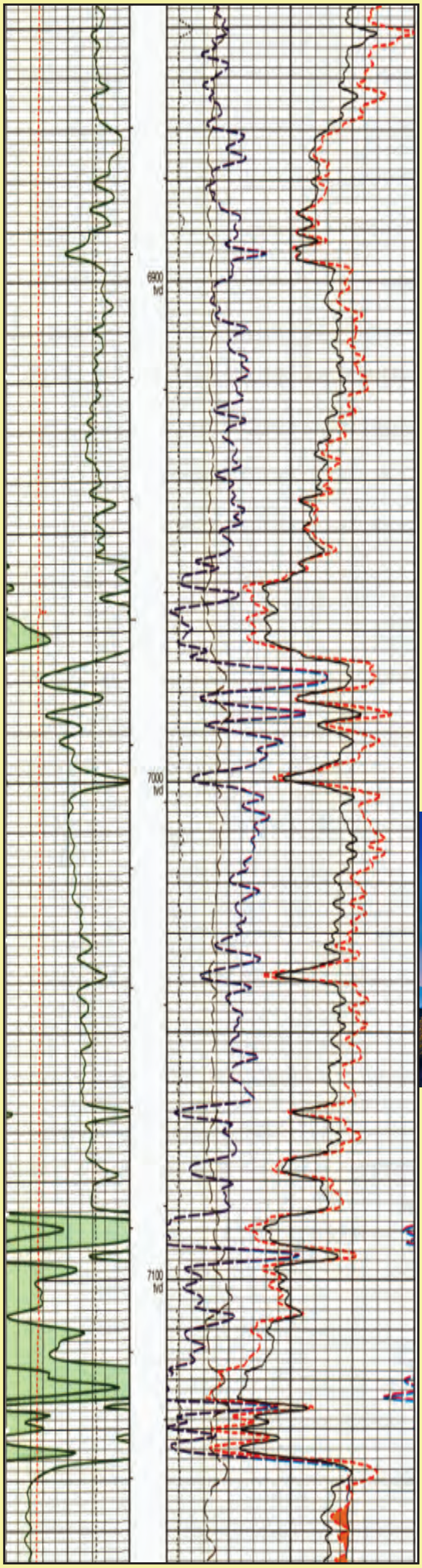

West Virginia
Geological and Economic Survey

LITHOSTRATIGRAPHY OF MIDDLE AND UPPER DEVONIAN ORGANIC-RICH SHALES IN WEST VIRGINIA

Ray Boswell and Susan Pool

WVGES Reports of Investigation -- 35

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West Virginia Geological & Economic Survey
Reports of Investigation 35

Lithostratigraphy of Middle and Upper Devonian Organic-Rich Shales in West Virginia

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Cover:

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B. Gamma-ray log stratigraphic cross-sections

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C-C', West to East 3
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D-D', West to East 4
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E-E', West to East 5
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List of Abbreviations (Abbreviations, Acronyms, and Symbols)

Abbreviation	Abbreviation Description
&	and
‘	feet
@	at
º	degrees
#	number
+	plus (i.e., and greater)
%	percent
API	American Petroleum Institute (API units used for measuring gamma-ray)
C.	central
CI	contour interval
Co.	County
DEN, Den	bulk density
DOE	Department of Energy
Dol	Dolomite
E	east
E.	eastern
EGSP	Eastern Gas Shales Project
F	degrees Fahrenheit
Fm	Formation
Ft	feet
g/cc, g/cm^3	grams per cubic centimeter
GAPI, gAPI	gamma-ray API units
geophysical well log(s)	log(s)
GR	gamma ray
Gr	Group
L	Lower
Ls	Limestone
M	Middle
Mbr	Member
MD	measured depth
MERC	Morgantown Energy Research Center
N	north
NE	northeast
Neut, Neut.	neutron
NETL	National Energy Technology Laboratory
No.	number
Ohm-m, ohm-m	Ohm-meters squared per meter
PA	Pennsylvania
pC	Precambrian
Phi	porosity
Sh	Shale
Ss	Sandstone

List of Abbreviations (continued)

Abbreviation	Abbreviation Description
ss	subsea
SW	southwest
U	Upper
U.S.	United States
U.S. DOE	United States Department of Energy
W	west
WV	West Virginia
WVGES	West Virginia Geological and Economic Survey

Lithostratigraphy of Middle and Upper Devonian Organic-Rich Shales in West Virginia

Ray M. Boswell (U.S. DOE/NETL) and Susan E. Pool (WVGES)

Abstract

Middle and Upper Devonian organic-rich shale formations in West Virginia include significant oil and gas source rocks and reservoirs. Formal lithostratigraphy for these units is well established in the southern and eastern portions of the State but is typically less well-defined in the northern and central areas where the units occur deep in the subsurface and where resource development is currently concentrated. Historically, subsurface lithostratigraphic terminology has been assigned by reference to units defined in outcrops along basin margins and extended into the subsurface through correlation of geophysical well logs. However, lateral changes in the lithology of units complicate the extension of lithostratigraphic designations defined in outcrop over long distances. Further, terminology emanating from the more distal northern (western New York) and western (Ohio and Kentucky) basin margins is not readily reconciled with terminology established in more proximal outcrops along the Allegheny Front and extended westward. Differences in the nature of information available from outcrop studies as opposed to that provided by logs further complicate the reconciliation of terminology. As a result, the geographic distribution and lithostratigraphic nomenclature for many Middle and Upper Devonian shales remains unsettled, particularly in the basin center.

In this study, correlation of log data from approximately 400 wells throughout West Virginia enables detailed mapping of organic-rich facies and allows the determination of appropriate vertical and lateral lithostratigraphic unit boundaries throughout the subsurface of northern, central, and southern West Virginia. All nomenclatural recommendations presented are based on precedence and utility. This study focuses on the Middle Devonian Hamilton Group and its constituent Marcellus and Mahantango formations. Within the Marcellus, a lower Union Springs Member, a middle Cherry Valley Member, and an upper Oatka Creek Member are recognized within northeastern West Virginia only. Throughout the rest of the subsurface of the central, western, and southern parts of the State, the Marcellus has no distinguishable members, although three informal sub-units can be mapped with moderate confidence over much of the area. In the Upper Devonian, the occurrence and limits of the Harrell Shale (and its basal Burket Shale Member), and its westward lateral transition into the largely-correlative Genesee Formation (with basal Geneseo Shale and upper West River Shale members) are mapped. Maps also detail the position at which the Sonyea Formation (with basal Middlesex Shale and upper Cashaqua Shale members), West Falls Formation (with basal Rhinestreet Shale and upper Angola Shale members), Java Formation (undifferentiated), and lower part of the Huron Member of the Ohio Shale transition eastward into age-equivalent strata of the Brallier Formation.

Introduction

Middle and Upper Devonian strata in the central Appalachian basin represent a major emerging oil and gas resource (Zagorski et al., 2012; 2017). The predominantly clastic units were deposited in a forearc setting (Kent, 1985; Ettensohn, 1985) in which basin subsidence was primarily in response to structural loading along the eastern margin of the North American craton (Faill, 1985). Basin fill was derived primarily via erosion of the Acadian highlands to the east and transportation of that sediment westward through non-marine, shoreline, shelf, and basin environments (Barrell, 1913; Caster, 1934; Dennison, 1985; Boswell and Donaldson, 1988).

Formal lithostratigraphy of Middle and Upper Devonian units first emerged in the 1830s and 1840s with the first geological survey work conducted in the United States. Study of outcrops in western New York established the basic stratigraphic succession of Onondaga, Marcellus, Hamilton, Portage, Chemung, and

Catskill (Hall, 1839; Vanuxem, 1839). Based on the common view that a single stratigraphic succession should be applicable to the entire Appalachian basin, Reger and Tucker (1924) rejected an incipient stratigraphy being developed along the Allegheny Front to apply the New York framework to units exposed in eastern West Virginia.

In the early 1900s, close observation of the relationships between the various units initiated a crisis in the emerging discipline of stratigraphy, as workers discovered that the major mappable lithologic units changed age dramatically as traced laterally (e.g., Williams, 1900; Chadwick, 1933, 1935). This observation clashed directly with the prevailing notion that every rock unit must represent one specific interval of time throughout its extent. It was through reference to these profound lateral age changes that the concept of diachronous "facies" was first developed and applied (Caster, 1934). Substantial work during this period focused on attempts to untangle and define litho-stratigraphic units from their chrono-stratigraphic origins. Subsequently, outcrop-focused work resulted in the abandonment of many long-established formation names for the coarse-clastic equivalents of the Devonian shales along the Allegheny Front in West Virginia, such as "Portage" (replaced by Brallier Formation, Woodward, 1943), "Catskill" (replaced by Hampshire Formation, Butts, 1940, 1945), and "Chemung" (replaced by Greenland Gap Group, Dennison, 1970). However, this stratigraphy was not readily extended to the age-equivalent fine-grained units that are largely restricted to the subsurface. Consequently, the full extent of the shale-rich sequence between the Onondaga Limestone and the base of the Mississippian was commonly designated only as "undifferentiated Devonian Shales" (e.g., Haught, 1959) in the basin center. By the mid-1970s, many of the original New York formations had been reclassified as informal facies in their type sections in western New York and replaced by a revised stratigraphic framework (e.g., Rickard, 1975).

In the 1970s, a series of studies under the U.S. Department of Energy's (DOE's) Eastern Gas Shales Project (EGSP) focused on extending the new lithostratigraphy being established in western New York southward and eastward into the basin center (e.g., Schwietering, 1979; de Witt and Roen, 1985). Later, with the emergence of sequence stratigraphy, more detailed geophysical well log (log) correlations were conducted to clarify the chrono-stratigraphic relationships across the center of the basin (Filer, 1994, 2002). Most recently, work focused in the outcrop belt of western New York has produced a detailed lithostratigraphy aligned with sequence stratigraphic concepts (e.g., Brett and Baird, 1996; Ver Straeten, 2007). As noted by Lash and Engelder (2011), the lithologic distinctions inherent in this new framework are commonly not compatible with stratigraphic studies utilizing subsurface data (i.e., log data) and therefore require significant simplification for broader lithostratigraphic applications within the basin interior.

At present, Middle and Upper Devonian lithostratigraphy is well established in the eastern outcrops of West Virginia and within the subsurface in the westernmost and southernmost portions of the State (**Figure 1**). However, within the center of the State, the interaction of these two sets of lithostratigraphic nomenclature remains unclear. As part of an ongoing effort at the West Virginia Geological and Economic Survey (WVGES) to assess shale gas potential (Pool, 2013; Pool et al., 2013; Moore et al., 2015), extensive log correlations have been conducted that support a refined definition of the extent of the lithostratigraphic units that requires no new formal stratigraphic names. Some names are new to the State and based on recent work conducted in neighboring areas (e.g., Carter et al., 2011; Lash and Engelder, 2011; Harper et al., 2017). Every attempt has been made to conform to the nomenclature provided by previous regional studies as much as possible (e.g., Patchen et al., 1985; Sevon and Woodrow, 1985; Ryder et al., 2009; Carter, 2010).

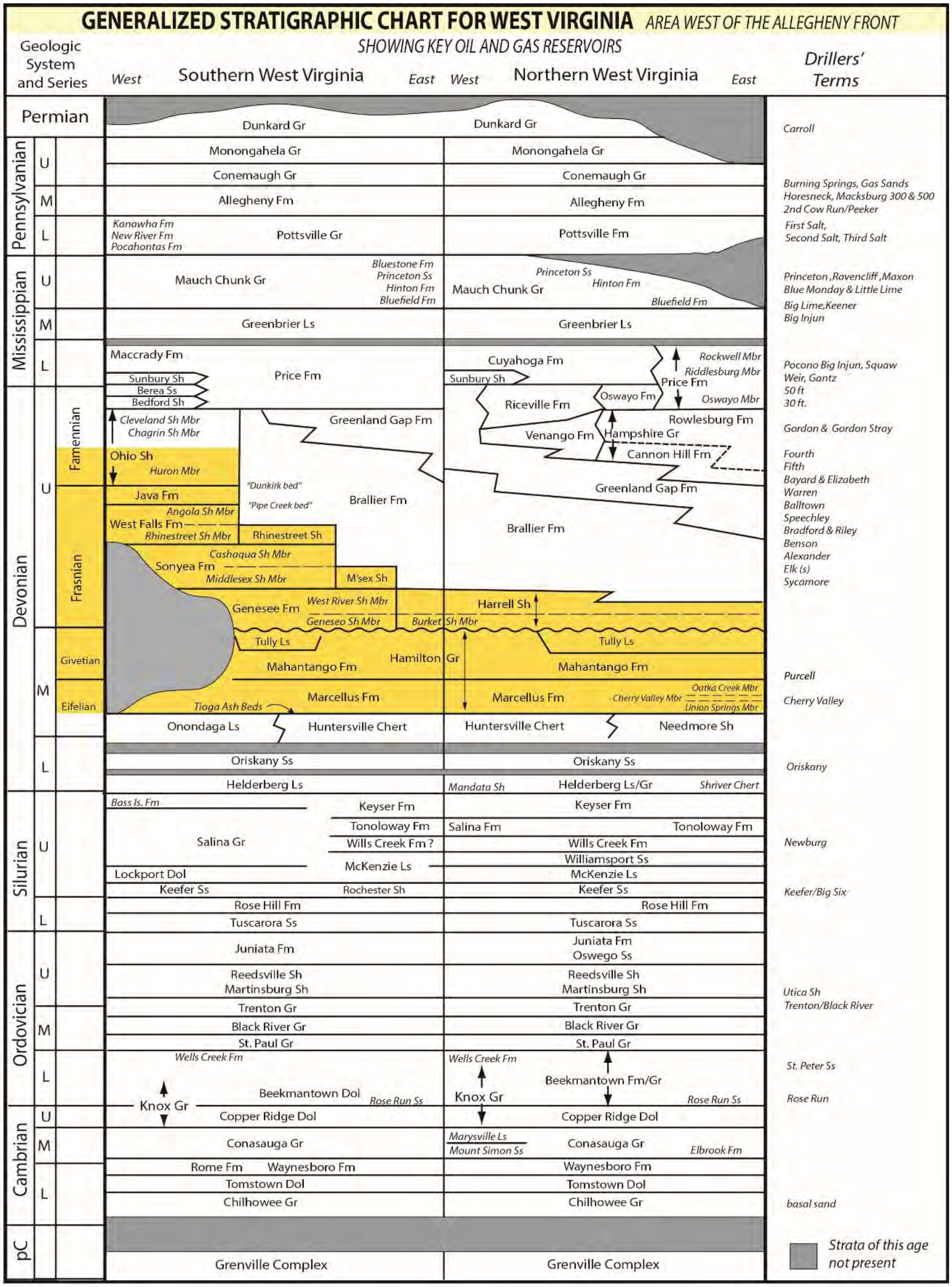


Figure 1. *Stratigraphic chart for West Virginia (for area west of the Allegheny Front). Units highlighted in color contain Middle and Upper Devonian organic-rich shales discussed in the text. Unit names in quotations are not formally recognized in West Virginia but are identified as informal correlative units to key formations recognized in neighboring states.*

Data and Methods

This study uses log data from 383 wells (**Figure 2**). The wells were chosen based on log availability, log quality, geographic location, borehole orientation, vintage, lack of structural complexity, and penetration into the Onondaga Limestone and equivalents. From these data, a network of 10 cross-sections was constructed using gamma-ray (GR) log data that enabled the distribution, thickness, and inferred lithology for selected Middle and Upper Devonian stratigraphic units to be recorded and mapped.

Lithostratigraphy refers to the delineation of geologic units based solely on lithology. The reliance on logs will clearly bias interpretations to those lithologic aspects that are best presented in such data. It should be noted that these are not always the same aspects that are most readily observed in study of the same units in outcrops or physical samples. As a result, lithostratigraphy based on different sources of information can produce somewhat different results. This may be particularly true in the case of organic-rich units, for which log response can be greatly impacted by radioactive constituents that have a relatively minor impact on the overall lithology or appearance of the unit in outcrop. Given that this is a subsurface study, the terminology that is most applicable to log-based studies will be favored.

For the purposes of lithologic interpretation, the most valuable log among the common suite of those available in West Virginia is the GR log, which records the radioactivity of the formation. In most instances, the GR log is valuable in assessing the shale content of formations (distinguishing sand-rich units from shale-rich units). Within anoxic environments, the enhanced preservation of organic matter may be accompanied by increased precipitation of uranium-bearing minerals, allowing a first-order interpretation of organic-rich from organic-poor lithologies from GR data (Schmoker, 1981). The distinction between sand-rich and carbonate-rich units (both display low GR values) is made through reference to the bulk density (DEN) log, which commonly records higher values for carbonate mineralogy (~2.71 g/cc) than for quartz-rich sandstone (~2.65 g/cc). The DEN log is also sensitive to zones of high organic content (which lowers DEN log readings). Therefore, lithostratigraphy based on DEN logs may produce different unit boundaries than work that is based primarily on GR logs.

Because different logging tools are run throughout a range of conditions over a period of decades, logs from different wells cannot be expected to have a consistent quantitative response. Therefore, lithology is determined using a “relative base-lining method” (e.g., Piotrowski and Harper, 1979). In this method, a “shale baseline” (equal to the pervasive maximum GR value) is visually determined for each well and is assumed to represent 100% shale content. “Base-lining” is typically used to determine “volume of shale,” but only works well for lithologies where natural radioactivity is predominantly associated with the occurrence of clay minerals (which include Potassium-40). Organic-rich units (which may concentrate other radioactive elements such as uranium) cannot readily be assigned a “volume of shale” using this method. However, thickness of a unit with elevated GR readings (for example, 100 API units above the 100% shale baseline) can be readily mapped and has been shown to be a useful proxy for organic content in the Marcellus Formation (Wang and Carr, 2013) (**Figure 3**).

As discussed above, when traced laterally, a correlative stratigraphic interval (an inferred chronostratigraphic unit) will commonly change lithology in a gradual manner. In the Middle and Upper Devonian of West Virginia, this change is typically manifested (as traced westward or toward more distal environments) as a gradual reduction in average grain size within an interval (fewer, thinner, and more shale-rich sand and silt interbeds), a corresponding increase in shale content, an increase in organic matter (for various reasons, including decreased “dilution” in coarser clastics), and increased occurrence of carbonate interbeds. These changes in lithology necessitate changes in lithostratigraphic units;

however, the lack of sharp lateral lithologic boundaries requires that arbitrary cut-offs be made. These cut-offs can be determined in various ways, each of which might produce slightly different, and equally justifiable, results. In this report, reasonable locations for these lateral unit boundaries are delineated based on the transition as judged to be from dominantly one lithology to dominantly another (**Figure 4a**). **Figures 4b**, **4c**, and **4d** summarize these results, which are discussed in further detail in the following sections. **Figure 5** is an example cross-section; other cross-sections can be found online (http://www.wvgs.wvnet.edu/www/MUDvnnSh/MUDvnnSh.htm). **Figures 6** to **9** provide example logs from across the State.

