

## **Lithostratigraphy and Petrophysics of the Devonian Marcellus Interval in West Virginia and Southwestern Pennsylvania**

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### **Abstract**

In the Appalachian basin, the Middle Devonian organic-rich shale interval, including the Marcellus Shale, is an important target for exploration. This unconventional gas reservoir is widespread across the basin and has the potential to produce large volumes of gas (estimated to have up to 1,307 trillion cubic feet of recoverable gas). Although the Middle Devonian organic-rich shale interval has significant economic potential, stratigraphic distribution, depositional patterns and petrophysical characteristics have not been adequately characterized in the subsurface. Based on log characteristics, tied to core information, the lithostratigraphic boundaries of the Marcellus and associated units were established and correlated throughout West Virginia and southwestern Pennsylvania. Digital well logs (LAS files) were used to generate estimates of lithology and to identify zones of higher gas content across the study area. In addition, a lithologic solution was calibrated to X-ray Diffraction (XRD) data. Using previous studies on organic shale, relationships between the natural radioactivity (as measured by the gamma-ray log) were incorporated with techniques to identify gas-prone intervals. The comparison between the Uranium content and the measured bulk density identified intervals in the Marcellus with high gas saturations and were used to generate an approach to correct water saturations. These techniques of identifying lithology and potential gas in the Marcellus are useful to identify areas of higher exploration potential and to target zones for fracture stimulation or to land a horizontal leg.

### **Introduction**

The widely distributed Devonian System of the central Appalachian basin is an important stratigraphic interval from both economic perspective and depositional history. Historically, the majority of petroleum production in the central Appalachians has come from the Upper Devonian. The Middle Devonian, specifically the organic-rich black shale intervals, including the Marcellus Shale, has a long history of marginal gas production (King, 2008), and was considered to be the primary source rock for Upper Devonian and younger conventional reservoirs in the basin. However, new knowledge and technology (e.g., fracture stimulation techniques, horizontal wellbores) indicate that the Middle Devonian units can comprise an extremely productive and widespread unconventional reservoir. Recent estimates of recoverable gas from unconventional shale gas reservoirs in the Appalachian basin have been rising rapidly

during the last decade, and by some estimates the Marcellus contains up to 1,307 trillion cubic feet of recoverable gas (Gold, 2008). The area of the Middle Devonian that we will examine encompasses of the state of West Virginia and southwest Pennsylvania. It is located in the central Appalachian basin and covers an area of approximately 23,500 mi<sup>2</sup> (60,865 km<sup>2</sup>) (Figure 1). The paleogeographic features that surround the study area are the Acadian Mountains to the east, the Cincinnati Arch to the west and the Rheic Ocean to the south (Figure 2). In terms of depositional history the middle Devonian interval represents the initiation of the Devonian-Mississippian anoxic event in the central Appalachian basin (Ettensohn, 1998). It has been suggested that the black shale units represent a deepening basin tied to Acadian tectophases. In these tectophases, the limestone units represent shallowing-upward periods of deposition (Ettensohn, 1998). Other ideas dispute bottom water anoxia and focus on localized enhanced organic matter preservation caused by high concentrations of primary organic matter and sediment being fluxed to the sea floor, as aggregate grains (e.g., Macquaker and others, 2009, Bohacs and others, 2009).

Units of the Middle Devonian interval have been studied primarily in New York and northern Pennsylvania (Ettensohn, 1998; Brett and Ver Straeten, 1994; Linsley, 1974). Work on the Middle Devonian interval in the central Appalachian basin has focused on the depositional characteristics in outcrop. Comprehensive studies on the subsurface relationships and petrophysics of the Middle Devonian interval are lacking in southwestern Pennsylvania and West Virginia (Ettensohn, 1998). The Middle Devonian stratigraphic succession in this area consists of the following formations in ascending order; the Onondaga Limestone (Eifelian), Marcellus Shale (Eifelian), Mahantango Shale (Givetian), Tully Limestone (Givetian), and Harrell Shale (Givetian) (Hasson and Dennison, 1988) (Figure 3). In this paper we define the petrophysical criteria to recognize stratigraphic intervals of the Middle Devonian, and the lithostratigraphic relationships in the subsurface are examined to better understand the depositional history and economic potential.

The purpose of this study is to provide a comprehensive stratigraphic and petrophysical analysis of the Middle Devonian interval in West Virginia and southwestern Pennsylvania. The goals of the proposed research are to integrate available core and well-log data to place the Middle Devonian of the central Appalachians into a stratigraphic framework that can be used to better understand the distribution and controls on the extent of organic-rich “black” shale and other facies. A second goal is to develop and refine techniques to recognize and document important lithologic and petrophysical parameters that influence the economic potential of various intervals of the Middle Devonian as unconventional reservoirs.

### **Middle Devonian Lithostratigraphic Units**

The Onondaga Limestone (Figure 3) is a fine-grained limestone that is distributed widely in the subsurface across the study area. On well logs, can be readily identified, by its PE value  $\geq 5$  in response to calcite and has a very sharp contact with the overlying Marcellus (Figure 4). In the cores that have been examined, the Onondaga Limestone has a sharp to gradational contact for approximately one foot with the overlying Marcellus Shale. The Marcellus Shale is typically found deposited on the limestone of the Onondaga Formation, but regional studies indicate that the contact is unconformable, and the Marcellus can be underlain by the Lower Devonian, Huntersville Chert or older strata (Anderson and others, 1985) (Figure 3). In several cases, the Onondaga Limestone has been misidentified with a number of discontinuous limestone members within and overlying the Marcellus interval (Anderson and others, 1985).

The Marcellus Shale in core and outcrop is predominantly gray-black to black thinly laminated non-calcareous fissile pyritic organic-rich shale (Figure 3). Total organic carbon (TOC) values have been reported of between 0.3 and 11 percent (Nyahay and others, 2007). In the subsurface, we define the Marcellus as having a gamma ray value greater than 200 API and a bulk density less than 2.55 g/cc (Figure 4). The Marcellus contains one or more thin-bedded limestone beds, including the Purcell Limestone (Figure 4). The Purcell is a fine-grained limestone that outcrops to the east of the study area. In the subsurface, the Purcell and other thin-bedded limestone beds can be readily recognized by the PE tool. The distribution of the Purcell is irregular across the study area and thickness can range from 0 to 50 feet (15.2m).

The Mahantango Shale consists of laminated marine shale, siltstone, very fine sandstone, and some limestone, with an occasional coral reef or biostrome and outcrops in eastern West Virginia and central Pennsylvania (Figure 4). In eastern West Virginia it is calcareous gray shale with occasional thin limestone beds. In central Pennsylvania, the Mahantango increases in thickness and depositional complexity and contains multiple limestone, sand, and shale units, including the Clearville and Chaneyville siltstone members. In the study area, the Mahantango log signature has gradational contacts with the underlying Marcellus Shale and the overlying Tully Limestone. The Mahantango is defined in the subsurface as having a gamma ray value of less than 200 API and a bulk density value greater than 2.55 g/cc (Figure 4).

In the study area, the Tully (Figure 4) is a fine-grained limestone and has been intensely studied in outcrop near its type section in New York where it increases significantly in depositional complexity. In the subsurface it can be defined by a cleaner (30-110 API) gamma ray signature and an approximate PE value of 5 barns/cc (Figure 5).

The Harrell Shale (Figure 4) is a dark-gray to black organic-rich fissile shale that is similar to the Marcellus in lithology and possibly its depositional environment. There are calcareous shale and limestone lenses at base near the contact with the Tully Limestone. It is defined by a gamma ray value of greater than 200 API and a bulk density value of less than 2.55 g/cc (Figure 5).

Stratigraphic Unit	Defining Characteristics		
	Gamma Ray	PE Value	Bulk Density
Onondaga Limestone	Clean (30-110 API)	Aprox. 5	2.71
Marcellus Shale	> 200 API	N/A	< 2.55
Purcell Limestone	< 200 API	Aprox. 5	2.71
Mahantango Shale	< 200 API	N/A	> 2.55
Tully Limestone	Clean (30-110 API)	Aprox. 5	2.71
Harrell Shale	> 200 API	N/A	< 2.55

**Table 1.** Summary of the defining characteristics of the stratigraphic units in the study area as displayed in Figure 4.

### **Depositional Environments**

The units in question for this study are thought to have been deposited in a stratified water column with oxic, sub-oxic, and anoxic zones. The oxic zone would correlate to the Tully, Purcell, and Onondaga limestone units. The Mahantango is interpreted as having been deposited in the sub-oxic zone. The Marcellus and Harrell shale units are interpreted to have been deposited in the anoxic zone. In order for a stratified water column to develop, the environment must have three things: a large influx of organic matter, low circulation, and low sediment input (Demaison and Moore, 1980, Ettensohn and Barron, 1982)). The excess of organic material that is input into the system would first be oxidized by the aerobic bacteria in the oxic zone, using the oxygen in the water column to degrade the organic matter. However, if there is a large amount of

organic matter in the system, excess organic matter would not be degraded by the aerobic bacteria and be incorporated into the sub-oxic zone. In the sub-oxic zone, the insufficient oxygen supply requires anaerobic bacteria to use nitrates as an oxidant. In addition to the increase consumption by the bacteria, anaerobic bacteria degrade organic matter much more slowly than aerobic bacteria. This process can allow for organic matter to move through the sub-oxic zone, into the anoxic zone (Demaison and Moore, 1980). In the anoxic zone, all the oxygen, as well as the available nitrates, has been consumed requiring the anaerobic bacteria to use any available sulfates as an oxidant to degrade the organic matter (Demaison and Moore, 1980). The byproduct of the degradation of organic matter with sulfates is hydrogen sulfide, which can accumulate in a pool at the ocean floor in a stratified water column. Once the organic matter moves into the anaerobic zone and reaches the sea floor, it can be incorporated into the sediment resulting in preservation of allowing for a large amount of organic matter. This depositional model is based on the modern depositional environment of the Black Sea, and is consistent with bottom waters that are synchronously anoxic (Demaison and Moore, 1980, Ettensohn and Barron, 1982). Recently micro-anoxic environments have been proposed, rather than synchronous anoxic bottom waters (e.g., Macquaker and others, 2009, Bohacs and others, 2009). These ideas dispute widespread bottom water anoxia, and focus on enhanced organic matter preservation resulting from localized anoxia resulting from by high concentrations of primary organic matter and sediment being fluxed to the sea floor, as aggregate grains. This would suggest that the entire basin was not synchronously anoxic, and consequently could explain rapid spatial changes in thickness of Middle Devonian organic-rich shale intervals, including the Marcellus Shale, and the presence of limestone members in the Marcellus.

