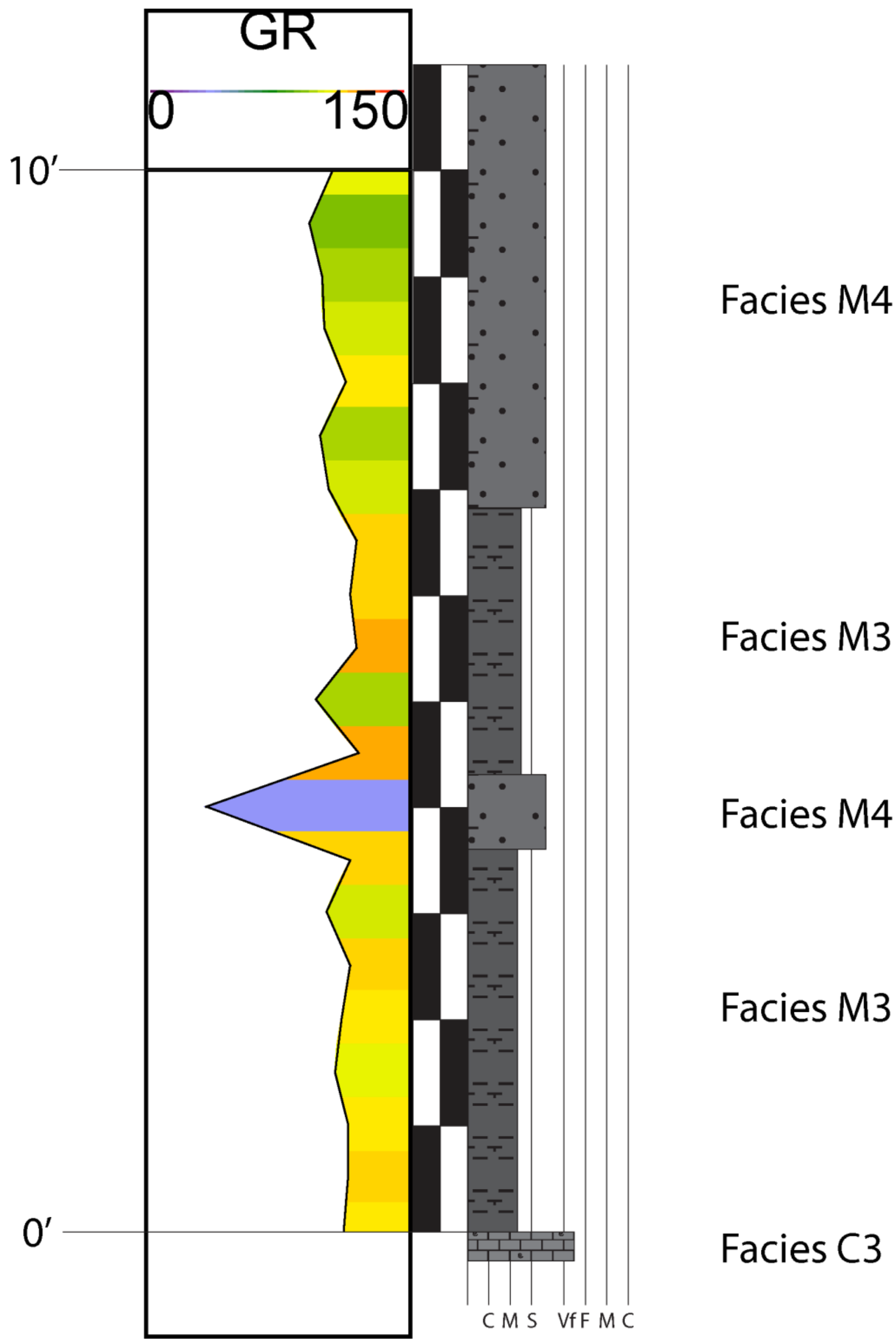
Squaw Point, Yates County, NY outcrop

42°34’01.5”N 76°55’16.4”W

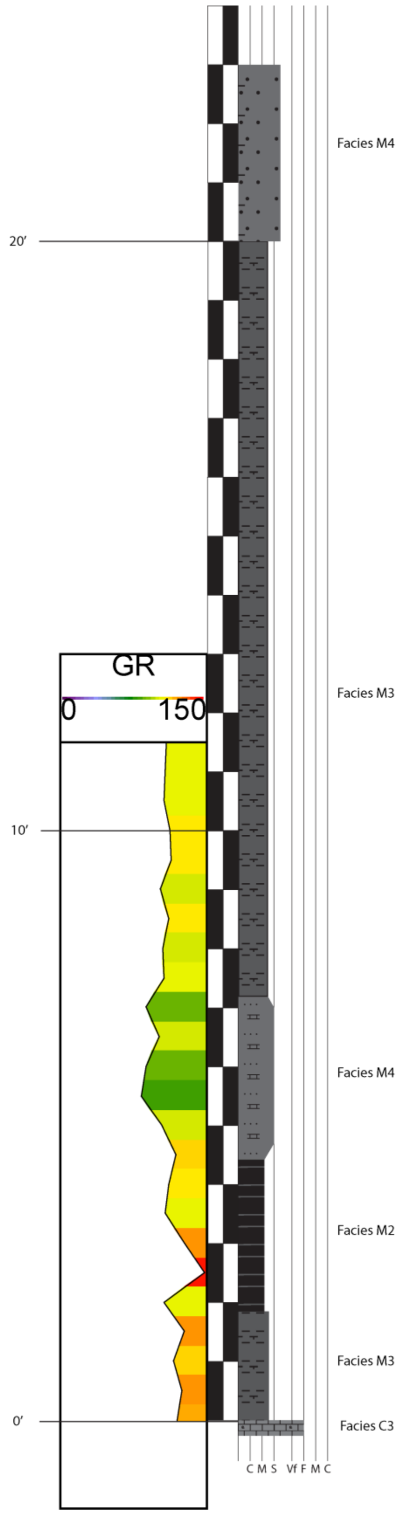