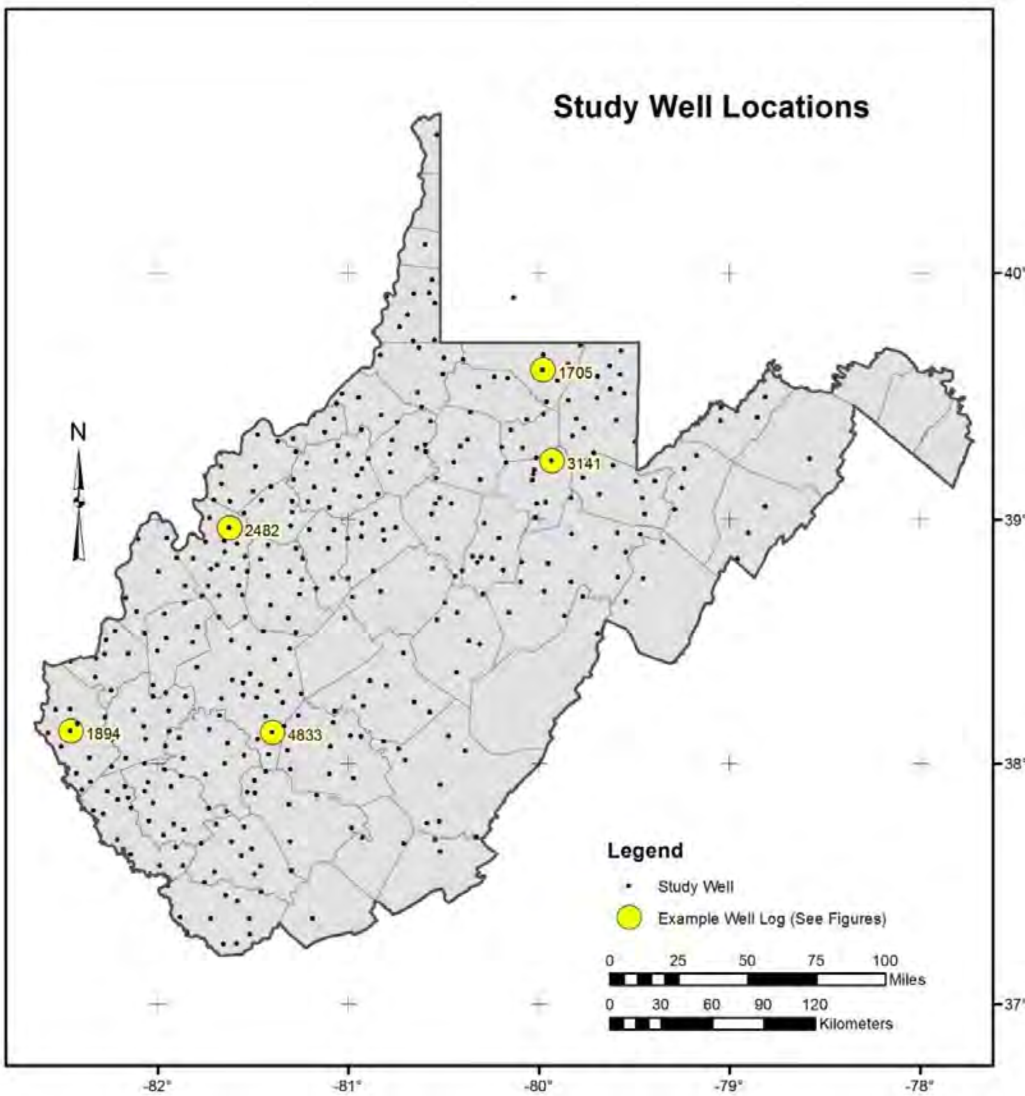


Figure 2. *Location of wells from which geophysical well log data were used in this study. Wells highlighted in yellow are shown in subsequent figures as follows: well #2482 (Jackson Co.) in* ***Figure 3****; well #3141 (Barbour Co.) in* ***Figure 6****; well #1705 (Monongalia Co.) in* ***Figure 7****; well #1894 (Wayne Co.) in* ***Figure 8****; and well #4833 (Kanawha Co.) in* ***Figure 9****.*

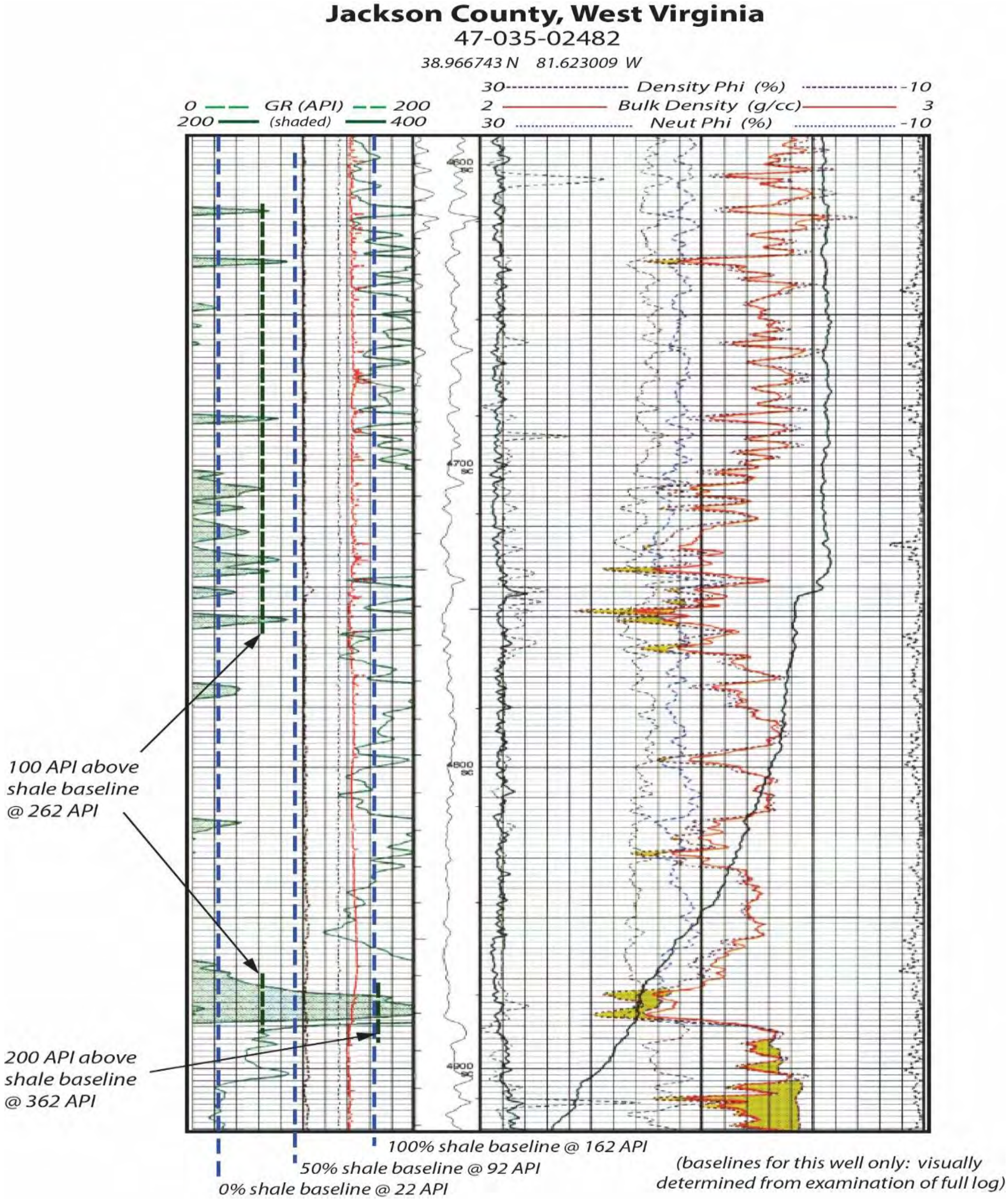


Figure 3. *Example geophysical well log used in this study, indicating how shale baselines (blue dashed) are applied to gamma-ray data (green) to assist in determination of lithology and thickness of organic-rich shales.*

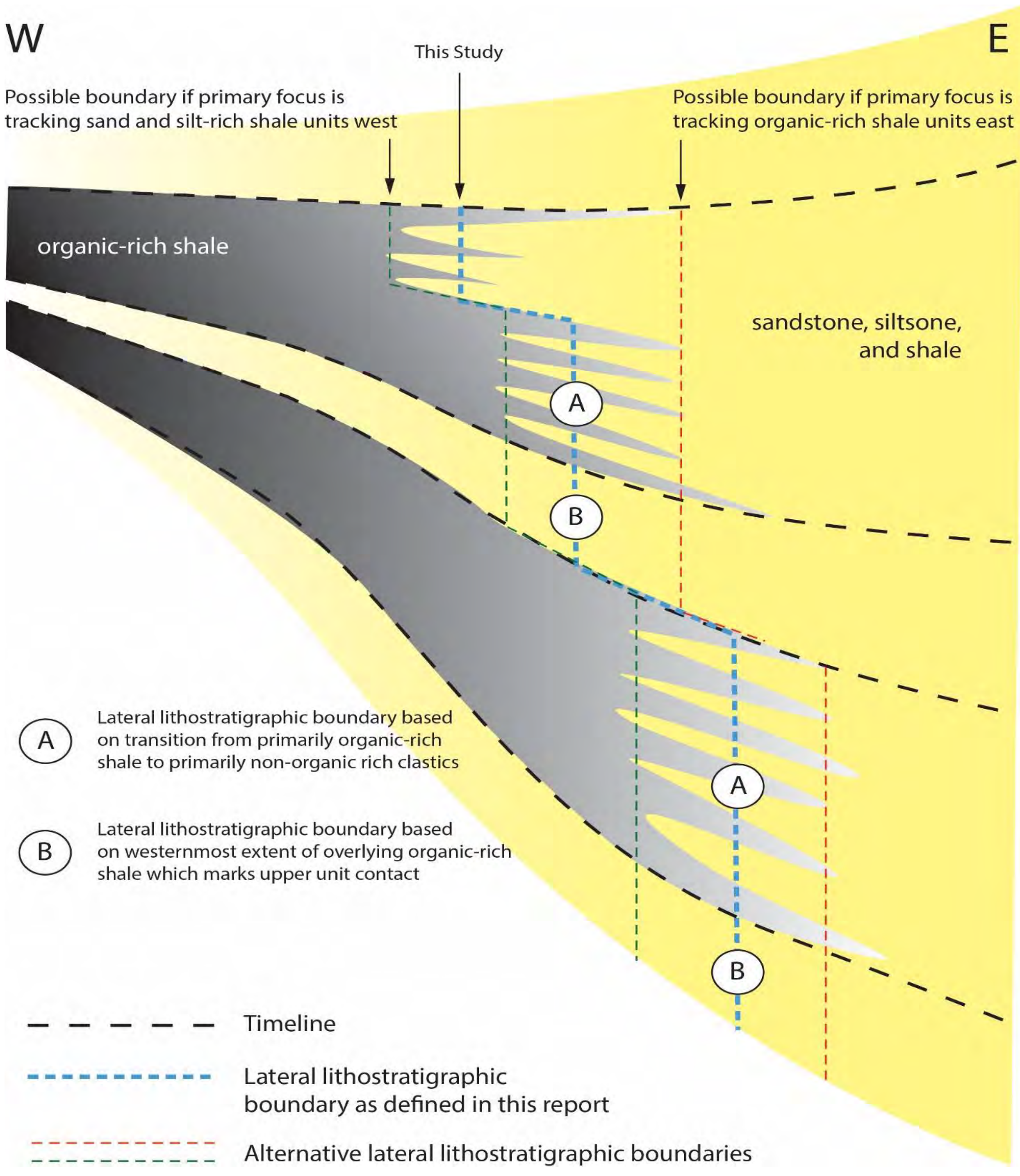


Figure 4a. *Schematic illustration showing the convention used to determine the position of lateral lithostratigraphic boundaries for organic-rich shale units. Blue dashed lines correspond to locations where the interval is assessed to transition from predominantly one lithology to the other. The boundaries are drawn as vertical to allow a clear demarcation between units in map view, and due to the modest dips within the study area, differ only slightly from boundaries drawn normal to the stratigraphy. Red and green dashed lines show alternative approaches to determining lateral lithostratigraphic boundaries.*

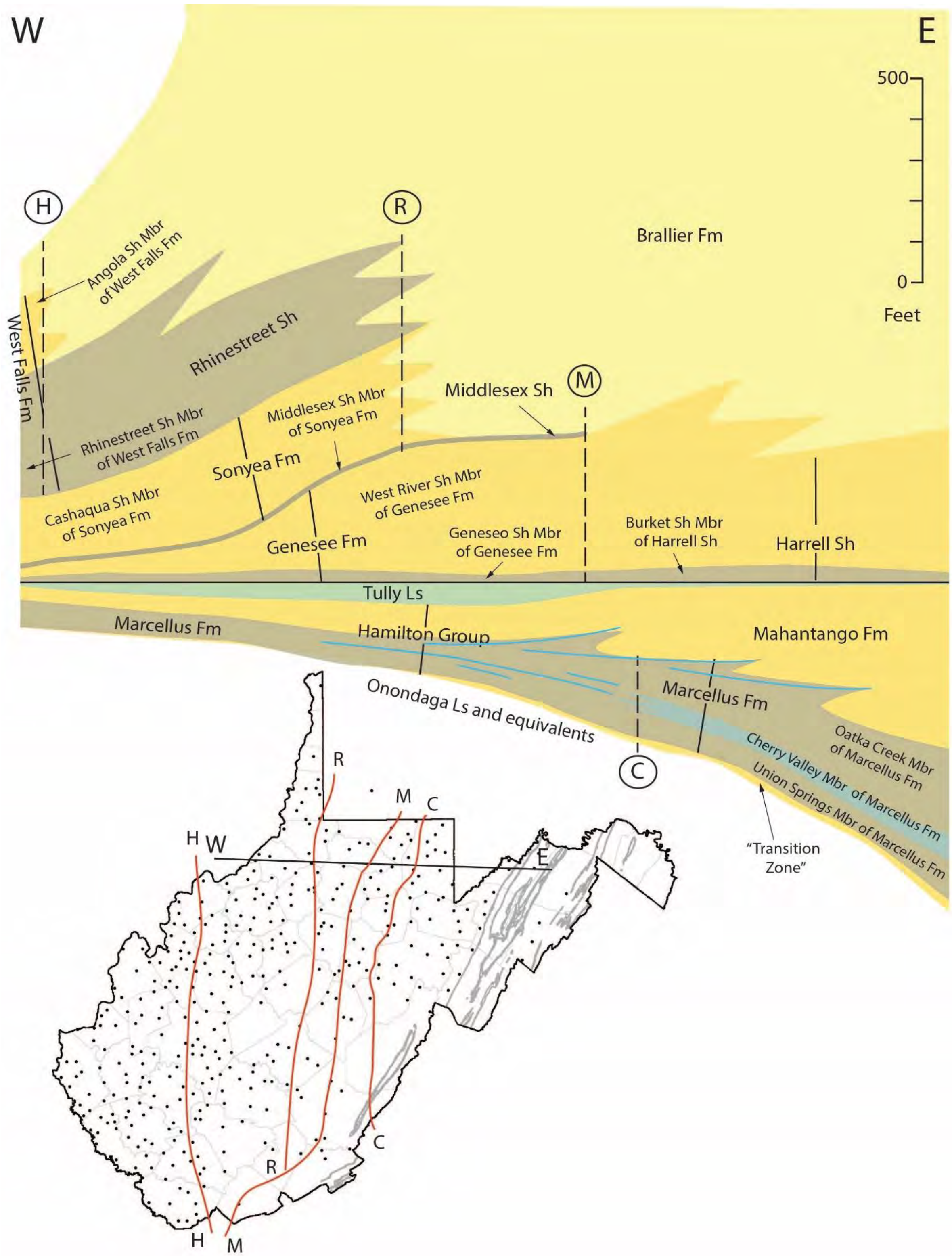


Figure 4b. *Schematic west to east cross-section showing the lithostratigraphy of organic-rich shales (brownish grey) and associated units in West Virginia. The insert shows the position of the lateral facies boundaries within the subsurface. Vertical scale is approximate. No horizontal scale.*

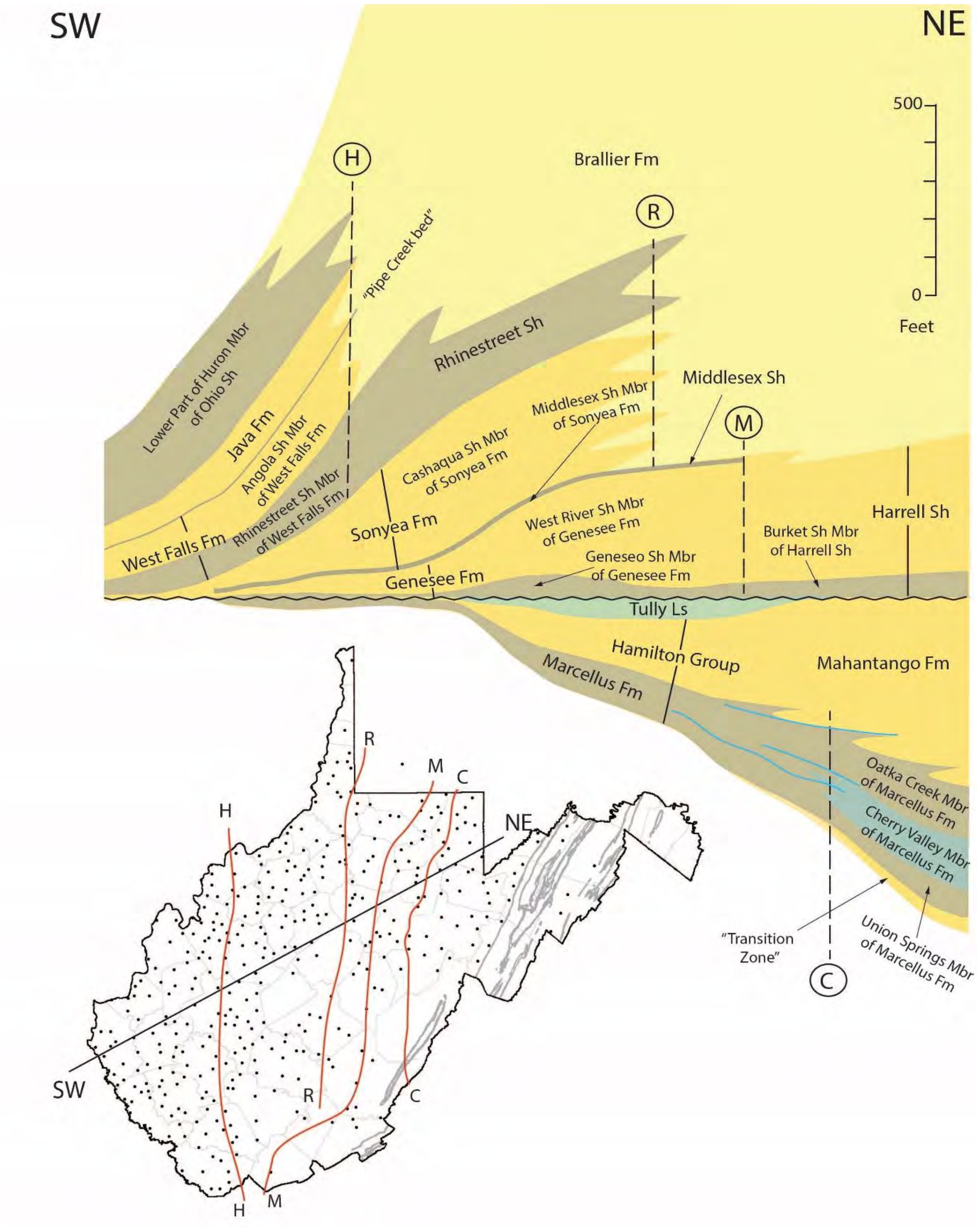


Figure 4c. *Schematic southwest to northeast cross-section showing the lithostratigraphy of organic-rich shales (brownish grey) and associated units in West Virginia. The insert shows the position of the lateral facies boundaries within the subsurface. Vertical scale is approximate. No horizontal scale.*