#### **Lithologic Analysis and Recognition of Gas-Rich Intervals**

X-ray diffraction (XRD) of 36 organic-rich Marcellus Shale core samples show that the interval is characterized by relatively high quartz contents (60%) and relatively low clay content (muscovite-illite 30%) (Figure 5). Pyrite, an important component that significantly affects log analysis, can range from 5 to 10%. The effect of pyrite and gas content in the Marcellus can be recognized on the Rhomaa Umaa plot (Figure 6). The Rhomaa-Umaa cross plot shows the effects of the small amount of pyrite (pulling the data to the right due to the high number of electrons associated with the iron in pyrite), and the gas pulling the data above the lithologic triangle (low Rhomaa due to the low density of gas). The influence of these two components must be taken into consideration when attempting to model the Marcellus lithology and petrophysical parameters (e.g., porosity).

In the Marcellus, a relationship associated with gas-rich intervals has been recognized between the gamma ray and density porosity (Ward, 2008). We note a similar relationship and associate this relationship specifically to the Uranium (U) content as recognized by the spectral gamma-ray log (Figure 7). The U-content is one of the major naturally occurring decay series that contribute to the gamma-ray response, and can be measured as parts per million (ppm) by the spectral gamma-ray tool. As measured in core samples of the Middle Devonian shale intervals, the elevated U-content is associated with increased total organic content (TOC). The decreased density (increased density porosity) as the U-content increases is attributed to increased gas content adsorbed to the organic material and as free-gas in matrix and fracture porosity. The relationship between the U-content and density porosity is used to highlight gas-rich intervals within the Middle Devonian shale units of the Appalachian basin (both free-gas and adsorbed). In general, using a cross-plot of U-content and density porosity shows that the Marcellus Shale has significant gas-rich intervals as compared to the Mahantango and Harrell shale units.

Uranium-content and density porosity can be plotted together to highlight potential gas-rich intervals (Figure 8). Using an appropriate scale, zones where the U-content exceeds the bulk density value are highlighted, and interpreted as having a high potential as gas-rich intervals. In addition, to the identification of gas-rich intervals in the Marcellus, similar gas-rich intervals are indicated in the Mahantango and Harrell shale units (Figure 8). The possible gas-rich intervals indicated in both the Mahantango and Harrell could influence exploration in other Middle Devonian shale units of the Appalachian basin.

The Uranium (U) content as indicated by the spectral log can be incorporated into other pay calculations. The water saturation for the Marcellus is typically calculated by using the Archie equation (Eq. 1) or the Simandoux shale correction for the Archie equation (Eq. 3). The Archie is a more conservative equation that was originally derived to be used in a clean (shale-free) lithology (e.g., sandstone). The equation does not take into account shale particles that suppress resistivity or the measured tortuosity of shale. The Archie equation significantly overestimates water saturations in the largely water-free Middle Devonian shale units of the Appalachian basin (Figure 9). We have directly incorporated the Uranium into a modified Archie equation (Eq. 2, Figure 9). We believe this modified Archie equation provides a better estimate of gas and water saturation in the Marcellus. Another approach to correcting for shale content is the Simandoux shale correction for the Archie equation. The Simandoux equation was derived specifically for sandy-shaly units to compensate for bound water by using an estimate for the volume of shale ( $V_{sh}$ ) determine from the gamma ray tool. When the Simandoux correction is applied to Middle Devonian shale units of the Appalachian basin, it overestimates intervals of high gas content (Figure 9). Uranium content was used to derive a ratio similar to  $V_{sh}$ . The relative volume of Uranium  $V_{uran}$  was substituted for a  $V_{sh}$  ratio in the Simandoux shale correction for the Archie equation (Eq. 4). The  $V_{uran}$  ratio is calculated by subtracting the Uranium ( $U_{log}$ ) value from  $U_{max}$  divided by  $U_{max}$  minus  $U_{min}$ . We believe the substitution of the  $V_{uran}$  ratio can provide an improved estimate of gas and water saturation in the organic-rich shale units.

### Equation 1

$$S_w = \left( \frac{R_w * a}{\Phi^m * Rt} \right)^{\frac{1}{n}}$$

### Equation 2

$$S_{wu} = \left( \frac{R_w * a}{\Phi^m * Rt * U_{log}} \right)^{\frac{1}{n}}$$

### Equation 3

$$S_w = \frac{\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + 4 * \left(\frac{\Phi^m}{a * R_w (1 - V_{sh})}\right) * \frac{1}{R_t} - \frac{V_{sh}}{R_{sh}}}}{2 * \left(\frac{\Phi^m}{a * R_w (1 - V_{sh})}\right)} \rightarrow V_{sh} = \frac{GR - Sand}{Shale - Sand}$$

### Equation 4

$$S_{wu} = \frac{\sqrt{\left(\frac{V_{uran}}{R_{Umax}}\right)^2 + 4 * \left(\frac{\Phi^m}{a * R_w (1 - V_{uran})}\right) * \frac{1}{R_t} - \frac{V_{uran}}{R_{Umax}}}}{2 * \left(\frac{\Phi^m}{a * R_w (1 - V_{uran})}\right)} \rightarrow V_{uran} = \frac{U_{log} - U_{max}}{U_{max} - U_{min}}$$

#### Isopach Maps of Middle Devonian Units

Using subsurface defined criteria, isopach maps of Middle Devonian units in the study area were constructed using log suites from more than 1452 available wells. In the study area the Marcellus Shale shows a decrease in thickness from over 180 feet (54.9 m) in the northeast to less than 10 feet (3m) in southwest West Virginia (Figure 10). Much of this decrease in thickness from 100 to 60 feet (30.4 to 18.3m) is concentrated along a northwest to southeast trend from Doddridge to Pocahontas counties in West Virginia (Figure 10, labeled B). This northwest to southeast trend persists in the overlying Middle Devonian units. An anomalous thick in the Marcellus Shale (Figure 10, label A) trends southwest to northeast from Roane to Tyler counties, West Virginia and is believed to be associated with the west-bounding limb of the Rome Trough structure, and suggests that the structure was active during deposition.

To better understand the distribution of potentially organic-rich intervals in the Marcellus Shale, an isopach map was constructed with gamma-ray values greater than 230 API (Figure 11). Based on examination of available spectral gamma-ray logs and core data, gamma-ray values greater than 230 API are indicative of high Uranium (U) concentration associated with high TOC and potential gas-rich intervals. The majority of pre-existing log suites do not contain spectral gamma-ray data, so the thickness of elevated gamma-ray curve (>230 API) is used as a proxy for organic-rich intervals in the Marcellus Shale (Figure 11). Based on the thickest “hot” gamma-ray zones, the potential gas-rich intervals are associated with intermediate thicknesses of the Marcellus Shale in a zone from central and north-central West Virginia to southwest Pennsylvania (Figure 11).

An isopach map of the Purcell Limestone Member of the Marcellus Shale shows a northeast to southwest thickness trend and the limestone unit generally does not occur in the west or central regions of the study area. (Figure 12). This map is representative of limestone units within the Marcellus Shale. The one exception is the west to east trend in the northern region of the study area (C). The Purcell is particularly interesting because it is encompassed by the Marcellus

Shale. The Purcell is interpreted as deposited in a relatively oxic environment, while the Marcellus Shale is believed to have been deposited in an anoxic environment. According to the widespread stratified water-column model, sea level would have had to drop sharply for the Purcell to be deposited, while remaining deep in the west and north. The relationships between these units might be better explained by relatively localized anoxic environments influenced by factors such as sediment supply, paleo-topography and water chemistry. The concentration of thicker organic-rich intervals in the Marcellus Shale in the zone from central and north-central West Virginia to southwest Pennsylvania suggests that simple water-column stratification model is inadequate (Figure 11).

An isopach of the Mahantango Shale shows that the unit can be as thick as 800 feet (243.9m) in the northeast of the study area and is decreasing to the south and to the west (Figure 13). The Mahantango outcrops to the northwest in central Pennsylvania and eastern West Virginia. In northwest Pennsylvania, the Mahantango is more depositionally complex than is observed in the subsurface and in the outcrop of eastern West Virginia. In central Pennsylvania, the Mahantango contains a variety of beds including limestone, conglomerates, sands and shale units that have a wide range of sedimentary structures (Duke, Prave and others, 1991). Moving south along the outcrop belt of eastern West Virginia and into the subsurface of southwest Pennsylvania and central West Virginia, the Mahantango lacks the variety of lithologies and sedimentary structures, and is primarily calcareous shale with occasional limestone beds. The thick organic-rich Marcellus Shale appears to wrap around the area where the overlying Mahantango is thickest. The northwest to southwest trend observed in the Marcellus Shale appears to affect the southwest extent of the Mahantango Shale (Figure 13, Trend D).

Across the study area, the Tully Limestone decreases in thickness to the south and east (Figure 14). The Tully is thickest to the north coinciding with the thinning of the underlying Mahantango Shale (Figure 13) and is absent where the Mahantango is thickest (Figure 14, E). The Mahantango does have a calcareous component in outcrop that could be correlative to the Tully Limestone. The clastic sediment content and rapid deposition of the Mahantango could have prevented development of the Tully Limestone. The southern extent of the Tully Limestone is marked by a northwest to southeast trend (F) in the same geographic area as recognized in the underlying Marcellus and Mahantango (Figures 10-14).

The thickest values for the Harrell Shale isopach are located in north-central West Virginia (Figure 15). The northwest to southwest trend observed in the underlying units appear to affect Harrell deposition, but not as severely as the underlying units (G). The Harrell Shale appears to be acting as a flooding sequence, because after the deposition of this unit carbonates do not appear in the stratigraphic section until the lower Mississippian. An isopach of the thickness of Harrell Shale with gamma ray values greater than 230 API was constructed (Figure 16). The thick potentially gas-rich interval runs in an arc through central West Virginia into the northern panhandle and extreme southwest Pennsylvania and is offset from the thick in the underlying Mahantango Shale (Figure 13).

### **Conclusions**

In the Appalachian basin, the Middle Devonian organic-rich shale interval, including the Marcellus Shale can be defined and mapped using electric log characteristics tied to core data. The Marcellus Shale is defined in the subsurface by a gamma-ray exceeding 200 API, and a bulk density of less than 2.55 g/cc. The Marcellus Shale has relatively high quartz and significant pyrite contents. The pyrite and gas contents in the organic rich shale intervals can exert a strong influence on lithologic analysis of the Marcellus and other Middle Devonian shale units. A

methodology is proposed using the correlation of higher organic content with higher Uranium content as recognized with the spectral gamma-ray data. Better definition of interval of higher gas potential (free and bound) in the Marcellus, Mahantango, and Harrell shale units is possible by coupling higher Uranium content with lower bulk density. Using the Uranium content as measured by the spectral gamma-ray log, modified Archie equation and Simandoux shale correction are proposed that may provide more accurate values for water and gas saturations in the Middle Devonian organic-rich shale units of the Appalachian basin.