Menteth Point, Ontario County, NY

46°48’14.9”N 77°18’48.9”W

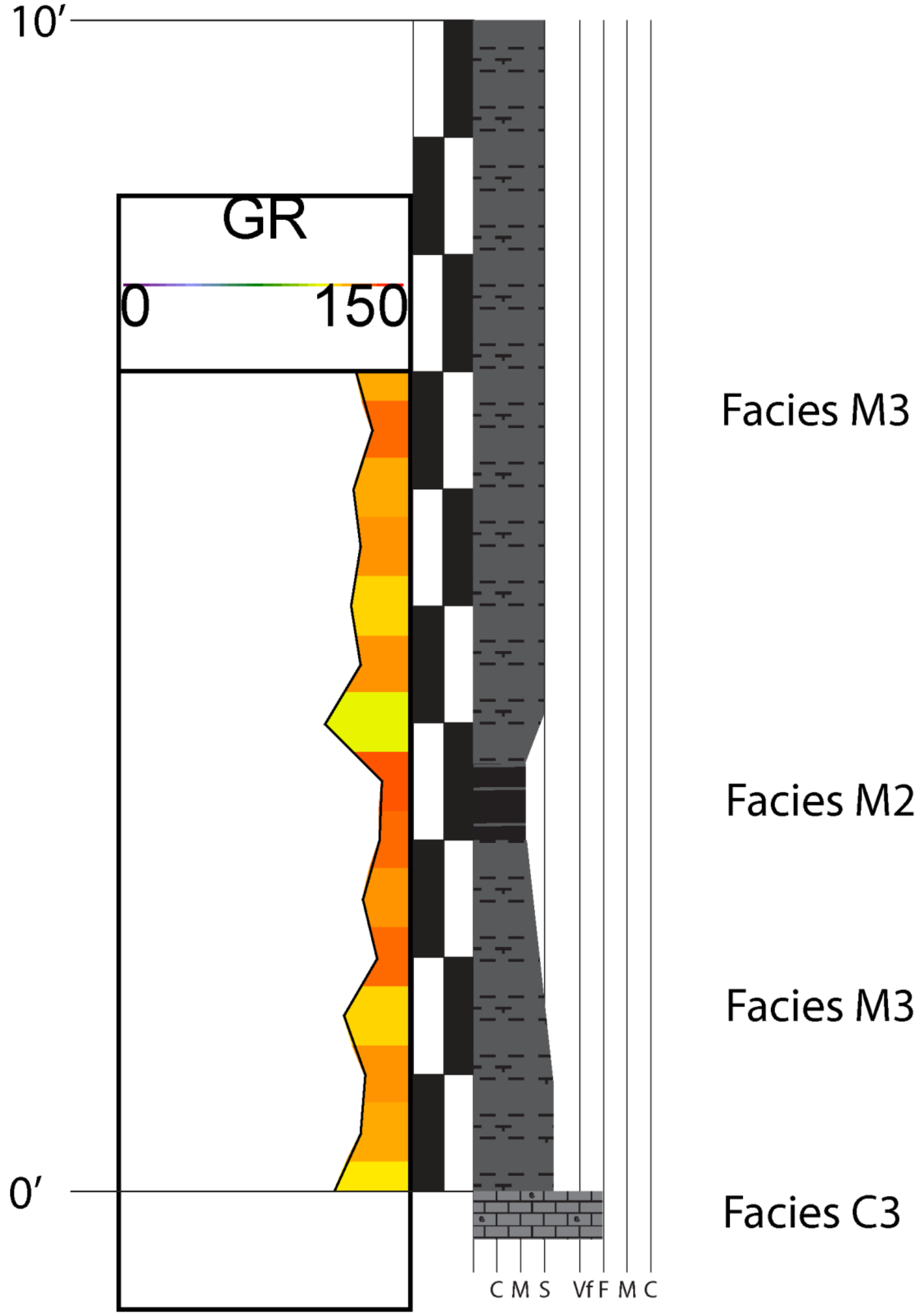
Appendix B – Outcrop Lithic and Synthetic Gamma Ray Logs