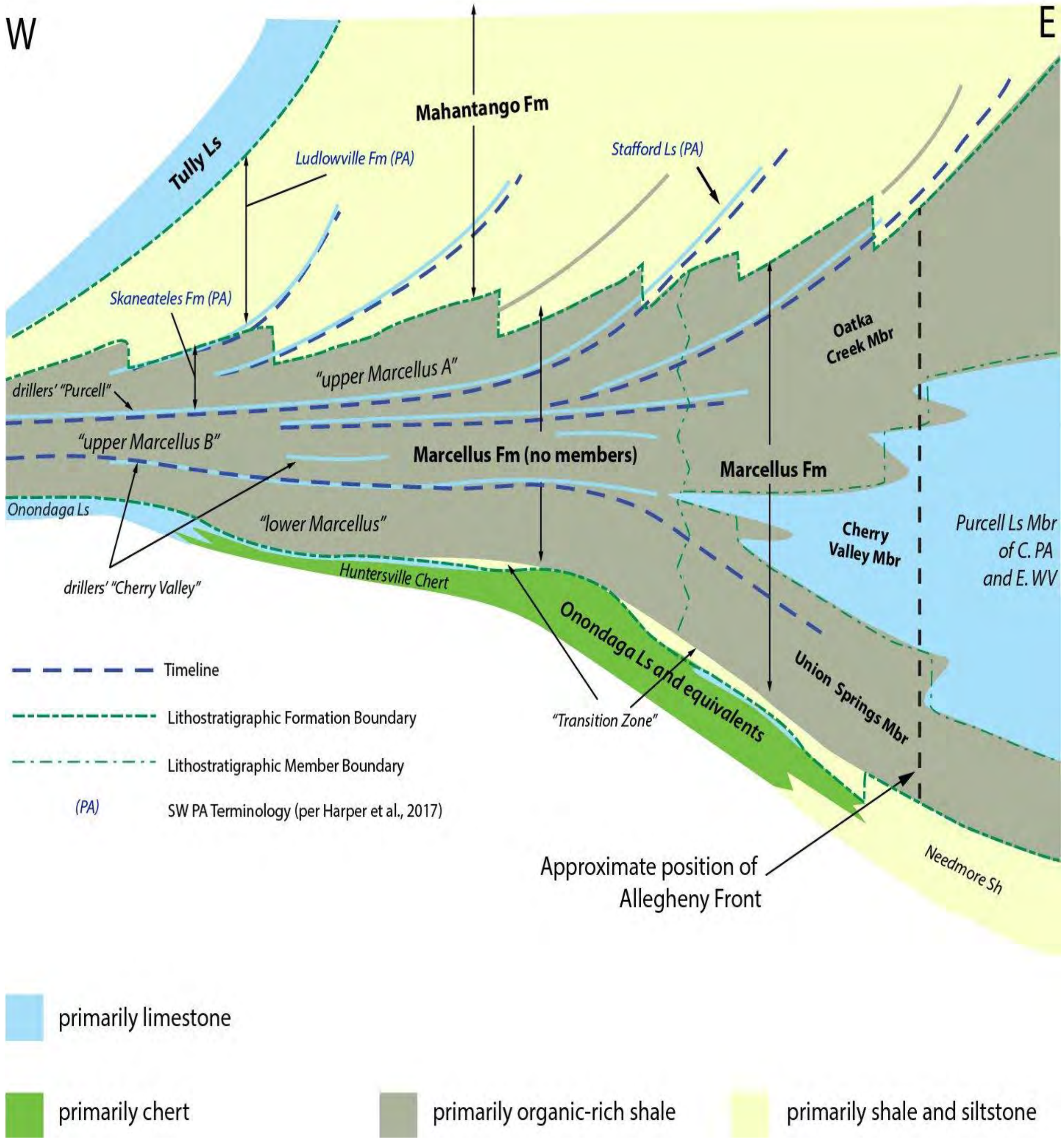
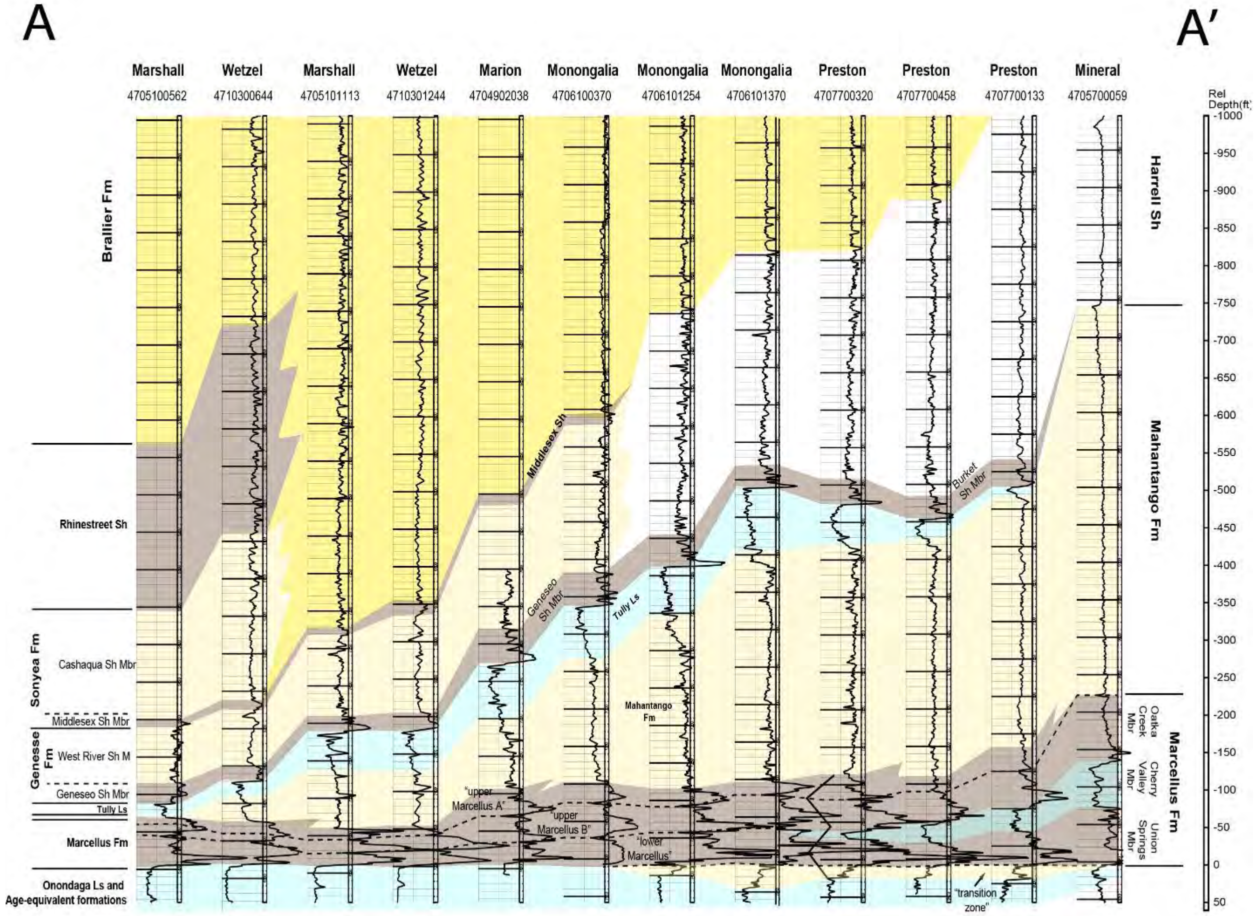


Figure 4d. *Schematic detail of recommended West Virginia lithostratigraphy for the Hamilton Group. The Hamilton consists of a basal Marcellus Formation and an overlying Mahantango Formation. The lithostratigraphic boundary (green lines) between these two formations is diachronous, becoming younger as traced westward into the basin. The Marcellus contains three members in northeastern West Virginia. To the west, several informal intervals were identified and mapped. Blue text indicates terminology used in southwestern Pennsylvania (Harper et al., 2017). No horizontal or vertical scale.*



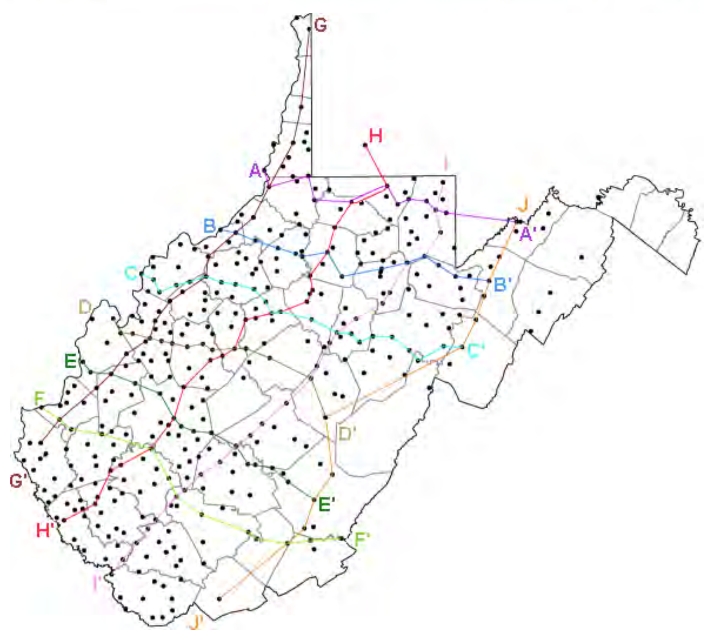


Figure 5. *Example west to east cross-section, A-A'. A-A' and other cross-sections can be found in high resolution on the West Virginia Geological and Economic Survey web site*.

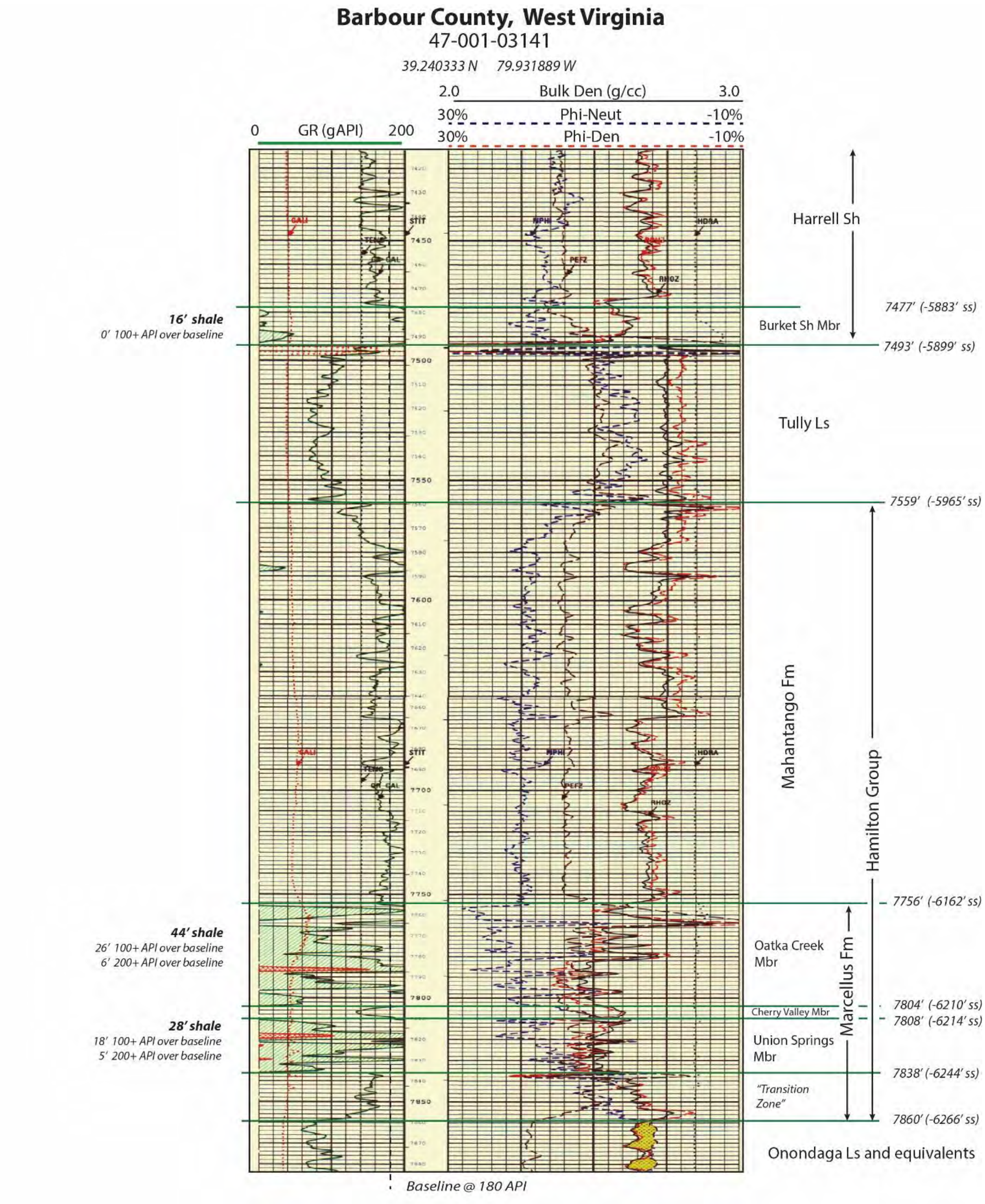


Figure 6. *Geophysical well log data from the Barbour-3141 well showing the correlation of Middle and Upper Devonian organic-rich shales and the assignment of unit thicknesses relative to gamma-ray baselines.*

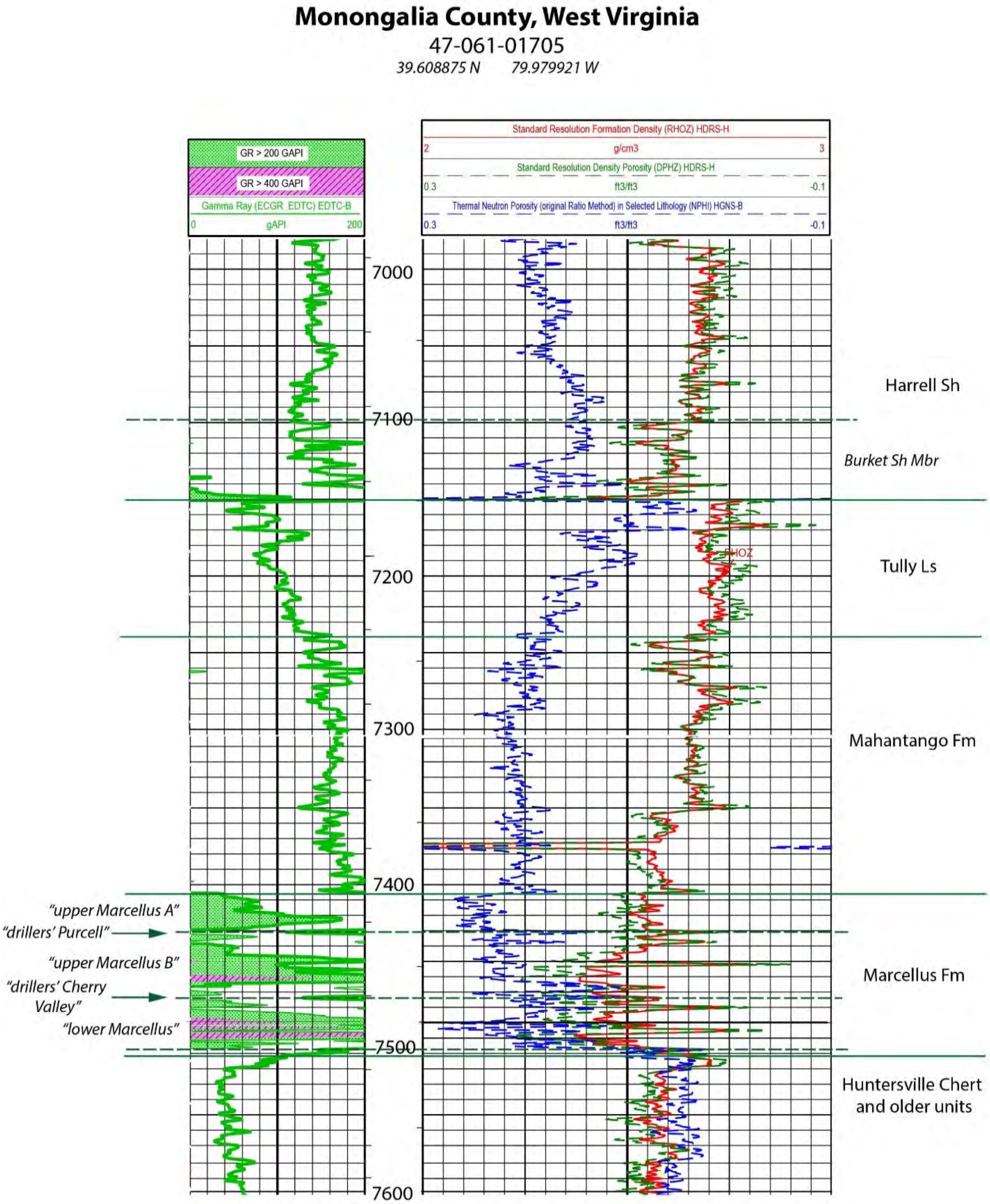


Figure 7. *Geophysical well log data from the Marcellus Shale Energy and Environmental Laboratory Science Well drilled by Northeast Natural Energy, showing the correlation of Middle and Upper Devonian organic-rich shales including informal units within the Marcellus Formation (Log data courtesy Northeast Natural Energy).*

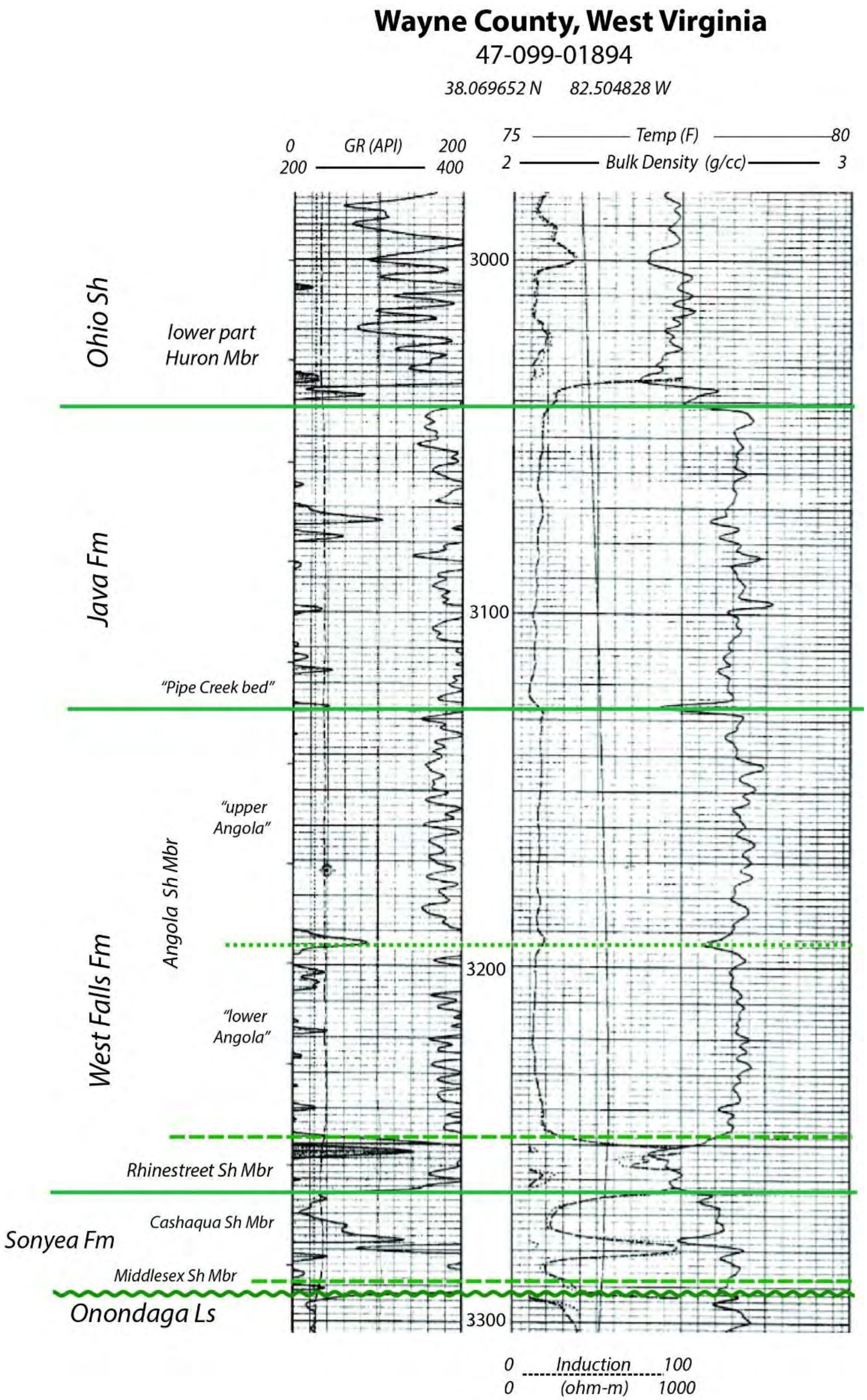


Figure 8. *Geophysical well log data from the Wayne-1894 well showing the correlation of Middle and Upper Devonian organic-rich shales.*

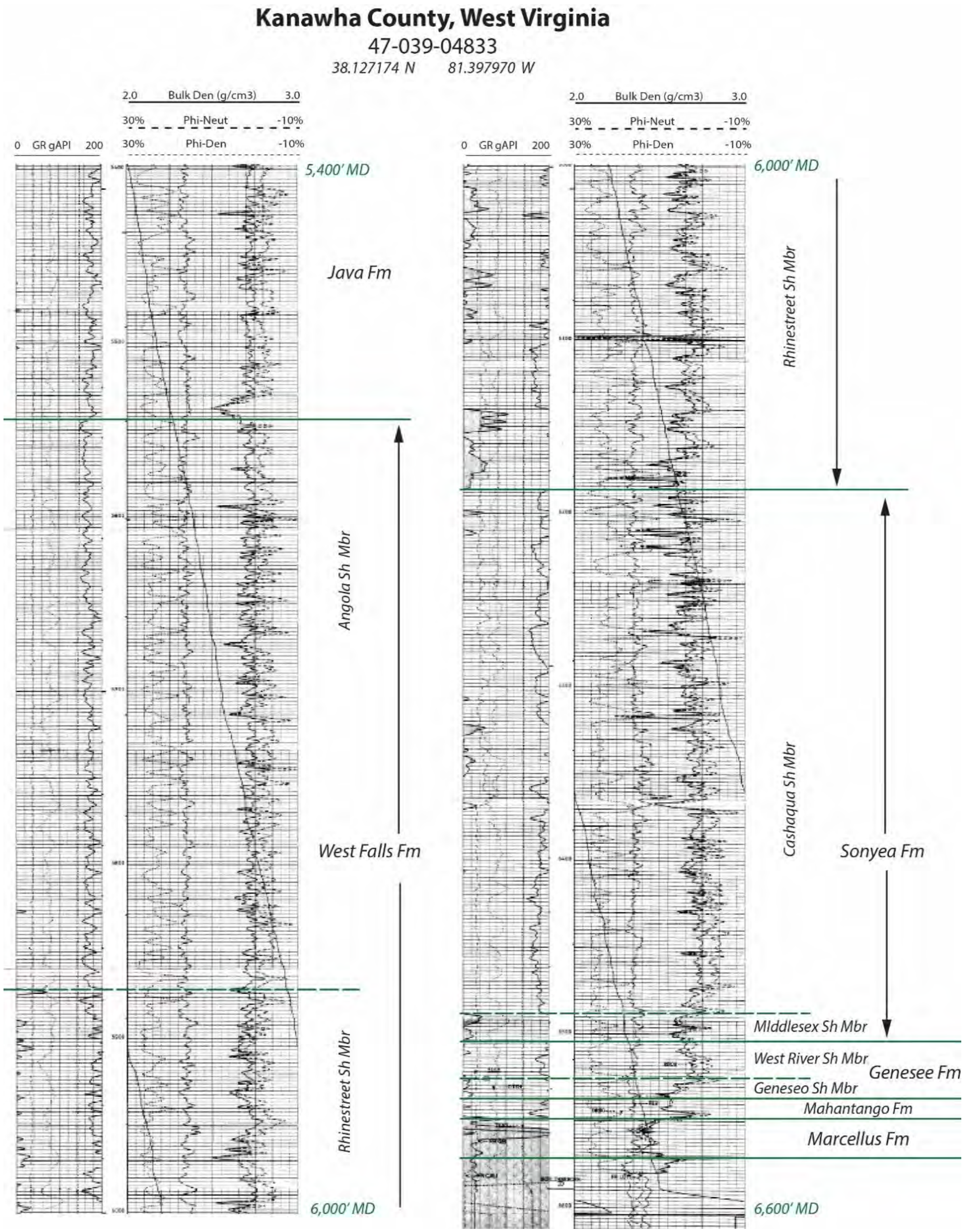


Figure 9. *Geophysical well log data from the Kanawha-4833 well showing the correlation of Middle and Upper Devonian organic-rich shales.*

Middle Devonian (Givetian) Marcellus-Mahantango-Tully Interval

Middle Devonian clastics of the Appalachian basin consist of those formations occurring stratigraphically between the underlying Onondaga Limestone and equivalents (**Figure 10**) and the overlying Genesee Formation and equivalents. In its type section in western New York, this interval was originally divided into four formations (from oldest to youngest: Marcellus Shale, Skaneateles Shale, Ludlowville Shale, and Moscow Shale) (Hall, 1839) that were soon combined within the Hamilton Group (Vanuxem, 1840). Equivalents of these units have subsequently been correlated southward into Pennsylvania (Willard, 1935; Lash and Engelder, 2011; Harper et al., 2017) and throughout the basin (de Witt et al., 1993).