Using explicitly defined log criteria the distribution of Middle Devonian units can be mapped in the subsurface across West Virginia and southwest Pennsylvania. The distribution of thickness and organic-richness of these units, including the Marcellus Shale, shows persistent trends that appear to be related to reactivation of the Rome Trough and to a northwest-southeast trend in central West Virginia. The thickness of organic potentially gas-rich zones in the Marcellus and Harrell shale units can be identified by mapping gamma ray values exceeding 230 API units. Spatial changes in thickness and organic-richness in the Marcellus Harrell shale units and the distribution of Middle Devonian limestone units (Purcell and Tully) may be better explained by fluctuations in localized anoxic environments, rather than widespread synchronous stratified anoxic bottom waters. These techniques of identifying lithology and relatively thick intervals of potential organic-rich Middle Devonian shale may assist in better identifying areas of higher exploration potential and to target zones for fracture stimulation or to land a horizontal leg.

#### **Acknowledgements**

We would like to first thank Dominion Exploration and Production for providing a large amount of the raster well data as well as multiple digital files. Also, thank you to the Department of Energy (DOE) for funding this project and the National Energy and Technology Lab (NETL) for allowing us to use their facilities for this study. Finally we would like to thank the physics department at WVU for performing the XRD analysis for this study.

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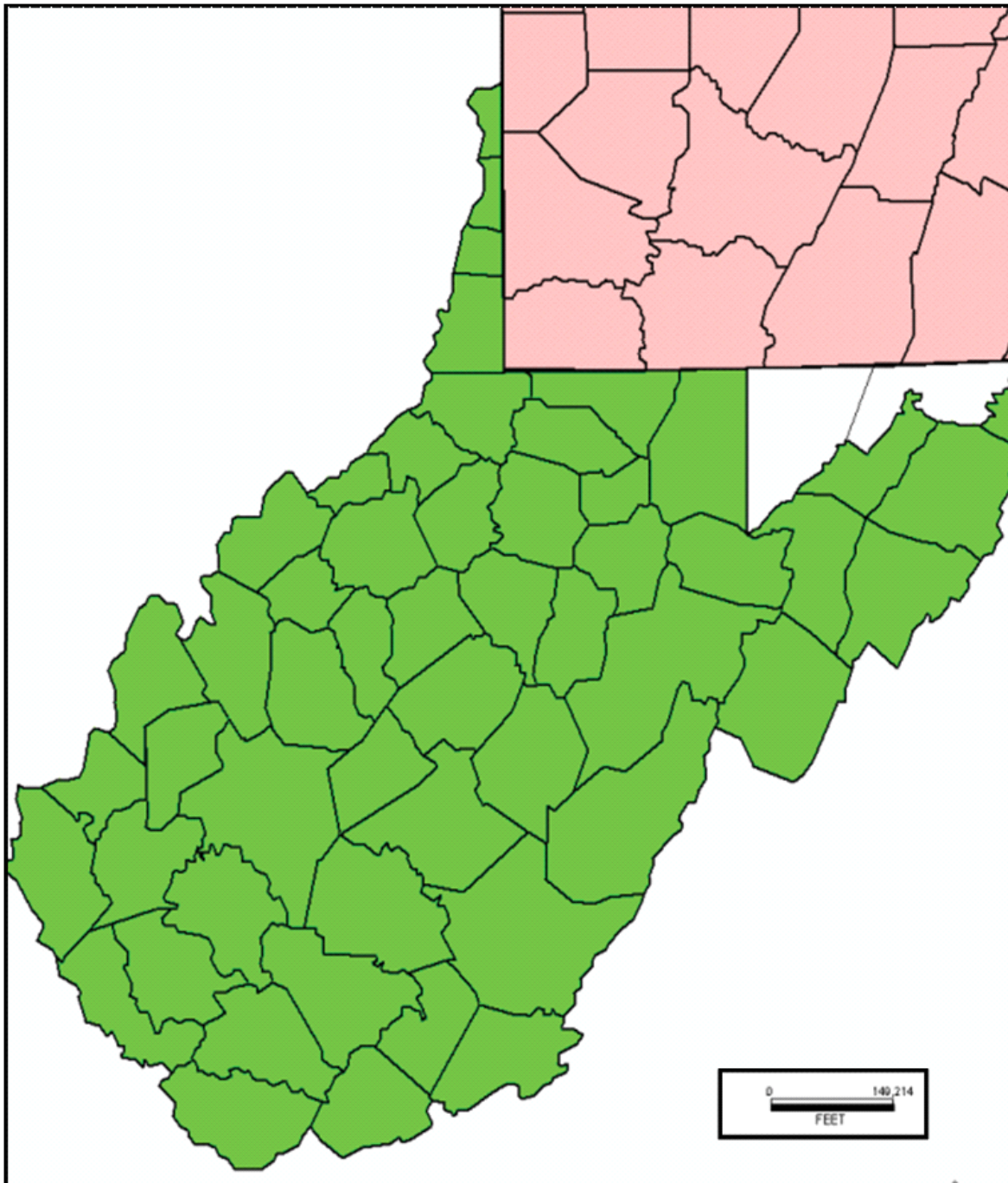
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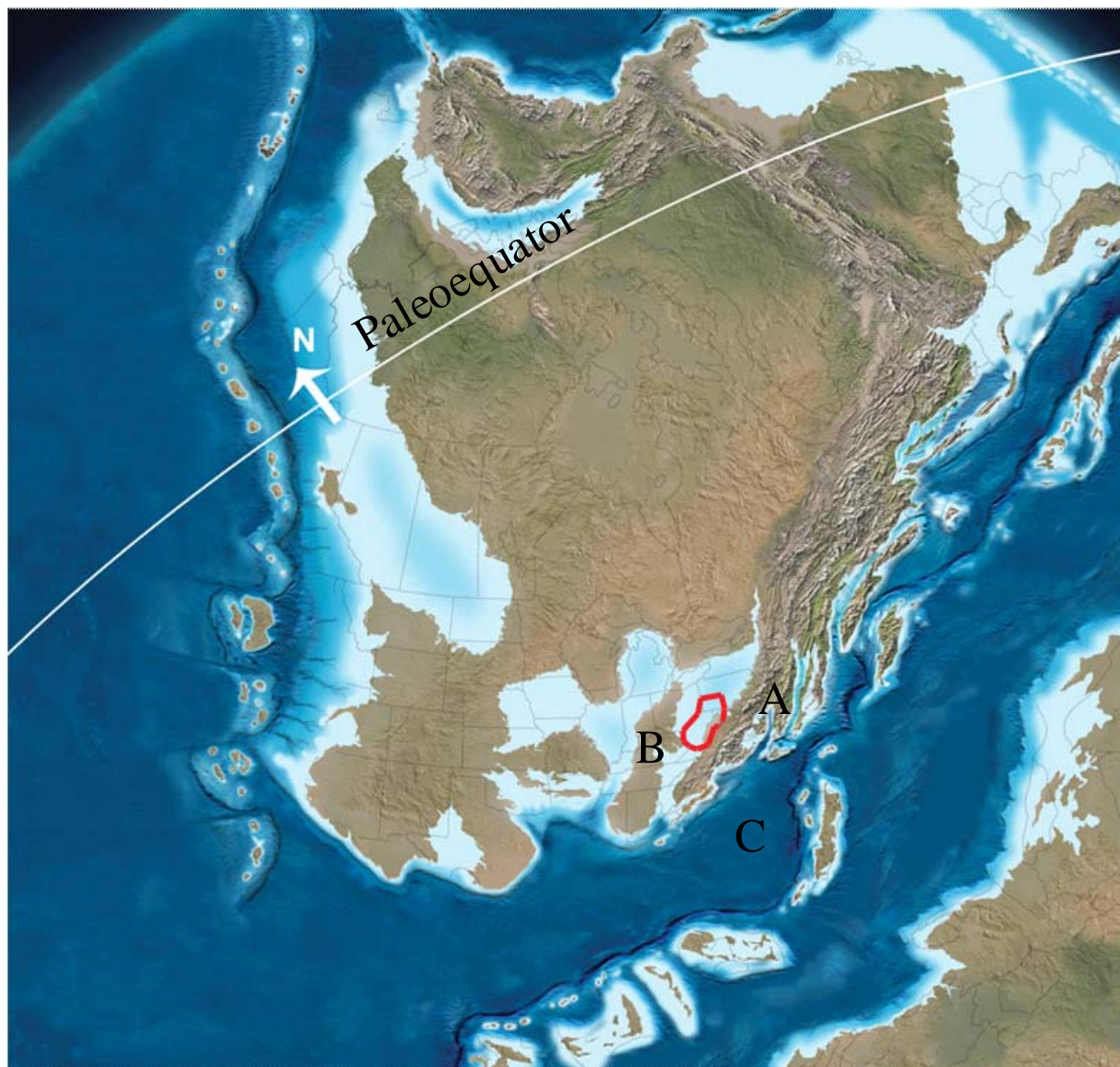
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## Figures