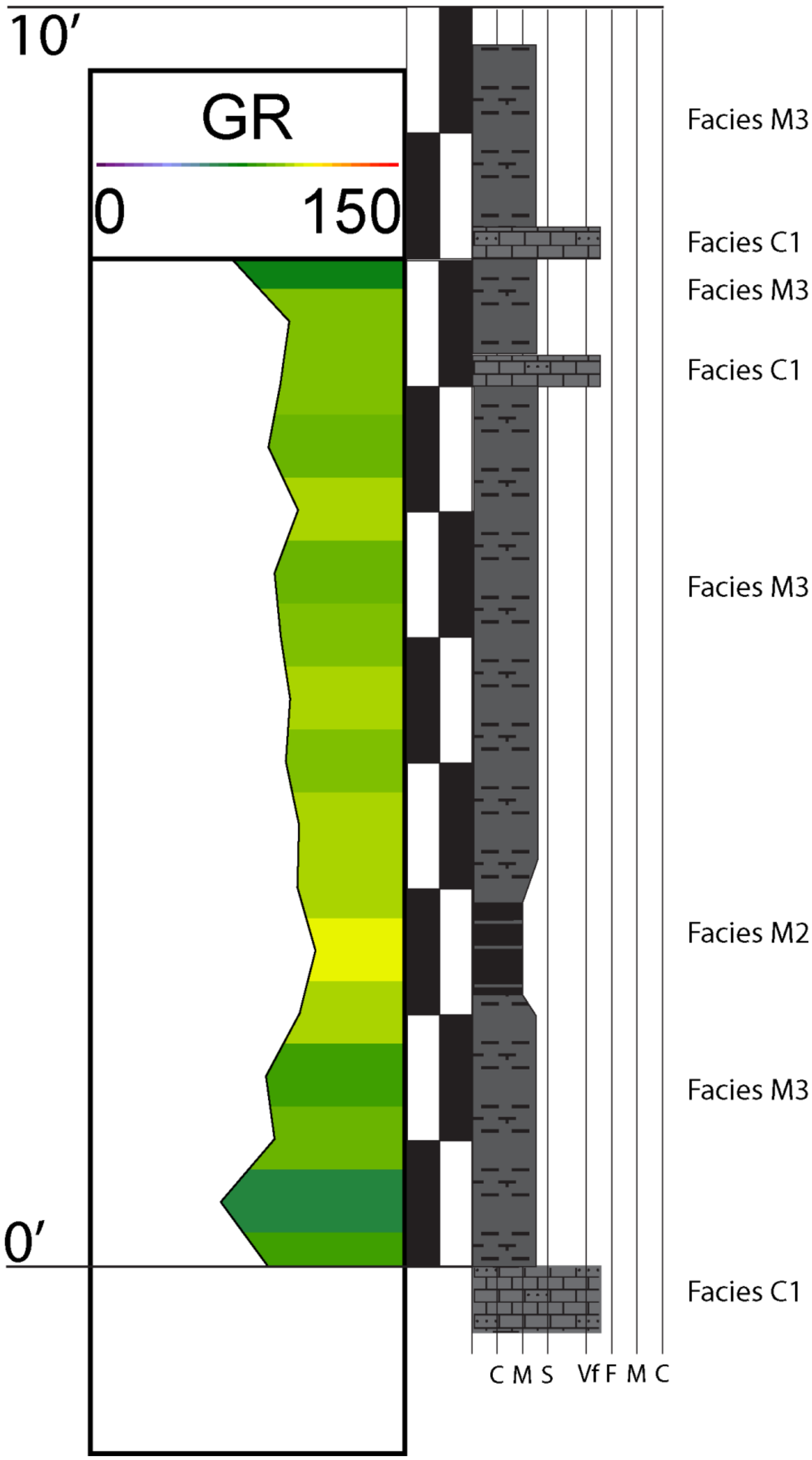
Taughanock Falls State Park outcrop, Tompkins County, New York