Marcellus: The "Marcellus Shale" of Hall (1839) is readily recognized in the subsurface of West Virginia by elevated GR responses that directly overlie the Onondaga Limestone and its equivalents (including the Needmore Shale and Huntersville Chert in northeastern West Virginia). The top of the unit becomes older eastward, with uppermost Marcellus units in the basin center being time-equivalent with lower Mahantango units to the east (**Figure 4d**). The Marcellus thins to zero thickness in extreme western West Virginia (Schwietering and Roberts, 1988) and thickens eastward (**Figure 11a**). The westward extent of the Marcellus is difficult to discern conclusively, as the section thins dramatically, bringing numerous organic-rich shale units into close association.

Throughout much of West Virginia, the contact between the Marcellus and the subjacent units appears to be gradational, resulting in a somewhat arbitrary placement of the formation contact. The occurrence of this gradational transition suggests that the Marcellus-Onondaga (and equivalents) contact is conformable throughout much of West Virginia. The contact might be locally unconformable where no transition zone exists, particularly in western and southern West Virginia (**Figure 11b**). Where the contact is gradational, it is placed at roughly the 50% shale baseline (similar to Lash and Engelder, 2011). The overlying non-radioactive unit (with GR log volume of shale estimates between 50% and 100%) is informally-designated as the "transition zone" and is considered as part of the Marcellus. As the "transition zone" is tracked into northeastern West Virginia, it grades laterally into the uppermost portions of the Needmore Shale (**Figure 11b**).

de Witt and Roen (1985) suggest that in southeastern West Virginia, the Marcellus Formation, the Mahantango Formation, and the Burket Shale Member of the Harrell Shale coalesce into the Millboro Shale (Cooper, 1939; Butts, 1940; see also Dennison, 1961 and de Witt et al., 1993). However, throughout the entirety of the area of this study, the higher GR response of the Burket and Marcellus render those units readily distinguishable from the Mahantango in log data. In describing this section from cores taken in the Monongalia County MERC #1 well, de Witt et al. (1993) note that log data were superior to visual observation in distinguishing these lithologies. Therefore, the Millboro Shale is not recognized in the study area, but remains a useful term for outcrop-based studies where log data are not available.

On outcrop in western New York, the Marcellus has historically included numerous members including a lower Union Springs Member, an intermediate limestone assigned to the Cherry Valley Member, and an upper Oatka Creek Member (Clarke, 1903; Cooper, 1930). More recently, detailed studies have allowed the recognition of a more extensive nomenclature that elevates the Marcellus to Subgroup status with several formations and many members (Ver Straeten and Brett, 2006 and related publications as reviewed in Lash and Engelder, 2011). On outcrop in central Pennsylvania (Cate, 1963; Harper et al., 2017) and the eastern panhandle of West Virginia (Patchen et al., 1985; Hasson and Dennison, 1988), the thick intermediate limestone-rich unit is recognized as the Purcell Limestone Member.

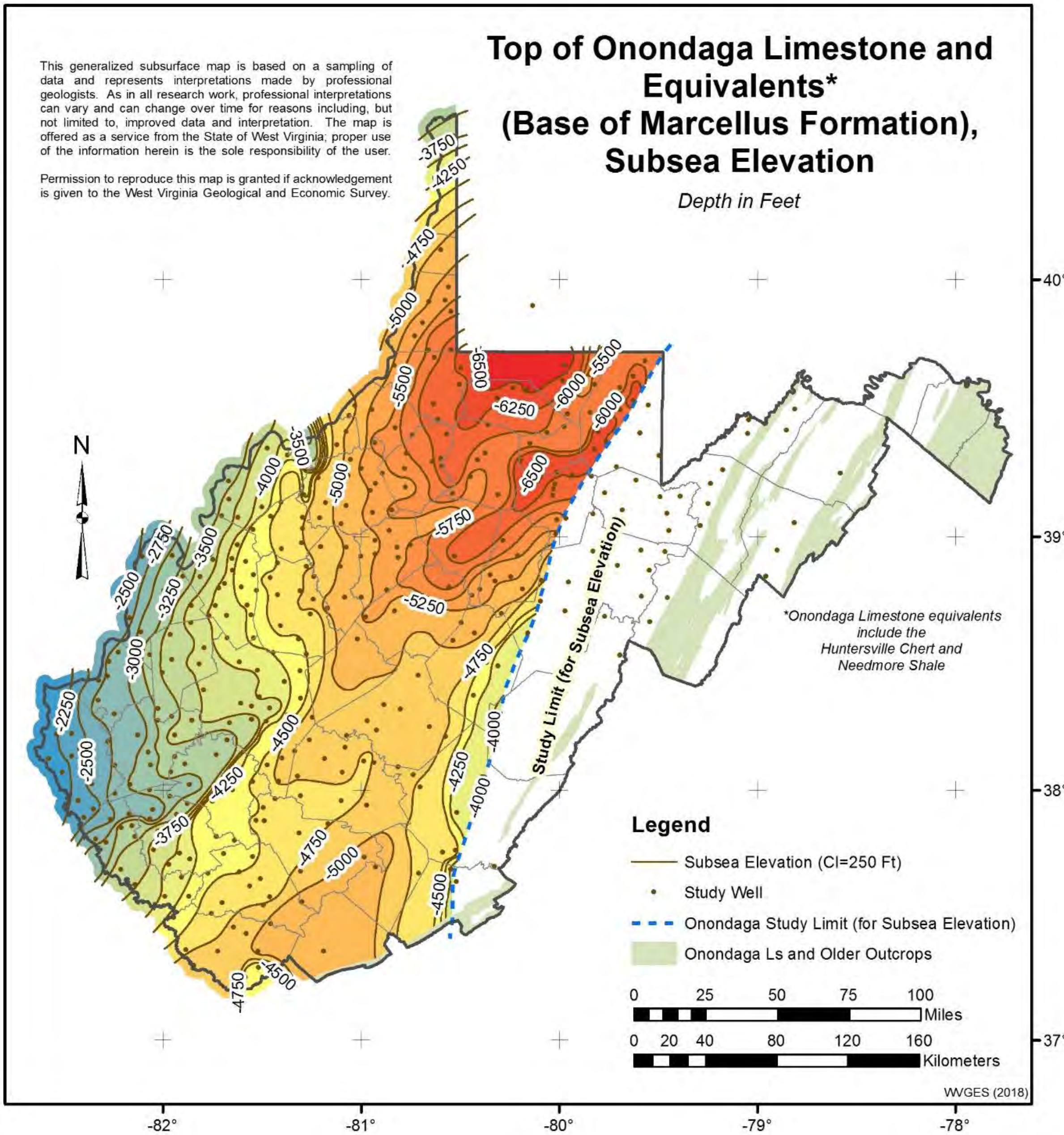


Figure 10. *Subsea elevation of the top of the Onondaga Limestone and equivalents (base of the Marcellus Formation) in the subsurface of West Virginia. Onondaga Limestone equivalents include the Huntersville Chert and the Needmore Shale. Structure to the east of the blue dashed line (in the fold and thrust belt) is highly complex and not well resolved by the data density used in this study and is therefore not shown.*

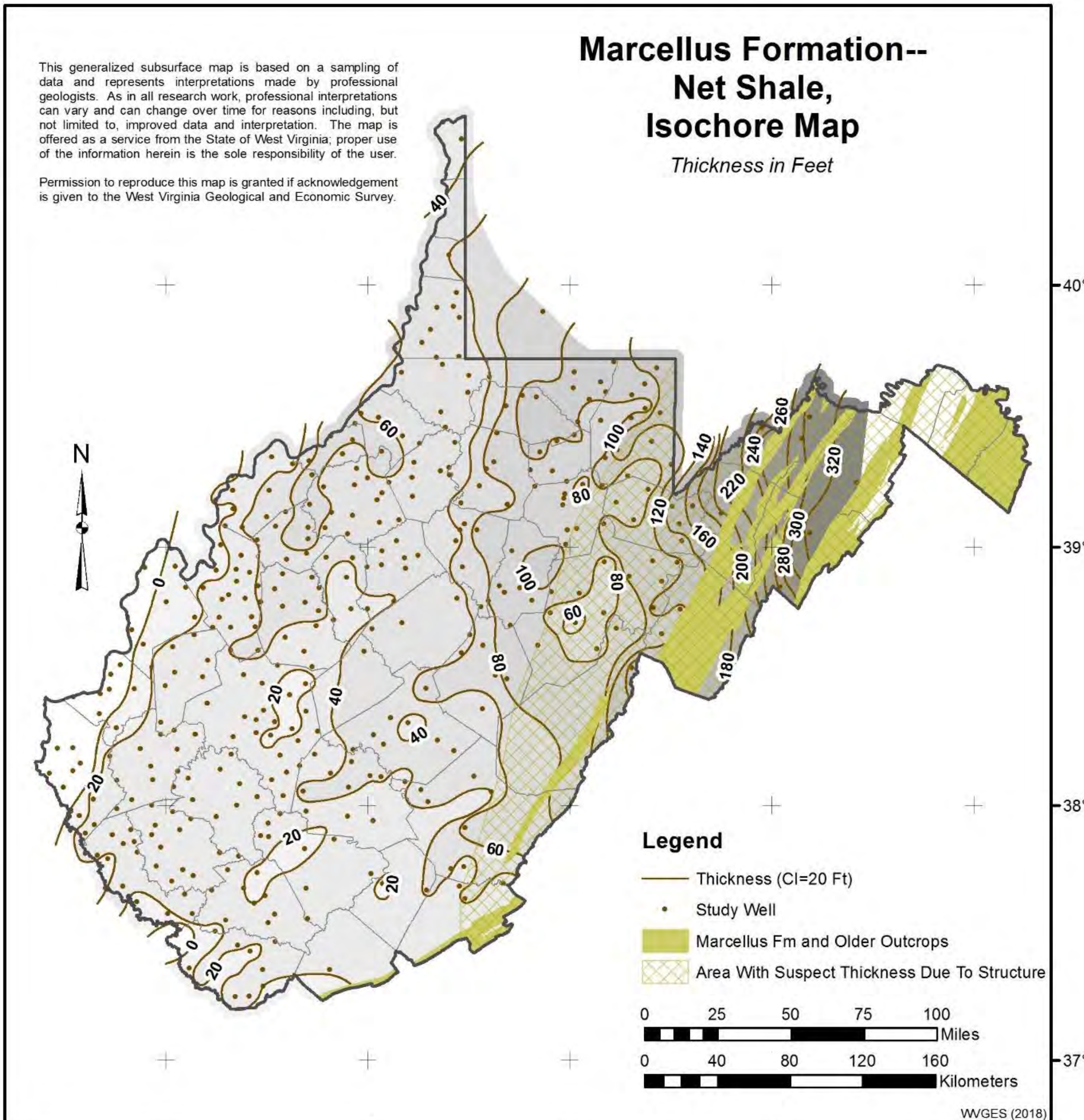


Figure 11a. *Isochore map of the organic-rich shale members of the Marcellus Formation in West Virginia. The map includes the Union Springs and Oatka Creek members in the northeastern part of the State and their equivalent informal units ("upper Marcellus A," "upper Marcellus B," and "lower Marcellus") in the western and southern parts of the State. The map excludes thickness assigned to the Cherry Valley Member and the "transition zone."*

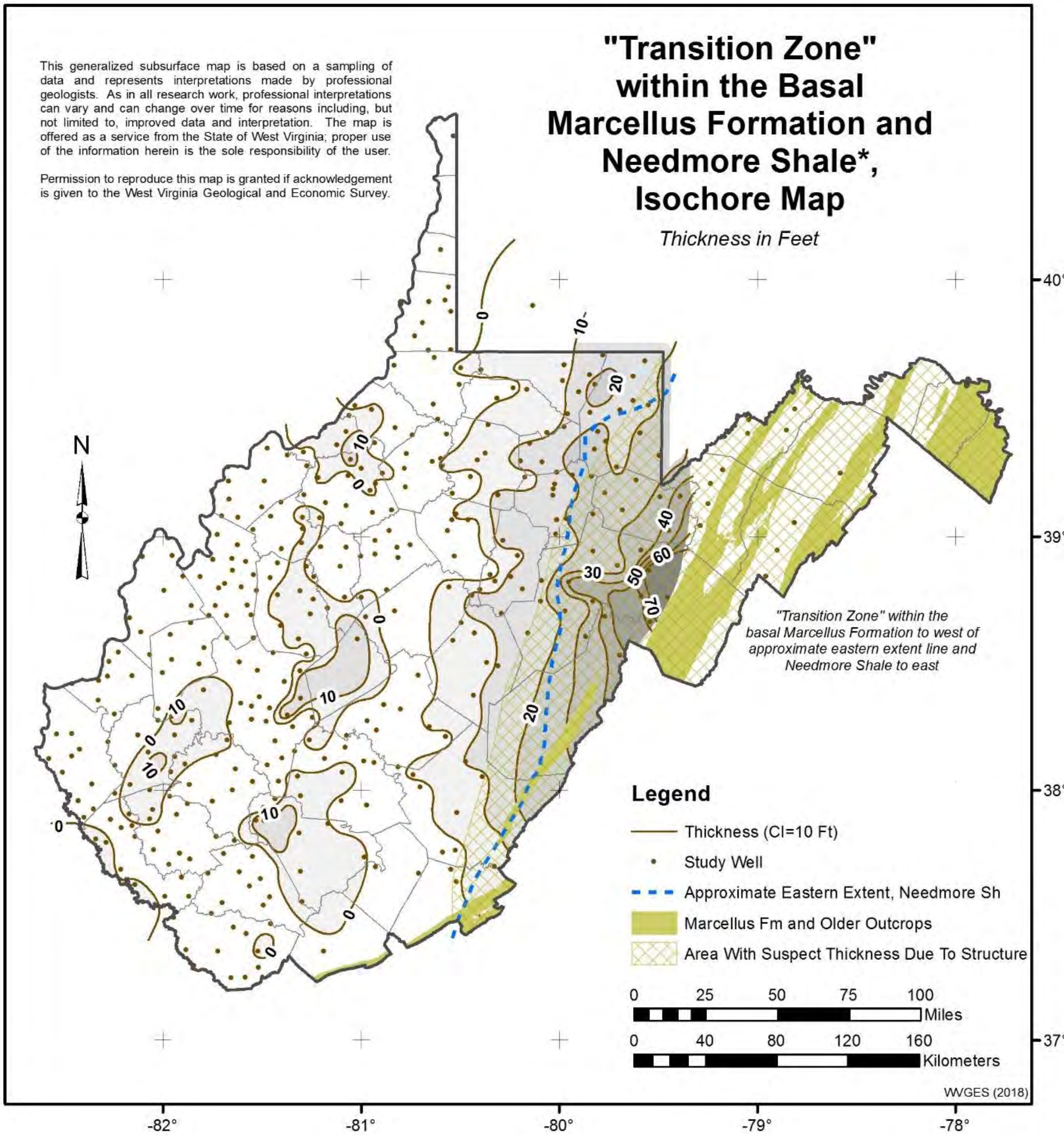


Figure 11b. *Isochore map of the "transition zone" that locally occurs at the base of the Marcellus Formation in West Virginia. The "transition zone" consists of shale units with gamma-ray readings generally less than the shale baseline, but significantly greater than the underlying Onondaga Limestone and its equivalents (i.e., gamma-ray readings between 50% and 100% shale). To the west of the dashed blue line, the "transition zone" is mapped as an informal unit within the Marcellus Formation. To the east of the line, contours reflect the full thickness of the Needmore Shale.*

Initial attempts to correlate the Marcellus throughout the subsurface (Schwietering, 1980) did not recognize any formal members. Subsequently, de Witt et al. (1993), recognized two members within the Marcellus locally in southwestern Pennsylvania and northern West Virginia: a lower "Cherry Valley Member" and an upper "Purcell Limestone Member" that represent separate thin limestone units. Lash and Engelder (2011) simplified the outcrop-based nomenclature of western New York for subsurface use and mapped three formal members throughout western Pennsylvania and into northern West Virginia: a basal, organic-rich Union Springs Member, an intermediate carbonate-rich Cherry Valley Member, and an uppermost organic-rich Oatka Creek Member.

Based on this study, the refined terminology of Lash and Engelder (2011), including the Union Springs Member, Cherry Valley Member, and Oatka Creek Member is formally adopted in those areas of northeastern West Virginia where the Cherry Valley Member is readily mappable (**Figures 4b** to **4d**, **5**, and **11c** to **11e**). Where the Cherry Valley Member is not present, or multiple limestones occur that have uncertain correlation to the Cherry Valley Member, there is no lithologic justification for distinguishing the Union Springs and Oatka Creek and therefore no formal members are recognized in the Marcellus. However, even in such areas, the Marcellus often is comprised of several distinct lobes of high-GR response separated by thin, low-GR units interpreted as limestones (e.g., **Figure 7**). These limestones (including those units separately denoted "Cherry Valley" and "Purcell" by de Witt et al., 1993) are generally too thin and discontinuous to warrant formal lithostratigraphic status. However, they are sufficiently present to allow recognition of three informal organic-rich units: a "lower Marcellus" (**Figure 11c**) roughly corresponding to the Union Springs Member, an "upper Marcellus B" (**Figure 11f**) roughly correlative with the lower portion of the Oatka Creek Member, and an "upper Marcellus A" (**Figure 11g**) roughly corresponding to the upper portion of the Oatka Creek Member. Isochore maps of the informal "upper Marcellus A" unit reveal linear north-northeasterly trending zones of thickening that reflect different positions of the facies transition between Marcellus and Mahantango lithologies (**Figure 11g**) as the boundary becomes progressively older as traced eastward.

The minor and discontinuous limestone units separating the "lower Marcellus" from the "upper Marcellus B" are correlative with the Cherry Valley Member and are therefore best referred to as informal drillers' "Cherry Valley" (**Figure 4d**). Based on observed industry usage, the limestone bed that generally separates the two informal "upper Marcellus" units in northcentral West Virginia is recognized as an informal drillers' "Purcell." It is likely that this unit is correlative with the Stafford Limestone Member of the Skaneateles Shale as mapped in southwestern Pennsylvania (Harper et al., 2017) and locally in West Virginia (Blood et al., 2017)—who also designate the "upper Marcellus A" of this study as the "Levanna Shale."