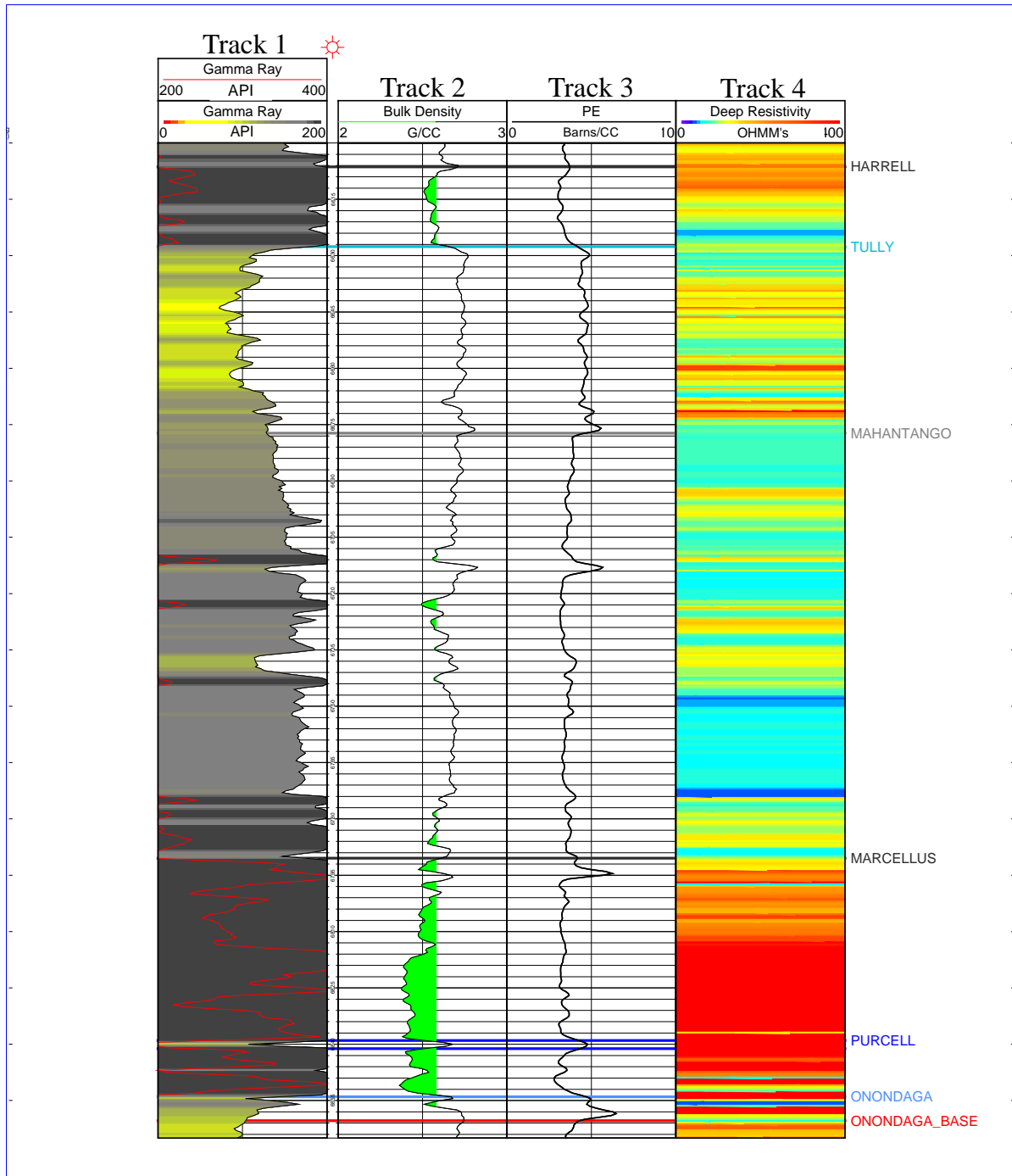
**Figure 1.**-The study area encompasses of the state of West Virginia and southwest Pennsylvania. It is located in the geological province of the central Appalachian basin and covers an area of approximately 23,500 mi<sup>2</sup> (60,865 km<sup>2</sup>).



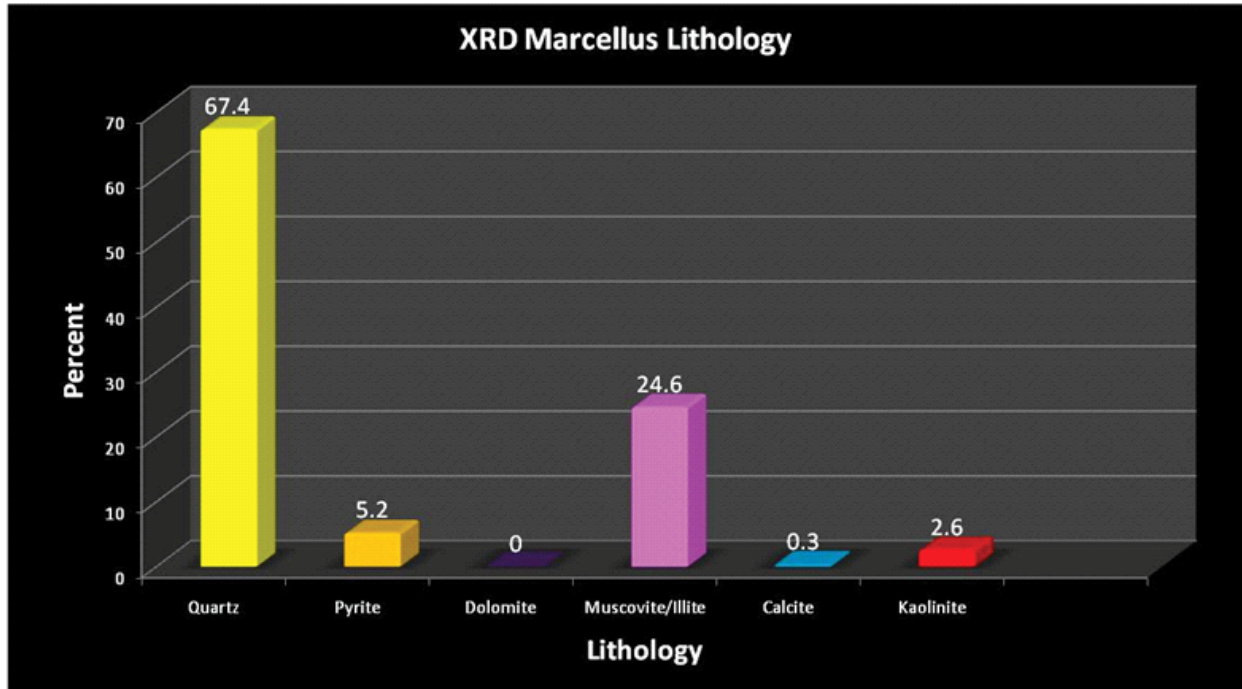
**Figure 2.-**The study area is outlined in red on the paleogeographic interpretation of the Middle Devonian (385 Ma). The paleogeographic features that surround the study area are the Acadian Mountains (A) to the east, the Cincinnati Arch (B) to the west and the Rhecic Ocean (C) to the south. This time is significant because it represents the beginning of the Devonian-Mississippian Anoxic Event in the central Appalachian basin. Modified from Blakey (<http://jan.ucc.nau.edu/~rcb7/RCB.html>)

<b>Devonian</b>	<b>Upper</b>	<b>Gordon</b>
		<b>Alexander</b>
		<b>Huron</b>
		<b>Rhinstreet Shale</b>
		Harrell Shale
	<b>Middle</b>	Tully Limestone
		Mahantango Shale
		Marcellus Shale
		Onondaga Limestone
		<b>Huntersville Chert</b>
		<b>Needmore Shale</b>
		<b>Oriskany Sandstone</b>

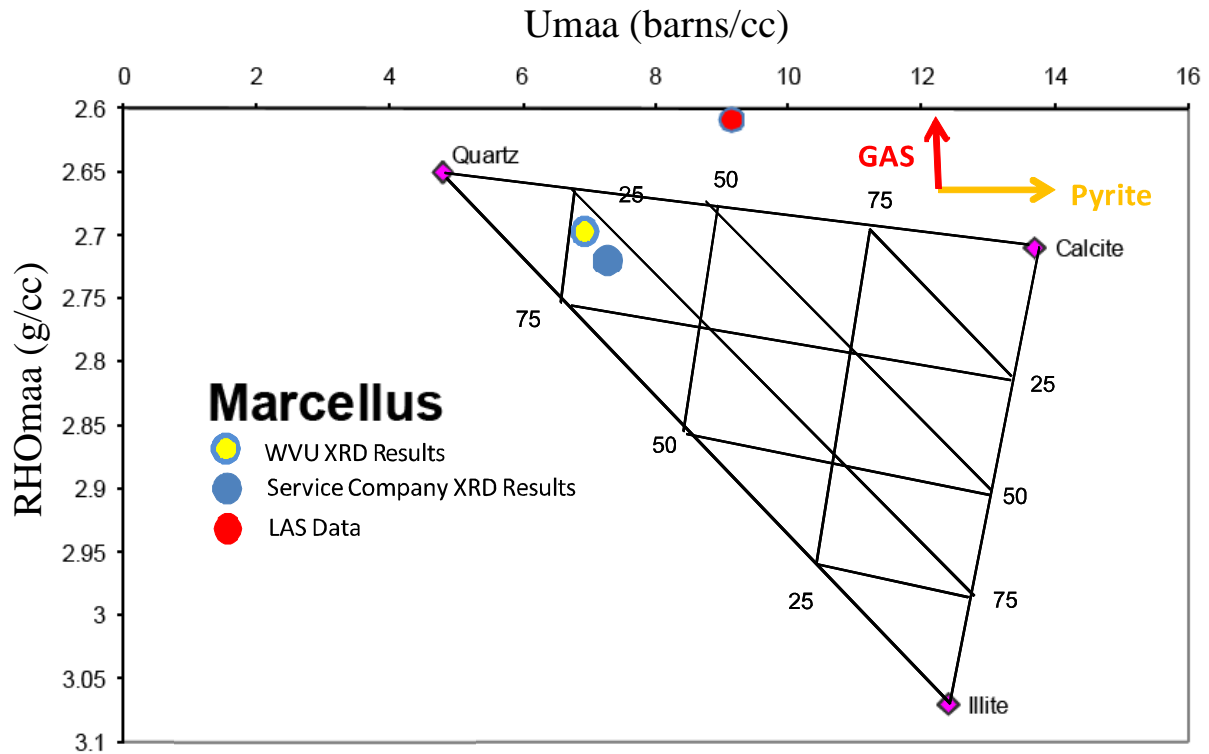
**Figure 3.** Stratigraphic column for the study area. Units that are the subject of this study are highlighted in green.