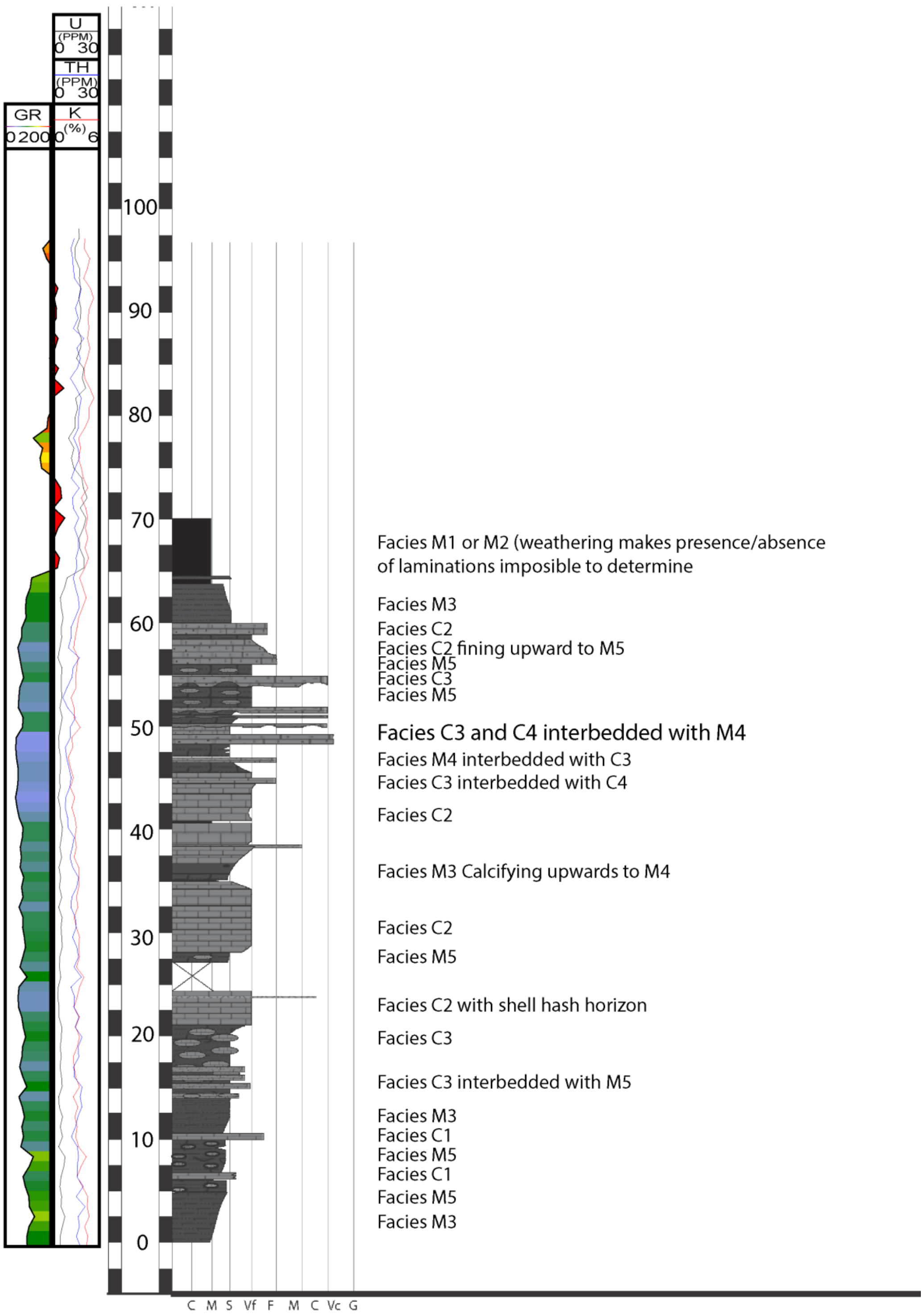
Lodi Point outcrop, Seneca County, New York



Squaw Point outcrop, Yates County, New York



Menteth Point outcrop, Ontario County, New York



Centroid Corp. outcrop, Centre Count, Pennsylvania