Generally, the Marcellus is referred to as either the "Marcellus Shale" or the "Marcellus Formation." Given that the unit is a complex mix of lithologies (Bruner et al., 2015; Wang and Carr, 2013), including argillaceous, calcitic, and siliceous mudstones; and also considering the occurrence of limestones within the unit, the term "Marcellus Formation" is formally adopted for use in West Virginia, following the similar usage in Pennsylvania (Lash and Engelder, 2011; Harper et al., 2017).

Mahantango: The Marcellus Formation is the only original "Hamilton Group" formation that has been clearly defined within West Virginia. Recognition of many of the New York-based shales is premised on reliable detection of thin limestone members that lie at the base of each unit. For example, the base of the Skaneateles Shale is marked by the thin, basal Stafford Limestone that is manifested as a conspicuous low-density spike at the top of the Marcellus on logs (Oliver et al., 1969; de Witt et al., 1993; Harper et al., 2017); however, Lash and Engelder

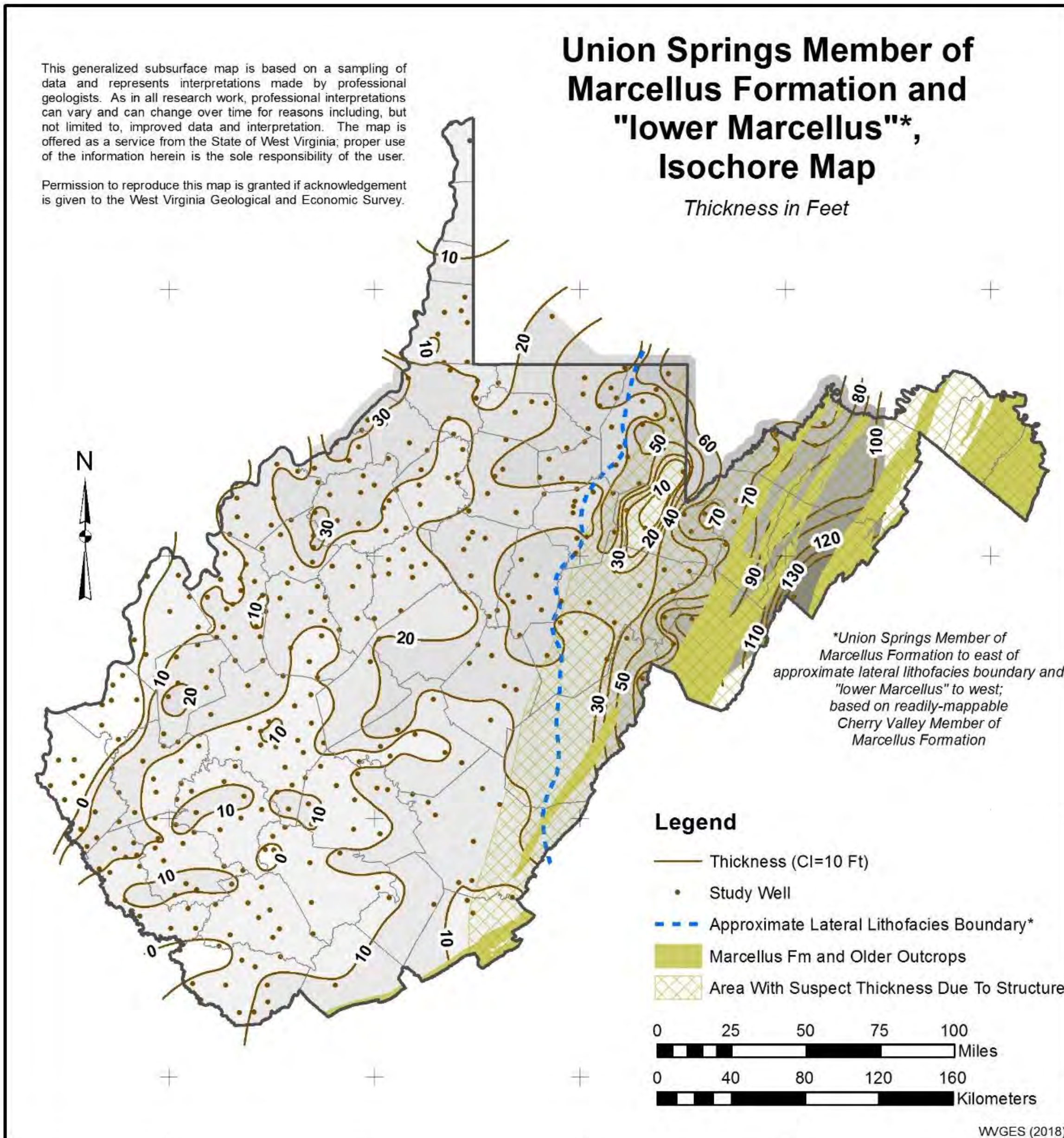


Figure 11c. *Isochore map of the Union Springs Member of the Marcellus Formation to the east of the approximate lateral lithofacies boundary (dashed blue line) and equivalent units of the informal "lower Marcellus" of the Marcellus Formation to the west of the boundary. The lateral transition between the two units is based on the westward occurrence of readily-mappable units of the Cherry Valley Member of the Marcellus Formation (**Figure 11d**); also see Line C on **Figures 4b** and **4c.** Local thin limestones (herein the drillers' "Cherry Valley") mark the upper boundary of the unit to the west of the dashed blue line.*

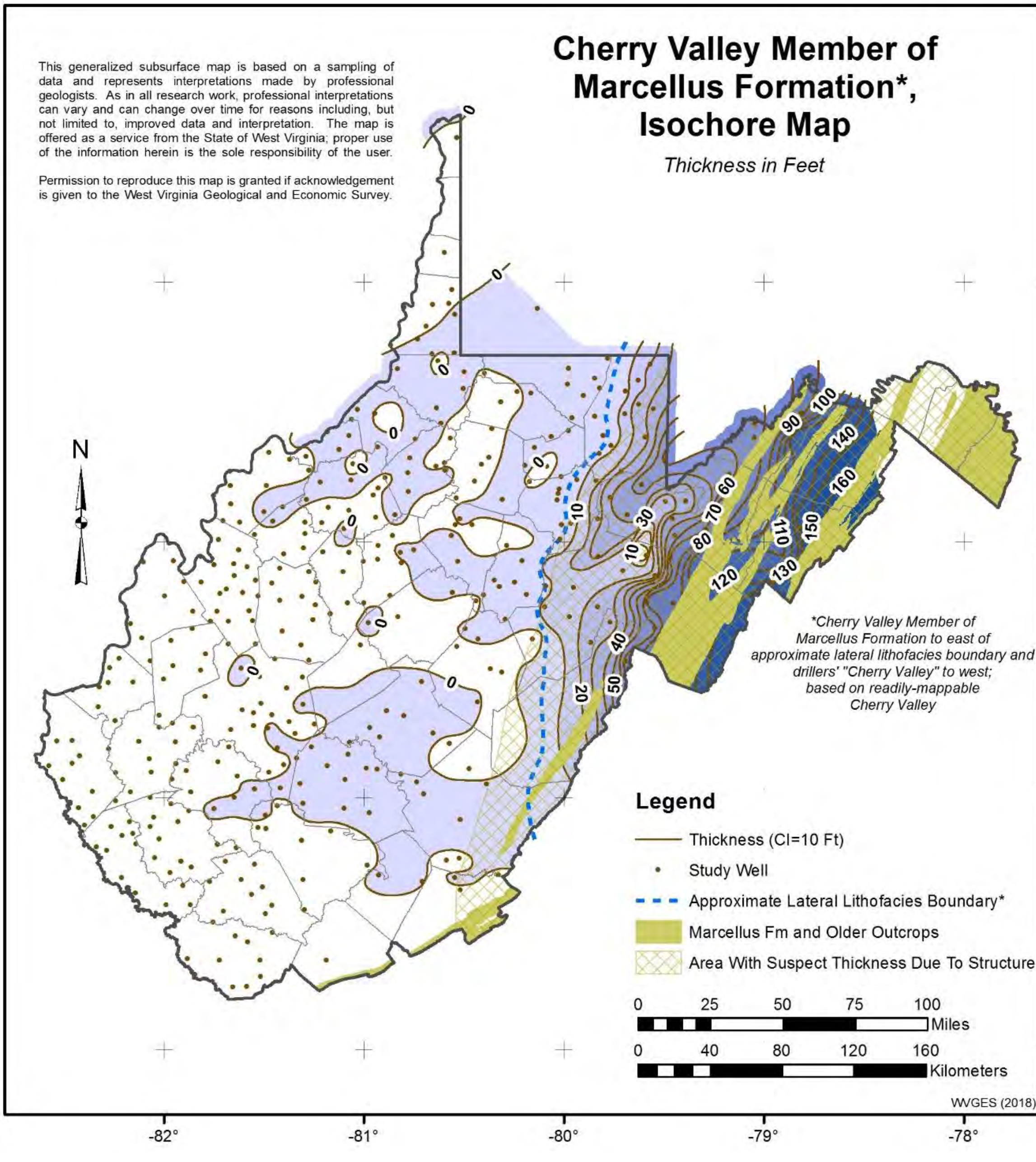


Figure 11d. *Isochore map of the Cherry Valley Member of the Marcellus Formation to the east of the approximate lateral lithofacies boundary (dashed blue line) and correlative drillers' "Cherry Valley" within the undifferentiated Marcellus Formation to the west of the boundary. The drillers' "Cherry Valley" is not clearly a single unit—multiple thin limestones of limited geographic extent are present. Mapped thicknesses of the Cherry Valley Member are suspect in the hachured area due to the increased structural complexity in that area, including possible high formation dips or missing or repeated sections due to faulting. For the lateral lithofacies boundary, also see Line C on **Figures 4b** and **4c**.*

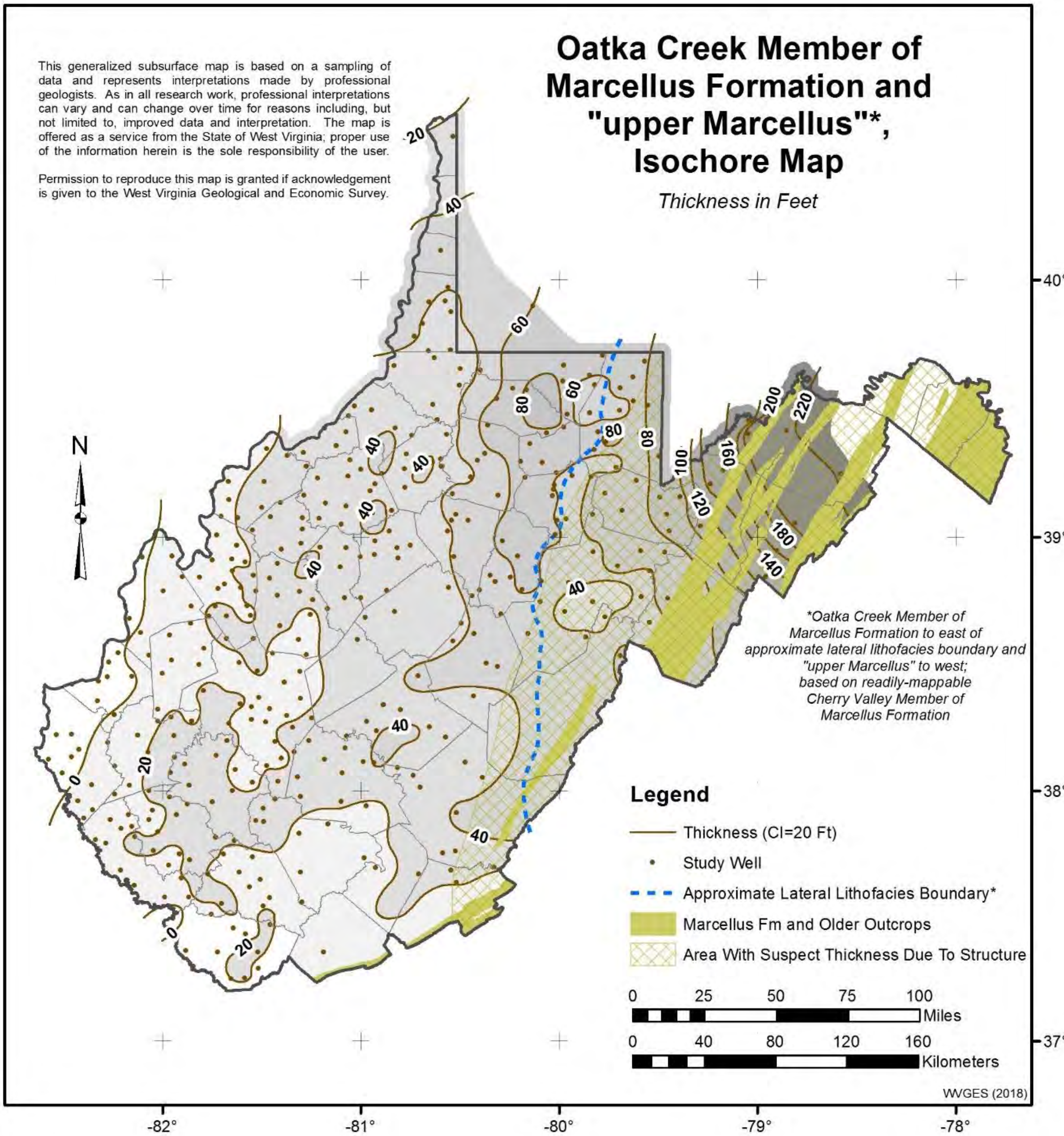


Figure 11e. *Isochore map of the Oatka Creek Member of the Marcellus Formation to the east of the approximate lateral lithofacies boundary (dashed blue line) and equivalent units of the informal "upper Marcellus" (including "upper Marcellus A" and "upper Marcellus B") of the Marcellus Formation to the west of the boundary. The lateral transition between the two units is based on the westward occurrence of readily-mappable units of the Cherry Valley Member of the Marcellus Formation (**Figure 11d**); also see Line C on **Figures 4b** and **4c**.*

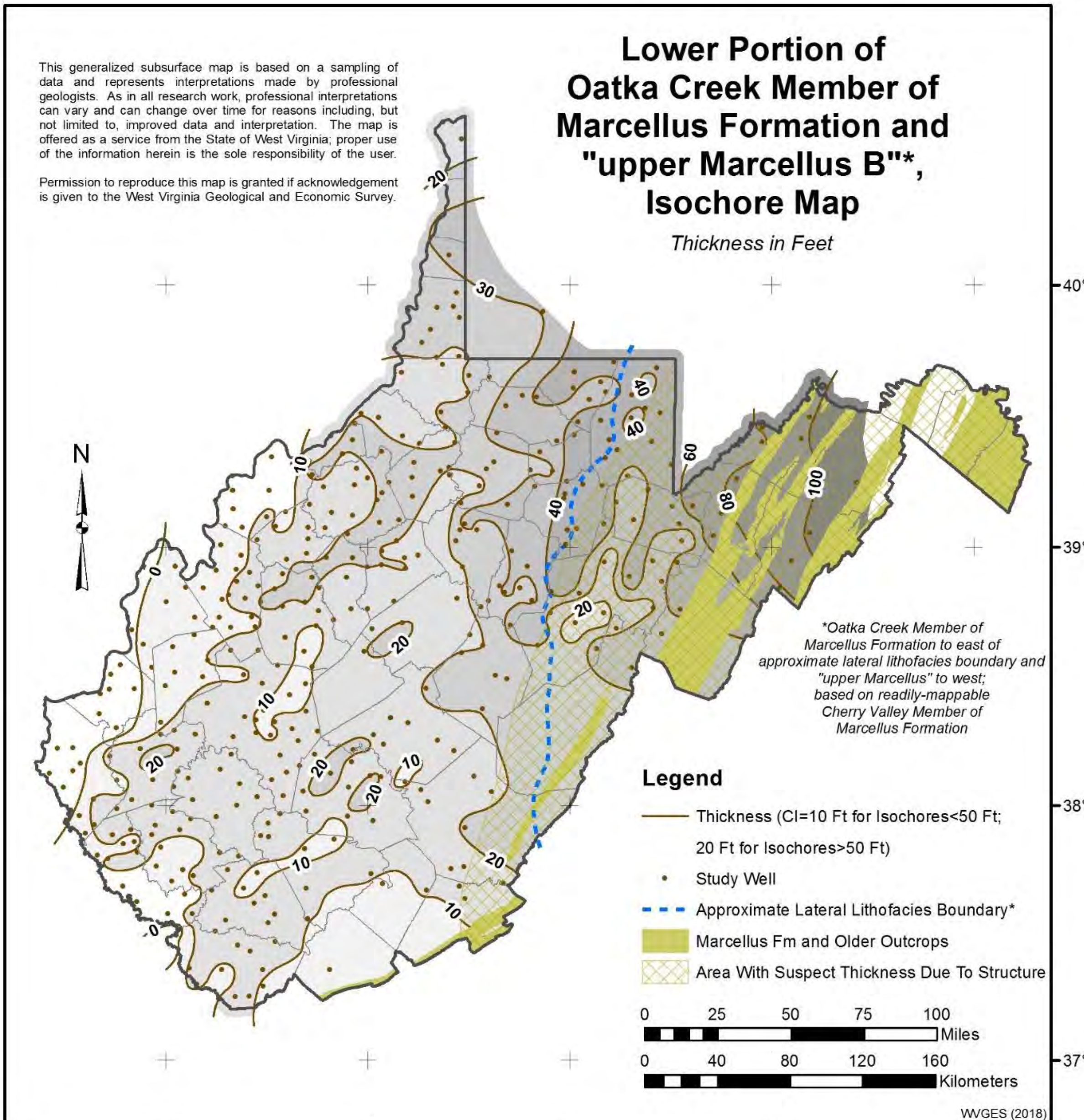


Figure 11f. *Isochore map of the lower portion of the Oatka Creek Member of the Marcellus Formation to the east of the approximate lateral lithofacies boundary (dashed blue line) and equivalent informal "upper Marcellus B" to the west of the boundary; also see Line C on* ***Figures 4b*** *and* ***4c****. For this study, the "upper Marcellus" was subdivided into "A" and "B" units due to a common gamma-ray spike on the well logs in the northcentral part of the State (the drillers' "Purcell") that likely is correlative with the Stafford Limestone of southwestern Pennsylvania.*

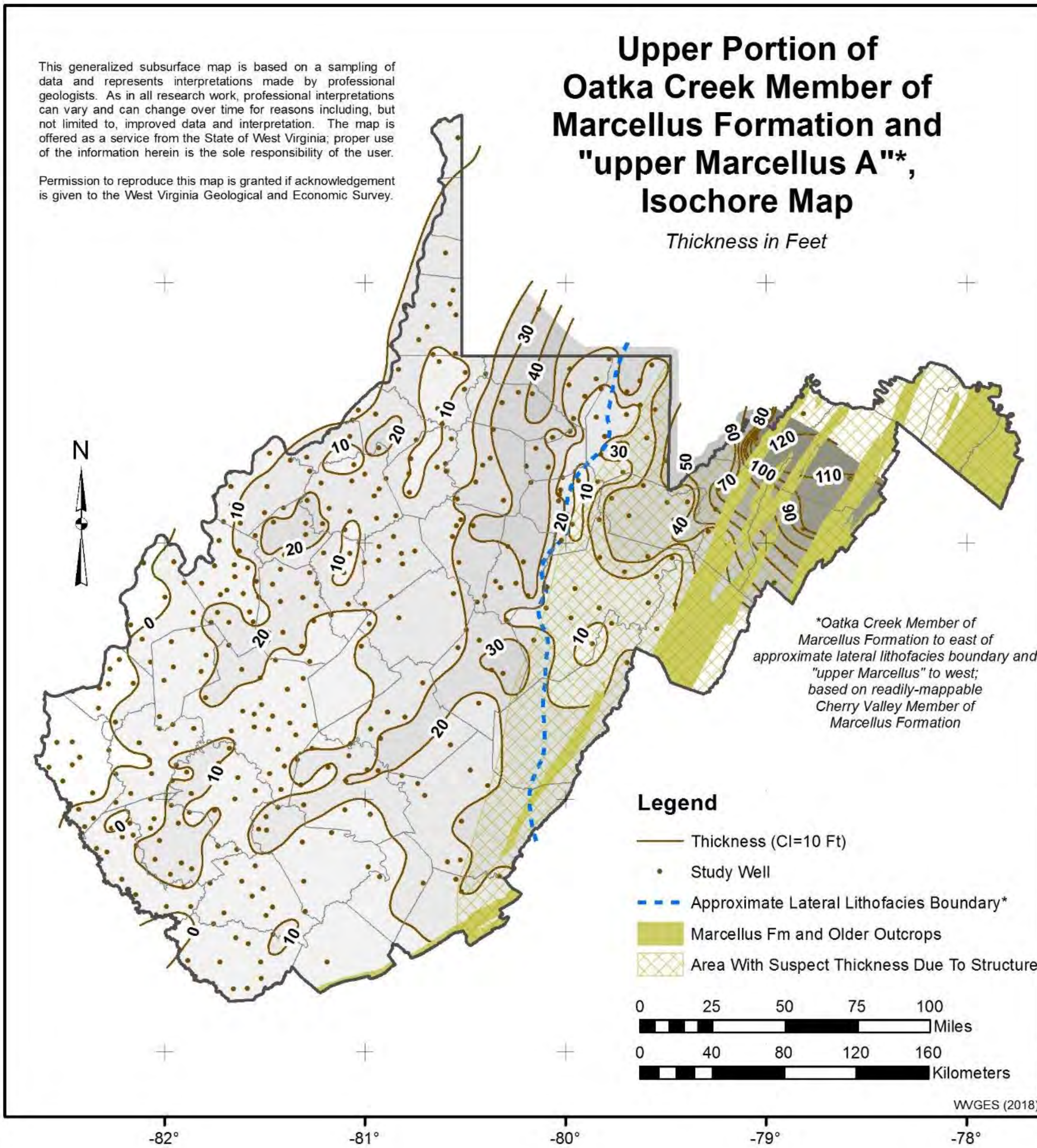


Figure 11g. *Isochore map of the upper portion of the Oatka Creek Member of the Marcellus Formation to the east of the approximate lateral lithofacies boundary (dashed blue line) and equivalent informal "upper Marcellus A" of the Marcellus Formation to the west of the boundary; also see Line C on* ***Figures 4b*** *and* ***4c****. The unit is closely correlative with the Skaneateles Shale of southwestern Pennsylvania (Harper et al., 2017).*

(2011) were unable to confidently extend the Stafford into West Virginia.