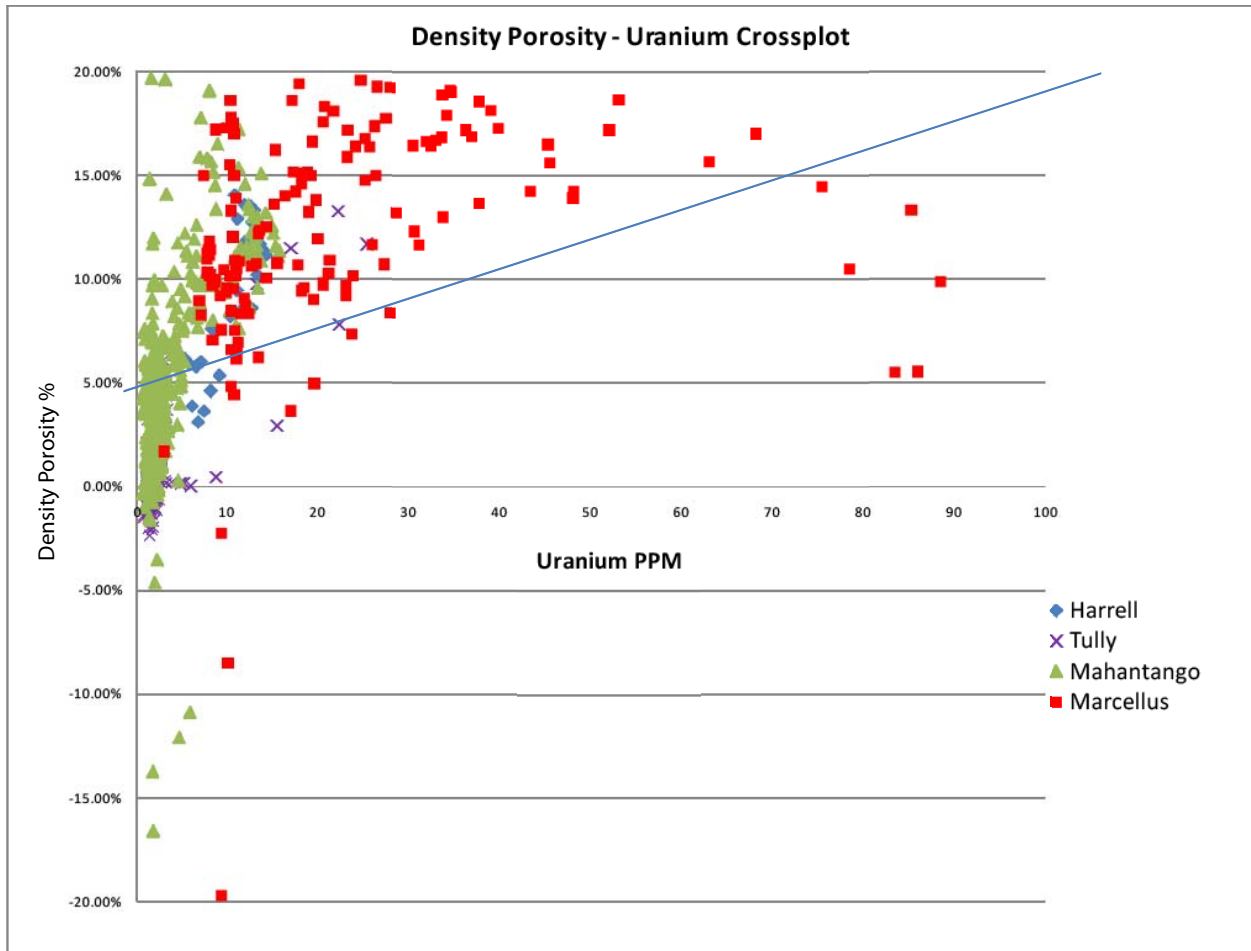
**Figure 4.** Type log for the interval in the study area of West Virginia and southwest Pennsylvania. The gamma ray curve is plotted on track 1 and ranges from 0 to 200 API. When the gamma ray exceeds 200 API it wraps around and is outlined in red. The bulk density curve is plotted in track two and is shaded green for bulk density values less than 2.55 g/cc. The PE curve is plotted on track 3 and ranges from 0 to 10 barns/cc. The Resistivity curve is plotted in track four and is color coded. The colder colors represent lower resistivity measurements where as the warmer colors represent up to 400 OHMM's.



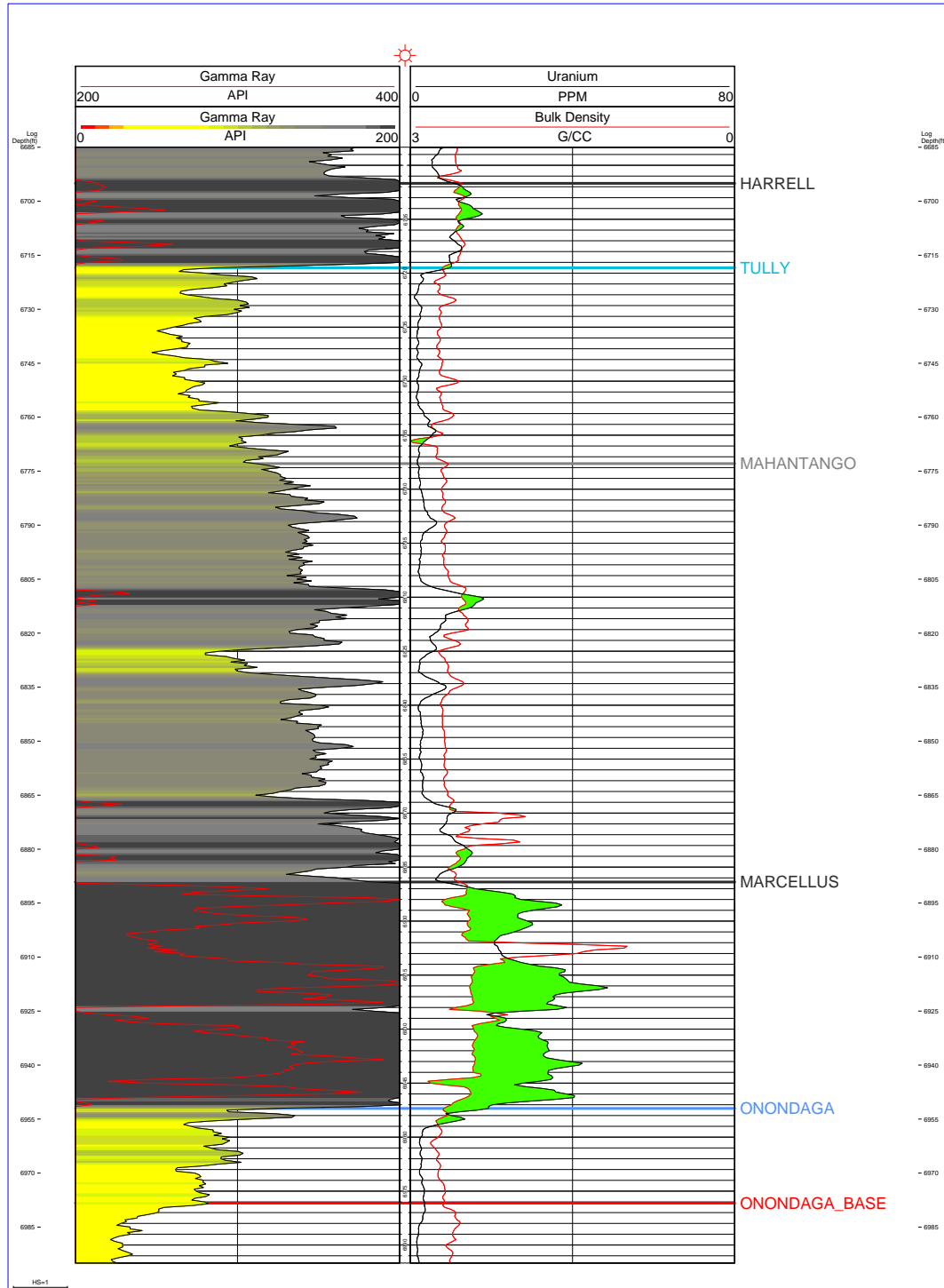
**Figure 5.-** Example of X-Ray Diffraction (XRD) results for a single core sample from the Marcellus in the study area (Figure 7). This sample has a high amount of quartz (67%) and fairly low amount of clay (24%), which is characteristic of the 36 Marcellus Shale core samples examined throughout the study area. Also it is important to identify the significant amount of pyrite. This sample has about 5% but the samples can range from 5-10% pyrite.



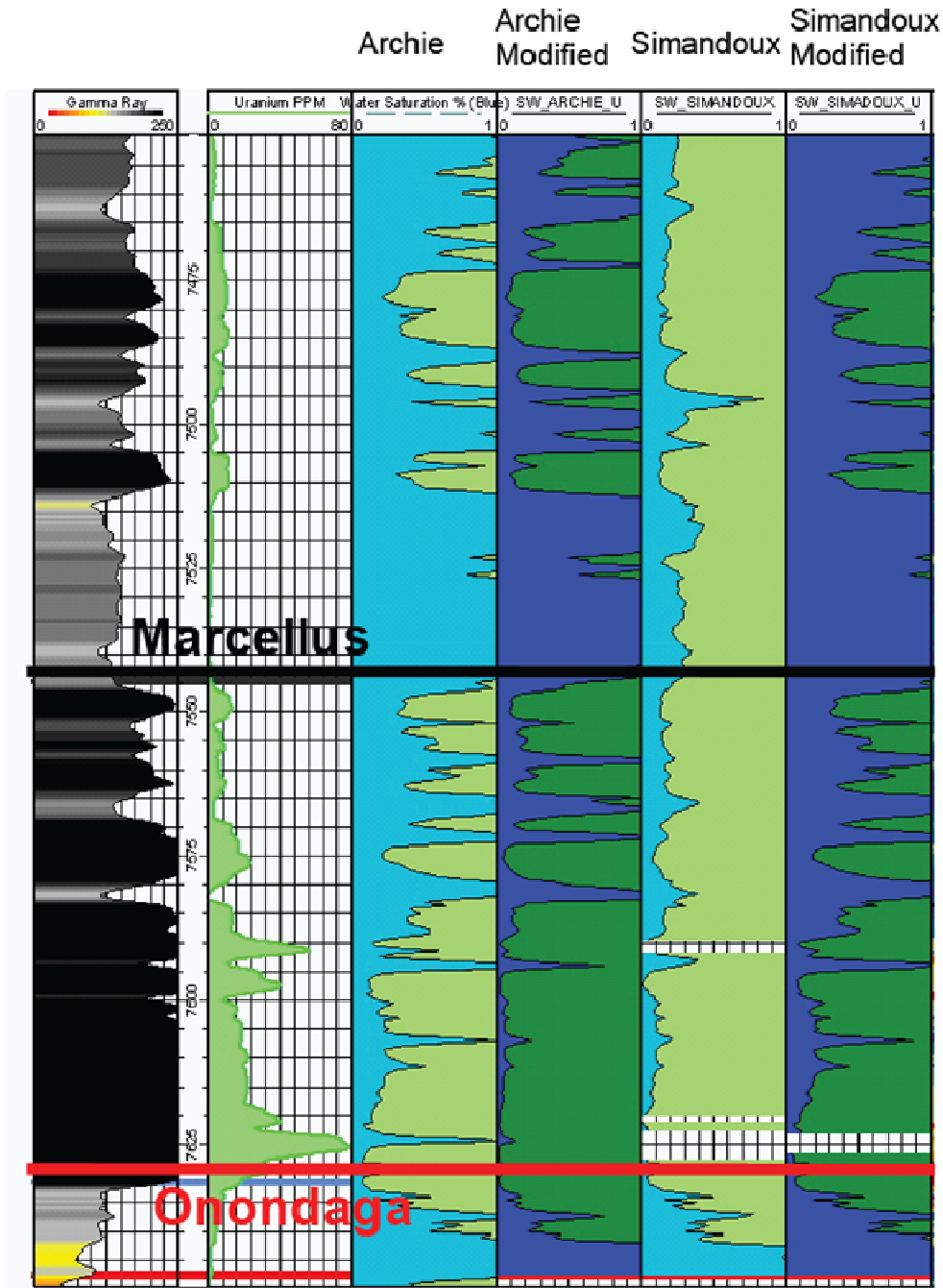
**Figure 6.** Example of a Rhomaa Umaa plot compared with XRD results from a single core sample of the Marcellus Shale. XRD results for the same sample analyzed at both West Virginia University and provided by a service company are shown (WVU yellow and the service company blue). The red circle is the result of the Rhomaa-Umaa crossplot for the same interval represented by the core sample showing that the effects of the small amount of pyrite (pulling the data to the right due to the high number of electrons associated with the iron in pyrite), and the gas pulling the data above the lithologic triangle (low Rhomaa due to the low density of gas). The influence of these two components must be taken into consideration when attempting to model the Marcellus lithology and petrophysical parameters (e.g., porosity).



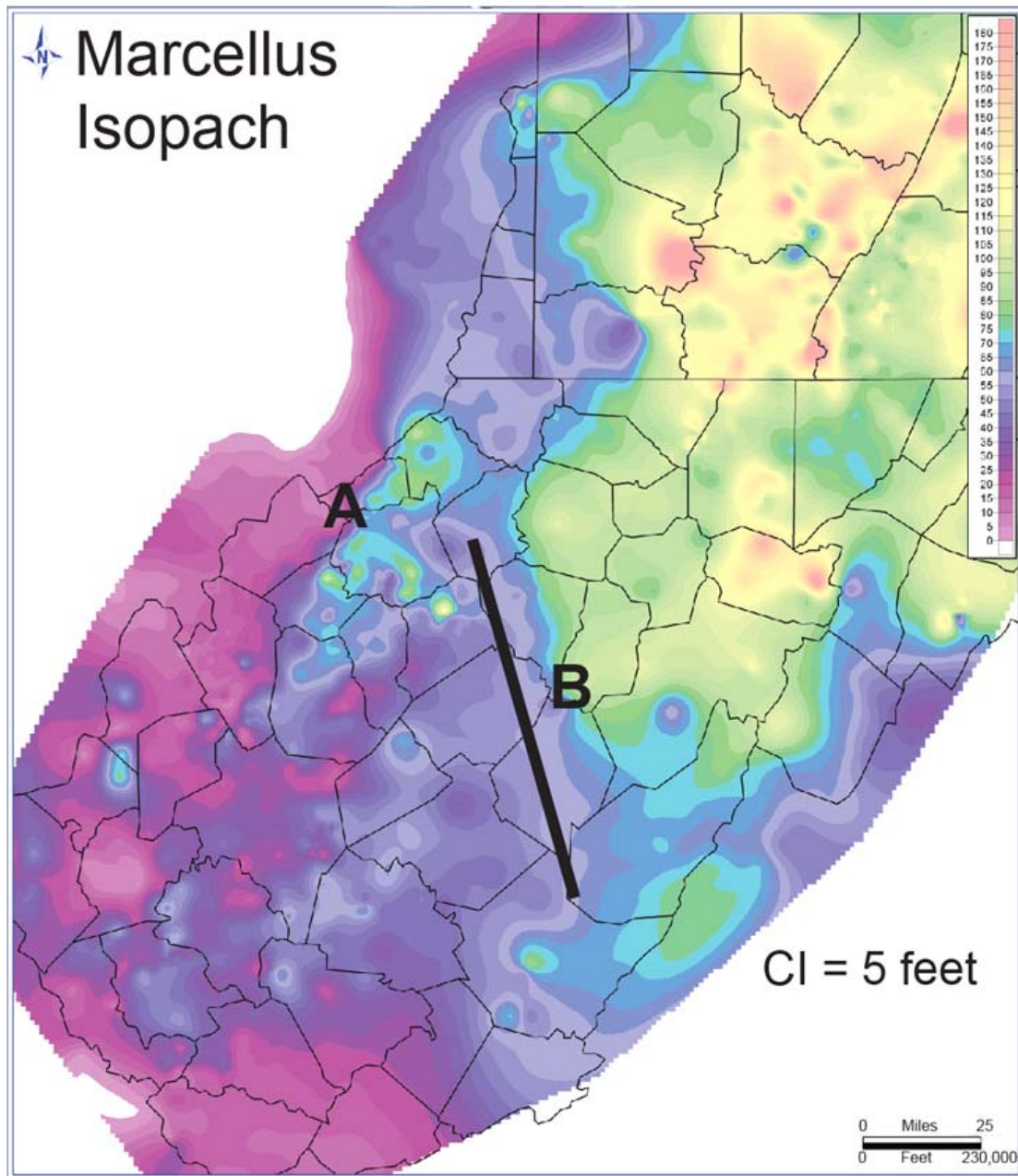
**Figure 7.** Crossplot of Uranium in ppm versus density porosity. Anything above the blue line is considered to be free gas or sorbed gas to organic matter.



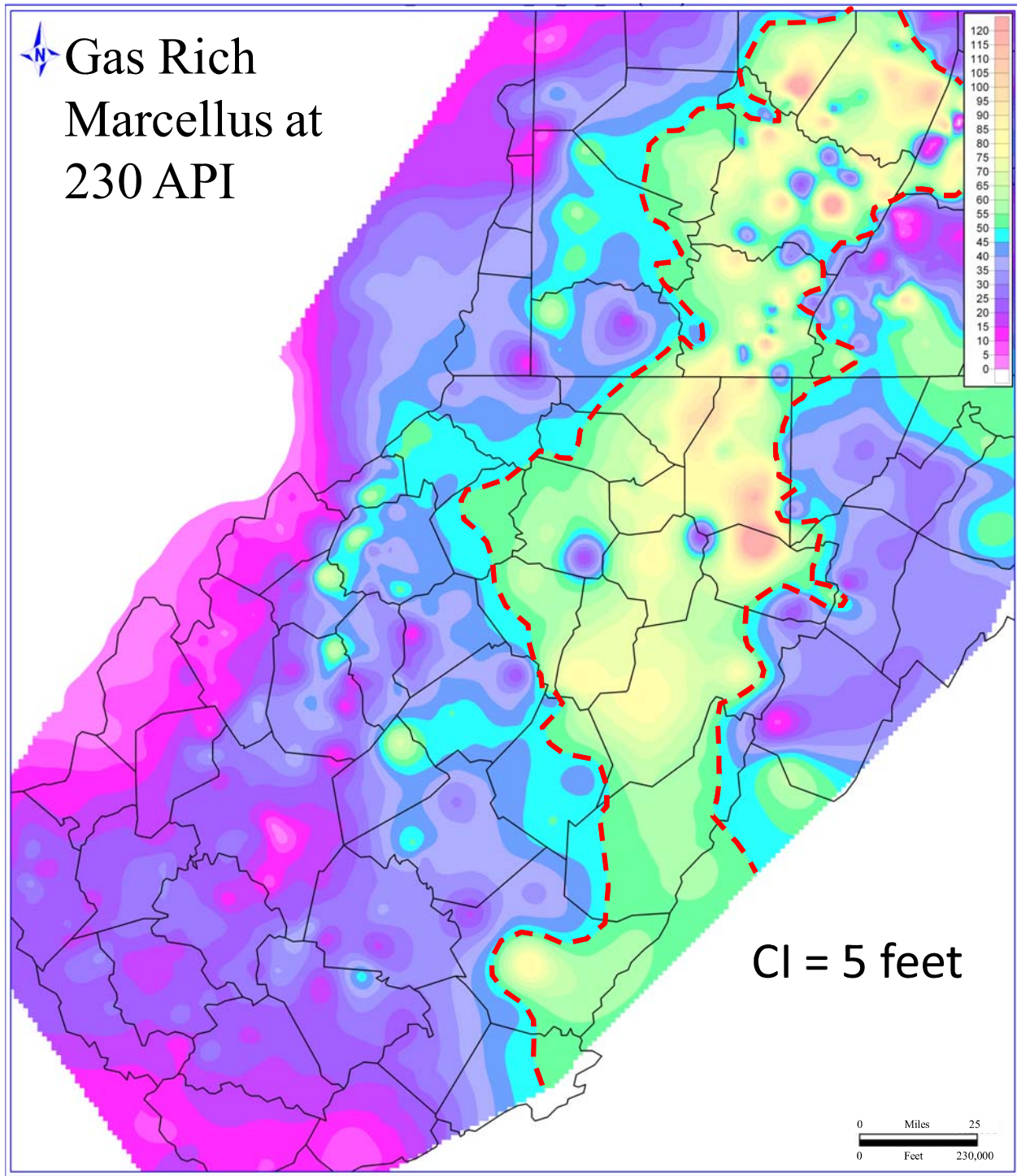
**Figure 8.** Uranium content and density porosity can be plotted together (Track 2) to highlight potential gas-rich intervals. Using an appropriate scale, zones where the U-content exceeds the bulk density value are highlighted, and interpreted as having a high potential as gas-rich intervals. In addition, to the identification of gas-rich intervals in the Marcellus Shale, similar gas-rich intervals are indicated in the Mahantango and Harrell shale units.