Correlation of the overlying Ludlowville and Moscow formations (which requires similar recognition of the basal Centerfield Limestone and Tichenor Limestone members, respectively), has been more difficult; for example, the interval is noted as "Moscow and Ludlowville undivided" by de Witt et al. (1993). As a result, the Skaneateles, Ludlowville, or Moscow shales cannot be confidently recognized widely in West Virginia. Given these difficulties with extending the earlier New York terminology, the interval of non-radioactive shale with minor limestone and silt/silty-sand units above the Marcellus is assigned to the Mahantango Formation (Willard, 1935). It is recognized that this unit is more distal in West Virginia (and therefore more fine-grained) than as described from its type location in central Pennsylvania (Willard, 1935; Duke and Prave, 1991); however, "Mahantango" has a long history of use in West Virginia (e.g., Schwietering, 1979; Cardwell, 1982) and has been consistently applied in the State without significant confusion.

Numerous members of the Mahantango have, on occasion, been mapped in south-central Pennsylvania (Harper et al., 2017) and eastern West Virginia (Dennison and Hasson, 1976; Woodrow et al., 1988); however, no sub-divisions of the unit can be confidently recognized in the study area. The Mahantango Formation thins from more than 400 feet in the eastern panhandle to zero feet in southwestern West Virginia (**Figure 12**).

Hamilton: In New York, "Hamilton Group" includes various formations equivalent to the Marcellus and Mahantango in West Virginia. The term "Hamilton" has been used inconsistently in West Virginia, where commonly only the Marcellus and Mahantango formations are recognized (per Filer, 1985; Cardwell, 1982) (**Figure 13**). The term Hamilton is retained within the State; however, where the Mahantango is not present, the Givetian section is represented by the Marcellus Formation with no Hamilton Group recognized (per Neal and Price, 1986; Sweeney, 1986; Caramanica, 1988; and Levendosky and McGill, 1988).

Tully: The Tully Limestone (Vanuxem, 1839) is a widespread and readily-correlated unit generally dated as latest Middle Devonian. It can be traced across northern and central West Virginia (de Witt et al., 1993) with confidence, where local thickness approaches 100 feet (**Figure 14**). The upper contact is characteristically sharp and represents the regional Acadian unconformity (Sloss, 1988); however, its basal contact with the Mahantango Formation is locally gradational and therefore arbitrary—it is placed here at the lowermost extent of elevated DEN log reading indicating significant carbonate content.

Upper Devonian (Basal Frasnian) Genesee-Harrell Interval

The Genesee Formation (Vanuxem, 1842) was defined in western New York for basal Upper Devonian "slate" that directly overlies the Tully Limestone. In the type area, the Genesee has subsequently been separated into six separate limestone and shale units within the Genesee Group; including the basal Geneseo Shale, Lodi Limestone, Penn Yan Shale, Renwick Shale, Genundewa Limestone, and West River Shale. Correlation of these units southward across Pennsylvania and into West Virginia have proven problematic. de Witt et al. (1993) refer to "*undivided Geneseo and Renwick shale members*" where the two are suspected to have merged. The Lodi Limestone is exceedingly thin and cannot be traced beyond New York. The Penn Yan Shale and West River Shale members (de Witt and Colton, 1978) are separated by a thin local Genundewa Limestone Member, and where that is not present the interval is called the *"Penn Yan and West River Member."* Although Penn Yan Shale Member has been extended across western Pennsylvania (Harper et al., 2017) and northern West Virginia (de Witt et al., 1993); the established practice in central and western West Virginia of recognizing two

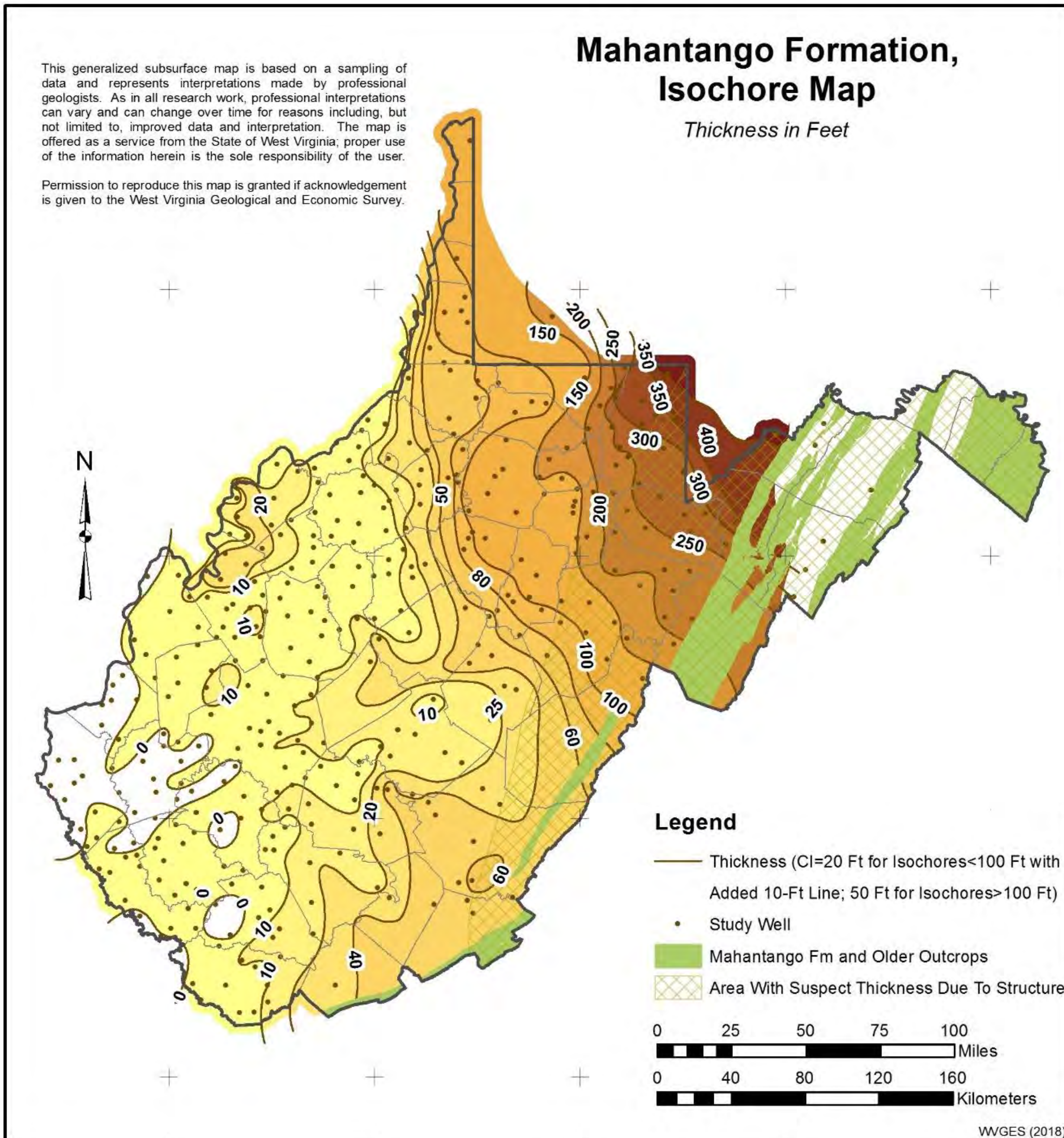


Figure 12. *Isochore map of the Mahantango Formation in West Virginia.*

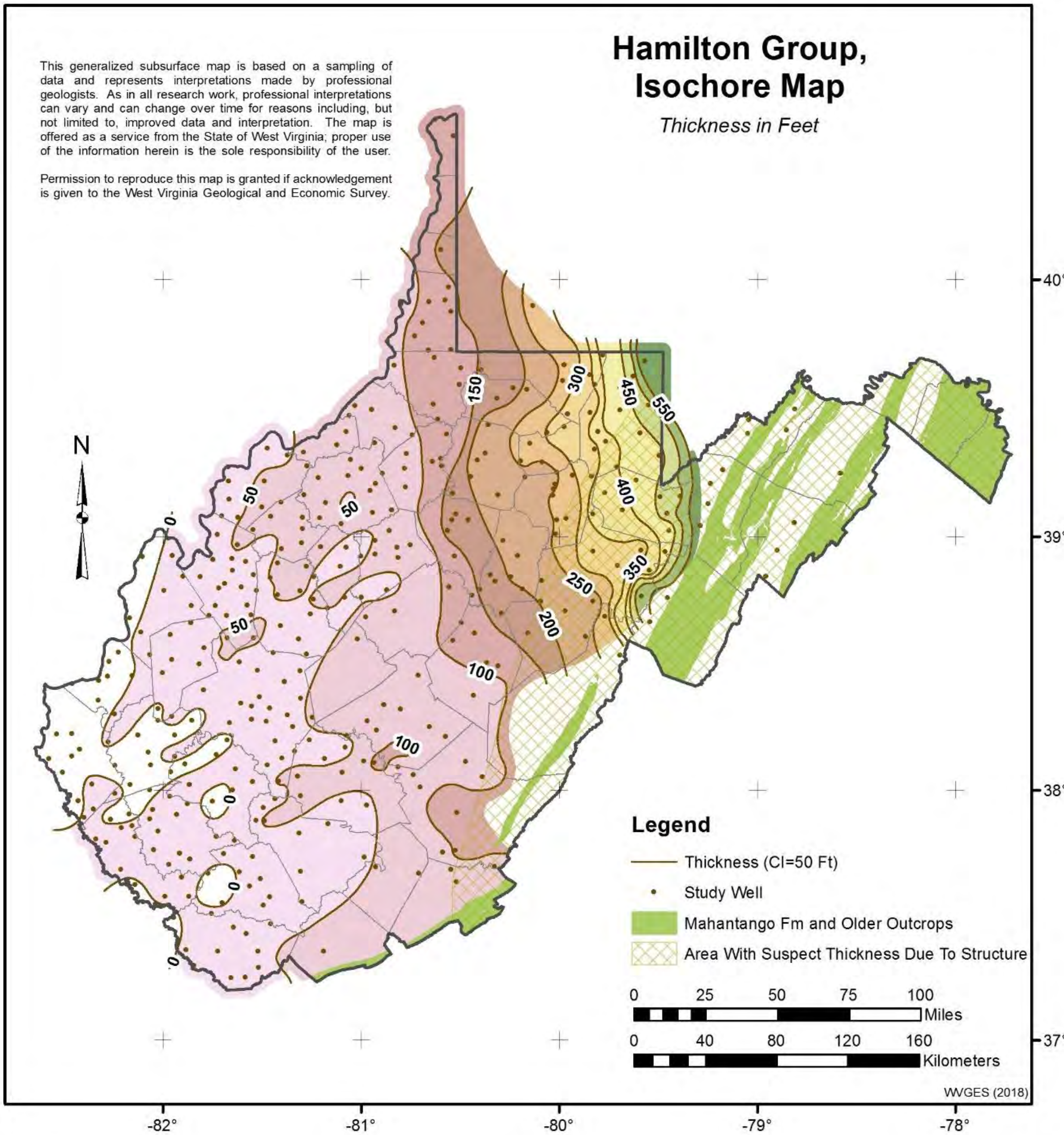


Figure 13. *Isochore map of the Hamilton Group in West Virginia. The Hamilton Group consists of the Marcellus Formation and the Mahantango Formation (where either or both formations are absent, the Hamilton Group does not exist).*

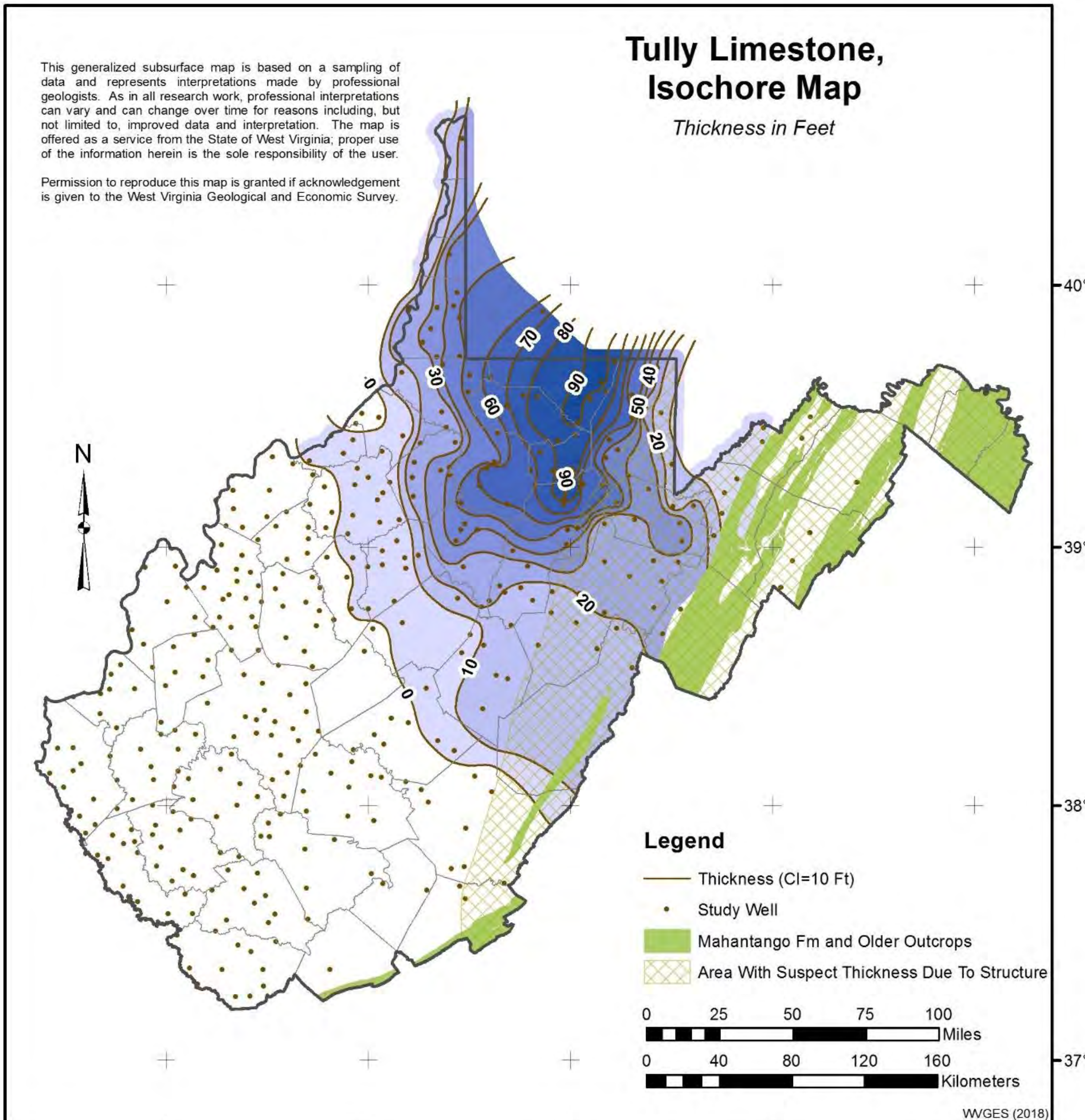


Figure 14. *Isochore map of the Tully Limestone in West Virginia. Minor limestones likely equivalent to the Tully can be observed locally throughout the State, but are very thin and difficult to confidently identify outside the contoured area given the available geophysical well log data.*

members within the Genesee Formation, a basal black Geneseo Shale Member (**Figure 15**) and an upper, non-radioactive West River Shale Member (Neal, 1979; Sweeney, 1986) (**Figure 16**) is recommended. This convention is consistent with that employed for the overlying Sonyea and West Falls formations in the State (described further below), which also consist of one basal, organic-rich ("black shale") member and one overlying less organic-rich ("grey shale") member.

The Genesee Formation is traced only as far east as the overlying Middlesex Shale Member of the Sonyea Formation (**Figures 15** and **16**), which forms its upper lithostratigraphic boundary (per Carter, 2010; Harper et al., 2017). Based on outcrop studies along the eastern margin of the basin (Hasson and Dennison, 1988), this interval has traditionally been referred to as the Harrell Shale, with the basal most organic-rich unit assigned to the Burket Shale Member (Butts, 1918). The stratigraphic top of the Harrell is recognized as the first occurrence of a significant and laterally-extensive siltstone/sandstone unit (the informal drillers' "Sycamore" unit) which marks the base of the Brallier Formation (Cardwell, 1982). As de Witt et al. (1993) were focused on extension of the western-based stratigraphy to the east, they do not consider the non-Burket units of the Harrell Shale in their work, although they do note the likely chronostratigraphic and lithostratigraphic equivalency of the Geneseo and Burket members. As traced into the eastern panhandle of West Virginia, the lower contact of the Harrell Shale (the Tully Limestone) is also lost, at which point the units equivalent to the Harrell may become indistinguishable from those of the subjacent Mahantango where the Burket Shale Member is not present (Hasson and Dennison, 1988), although that situation was not encountered within the area of this study.

While the nomenclature is relatively clear along the eastern and western margins of the State, the terminology is used inconsistently in the basin center where the Geneseo/Burket is currently gaining attention as a possible target for oil and gas development (e.g., VanMeter, 2012). In this report, the interval is assigned to the Genesee Formation with West River Shale and Geneseo Shale members as far east as the Middlesex Shale Member can be recognized (see **Figures 4b**, **4c**, **5**, and **17**). From that point east, the interval is referred to as the Harrell Shale with a basal organic-rich Burket Shale Member (**Figure 15**). This usage will conform reasonably well to regional correlations (Patchen et al., 1985; Woodrow et al., 1988; Carter, 2010; Harper et al., 2017) as well as Schwietering (1979) who used the term Burket for the unit within the EGSP MERC #1 well drilled in Monongalia County. Similarly, Cardwell (1982) reports Harrell Shale with Burket Member in Harrison and Doddridge counties, but finds the units difficult to distinguish to the south in Gilmer and Lewis counties (Cardwell, 1981). Schwietering (1980) reports Harrell with Burket in central West Virginia, but Genesee in southwestern West Virginia.