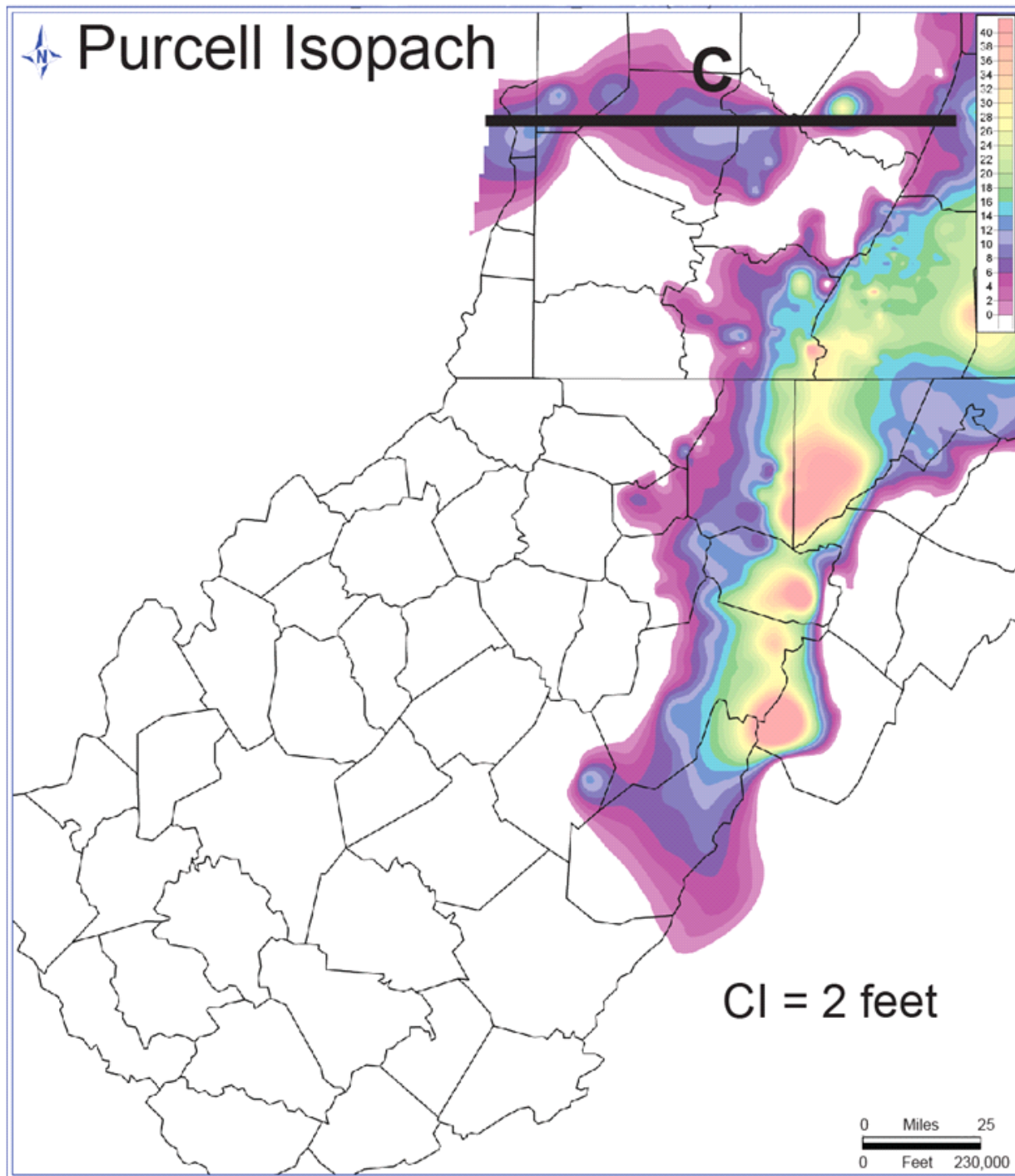
**Figure 9.** Log illustrating multiple approaches to calculating water and gas saturation in the Marcellus Shale. The light blue and dark blue represent  $S_w$  and the light green and dark green represent  $S_g$ . The Archie equation significantly overestimates water saturations (Track 3). Incorporating Uranium into a modified Archie equation provides a better estimate of gas and water saturation (Track 4). The Simandoux equation overestimates intervals of high gas content (Track 5). Relative Uranium content ( $V_{uran}$ ) was substituted for  $V_{sh}$  to construct a modified Simandoux correction for Archie equation (Track 6). We believe the substitution of the  $V_{uran}$  ratio can provide an improved estimate of gas and water saturation in the organic-rich shale units of the Appalachian basin.



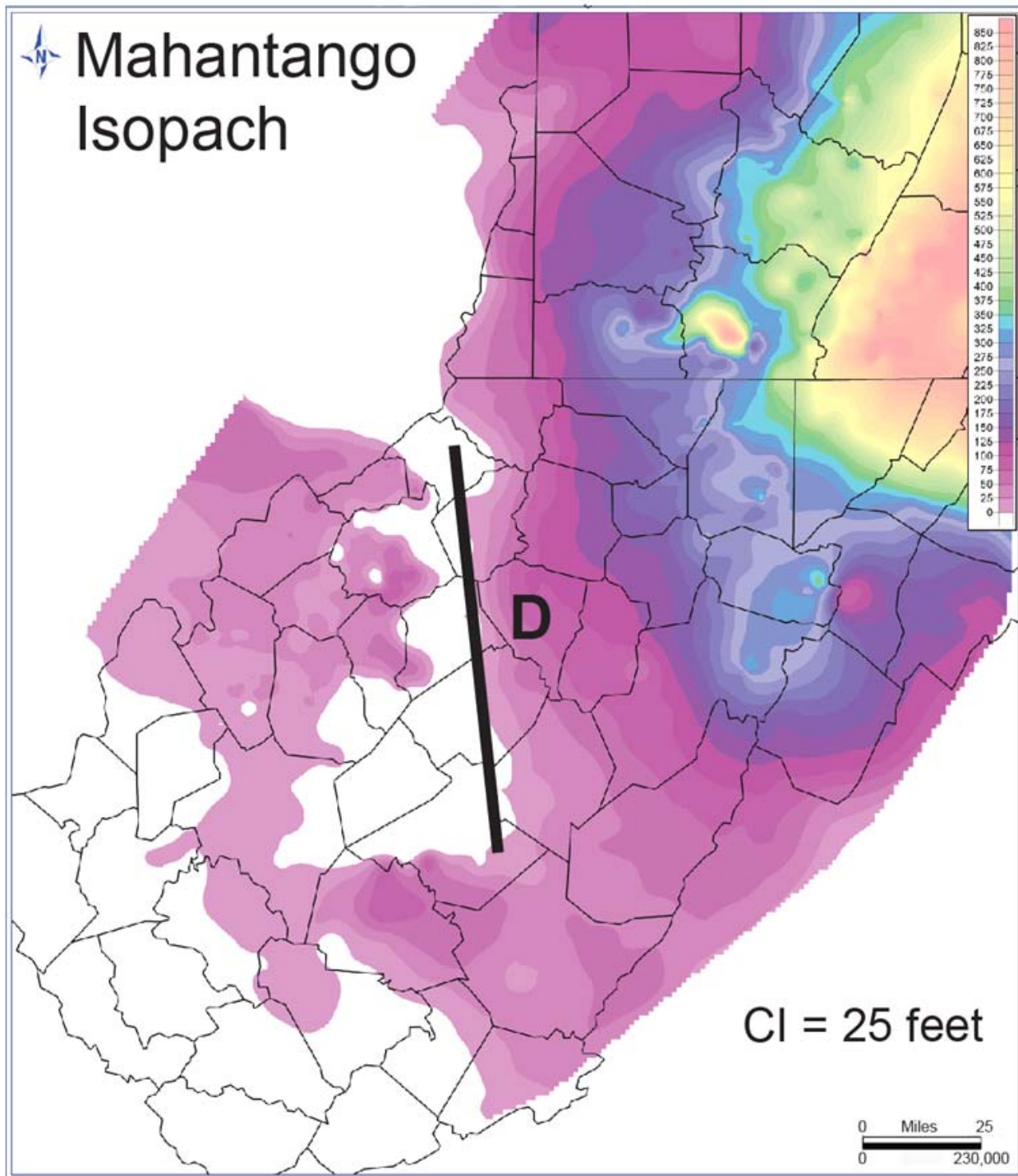
**Figure 10.** Isopach of the Marcellus Shale across the study area showing a decrease in thickness from over 180 feet (54.9 m) in the northeast to less than 10 feet (3m) in southwest West Virginia. Rapid decrease in thickness is concentrated along a northwest to southeast trend from Doddridge to Pocahontas counties in West Virginia (B). This feature persists and influences the deposition of the overlying units (Figure 13-15) An anomalous thick in the trends southwest to northeast from Roane to Tyler counties, West Virginia (A), and is associated with the west-bounding limb of the Rome Trough structure. Trend A suggests that the Rhome trough was active during Marcellus deposition but does not appear to influence the overlying units.



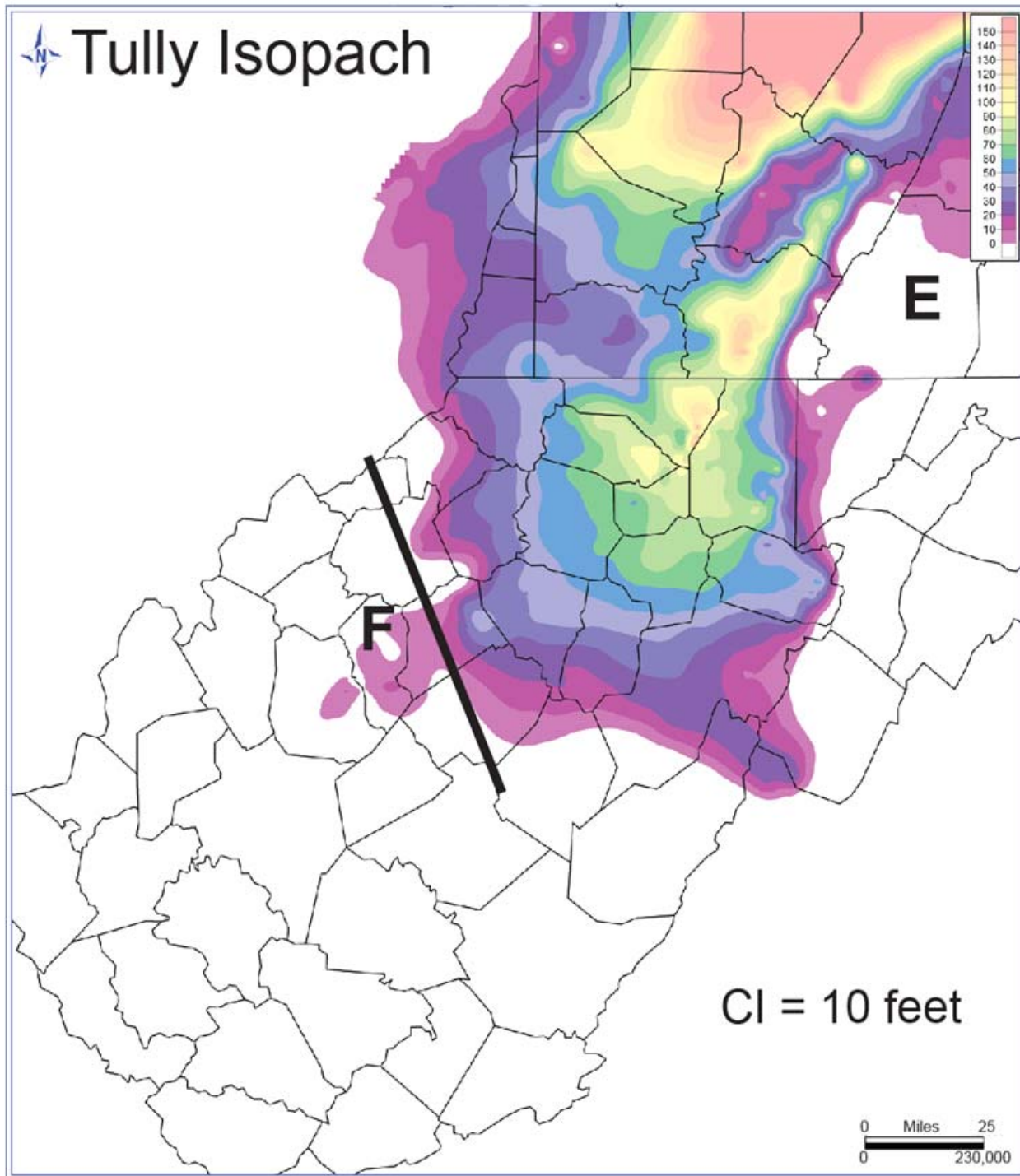
**Figure 11.** Isopach map of intervals of the Marcellus Shale with gamma-ray values greater than 230 API. The thickness of elevated gamma-ray curve (>230 API) is used as a proxy for thick organic-rich intervals in the Marcellus Shale. The thickest potential gas-rich intervals are associated with intermediate thicknesses of the Marcellus Shale in a zone from central and north-central West Virginia to southwest Pennsylvania (red dashed line).



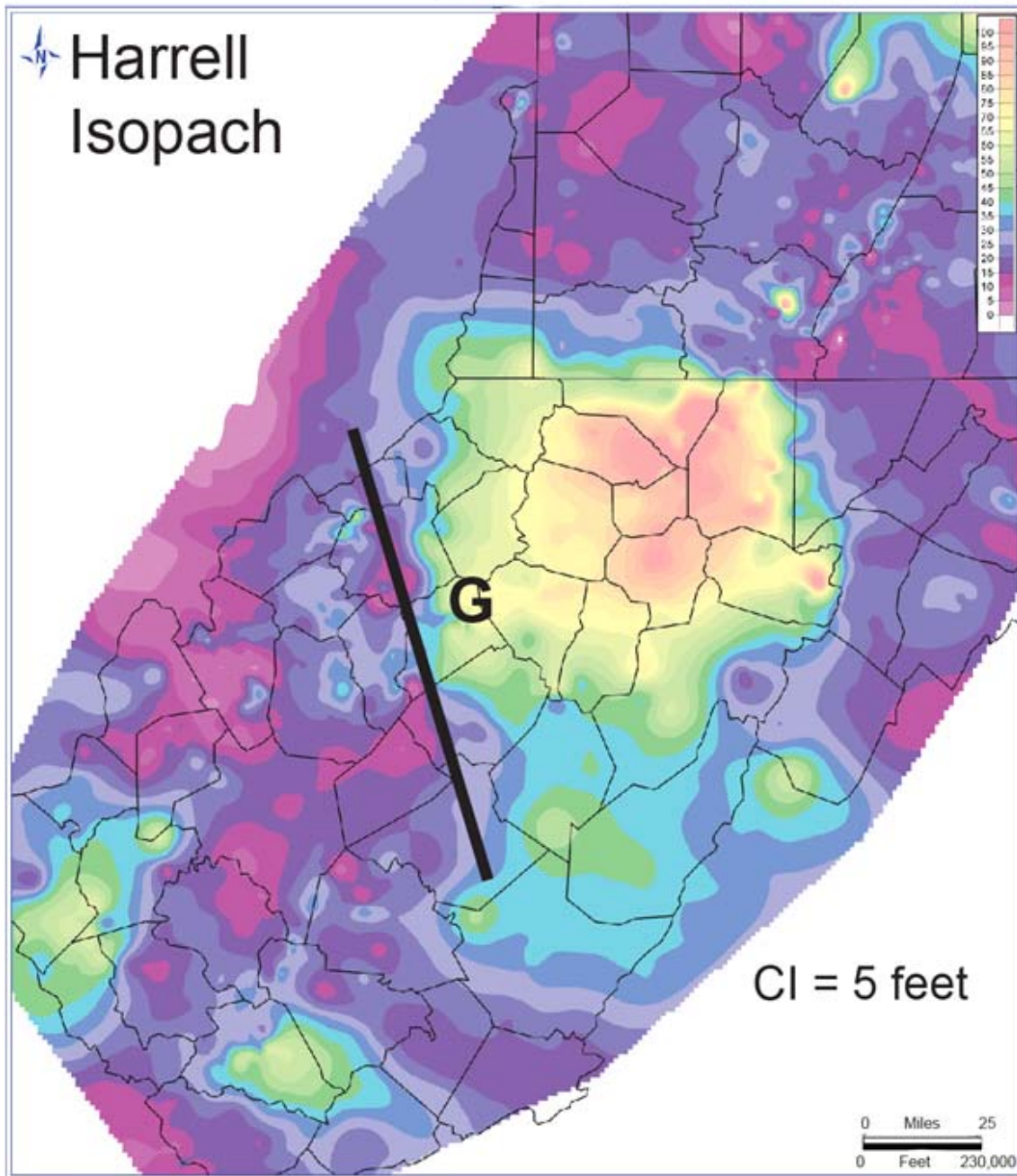
**Figure 12.** Isopach of the Purcell Limestone Member within the Marcellus Shale showing a northeast to southwest trend and the limestone unit generally does not occur in the west or central regions of the study area. The one exception is the thin west to east trend in the northern region of the study area (C). The relationship between the Purcell and the enclosing Marcellus Shale might be better explained by relatively localized anoxic environments influenced by factors such as sediment supply, paleo-topography and water chemistry.



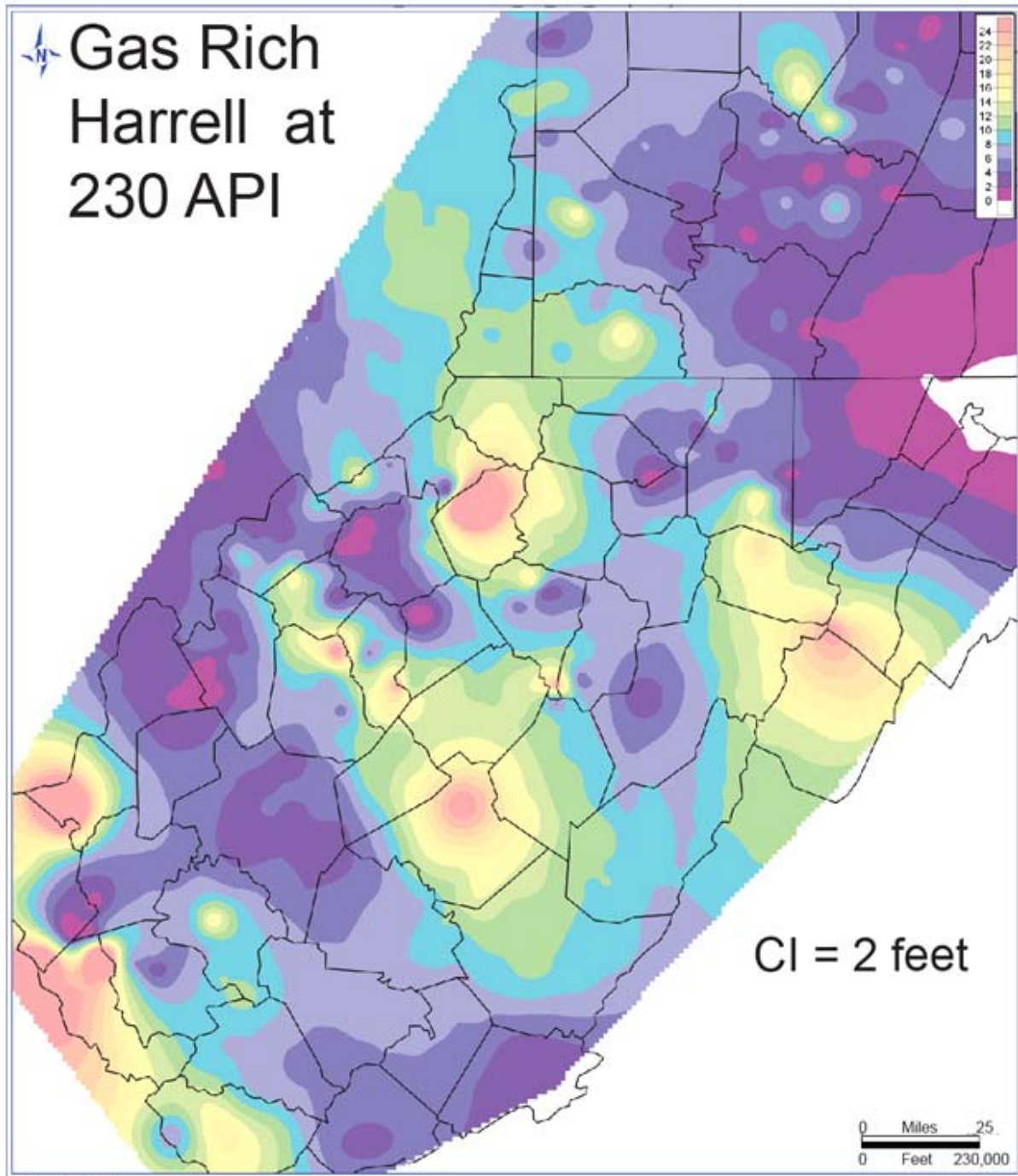
**Figure 13.** Isopach of the Mahantango Shale showing that the unit can be as thick as 800 feet (243.9 m) in the northeast of the study area and decreases to the south and to the west. The thick organic-rich Marcellus Shale (Figure 11) appears to wrap around the area where the overlying Mahantango is thickest. The northwest to southwest trend observed in the Marcellus Shale (Figure 11) appears to affect the southwest extent of the Mahantango Shale (D).



**Figure 14.** Isopach of the Tully Limestone showing decreases in thickness to the south and east. The Tully is thickest to the north coinciding with the thinning of the underlying Mahantango Shale (Figure 13) and the Tully is absent where the Mahantango is thickest (E). The southern extent of the Tully Limestone is marked by a northwest to southeast trend in the same geographic area as recognized in the underlying Marcellus and Mahantango (Figures 10-13).



**Figure 15.** Isopach of the Harrell Shale illustrating a thick in north-central West Virginia. There is a rapid change in thickness in the Harrell (G) that is recognized in the underlying Tully, Mahantango, and Marcellus (Figures 10-14).



**Figure 16.** Isopach of the thickness of Harrell Shale with gamma ray values greater than 230 API was constructed showing the thick potentially gas-rich interval running in an arc through central West Virginia into the northern panhandle and extreme southwest Pennsylvania and is offset from the thick in the underlying Mahantango Shale (Figure 13).