Upper Devonian (Upper Frasnian) Sonyea-West Falls-Java Interval

The upper Frasnian consists of a series of shale-rich units that include, from oldest to youngest, the Sonyea (Chadwick, 1933), West Falls (Pepper et al., 1956), and Java (de Witt, 1960) formations. Throughout much of the central Appalachian basin, each of these units contains a basal organic-rich member and an overlying grey shale member. The Sonyea Formation was designated to encompass earlier organic-rich Middlesex (**Figure 17**) and organic-poor Cashaqua (**Figure 18**) shale members (Hall, 1840). The West Falls Formation similarly couples a lower, thick, and organic-rich (**Figure 19**) Rhinestreet Shale Member (Clarke and Luther, 1904) with an upper (**Figure 20**) organic-poor Angola Shale Member (Clarke, 1903; Hartnagel, 1912). Locally in West Virginia, a conspicuous thin bed with high-GR log signature allows the Angola Shale Member to be split into informal "upper Angola" and "lower Angola" units. The overlying Java Formation (de Witt,

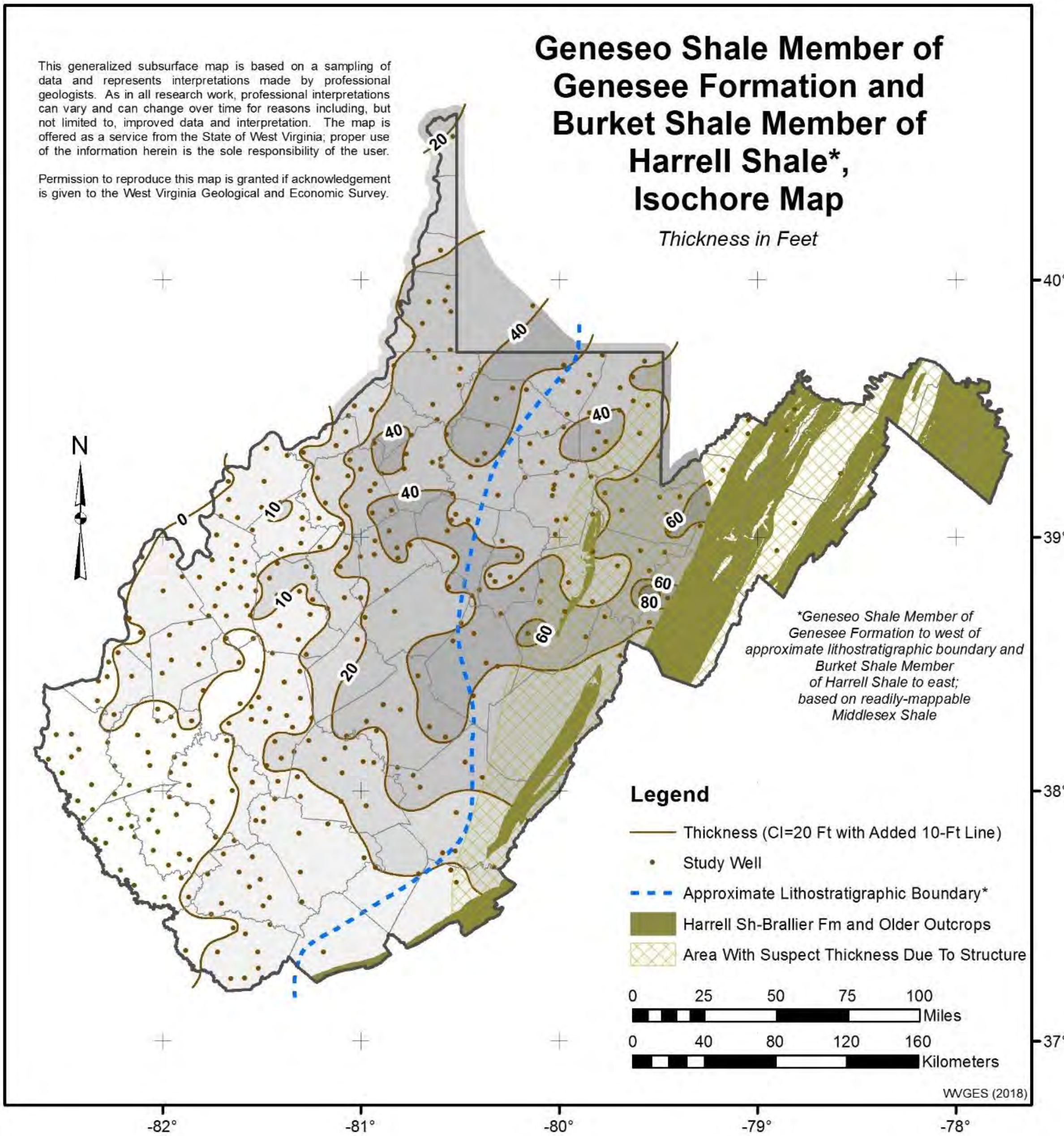


Figure 15. *Isochore map of the Geneseo Shale Member of the Genesee Formation to the west of the approximate lithostratigraphic boundary (dashed blue line) and Burket Shale Member of the Harrell Shale to the east of the boundary. The location of the lithostratigraphic boundary is based on the eastward occurrence of readily-mappable Middlesex Shale (**Figure 17**); also see Line M on **Figures 4b** and **4c.***

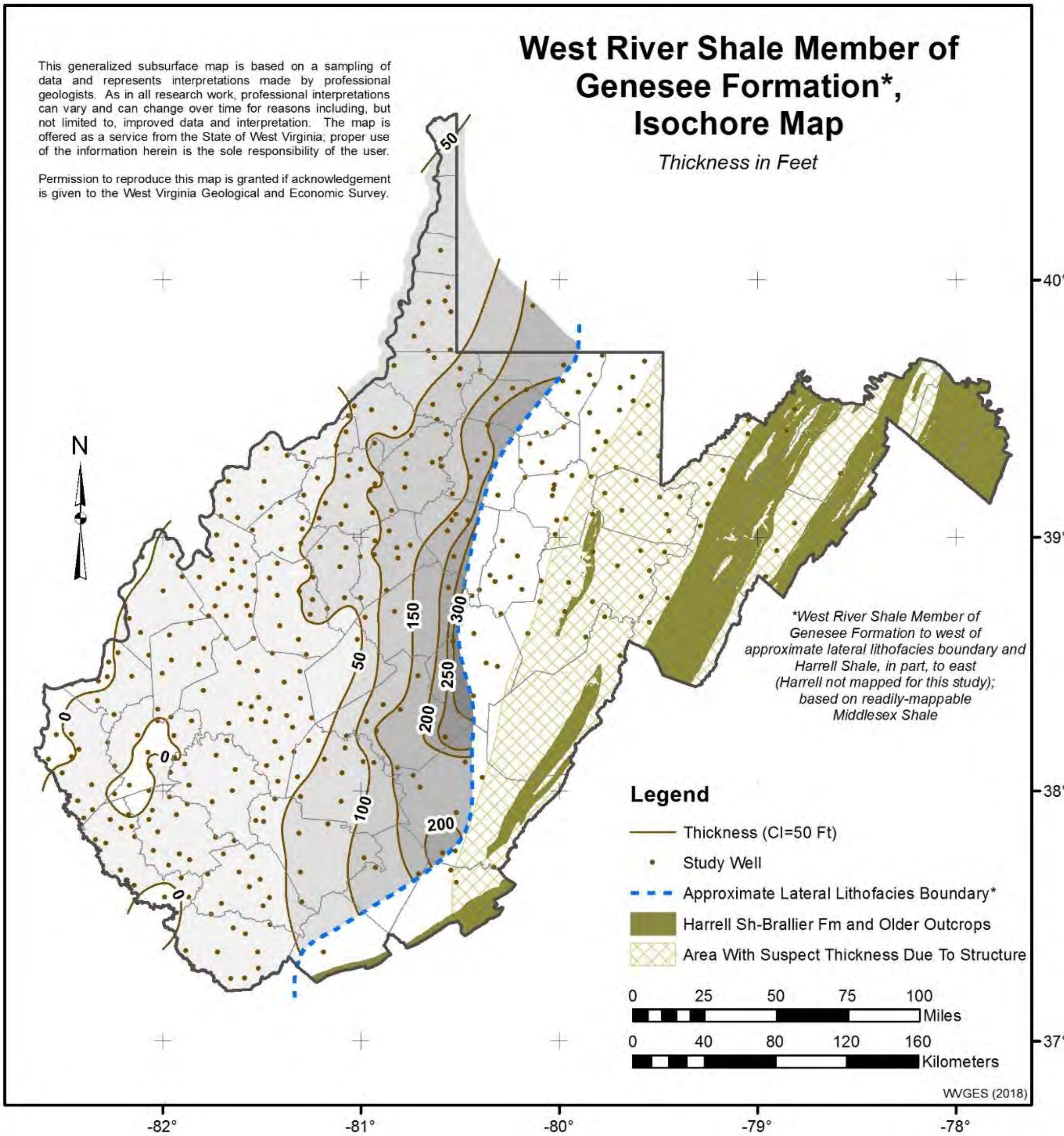


Figure 16. *Isochore map of the West River Shale Member of the Genesee Formation in West Virginia. The unit grades laterally into age-equivalent strata within the Harrell Shale along the approximate lateral lithofacies boundary (dashed blue line). The lithofacies boundary is based on the eastward occurrence of readily-mappable Middlesex Shale (**Figure 17**); also see Line M on **Figures 4b** and **4c.***

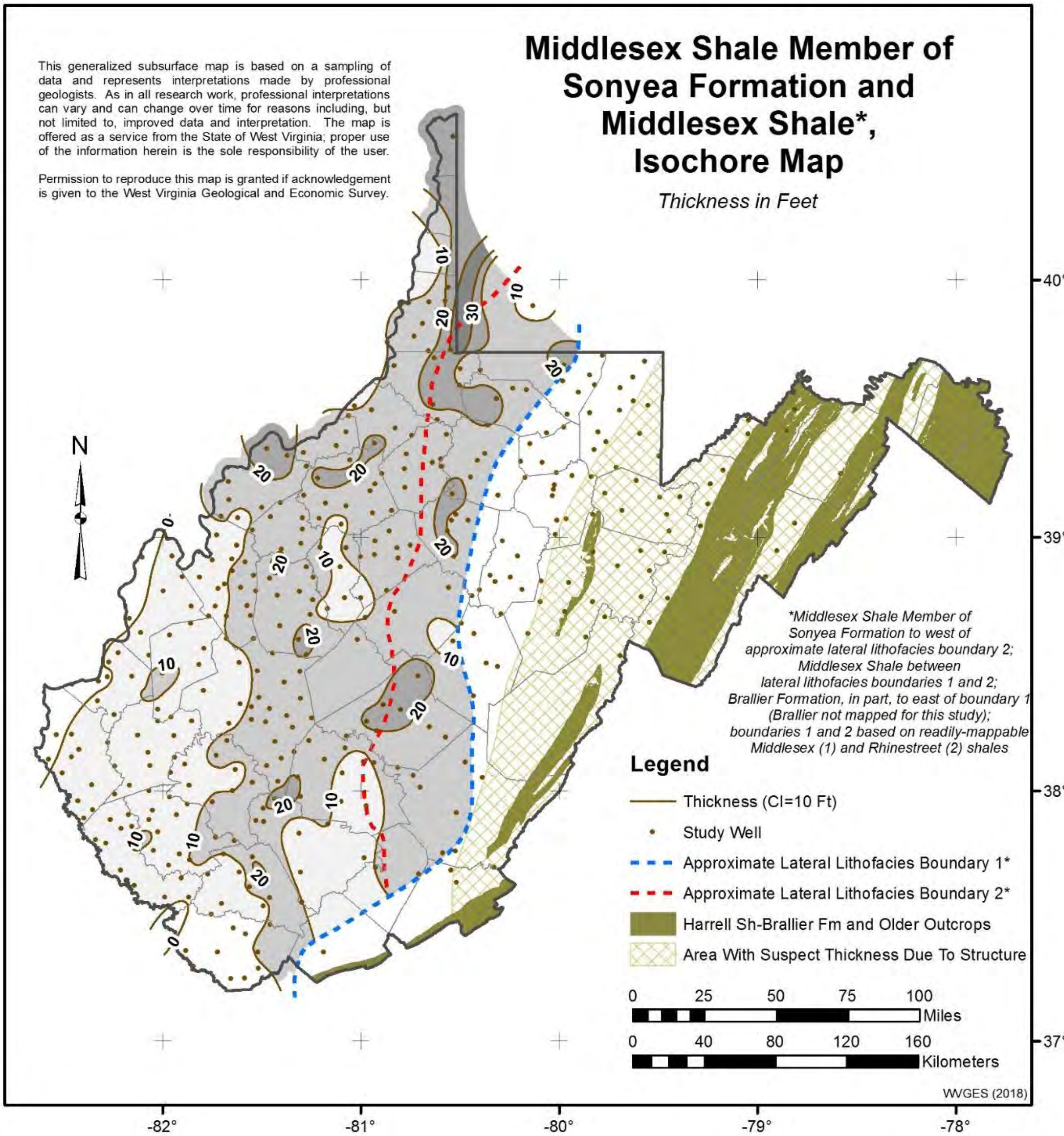


Figure 17. *Isochore map of the Middlesex Shale and Middlesex Shale Member of the Sonyea Formation in West Virginia. The Middlesex Shale grades laterally into age-equivalent and eastwardly-thickening strata within the Brallier Formation to the east of approximate lateral lithofacies boundary 1 (dashed blue line); also see Line M on* ***Figures 4b*** *and* ***4c****. The unit becomes the Middlesex Shale Member of the Sonyea Formation to the west of approximate lateral lithofacies boundary 2 (dashed red line); also see Line R on* ***Figures 4b*** *and* ***4c****. Lithofacies boundaries 1 and 2 are based, respectively, on the eastward occurrence of the Middlesex Shale and Rhinestreet Shale (****Figure 19****).*

1960) (**Figure 21**) combines the organic-rich Pipe Creek Shale (Chadwick, 1923) and overlying organic-poor Hanover Shale (Chadwick, 1933) as members. The top of the Frasnian is located within the uppermost Java Formation (Over, 2002). In northwestern Pennsylvania and western New York, additional members are recognized in the upper portions of the West Falls (Nunda Member) and Java (Wiscoy Member) formations to accommodate specific sand-rich units (Milici, 1996); however, these members are not observed in West Virginia.

The Sonyea, West Falls, and Java formations, along with their six shale-rich members, were identified throughout the subsurface of eastern Ohio, western Pennsylvania, and West Virginia via GR log correlation (de Witt and Roen, 1985; de Witt et al., 1993). However, in West Virginia, the unit attributed as the Pipe Creek Shale Member of the Java Formation is a very thin unit (a single spike in well logs) with distinctive high-GR and low-DEN log response suggesting that the mapped unit may be volcanogenic in origin (Caramanica, 1988; Roen, 1980), and potentially not the lithostratigraphic equivalent of the shale unit originally mapped in New York. Therefore, the unit, where observed in West Virginia, is most appropriately noted as an informal "Pipe Creek bed" (following the usage of Dowse, 1980). As such, the Java Formation is recognized in West Virginia with no formal members, following common (but not exclusive) usage (Schwietering, 1980; Filer, 1985; Neal and Price, 1986; Sweeney, 1986; Ryder et al., 2008). The Sonyea, West Falls, and Java formations are traced eastward through the subsurface where they grade laterally into organic-poor and siltstone-rich lithologies of the Brallier Formation (Milici, 1996; Donaldson et al., 1996). These lateral transitions of the organic-poor units (**Figures 4b**, **4c**, and **5)** are noted via blue lines on the individual unit isochores (**Figures 17** to **21**) that are placed at the eastern extent of the highly-radioactive facies within the overlying organic-rich unit. These boundaries provide a reasonable approximation of the lateral transition into dominantly "Brallier-like" lithology. Note also, that with respect to both the Sonyea and West Falls formations, the basal organic-rich member can be mapped farther east than the corresponding upper shale member. Where this occurs, the Sonyea and West Falls are no longer recognized, and the organic-rich units are elevated to formation status (i.e., Middlesex Shale, Rhinestreet Shale) per the usage of Harper et al. (2017).

Mapping the Middlesex (**Figure 17**) is particularly complex. The unit is most clearly identified in the western and southern parts of the State by elevated GR within a slightly thicker unit of reduced DEN. While the GR data was used in this report to establish the boundaries of the unit, reliance on the DEN log to define the unit is equally valid and would have produced a thicker and perhaps more extensive Middlesex unit.

Upper Devonian (Famennian) Ohio Shale Interval

The Famennian interval is represented in outcrop along the western margin of the basin by the Ohio Shale (Andrews, 1871). The Ohio Shale combines two previously-recognized black shales observed in outcrop in northeastern Ohio, the older Huron and the younger Cleveland shales (Newberry, 1871) as members. Correlation southward into Kentucky and eastward into West Virginia resulted in the recognition of a medial, less organic-rich, Chagrin Shale Member (de Witt and Roen, 1985) which was tracked farther west as the Three Lick Bed (Provo et al., 1977). In the primary "Big Sandy" region where the lower part of the Huron Member (**Figure 22**) has been a major gas producing unit since the 1920s (Ley, 1935; Boswell, 1996), the Huron Member has also been subdivided into informal "lower Huron," "middle Huron," and "upper Huron" units with the middle unit being characterized by generally lower GR responses (Schwietering and Roberts, 1988). In the subsurface of West Virginia, the

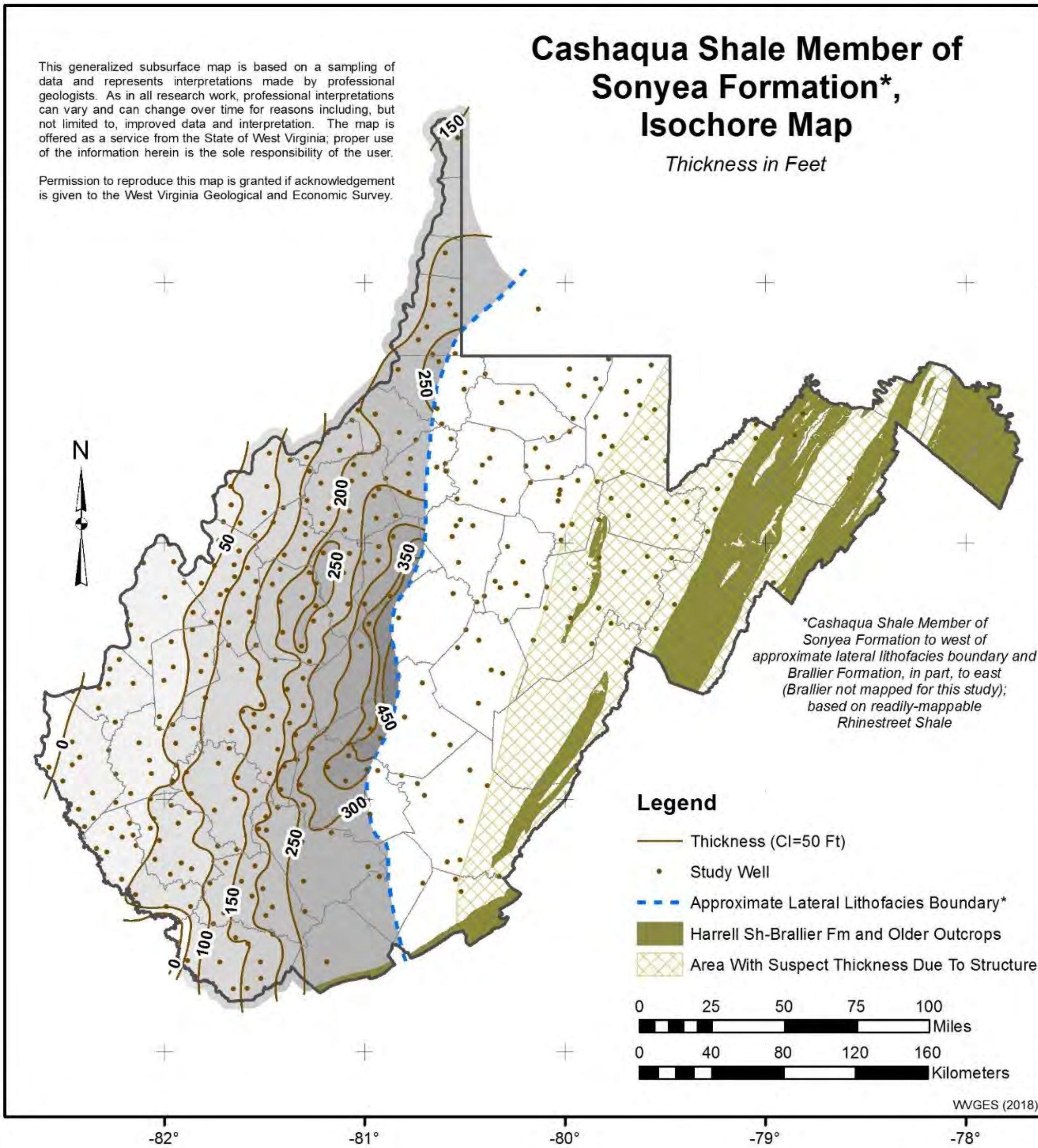


Figure 18. *Isochore map of the Cashaqua Shale Member of the Sonyea Formation in West Virginia. The unit grades laterally into age-equivalent and eastwardly-thickening strata within the Brallier Formation along the approximate lateral lithofacies boundary (dashed blue line). The location of the lithofacies boundary is based on the eastward occurrence of readily-mappable Rhinestreet Shale (**Figure 19**); also see Line R on **Figures 4b** and **4c**.*

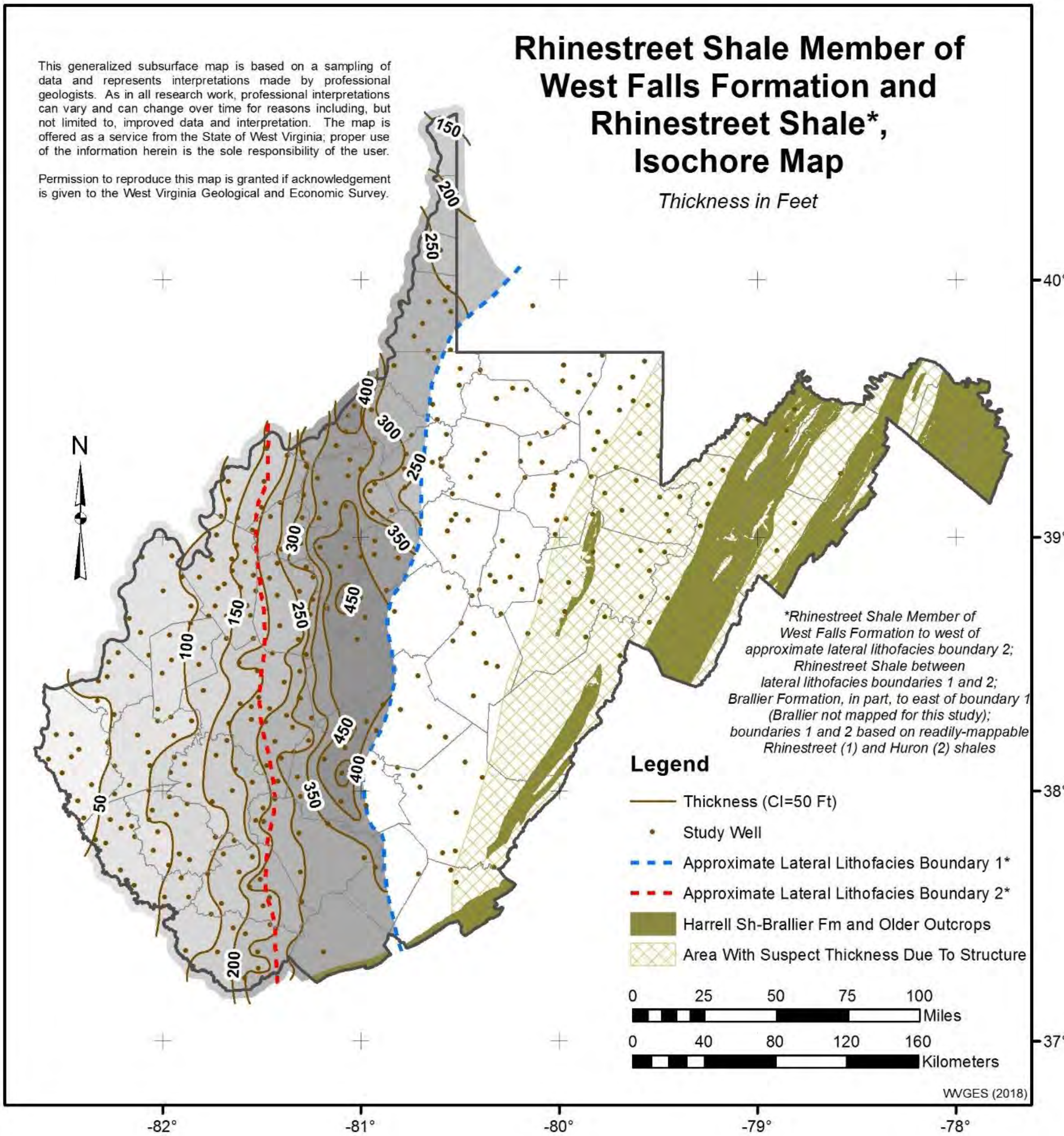


Figure 19. *Isochore map of the Rhinestreet Shale and Rhinestreet Shale Member of the West Falls Formation in West Virginia. The Rhinestreet Shale grades laterally into age-equivalent and eastwardly-thickening strata within the Brallier Formation to the east of approximate lateral lithofacies boundary 1 (dashed blue line); also see Line R on* ***Figures 4b*** *and* ***4c****. The unit becomes the Rhinestreet Shale Member of the West Falls Formation to the west of approximate lateral lithofacies boundary 2 (dashed red line); also see Line H on* ***Figures 4b*** *and* ***4c****. Lithofacies boundaries 1 and 2 are based, respectively, on the eastward occurrence of the Rhinestreet Shale and the lower part of the Huron Member of the Ohio Shale (****Figure 22****).*

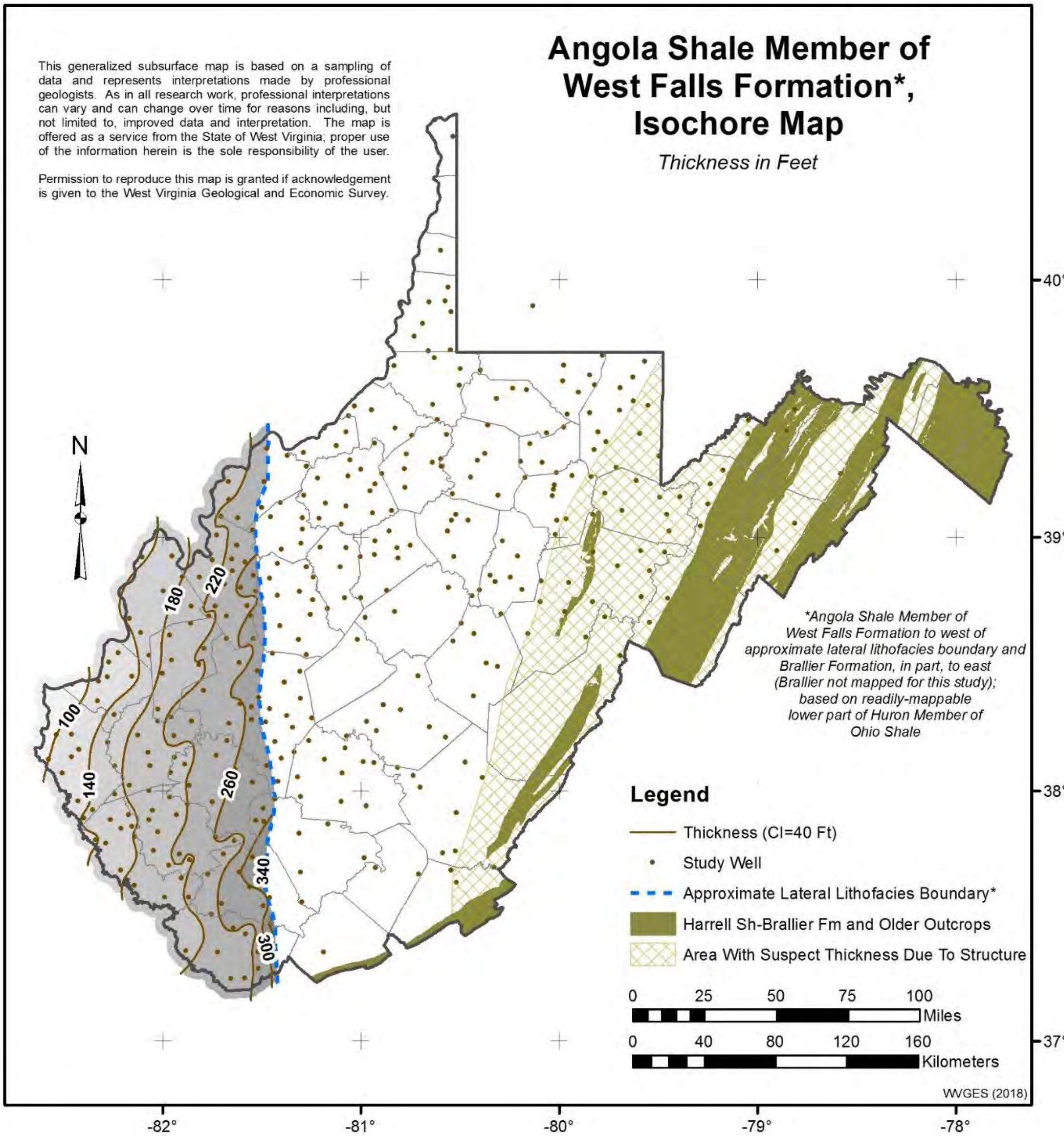


Figure 20. *Isochore map of the Angola Shale Member of the West Falls Formation in West Virginia. The unit grades laterally into age-equivalent and eastwardly-thickening strata within the Brallier Formation to the east of the approximate lateral lithofacies boundary (dashed blue line). The lithofacies boundary is based on the eastward occurrence of readily-mappable Huron (i.e. the lower part of the Huron Member of the Ohio Shale) (**Figure 22**); also see Line H on **Figures 4b** and **4c**.*

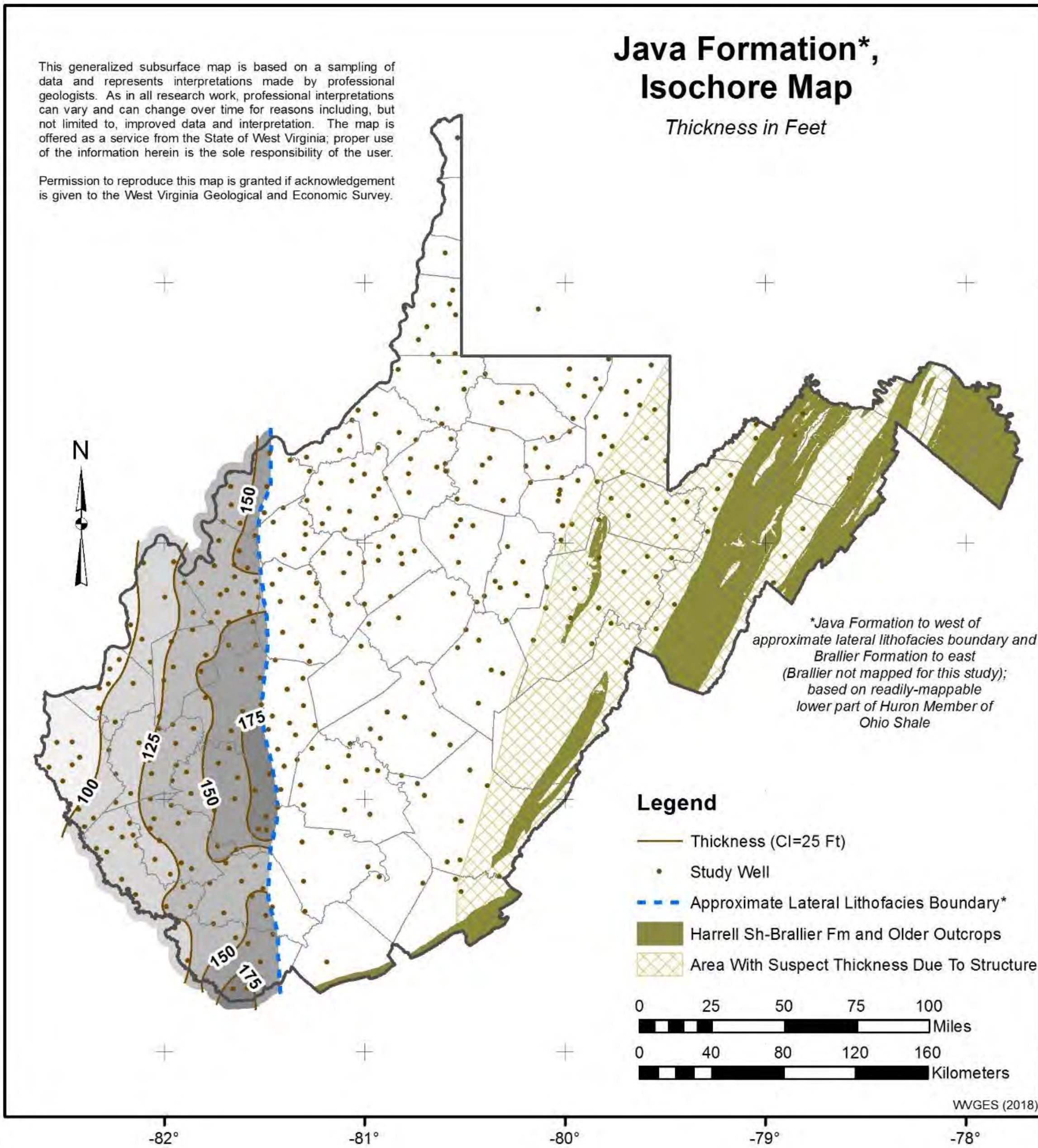


Figure 21. *Isochore map of the Java Formation in West Virginia. The unit grades laterally into age-equivalent and eastwardly-thickening strata within the Brallier Formation to the east of the approximate lateral lithofacies boundary (dashed blue line). The lithofacies boundary is based on the eastward occurrence of readily-mappable Huron (i.e. the lower part of the Huron Member of the Ohio Shale) (**Figure 22**); also see Line H on **Figures 4b** and **4c**.*

unit above the "lower part of the Huron" has been assigned to either undifferentiated Ohio Shale (e.g., Caramanica, 1988), to Brallier Formation (de Witt et al., 1993), or to Chagrin Shale (e.g., Milici, 1996), or to undifferentiated "Devonian shale."

In northwestern Pennsylvania and western New York, lateral equivalents of the Ohio Shale are assigned to the Perrysburg Formation (Pepper and de Witt, 1951) which includes three members, including a basal organic-rich Dunkirk Shale (Clarke, 1903), a South Wales Member, and an upper Gowanda Shale Member. The Dunkirk is equivalent to the extensive but thin organic-rich shale at the base of the lower part of the Huron Member farther to the south. de Witt and Roen (1985) noted an arbitrary lateral termination of the Perrysburg as tracked south which is based on the southward mappable extent of the Dunkirk Shale Member. The mapping of de Witt and Roen (1985) places Perrysburg Formation with basal Dunkirk Shale Member in the northern West Virginia panhandle. Ryder et al. (2009) extended the Dunkirk Shale Member of the Perrysburg Formation into Wetzel and Marion counties, West Virginia, counter to prior use in the area. Given that this delineation of the extension of Perrysburg into northernmost West Virginia is recognized as somewhat arbitrary, retaining the term Huron Member of the Ohio Shale throughout all the West Virginia subsurface is recommended. However, locally in West Virginia, the high-GR basal units of the lower part of the Huron can be recognized well to the east of the bulk of the Huron units. In such cases, it is appropriate to refer to this thin unit as the "Dunkirk bed" within the Brallier Formation (e.g., Caramanica, 1988; Boswell et al., 1996).

Summary

Devonian organic-rich shales have been a major contributor of natural gas production in West Virginia since the 1920s. These units were deposited in extensive, basin-wide depositional environments and it is appropriate that the recognized lithostratigraphy reflect this to the extent possible. Prior work conducted primarily under the auspices of the Eastern Gas Shales Project (EGSP), the U.S. Geological Survey, and the Pennsylvania and West Virginia geological surveys, have produced a regionally consistent stratigraphic nomenclature that appropriately extend and refine units originally defined in the basin's northern (western New York) and western (central Ohio and Kentucky) outcrops throughout much of the basin interior primarily through evaluation of log data. Detailed outcrop-based stratigraphic studies along the Allegheny Front have produced a well-documented lithostratigraphy along the basin's eastern margin. As interest in shale gas production has shifted farther into the basin center, ambiguities emerged as to how the established basin-margin stratigraphy can be correctly integrated into a coherent scheme. This report utilizes interval isochore maps and statewide lithostratigraphic cross-sections prepared at the West Virginia Geological and Economic Survey (WVGES) to define how these different sets of nomenclature can be effectively reconciled in the West Virginia subsurface.

A summary of the study findings includes the following for West Virginia:

1) The name Marcellus Formation is formally adopted. The Marcellus Formation includes three members recognized in the north-eastern subsurface: a basal Union Springs Member, an intermediate Cherry Valley Member, and an upper Oatka Creek Member. No members of the Marcellus Formation are assigned westward of the readily-mappable extent of the Cherry Valley. The Cherry Valley is correlative with the Purcell Limestone Member in the panhandle of eastern West Virginia and in central Pennsylvania.

2) The section between the Tully Limestone and the Marcellus Formation is assigned to the Mahantango Formation. No members are recognized in the Mahantango Formation.

3) The Burket Shale Member of the Harrell Shale is recognized as a lateral equivalent of the

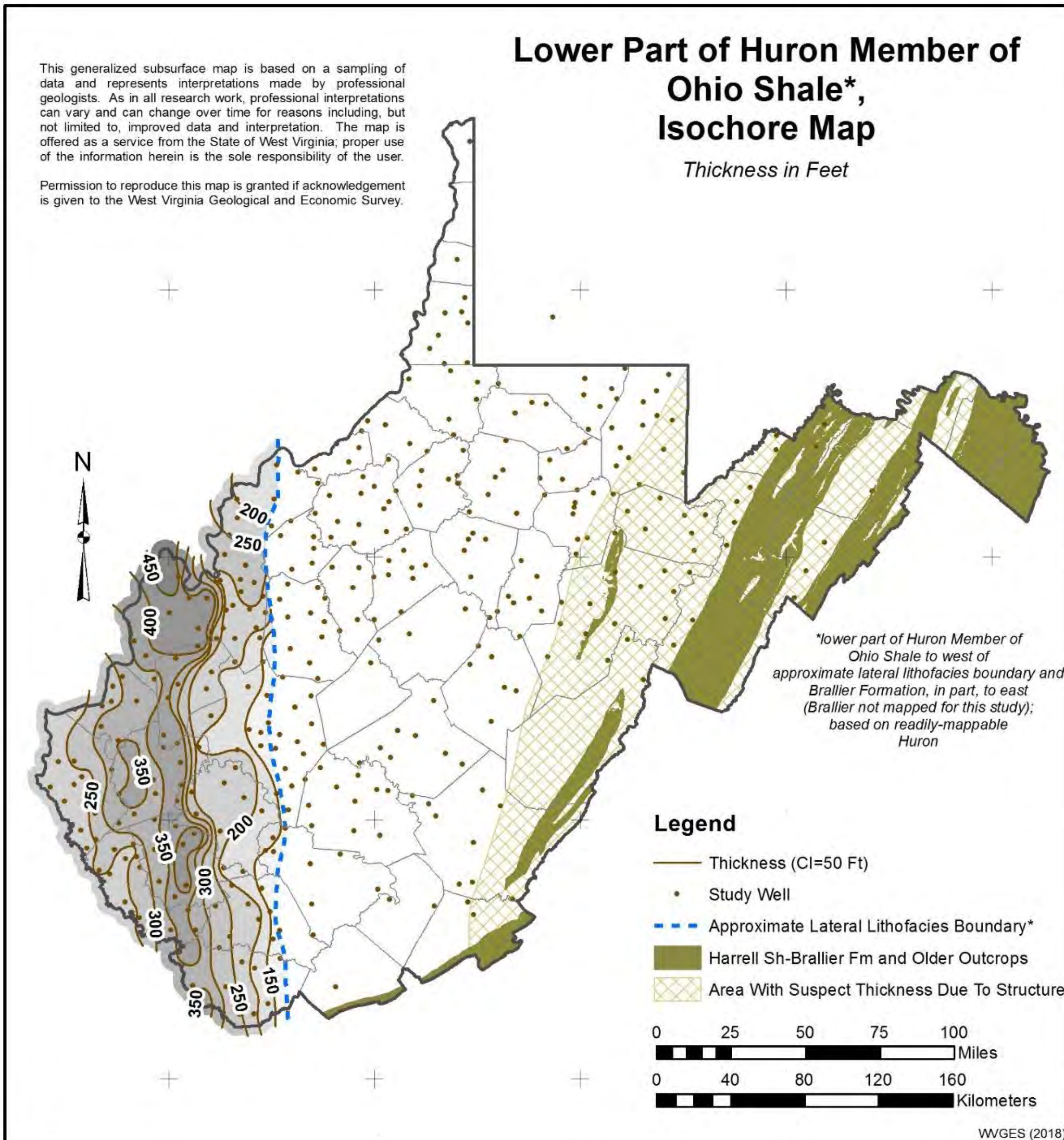


Figure 22. *Isochore map of the lower part of the Huron Member of the Ohio Shale in West Virginia. The unit grades laterally into age-equivalent and eastwardly-thickening units within the Brallier Formation to the east of the approximate lateral lithofacies boundary (dashed blue line). The lithofacies boundary is based on the eastward occurrence of readily-mappable Huron (i.e. the lower part of the Huron Member of the Ohio Shale); also see Line H on* ***Figures 4b*** *and* ***4c****.*

Geneseo Shale Member of the Genesee Formation. The lateral transition occurs coincident with the eastern extent of mappable Middlesex Shale.

4) The eastern extent of the West Falls and Sonyea formations are based on the mappable extent of the overlying organic-rich shale unit which is needed to establish the upper contact of the unit. Where the basal organic-rich shale member extends eastward of this point, that unit is elevated to formation status.

5) The Java Formation in West Virginia is recognized with no members. The "Pipe Creek shale" can be identified locally as an informal bed.

6) Neither the Perrysburg Formation nor the Dunkirk Shale are recognized as formal units in West Virginia. The Dunkirk is identified locally as an informal bed.

Additional Materials

Additional materials are available from the WVGES web site (http://www.wvgs.wvnet.edu/www/MUDvnnSh/MUDvnnSh.htm) including:

A. Excel spreadsheet of study well and formation data,

B. gamma-ray log stratigraphic cross-sections and cross-section base map, and

C. Middle and Upper Devonian organic-rich shales interactive map.

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